CLIMATE CHANGE:

WHAT WE KNOW, WHAT WE DON'T KNOW, WHAT WE CAN DO, & WHAT HAPPENS IF WE DON'T

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Contents

The cumulative scientific evidence is unequivocal: Climate change is a threat to human well-being and planetary health. Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all.

—IPCC Working Group II, March 2022[1]

Time is up and we know it —Deloitte Economic Group, 2022[2]

1. What are the key established facts concerning the effects of climate change?

Global average temperatures have increased by 1.1° C since 1880.[3]

The global climate is warming at a rate 10 times faster than any previous period in the geological record. Since 1981, the rate of warming has been at +0.18° C per decade. The ten warmest years in the 1880–2022 record have all occurred since 2010.[4] The World Meteorological Organization (WMO) predicts that global average temperature will at least temporarily reach 1.5° C above preindustrial levels sometime before 2028.[5]

Increased atmospheric levels of five greenhouse gases (ghgs) correlate to, and account for, the warming trend:

- Water vapor
- Carbon dioxide (CO_2)
- Methane (CH_4)
- Nitrous oxide (N_2O)
- Chlorofluorocarbons (CFCs)[6]

Human activity is the major contributor to this increase in ghgs and associated warming.[7]

The major predictable effects of warming include:

- Change will continue through this century and beyond
- Temperatures will continue to rise[8]

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1. "Climate Change 2022: Impacts, Adaptation and Vulnerability. Summary for Policymakers." Section D.5.3. IPCC Working Group II, March 2022, https://www.ipcc.ch/report/ar6/wg2/.
2. Pradeep Philip, Claire Ibrahim, and Cedric Hodges, "The Turning Point: A Global Summary," Deloitte Economics Institute, May 2022, https://www.deloitte.com/content/dam/assets-shared/legacy/docs/gx-global-turning-point-report.pdf.
3. "World of Change: Global Temperatures," Earth Observatory at NASA Goddard Space Flight Center, accessed April 6, 2022, https://earthobservatory.nasa.gov/world-of-ange/global-temperatures.
4. Rebecca Lindsey and LuAnn Dahlman, "Climate Change: Global Temperature," National Oceanic and Atmospheric Administration, January 18, 2023, https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature.
5. Matthew Cappucci, "Global Temperatures Could Soon Briefly Breach Climate Threshold, Scientists Warn," *Washington Post*, May 17, 2023, https://www.washingtonpost.com/climate-environment/2023/05/17/climate-change-threshold-el-nino-record-global-heat/.
6. "The Causes of Climate Change," NASA Jet Propulsion Laboratory and California Institute of Technology, accessed February 6, 2020, https://climate.nasa.gov/causes/.
7. "The Causes of Climate Change."
8. Projections are that global average atmospheric temperatures will likely increase by 1.5° C within the next two decades, and, based on current policies, 3° C by the year 2100. Brad Plumer and

- Frost-free season (and growing season) will lengthen
- Changes in precipitation patterns will occur
- There will be more, and more severe, droughts and heat waves
- Hurricanes will become stronger and more intense
- Sea level will rise from 1 to 8 feet by 2100, due to melting glaciers and ice sheets, and to the expansion of sea water as it warms
- The Arctic is likely to become ice-free[9]
- Increased wildfires, flooding, and crop failures[10]
- Effects on human health, including deadly heat and humidity[11] and degradation of air, water, food, and shelter.[12]
- Currently populated regions of the planet, especially near the equator, will become effectively uninhabitable by the end of the 21st century, displacing billions of people.[13]

Ocean acidification is not directly a result of climate change, but is a separate, undesirable global effect attributed to the increase in CO_2.[14]

Biodiversity loss during the industrial era has been extensive ("83% of wild mammal biomass, and half that of plants"), largely due to habitat loss and pollution. Climate change will contribute and likely accelerate further biodiversity loss.[15]

Henry Fountain, "A Hotter Future Is Certain, Climate Panel Warns. But How Hot Is Up to Us," *New York Times,* August 9, 2021, https://www.nytimes.com/2021/08/09/climate/climate-change-report-ipcc-un.html.

9. "The Effects of Climate Change," NASA Jet Propulsion Laboratory and California Institute of Technology, accessed February 6, 2020, https://climate.nasa.gov/effects/.
10. Oliver Milman, Andrew Witherspoon, Rita Liu, and Alvin Chang, "The Climate Disaster is Here—This is What the Future Looks Like," *The Guardian*, October 14, 2021, https://www.theguardian.com/environment/ng-interactive/2021/oct/14/climate-change-happening-now-stats-graphs-maps-cop26.
11. Casey Crownhart, "How Hot Is Too Hot for the Human Body?" *MIT Technology Review*, July 10, 2021. https://www.technologyreview.com/2021/07/10/1028172/climate-change-human-body-extreme-heat-survival/.
12. "Climate Change and Health," World Health Organization, October 30, 2021, https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health.
13. T. M. Linton, C. Xu, J. F. Abrams, et al. "Quantifying the Human Cost of Global Warming," Nature Sustainability, May 23, 2023, https://doi.org/10.1038/s41893-023-01132-6.
14. "Science and Climate: Ocean Acidification," University of California, Davis, accessed February 8, 2020, https://climatechange.ucdavis.edu/science/ocean-acidification/.
15. H. O. Pörtner, R. J. Scholes, J. Agard, E. Archer, A. Arneth, X. Bai, D. Barnes, M. Burrows, L. Chan, W. L. Cheung, S. Diamond, C. Donatti, C. Duarte, N. Eisenhauer, W. Foden, M. A. Gasalla, C. Handa, T. Hickler, O. Hoegh-Guldberg, K. Ichii, U. Jacob, G. Insarov, W. Kiessling, P. Leadley, R. Leemans, L. Levin, M. Lim, S. Maharaj, S. Managi, P. A. Marquet, P. McElwee, G. Midgley, T. Oberdorff, D. Obura, E. Osman, R. Pandit, U. Pascual, A. P. F. Pires, A. Popp, V. Reyes-García, M. Sankaran, J. Settele, Y. J. Shin, D. W. Sintayehu, P. Smith, N. Steiner, B. Strassburg, R. Sukumar, C. Trisos, A. L. Val, J. Wu, E. Aldrian, C. Parmesan, R. Pichs-Madruga, D. C. Roberts, A. D. Rogers, S. Díaz, M. Fischer, S. Hashimoto, S. Lavorel, N. Wu, H. T. Ngo, *IPBES-IPCC Co-sponsored Workshop Report on Biodiversity and Climate Change*, IPBES and IPCC, 2021, p. 14, https://doi.org/10.5281/zenodo.4782538.

1.1 "When did they know?" A timeline

1856: Eunice Foote did experiments to show that atmospheric CO_2 increases the absorption of thermal radiation from the sun, raising the temperature of the atmosphere: the greenhouse effect. John Tyndall published similar findings in 1859, apparently independently of Foote's work.[16]

1912: A New Zealand newspaper published a short article titled "Coal Consumption Affecting Climate" in August, 1912. The article described the connection between burning coal and increased CO_2 levels, resulting in the greenhouse effect and a rise in earth temperatures.[17]

1956: Physical oceanographer Roger Revelle testified on March 8 "in support of federal funding to monitor atmospheric and oceanic carbon dioxide levels [which] was the first time that manmade global warming was discussed in the Congressional record."[18]

1957-58: The International Geophysical Year. On May 1, in Congressional testimony for support of the IGY, Roger Revelle addressed the likely effects of continuing to burn coal, oil, and natural gas: "If we look at the probable amounts of these substances that will be burned in the future, it is fairly easy to predict that the carbon dioxide content of the atmosphere could easily increase by about 20 percent. This might, in fact, make a considerable change in the climate. It would mean that the lines of equal temperature on the earth would move north and the lines of equal rainfall would move north and that southern California and a good part of Texas, instead of being just barely livable as they are now, would become real deserts."[19]

A scene from the International Geophysical Year: "It's June 1957, and Prince Philip is addressing the nation, warning about the threat of rising seas caused by melting glaciers."[20]

1966: James Lovelock prepared a report titled "Combustion of Fossil Fuels: Large Scale Atmospheric Effects" for Shell Oil. Lovelock identified two trends, both due to fossil fuel use: the greenhouse effect causing global temperature increase, and atmospheric turbidity (air pollution) causing global temperature decrease. He predicted that the cooling effect would predominate over the warming effect.[21]

James R. Garvey, president of Bituminous Coal Research Inc., a coal mining and processing research organization, published an article in the *Mining Congress Journal:*

> "There is evidence that the amount of carbon dioxide in the earth's atmosphere is increasing rapidly as a result of the combustion of fossil fuels," wrote Garvey. "If the future rate of increase continues as it is at the present, it has been predicted that, because the CO_2

16. Natasha Ishak, "Meet Eunice Foote, the Mother of Climate Science Whose Work Was Ignored Because of Her Sex," All That's Interesting, March 27, 2020, https://allthatsinteresting.com/eunice-foote and Roland Jackson, "Eunice Foote, John Tyndall and a Question of Priority," *Notes and Records: The Royal Society Journal of the History of Science*, February 13, 2019, https://doi.org/10.1098/rsnr.2018.0066
17. Sustainable Business Network, 2016, "This is from a local newspaper letters column. . .," Facebook, image, October 12, 2016, https://www.facebook.com/SustainableBusinessNetworkNZ/photos/a.403513914925/10154115514619926/.
18. Brad Johnson, "In 1957, Climate Scientist Warned Congress That Fossil-Fueled Global Warming Could Turn California into a Desert," *Hill Heat*, September 10, 2020, http://www.hillheat.com/articles/2020/09/10/in-1957-climate-scientist-warned-congress-the-continued-burning-fossil-fuels-could-turn-california-into-a-desert?s=03
19. Johnson, September 10, 2020.
20. Alice Bell, "'Spandex Jackets for Everyone' – the International Geophysical Year," A Short History of Climate Change (blog), May 24, 2017, https://www.climatehistories.com/histories/2017/5/24/spandex-jackets-one-for-everyone-the-international-geophysical-year.
21. Leah Aronowsky, "Gas Guzzling Gaia, or: A Prehistory of Climate Change Denialism," *Critical Inquiry,* vol. 47, no. 2, Winter 2021, https://doi.org/10.1086/712129.

> envelope reduces radiation, the temperature of the earth's atmosphere will increase and that vast changes in the climates of the earth will result.
>
> "Such changes in temperature will cause melting of the polar icecaps, which, in turn, would result in the inundation of many coastal cities, including New York and London," he continued.[22]

1972: Lester Machta, with the National Oceanographic and Atmospheric. Agency, presented a paper "Prediction of CO_2 in the Atmosphere" at a conference on Carbon and he Biosphere in Upton, NY. On 17 May 1972 the *New York Times* reported Machta's prediction that, following current trends, atmospheric CO_2 levels would increase by 20% and drive a global temperature increase of 1° F by the year 2000.[23]

1977: "The most-publicized report came from the National Academy of Sciences in 1977. It warned that average temperatures may rise 6 degrees Celsius by 2050 due to the burning of coal."[24] Most of the research published in this report, *Energy and Climate,* had been presented at an American Geophysical Union meeting in December 1974.[25]

On 7 July 1977, Frank Press, director of the Office of Science and Technology Policy in the U. S. White House, sent a memo to President Carter with the subject "Release of Fossil CO_2 and the Possibility of a Catastrophic Climate Change." Secretary of Energy James Schlesinger advised the President that "the policy implications of this issue are still too uncertain to warrant Presidential involvement and policy initiatives."[26]

Exxon conducted its own analysis and modeling of global warming driven by fossil fuel use beginning in 1977. A 2023 review of this research concluded that "in private and academic circles since the late 1970s and early 1980s, ExxonMobil predicted global warming correctly and skillfully."[27]

1981 and earlier: Internal documents show that Exxon and ExxonMobil knew that fossil fuels affected climate change in 1981. They considered regulation around this affect to be a business risk.[28] Exxon has been accused of funding climate denial research and think tanks in the intervening years.[29]

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22. Élan Young, "Exxon knew—and so did coal," *Grist*, November 29, 2019, https://grist.org/energy/exxon-knew-and-so-did-coal/.
23. David A. Andelman, "20% Rise Feared in Carbon Dioxide," *New York Times*, May 17, 1972, p. 6. Via *New York Times Archives*, https://www.nytimes.com/1972/05/17/archives/20-rise-feared-in-carbon-dioxide-expert-bases-prediction-for-year.html. The paper by Lester Machta was published in *Carbon and the Biosphere: Proceedings of the 24th Brookhaven Symposium on Biology, Upton, New York, May 16 - 18, 1972,* ed. George M. Woodwell and Erene V. Pecan, Brookhaven National Laboratory, Technical Information Center, Office of Information Services, United States Atomic Energy Commission, August 1973, https://www.biodiversitylibrary.org/item/22618.
24. Ben Block, "A Look Back at James Hansen's Seminal Testimony on Climate, Part One," *Grist*, June 16, 2008, https://grist.org/article/a-climate-hero-the-early-years/.
25. National Academies of Sciences, Engineering, and Medicine, *Energy and Climate: Studies in Geophysics*, Washington, DC: The National Academies Press, 1977, https://doi.org/10.17226/12024.
26. Emma Pattee, "The 1977 White House Climate Memo that Should Have Changed the World," *The Guardian*, June 14, 2022. https://www.theguardian.com/environment/2022/jun/14/1977-us-presidential-memo-predicted-climate-change.
27. G. S. Supran, S. Rahmstorf, and N. Oreskes, "Assessing ExxonMobil's Global Warming Projections," *Science*, vol. 379, no. 6628, 2023, https://doi.org/10.1126/science.abk0063.
28. Suzanne Goldberg, "Exxon Knew About Global Warming More Than 30 Years Ago," *Mother Jones*, July 9, 2015, https://www.motherjones.com/environment/2015/07/exxon-climate-change-email/.
29. "ExxonMobil's Funding of Climate Science Denial," *Desmog*, accessed February 8, 2020, https://www.desmogblog.com/exxonmobil-funding-climate-science-denial

By 1989 the company was a founder of the Global Climate Coalition, a group of corporations that worked "to stall action on climate change."[30]

As of Fall 2019, the New York attorney general's office was suing Exxon, "arguing that one of the world's largest oil and gas companies misled its shareholders and the public by misrepresenting the risks that climate change poses to the value of its oil and gas assets."[31]

1988: James Hansen was an early prominent climate scientist at NASA's Goddard Institute. In 1988, he told a U.S. Senate Committee that he was 99 percent confident that global temperatures were increasing, and that this was due to human activity rather than natural variation.[32]

1988–90: The Intergovernmental Panel on Climate Change is a large body of scientific experts, established by the World Meteorological Organization and the United Nations Environment program in 1988, to research and report on the science of climate change. In the 1990 report, Working Group I reported scientific certainty that human activity was contributing to greenhouse gas increases in the atmosphere, and that this was responsible for over half of the observed enhanced greenhouse gas effect.[33]

1989: Bill McKibben published *The End of Nature* with Random House. This was the first book that brought climate change to the attention of the general public.

1991: Shell Oil produced a 28-minute documentary on climate change, "Climate of Concern," in 1991.[34]

The Climate Accountability Institute reports that half of all CO_2 emissions since 1751 have been emitted since 1988, when "the evidence and risks of human-caused warming first became widely known."[35]

1.2 Responding to doubts and challenges to climate information

How can one respond to dismissive assertions that "Greenland was green!" or "We're coming out of the Little Ice Age" or "It's just Pacific decadal oscillation"? These and other one-line rejections of climate science pop up in the replies to any report or policy proposal involving climate change. They can come across as being very persuasive, authoritatively implying some esoteric knowledge of science or deep history that has been overlooked by scientists.

Most are built on the premise that the speaker has access to information that climate experts lack, or that experts are not considering for some (possibly nefarious) reason.

The first response to such assertions is that climate experts *also* have access to the internet, they know how to use Google, and they can in fact read the blog or watch the video in question. What

30. "Exxon Denied its Own Climate Research," Living on Earth, 2015, https://www.loe.org/shows/segments.html?programID=15-P13-00043&segmentID=1
31. Lee Wasserman, "Did Exxon Deceive Its Investors on Climate Change?" *New York Times*, October 21, 2019, https://www.nytimes.com/2019/10/21/opinion/exxon-climate-change.html.
32. Block, "A look back."
33. W. M. Adams, *Green Development: Environment and Sustainability in a Developing World*, 4th ed, Routledge, 2020, p. 69.
34. Inae Oh, "In 1991, Shell Produced This Alarming Video Warning About Climate Change Dangers," *Mother Jones*, February 28, 2017, https://www.motherjones.com/environment/2017/02/shell-climate-change-documentary/; Jelmer Mommers, "Shell made a film about climate change in 1991 (then neglected to heed its own warning)," *The Correspondent*, February 28, 2017, https://thecorrespondent.com/6285/shell-made-a-film-about-climate-change-in-1991-then-neglected-to-heed-its-own-warning/692663565-875331f6.
35. "Carbon Majors," Climate Accountability Institute, October 8, 2019. http://climateaccountability.org/carbonmajors.html

may feel like privileged, rare knowledge of some obscure phenomenon is in fact neither privileged nor rare. Anybody can access it, and they have.

The second response is that climate experts have, in fact, already looked at these possibilities. If someone became aware of and is passionately convinced by one of these explanations, after an hour or two of "doing their own research," we can expect that climate experts have already looked into it. That esoteric-sounding objection has been taken seriously. It is not included in the mainstream science because it has already been thoroughly considered and, as a result of that consideration, it has been rejected as an explanation. (That the objectors even know about these proposed alternative explanations is, ironically, due to the work of the very scientists and media that they distrust.)

Of course no one person has sufficient expertise to handle every objection. The fact that one particular person is unable to refute every such alternative explanation on the spot does not mean these explanations have not been refuted.

Expert responses to such skeptical objections are readily available, however. One comprehensive source is the "Global Warming & Climate Change Myths" page maintained by Skeptical Science, a non-profit science education organization founded by John Cook, a climate scientist. This page was compiled with the input of many, many experts in various fields. It lists 198 common climate objections, and provides both brief and more detailed explanations about why each objection fails.[36]

2. What are the major areas of uncertainty about the effects of climate change?

2.1 Uncertainty due to lack of scientific knowledge

- **Climate sensitivity**: How sensitive is atmospheric temperature to increased CO_2 levels? This concerns "the amount of global surface warming that will occur in response to a doubling of atmospheric CO_2 concentrations compared to pre-industrial levels." "Estimates have put climate sensitivity somewhere between 1.5C and 4.5C of warming for a doubling of pre-industrial CO_2 levels. This range has remained stubbornly wide, despite many individual studies claiming to narrow it."[37] "Estimates of the **equilibrium climate sensitivity (ECS)** based on observed climate change, climate models and feedback analysis, as well as paleoclimate evidence indicate that ECS is likely in the range 1.5° C to 4.5° C with high confidence, extremely unlikely less than 1° C (high confidence) and very unlikely greater than 6° C (medium confidence). The transient climate response (TCR) is likely in the range 1° C to 2.5°C and extremely unlikely greater than 3° C, based on observed climate change and climate models."[38] More recent models suggest that "ECS is high, at least ~4° C."[39]
- "The **transient climate response, TCR**, is the temperature change at the time of CO_2 doubling and the equilibrium climate sensitivity, T2x, is the temperature change after the system has reached a new equilibrium for doubled CO_2, i.e., after the additional warming commitment has been realised."[40]
- How **quickly will climate conditions respond** to reductions in ghg emissions?[41]

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36. "Global Warming & Climate Change Myths," *Skeptical Science*, 2021, https://skepticalscience.com/argument.php
37. Zeke Hausfather, "Explainer: How scientists estimate 'climate sensitivity'," CarbonBrief, June 19, 2018, https://www.carbonbrief.org/explainer-how-scientists-estimate-climate-sensitivity.
38. Matthew Collins, et al., "Long-term Climate Change," 1033.
39. James Hansen and Makiko Sato, "Global Warming in the Pipeline," Columbia University, December 13, 2022, http://www.columbia.edu/~jeh1/Documents/PipelinePaper.2022.12.22.pdf
40. "Working Group I: The Scientific Basis," Intergovernmental Panel on Climate Change, accessed February 8, 2020, https://archive.ipcc.ch/ipccreports/tar/wg1/345.htm.
41. Oliver Milman, "Global heating could stabilize if net zero emissions achieved, scientists say," *The Guardian*, January 7, 2021, https://www.theguardian.com/environment/2021/jan/07/global-heating-stabilize-net-zero-emissions; Bob Berwyn, "Many Scientists Now Say Global Warming

- There is **general uncertainty about the details of some physical/biological/chemical laws** that guide natural processes. E.g., cloud dynamics, the persistence of atmospheric aerosols that have a cooling effect[42]
- How stable are **the Antarctic ice sheets**? Are they locked to the land underneath, or not?[43]
- What is the effect of **sulfate aerosols in cooling the atmosphere** ("global dimming")? Effects are short-lived, but there are a lot of these pollutants up there.[44]
- When have/will we reach **peak oil**, and see a decline in petroleum use due to normal economic forces?

2.1.1 Tipping points

What and where are the **tipping points** for various systems? A) How many and which systems are vulnerable to abrupt, non-linear change (e.g. sudden changes in ocean currents, collapse of ice shelves) B) What are the physical/chemical mechanisms involved in various locations? C) At what level of warming do they occur? D) At what point in time do they occur?

"Several components or phenomena in the climate system could potentially exhibit abrupt or nonlinear changes, and some are known to have done so in the past. Examples include the AMOC [Atlantic Meridional Overturning Circulation, including the Gulf Stream], Arctic sea ice, the Greenland ice sheet, the Amazon forest and monsoonal circulations. For some events, there is information on potential consequences, but in general there is low confidence and little consensus on the likelihood of such events over the 21st century."[45]

"We explore the risk that self-reinforcing feedbacks could push the Earth System toward a planetary threshold that, if crossed, could prevent stabilization of the climate at intermediate temperature rises and cause continued warming on a 'Hothouse Earth' pathway even as human emissions are reduced."[46]

Lenton et al. identified nine "Policy-Relevant Tipping Elements in the Climate System" in 2008:[47]

1. Arctic summer sea-ice
2. Greenland ice sheet (GIS)
3. West Antarctic ice sheet (WAIS)
4. Atlantic thermohaline circulation (THC)
5. El Niño–Southern Oscillation (ENSO)-

Could Stop Relatively Quickly after Emissions Go to Zero," *Inside Climate News*, January 3, 2021, https://insideclimatenews.org/news/03012021/five-aspects-climate-change-2020/

42. Mark Lynas, *Six Degrees: Our Future on a Hotter Planet,* Washington, DC: National Geographic, 2008, p. 129.
43. Lynas, *Six Degrees*, p. 188.
44. Lynas, *Six Degrees*, p. 273.
45. Matthew Collins et al., "Long-term Climate Change: Projections, Commitments and Irreversibility," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, eds. T. F. Stocker, et al., Cambridge: Cambridge University Press, 2013, 1033, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter12_FINAL.pdf.
46. Will Steffen et al., "Trajectories of the Earth System in the Anthropocene," ed. William C. Clark, *Proceedings of the National Academy of Science of the United States of America,* vol. 115, August 2018, pp. 8252-8259, https://doi.org/10.1073/pnas.1810141115.
47. T. M. Lenton, H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber, "Tipping Elements in the Earth's Climate System," *Proceedings of the National Academies of Sciences*, vol. 105, no. 6, 2008, pp. 1786–1793, https://www.pnas.org/doi/epdf/10.1073/pnas.0705414105

6. Indian summer monsoon (ISM)-
7. Sahara/Sahel and West African monsoon (WAM)-
8. Amazon rainforest
9. Boreal forest

Steffen et al. in 2018 represented the risk of crossing these and several other tipping points in a global map:

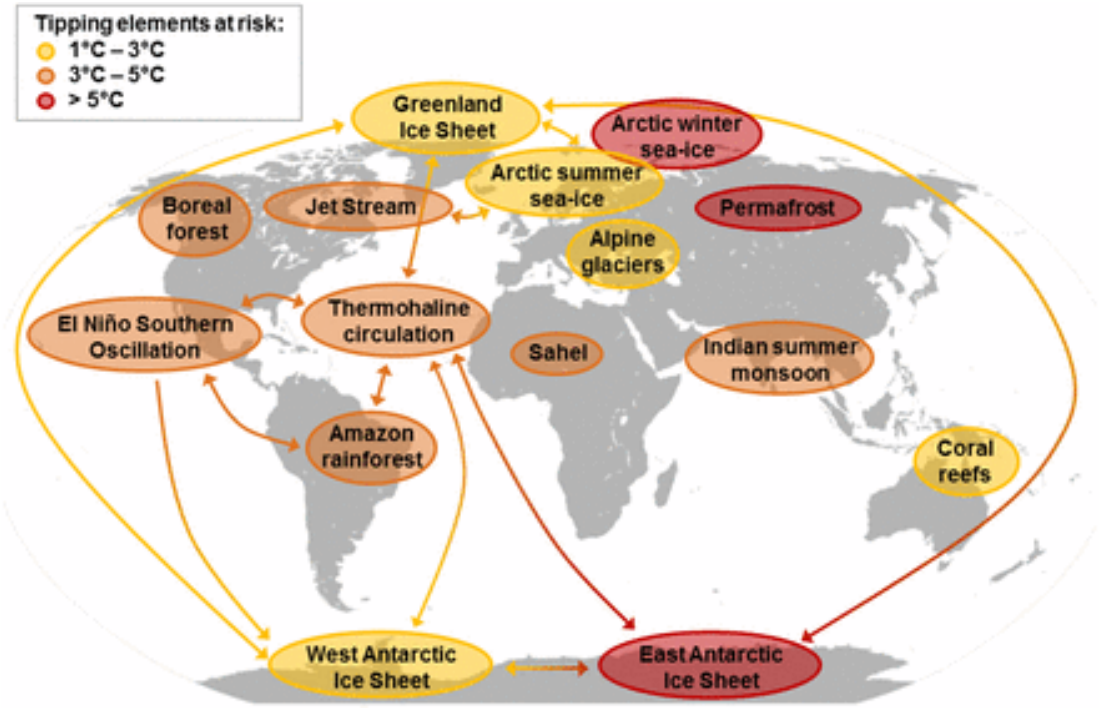


Figure 1. Map of tipping points from Steffen, et al. (2018).

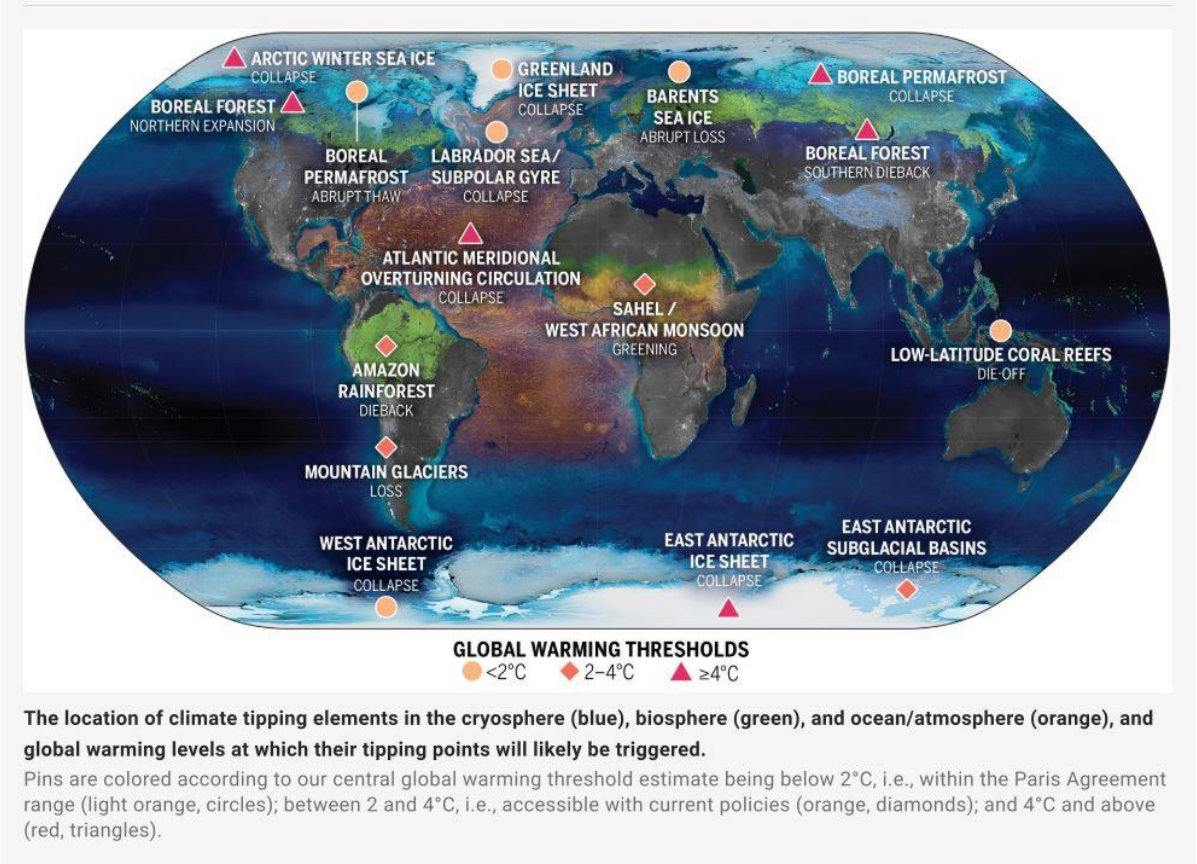
Lenton et al. revisited the question of tipping points in 2019, providing a revised list of the most concerning systems (items marked "+" replaced items marked "–" in the previous list):[48]

1. Amazon rainforest
2. Arctic sea ice
3. Atlantic circulation
4. Boreal forest
5. Coral reefs+
6. Greenland ice sheet
7. Permafrost+
8. West Antarctic ice sheet
9. Wilkes Basin, East Antarctica+

Building on Lenton's previous research, McKay et al. in in 2022 evaluated the current risk levels for all proposed tipping points. They found that the current level of warming, about 1.1° C above pre-industrial levels, already risks triggering five tipping points:[49]

[48] T. M. Lenton, J. Rockström, O. Gaffney, S. Rahmstorf, K. Richardson, W. Steffen, and H. J. Schellnhuber, "Climate Tipping Points—Too Risky to Bet Against," *Nature,* vol. 575, 2019, pp. 592–595.

[49] McKay, David I. Armstrong, Arie Staal, Jesse F. Abrams, Ricarda Winkelmann, Boris Sakschewski, Sina Loriani, Ingo Fetzer, Sarah E. Cornell, Johan Rockström, and Timothy M. Lenton. "Exceeding 1.5° C Global Warming Could Trigger Multiple Climate Tipping Points." *Science*, vol.



The location of climate tipping elements in the cryosphere (blue), biosphere (green), and ocean/atmosphere (orange), and global warming levels at which their tipping points will likely be triggered.

Pins are colored according to our central global warming threshold estimate being below 2°C, i.e., within the Paris Agreement range (light orange, circles); between 2 and 4°C, i.e., accessible with current policies (orange, diamonds); and 4°C and above (red, triangles).

Figure 2. Map of tipping points from McKay et al. (2022)

Possible tipping points

- **"Collapse of major ice sheets in Greenland and Antarctica:** Melting of these ice sheets is an ongoing process; however, there are signs that moderate melting may accelerate into a runaway situation that leads to a relatively sudden loss of large amounts of ice. Such a collapse could lead to dramatic changes in sea level, and could also impact ocean circulation." [Greenland's tipping point will be hit at global increase of 1.2° C][50]
- **"Disruption of thermohaline circulation [AMOC]:** If the ocean's circulation changed dramatically or even shut down altogether, the transfer of heat in the climate system would be altered in a huge way."[51]
- **"Sudden release of methane:** If the potent greenhouse gas methane were released rapidly from its stores in Arctic permafrost and special ices beneath the seafloor (called methane hydrates or clathrates), the rate of warming would increase. Methane releases would generate a feedback loop of increased greenhouse warming by methane driving further methane emissions. Some scientists suspect that sudden increases in methane may have played a role in major extinction events in the past."[52]

377, no. 6611, September 9, 2022, https://www.science.org/doi/10.1126/science.abn7950. See also: Courtney Lindwall, "Climate Tipping Points Are Closer Than Once Thought," Natural Resources Defense Council, November 15, 2022, https://www.nrdc.org/stories/climate-tipping-points-are-closer-once-thought.

50. Lynas, *Six Degrees*, p. 88.
51. "Predictions of Future Global Climate," University Corporation for Academic Research, 2011, https://scied.ucar.edu/longcontent/predictions-future-global-climate.
52. "Predictions of Future Global Climate."

- **"Ocean uptake of carbon:** Today, the ocean is absorbing CO_2 that would otherwise stay in the atmosphere. At some point seawater will become saturated with CO_2 and unable to absorb any more. At that point, anthropogenic emissions of CO_2 would all land in the atmosphere, increasing the rate of greenhouse warming. Acidification of the oceans could also disrupt marine life, causing photosynthesizing plankton to succumb, preventing them from removing CO_2 from the air. Shells of many types of marine organisms might begin to dissolve in the presence of the acidic oceans, releasing the carbon stored within the shells back into the environment."[53]
- **Loss of Arctic sea ice:** Ice and snow reflect 80% of the sun's heat; open ocean can absorb up to 95%. Once a crucial amount of ice is lost, the heating process speeds up and heat is subsequently all trapped in the ocean rather than reflected out.[54]

  In March 2022, record high temperatures were recorded at both the North Pole and in Antarctica, with corresponding ice melt. A floating ice shelf in East Antarctica, which had been considered relatively stable, collapsed disintegrated in a matter of days in mid-March 2022.[55] These extreme polar temperatures exceeded accepted climate change predictions "to a worrying extent."[56]

- **Phytoplankton die-off:** surface phytoplankton absorb a great deal of atmospheric CO_2, as part of the "biological carbon pump." "Marine phytoplankton perform half of all photosynthesis on Earth" "the biological pump takes carbon out of contact with the atmosphere for several thousand years or longer and maintains atmospheric CO_2 at significantly lower levels than would be the case if it did not exist. An ocean without a biological pump. . . would result in atmospheric CO_2 levels ~400 ppm higher than present day."[57]

  Ocean acidification, warming, and changes in circulation will affect various phytoplankton in ways that are presently unpredictable: populations may increase, or decrease, or disappear. If they decrease significantly, diminishing the biological carbon pump system, acidification and warming will accelerate significantly.

  Phytoplankton "absorb half of the carbon dioxide we create. If we wipe them out, that process will stop. We are altering the entire chemistry of the oceans without any idea of the consequences"[58]
- **Desertification of Africa:** the substrate of the lower third of the continent is sand. Somewhere above 2 C, the vegetation begins to die back, exposing the sand, leading to hot, dry, "violently blowing sand"[59]
- **Methane production in the melting Arctic:** (see below on anaerobic bacteria in melting permafrost—this could become a major feedback that leads to runaway warming)
- **Methane hydrate releases from the oceans:** this trapped methane is naturally sequestered at depth in the oceans. At warmer temperatures it becomes unstable and rises, become even

53. "Predictions of Future Global Climate."
54. Lynas, *Six Degrees*, p. 48.
55. Kathryn Hansen, "Ice Shelf Collapse in East Antarctica," NASA Earth Observatory, https://earthobservatory.nasa.gov/images/149640/ice-shelf-collapse-in-east-antarctica.
56. Fiona Harvey, "Heatwaves at Both of Earth's Poles Alarm Climate Scientists," *The Guardian*, March 20, 2022, https://www.theguardian.com/environment/2022/mar/20/heatwaves-at-both-of-earth-poles-alarm-climate-scientists.
57. Samarpita Basu and Katherine R. M. Mackey, "Phytoplankton as Key Mediators of the Biological Carbon Pump: Their Responses to a Changing Climate," *Sustainability* 10, no. 3, March, 2018, 869, https://doi.org/10.3390/su10030869.
58. Lynas, *Six Degrees*, p. 78.
59. Lynas, *Six Degrees*, p. 127.

less stable at lower pressures. Significant atmospheric methane releases become more likely as the oceans warm.[60] The tipping point is not known.[61]

A 2017 study concluded that "current warming of ocean waters is likely causing gas hydrate deposits to break down at some locations. However, not only are the annual emissions of methane to the ocean from degrading gas hydrates far smaller than greenhouse gas emissions to the atmosphere from human activities, but most of the methane released by gas hydrates never reaches the atmosphere. Instead, the methane often remains in the undersea sediments, dissolves in the ocean, or is converted to carbon dioxide by microbes in the sediments or water column."[62]

Observation of an undersea methane release off the eastern coast of Siberia in 2020 raises more concerns, however: "While the methane bubbles are still being absorbed by the ocean, the researchers did measure methane concentrations near the surface that were four to eight times higher than normal, and said this methane would make it into the atmosphere."[63]

Additional information

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Alan Buis, "Part 2: Selected Findings of the IPCC Special Report on Global Warming," NASA Global Climate Change, June 19, 2019, https://climate.nasa.gov/news/2865/a-degree-of-concern-why-global-temperatures-matter/.

"Impacts of a 4° C Global Warming," *GreenFacts*, accessed February 8, 2020, https://www.greenfacts.org/en/impacts-global-warming/l-2/index.htm.

Julia Blocher and Richard Betts, "Preparing for a Future beyond 'Dangerous' Climate Change," United Nations University (blog), November 25, 2015, https://ehs.unu.edu/blog/articles/preparing-for-a-future-beyond-dangerous-climate-change.html.

Mark S. Williamson, et al., "Combination of Impacts Information with Assessment of Likelihood of Different Climate Tipping Points to Produce First Comprehensive Risk Assessment of Climate Tipping Points under Different Scenarios," High-End Climate Impacts and Extremes (HELIX) Project, Tyndall Centre for Climate Change Research, April 25, 2016, https://helixclimate.eu/wp-content/uploads/2018/07/Deliverable-10.2-Comprehensive-risk-assessment-of-climate-tipping-points-under-different-scenarios.pdf.

2.1.2 Feedback loops

The most comprehensive survey of potentially climate-relevant feedback loops was presented in 2023 by a team of researchers led by William J. Ripple. They identified a total of 56 loops (20 physical, 21

60. Lynas, *Six Degrees*, p. 223.
61. Lynas, *Six Degrees*, p. 228.
62. "Gas Hydrate Breakdown Unlikely to Cause Massive Greenhouse Gas Release," USGS, February 9, 2017, https://www.usgs.gov/news/gas-hydrate-breakdown-unlikely-cause-massive-greenhouse-gas-release.
63. Olivia Rosane, "Scientists Say Methane Release Is Starting in Arctic Ocean. How Concerned Should We Be?" *EcoWatch*, October 28, 2020, https://www.ecowatch.com/methane-release-arctic-ocean-2648529839.html. See also Jonathan Watts, "Arctic Methane Deposits 'Starting to Release', Scientists Say," *The Guardian*, October 27, 2020, https://www.theguardian.com/science/2020/oct/27/sleeping-giant-arctic-methane-deposits-starting-to-release-scientists-find.

biological, and 15 human behavior-driven) that ought to be considered in climate modeling.[64] Thirty-four of these loops would contribute to temperature increases, eight would help to reduce it; effects of the remaining fourteen cannot be determined at present. The following lists come from the "Supplemental Tables" in Ripple et al.

Feedback loops that contribute to warming

What and where are there **undesirable feedback loops** (positive system reinforcements) that are likely to be established as temperatures rise and physical/chemical/biological/human systems change? E.g., deforestation may lead to greater drought which leads to more deforestation. The same questions about specifics arise here as with the tipping points.

Physical (abiotic)

- Water vapor: Increasing water vapor content due to warming
- Sea ice albedo: Sea ice melting or not forming
- Glacier and ice sheet albedo: Increasing glacier & ice sheet melting and marine ice sheet instability
- Sea level rise: Rising sea levels (caused by ice melting)
- Snow cover: Snow metamorphosis and decreasing snow cover
- Clouds: Changing cloud distribution (extent and height) and optical properties
- Ocean solubility pump: Increasing atmospheric CO2 levels
- Methane hydrates: Increasing methane hydrate dissociation rates
- Glacier and ice sheet elevation: Decreasing glacier and ice sheet mass balance and elevation
- Antarctic rainfall: Decreasing Antarctic ice sheet extent leading to increasing precipitation

Biological

- Peatlands: Decreasing soil organic carbon due to lowering of water table, increasing vulnerability to fire, increasing metabolization
- Wetlands (expansion): Increasing precipitation and boreal near-surface soil moisture potentially leading to expansion of wetlands
- Freshwater ecosystems: Increasing aquatic plant growth rates (negative feedback) and microbial methane production (positive feedback)
- Forest dieback: Dieback of Amazon, boreal, and other forests
- Northern greening: Potential expansion of high latitude/elevation forests & woody vegetation into tundra, increasing Arctic/ northern vegetation (warmer & longer growing seasons, nutrient fertilization)
- Insect outbreaks (forests): Changing insect distributions & abundances; decreased host tree defense
- Wildfire: Increasing fire frequency and/or severity and/or extent in some regions
- Soil carbon (other): Increasing loss of soil carbon to the atmosphere
- Soil nitrous oxide: Accelerated decomposition and changing soil microbial activity affecting substrate availability for denitrification
- Permafrost: Increasing thawing and decomposition
- Evapotranspiration from soils and plants: Increasing evaporation from soils, plants open stomata less widely
- Microbial respiration (other) : Increasing respiration rates for many prokaryotic microbes

64. William J. Ripple, Christopher Wolf, Timothy M. Lenton, Jillian W. Gregg, Susan M. Natali, Philip B. Duffy, Johan Rockström, and Hans Joachim Schellnhuber, "Many Risky Feedback Loops Amplify the Need for Climate Action," *One Earth*, vol. 6, February 17, 2023, https://doi.org/10.1016/j.oneear.2023.01.004

- Plant stress: Increasing chronic & extreme thermal and moisture stress
- Desertification: Increasing chronic aridification & hotter drought stress extremes leading to expanding deserts
- Coastal productivity: Increasing degradation of coastal ecosystems (e.g., mangroves, seagrass beds, salt marshes) due to heat stress and loss of coral reef protection
- Ocean metabolic rates: Potentially increasing phytoplankton/bacterial respiration rates

Human

- Human mobility: Potentially increasing movement (vehicle miles travelled) due to warming
- Coral reefs: Increasing coral die-off, loss of associated fisheries and other ecosystem services
- Freshwater: Declining freshwater availability in certain regions
- Policy paralysis: Climate change becomes an increasingly large policy issue
- Economic disruption: Increasing frequency of economic disruptions (natural disasters, crop failures, etc.)
- Political disruption: Increasing political upheaval (e.g., due to mass migrations)
- Geopolitics: Increasing large and unequal climate impacts on countries
- Human conflict: Increasing conflict (declining resources)

Feedback loops that mitigate warming

What and where are there desirable feedback loops (negative system reinforcements)?

Physical (abiotic)

- Planck (black body) radiation: Increasing mean surface and atmosphere temperature
- Lapse rate: Changing relationships between temperature and altitude
- Sea ice growth: Decreasing sea ice thickness, increasing open-water fraction, decreasing insulation
- Chemical weathering: Increasing carbonate and silicate weathering rates

Biological

- Biogenic volatile organic compounds (BVOCs): Changing BVOC emission rates
- Sahara and Sahel greening: Possibly increasing rainfall in Sahara and Sahel
- CO2 fertilization: Increasing CO2 concentration possibly leading to increasing net primary productivity (NPP)

Human

- Mitigation: Increasing sense of urgency as climate change intensifies and damages increase

Feedback loops with undetermined effect

Physical (abiotic)

- Dust: Changing dust aerosol abundance
- Other aerosols: Changing atmospheric aerosol (e.g., sulfate, sea salt) concentrations
- Ocean circulation: Slowing of the Atlantic Meridional Overturning Circulation (AMOC)
- Ozone: Strengthening of the Brewer-Dobson circulation, increasing stratosphere-to-troposphere transport
- Atmospheric chemical reaction rates: Changing chemical reaction rates in the atmosphere

Biological

- Ocean biological pump: Increasing CO2 in ocean, ocean acidification, warming, decreasing upwelling
- Phytoplankton dimethyl sulfide (DMS): Changing DMS emissions from plankton (due to ocean acidification, increasing stratification, etc.)

Human

- Climate related disasters: Increasing forest fire, tropical storm, flood, and coastal erosion frequency or intensity in some regions
- Human migration: Increasing uninhabitable area due to extreme heat, sea level rise, permafrost thaw, coastal flooding, and potential soil degradation
- Transport routes: Changing transport routes (e.g., due to decreasing Arctic sea ice)
- Energy demand: Increasing global mean temperature
- Agriculture: Changing crop yields overall, changing agricultural suitability, water supply and demand
- Economic growth: Decreasing macroeconomic production and human consumption

2.2 Uncertainty due to indeterminacy of future events—especially, human responses

The most likely warming scenario over the next few centuries is between 1.5° and 6.0° C. This is a wide range, and is largely due to **a single indeterminant factor**: how will humans respond to the situation by limiting ghg emissions, and removing ghgs from the atmosphere, starting now?

In spite of increasing awareness and concern over global warming, and after forty years of international discussion about addressing climate change in a concerted way, little progress has been made. The following graphic illustrates the near-linear increase in atmospheric CO_2 from 1958 to 2022, indicating dates of major climate policy conferences:[65]

65. Peter Gericke, Marius Hasenheit, Tadzio Müller, and Wiebke Witt, "Trends in Atmospheric CO_2 vs. Global Temperature Change, 1958-2020, with Climate Conference Dates Indicated," *Sustentio*, Virale Klimakommunikation, January 10, 2022, https://sustentio.com/2022/climateinactionstripes-virale-klimakommunikation.

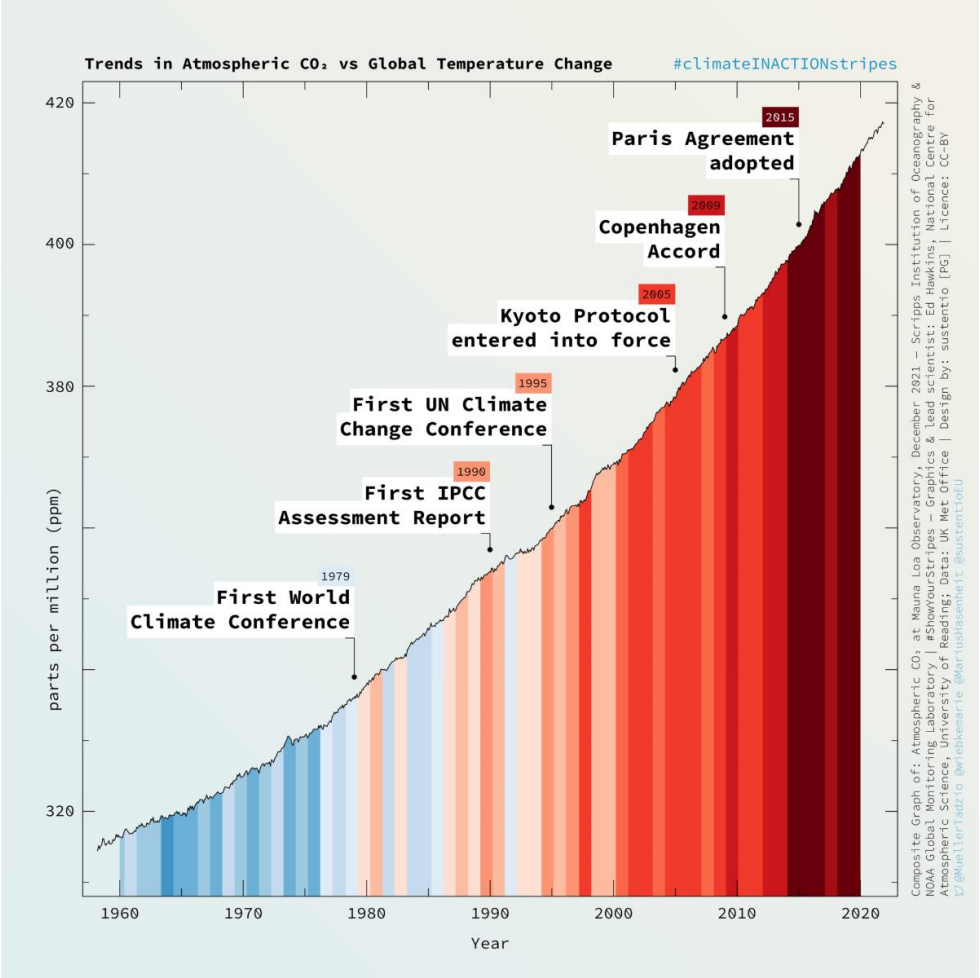

Figure 3. Graph from Gericke et al. (2022)

Other sources of uncertainty:

- Prospect of **new technologies** for energy production, sequestration, mitigation, adaptation.
- Unpredictable/independent **geopolitical events** that may realign economic and industrial activities on a global scale. Such events are likely to be connected to ongoing climate change to some degree (war, mass migration, economic collapse, political revolutions).
- **Political leadership can make a difference:** almost immediately after taking office, President Biden took a number of steps to address climate change, including rejoining the Paris Accord.[66]
- **Public attitudes toward ghg mitigation can change:** in the U.S., which is responsible for disproportionate amount of GHG emissions, there has been a powerful climate denial movement that has blocked significant changes. There has been some movement away from this denial position in recent years, though talk of climate change as a scientific or political reality still meets with opposition.[67]

66. Valerie Volcovici, "Factbox: Biden Mobilizes The Federal Government To Tackle Climate Change," *Reuters*, January 27, 2021 https://www.reuters.com/article/us-usa-biden-climate-factbox-idUSKBN29W30X, and Bill McKibben, "The Biden Administration's Landmark Day in the Fight for the Climate," *New Yorker*, January 28, 2021, https://www.newyorker.com/news/daily-comment/the-biden-administrations-landmark-day-in-the-fight-for-the-climate
67. R. Schiffman, "Climate Deniers Shift Tactics to 'Inactivism,'" *Scientific American,* January 12, 2021, https://www.scientificamerican.com/article/climate-deniers-shift-tactics-to-inactivism/. This is an interview with Michael Mann, author of *The New Climate War: The Fight to Take Back Our Planet*. See also D. Wallace-Wells, "After Alarmism: The War on Climate Denial Has Been Won. And

- Unpredictable/independent **natural disasters** that may realign economic, political, and industrial activities on a global scale (earthquakes, volcanic eruptions, sunspot activity, magnetic pole realignment, lethal epidemic(s), even a comet strike [it's happened before…]). Some events, and the scale of their effects, are likely to be connected to ongoing climate change to some degree (esp. the effects of drought cycles, large storms, flooding).
- **The Covid-19 pandemic** beginning in early 2020 disrupted life everywhere, changing behavior in fundamental ways. The global lockdown caused a sudden drop in fuel consumption and corresponding emissions—at one point as much as a 17% reduction in emissions; overall, the reduction was a few percent.[68] *[Text retained from April 2022 version for nostalgic reasons: There may be continued emphasis on working from home, with reduced commuting, after the pandemic is controlled. Other changes from the pandemic may become apparent over time. The crisis may present an opportunity to introduce fundamental, long-term changes to address climate change. The lockdown-induced reduction in ghg emissions in 2020 will not, by themselves, have much impact on global atmospheric CO_2 levels, however.[69]]* In September 2022 the World Meteorological Organization (WMO) issued a report, *United in Science*, which "shows that greenhouse gas concentrations continue to rise to record highs. Fossil fuel emission rates are now above pre-pandemic levels after a temporary drop due to lockdowns."[70]

3. What are the most likely effects of climate change in various possible scenarios?

Current status

We have already seen **at least 1.1° C increase since 1880**; atmospheric **CO_2** concentration was at **414 ppm** as of January 2020, **415.77 ppm** in January 2021, **417.99 ppm** in January 2022, and **419.47 ppm** in January 2023.[71] The World Meteorological Organization (WMO) predicts that global average temperature will at least temporarily reach **1.5° C** above preindustrial levels sometime **before 2028**.[72]

Lacking immediate and dramatic global efforts to reduce fossil fuel use, we are now effectively committed to seeing 1.5° C increases by the year 2050. It is difficult to predict how much higher actual increases will turn out.

The good news: A 2022 study indicates that the worst-case scenarios—with global temperature increases above 3° C—are very unlikely "if current trends continue and countries adopt the climate policies they have already announced to reduce greenhouse

That's Not the Only Good News," Intelligencer, *New York Magazine*, January 19, 2021, https://nymag.com/intelligencer/article/climate-change-after-pandemic.html.

68. Matt McGrath, "Climate Change: Covid Pandemic Has Little Impact on Rise in CO_2," *BBC News*, 23 November 2020, https://www.bbc.com/news/science-environment-55018581, and Bob Henson, "Key Takeaways from the New IPCC Report," *Yale Climate Connections*, August 9, 2021, https://yaleclimateconnections.org/2021/08/key-takeaways-from-the-new-ipcc-report/. Henson draws from "Climate Change 2021: The Physical Science Basis," IPCC Working Group I, August 6, 2021, https://www.ipcc.ch/report/sixth-assessment-report-working-group-i/
69. Mark Dwortzan, "How will COVID-19 ultimately impact climate change?" *MIT News*, January 29, 2021 https://news.mit.edu/2021/how-will-covid-19-ultimately-impact-climate-change-0129.
70. "World Meteorological Organization. "United in Science: We are Heading in the Wrong Direction." United Nations, 13 September 2022. https://unfccc.int/news/united-in-science-we-are-heading-in-the-wrong-direction
71. "Daily CO_2," *CO2.earth*, Pro Oxygen, accessed April 5, 2022, https://www.co2.earth/daily-co2, and "Average monthly carbon dioxide (CO_2) levels in the atmosphere worldwide," *Statista*, https://www.statista.com/statistics/1091999/atmospheric-concentration-of-co2-historic/.
72. Cappucci.

emissions."[73] **The most likely scenarios involve overall temperature increases of 2° C to 3° C by the year 2100.**

Additional information

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M. Collins, R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein, X. Gao, W. J. Gutowski, T. Johns, G. Krinner, M. Shongwe, C. Tebaldi, A. J. Weaver and M. Wehner, "Long-term Climate Change: Projections, Commitments and Irreversibility," in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley. Cambridge University Press, New York, 2013, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter12_FINAL.pdf.

N. W. Arnell, J. A. Lowe, A. J. Challinor, and T. J. Osborn, "Global and Regional Impacts of Climate Change at Different Levels of Global Temperature Increase," *Climatic Change*, vol. 155, no. 377, 2019, https:// doi.org/10.1007/s10584-019-02464-z.

1.5° C – The Paris agreement target (2015)

"The essential goal of the Paris agreement of 2015 has been to limit the rise in average global temperatures to no more than 2° C above pre-industrial levels – a time period centered roughly on the mid-19th century. The aspirational or wished-for objective of the agreement is to strive for a rise in temperatures that doesn't exceed 1.5° C."[74]

With considerable effort, change could still be limited to 1.5° C. The 2018 IPCC Special Report "Global Warming of 1.5 ºC" indicated what would need to be done, and indicated that changes must be implemented by 2030 in order to restrict warming to 1.5° C.[75]

Writing about the effects of climate change in Australia, a group of scientists previously recognized for their accomplishments by the Australian Research Council (the ARC Laureats) "further increases in extreme fire risk, heat waves and flooding rains; ecosystems degraded and wild species forced to migrate or vanish; agricultural activities moved or abandoned, challenging our food security; and so on. If strong action is *not* taken, environmental degradation and social disruption will be much greater

73. Andrei Ionescu, "Worst-case Climate Scenarios Are No Longer Plausible," Earth.com, February 21, 2022, https://www.earth.com/news/worst-case-climate-scenarios-are-no-longer-plausible/. Ionescu reports on Roger Pielke, Jr., Matthew G. Burgess, and Justin Ritchie, "Plausible 2005–2050 Emissions Scenarios Project between 2° C and 3° C of Warming by 2100," *Environmental Research Letters*, vol. 17, no. 2, February 11, 2022, 024027, https://di.org/10.1088/1748-9326/ac4ebf.
74. Bruce Lieberman, "1.5 or 2 Degrees Celsius of Additional Global Warming: Does It Make a Difference?" *Yale Climate Connections*, August 4, 2021, https://yaleclimateconnections.org/2021/08/1-5-or-2-degrees-celsius-of-additional-global-warming-does-it-make-a-difference/.
75. 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*, eds. V. Masson-Delmotte, et al., 2018, https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_Low_Res.pdf.

and in many cases adaptation will no longer be achievable. It would be naive to assume that such a world will still support human societies in their current form and maintain human well-being."[76]

"Global emissions of greenhouse gases have, however, continued to rise, making it more and more likely that this 2° C 'guardrail' will be exceeded."[77]

"Changes include increases in both land and ocean temperatures, as well as more frequent heatwaves in most land regions (*high confidence*). There is also (*high confidence*) global warming has resulted in an increase in the frequency and duration of marine heatwaves. Further, there is *substantial evidence* that human-induced global warming has led to an increase in the frequency, intensity and/or amount of heavy precipitation events at the global scale (*medium confidence*), as well as an increased risk of drought in the Mediterranean region (*medium confidence*)."[78]

The major predictable effects of warming

- Change will continue through this century and beyond
- Temperatures will continue to rise
- Frost-free season (and growing season) will lengthen
- Changes in precipitation patterns will occur
- There will be more, and more severe, droughts and heat waves
- Hurricanes will become stronger and more intense
- Sea level will rise from 1 to 8 feet by 2100, due to melting glaciers and ice sheets, and to the expansion of sea water as it warms
- The Arctic is likely to become ice-free[79]
- Increased wildfires, flooding, and crop failures[80]
- Effects on human health, including deadly heat and humidity[81] and degradation of air, water, food, and shelter.[82]
- Currently populated regions of the planet, especially near the equator, will become effectively uninhabitable by the end of the 21st century, displacing billions of people.[83]

76. "An Open Letter on Australian Bushfires and Climate: Urgent Need for Deep Cuts in Carbon Emissions," accessed February 8, 2020, https://laureatebushfiresclimate.wordpress.com/.
77. Julia Blocher and Richard Betts, "Preparing for a future beyond 'dangerous' climate change," United Nations University (blog), November 25, 2015, https://ehs.unu.edu/blog/articles/preparing-for-a-future-beyond-dangerous-climate-change.html.
78. IPCC, *Global Warming of 1.5° C*; Alan Buis, "Part 2: Selected Findings of the IPCC Special Report on Global Warming," NASA Global Climate Change, June 19, 2019, https://climate.nasa.gov/news/2865/a-degree-of-concern-why-global-temperatures-matter/.
79. "The Effects of Climate Change," NASA Jet Propulsion Laboratory and California Institute of Technology, accessed February 6, 2020, https://climate.nasa.gov/effects/.
80. Oliver Milman, Andrew Witherspoon, Rita Liu, and Alvin Chang, "The Climate Disaster is Here—This is What the Future Looks Like," *The Guardian*, October 14, 2021, https://www.theguardian.com/environment/ng-interactive/2021/oct/14/climate-change-happening-now-stats-graphs-maps-cop26.
81. Casey Crownhart, "How Hot Is Too Hot for the Human Body?" *MIT Technology Review*, July 10, 2021. https://www.technologyreview.com/2021/07/10/1028172/climate-change-human-body-extreme-heat-survival/.
82. "Climate Change and Health," World Health Organization, October 30, 2021, https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health.
83 T. M. Linton, C. Xu, J. F. Abrams, et al. "Quantifying the Human Cost of Global Warming," Nature Sustainability, May 23, 2023, https://doi.org/10.1038/s41893-023-01132-6.

Effects in the US

- *Northeast*. Heat waves, heavy downpours and sea level rise pose growing challenges to many aspects of life in the Northeast. Infrastructure, agriculture, fisheries and ecosystems will be increasingly compromised. Many states and cities are beginning to incorporate climate change into their planning.
- *Northwest*. Changes in the timing of streamflow reduce water supplies for competing demands. Sea level rise, erosion, inundation, risks to infrastructure and increasing ocean acidity pose major threats. Increasing wildfire, insect outbreaks and tree diseases are causing widespread tree die-off.
- *Southeast*. Sea level rise poses widespread and continuing threats to the region's economy and environment. Extreme heat will affect health, energy, agriculture and more. Decreased water availability will have economic and environmental impacts.
- *Midwest*. Extreme heat, heavy downpours and flooding will affect infrastructure, health, agriculture, forestry, transportation, air and water quality, and more. Climate change will also exacerbate a range of risks to the Great Lakes.
- *Southwest*. Increased heat, drought and insect outbreaks, all linked to climate change, have increased wildfires. Declining water supplies, reduced agricultural yields, health impacts in cities due to heat, and flooding and erosion in coastal areas are additional concerns.[84]

Other effects of warming

- **Impacts on ocean currents:** Large-scale ocean currents called thermohaline circulation, driven by differences in salinity and temperature, may also be disrupted as climate warms. Changes in precipitation patterns and the influx of fresh water into the oceans from melting ice can alter salinity. Changing salinity, along with rising water temperature, may disrupt the currents. In an extreme case, thermohaline circulation could be disrupted or even shut down in some parts of the ocean, which could have large effects on climate.
- **Changing severe weather:** Some climate scientists believe that hurricanes, typhoons, and other tropical cyclones will (and may have begun to already) change as a result of global warming. Warm ocean surface waters provide the energy that drives these immense storms. Warmer oceans in the future are expected to cause intensification of such storms. Although there may not be more tropical cyclones worldwide in the future, some scientists believe there will be a higher proportion of the most powerful and destructive storms. Some scientists believe we are already seeing evidence for an upswing in the numbers of the most powerful storms; others are less convinced.
- **More clouds:** Clouds are a bit of a wild-card in global climate models. Warmer global temperatures produce faster overall evaporation rates, resulting in more water vapor in the atmosphere... and hence more clouds. Different types of clouds at different locations have different effects on climate. Some shade the Earth, cooling climate. Others enhance the greenhouse effect with their heat-trapping water vapor and droplets. Scientists expect a warmer world to be a cloudier one, but are not yet certain how the increased cloudiness will feed back into the climate system. Modeling the influence of clouds in the climate system is an area of active scientific research.
- **Changes to life and the carbon cycle:** Climate change will alter many aspects of biological systems and the global carbon cycle. Temperature changes will alter the natural ranges of many types of plants and animals, both wild and domesticated. There will also be changes to the lengths of growing seasons, geographical ranges of plants, and frost dates.

  Models of the global carbon cycle suggest that the Earth system will be able to absorb less CO_2 out of the atmosphere as the climate warms, worsening the warming problem.[85]

84. "The Effects of Climate Change."
85. "Predictions of Future Global Climate."

- **Less freshwater** will be available, since glaciers store about three-quarters of the world's freshwater.
- **Some diseases** will spread, such as mosquito-borne malaria (and the 2016 resurgence of the Zika virus).[86]

2.0° C

All of the predicted effects will be increased. From the IPCC Special Report:

- **Extreme heat days/waves get 25% worse:** "Extreme hot days in mid-latitudes warm by up to about 3° C at global warming of 1.5° C and about 4° C at 2° C, and extreme cold nights in high latitudes warm by up to about 4.5° C at 1.5° C and about 6° C at 2° C (*high confidence*)."
- Sea level rise of 7–20 feet.[87]
- **We lose more of the permafrost, and release more of the methane locked inside:** "Limiting global warming to 1.5° C rather than 2° C is projected to prevent the thawing over centuries of a permafrost area in the range of 1.5 to 2.5 million km2 (*medium confidence*)."
- **We lose more ocean life:** "Limiting global warming to 1.5° C compared to 2ºC is projected to reduce increases in ocean temperature as well as associated increases in ocean acidity and decreases in ocean oxygen levels (*high confidence*). Consequently, limiting global warming to 1.5° C is projected to reduce risks to marine biodiversity, fisheries, and ecosystems, and their functions and services to humans…"
- **The arctic sea ice disappears completely:** "There is *high confidence* that the probability of a sea ice-free Arctic Ocean during summer is substantially lower at global warming of 1.5° C when compared to 2° C."
- **Ocean acidification gets worse:** "The level of ocean acidification due to increasing CO_2 concentrations associated with global warming of 1.5° C is projected to amplify the adverse effects of warming, and even further at 2° C, impacting the growth, development, calcification, survival, and thus abundance of a broad range of species, for example, from algae to fish (*high confidence*)."
- **Tropical diseases move further north:** "Risks from some vector-borne diseases, such as malaria and dengue fever, are projected to increase with warming from 1.5° C to 2° C, including potential shifts in their geographic range (*high confidence*)."
- **Crop yields and the nutritional value of foods decreases even further:** "Limiting warming to 1.5° C compared with 2° C is projected to result in smaller net reductions in yields of maize, rice, wheat, and potentially other cereal crops, particularly in sub-Saharan Africa, Southeast Asia, and Central and South America, and in the CO_2-dependent nutritional quality of rice and wheat (*high confidence*)."
- **The chances of crossing tipping points or of triggering feedback loops increase:** "For global warming from 1.5° C to 2° C, risks across energy, food, and water sectors could overlap spatially and temporally, creating new and exacerbating current hazards, exposures, and vulnerabilities that could affect increasing numbers of people and regions (*medium confidence*)."

86. "Effects of Global Warming," *National Geographic*, accessed February 8, 2020, https://www.nationalgeographic.com/environment/global-warming/global-warming-effects/.
87. Henson, "Key Takeaways from the new IPCC Report."

- **It gets harder and more expensive to adapt to the more extreme effects:** "Adaptation is expected to be more challenging for ecosystems, food and health systems at 2° C of global warming than for 1.5° C (*medium confidence*)." [88]

3.0° C

The effects of warming become even more serious:

- "30-50% of species are likely to be wiped out."
- "More than 1.5 billion people will be displaced from their home regions."
- "Yields of staple crops will face major decline, triggering sustained food supply disruptions globally."
- "Much of the tropics will be rendered uninhabitable for humans."

As Jason Hickel notes, "Such a world is not compatible with civilization as we know it."[89]

4.0° C

This level of warming "is what scientists are nearly unanimously predicting will happen by the end of the century if no significant policy changes are undertaken."[90] As warming increases, precise effects are harder to predict. This level of warming may occur well within current generations' lifetimes.

"If the currently planned actions are not fully implemented, a warming of 4° C could occur as early as the 2060s. Such a warming level by 2100 would not be the end point: a further warming to levels over 6° C would likely occur over the following centuries."[91]

Kemp et al. call for more study of the effects of warming levels 4.0° C and above. While these levels appear less likely than the 2.0–3.0° C range, based on current knowledge of complex climate-ecological systems, that knowledge is incomplete: there are many "unknown unknowns" waiting to be discovered.[92] Changes of this magnitude are well within the realm of possibility over the next seven decades.

4.0° C warming would bring more of the same effects as lower levels, but these effects would be more severe.

> "At the global scale, all the impacts that could plausibly be either adverse or beneficial are adverse, and impacts and risks increase with temperature change. For example, the global average chance of a major heatwave increases from 5% in 1981–2010 to 28% at 1.5 ° C and

88. IPCC, "Summary for Policymakers," 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*, eds. V. Masson-Delmotte et al., 2018, https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf.
89. Jason Hickel, "What would It Look Like If We Treated Climate Change as an Actual Emergency?" *Current Affairs*, November 15, 2021, https://www.currentaffairs.org/2021/11/what-would-it-look-like-if-we-treated-climate-change-as-an-actual-emergency.
90. "Impacts of a 4° C global warming," *GreenFacts*, accessed February 8, 2020, https:// www. greenfacts.org/en/impacts-global-warming/l-2/index.htm.
91. "Impacts of a 4° C global warming."
92. Luke Kemp, Chi Xuc, Joanna Depledge, Kristie L. Ebi, Goodwin Gibbins, Timothy A. Kohler, Johan Rockström, Marten Scheffer, Hans Joachim Schellnhuber, Will Steffen, and Timothy M. Lenton, "Climate Endgame: Exploring Catastrophic Climate Change Scenarios," *PNAS*, vol. 119, no. 34, 2022, e2108146119, https://doi.org/10.1073/pnas.2108146119.

> 92% at 4 ° C, of an agricultural drought increases from 9 to 24% at 1.5 ° C and 61% at 4 ° C, and of the 50-year return period river flood increases from 2 to 2.4% at 1.5 ° C and 5.4% at 4 ° C. The chance of a damaging hot spell for maize increases from 5 to 50% at 4 ° C, whilst the chance for rice rises from 27 to 46%. There is considerable uncertainty around these central estimates, and impacts and risks vary between regions. Some impacts—for example heatwaves—increase rapidly as temperature increases, whilst others show more linear responses."[93]

Specific effects:

- The largest warming will occur over land and range from 4° C to 10° C.
- Warming of 4° C will likely lead to a sea-level rise of 62–72 feet at 5° C of warming.[94]
- a 4° C warming would significantly exacerbate existing water scarcity in many regions, particularly northern and eastern Africa, the Middle East, and South Asia, while additional countries in Africa would be newly confronted with water scarcity on a national scale due to population growth.
- Recent research suggests that large-scale loss of biodiversity is likely to occur with a temperature increase of 4° C. Climate change and high CO_2 concentration would drive the earth´s ecosystems into a state unknown in human experience.
- Significant risk of high-temperature thresholds being crossed that could substantially undermine food security globally with a 4° C temperature increase. . . . significant effects have been observed in the United States when local daily temperatures increase to 29° C for corn and 30° C for soybeans.[95]

Kemp et al. note that there is "an increasing probability of multiple 'breadbasket failures' [i.e., maize crop failures] (causing a food price shock) with higher temperatures" and that "50 to 75% of the global population could be exposed to life-threatening climatic conditions by the end of the century due to extreme heat and humidity."[96] Risk areas they recommend for further research include:

- Potential "Hothouse Earth" and other extreme planetary scenarios
- Potential tipping points and their effects
- Mass morbidity and mortality due to famine and undernutrition, extreme weather events, conflict, and vector-borne diseases
- Societal risk cascades involving conflict, disease, political change, and economic crises, as well as the epistemic risks related to the rapid spread of misinformation and disinformation
- Threats interacting with climate change, "including rising inequality, demographic stresses, misinformation, new destructive weapons, and the overshoot of other planetary boundaries. There are also natural shocks, such as solar flares and high-impact volcanic eruptions, that present possible deadly synchronicities"[97]

The World Economic Forum has developed a series of graphics to illustrate the effects of 4.0 C warming.[98]

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93. Arnell, et al., "Global and regional impacts of climate change," 377–391.
94. Henson, "Key Takeaways from the new IPCC Report."
95. "Impacts of a 4° C global warming."
96. Kemp et al., p. 5.
97. Kemp et al., pp. 6–7.
98. See Andrew Berkley and John Letzing, "The Worst-case Climate-change Scenario Could Look Like This. We Need to Avert It," World Economic Forum, September 23, 2020, https://www.weforum.org/agenda/2020/09/the-worst-case-climate-change-scenario-could-look-like-this-we-need-to-avert-it/.

6.0° C and beyond

There are very few reliable projections for this level of warming. Accurate predictions are very difficult due to the number of tipping points and compound effects that would be expected. High-End Climate Impacts and Extremes (HELIX) offers technical reports on modeling, mostly restricted to regional effects in specific domains.[99]

Kemp et al. point out that extreme increases up to 8.0° C are indeed possible, especially after the year 2100. Feedback loops and tipping points are not well-understood: "abrupt and/or irreversible changes may be triggered at a temperature threshold. Such changes are evident in Earth's geological record, and their impacts cascaded across the coupled climate–ecological–social system."[100]

This highly questionable chart is at least a provocative visual representation:

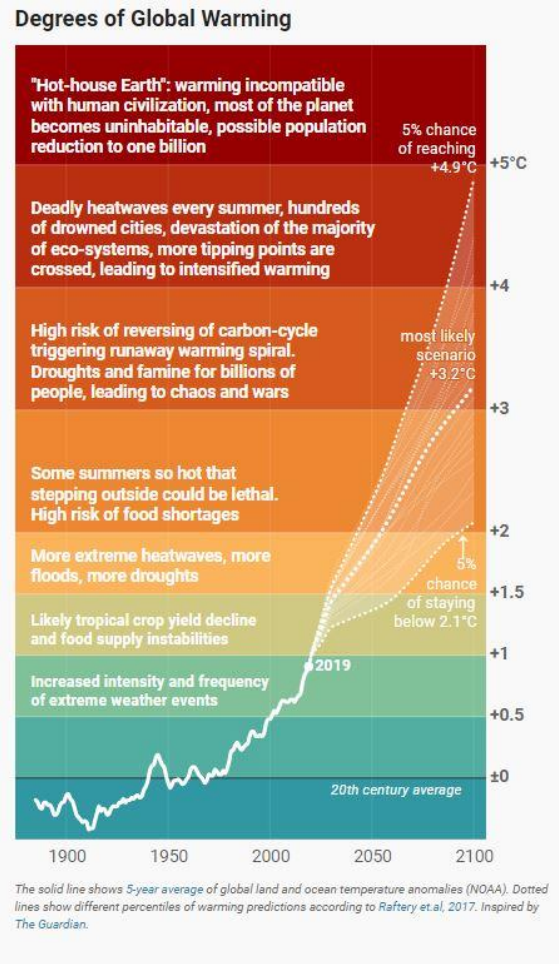
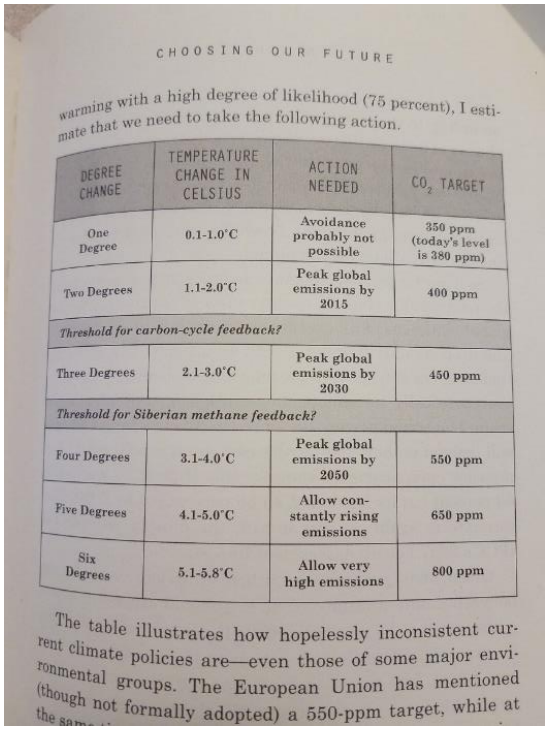


Figure 4. Image from Gregor Aisch, "What Different Degrees of Global Warming Look Like," September 26, 2019, Chartable (blog), https://blog.datawrapper.de/climate-crisis-global-warming/.



CHOOSING OUR FUTURE

warming with a high degree of likelihood (75 percent), I estimate that we need to take the following action.

DEGREE CHANGE	TEMPERATURE CHANGE IN CELSIUS	ACTION NEEDED	CO_2 TARGET
One Degree	0.1-1.0°C	Avoidance probably not possible	350 ppm (today's level is 380 ppm)
Two Degrees	1.1-2.0°C	Peak global emissions by 2015	400 ppm
Threshold for carbon-cycle feedback?			
Three Degrees	2.1-3.0°C	Peak global emissions by 2030	450 ppm
Threshold for Siberian methane feedback?			
Four Degrees	3.1-4.0°C	Peak global emissions by 2050	550 ppm
Five Degrees	4.1-5.0°C	Allow constantly rising emissions	650 ppm
Six Degrees	5.1-5.8°C	Allow very high emissions	800 ppm

The table illustrates how hopelessly inconsistent current climate policies are—even those of some major environmental groups. The European Union has mentioned (though not formally adopted) a 550-ppm target, while at the

Figure 5. Image from Lynas, *Six Degrees*, 279.

See also David Wallace-Wells, *The Uninhabitable Earth: Life After Warming* (2019) and other works by Wallace-Wells.

99. "High-End Climate Impacts and Extremes (HELIX)," Tyndall Centre for Climate Change Research, https://helixclimate.eu/.
100. Kemp et al., p. 2.

4. What are the most promising options for responding to climate change?

- To reduce future level of greenhouse gas emissions
- To mitigate systems changes that will contribute to atmospheric ghg increases
- To sequester carbon already in atmosphere[101]
- To otherwise avoid the effects of climate change

The IPCC reports identify specific targets and the most effective points to intervene in our current systems to reach those targets. The March 2022 IPCC Working Group II report describes five possible scenarios, called "shared socioeconomic pathways" (SSPs). Each represents a future determined by different levels of ghg reduction. The most aggressive pathway, called SSP1-1.9, represents average global warming below 1.9° C; the pathway of continuing current emissions trends, called SSP5-8.5, represents a catastrophic increase of 8.5° C by the year 2100.[102]

As a reference point for the kind of reductions involved, this report indicates that in order to keep global average warming below 1.9° C, total CO_2 emissions would need to be reduced by 25% by 2030, and by about 50% by 2035.[103]

4.1 Accelerating adoption of renewable energy

Drastic reduction in fossil fuel use is the single most effective and urgent step in addressing climate change. This will require not only improving energy efficiency and using replacements for many existing systems, but also introducing clean and convenient sources of energy to replace fossil fuels.

Generating electricity from coal-fired plants is an especially powerful driver of climate change and other environmental problems. Coal mining involves destruction of the land, creates pollution, and involves the release of methane into the atmosphere.[104] The emissions from burning coal include:

- Sulfur dioxide (SO2), which contributes to acid rain and respiratory illnesses
- Nitrogen oxides (NOx), which contribute to smog and respiratory illnesses
- Particulates, which contribute to smog, haze, and respiratory illnesses and lung disease
- Carbon dioxide (CO2), which is the primary greenhouse gas produced from burning fossil fuels (coal, oil, and natural gas)
- Mercury and other heavy metals, which have been linked to both neurological and developmental damage in humans and other animals
- Fly ash and bottom ash, which are residues created when power plants burn coal[105]

101. While there is a great deal of speculative discussion about advanced carbon removal technologies, these new technologies have not been fully developed or proven to be effective. Many scientists are skeptical about whether they could be developed at adequate scale to be effective, and in any case the cost of deploying such technologies would be extremely high. Lower-technology sequestration strategies, such as reforestation and regenerative agriculture, appear to be more accessible. See, for example, Fiona Harvey, "Scientists Urge End to Fossil Fuel Use as Landmark IPCC Report Readied," *The Guardian*, April 3, 2022, https://www.theguardian.com/environment/2022/apr/03/scientists-urge-end-to-fossil-fuel-use-as-landmark-ippc-report-readied.
102. Henson, "Key Takeaways from the new IPCC Report." See also "Climate Change 2021: The Physical Science Basis."
103. Henson, "Key Takeaways from the new IPCC Report."
104. "Coal Explained: Coal and the Environment," U.S. Energy Information Administration, November 16, 2022, https://www.eia.gov/energyexplained/coal/coal-and-the-environment.php.
105. "Coal Explained."

Both European nations and the United States have seen drastic reductions in coal power in recent years, largely due to more cost-effective alternatives—notably, of renewables.[106] While this is encouraging news, the U.S., the third-largest coal consuming nation, accounts for only 8.5% of global coal consumption; European nations each consume far less. The two largest coal consumers are China (50.5% of global total) and India (11.3%).[107] At present, both countries are increasing their reliance on coal.

An incredibly important outstanding question is whether it is feasible for the world to function on (very near to) 100% renewable energy.

In an extensive review of the renewable energy systems analysis literature published in 2022, Breyer et al. conclude that **100% renewable energy can power the world, using existing technologies, at an affordable cost**.[108]

Renewable energy systems are:

- solar energy
- wind energy
- hydropower
- bioenergy
- geothermal
- ocean energy (tidal, wave, ocean current, ocean thermal)

The authors predict that photovoltaic solar and wind energy will be central to future energy systems.[109] Notably, this study includes zero reliance on nuclear power, which many people regard as a problematic energy source.

The April 2022 IPCC Working Group III report shows a dramatic reduction in cost, and a corresponding increase in use, for key renewable energy technologies.[110] This is a promising trend, as fossil fuels are now in some cases a more expensive and less attractive option than renewables:

106. Annabel Cossins-Smith, "Coal Demand in Europe Drops over Winter, Despite Energy Crisis," *Power Technology*, April 27, 2023, https://www.power-technology.com/news/eu-coal-demand-drops-over-winter/; Oliver Millman, "US Renewable Energy Farms Outstrip 99% of Coal Plants Economically," *The Guardian,* January 30, 2023, https://www.theguardian.com/us-news/2023/jan/30/us-coal-more-expensive-than-renewable-energy-study.

107 "Coal Consumption by Country," Worldometer, accessed May 24, 2023, https://www.worldometers.info/coal/coal-consumption-by-country/.

108. Christian Breyer, Siavash Khalili, Dmitrii Bogdanov, Manish Ram, Ayobami Solomon Oyewo, Arman Aghahosseini, Ashish Gulagi, A. A. Solomon, Dominik Keiner, Gabriel Lopez, Poul Alberg Østergaard, Henrik Lund, Brian V. Mathiesen, Mark Z. Jacobson, Marta Victoria, Sven Teske, Thomas Pregger, Vasilis Fthenakis, Marco Raugei, Hannele Holttinen, Ugo Bardi, Auke Hoekstra, and Benjamin K. Sovacool, "On the History and Future of 100% Renewable Energy Systems Research," *IEEE Access*, July 22, https://doi.org/10.1109/ACCESS.2022.3193402.

109. Assaad Razzouk (@AssaadRazzouk), "A brand new scientific paper (474 references) reviews all published research on 100% renewables to show, unequivocally, that 100% renewable energy 'can power all energy in all regions of the world at low cost'," Twitter.com, 3:43 pm, 11 August 2022, https://twitter.com/AssaadRazzouk/status/1557814905822224384.

110. "Climate Change 2022: Mitigation of Climate Change. Summary for Policymakers," Section B.4.3, IPCC Working Group III, April 2022, https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/.

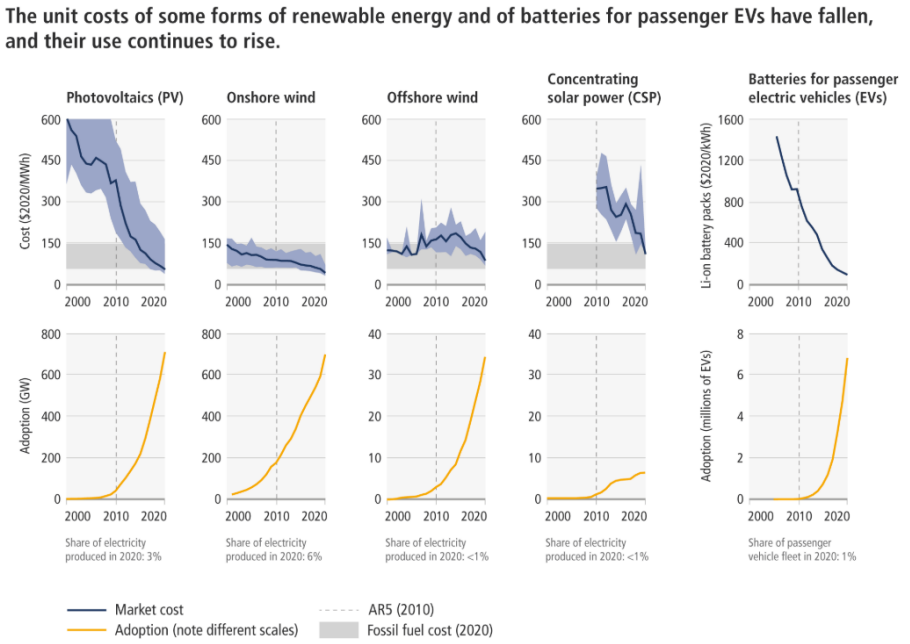


Figure 6. Falling costs and increasing use of renewable energy technologies

In a separate study, Way et al. demonstrate that a transition to renewable energy (solar energy, wind energy, batteries, and electrolyzers) will be more cost-effective than continuing with our fossil fuels. The more rapid the transition, the greater the savings—up to $12 trillion in the best case scenario.[111]

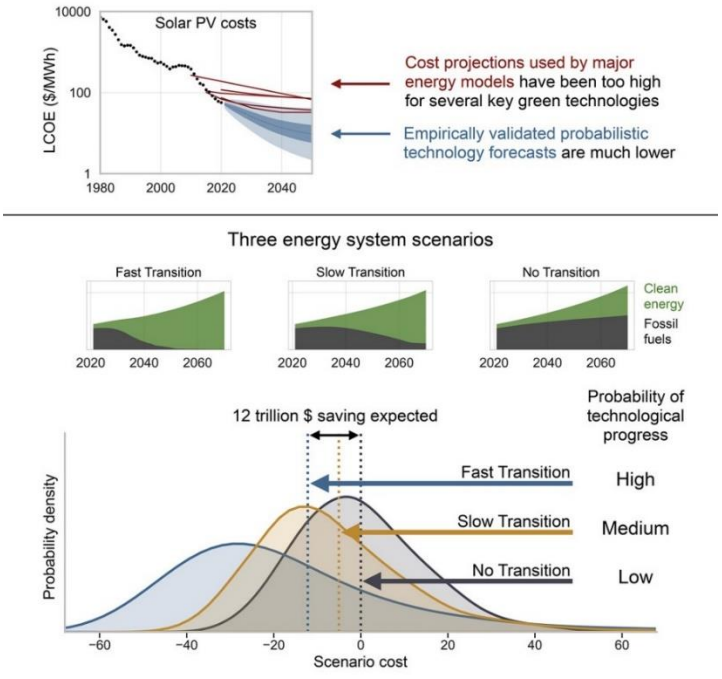


Figure 6. Energy transition scenarios from Way et al., 2022.

111. Rupert Way, Matthew C. Ives, Penny Mealy, and J. Doyne Farmer, "Empirically Grounded Technology Forecasts and the Energy Transition," *Joule*, vol. 6, no. 9, September 21, 2022, pp. 2057-82, https://www.cell.com/joule/fulltext/S2542-4351(22)00410-X.

4.2 Response frameworks and strategies

What systemic changes need to occur for a sustainable future? The following five frameworks present and compare various available intervention points to address ghg emissions across various economic and industrial sectors.

Climate Stabilization Wedges strategy (2000)[112]

"Keeping emissions flat for 50 years will require trimming projected carbon output by roughly 8 billion tons per year by 2060, keeping a total of 200 billion tons of carbon from entering the atmosphere."

"Each of the 15 strategies below has the potential to reduce global carbon emissions by at least 1 billion tons per year by 2060, or 1 wedge. A combination of strategies will be needed to build the eight wedges of the stabilization triangle."[113]

Efficiency

- Double fuel efficiency of 2 billion cars from 30 to 60 mpg.
- Decrease the number of car miles traveled by half.
- Use best efficiency practices in all residential and commercial buildings.
- Produce current coal-based electricity with twice todays efficiency.

Fuel Switching

- Replace 1400 coal electric plants with natural gas-powered facilities.

Carbon Capture and Storage

- Capture AND store emissions from 800 coal electric plants.
- Produce hydrogen from coal at six times today's rate AND store the captured CO_2.
- Capture carbon from 180 coal-to-synfuels plants AND store the CO_2.

Nuclear

- Add double the current global nuclear capacity to replace coal-based electricity.

Wind

- Increase wind electricity capacity by 10 times relative to today, for a total of 2 million large windmills.

Solar

- Install 100 times the current capacity of solar electricity.
- Use 40,000 square kilometers of solar panels (or 4 million windmills) to produce hydrogen for fuel cell cars.

Biomass Fuels

- Increase ethanol production 12 times by creating biomass plantations with area equal to $1/6^{th}$ of world cropland.

Natural Sinks

- Eliminate tropical deforestation.
- Adopt conservation tillage in all agricultural soils worldwide

112. Princeton Environmental Institute, "Stabilization Wedges Introduction," Princeton Environmental Institute Carbon Mitigation Initiative, accessed February 9, 2020, https:// cmi. princeton. edu/resources/stabilization-wedges/introduction/.

113. Princeton Environmental Institute, "Stabilization Wedges Introduction."

Planetary Boundaries Tracking (2009)

This project is housed at the Stockholm Resilience Centre, Stockholm University. "The planetary boundaries concept presents a set of nine planetary boundaries within which humanity can continue to develop and thrive for generations to come. In 2009, former center director Johan Rockström led a group of 28 internationally renowned scientists to identify the nine processes that regulate the stability and resilience of the Earth system. The scientists proposed quantitative planetary boundaries within which humanity can continue to develop and thrive for generations to come. Crossing these boundaries increases the risk of generating large-scale abrupt or irreversible environmental changes."[114]

As of 2020, *genetic diversity*, *phosphorous emissions*, and *nitrogen emissions* are measured as "high risk," while *climate change* and *land system change* measure as "increasing risk." There are not yet established measures for *atmospheric aerosol loading* (which affects climate change), *novel entities*, or *functional diversity*.

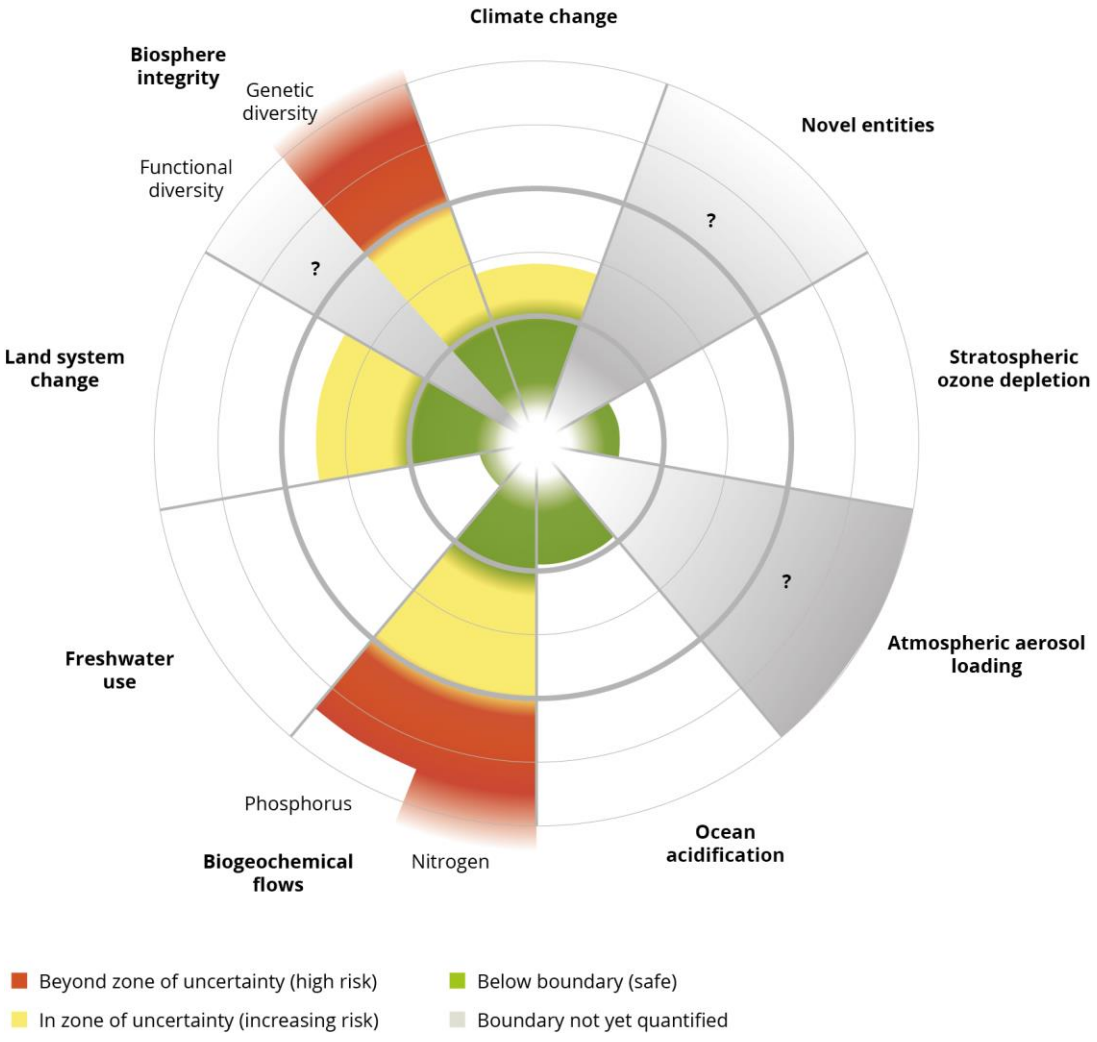


Figure 6. "Planetary Boundaries" (2020). Image: Eionet based on Steffen et al. 2015

114. "Planetary Boundaries," Stockholm Resilience Centre, Stockholm University, accessed April 9, 2022, https://www.stockholmresilience.org/research/planetary-boundaries.html.

J. Rockström et al, "Planetary Boundaries: Exploring the Safe Operating Space for Humanity," *Ecology and Society,* vol. 14, no. 32, 2009. http://www.ecologyandsociety.org/vol14/iss2/art32/

W. Steffen, K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, S. R. Carpenter, W. de Vries, C. A. de Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L. M. Persson, V. Ramanathan, B. Reyers, and S. Sörlin, "Planetary Boundaries: Guiding Human Development on a Changing Planet," *Science,* vol. 347, no. 6223, 2015. https:// doi.org/10.1126/science.1259855

European Environment Information and Observation Network (Eionet), "Status of the Nine Planetary Boundaries," European Environment Agency, November 23, 2020, https://www.eea.europa.eu/soer/2020/soer-2020-visuals/status-of-the-nine-planetary-boundaries/view

The "planetary boundaries" represent an "environmental ceiling" or systems limits, beyond which environmental degradation will make human life on the planet physically precarious. Kate Raworth introduced a social dimension to the planetary boundaries model. These "social foundations" describe lower limits beyond which social justice standards identified in the UN 2015 Sustainable Development Goals would not be met. The space lying between the planetary boundaries and the social foundations describes a "doughnut" of optimal conditions for human life.

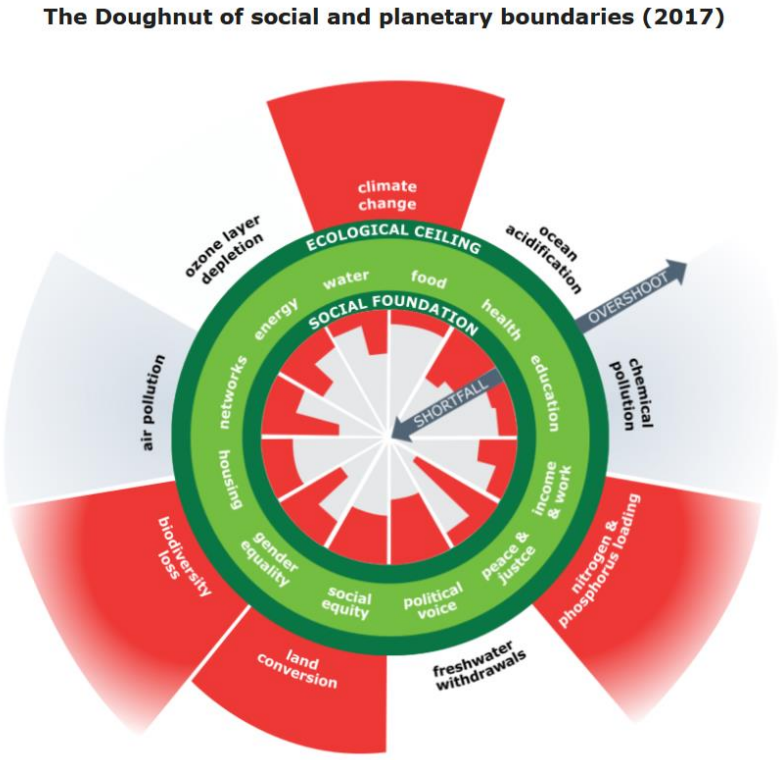


Figure 5. Raworth's "Doughnut" between Planetary Boundaries and Social Foundations

Raworth, K., "Exploring Doughnut Economics," 2013–21, https://www.kateraworth.com/

Project Drawdown (2014)[115]

Ranks 80 different solutions in terms of effectiveness at CO_2 emissions reduction/ avoidance/ sequestration. These are sorted into eight "sectors":

- Materials
- Electricity
- Food
- Women and children
- Land Use
- Buildings and cities
- Transport
- Coming attractions (promising but not-yet-established solutions)

The top 10 solutions are:

	Solution	**Sector**
1.	Refrigerant Management	Materials
2.	Wind Turbines (Onshore)	Electricity Generation
3.	Reduced Food Waste	Food
4.	Plant-Rich Diet	Food
5.	Tropical Forests	Land Use
6.	Educating Girls	Women and Girls
7.	Family Planning	Women and Girls
8.	Solar Farms	Electricity Generation
9.	Silvopasture	Food
10.	Rooftop Solar	Electricity Generation

The claim is that if adopted, the recommended solutions could reverse the trend of increasing ghg emissions by 2050.

Net-Zero America (2018)[116]

Scientific, technical, and economic analysis of various strategies to achieve net-zero emissions. Offer specific recommendations organized around five "pillars":

- Pillar 1: End-use energy productivity—efficiency and electrification
- Pillar 2: Clean electricity
- Pillar 3: Bioenergy and other zero-carbon fuels and feedstocks
- Pillar 4: CO_2 capture, transport, usage, and geologic storage
- Pillar 5: Reduced non- CO_2 emissions
- Pillar 6: Enhanced land sinks

115. "Solutions," Project Drawdown, accessed February 8, 2020, https://www.drawdown.org/solutions.

116. E. Larson, C. Greig, J. Jenkins, E. Mayfield, A. Pascale, C. Zhang, J. Drossman, R. Williams, S. Pacala, R. Socolow, EJ Baik, R. Birdsey, R. Duke, R. Jones, B. Haley, E. Leslie, K. Paustian, and A. Swan, "Net-Zero America: Potential Pathways, Infrastructure, and Impacts: Interim Report," Princeton University, Princeton, NJ, December 15, 2020. https:// environmenthalfcentury.princeton.edu/

World Scientists' Warning: Six Steps (2020)[117]

Energy. Swiftly phasing out fossil fuels is a top priority. This can be achieved through a multipronged strategy based on rapidly transitioning to low-carbon renewables such as solar and wind power, implementing massive conservation practices, and imposing carbon fees high enough to curtail the use of fossil fuels.

Short-lived pollutants. Quickly cutting emissions of methane, black carbon (soot), hydrofluorocarbons and other short-lived climate pollutants is vital. It can dramatically reduce the short-term rate of warming, which may otherwise be difficult to affect. Specific actions to address short-lived pollutants include reducing methane emissions from landfills and the energy sector (methane), promoting improved clean cookstoves (soot) and developing better refrigerant options and management (hydrofluorocarbons).

Nature. We must restore and protect natural ecosystems such as forests, mangroves, wetlands and grasslands, allowing these ecosystems to reach their ecological potential for sequestering carbon dioxide. The logging of the Amazon, tropical forests in Southeast Asia, and other rainforests including the proposed cutting in the Tongass National Forest of Alaska is especially devastating to the climate. Creation of new protected areas, including strategic forest carbon reserves, should be a top priority. Payment for ecosystem services programs offer an equitable way for wealthier nations to help protect natural ecosystems.

Food. A dietary shift toward eating more plant-based foods and consuming fewer animal products, especially beef, would significantly reduce emissions of methane and other greenhouse gases. It would also free up agricultural lands for growing human food and, potentially, reforestation ("Nature" step). Relevant policy actions include minimizing tillage to maximize soil carbon, cutting livestock subsidies and supporting research and development of environmentally friendly meat substitutes. Reducing food waste is also critical, given that at least one third of all food produced is wasted.

Economy. We must transition to a carbon-free economy that reflects our dependence on the biosphere. Exploitation of ecosystems for profit absolutely must be halted for long-term sustainability. While this is a broad, holistic step involving ecological economics, there are specific actions that support this transition. Examples include cutting subsidies to and divesting from the fossil fuel industry.

Population. The global human population, growing by more than 200,000 people per day, must be stabilized and gradually reduced using approaches that ensure social and economic justice such as supporting education for all girls and women, and increasing the availability of voluntary family planning services.

Adaptation Strategies and Actions from the US-EPA (2019)

The U. S. Environmental Protection Agency maintains a website with suggested adaptation strategies in the areas of air, water, waste, and public health. The website lists 164 specific actions (e.g., "Manage water demand," "Restrict or prohibit development in erosion zones") in a searchable database.[118]

117. W. J. Ripple, C. Wolf, T. M. Newsome, P. Barnard, and W. R. Moomaw, "The Climate Emergency: 2020 in Review," *Scientific American,* January 6, 2021, https:// www. scientificamerican.com/article/the-climate-emergency-2020-in-review/

118 "Strategies for Climate Change Adaptation," U.S. Environmental Protection Administration, June 27, 2019, https://www.epa.gov/arc-x/strategies-climate-change-adaptation.

5. What recent U. S. policy addresses climate change?

Two major recent policy proposals have been advanced in the U. S. to begin to address climate change.

The Green New Deal, 2019 (GND)

The Green New Deal is a proposed framework that directs U.S. policy toward addressing climate change across all areas of government influence. As of May 2023 it had not yet been adopted by the U.S. Congress; aspects of the framework were incorporated in the Inflation Reduction Act which was signed into law in August 2022. It is one among a broad array of response frameworks that includes:

Pure laissez-faire capitalism: This will likely lead us to between 6°–8.5° C warming as quickly as possible. There is no reason to think that the invisible hand of the market is good at solving complex global problems, especially those that involve a moral element that runs counter to self-interest. It did not end slavery, it did not solve pollution or the endangered species problem in the 1970's, it did not lead petroleum companies to address climate change when they became aware of it in the 1970's and earlier.

There are some notable free-market moves toward lowering emissions, however. In 2021 BlackRock, Inc., the world's largest asset manager, announced that companies it invests in need to develop a strategy to reach net-zero emissions by 2050.[119]

Capitalism has not addressed problems of poverty, homelessness, health care, war, or systemic racial and sexual discrimination. Defenders of this approach may object that it is not supposed to address these kinds of problems—and that's precisely my point. Like these other large-scale wicked problems, climate change is not a merely technical or economic problem in search of a "silver bullet" linear solution.

Moreover, the free market and capitalist ideology have already had 50 years to address climate change, and they have failed. To endorse this approach to the exclusion of any others is to be motivated by factors other than the belief that it will effectively address climate change.

The Green New Deal would look like one of the following:

Mild Keynesean capitalism with some guidance and regulation

Planned Keynesean capitalism that relies largely on existing market mechanisms and principles of private property ownership, competition, etc. It would use regulations, penalties, taxes, and subsidies to direct people's economic behavior toward desired ends.

The Inflation Reduction Act of 2022 (IRA)

The Act includes close to $370 billion in investments promoting clean energy and environmental justice. It should reduce U.S. ghg emissions by 31–44% by the year 2030; without the Act, reductions would have been 24–35% during that time. While this is still short of the 50–52% reduction target set for the U.S., it is a promising development.[120] Barbenell reports that key provisions of the Act include:

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119. Simon Jessop and Ross Kerber, "BlackRock's Fink Warns Companies They Need to Show a Net-zero Plan," Reuters, January 26, 2021, https://www.reuters.com/article/us-blackrock-governance-ceo-letter/blackrocks-fink-warns-companies-they-need-to-show-a-net-zero-plan-idUSKBN29V1EK.

120. Melissa Barbanell, "Brief Summary of the Climate and Energy Provisions of the Inflation Reduction Act of 2022," World Resources Institute, October 28, 2022, https://www.wri.org/update/brief-summary-climate-and-energy-provisions-inflation-reduction-act-2022.

- Clean electricity tax credits for zero-carbon electricity sources (including wind, solar, geothermal, and nuclear), and for generation from existing nuclear plants and electricity storage technologies
- A ten-year timeline for tax credits to promote new manufacturing facilities and projects
- A $250-billion expansion of financing authority in the U.S. Department of Energy's Loan Programs Office
- A $30 billion expansion in production tax credits for the manufacture of solar panels, wind turbines, batteries and critical minerals processing by
- A $10-billion investment tax credit for clean energy manufacturing
- Nearly $6 billion to help existing heavy manufacturing (such as steel and cement) to reduce emissions
- Bonus credits if components are produced domestically
- Tax credits for carbon capture projects
- A 10-year incentive for clean hydrogen production
- Tax credits for projects built in communities where coal was an economic driver, or in disadvantaged communities with a high unemployment rate
- Direct incentives to property owners to convert furnaces and/or water heaters to heat pumps, to install rooftop solar, and perform energy-efficient retrofits of homes, apartments and affordable housing
- Provisions to address equity and environmental justice, and to reduce pollution in low-income and disadvantaged communities
- A $27 billion Greenhouse Gas Reduction Fund to support rapid deployment of low- to zero-emission technologies.
    - $7 billion for rooftop solar and air-pollution abatement technologies in disadvantaged communities
    - $8 billion for financial and technical assistance for clean energy projects benefitting low-income and disadvantaged communities
    - $12 billion for direct and indirect investments in renewable energy projects nationwide
- Tax credits to families for the purchase of both new and used electric cars

A summary of IRA programs from the U.S. Senate details additional supports for farmers, orestland owners, and rural communities:[121]

- More than $20 billion to support climate-smart agriculture practices
- $5 billion in grants to support healthy, fire resilient forests, forest conservation and urban tree planting
- Tax credits and grants to support the domestic production of biofuels, and to build the infrastructure needed for sustainable aviation fuel and other biofuels
- $2.6 billion in grants to conserve and restore coastal habitats and protect communities that depend on those habitats

Beyond the GND and IRA:

> A regime of **centrally-planned economic structures**, including some free markets and some regulated markets. Some version / degree of socialism.

121 "Summary of the Energy Security and Climate Change Investments in the Inflation Reduction Act of 2022," U. S. Senate, 2022, https://www.democrats.senate.gov/imo/media/doc/summary_of_the_energy_security_and_climate_change_investments_in_the_inflation_reduction_act_of_2022.pdf.

Frameworks that involve root-level cultural change, different conceptions of value:

Zero-growth economy, circular economy, and/or "degrowth" economy

The authors of the 2021 IPBES-IPCC *Report on Biodiversity and Climate Change* call for a turn to alternative concepts of value and the economy:

> "This may involve the redistribution of benefits and costs of actions and even more profoundly, a collective shift of individual and shared values concerning nature. An example is moving away from a conception of economic progress based solely on GDP growth, to one of human development based on inclusive wealth and which considers the multiple values of nature for a good quality of life while not overshooting biophysical and social limits. Another example is the external recognition of indigenous peoples' and community conserved territories and areas (ICCA), initiated, designed, and governed by indigenous communities. While ICCA might be designed to support livelihoods, well-being, and cultural and spiritual values, they can lead to the conservation of natural and modified ecosystems and its biodiversity and associated benefits, including climate benefits."[122]

Per-capita energy use in developed countries is the most significant, disproportional contributing factor to ghg emissions. If we were to measure economic success in terms of human development, well-being, or quality of life, rather than in terms of annual GDP growth, we could unlink success from consumption. Reducing energy use need not detract from quality of life: moving toward more efficient home energy use (heating and cooling) could be entirely neutral; moving toward more energy-efficient transportation (and eliminating the need for many single-passenger automobile commutes) could be beneficial for quality of life. As Rob Jackson says, "We could nudge energy use downwards in a bunch of hyper-consuming countries and not just make a more equitable world, but perhaps make ourselves healthier and happier."[123]

6. What are the main economic-political debate points?

6.1 How will we pay for measures to address climate change?

How will we pay to make the transition to renewable fuels, to switch over to machines and infrastructure that run on these fuels, to redesign and reconstruct the built environment that has locked many people into high-consumption behaviors, to implement carbon sequestration technologies, to transition to entire food system to a sustainable model? These and other sustainability measures will unquestionably be expensive.

When considering this question it will help to remember that a balance sheet always has two sides. Against the considerable costs involved in addressing climate change, we must balance two other costs.

First, over the course of the next thirty to fifty years, most of our current machines and infrastructure will need to be replaced anyway. Highways and bridges become unsafe, buildings must be refurbished or replaced, new construction goes in to meet emerging demands, machines wear out or become obsolete due to new technology. Where the transition to sustainable

122. Pörtner et al., p. 22.

123. Robert B. Jackson, et al., "Human Well-being and Per Capita Energy Use," *Ecosphere*, 2022, 13:e3978, https://doi.org/10.1002/ecs2.3978; reported in Laura Benshoff, "How Much Energy Powers a Good Life? Less than You're Using, Says a New Report," All Things Considered, National Public Radio, April 12, 2022, https://www.npr.org/2022/04/12/1092045712/how-much-energy-powers-a-good-life-less-than-youre-using-says-a-new-report. See also Adams, *Green Development*, ch. 7.

replacements is not obviously the preferred choice (due to cost or effectiveness) we can subsidize it.

Second, the cost of *not* addressing the increasing harms from climate change is quite considerable. The Deloitte Economics Institute in 2022 modelled global economic effects of two paths forward: reaching global warming of 3° C by the end of the century, or else decarbonizing to achieve global net zero by 2050. The report could not be more clear: a single page toward the front of the report declares "Time is up and we know it." The report predicts that *not* addressing global warming will depress global GDP by "nearly 8% in 2070"; it would incur global economic losses of $178 trillion in present U.S. dollars by 2070.[124] The future is and always has been expensive. We right now have an opportunity to reject a frankly miserable future in favor of one that supports higher quality of life, for approximately the same cost.

6.2 Will addressing climate change help or hurt the economy?

The measures needed to address climate change, to restrain increases to 1.5 C or 2.0 C, will be economically significant. Will they be harmful or helpful to the economy?

1. Note that "the economy" is a collection of measurements, an aggregate of phenomena that names a huge variety of discrete activities; it is not an entity in itself that merits protection at all costs. "The economy" is not an entity that has rights or intrinsic value. We would be better to focus on the effects of various climate change strategies on identifiable groups of people.
2. We can imagine climate mitigation strategies that have positive and negative effects on people. There is an opportunity and an obligation to implement positive ones.
3. Large-scale changes to our economic system have been implemented before, with positive effects: "Many argue that actions to achieve this would be economically destructive. This claim has no basis, nor is it consistent with Australia's traditional optimism and ingenuity, nor with historical experience. Similar objections were raised in the past against government policies to limit air pollution, environmental toxins and ozone-destroying chemicals, but we collectively found ways to achieve mitigation at manageable cost, and with net benefits to society that are clear in hindsight." [125]

6.3 Do we need to address "non-environmental" factors in addressing climate change?

Why is it necessary to include aspects of the Green New Deal that address "non-environmental" social factors such as education, income, health care, and employment?

The Economist and other conservative voices argue against this, to advocate addressing *only* factors most directly related to ghg emissions. They promote several "sensible policies":

- a carbon tax
- subsidies for nuclear power
- research for carbon-capture and carbon storage technologies
- move away from coal
- more energy from natural gas and bioenergy[126]

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124. Mark Segal, "Deloitte Pegs Price Tag of Climate Inaction at $178 Trillion over 50 Years," ESGtoday: Finance with Purpose, May 24, 2022, https://www.esgtoday.com/deloitte-pegs-price-tag-of-climate-inaction-at-178-trillion-over-50-years/. Segal reports on Pradeep Philip, Claire Ibrahim, and Cedric Hodges, "The Turning Point: A Global Summary," Deloitte Economics Institute, May 2022, https://www.deloitte.com/content/dam/assets-shared/legacy/docs/gx-global-turning-point-report.pdf.
125. "An Open Letter on Australian Bushfires and Climate: Urgent Need for Deep Cuts in Carbon Emissions," Laureates Open Letter, accessed February 8, 2020, https://laureatebushfiresclimate.wordpress.com/.
126. I. K., "The Problem with the Green New Deal," *The Economist*, February 11, 2019.

The resolution introduced to the U.S. House of Representatives in 2019 by Rep. Alexandria Ocasio-Cortez advocates (* are *directly* connected to ghg reduction):

- *Net-zero ghg emissions by 2050
- *Efficiency upgrades to all buildings
- *Electric vehicles rather than internal combustion
- Job creation and job training
- Livable wage & universal basic income
- Clean air, clean water, and healthy food recognized and provided as human rights
- Universal health care
- Family and medical leave
- Paid vacations
- Retirement security
- Stronger unions
- Affordable housing
- Access to nature for recreation
- Ending oppression, inequality, racism

Development theory has long recognized that **undesirable public behaviors, such as ghg emissions, are usually the result of poverty and other choice-limiting factors** that drive people to the most convenient, and lowest-cost solutions, to meet their needs. It is thus necessary to address factors that contribute to poverty and instability. Health care, social equity, employment, education, peace, etc. make it feasible for people to move toward a low-carbon economy and to implement mitigation measures.

Jane Goodall identifies four large-scale wicked problems that are linked to climate change:

- Poverty
- Unsustainable lifestyles
- Corruption
- Human population growth[127]

6.4 Is this hostile to free markets?

Is a free-market economy structure inherently problematic as contributor to climate change? As a barrier to appropriate responses to climate change? This case is made by Naomi Klein in *This Changes Everything: Capitalism vs. The Climate* (2015).

My take: **The market is a powerful calculator** for solving some kinds of complex distribution problems. It has its place as a tool in appropriate circumstances. But **capitalism as an ideology and economic framework** is in a couple of respects inherently problematic.

1. It encourages **limitless growth**, which involves some degree of limitless consumption, which involves some degree of limitless consumption of finite resources (both stocks and sinks). This is doomed by physics, as Georgescu-Roegan demonstrated in the 1970's.

   Note that the rate of growth in ghg emissions in the U.S. as of early 2019 was 3.4% in the U.S., and 2.7% globally.[128] The growth on US GDP for the same time was 2.9%, and global growth is estimated at 3.9%.
2. Conventional economics assumes the **principle of full substitutability** for any resource, including those that have no substitute (air, water, soil, climate).

127. Jane Goodall, "These 4 Issues May Not Seem Related to Climate Change. But They Are and We Need to Solve them Now," *Time*, September 12, 2019.
128. Lisa Friedman, "What Is the Green New Deal? A Climate Proposal, Explained," *New York Times*, 21 February 2019.

3. It tolerates, and even encourages, **extreme inequalities** and the concentration of resources under the control of a very few people. This a) puts key decisions in too few, unaccountable people's hands and b) deprives many, many people of the capability to make more sustainable decisions about the consumption and waste that drive climate change. For example, 71 percent of all ghg emissions since 1988 have occurred due to 100 companies—mostly petroleum and coal companies.[129]
4. It encourages a degree of **technological optimism** that can verge on delusion: blind faith in new zero-emissions energy sources, global climate engineering schemes, extensive colonization of other planets.

129. Richard Heede, "Carbon Majors: Accounting for carbon and methane emissions 1854 - 2010, Methods & Results Report," Climate Mitigation Services, April 7, 2014. http://climateaccountability.org/pdf/MRR%209.1%20Apr14R.pdf. See also: Naomi Klein, *On Fire: The (Burning) Case for a Green New Deal*, New York: Simon & Schuster, 2019, p. 283.