Impacts of Climate Change

At first global warming sounded like a good idea, especially to people in Northern climes. But starting in the 1960s, scientists recognized long-range problems, concentrating at first on sea-level rise and a threat to food supplies. New items were gradually added to the list, ranging from the degradation of ecosystems to threats to human health to risks of international conflict. Experts in fields from forestry to economics, even national security experts, pitched in to assess the range of possible consequences. It was difficult to make solid predictions given the complexity of the global system, the differences from one region to another, and the ways human society itself might try to adapt to the changes. But by the start of the 21st century it was clear that climate change would bring serious harm to most regions. Indeed many kinds of damage were beginning to appear. At first the changes were apparent only in global statistics, but in the 2010s scientists began to show how global warming made particular heat waves, storms, and other disasters more likely or worse. (For detailed discussion of flooding f rom sea-level rise and intense storms see the separate essay on "Ice Sheets, Rising Seas, Flood."Current scientific understanding of impacts is summarized at the bottom of this essay).

"As scientists, it's a little humbling that we've kind of been saying this for 20 years now, and it's not until people notice daffodils coming out in December that they start to say, 'Maybe they're right.'" — Myles R. Allen[1]

Through the first half of the 20th century, when global warming from the greenhouse effect was only a speculation, the handful of scientists who thought about it supposed any warming would be for the good. Svante Arrhenius, who published the first calculations in 1896, claimed that the world "may hope to enjoy ages with more equable and better climates."[2] Most people assumed that a "balance of nature" made catastrophic consequences impossible, and if any change did result from the "progress" of human industry, it would be all to the good. In any case nobody worried about the impacts of a climate change that scientists expected would only affect their remote descendants, several centuries in the future, if it happened at all.

A few scientists took a closer look in the late 1950s when they realized that the level of carbon dioxide gas (CO_2) in the atmosphere might be rising, suggesting that the average global temperature might climb a few degrees Celsius before the end of the 21st century. Roger Revelle, the most senior of these researchers, publicly speculated that in the 21st century the greenhouse effect might exert "a violent effect on the earth's climate" (as *Time* magazine put it). He thought the temperature rise might eventually melt the Greenland and Antarctic icecaps, raising sea level enough to flood coastlines. Noting that climate had changed abruptly in the past, perhaps bringing

[1] Allen quoted by Justin Gillis, "Wild Weather, Across the Map," *New York Times,* Dec. 31, 2015.

[2] Arrhenius (1908), p. 63.

the downfall of civilizations in the ancient world, in 1957 Revelle told a Congressional committee that the greenhouse effect might someday turn Southern California and Texas into “real deserts.” He also remarked that the Arctic Ocean might become ice-free, to Russia’s advantage. A more famous scientist, Edward Teller, told a meeting of chemists in 1957 that a 10% rise of the CO_2 level, which he expected by the end of the century, would melt so much ice that “Such places as New York and Holland would be inundated.”

Everyone understood this was colorful speculation, more science fiction than scientific prediction. A more cautious senior scientist told his colleagues that they should take seriously the possibility of “warming, and possible changes in rainfall and cloudiness” by the early 21st century. Meanwhile a pair of graduate students suggested that the CO_2 greenhouse effect “could raise such problems as coastal flooding due to rise in sea level and increased aridity in certain areas.”[1]

More scientists began to look at the matter after 1960, when observations showed the level of CO_2 in the atmosphere was indeed rising rapidly. In 1963 a path-breaking meeting on “Implications of Rising Carbon Dioxide Content of the Atmosphere” was convened by the private Conservation Foundation. “Conservation” was the traditional term for a movement that was developing into “environmentalism,” centered on the growing realization that human activities had expanded to the point where they could damage vital ecosystems on a global scale. A majority of the meeting’s funding came from oil companies, already sensing a threat to their business. Participants in the meeting began to frame greenhouse warming as an environmental problem—something “potentially dangerous” to biological systems as well as to humans.

The meeting set the pattern for many later exercises. It brought together experts in carbon dioxide and climate (in fact the *only* experts at that time: Gil Plass and Dave Keeling) with a handful of experts in fisheries, agriculture and so forth. And it resulted in a “consensus” report, which warned that if fossil fuel burning continued, “the earth will be changed, more than likely for the worse.” But the group, like many later ones, admitted ignorance, and called for more research. They could scarcely say what dangers might await. They suspected forest productivity would improve, which did not sound bad, and that the distribution of species including commercial fisheries would change, which could be bad or good. The only thing they felt confident about was that rising temperatures would increase melting of the world’s glaciers, raising the sea level and

[1] Time (1956). Real deserts: Revelle in United States Congress (85:2), House of Representatives, Committee on Appropriations, *Report on the International Geophysical Year* (Washington, D.C.: Government Printing Office, 1957), pp. 104-106. Ice-free: see note near end of this essay. Teller at the Southwest regional meeting of the American Chemical Society (Tulsa, OK); “Teller Sees World-Flooding Peril Due to Industrial Overheating,” *Washington Post*, Dec. 8, 1957, p. 1. Teller’s end-of-the century estimate is in a similar statement (“All the coastal cities would be covered”) in Teller (1960). Lloyd V. Berkner, “Horizons of Meteorology,” talk to American Meteorological Society and American Geophysical Union, May 1, 1957, Am. Met. Soc. records, Box 12; my thanks to Alan Needell for this information. Wallace Broecker and Bruno Giletti in the student magazine *Yale Scientific*, 1957, according to Broecker and Kunzig (2008), p. 71.

bringing "immense flooding" of low-lying areas. Peering dimly into a future that seemed centuries ahead, they thought a warming of just a few degrees could melt the polar ice caps and inundate cities like New York and London, while "many life forms would be annihilated both on land and in the sea." There were no numbers or probabilities attached to any of this; if it was science, that was only in the sense that scientists were making their best guesses, and admitting that it was sheer guesswork.[1]

Global warming caught the attention of the U.S. President's Science Advisory Committee. In 1965 they reported that "By the year 2000 the increase in atmospheric CO_2 ... may be sufficient to produce measurable and perhaps marked changes in climate..." Without attempting to say anything specific, they remarked dryly that the resulting changes "could be deleterious from the point of view of human beings."[2] The following year, a panel of the U.S. National Academy of Sciences took a different tack, warning against "dire predictions of drastic climatic changes." Dire predictions of one or another imminent climate catastrophe had in fact been a staple of the popular press for decades, as magazines, books and other media peddled colorful speculations of every variety. The Academy panel expected no extraordinary climate change in their lifetimes. As for the long run, they remarked that the geological record showed swings of temperature comparable to what the greenhouse effect might cause, and "although some of the natural climatic changes have had locally catastrophic effects, they did not stop the steady evolution of civilization."[3]

That was not entirely reassuring. Concern grew among the few scientists who paid attention to climate theories. Meanwhile the rise of environmentalism was raising public doubts about the benefits of human activity for the planet; smoke in city air and pesticides on farms were no longer tokens of "progress" but instigators of regional or even global harm. A landmark study on "Man's Impact on the Global Environment," conducted at the Massachusetts Institute of Technology in 1970, suggested that greenhouse warming might bring "widespread droughts, changes of the ocean level, and so forth," but could not get beyond such vague worries.[4] A meeting in Stockholm the following year came to similar conclusions, and added that we might pass a point of no return if the Arctic Ocean's ice cover disappeared. That would change the world's weather in ways that the scientists could not guess at, but that they thought might be serious. Their main point in

[1] Conservation Foundation (1963), pp. 1, 5, 6, 14. Specifically, they posited a 4X increase of CO_2 several centuries ahead causing a 7°C rise (a good guess as later calculations found) and said "a change even half as great" would have these impacts. See Rebecca John, "1963 Conference Put Carbon Dioxide and Climate Change in the Spotlight," DeSmog.com (Jan. 30, 2024), online at https://www.desmog.com/2024/01/30/conservation-foundation-conference-1963-big-oil-co2-climate-change/

[2] President's Science Advisory Committee (1965), pp. 126-27.

[3] National Academy of Sciences (1966), Vol. 2, "Research and Development," p. 88.

[4] SCEP (1970), p. 18.

bringing up the Arctic ice, however, was simply to illustrate "the sensitivity of a complex and perhaps unstable system that man might significantly alter."[1]

Up to this point, scientists expected that greenhouse warming, if it happened at all, would bring no serious impacts until well into the 21st century. And the 21st century seemed so far away! But was climate change really so distant? In the early 1970's the world saw vivid illustrations of climate fluctuations as savage droughts afflicted the American Midwest, devastated the Russian wheat crop and brought starvation upon millions in Africa. Studies of climate were still in their infancy, and scientists were debating whether the greenhouse effect from CO_2 emissions might be overwhelmed by the cooling caused by other forms of pollution. A few scientists speculated that industrial emissions of aerosols might cause severe cooling, while others suspected that natural cycles might bring a new ice age within the next few centuries. Nobody knew whether warming or cooling was more likely.

Studies of the impacts of climate change therefore tended to address generalities such as how a given type of crop would respond to either a rise or a drop in temperature. An example was a 1974 report commissioned by the U.S. Central Intelligence Agency (CIA). What if the climate altered radically within a few decades—perhaps the sudden freeze that some journalists warned might grip the planet? The report concluded that the world's food supply might be imperilled. There would be mass migrations, perhaps even wars as starving nations fought for the remaining resources. Scientists scoffed at the scenario, for none of them expected a radical climate shift, whether warming or cooling, could come so swiftly. But for a more distant future, the grim speculations could not be entirely dismissed.

Governments were now putting some of the environmental movement's demands into law; that created a practical need for formal "environmental impact" assessments. A new industry of expert consultants strove to forecast effects on the natural environment of everything from building a dam to regulating factory emissions. On a broader scale, people concerned about the environment applied increasingly sophisticated scientific tools to study the impacts of deforestation, acid rain, and many other large-scale activities. They looked at impacts not only on natural ecosystems but on human health and economic activities. Assessing the long-term impact of greenhouse gases fitted easily into this model.

One example was a 1977 report on "Energy and Climate" from a panel of geophysicists convened by the U.S. National Academy of Sciences. By this time the speculations about cooling had faded away, while many scientists felt that greenhouse warming was a strong possibility. Models of all sorts, from elementary radiation physics to elaborate computer exercises, projected an average global warming of three degrees, give or take, following a doubling of the atmosphere's CO_2 level. What would that mean? Like all studies of this period, the experts just thought through on general physical principles what sort of consequences might result—they had no detailed scientific projections or observations to cite, just what seemed sensible.

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[1] Wilson (1971), pp. 17, 182.

The panel got fairly specific about these potential consequences. On the positive side, the Arctic Ocean might eventually be opened to shipping. On the negative side, there would be "significant effects in the geographic extent and location of important commercial fisheries... marine ecosystems might be seriously disrupted." Stresses on the polar ice caps might lead to a surge of ice into the sea, bringing a "rise in sea level of about 5 meters within 300 years." As for agriculture, there would be "far-reaching consequences" which "we cannot specify... We can only suggest some of the possible effects. A few of these would be beneficial; others would be disruptive." There could be terrible "human disasters" like the recent African droughts. However, the panel made clear they could not foresee what would actually happen. They concluded vaguely that "world society could probably adjust itself, given sufficient time and a sufficient degree of international cooperation. But over shorter times, the effects might be adverse, perhaps even catastrophic."[1]

Two years later another Academy panel said much the same, and took brief note of an additional threat—the rise of CO_2 in the atmosphere would make the oceans more acidic. Here too they found the consequences beyond guessing. Overall the experts could only conclude that as the world warmed, "the socioeconomic consequences may well be significant, but... cannot yet be adequately projected."[2]

All these committees managed to reach a consensus on what they were saying: everybody signed off on the conclusions. They could do that because in most areas they agreed to tell the public that they were uncertain—except they were certain there were risks, serious possibilities that needed to be addressed with dedicated research efforts.

Economists and social scientists were just beginning to take an interest in the topic. In 1980 the Academy appointed an "Ad hoc Study Panel on Economic and Social Aspects of Carbon Dioxide Increase," the first semi-official attempt to address these aspects directly, separate from the science. The panel's lame conclusion was that any problems would come so slowly that they would be overtaken by unpredictable technological and social changes. At worst, people who found themselves in a region with worsening climate could migrate to a better place, as had often happened in the past. This was supposed to be reassuring.

As studies proliferated, the topic of "climate impact studies" was starting to look like a respectable field of research. The significant reports of the late 1970s had all been American, and many scientists wanted to internationalize impact studies. An attempt was initiated by the International Council of Scientific Unions (ICSU), the United Nations Environmental Programme (UNEP) and the World Meteorological Organization (WMO)—the march of acronyms signals the increasing levels of complexity and bureaucracy that were coming into play. However, a one-week meeting in Villach, Austria, in 1980 did not get any farther than the earlier U.S. Academy

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[1] National Academy of Sciences (1977), pp. 8-14.

[2] National Academy of Sciences (1979), pp. 3, 24-27. A pioneering 1965 report to the US government had predicted "increased acidity of fresh waters" witihout mentioing the oceans, and thought it would "have no significant effect on most plants." President's Science Advisory Committee (1965), p. 124.

studies, and its report was not widely circulated. “The ‘internationalisation’ of the assessment effort was not very successful,” admitted one of the leaders, Bert Bolin. A more substantial team effort, assembled in Stockholm, again reached the same conclusions as the American panels—global warming would have profound consequences for ecosystems, agriculture, water resources, the sea level and so forth.[1]

More categories of impacts emerged, and each began to attract its own little band of specialists. For example, an elaborate 1983 study by the U.S. Environmental Protection Agency (EPA), with more than 100 reviewers, studied sea-level rise. The experts concluded that by the end of the 21st century they “could confidently expect major coastal impacts, including shoreline retreat... flooding, saltwater intrusion, and various economic effects.” A more general EPA report that year predicted that climate change would bring “a change in habitability in many geographic regions” within only a few decades, with potentially “catastrophic” consequences. The clear implication was that work on new energy policies should get underway without delay.[2]

This was published almost simultaneously with a 1983 U.S. Academy report, the most detailed assessment up till then. The studies at this point were starting to look less like seat-of-the-pants guesses; they had numbers, equations, references to a nascent peer-reviewed scientific literature. It started with computer projections of future temperature rise along with changes in precipitation, soil moisture and so forth. In a category like agriculture, the experts looked, for example, at how soybean yields had varied with temperature in the past, and what a physiological simulation for wheat said about the response to changes in solar radiation and soil moisture. For sea-level rise, you could calculate how much sea water would expand with heat, and make a rough model (very rough!) of what might happen to the Antarctic ice sheets, and you could look at coral-reef records of sea level during previous warm epochs. With less attempts at precision, the report also pointed out that an increase in extreme summer temperatures would worsen the “excess human death and illness” that came with heat waves. Also, melting of permafrost in the Arctic could require adaptations in engineering. Also, climate shifts “may change the habitats of disease vectors.” Finally and most important, “In our calm assessments we may be overlooking things that should alarm us.” For there might be effects that no expert could predict or even imagine, effects all the more dangerous because they would take the world by surprise.

Overall, then, the Academy and EPA reports were in rough agreement on the likely consequences. However, the summary of the Academy’s report (all that most reporters read) was far from alarming, expressing confidence that as civilization had adapted to climate changes in the past, so we would do in future. The summary neglected to mention dangers that some of the experts believed were serious—for example, a warning in the body of the report that the disintegration of Antarctic ice might bring a catastrophically swift sea level rise. Dominated by conservative scientists, the Academy did not recommend any government policy changes (aside from the customary plea for more funds for research). This would be one area relating to impacts where scientists would disagree with one another in the 1980s and 1990s: not about what impacts

[1] Ad hoc panel: Oreskes et al. (2008b), p. 124; Bolin (2007), p. 34.

[2] Hoffman et al. (1983) as cited by Oreskes et al. (2008b), pp. 134-35, see also pp. 140-41. Seidel and Keyes (1983), quotes pp. ix, 7-7.

were likely, but about whether governments should take action to restrict greenhouse gas emissions, or wait and let society adapt on its own?

Meanwhile, in 1982 Bolin spoke about an international effort with Dr. Mustafa Tolba, the dynamic executive director of UNEP. Tolba, a former professor of biology at Cairo University, wanted to go beyond physical climate studies to bring attention to global ecosystems. That was the sort of “environmental” study that UNEP could support. Later WMO was brought in, and ICSU agreed to publish the results to help them become widely read. The resulting 560-page report, Bolin was proud to say, brought the greenhouse problem “much more to the forefront in the scientific community than earlier assessments had done, particularly amongst those engaged in analysis of the terrestrial ecosystems.” The sequel was a 1985 UNEP/WMO/ICSU conference in Villach, energetically chaired by Tolba, which further publicized the scientists’ warnings. The assembled experts went on to call for policy initiatives—not to restrict greenhouse gases, to be sure, but at least to mobilize an internationally coordinated effort to study policy options.[1]

The studies to this point had used a simple cause-and-effect model. Physical scientists would run computer models to predict changes in precipitation and the like. Others would follow by calculating immediate consequences, for example using historical records to predict how corn yields would vary with the weather. But if farmers could no longer get good results from corn, wouldn’t they plant something more suited to their new climate? During the 1980s, some impact studies began to take account of how humans might adapt to climate change. By the end of the decade, some studies were linking models of crop responses with economic models. Complex interactions were no less crucial in natural ecosystems. Life scientists began to calculate how forests, coral reefs and so forth might respond to the rise of greenhouse gases. For example, could tree species move their ranges pole-ward fast enough to keep up with the temperature rise? At a still higher level of complexity, some studies began to account for the way one type of climate impact might interact with another.

These more sophisticated approaches guided the first comprehensive official U.S. government report, ordered up by Congress in 1986 from the Environmental Protection Agency. The EPA’s findings continued the trend toward predicting more serious, more numerous, and more specific kinds of damage. The experts concluded (as summarized by the *New York Times* in 1989) that “Some ecological systems, particularly forests... may be unable to adapt quickly enough to a rapid increase in temperature... most of the nation’s coastal marshes and swamps would be inundated by salt water... an earlier snowmelt and runoff could disrupt water management systems... Diseases borne by insects, including malaria and Rocky Mountain spotted fever, could spread as warmer weather expanded the range of the insects.” Some of this was already vaguely grasped by the minority of people who followed scientific news closely. Other predictions had been mentioned in passing before but were only now coming under detailed discussion. One reason was that studies had centered on the developed nations where scientists themselves lived and

[1] National Academy of Sciences (1983), pp. 45, 50, 53, on pests see also pp. 405-07. This followed a preliminary report, National Research Council (1982). Here and below I draw especially on Long and Iles (1997). They identify the first World Climate Conference (Geneva, 1979) as “the first major conference to address human health” (p. 8). Bolin (1986), pp. 35-38.

found their funding; problems like the disruption of water supplies as glaciers dwindled, which could devastate impoverished villages in the Andes and Himalayas, got scant attention before the late 1990s. As people took a more global view, what came most to the fore was disease.[1]

Studies of how climate change might affect human health expanded particularly swiftly in the 1990s, catching the attention not only of experts but also the public. Here as in some other categories, the work was increasingly supervised not by a particular government but by international organizations, from the venerable World Health Organization to the new Intergovernmental Panel on Climate Change (IPCC, established 1988). Warnings of severe, even existential, health impacts on civilization had appeared in medical journals in 1989, but the global issue was not followed up as research devolved into specialized studies of one or another specific problem. With health as in some other categories, global generalizations seemed less useful than studies at a regional level. For example, insect vectors of tropical diseases like dengue fever and malaria (which already affected half a billion people) would expand their ranges. The main impacts would be felt in developing nations, but people in the developed world tended to worry chiefly about the spread of such diseases to the temperate zones.[2]

Any regional analysis had to start with the climate changes that would result from a given level of greenhouse gases, as calculated by computer models. But although the increasingly sophisticated models had come to a rough agreement on global features like the rise of average temperature, they differed in the regional details. In places where many factors balanced one another, for example the Sahel region between the Sahara desert and the African rainforest, one model might predict a benign increase of rainfall and another, terrible droughts. Policy-makers did not much care about the average global temperature—they wanted to know how things would change in their own locality.

Unable to make quantitative predictions of just what might happen in each region, at the outset the IPCC had decided to study "vulnerabilities," that is, the nature of damage that a given system might sustain from any of the likely sorts of climate change. This was in line with an established practice of vulnerability studies in many other areas, from food supplies to earthquakes. The experts also considered benefits, but the very term "vulnerability" showed that most of them believed the net effects of greenhouse warming would be harmful. Some disagreed, bringing a serious controversy during the discussions leading to the IPCC's initial report of 1990. The eminent Russian climatologist Mikhail Budyko argued, on the basis of his reconstruction of climates in the distant past, that warming would have important benefits. For Siberia, at least, he

[1] Philip Shabecoff, "Draft Report on Global Warming Foresees Environmental Havoc in U.S.," *New York Times*, October 20, 1988, reporting on draft of United States, Environmental Protection Agency (1989). My search of the Google news archive at http://news.google.com/archivesearch/ found that newspaper and news magazine items on disease spread by climate change and the threat to water supplies from earlier snowmelt began to appear in 1988-89. Items on impacts on water supplies due to the disappearance of glaciers started appearing only in 1997; scientific studies began around the same time. Harm to water supplies was noted, for example, by Revelle and Waggoner (1983).

[2] Butler (2018); Long and Iles (1997), pp. 29-33.

had a point—so long as the warming did not soar higher than in the earlier interglacial epochs he had studied.

In the usual IPCC fashion, the IPCC's 1990 Working Group on impacts forged a consensus by admitting deep scientific uncertainty. The panel couldn't even say whether net global agricultural potential would increase or decrease on a doubling of atmospheric CO_2. While acknowledging there might be benefits in some northern locales, they warned that "there may be severe effects in some regions," ranging from extinction of species to a one-meter rise in sea level by 2100 that would displace many millions of people. Droughts could be a problem, although in areas like the Western United States with elaborate dam systems, the panel thought the problem would be manageable. On the other hand, they foresaw increased frequency and severity of flooding. And an "increased incidence of disturbances such as pest outbreaks and fire are likely to occur in some areas."[1]

To get farther, the impacts analysts needed results from large-scale computer General Circulation Models (GCMs). The modelers, however, had their own concerns. In the early 1990s some were reported to complain that impact analysts were liable to misuse the model results, drawing broad conclusions that were unsupportable, and thus casting discredit on the modelers' work. On the other side, one impacts group complained that "the majority of numerical climate modelers remain more interested in understanding the climate system and how it works than in providing results to the climate impacts assessment community. Some, though by no means all, are quite hostile to the suggestion that they become 'service providers,' which is part of the reason why many of the GCM experiments were (and still are) undertaken with little or no thought that the results might be used in this way."[2]

The IPCC and the modeling community solved the problem in 1997 with a pioneering report on "The Regional Impacts of Climate Change." Each of seven regions of the globe got its own detailed account of vulnerabilities, based on a set of runs of GCMs expressly carried out for the impacts exercise. Runs of more than a dozen different GCMs were compared in order to assess the degree of reliability. At this level it was obviously necessary to consider not only the local climate and ecological systems, but also the local economic, social and political conditions and trends, drawing in the social sciences as equal partners with geophysics and biology. It was becoming a standard practice to consider how people might adapt. For example, the panel concluded that Africa was "the continent most vulnerable to the impacts of projected changes." That was not just because so many parts of Africa were already water-stressed, subject to tropical diseases, and so forth, but still more because population pressure and political failings were causing environmental degradation that would multiply the problems of climate change. Above all, Africa's "widespread poverty limits adaptation capabilities." By contrast, the carefully

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[1] Budyko: Bolin (2007) p. 64. IPCC (1990b), pp. 2-3.

[2] Ann Henderson-Sellers and Wendy Howe, "MECCA Achievements and Lessons Learned," in Howe and Henderson-Sellers, eds., *Assessing Climate Change: Results from the Model Evaluation Consortium for Climate Assessment* (Amsterdam: Gordon and Breach, 1997), p. 377, as quoted in Hundebøl and Nielsen (2014), pp. 462-63, see 456-57.

managed agricultural systems of Europe and North America might even contrive to benefit from a modest warming and rise in the level of CO_2 (which could act as a fertilizer for some crops, although much less effectively than in greenhouses). But the developed nations would certainly suffer some harmful impacts as well.[1]

An elaborate assessment exercise that the U.S. government pursued at the end of the 1990s also compared models. The authors displayed, side by side, the results of two separate computer models (one constructed in the United Kingdom and one in Canada). In some regions the model predictions agreed; there seemed little doubt, for example, that Southern California would get a lot drier. In other regions they diverged, as when one model projected more rain in the Southeast and the other, less. Overall, the American experts agreed with the IPCC that highly managed ecosystems of farming and forestry might do quite well in the first half century of serious warming. On the other hand, nothing could prevent damaging changes in some natural ecosystems and expensive difficulties along the coasts. As for threats to health, there would be some problems but "adaptation is likely to help protect much of the U.S. population." And finally, "some aspects and impacts of climate change will be totally unanticipated," which people could interpret optimistically or pessimistically, according to taste.[2] Scientists in another major industrial country, chilly Russia, foresaw even less worrisome results from global warming. These assessments, and the publics they addressed, could see the impacts as manageable because they were looking little more than half a century ahead. The late 21st century was so far away! Surely by then, humanity would have taken control of its emissions so that CO_2 would not rise dangerously far above the pre-industrial level... wouldn't we?

The future state of the climate would depend crucially on what emission controls nations chose to impose. That exposed a problem with the standard way of predicting impacts. Scientists had tried to look into the future by extrapolating the visible trends and forces along a single line, calculating a most likely outcome within a range of possibilities: "global average temperature will rise three degrees plus or minus 50%" or the like. People would then estimate the consequences of a three-degree rise.

Professional "futurologists" in the social sciences, and the policy-makers they advised, had abandoned that method of prediction decades earlier, when they realized that most of their predictions had been far off the mark. They turned to an approach practiced by military planners and wargamers since the 1940s: instead of trying to predict the most likely future, imagine a wide range of possible futures, and for each of these develop a detailed "scenario". The aim was to stimulate thinking about how your operations should be structured so they would hold up under any of the likely contingencies. This approach was applied to environmental questions in the 1970s by studies that sketched out a set of very different possible futures for pollution, exhaustion of natural resources, food production and so forth, depending on just what policies governments

[1] Watson et al. (1997), quote p. 6; open-air fertilization vs. greenhouses: Long et al. (2006).

[2] National Assessment Synthesis Team (2000-2001), quotes p. 9

might adopt.[1] Since the 1980s most corporations and government agencies had used scenarios for their planning.

The IPCC had taken up this approach from the outset, assembling experts to write scenarios in a lengthy intergovernmental process. The result, published in 1992, was a set of six different scenarios, each describing a way that the world's population, economies, and political structures might evolve over the decades. Experts in various fields of physical and social science could try to figure how much of each of the various greenhouse gases would be emitted by the society of a given scenario, then compute the likely climate changes, and then estimate how that society would try to adapt. Much was omitted from these scenarios, not least the feedback loop by which when climate changes altered the socio-economic system, that would affect the emissions in return. A second try in 1996 produced no fewer than 40 different scenarios, grouped into families in terms of rate of economic growth, sensitivity to environmental problems, degree of international cooperation and so forth.[2] (The effort continued with a "Special Report on Emissions Scenarios" issued in 2000 with scenarios for the third and fourth IPCC reports, followed by "Representative Concentration Pathways" or RCPs for the fifth report and in 2017, after much debate and delay, "Shared Socioeconomic Pathways" or SSPs for the sixth report.)

There were so many unknowns, and so many differences from region to region with each region demanding its own detailed study, that the small community of researchers could explore in depth only a few of the possibilities. Many research projects used only one scenario, a middle one with emissions neither sharply restricted nor rising explosively. Over the following decades actual global emissions would climb faster than in these moderate projections, although not quite as fast as in the maximum-emissions scenario.

That worst-case scenario, later named RCP 8.5, was often called the "business as usual" pathway. That was the path roughly followed by the cumulative greenhouse effect of emissions (although not the specific gases) into the 2010s. Then efforts to restrain greenhouse gases, aided by ever cheaper solar and wind power, began to bend emissions toward a more modest rate of increase. Around this time experts recognized that this maximum pathway, basically burning coal and oil as fast as possible, could never have been sustained to the end of the century. Among other constraints, long before 2100 the ever-rising emissions would have changed the climate enough to cripple the global economy. Misnaming this pathway "business as usual" inspired many exaggerated prophecies of doom. Even scientific reports persisted into the 2020s in calculating the impacts of RCP 8.5 in 2100 as if it was a serious possibility.

In its main reports the IPCC not only laid out clearly the range of scenarios it had investigated, but got increasingly specific about whether the consensus of experts judged a given impact for a given scenario to be "more likely than not," "likely," "very likely," or "virtually certain." There was plenty of uncertainty, not least because the laborious studies lagged behind the science; the panel's 2001 impact assessments relied on older computer model results that were derived from

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[1] The influential pathbreaker was Meadows et al. (1972).

[2] J. Leggett et al., "Emissions Scenarios for the IPCC: an Update," in IPCC (1992), pp. 68-95.

the still older 1992 emission scenarios. (It was only around 2009 that the impacts community figured out ways to work through the different stages in parallel rather than sequentially.)[1]

Meanwhile the impacts community had come to understand that some consequences of climate change would be more dramatic and damaging than they had realized. Up to around 1990, impacts analysts had relied chiefly on generalized statements referring to changes in the average temperature, precipitation, etc. Basic physics dating back to the 19th century (the Clausius–Clapeyron equation) taught that warmer air holds more moisture, and indeed already in 1967 the first plausible computer model of global warming had calculated that both evaporation and precipitation would increase. The hydrological cycle would be suprecharged, making dry regions drier and wet regions wetter. This focus on changes in averages fitted into the traditional climatology—a geography exercise where regional climates were categorized as "semi-arid" or "Mediterranean" or whatever, based on their typical seasonal weather. Economists could calculate the damage of a transition from one category to another.

However, the greatest weather damage actually comes from rare but devastating extreme events—flooding in once-in-a-century downpours, mortality and crop losses in exceptional heat waves, and the like. What if a modest increase in the average temperature made such events more frequent and worse? Few experts thought about that, and the 1990 IPCC study found no reliable indications in past weather records of changes in floods or droughts. The report only briefly mentioned heat waves, storms, blizzards and the like.[2]

While the IPCC report was being written, the NASA computer group found something more ominous. In their model, when warming accelerated the movement of moisture in the atmosphere that brought "an increased frequency of extreme wet situations, as well as increased drought." On the wet side, they anticipated worse thunderstorm downpours and tropical cyclones. On the dry side, "the model results suggest that severe drought (5% frequency today) will occur about 50% of the time by the 2050s." However, they admitted that results from different models were inconsistent. Aside from a few such speculative forays, computer modelers didn't even attempt to project future changes in extreme events, beyond vague generalities and a few guesses for increases of droughts in a small number of specific watersheds. The models of the early 1990s were ill suited to produce detailed numbers for specific types of extreme weather events.[3]

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[1] On RCP 8.5 see Schwalm et al. (2020). Moss et al. (2010) includes an impacts studies historical timeline. For its 2013 report, the IPCC replaced the clumsy socioeconomic scenarios with four batches of numbers representing different pollution emissions at many points on the globe to 2100 and beyond; see IPCC (2014c) and G.P. Wayne, "The Beginner's Guide to Representative Concentration Pathways," http://www.skepticalscience.com/docs/RCP_Guide.pdf.v. For "business as usual" see Burgess et al. (2021).

[2] The pioneer for heat waves was Mearns et al. (1984). Manabe and Wetherald (1967). IPCC (1990a), ch. 6 and section 7.11; IPCC (1990c) ch. 4.

[3] "Increased frequency," Hansen et al. (1989); "results suggest," Rind et al. (1990). Another pioneering study used the Japanese Meteorological Research Institute's model , NodaP

Progress in computer modeling was as rapid as advances in the computers themselves. In 1995 a review of the latest studies reported that extreme precipitation events and thus disastrous floods might in fact become more common. The situation, the reviewers remarked, “poses a classic scientific dilemma, common to much climate change research: whether it is appropriate to ‘go public’ with results in which we have limited confidence.” In the next IPCC report, also completed in 1995, the Working Group on impacts mentioned “extreme events” 106 times in its synthesis, with an entire section devoted to generalized warnings about heat waves, landslides due to flooding, and so forth. But the scientists could get no farther than acknowledging that “Small changes in the mean climate... can produce relatively large changes in the frequency of extreme events;” they could not quantify the likelihood.[1]

Modelers rose to the challenge. For example, runs by one leading group in preparation for the 2001 IPCC reports projected “much more frequent occurrence of severe heat stress conditions in U.S. cities during summer”— heat waves that now happened only 1% of the time would happen eight times more frequently by the end of the century. Another group found “large increases in the severity of drought conditions,” although they had less confidence in their ability to put numbers on the problem. Changes in hurricanes and typhoons were still harder to calculate. It was not until the 2010s that a consensus gradually formed (based less on models than on statistics that now had half a century of warming to study): it seemed that hurricanes and typhoons were not becoming more numerous, but the strongest ones were becoming even stronger. Scientists remained uncertain whether the trend would worsen as the world got warmer, but they could not ignore a series of record-breaking tropical cyclones that assaulted North America and East Asia. By 2020 some experts were thinking of extending the five categories of storm severity to a category 6. From this time forward, stern warnings about extreme events became a main feature of IPCC reports and other impacts statements.[2] *For a full discussion of storms and extreme flood events see the essay on “Ice Sheets, Rising Seas, Floods”*

By 2001 almost all the major likely impacts of the climate changes caused by human activities (“anthropogenic climate change” as people were now calling it) were roughly understood on the global scale. The later IPCC reports were mainly distinguished by an increasing regional specificity, an increasing understanding of how a given impact like a heat wave could harm people, and an increasing certainty that the impacts were already showing up—”likely” shifted to “very likely” and the wording of the executive summaries of the reports got stronger in an effort to make people pay heed.[3] Now the task of impacts researchers was to pin down the specific likely consequences in each of the many different regions, ecosystems and human systems.

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and Tokioka (1989).

[1] Fowler and Hennessy (1995), quote p. 284. IPCC (1996b), section 12.4; IPCC (1996a), ch. 6, p. 336.

[2] Heat waves: Dai et al. (2001), p. 507. Drought: Gregory et al. (1997). Tropical cyclones: Patricola and Wehner (2018).

[3] See IPCC (2014c).

The field of impacts and vulnerabilities research was expanding explosively, along with related studies on how civilization might adapt to the foreseeable impacts. Between 2005 and 2010 alone, the number of scientific publications available on these subjects more than doubled. Scholars who studied the two-decade series of IPCC assessments reported a clear trend toward more complex and more interdisciplinary analysis, in which climate impacts were combined with other stresses and with potential adaptations. The trend responded to the evolving needs of policy-makers. The scientists' first goal had been to evaluate the overall danger to the world associated with a given level of greenhouse gases, in order to advise governments how much effort they should make to restrict emissions. By the time that question was answered, greenhouse gases had risen to a level where some serious impacts were inevitable. Leaders in governments and business organizations were now asking for detailed and precise assessments so they could shape policies for adapting to the changes.[1]

The scientists' attempts at precision could be misleading. For example, studies published from the 1970s into the mid 1980s estimated that by 2100, the sea level might rise anywhere from a few tenths of a meter to a few meters. The upper limit dropped to about half a meter in the IPCC's 1995 report, and it stayed there in the reports through 2007— many readers did not notice that the 2007 report explicitly did not include an addition that might come if polar ice sheets began to surge into the oceans in the next few decades. Most scientists considered that quite unlikely, but there were always some who argued that it was possible. Not until its 2013 report did the IPCC grudgingly admit that the sea level might rise a meter and a half by 2100. And even then the IPCC gave scant attention to such impacts that did not seem fairly likely to happen, even if they would be catastrophic in the event they did befall us.

This was different from the practice in many other kinds of impact studies. For example, the building codes of cities in earthquake zones, and evacuation plans for people living near nuclear reactors, dealt with problems that might have less than one chance in a hundred of happening in the next century. The IPCC, by contrast, was preoccupied with impacts that were more likely than not.

There were still people arguing that climate change would be beneficial. These included a few scientists and a large number of conservatives, amply funded by right-wing private American institutes and corporations. For example, a Hoover Institution publication held that "Global warming, if it were to occur, would probably benefit most Americans." There would be lower heating bills and other energy savings, and besides, "More people die of the cold than of the heat." (Indeed more Americans die in winter than in summer. However, statistical research beginning in the 1990s concluded in the early 2020s that global warming will boost mortality in heat waves more than it will reduce mortality during cold spells; this will be a severe problem for tropical countries.) As late as 2009 the U.S. Chamber of Commerce claimed that "a warming of

[1] Also, the number of scientific publications in English with both "climate change" and "impacts" rose from 232 in 1981-1990= 232 to 16,218 in 2001-2010: Fig. 1.1 (D) in Virginia Burkett et al., eds., Chapter 1 of IPCC (2014d), online at http://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-Chap1_FGDall.pdf , see also for a brief discussion of recent IPCC impacts history. Study of IPCC assessments: Füssel and Klein (2006).

even 3°C in the next 100 years would, on balance, be beneficial to humans." Others asserted, as a Heartland Institute publication declared, that "More carbon dioxide in the air would lead to more luxuriant crop growth and greater crop yields," taking no account of the likely heat waves and droughts.

Little if any hard analysis backed up such statements, but there was some truth in them. As Russians in particular noticed, a bit of warming would bring some benefits to cold regions. But even in those regions the people, crops and entire ecosystems would eventually suffer more harm than good, according to the voluminous and detailed studies worked up by teams of economists, epidemiologists, agronomists and other experts.

The public scarcely knew that these teams existed and never read their reports. The experts' conclusions reached ordinary people at most as a summary paragraph or two in a news story, perhaps "balanced" by a statement from one of the institutions committed to denying any problem existed. Meanwhile some media featured exaggerated warnings of doom. "Global heating will all but eliminate people from the Earth," exclaimed a well-known scientist; a high-ranking bank officer declared that inaction on emissions would bring "the extinction of the human race."[1]

Reality descended upon the abstract world of impact studies as actual consequences of global warming began to appear. In the late 1990s, field surveys of sensitive and well-studied groups like birds and butterflies found them measurably shifting their ranges, or even facing extinction, in just the ways that could be predicted from the observed warming. The 2001 IPCC impacts working group tentatively reported "preliminary indications that some human systems have been affected by recent increases in floods and droughts."[2] Along with future possibilities some experts began to estimate the role that global warming might have already played in one or another actual disaster. It turned out that because of unexpected complexities, the rich nations were not as safe as some had thought.

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[1] Heat mortality: Kinney et al. (2015), Gasparrini et al. (2017), Burkart et al. (2021), Carleton et al. (2022); see below for other adverse health effects. An explainer: Andrew Dessler, "Unraveling the Debate: Does Heat or Cold Cause More Deaths?" The Climate Brink, July 13, 2023, online at https://www.theclimatebrink.com/p/unraveling-the-debate-does-heat-or. Kate Sheppard, "Chamber: Global Warming Is Good for You," MotherJones.com, Oct. 2, 2009, online at https://www.motherjones.com/politics/2009/10/more-chamber-commerces-climate-denial/ ; other conservative quotes from McCright and Dunlap (2000), pp. 514-15. Lovelock (2009), p. 6; Kevin Parker, global head of Deutsche Bank Asset Management, quoted in John M. Broder, "Climate Deal Likely to Bear Big Price Tag," *New York Times* Dec. 9, 2009.

[2] Landmark studies included Parmesan (1996), finding a latitude shift in a North American butterfly (*Euphydryas editha*, Edith's Checkerspot) and attributing it to climate change, Parmesan et al. (1999) with "the first large-scale evidence of poleward shifts in entire species' ranges" from Europe, and the formal attribution of climate impacts on 279 of 1700 species studied, Parmesan and Yohe (2003). In 2021 Edith's Checkerspot was one of dozens of American butterflies found to be in decline due to warming, Forister et al. (2021). IPCC (2001b), section 2.2.

One example: in 2003 a heat wave of unprecedented scope killed 70,000 people in Europe. Nobody had foreseen that isolated old people could not save themselves when the traditional August vacation emptied the cities. Another example: bark beetles, no longer controlled by winter freezes, devastated millions of acres of forests from Alaska to Arizona and from Germany to Siberia. Vast tracts turned from green to ghastly gray; the weakened timber was prey to forest fires. A remark on wildfires following insect outbreaks had been buried on page 752 of one of the IPCC's 2001 reports, which even mentioned pine beetles among possible problems, but nobody had prepared for this particular impact of global warming. By 2010 a world-wide increase in record-breaking and devastating heat waves, droughts and floods had convinced many insurance companies and ordinary citizens that something unprecedented was happening to the weather.

But would the 2003 European heat wave, for example, have happened anyway, even if humans had not pumped greenhouse gases into the atmosphere? A group of scientists took up the question and concluded that human influence had indeed doubled the odds that such a disaster would come. Their landmark 2004 paper was only the first of a new breed of research papers aimed at the "attribution" question—a question of interest not only to scientists but also to lawyers seeking liability for damage. It was a controversial topic, and difficult to study. "Better [computer] models are needed before exceptional events can be reliably linked to global warming," opined the editors of *Nature* in 2012. But with a proliferation of widely available and increasingly powerful models came studies that calculated that global warming had either made a particular event more probable or increased its severity—floods in Britain in 2000, a devastating 2011 Texas heat wave and drought, droughts in the Mediterranean. Especially telling were two independent analyses of a 2010 heat wave that killed 50,000 people in Russia, concluding that such events would become much more likely as the planet warmed. Further studies blamed global warming for marked world-wide increases seen in heat waves and extreme precipitation events in general. As a pair of researchers noted, the emerging observational evidence was "confirming both theory and model predictions made decades ago." Environmentalists began to consider hitting fossil fuel corporations with huge liability lawsuits.[1]

Most of the damage during the first two decades of the century resulted from an increase in persistent weather patterns. There were unusually prolonged summer droughts, lingering incursions of freezing Arctic air in winter, and unprecedented downpours from storms like Hurricane Harvey in 2017, which rapidly intensified and then stalled disastrously over Houston.

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[1] Bark beetles: IPCC (2001c). European 2003 heat wave: Stott et al. (2004). Liability:Allen (2003). Editorial: Nature (2012). British floods: Pall et al. (2011); other extreme precipitation: Min et al. (2011); Shiu et al. (2012); Westra et al. (2013); see Liu et al. (2009). Texas 2011:Peterson et al. (2012); Mediterranean: Hoerling et al. (2012). Russia 2010: Rahmstorf and Coumou (2011), see discussion in Otto (2016). Heat waves in general: Hansen et al. (2012), Perkins et al. (2012); heat waves and precipitation events (an influential review): Coumou and Rahmstorf (2012); Fischer and Knutti (2015); Donat et al. (2016) . Rainfall events: Lehmann et al. (2015); hot, dry, wet spells: Diffenbaugh et al. (2017). See also Jane C. Hu, "The Decade of Attribution Science," Slate.com (Dec. 19, 2019), online at https://slate.com/technology/2019/12/attribution-science-field-explosion-2010s-climate-change.html. "Confirming:" Fischer and Knutti (2016).

The masses of hot air that made heat waves were also traveling more slowly and lasting longer. These "extreme extremes," abnormally intense and persistent weather events, showed up mainly in northern mid-latitudes (and therefore caught the attention of people in the chief industrialized nations). Researchers, taken aback, worried that damage was arriving decades sooner than they had anticipated. They set to querying weather statistics, meteorological theory, and computer models for an explanation.

Around 2012 some novel ideas arose. Was the intense warming of the Arctic making the jet stream wobble and weakening the "polar vortex" that usually trapped cold air over the Arctic Ocean? The concern seemed to be validated by severe, lingering heat waves and unprecedented cold spells that shocked large regions of the United States in the early 2020s. Many experts were dubious. The possible mechanisms turned out to be complex, frustrating computer modelers who tried to reproduce the patterns that other teams extracted from weather data. The failure of modelers to find a strong Arctic influence seemed to say that the recent disasters were just a run of exceptionally bad luck. But the models were far from complete and debate continued. As a reviewer explained, this was a "messy but necessary exploratory phase" of research. Asked about the frequency of dangerously persistent events with future warming, different models got wildly different results.

In the news media the most visible weather events, storms, were rarely connected with climate change. Most experts continued to say that it was impossible to tell whether global warming had "caused" a particular storm. One general trend in storms, however, was becoming clear: extreme precipitation events were increasing along with global warming. And now some scientists began to claim that after an exceptional storm, they could calculate whether global warming had made it worse. For example, one team reported that when superstorm Sandy struck New York City in 2012, "It is quite possible that the subways and tunnels might not have flooded without the warming-induced increases in sea level and in storm intensity and size, putting a potential price tag of human climate change on this storm in the tens of billions of dollars."[1]

[1] Circulation changes: an early attempt was Meehl and Tebaldi (2004). Other early work on the effects of Arctic sea ice loss included Honda et al. (2009), Deser et al. (2010), Overland et al. (2011), Overland et al. (2012), Trenberth and Fasullo (2012), Hudson (2012); the breakthrough paper, for its " evidence supporting two hypothesized mechanisms," was Francis and Vavrus (2012). An interim review: Cohen et al. (2014). Attempts at explanations: Petoukhov et al. (2013), Coumou et al. (2015), Francis and Vavrus (2015), Sun et al. (2016), Mann et al. (2017), Mann et al. (2018); Vavrus et al. (2017), Kim et al. (2017), Cohen et al. (2018); reviews: Coumou et al. (2018), Cohen et al. (2020). Modelers: Blackport and Screen (2020), Voosen (2021a); "messy:" Vavrus (2018). Reviews: Coumou et al. (2018), Cohen et al. (2020). For slower heat waves and possible mechanisms see Luo et al. (2024). Robert McSweeney, "Q&A: How Is Arctic Warming Linked to the 'Polar Vortex' and Other Extreme Weather?" CarbonBrief.org, Jan. 31, 2019, online at https://www.carbonbrief.org/qa-how-is-arctic-warming-linked-to-polar-vortext-other-extreme-weather. Wildly different results: Mann et al. (2018). Cohen et al. (2023) found "no detectable trend in mid-latitude cold extremes." For a risk that a stable jet-stream pattern might cause simultaneous crop failures around the Northern Hemisphere see Kornhuber et al. (2020), Rogers

The American Meteorological Society (AMS) launched an annual series of special issues of its *Bulletin* to investigate attribution of various kinds of weather disasters. In the second issue, covering extreme weather events of 2012, half of the studies found evidence that anthropogenic climate change had added to the damage, although natural variability still mostly dominated. Starting in 2014, an international collaboration of scientists undertook the challenging task of attributing damage from extreme weather events to human influence while the disasters were still in the news. In 2016 a panel of the U.S. National Academy of Sciences gave attribution studies the stamp of approval: "it is now often possible to make and defend quantitative statements" on how anthropogenic climate change affected droughts, heat waves, and so forth. In 2017, for the first time, studies in the AMS *Bulletin* found that without global warming some harmful events "would not have been possible." By 2020 scientists were tentatively adding up costs not just in money but in human lives. The losses were undeniable in heat waves that would have been far less severe without global warming. For example, *The Lancet,* a leading medical journal, reported that "During the past 20 years, there has been a 53.7% increase in heat-related mortality in people older than 65 years, reaching a total of 296,000 deaths in 2018."

Over the decades scientists had painstakingly taught weather reporters to avoid claiming that climate change could be held responsible for any particular isolated weather event. Now an editor of the *Bulletin* admitted, "We kind of had to say, `Remember how we told you we could never say that? Well, we're saying that'."[1]

One thing was certain: the weather was changing and would change a lot more. This was not just global warming but "global weirding." Why, for example, had ice melted at the North Pole in February 2017 while snow covered Rome? Why were there not only prolonged heat waves but unrelenting winter cold spells? If scientists debated whether the spate of jet stream excursions and blocking patterns was normal random weather or exacerbated by global warming, there was clearly much they did not understand. That pointed to a bigger problem: crucial changes in the weather regime might not be imagined until they had already begun to show up.

In 2018 the IPCC issued a special report on the impacts of a 1.5°C rise since the 1800s—only half a degree beyond what had already happened, and due around mid century. The findings shocked even climate experts. "Multiple lines of evidence" predicted dire harm, both worse and sooner than previous assessments had expected. Other studies warned that once we reached 2°C

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et al. (2022). Storm downpour trend: Westra et al. (2013). Sandy: Trenberth et al. (2015a); another study calculated the added cost from sea-level rise alone at $8 billion, Strauss et al. (2021).

[1] American Meteorological Society (2013). National Academies of Sciences (2016), p. 14. "Not Possible in a Preindustrial Climate:" American Meteorological Society (2018) (published Dec. 2017), see, e.g., Imada et al. (2018), and Nature (2017). Heat wave mortality (also economic losses): Watts et al. (2020); see also Kinney et al. (2015) and Carleton et al. (2022); Imada et al. (2019) was the first demonstration of specific deaths undeniably caused by global warming. "We're saying that," Stephanie Herring in Adam Rogers, "How to Fight Climate Change: Figure out Who's to Blame, and Sue Them," Wired.com (May 4, 2018), online at https://www.wired.com/story/climate-attribution-sue/. {from floods n. 35}

of warming, an irreversible "cascade" of interacting feedback processes might overwhelm the global carbon system. The planet could transform over centuries into its ancient "hothouse Earth" state with balmy summers at the ice-free poles, uninhabitable tropical deserts, and seas tens of meters higher.

Even now, record-breaking droughts in the American Southwest, Amazon basin, Australia, and the Mediterranean looked like harbingers of permanent changes in precipitation and temperature patterns that could turn crucial agricultural areas into dust bowls. These regions and others from the Middle East to Southeast Asia seemed likely to be severely damaged already by mid-century, with worse later on.

More generally scientists had long expected, and a widely noted 2006 computer study calculated, that with global warming "wet regions get wetter and dry regions drier" in a kind of balance. The rains missing from drought regions would come down elsewhere, exacerbating regional floods. The 2021 IPCC report,for example, predicted "stronger changes in both wet and dry extremes" and used the phrase "wet or dry" more than a hundred times. This focus on the hydrological cycle echoed the tradition of classifying a climate as, say, "arid" strictly in terms of precipitation, carrying on the ancient practice of farmers anxiously watching for rain.

The damage wrought by unprecedented heat waves, however, showed that rainfall was only half the picture. The other half was the drying out of soils as heat increased evaporation. (It turned out that transpiration of moisture from plants also mattered.) A 2015 study, not widely noted at the time, warned that over land surfaces, the increase of evapotranspiration was tending to exceed the increase of precipitation, leading to "a robust drying tendency at almost all latitudes." Yet for years, as a United Nations study recalled, "rigorously documenting aridity's rise was challenging and controversial." One plain measure, published in 2023, was that globally lakes were losing water on balance—dry kept getting drier, but wet got wetter only spasmodically. Finally in 2025 a definitive study, using three different data sets, showed that soils around the world had been drying out. The loss of water from land was so great that it was adding signicantly to sea-level rise.[1]

While farmers might suffer quietly, the hot and dry conditions brought spectacular wildfires. Among the disasters in the summer of 1988 that had awakened the public at large to the risk of global warming, the most shocking was a forest fire that devastated Yellowstone National Park.

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[1] "Global weirding" was coined by conservationist Hunter Lovins and popularized by columnist Thomas Friedman. IPCC (2018a); Lenton et al. (2019), Steffen et al. (2018). Drought: Romm (2011); Dai (2011). Dai (2012) predicted "devastating impacts" late in the century. For a controversial contrary view see Sheffield et al. (2012). Wet/dry: Held and Soden (2006), anticipated by Hansen et al. (1989), see also above (Clausius-Clapeyron). Whether in general dry regions were already getting drier and wet regions wetter was still uncertain in 2014, Greve et al. (2014). "Wet and dry:" IPCC (2021a), §8.5.1.2.2, p. 1141."Robust drying tendency:" Byrne and O'Gorman (2015). "Controversial:" Vicente-Serrano et al. (2024), p. 7, reporting a net global drying trend 1990-2020. Lakes: Yao et al. (2023). On drying in Western US see Zhuang et al. (2024). Three data sets: Seo et al. (2025).

Would global warming bring more of that? Research proliferated; the 1,031 pages of the IPCC's 2001 report on impacts include more than 400 mentions of "fire;" the 2007 report similarly put wildfires on the same level as floods, drought, and disease.

Wildfire damage was in fact increasing in important regions, and some people began to hold climate change at least partly responsible. Critics replied that the real cause was poor management that had made forests more flammable, plus the expansion of housing into risky places. The total global area burned had actually been decreasing for centuries, simply because forests and grasslands were being relentlessly converted to farmland. However, after 2001 two decades of monster wildfires around the globe aroused "a nagging suspicion" in many scientists, as a veteran climate journalist reported, that "wildfires have increased somehow, and climate change is almost certainly a factor." Patterns of precipitation were diverging ever farther from what the vegetation was adapted to tolerate, and hot, dry "fire weather" was becoming more common. In 2024, studies at last produced unequivocal evidence that climate change was raising the world's total burned area; the frequency of extreme conflagrations in particular was rising globally—indeed had doubled over the past two decades.[1]

Forestry experts had traditionally studied wildfires as an economic issue in the context of forest health and the loss of valuable timber, much as agricultural experts studied crop yields. Research on other impacts spread only when they began to actually happen. For example, the comprehensive 2007 IPCC impacts report gave only a single sentence to the risk that smoke from forest fires might affect health over a large region. In 2010 forest fires in Siberia impelled citizens in distant Moscow to wear face masks, but the IPCC's voluminous 2014 impacts report still allowed wildfire smoke only a few superficial (and erroneous) sentences. In the early 2020s

[1] Wildfires: IPCC (2001c), IPCC (2007c). Regional increases: e.g., a landmark paper found that "large wildfire activity [in the Western U.S.] increased suddenly and markedly in the mid-1980s... The greatest increases occurred ... where land-use histories have relatively little effect on fire risks ...," Westerling et al. (2006); see Liu et al. (2010); Jolly et al. (2015); in the Western U.S., "human-caused climate change... doubled the cumulative forest fire area since 1984," Abatzoglou and Williams (2016); in the disastrous 2017 British Columbia fires, nine-tenths of the area burned "can be attributed to anthropogenic climate change," Kirchmeier-Young et al. (2018); Canadian fire season of 2023: Jain et al. (2024). "Nagging suspicion:" Tollefson (2024a). Changing hydrological patterns: e.g., "whiplash" of excess rain followed by drought, Swain et al. (2025) (published weeks before a catastrophic Los Angeles fire exacerbated by that pattern). Fire weather: Zhuang et al. (2021), IPCC (2022), SPM.B.1.1, Liu et al. (2022), see also United Nations Environment Programme (2022). Other exceptionally devastating wildfires through 2020 included outbreaks in Greece 2007; around the Mediterranean 2009; Australia 2009 and 2019-20 (the "black summer," an important impetus to studies, in particular on unhealthy smoke); Russia 2010, 2015, and 2019; India 2016 and 2019; California 2018 and 2020; Brazil 2019. "Climate change increased global burned area by 15.8%" 2003–2019: Burton et al. (2024a); frequency of extreme wildfires: Cunningham et al. (2024).

researchers finally began to investigate the harm if tens of millions of people inhaled noxious smoke from wildfires—by now an annual occurrence.[1]

Looking farther ahead, the rise of sea level was clearly going to be as dangerous as predictions had long foreboded. Already "king tides" periodically flooded streets in Florida that used to stay dry, while elsewhere storm surges were reaching farther inland. It was becoming clear that global warming was responsible, and would make the flooding progressively worse. The melting of Greenland and the retreat of Antarctic ice sheets were proceeding faster than experts had expected and now looked irreversible. An extrapolation of the rise found that by 2060, "100-year floods on some coastlines could be a near annual occurrence." In the worst case, by 2100 there could be another two meters (6 feet) of sea-level rise. Coastal regions including entire cities would have to be evacuated. If you were willing to look much farther ahead, over centuries the loss of ice was likely to end with the seas six meters higher if not more.[2]

Another long-term problem was ocean acidification. Experts had long understood that most of the CO_2 we added to the atmosphere would wind up dissolved in the oceans, and that would make the sea water more acidic. Already in 1979 a National Academy of Sciences report had mentioned the effect in passing. But hardly anyone saw acidification as a serious problem, and it was not even mentioned in the IPCC's reports through 2001. The breakthrough came in a 2003 paper that calculated the change in coming centuries. Humanity's emissions were so massive that the acidity of the world-ocean would climb to a level not seen in hundreds of millions of years, except during rare catastrophic events. Some scientists raised an apocalyptic possibility—could acidification bring the sort of mass extinction seen only a few times previously in the planet's history?

Biologists hastened to launch laboratory and field studies of the effects of ocean acidification (a term few of them had heard before 2003). The obvious initial research target was to find whether the shells of sea creatures would dissolve, or at least become more difficult for the creatures to construct. The answer was "Yes" for some important species. Acidification might already be the reason some oyster hatcheries were struggling. As studies expanded, more complex systemic effects came to light. For example, a clever natural experiment looked at coral reefs where undersea volcanic seeps of CO_2 acidified the water, and found the reefs severely impoverished. It became clear that whatever else might happen, continued CO_2 emissions by humanity were certain to gravely damage coral reefs before the end of the century, with "huge economic effects on food security for hundreds of millions of people." Unless humanity launched a heroic technological effort, the changes in seawater would persist for many thousands of years.[3]

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[1] Fires in forests treated like crops, e.g., United States, Environmental Protection Agency (1989).Smoke: IPCC (2007c), p. 402; erroneous: IPCC (2014d), p.729, citing for "forest fires" Johnston et al. (2012), which actually included peat and grasslands fires plus fires set to clear land for planting.

[2] Coastal flooding "near annual:" Voosen (2020). Sea level: Kopp (2009); Dutton et al. (2015).

[3] National Academy of Sciences (1979), pp. 24-27; Caldeira and Wickett (2003), followed up by a landmark symposium, SCOR/IOC (2004). In English-language books the

The threat global warming posed to marine ecosystems became visible in the mid 2010s when a "blob" of unusually warm water lingered for years in the Northeast Pacific Ocean, producing blooms of toxic algae that devastated fisheries. Studies that focused on average warming had overlooked the impact of such rare but extreme events. Researchers began to study such "marine heat waves," and in 2020 reported that damaging events had "increased more than 20-fold as a result of anthropogenic climate change."[1]

Additional stress on marine life would come from lack of oxygen, "anoxia," for warmer water dissolves less of the gas. Moreover, warming was increasing the stratification of the oceans (less mixing between the heated surface and deeper layers), which among other problems would amplify the anoxia. Like acidification, this problem was first noticed early in the 21st century. As geologists announced that ocean anoxia had figured in some mass extinctions of the past, computer studies found that if emissions continued unchecked, the average oxygen content of seawater would drop several percent. That didn't sound too bad. However, some large marine regions were already oxygen-poor, mainly because excess fertilizer washed from farms into the sea, where it promoted blooms of plankton that sucked up oxygen. A further drop due to warming would raise a serious risk of "more frequent mortality events." Some researchers turned to studying the combined effects on marine life of lowered oxygen plus acidification (not good). Meanwhile deadly ocean regions with low oxygen levels were found to be expandig. A geophysicist warned of "a decimation... affecting key coastal fisheries and coral reefs." [2]

Land ecosystems, too, were under increasing stress, and not only from extreme events like heat waves. An alarm was sounded around the start of the 21st century when people began to notice that some plants were flowering earlier in the Spring than in former times (one pioneering study drew on meticulous records made by Henry Thoreau made in the 1850s). Farmers were pleased that growing seasons were getting longer. But by the 2020s, ecologists had become seriously concerned for the fine-tuned synchronization that

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phrase "ocean acidification" was rare until 2002, then the frequency shot up; see https://books.google.com/ngrams. For earlier history see Brewer (2013); pioneering studies of effects include Gattuso et al. (1998), Kleypas et al. (1999) and Riebesell et al. (2000). A review of "the other CO_2 problem:" Doney et al. (2009). Seeps: e.g., Fabricius et al. (2011). "Economic effects": Carpenter et al. (2008).

[1] 20-fold: Laufkötter et al. (2020), see also Oliver et al. (2018). An early survey of the literature: Holbrook et al. (2019).

[2] Ocean anoxia: one pioneering computer study was Matear and Hirst (2003), q.v. for references to earlier work; Veron (2008); Hönisch et al. (2012). "Mortality events:" Shaffer et al. (2009); expansion of low-oxygen regions ("deoxygenation"): Breitburg et al. (2018); "decimation:" Kendall (2023); for a somewhat more optimistic view see Moretti et al. (2024) . Stratification observed (as long predicted): Li et al. (2020).

many species relied on—buds opening as pollinating insects emerged, birds laying eggs when food for their young was due to appear, and so forth. There were countless unexpected ways climate change could damage ecosystems.[1]

Humans were another species experiencing new stresses. Sometimes global warming was helpful, for example decreasing pneumonia as winters got warmer. But for the majority of infectious diseases, climate hazards were making things worse. Unexpected health problems emerged. For example, by the 2020s longer pollen seasons and smoke from wildfires were aggravating respiratory difficulties. The IPCC's comprehensive 2022 report on impacts listed a startling variety of health problems that had begun to visibly afflict people, ranging from cholera epidemics to psychological difficulties following "loss of livelihoods." Other psychological problems, related to anxiety, anger and grief over a future devastated by climate change, were beginning to weigh on many lives. *(For psychological and mental health impacts see the essay on "The Public and Climate Change.")* In 2021 the World Health Organization, in the midst of the devastating Covid-19 pandemic, called climate change "the biggest health threat facing humanity."[2]

Other kinds of impacts, however, could mean little to people unless they were translated into specific human outcomes. For example, if an aquifer turned brackish as the sea level rose, exactly what difference would that make to anyone? Since the early 1970s, a few economists had been developing increasingly detailed projections of the economic costs and benefits of global warming, working up from regional examples to global estimates. Of course, it was not easy to put a dollar value on hotter summers or the devastation of the world's coral reefs. Some free-market economists calculated that the cost of climate change would be negligible or at any rate bearable; they warned that taxing or regulating emissions would be too economically damaging to be worthwhile. The pioneer, William Nordhaus, got a Nobel Prize for his work. Others replied with calculations that gave opposite results.

Starting in the 1990s, climate economics grew into a minor specialty with increasingly sophisticated models. Some economists began to argue that it would be much cheaper overall to restrict greenhouse emissions now rather than allow them to accumulate. They were contradicted by other professionals (some of them, of course, in the pay of fossil-fuel corporations) who calculated very high costs for restricting emissions while scarcely taking benefits into account.

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[1] Growing seasons (phenology): Menzel and Fabian (1999), Thoreau: Miller-Rushing and Primack (2008).

[2] More than half: Mora et al. (2022). Pollen: Anderegg et al. (2021), Kurganskiy et al. (2021). IPCC (2022), SPM.B.1.4; World Health Organization, "Climate Change and Health," October 30, 2021, online at https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health, see also Atwoli et al. (2021);

All these early economic models were essentially hand-waving, with equations based on assumptions derived from little but personal intuition.[1]

Particularly influential arguments came from Bjørn Lomborg, a Danish political scientist who wrote a best-selling book and in 2004 assembled a panel of prominent economists to analyze various approaches (the "Copenhagen Consensus"). Lomborg and his panel argued that it would be far better for humanity to spend its money on immediate problems like malaria than on long-term problems like global warming—although they did agree that governments would do well to spend far more money on research on ways to reduce greenhouse emissions.[2] The debate evolved into a discussion of basic principles, exposing issues that the public and policy-makers scarcely appreciated. Some economists pointed out that the conventional methods of their field were not suited to deal with such a question, where the largest consequences were generations ahead and the range of possibilities extended to utter devastation. Hardly any impact study looked farther ahead than 2100; the 22nd century just seemed too far away.

Governmental and international bodies stepped in, supporting elaborate professional studies. One major influence in shifting debate from geophysical to economic impacts was the groundbreaking *Stern Review on the Economics of Climate Change*, produced for the British government in 2006 by Nicholas Stern, former chief economist of the World Bank, with a staff of 20. Stern framed the question in a businesslike "risk management" manner, studying the worst case plausible enough to be worth buying insurance against (under the assumption that the well-being of future generations has significant value for us in the present). His team calculated that if global warming in the 21st century was in the upper range of what scientists thought likely, the direct effects would cut the annual Global Domestic Product by some 5%. Indirect effects might possibly raise that as high as 20%, equivalent to the Great Depression of the 1930s or the damage in one of the

[1] Discussions began with D'Arge and Kogiku (1973), arguing that CO_2 emissions should be restricted, and Nordhaus (1974), saying the greenhouse effect should not constrain energy growth in the near future at least. Long and Iles (1997) point to the U.S. Department of Transportation's Climatic Impact Assessment Program (aimed not at the greenhouse effect but aircraft emissions) for producing, in 1975, "the first assessment to focus on social and economic measures," (p. 6) and the 1989 U.S. Environmental Protection Agency study as "the first extensive appearance of an economic analysis of impacts." The pioneering model Nordhaus (1991) found "no strong presumption of substantial net economic damages" from global warming (p. 933), but it laid out clearly basic assumptions and options including setting a price on emissions; by the time Nordhaus shared the 2018 Nobel Memorial Prize in Economic Sciences he agreed that emissions must be strictly restrained. For changes in IPCC strategy between the 4th and 5th Assessment Reports see Dahan (2010), p. 289. Underestimate: DeFries et al. (2019), online at http://www.lse.ac.uk/GranthamInstitute/publication/the-missing-economic-risks-in-assessments-of-climate-change-impacts/. Fossil-fuel support: Franta (2021). See Ackerman et al. (2009) for an influential and scathing critique of economists'"Integrated Assessment Models,"

[2] Lomborg (2001); Lomborg (2004), see also Lomborg (2007). For criticism of factual errors see http://www.lomborg-errors.dk and Friel (2010). {from public2 n.147a}

20th century's world wars—maintained perpetually. The economists made a rough estimate of the cost of preventing that, most likely a modest 1% reduction in Global Domestic Product. Climate change, Stern concluded, "is the greatest market failure the world has ever seen."

The IPCC's 2007 report reached a similar conclusion, and by 2015 a survey found a "clear consensus among economic experts that climate change poses major risks to the economy." Conservative economists stuck with their conventional wisdom: while global warming might do some harm, regulating emissions would be much worse for economic progress. But as climate economics surged from a niche specialty to a mainstream profession, studies converged. They found that on a plain cost-benefit basis it would pay to slash emissions. And that was assuming the future went as expected, that none of the calamities that scientists considered unlikely, but possible, would turn up. As Nordhaus admitted, "research has increased rather than reduced uncertainties." Estimates of the damage to the global economy expected by 2100 still ranged from tolerable to devastating. Economists labored to boil down their cost calculations to a single useful number: dollars per ton emitted, the "social cost of carbon." The calculations rose to prominence in the early 2000s as they became embedded in policies to regulate emissions. The result was fervent professional, political, and legal controversy.[1]*

By 2020 business institutions ranging from the Davos Economic Forum to central banks agreed that, as a *Wall Street Journal* columnist put it, "Climate change's impact is no longer distant and imperceptible." With economic analysis growing more sophisticated, attention turned from global averages to the costs for particular regions and groups. Early estimates suggested that the less-developed regions like Africa and South Asia would be hit hardest, but more detailed studies found that China and even the United States would also be major losers. Insurance companies and

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[1] Stern (2006) , p. 3. IPCC (2007e), and check the IPCC website http://www.ipcc.ch for subsequent reports. Survey: Howard and Sylvan (2015). For example, Burke et al. (2015), widely cited, said that unchecked warming would reduce global incomes "roughly 23% by 2100... losses many times larger than leading models indicate." Criticism by Nordhaus and other economists centered on Stern's use of a "zero discount." That bestowed as much value on costs to all later generations as costs to ourselves, and could be used to justify almost any expense. But the critics' preferred discounting, say at 3-4% per year, assumed the world economy was certain to expand indefinitely without a hitch—our grandchildren would be so fabulously wealthy that they could solve any problem, even as the environment deteriorated around them. Conventional economics also left out prudent insurance-style evaluation of the cost of altogether catastrophic impacts that scientists thought unlikely but entirely possible: a "fat tail" probability distribution, see Weitzman (2007), Weitzman (2009), popularized in Wagner and Weitzman (2015). The conventional calculations using averages underestimated economic and financial losses by "up to 82% when neglecting tail acute risks," according to Bressan et al. (2024). Devastating: e.g., Kotz et al. (2024), Neal et al. (2025). For a summary of the economics see Jamieson (2014), chapter 4. Niche, converged: Frances C. Moore, "The Expanding and Maturing Field of Climate Change Economics," in *Nature Climate Change* (2021). Uncertainties: "William D. Nordhaus – Biographical – 2018," NobelPrize.org, Nobel Prize Outreach AB 2021 (2021), online at https://www.nobelprize.org/prizes/economic-sciences/2018/nordhaus/facts

bondholders took to analyzing the impacts on particular economic sectors and individual companies, estimating how much the increase in events such as storms and droughts might cost them. The answers added up to trillions of dollars. "Our societies are much more vulnerable than we originally thought to even relatively small changes in the weather," an expert in climate impacts explained. "The predictions were right, but it hurts much more than anyone had expected."[1]

As usual the poor would suffer far more than the rich, between nations and still more within nations. That was especially troubling because the richest nations and individuals were responsible for most of the greenhouse gases in the atmosphere. Moreover, many corporations and wealthy individuals and their political representatives fought efforts to mitigate climate change. Were they wilfully refusing to understand the harm they were causing, or did they expect to prosper even if everyone else went to the devil? Among the various impacts of global warming, the moral impact might not be the least.

There was an even more sobering way to frame climate change—as a security threat. For half a century, forward-looking military officers had considered with increasing concern what global warming might mean in their area of responsibility. They would surely be called upon, for example, if weather disasters multiplied. In 2003, defense intellectuals in the Pentagon commissioned a report on "An Abrupt Climate Change Scenario and its Implications for United States National Security." As reported in a leak to the press, the authors warned of a risk that "mega-droughts, famine and widespread rioting will erupt across the world.... abrupt climate change could bring the planet to the edge of anarchy as countries develop a nuclear threat to defend and secure dwindling food, water and energy supplies." The authors concluded that "the threat to global stability vastly eclipses that of terrorism." The report was strikingly similar to the CIA report prepared three decades before (see above). Again the specific worst-case scenario, an abrupt change in ocean circulation, was something scientists considered extremely unlikely. By now, however, impact studies had sketched out a range of more plausible scenarios that looked

[1] The literature is extensive; see e.g., Diffenbaugh and Burke (2019); Ricke et al. (2018), and the extensive discussion of mitigation in IPCC (2022). Greg Ip, "Economic Impact of Climate Change Is Here," *Wall Street Journal*, Jan. 17, 2020, online at https://www.wsj.com/articles/for-the-economy-climate-risks-are-no-longer-theoretical-11579174209. For bond risk estimated by Moody's see Tim Quinson, "Environmental Debt Risk Is Bigger Than Japan's GDP," Bloomberg.com, January 6, 2021, online at https://www.bloomberg.com/news/articles/2021-01-06/environmental-debt-risk-is-more-than-japan-s-gdp-green-insight. For a deep dive into the financial risks from the perspective of central banks, see Bolton et al. (2020). "More vulnerable:" Friedrike Otto in "Is Climate Change to Blame?" Climate Central webinar, June 12, 2024, online at https://climatecommunication.yale.edu/news-events/is-climate-change-to-blame-understanding-and-communicating-the-link-between-climate-change-and-extreme-weather/

bad enough. In a dry phrase that spread swiftly after its introduction around 2007, military officers called climate change a "threat multiplier."[1]

If you thought like a military officer, used to considering worst cases, the IPCC's approach—concentrating on what everyone could agree was most likely, while ignoring less likely but more dangerous scenarios—was not "conservative" at all, but irresponsible. Some climate scientists became concerned that most research on impacts looked at a temperature rise of 2°C or less, although the warming could go well above that. They thought there was a real chance (five percent?) that the world would arriv

[1] In 1956 a leading scientist speculated that in a distant future we might "find that the Arctic Ocean will become navigable... the Russians will become a great maritime nation." Testimony of Roger Revelle, U.S. Congress, House 84 H1526-5, Committee on Appropriations, *Hearings on Second Supplemental Appropriation Bill (1956)*, pp. 474 and 473. (See also note on submarines in "Government" essay.) Already in the 1970s, a couple of studies like the CIA study noted above had framed global warming as a security problem. Environmentalists since the early 1970s had argued more generally that the world would be more secure if it spent less money on military defense and more on defense against pollution and other environmental dangers. The groundbreaking 1988 Toronto Conference concluded that changes in the atmosphere were a major threat to global "security," and for climate change in particular the "ultimate consequences could be second only to a global nuclear war." For all this see Barnett (2001), who gives the quote from World Meteorological Organization (1989). Report for Pentagon: Schwartz and Randall (2003), reported by Stipp (2004); quote: Mark Townsend and Paul Harris, "Now the Pentagon Tells Bush: Climate Change Will Destroy Us," *The Observer,* February 22, 2004. An internet newspaper archive search will show, e.g., the Science Advisor to UK Prime Minister Tony Blair, Sir David King, calling climate change the greatest threat facing humanity, worse than terrorism. See report issued in 2007 by a group of retired three- and four-star admirals and generals: CNA corporation (2007), and report of a 2007 conference of academics and serving officers, Pumphrey (2008). At the request of Congress, in 2008 the CIA weighed in officially with a classified report declaring climate change had a "potential to seriously affect U.S. national security interests." Siobhan Gorman, "Report Says U.S. Security Faces Challenges From Global Warming," *Wall Street Journal*, June 25, 2008, online at http://online.wsj.com/article/SB121439562868003087.html.

The first substantial appearance of climate change in a top-level U.S. military policy document was in the 2010 Quadrenniel Defense Review, worrying about both political instability and disaster response. By 2014 the Pentagon saw not only a future but a present threat: "Climate change... poses immediate risks to U.S. national security." - Dept. of Defense, "2014 Climate Change Adaptation Roadmap" (formerly online at http://ppec.asme.org/wp-content/uploads/2014/10/CCARprint.pdf , now removed), see "Pentagon Signals Security Risks of Climate Change," *New York Times,* Oct. 13, 2014. Center for Climate & Security, "Climate and Security Resources: U.S. Government, Defense," online at https://climateandsecurity.org/resources/u-s-government/defense'/. "Threat multiplier" introduced in CNA (Center for Naval Analysis), "National Security and the Threat of Climate Change," CNA Corporation, Alexandria, VA, 2007.

e at a climate too harsh to sustain a decent civilization. “There is a low probability that the change will be catastrophic,” a leading scientist explained. “But you would not get on an airplane if you thought there was a five percent chance that it was going to crash.”[1]

The crash many worried about was less a geophysical than a social collapse. Through the early 2000s, social scientists and historians vigorously debated whether climate change really could provoke civil unrest and warfare. A 2013 review of many papers concluded that strong departures from normal climate conditions (droughts, heat waves, etc.) did increase the likelihood of conflict, both domestic and international. That remained controversial, but by 2020 it was a common belief among experts that climate change was among the forces that could aggravate conflict. Indeed high temperatures, as police officers had long noticed in heat waves, promoted hostility, aggression and violence at every level.

Attention focused most strongly on the “climate refugees” who might swarm by hundreds of millions from regions that were drought-stricken, inundated, or rendered unlivable by heat waves. Already in 1979 an influential report to the U.S. Department of Defense had projected that global warming could afflict large areas with “‘Dust Bowl’ conditions”—a phrase that would have reminded its readers of the 1930s migration of millions displaced from the American Plains states— and warned that “The social and political consequences of shifts of population... could be highly disruptive.” By the 2010s disruptive internal migration was indeed apparent in low-lying Bangladesh, while devastating droughts in Syria and Central America seemed at least partly to blame for the breakdown of local order and the multitudes of asylum-seekers who upended politics in Europe and the United States. Even the cautious IPCC, in a 2022 report, said that

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[1] Research on impacts: Jehn et al. (2022). “Five percent:” V. Ramanathan quoted by Gary Robbins, “Scripps Says Climate Change May Represent ‘Existential’ Threat to Humanity,” *San Diego Union Tribune*, Sept. 14, 2017, online at http://www.sandiegouniontribune.com/news/science/sd-me-scripps-climatechange-20170914-story.html, see Xu and Ramanathan (2017). Similarly, “Nobody would board an aircraft with a five per cent risk of crashing,” S. Rahmstorf (referring to his estimate of chance of a collapse of the Atlantic Ocean circulation, AMOC, before 2100), pers. comm., Aug. 8, 2017, cited by David Spratt and Ian Dunlop, “What Lies Beneath. The Understatement of Existential Climate Risk,” Melbourne: Breakthrough, 2018, online at https://www.breakthroughonline.org.au/whatliesbeneath. Sherwood et al. and IPCC (2021b) give a roughly 5% probability that at a doubled CO_2 level, which we will easily reach if current emissions continue unchecked, the global temperature rise will exceed 5° C, a heating where most ecosystems including industrial civilization would almost surely collapse. More realistically, the IPCC estimates that if nations continue their modest efforts but fail to enact new and sweeping policy changes (i.e., if they take the SSP2-4.5 pathway), there is a 90% or better probability that warming by 2100 will be somewhere between 2.1 and 3.5°C, IPCC (2021b), Table SPM.1, p. 14. That implies a ~5% risk of a rise somewhere above 3.5°C, where it is unlikely anyone could maintain an even partially prosperous and democratic society. There is a further unquantifiable risk that the IPCC range is too narrow.

climate change was already contributing to "humanitarian crises" and might be exacerbating some "intrastate violent conflicts." Many well-informed military officers and other national security experts, along with many political leaders and a majority of the world's public, now believed that global climate change might be the most dangerous long-term risk that civilization faced.[1]

The main driver of social disruptions was not the gradual changes in a region's average temperature and so forth; it was rare but devastating events, the unprecedented heat waves and droughts, the unanticipated floods and wildfires that wrecked entire communities. Such "tail events," once highly unlikely but now happening more and more frequently, were poorly represented in computer climate models and the economic models derived from them. Some climate researchers began to point out how, in the inescapable mathematics of statistics, when you shift an average only a little, the frequency of unlikely events can rise a great deal. "Changes in heat extremes," a research team pointed out dryly in 2016, "...could exceed estimates generated from model outputs of mean temperature." Another team worried about unprecedented combinations of heat and humidity going beyond what the human body could survive. They warned that "the most extreme humid heat is highly localized in both space and time and is correspondingly substantially underestimated...." Was it possible, as a science-fiction novel depicted, that a million people could die when power failed during a heat wave?[2]

The IPCC did not give full attention to the problem until its sixth science assessment, published in 2021, which for the first time devoted a full chapter to "Weather and Climate Extreme Events." Throughout the report the authors showed a new concern for events that might be judged very unlikely, but that would have terrible consequences if they did occur—a collapse of ice sheets for example, or a shutdown of ocean circulation, or novel meteorological patterns that brought heat waves, droughts and wildfires to many regions of the world at once. Worse, there could be "compound extreme events" where different effects multiplied one another, like bigger storm surges on top of a higher sea level. The authors admitted that the IPCC's past practice of sticking to the most likely outcomes had been a mistake. The world should beware of impacts, however extreme, that "cannot be ruled out." Some experts felt that these guarded statements were still

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[1] In 2007, 64% of all Americans felt that their country was "in as much danger from environmental hazards, such as air pollution and global warming, as it is from terrorists," Yale Center for Environmental Law and Policy: www.yale.edu/envirocenter. For international opinion see, e.g., 2007 Chicago Council on Global Affairs poll at worldpublicopinion.org. Worse than expected (2015 survey): Bray and von Storch (2016).

Review: Hsiang et al. (2013); another study with good references: Schleussner et al. (2016); experts agreed: e.g., Mach et al. (2019); a more recent review: Degroot (2018). For temperature see Stechemesser et al. (2022) (with references to reviews). "Dust Bowl:" JASON (Gordon MacDonald, chair) (1979), pp. 26-27. Asylum-seekers: Abel et al. (2019). Confidence (medium for intrastate, high for humanitarian): IPCC (2022), SPM.B.1.7.

[2] "Exceed estimates:" Horton et al. (2016); "substantially underestimated:" Raymond et al. (2020); fiction: Robinson (2021). A little-noticed 2012 IPCC report on "the Risks of Extreme Events and Disasters" explained the effects of shifting a bell curve, IPCC (2012).

inadequate, and called for an IPCC "Special Report on Catastrophic Climate Change." Experts hoped to get a grip on the problem as their computers grew powerful enough to probe the fine details of local weather; meanwhile climate change itself gave experts ever more actual cases to study. *See the essay on Rapid Climate Change for discussion of some (presumably) low-probability, but high-impact and perhaps irreversible global processes.*

Even as the IPCC admitted the possibility of terrible impacts, it continued to underplay them. The panel's estimate of the global temperature rise we would get in this century without stronger action was uncertain, but very likely somewhere 2°C and 5°C. However, the main attention of the IPCC and the research it inspired went to projecting impacts at a 2°C rise or even less. A study of IPCC reports found that "coverage of temperature rises of 3°C or higher is underrepresented relative to their likelihood." There was little hard research to describe a world above 3°C, let alone 5°C. Those who did talk about such possibilities could only suggest comprehensive collapses beyond the ability of the social and ecological sciences to fathom.[1]

In a 2014 assessment of impacts. the IPCC had noted that long-predicted problems were starting to become evident. By 2022, when the next major IPCC report on impacts appeared, suffering from climate change had grown explosively. Grievous damage was appearing at lower temperatures, and thus sooner, than the experts had anticipated. Some of the losses were already irreversible. As the United Nations Secretary-General summed up the report, "Nearly half of humanity is living in the danger zone—now. Many ecosystems are at the point of no return—now."[2]

What do we know about the impacts of climate change? A large body of scientific studies, exhaustively reviewed, has produced a long list of possibilities. By 2020 most of the projected impacts were already becoming painfully evident. Consequences vary by region; some places will at first be little affected, except indirectly, while other places will be affected much worse than the average. Of course, climate change is only one of the great forces bearing on our future. Continuing technological progress may raise prosperity faster than global heating can reduce it; on the other hand, chemical pollution, resource depletion, and other assaults on the environment will add their own damages.

The following are the likely consequences of warming between two and three degrees Celsius—that is, what we may expect before the end of the century if nations keep their promises to ratchet up their work to reduce greenhouse gas emissions.[3]

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[1] IPCC (2021a), ch. 11, see Duncombe (2021). IPCC (2021b), section C.3, section A.35, "cannot be ruled out" section B.5.3, see also IPCC (2021a), Box TS.3 and section 11.8. Special report, "underrepresented:" Kemp et al. (2022).

[2] IPCC (2014d), IPCC (2022a). "Danger zone:" António Guterres, UN news release, Feb. 28, 2022 (no longer online but widely reported in media).

[3] IPCC (2022a); this is not greatly different from IPCC (2007c), and in fact except for the timing of arrival of impacts, reviews such as Grassi (2000) have been only modestly revised by more recent work. For latest results see the IPCC's site, http://ipcc.ch/. For regional changes in

* **Nearly every region will continue to get warmer,** especially land areas at night and in winter. Warming may bring some temporary benefits (for example, to agriculture in Canada and Siberia) as well as harm; tourism and other major industries will be disrupted. Human mortality in winter will decrease, but the gain will be swamped by a dramatic increase of deaths during heat waves along with other health problems. Places less directly affected may be destabilized by a press of refugees from regions now uninhabitable.

* **Sea levels will continue to rise for many centuries.** The last time the planet was a degree or two warmer than now, the sea level was at least 6 meters (20 feet) higher. That submerged coastlines where hundreds of millions of people now live, including cities from New York to Shanghai. The rise will probably be so gradual that later generations can simply abandon their parents' homes, but ruinously swift advances are possible. Meanwhile storm surges will cause emergencies.

* **Weather patterns will keep changing** with extreme weather events increasingly frequent and destructive. Many regions now subject to drought will get drier (because of heat as well as less precipitation), with bigger wildfires. Storms with more intense rainfall will bring worse floods. Most mountain glaciers and winter snowpack will keep shrinking, jeopardizing vital water supply systems.

* **Agriculture and ecosystems will be increasingly stressed.** Some managed agricultural and forestry systems might benefit for a few decades, but eventually global food supplies will be endangered by more frequent and extreme droughts; widespread conflict and starvation may follow. Regions not directly impacted will suffer indirectly from higher food costs. Uncounted valuable species, especially in the Arctic, mountain areas, and tropical seas, must shift their ranges. Many that cannot face extinction. A variety of pests and tropical diseases will continue to spread into warmed regions.

* **Increased carbon dioxide levels affect biological systems** independent of climate change. Fertilization is promoting growth in some forests and crops (which may become less nutritious), and also encourages invasive weeds. The oceans will continue to become markedly more acidic, destroying coral reefs, and probably harming fisheries and other marine life.

* **There will be significant unforeseen impacts.** Most of these will probably be harmful, since human and natural systems are well adapted to the climate of the past ten thousand years.

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the United States see the U.S. National Climate Assessment and other Global Change Research Program reports at http://globalchange.gov/. For data on current impacts see https://www.epa.gov/climate-indicators. A good popular account is Lynas (2020), supplanting Lynas (2007). A best-selling account of current and future heat impacts in particular: Goodell (2023). On regional variations see Deser et al. (2012).

That is the *best* we can hope for unless many nations strongly accelerate their efforts. If we do not turn the long rise of greenhouse gas emissions down sharply, starting now, the global temperature rise is likely to reach or exceed 3°C by the end of the century. Heat waves, spreading tropical diseases and weather-related catastrophes will bring many excess deaths; some regions vital to world food production will turn into dust bowls; hunger, economic upheavals, and many millions of refugees fleeing rising seas and deadly heat will undermine civil government and international peace, and we will face a radical impoverishment of the ecosystems that sustain our civilization.[1]

Scientists have not been able to pin down precisely how far temperatures will rise for a given level of CO_2. We could be lucky, and see temperatures level off at a lower level than expected. If we are unlucky and the less favorable but quite possible estimates turn out to be correct, only immediate and strenuous efforts can avoid a world of mass death, failed states, and desperate tyrants with nuclear weapons. If we bet that the actual climate physics will turn out to behave no worse than the middle range of current estimates, we still need to quickly change many things. The effort will not only ensure a stable and prosperous future, but in the short term can strengthen the economy and improve daily life.

All this is about people who are now alive. What about later generations? We have delayed so long that we find ourselves in an unprecedented crisis of human and geological history. ***The policies established in this decade will determine Earth's climate for the next 10,000 years***. If we do not get global emissions moving downward by 2030, and maintain the decline to zero within a few decades, we risk triggering irreversible feedbacks. Climate scientists cannot rule out a possibility, small but genuine, that greenhouse gases will reach a level that Earth has not seen in tens of millions of years. The full consequences would take centuries to be fully realized as the planet settled into a "hothouse" state. The oceans would rise tens of meters, soaring temperatures would render most regions uninhabitable, many ecosystems would collapse—a planet grossly unlike the one to which the human species is adapted. Only with strong and prompt action can we avoid this perhaps small but certainly appalliing risk.[2]

> *What can people do about global warming, and what should we do? See my Personal Note and Links.*

Related:
The Public and Climate
Government: The View from Washington, DC

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[1] E.g., Sokolov et al. (2009); Wallace-Wells (2017) and Wallace-Wells (2019), describing the worst plausible case, was rightly criticized for exaggeration but many of the statements were defensible, see references at http://nymag.com/daily/intelligencer/2017/07/climate-change-earth-too-hot-for-humans-annotated.html.

[2] Clark et al. (2016); Steffen et al. (2018).