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. Experts in fields from forestry to economics, even national security experts, pitched in to assess the range of possible consequences. It was impossible 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 many regions—some more than others. Indeed many kinds of damage were already beginning to appear. (This essay does not try to cover the entire history of impact studies, but sketches some examples. Current scientific understanding of impacts is summarized at the end).

“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

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.” 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 (CO₂) 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 the downfall of entire civilizations in the ancient world, in 1957 Revelle told a Congressional committee that the greenhouse effect might someday turn Southern California and

2 Arrhenius (1908), p. 63.
Texas into “real deserts.” He also remarked that the Arctic Ocean might become ice-free, to
Russia’s advantage. Everyone understood this was all speculation, more science fiction than
scientific prediction. Another senior scientist, more cautious, 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 reported that the CO₂ greenhouse
effect “could raise such problems as coastal flooding due to rise in sea level and increased aridity
in certain areas.”

More scientists began to look at the matter after 1960, when observations showed the level of
CO₂ 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.
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 a century ahead. 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 bringing “immense flooding” of low-lying areas. 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.

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 CO₂ ... may be sufficient
to produce measurable and perhaps marked changes in climate...” Without attempting to say

1 Time (1956). Real deserts: Revelle in United States Congress (85:2), House of
Representatives, Committee on Appropriations, Report on the International Geophysical Year
of this essay. 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. “Such problems”: Wallace Broecker and Bruno
Giletti writing in the student magazine Yale Scientific in 1957, according to Broecker and

2 Conservation Foundation (1963), pp. 1, 5, 14. They also speculated (p. 6) that “many
life forms would be annihilated” in the tropics if emissions continued unchecked for several
centuries, a time too far away to mean much to anybody.
anything specific, they remarked dryly that the resulting changes “could be deleterious from the point of view of human beings.” 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.”

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

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 CO₂ 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

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1 President’s Science Advisory Committee (1965), pp. 126-27.
might grip the planet? The report concluded that the entire 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 CO₂ 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. 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 CO₂ 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

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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 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, 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. Dominated by conservative scientists, the Academy did not recommend any government policy changes, aside from the scientists’ 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 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

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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, notably the expansion of diseases, had been mentioned in passing before but were only now coming under detailed discussion.¹

Studies of how climate change might affect human health expanded particularly swiftly in the 1990s, catching the attention not only of experts but 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). Yet with health as in some other categories, it was becoming clear that global generalizations were of little value compared with 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 how such diseases might spread 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 rain-forest, 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, the IPCC 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 by now 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 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 tens of 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.”

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 unsupported, 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.”

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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 managed agricultural systems of Europe and North America might even contrive to benefit from a modest warming and rise in the level of CO₂ (which could act as a fertilizer for some crops), although 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 CO₂ would not rise to three or four times 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.

¹ Watson et al. (1997), quote p. 6
² National Assessment Synthesis Team (2000-2001), quotes p. 9
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 might adopt. 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 by which climate changes might affect the socio-economic system and thereby the emissions themselves. 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. There were so many unknowns, and so many differences from region to 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.

In its own 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 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 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.)

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1 The influential pathbreaker was Meadows et al. (1972).
3 Moss et al. (2010), including 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.
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. In reality, the majority of weather damage typically comes from rare but devastating extreme events—floods due to once-in-a-century downpours, mortality and crop losses in exceptional heat waves, and the like. Would such events become more common after a modest increase in the average precipitation or temperature? Simple physics made that seem likely: a warmer atmosphere would hold more moisture, exaggerating everything. But the 1990 IPCC study had found no reliable indications in past weather records of changes in extreme events resulting from the modest increase in temperature since the 1950s. The scientists only briefly mentioned heat waves, storms, blizzards, and the like.¹

However, in 1990 the NASA computer group published a warning: “If greenhouse gas emissions continue to increase rapidly, the model results suggest that severe drought (5% frequency today) will occur about 50% of the time by the 2050s” in the United States. But 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 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.²

In the next IPCC report, 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.³

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 that “The probability of heavy daily precipitation increases by more than 50% in many locations.” And a third group found “large increases in the severity of drought conditions,” although they had less confidence in their ability to put numbers on the problem. It seemed likely that ordinary storms would become worse as more moisture was added to the atmosphere, but models could not quantify this. Changes in hurricanes and typhoons were still harder to calculate, and only around 2010 did a weak consensus emerge—the strongest ones would probably become even stronger.

¹ The pioneer for heat waves was Mearns et al. (1984). IPCC (1990a), ch. 6 and section 7.11; IPCC (1990c) ch. 4.
² NASA group: Rind et al. (1990). Fowler and Hennessy (1995) review computer studies emphasizing the likelihood of an increase in extreme precipitation events; until this point people had mainly talked about increases in average precipitation.
³ IPCC (1996b), section 12.4; IPCC (1996a), ch. 6, p. 336.
Meanwhile stern warnings about other kinds of extreme events became a main feature of IPCC and other impacts statements from this time forward.¹

In fact, 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 well understood on the global scale. The later IPCC reports were mainly distinguished by their increasing regional specificity, and their increasing certainty that the impacts were well on their way—"likely" shifted to "very likely" and the wording of the executive summaries of the reports got increasingly strong in hopes that people would pay heed.² 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.

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.³

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.

² See IPCC (2014c).
³ 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).
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. 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.” Many 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, however, 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.”

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.” 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. One example: in 2003 a heat wave of unprecedented scope killed tens of thousands in Europe. Nobody had foreseen that 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

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2 Landmark studies included Parmesan (1996), finding a latitude shift in a North American butterfly (Edith’s Checkerspot) and attributing it to climate change, and Parmesan et al. (1999) with “the first large-scale evidence of poleward shifts in entire species’ ranges” from Europe. IPCC (2001b), section 2.2.
Alaska to Arizona, leaving the weakened timber prey to an unprecedented outbreak of forest fires. 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. 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. Nevertheless studies claimed confidently that global warming had contributed to the severity of floods in Britain in 2000, a heat wave that killed 50,000 people in Russia in 2010, a devastating 2011 Texas heat wave and drought, and droughts in the Mediterranean. Further studies blamed global warming for marked world-wide increases of heat waves and extreme precipitation events in general. By 2012 modelers and meteorologists were working to pin down specific changes in wind patterns that contributed to such disasters.¹

The American Meteorological Society launched an annual series of special issues of its *Bulletin* to investigate attribution of various kinds of weather disasters. In the second issue, covering events of 2012, “approximately half of the analyses found some evidence that anthropogenic climate change was a contributing factor to the extreme event examined,” although natural variability still mostly dominated. But it wasn’t until 2016 that a panel of the US 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.²

In the public eye, the biggest question was storms. Most experts insisted that it was impossible or even meaningless to say whether global warming had “caused” a particular storm. But some began to claim that given a 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

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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.”

One thing was certain: the weather was changing, and would change a lot more. This was not just global warming but “global weirding.” For example, one of the most obvious and ominous changes was a rapid decline in the ice pack that covered the Arctic Ocean. According to one hypothesis, exposing the atmosphere to the ocean would change circulation patterns in a way that would, paradoxically, bring severe winter incursions of cold air into North America and Siberia. Or maybe not. The biggest problem was that important changes in the weather regime would seldom become clear until they had already happened.¹

Drought seemed to be the most severe problem for the near term, that is, the lifetimes of people already born. One immediate consequence was wildfires, common in hot and dry seasons. Numerous catastrophic wildfires around the globe early in the 21st century caught public attention. Scientists could not say what role global warming played in the outbreak — but as the planet warmed further, a future plague of wildfires seemed almost certain. Meanwhile 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 suffer severely already by mid-century, and much more later on.²

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. The melting of Greenland and the retreat of Antarctic ice sheets were proceeding faster than experts had expected and now looked irreversible. In the worst case, by 2100 there could be another meter (6 feet) of sea-level rise. Coastlines and entire cities where many millions lived would eventually have to be evacuated.

Another long-term problem was ocean acidification. Experts had long understood that most of the CO₂ 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 it as a serious matter until a 2003 paper calculated the future rise in acidity. It would reach a level not seen in millions of years, perhaps devastating sea life. Some scientists raised an apocalyptic possibility: could the ocean waters lose their oxygen, bringing the sort of mass extinction seen only a few times previously in the

¹ Sandy: Trenberth et al. (2015). “Global weirding” was coined by conservationist Hunter Lovins and popularized by columnist Thomas Friedman. Sea ice loss: Overland et al. (2011), see Cohen et al. (2014).

planet’s history? Biologists hastened to study the effects of acidification in the laboratory and in the field. For example, a clever natural experiment looked at coral reefs where undersea volcanic seeps of CO₂ acidified the water, and found the reefs severely impoverished. It became clear that whatever else might happen, continued CO₂ 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.”

A description of impacts meant little to people unless it was translated into specific human terms. For example, if an aquifer turned brackish as the sea level rose, exactly what difference would that make to anyone? Since the early 1970s, economists had been developing increasingly detailed projections of the economic benefits and costs 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 destruction of the world’s coral reefs. In response to environmentalist warnings, a few free-market economists worked up calculations that found negligible costs from climate change, and warned that taxing or regulating emissions would wreck the economy. Others replied with calculations that gave opposite results. Economic analysis took off in the early 1990s with increasingly numerous and sophisticated studies.

The most influential skeptical work 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. 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 framed to deal with such an issue, where the main consequences were many years ahead and might bring anything from discomfort to devastation. Hardly any impact study looked farther ahead than 2100; the 22nd century just seemed too far away.

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2 Discussions began with D’arge and Kogiku (1973), arguing that CO₂ 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.”

Governmental and international bodies stepped in, supporting elaborate professional studies. Particularly influential 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 had 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 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. The IPCC’s 2007 report and later analyses reached a similar conclusion; by 2015 a survey found a “clear consensus among economic experts that climate change poses major risks to the economy.” Climate change, Stern concluded, “is the greatest market failure the world has ever seen.”

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 bad enough. (And according to many climate scientists, even worse than they had expected just a few years ago.) If you thought like a military officer, used to considering worst cases, the IPCC’s

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1 Stern (2006), p. 3. All these numbers were highly uncertain; Stern’s estimated cost of stabilizing CO₂ at a level he thought reasonably safe (550ppm) might be anywhere from 3.5% of GDP to -1% (net benefit), p. xiv. IPCC (2007e), and check the IPCC website http://www.ipcc.ch for subsequent reports. Survey: Howard and Sylvan (2015). Criticism by economists, much of it technical, centered on Stern’s use of a “0% 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. And it ignored 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). For a summary of the economics see Jamieson (2014), chapter 4.
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.

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. 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 the impacts of global warming ranked among the most dangerous long-term risks that civilization faced.¹

¹ In 1956 a leading scientist speculated that in a distant future we might “find that the Arctic Ocean will become navigable... If the Russian coastline increases by something like 2,000 miles or so, 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 mankind” and “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 Quadrennial 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,” online at http://www.acq.osd.mil/ie/download/CCARprint.pdf, see “Pentagon Signals Security Risks of Climate Change,” New York Times, Oct. 13, 2014. 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
What do we know about the impacts of global warming? A large body of scientific studies, exhaustively reviewed, has produced a long list of possibilities. Nobody can say that any of the items on the list are certain to happen. But the world’s climate experts almost all agree that the impacts listed below are more likely than not to happen. For some items, the probabilities range up to almost certain. Consequences will vary by region; some places will at first be little affected, except indirectly, while other places will be affected much worse than the average.

The following are the likely consequences of warming by two or three degrees Celsius—that is, what we may expect if humanity manages to begin restraining its emissions soon, so that greenhouse gases do not rise beyond twice the pre-industrial level. Without strong action the doubling will come well before the end of this century, bringing the planet to temperatures not seen since the spread of agriculture. By 2007, many of the predicted changes were observed to be actually happening. (For details see the IPCC and USGCRP impacts reports.)

* Most places will continue to get warmer, especially at night and in winter. The temperature change will benefit some regions while harming others—for example, patterns of tourism will shift. The warmer winters will improve health and agriculture in some areas, but globally, food supplies will be endangered due to more frequent and extreme summer heat waves and other effects. Regions not directly harmed will suffer indirectly from higher food prices and a press of refugees from afflicted regions.

* Sea levels will continue to rise for many centuries. The last time the planet was 3°C 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 a ruinously swift rise cannot be entirely ruled out. Meanwhile storm surges will cause emergencies.

* Weather patterns will keep changing toward an intensified water cycle with stronger floods and droughts. Many regions now subject to droughts will probably get drier, because of heat as well as less precipitation. Extreme weather events will become more frequent and worse. In particular, storms with more intense rainfall are liable to bring worse floods. Some places will get more snowstorms, but most mountain glaciers and winter snowpack will shrink, jeopardizing


1 IPCC (2014c); this is not seriously different from IPCC (2007c); for latest results see the IPCC’s site, http://ipcc.ch/. For regional changes in the United States see the U.S. Global Change Research Program reports at http://globalchange.gov/. For a good popular account see Lynas (2007). Note that reviews such as Grassi (2000) have been only modestly revised by more recent work. On regional variations see Deser et al. (2012).

2 Kopp (2009); Dutton et al. (2015).
important water supply systems. Each of these things has already begun to happen in some regions.\(^1\)

* **Ecosystems will be stressed**, although some managed agricultural and forestry systems will benefit, at least in the early decades of warming. Uncounted valuable species, especially in the Arctic, mountain areas, and tropical seas, must shift their ranges. Many that cannot will face extinction. A variety of pests and tropical diseases are expected to spread to warmed regions. These problems have already been observed in numerous places.

* **Increased carbon dioxide levels will affect biological systems** independent of climate change. Some crops will be fertilized, as will some invasive weeds (the balance of benefit vs. harm is uncertain). The oceans will continue to become markedly more acidic, gravely endangering 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 present climate.

The climate system and ecosystems are complex and only partly understood, so there is a chance that the impacts will not be as bad as predicted. There is a similar chance of impacts grievously worse than predicted.

If the CO\(_2\) level keeps rising to well beyond twice the pre-industrial level along with a rise of other greenhouse gases, as must inevitably happen if we do not take strong action soon, the results will certainly be worse. Under a “business as usual” scenario, calculations give even odds that global temperature will rise 5°C or more by the end of the century—causing a radical reorganization and impoverishment of many of the ecosystems that sustain our civilization.\(^2\)

All this is projected to happen to people who are now alive. What of the more distant future? As one group of scientists remarked, “the next few decades offer a brief window of opportunity to minimize large-scale and potentially catastrophic climate change that will extend longer than the entire history of human civilization thus far.”\(^3\) If emissions continue to rise for a century—whether because we fail to rein them in, or because we set off an unstoppable feedback loop in which the warming itself causes ever more greenhouse gases to be evaporated into the air—then the gases will reach a level that the Earth has not seen since tens of millions of years ago. The consequences will take several centuries to be fully realized, as the Earth settles into its new state. It is probable that, as in the distant geological eras with high CO\(_2\), sea levels will be many tens of meters higher and the average global temperature will soar far above the present value: a planet grossly unlike the one to which the human species is adapted.

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\(^1\) For North America, see Karl et al. (2008).


\(^3\) Clark et al. (2016).
What can people do about global warming, and what should we do? See my Personal Note and Links.

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