IN THE UNITED STATES DISTRICT COURT
FOR THE SOUTHERN DISTRICT OF NEW YORK

UNITED STATES OF AMERICA and UNITED STATES ENVIRONMENTAL PROTECTION AGENCY, *Plaintiffs*, v. STATE OF NEW YORK, KATHLEEN HOCHUL, in her official capacity as Governor of New York, LETITIA JAMES, in her official capacity as New York Attorney General, and AMANDA LEFTON, in her official capacity as Commissioner of the New York Department of Environmental Conservation, *Defendants*.	No. 1:25-cv-03656-PKC

DECLARATION OF JUSTIN S. MANKIN, Ph.D.

Pursuant to 28 U.S.C. § 1746, Justin S. Mankin, Ph.D., declares under penalty of perjury that the following is true and correct:

1. I submit this declaration in support of defendants' (together the "State") opposition to plaintiffs' (together the "United States") motion for summary judgment.

EDUCATIONAL BACKGROUND AND EXPERIENCE

2. I received my Bachelor of Arts degree in Political Science from Columbia University, a Master of Science degree in Global Politics and Development Economics from the London School of Economics, a Master of Public Administration degree in Environmental Science and Policy from Columbia University, and a Doctorate of Philosophy in Environment and Resources focused on Earth System Science from

Stanford University. I did my postdoctoral training at Lamont-Doherty Earth Observatory of Columbia University and the National Aeronautics and Space Administration Goddard Institute for Space Studies.

3. I am an Associate Professor in the Department of Geography, the program in Ecology, Evolution, Environment & Society, and the Department of Earth Sciences at Dartmouth College, located in Hanover, New Hampshire. I am also an Adjunct Associate Research Scientist in the Division of Ocean & Climate Physics at the Lamont-Doherty Earth Observatory of Columbia University. At Dartmouth, I direct the Climate Modeling & Impacts Group, where I lead a research team that works to understand the impacts of human-caused global warming on our water, food, infrastructure, and economic and physical security.

4. My areas of expertise include climate variability and dynamics; climate attribution, prediction, and projection; drought and ecohydrology; earth system modeling; and the socioeconomic and ecosystem impacts of climate change. Much of my scientific research centers on using observations and models to quantify the impacts and costs of global warming to date and to estimate how those impacts and costs may evolve into the future. I have over 15 years of research experience in these areas and have authored over 65 peer-reviewed publications on these topics. My climate research has been published in leading peer-reviewed scientific journals, like *Science*, *Nature,* and the *Proceedings of the National Academy of Sciences*.

5. I also serve in numerous leadership and community roles that reflect both my scientific expertise and my commitment to advancing climate research. I was

co-lead of the National Oceanic and Atmospheric Administration's (NOAA) *Drought Task Force IV* (2020–2024), coordinating drought science across federal, academic, and state partners. I was selected and served as a graphics lead author to the *U.S. Global Change Research Program's Sixth National Climate Assessment (NCA6*, now disbanded*)* and I am currently a member of the *National Academies of Sciences, Engineering, and Medicine* consensus study on the future of drought in the United States. I contribute to advancing national research priorities as part of the *U.S. Climate Variability and Predictability Program Working Group on Accelerating Research on the Scientific Foundations of Regional Climate Risk Information*, serve with the *University Corporation for Atmospheric Research*, and currently co-lead the drought section of *Water Cycles Priorities* for the next *National Aeronautics and Space Administration (NASA) Decadal Survey*. Beyond these activities, I help strengthen the scientific community through editorial leadership, serving as an editor for the American Geophysical Union's *Earth's Future* and the American Meteorological Society *Journal of Climate*. I also serve on the *American Meteorological Society Committee on Climate Variability and Change* and remain active in professional and academic societies, including American Geophysical Union, American Meteorological Society, the American Association of Geographers, and American Association for the Advancement of Science. Across these roles, I work to guide the direction of climate research, foster collaboration, and support the next generation of scientists.

6. My credentials, research and publications are summarized in my curriculum vitae, which is included as Exhibit A to this declaration.

7. I have been retained by the Office of the New York State Attorney General, which represents defendants (together the "State") in this action to explain the different types of emissions that climate scientists consider in connection with attributing greenhouse gas emissions to companies that extract or refine and then sell fossil fuels. I also explain the methodological approaches scientists take in making attributions of particular climate-change harms from the greenhouse gas emissions traceable to particular fossil fuel extractors or refiners.

8. I have reviewed New York's Climate Change Superfund Act (the "Act"), the United States' complaint, the United States' Memorandum in Support of Motion for Summary Judgment and have consulted the resources cited in this declaration, identified in footnotes throughout. Resources cited that are not publicly available online are included in Exhibit B. I understand that the United States asserts that the Act seeks recovery from companies for greenhouse gas emissions without any certainty that those emissions caused in-state harm.

9. This declaration does not seek to provide any opinion of the various legal requirements under the Act, such as the conditions upon which New York may regulate or impose consequences on fossil fuel companies that cause in-state harm.

10. Instead my declaration outlines that peer-reviewed consensus-based science *can*, with high degrees of confidence, trace state-level harms back to particular emissions, such as those originating with the production and sale of fossil

fuels made by individual companies. Such methods collectively fall under a scientific discipline called *climate attribution science.* The science that causally traces particular emissions (like those from a company) to particular harms (like those endured by New York) is called *end-to-end climate damage attribution.* Briefly, using publicly available, peer-reviewed greenhouse gas emissions inventories from individual companies (built on voluntary reporting data from companies given their production (Scope 1) and sale (Scope 3) of fossil fuels), peer-reviewed attribution science methods can estimate changes in the likelihood and magnitudes of impactful extreme weather and climate at the state-level. Moreover, peer-reviewed methods can document the economic losses from changes in those emissions-driven hazards, thus providing an estimate of state-level damages traceable to individual sets of emissions. While I have not been asked to review any specific proposed attribution methods that the New York State Department of Environmental Conservation may apply in the future in developing or adopting regulations to implement the Act, I first outline the greenhouse gas emissions accounting protocol associated with the production and sale of fossil fuels; I then discuss climate attribution science, emphasizing how, with high degrees of confidence, science can assess the causal role of particular greenhouse gas emissions to state-level harms.

DISCUSSION

Greenhouse Gases Attributable to Companies that Produce and Sell Fossil Fuels

11. The Climate Change Superfund Act defines "covered greenhouse gas emissions" with respect to any entity, as "the total quantity of greenhouse gas

emissions, expressed in metric tons of carbon dioxide equivalent, as defined in section 75-0101 of this chapter attributable to the total amount of fossil fuels extracted by that entity during the covered period, as well as the total amount of crude oil refined by that entity during the covered period. For the purposes of this article, covered greenhouse gas emissions include those emissions attributable to all fossil fuel extraction and refining worldwide by such entity and are not limited to such emissions within the state." N.Y. Env't Conserv. L. § 76-0101(8).

12. The Act defines the "covered period" for covered greenhouse gas emissions as the period from January 1, 2000 to December 31, 2024. N.Y. Env't Conserv. L. § 76-0101(9).

13. The Act also defines a "responsible party" as "any entity (or a successor in interest to such entity described herein), which, during any part of the covered period, was engaged in the trade or business of extracting fossil fuel or refining crude oil and is determined by the department to be responsible for more than one billion tons of covered greenhouse gas emissions. The term responsible party shall not include any person who lacks sufficient contacts with the state to satisfy the due process clause of the United States Constitution." N.Y. Env't Conserv. L. § 76-0101(21).

14. Greenhouse gas emissions from organizations are typically delineated by their scope, or operational boundaries, following guidance from the Greenhouse

Gas (GHG) Emissions Protocol.[1] The GHG Protocol emerged in the 1990s from a collaboration between the World Resources Institute and the World Business Council for Sustainable Development, which together sought to define standardized practices to identify and delineate the emissions that organizations directly control via their operations (defined as *Scope 1*) from those that they indirectly influence through energy choices in pursuit of their activities (defined as *Scope 2*) from those for which they are responsible across their full value chain (*Scope 3*).

15. Defining organizational emissions in this standardized way achieves the GHG Protocol's key principles: (1) *relevance*, meaning a focus on inventorying the emissions that matter to all potential stakeholders both in and outside the organization; (2) *completeness*, meaning the inventory accounts for all emissions and formalizes a process to disclose and justify exclusions; (3) *consistency*, meaning that the inventories and their boundaries are consistent over time to allow for effective benchmarking and tracking; (4) *transparency*, meaning that the protocol is auditable, as methods, data sources, and assumptions are fully disclosed; and (5) *accuracy*, meaning that the reported inventories are true and integrous.[2]

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[1] *The Greenhouse Gas Protocol: A Corporate Accounting and Reporting Standard. Revised Edition.* World Resources Institute and World Business Council for Sustainable Development, Mar. 2004. ISBN 1-56973-568-9. Perma | ghgprotocol.org. Accessed 15 Oct. 2025.

[2] See Greenhouse Gas Protocol, p. 7.

16. The GHG Protocol has become the standard across corporate entities responsive to the Climate Disclosure Project,[3] a global nonprofit that provides a disclosure system for entities to voluntarily report their environmental impacts, such as emissions. For example, in 2023, some 97% of emissions-disclosing Standard and Poor's (S&P) 500 companies reported to the Climate Disclosure Project that they used the GHG Protocol.[4] The GHG Protocol also undergirds the EPA's Center for Climate Leadership, which provides guidance on how organizations can manage greenhouse gas emissions. So the GHG Protocol 'Scopes' are the global standard for delineating and tracking organizational emissions, irrespective of size, operations, and sector, ensuring consistency and comparability across industries worldwide.

17. It is worth considering how the GHG Protocol scopes are formally defined: *Scope 1* emissions are those direct emissions from sources fully controlled by an organization.[5] In contrast, *Scope 2* emissions are indirect emissions associated with the energy purchased by an organization. Lastly, *Scope 3* emissions are indirect emissions as part of the organization's entire value chain; they are the most complicated to inventory. An application of the GHG Protocol to a university might be something along the lines of campus-based boilers and fleet vehicles constituting

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[3] *Carbon Disclosure Project (CDP).* Perma | CDP: Turning Transparency to Action. Accessed 15 Oct. 2025.

[4] *About Us.* Greenhouse Gas Protocol, Perma | About Us | GHG Protocol. Accessed 15 Oct. 2025.

[5] *Scope 1 and Scope 2 Inventory Guidance.* U.S. Environmental Protection Agency, last updated 23 Apr. 2025, Perma | Scope 1 and Scope 2 Inventory Guidance | US EPA. Accessed 15 Oct. 2025.

Scope 1 emissions, its purchased electricity constituting Scope 2, and the supply chains, waste, and commuting to and from university constituting Scope 3.

18. As applied to fossil fuel companies, Scope 1 emissions would include, for example, direct emissions from flaring or venting, fugitive methane from extraction, refining, and other operations, as well as the companies' own fuel inventory for vehicle fleets, equipment, and other infrastructure. A fossil fuel company's Scope 2 emissions are similar to other organizations, being those from energy supplied to the company for its operations (e.g., externally sourced electricity, steam, heating, cooling, and fuels). Scope 3 constitute the emissions across the rest of the fossil fuel company value chain. In particular, the most dominant sources of Scope 3 emissions are the emissions from the use of the fossil fuel companies' sold products (known as Scope 3 Category 11 in the GHG Protocol), namely their gasoline, diesel, natural gas, or coal that is combusted by downstream users.

19. Scope 3 represents the dominant emissions category for organizations generally.[6] The GHG Protocol's Corporate Value Chain Standards[7] were developed to help companies standardize estimates of Scope 3 emissions owing to the complexity of tracking them. The standard articulates 15 different categories over which

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[6] "Corporates' Supply Chain (Scope 3) Emissions Are on Average 11.4 Times Higher Than Operational Emissions." *Carbon Disclosure Project (CDP)*, 10 Feb. 2021, Perma | Corporates' supply chain scope 3 emissions are 26 times higher than their operational emissions - CDP

[7] See p. 4 in Bhatia, Pankaj, et al. *Corporate Value Chain (Scope 3) Accounting and Reporting Standard: Supplement to the GHG Protocol Corporate Accounting and Reporting Standard.* World Resources Institute and World Business Council for Sustainable Development, 2011, Perma | ghgprotocol.org

organizational Scope 3 emissions can occur both upstream (in the supply chain, Categories 1-8) and downstream (product use and end of life, Categories 9-15) from organizational activities.[8]

20. The Carbon Majors Database, a publicly available and peer-reviewed database of the emissions inventories from 180 of the world's largest fossil fuel companies,[9] provides year-on-year estimates of the Scope 1 and 3 emissions and accords very well with both independent estimates and firm disclosures.

Attributing Climate Change Damages to Fossil Fuel Companies

21. As I understand, the United States has contended that the Act "penalizes companies for greenhouse gas emissions without any certainty that those emissions caused in-state harm." US Br. 25. This statement is based on an inaccurate appraisal of the state of the science. *Peer-reviewed, consensus-based climate attributions can provide causal assessments of the warming, hazards, and local harms promulgated by any set of greenhouse gas emissions, including those scoped to a company*. As I discuss in detail below, peer-reviewed scientific research has leveraged consensus-based methods (e.g., empirical and modeling approaches used in both the Intergovernmental Panel on Climate Change (IPCC) Assessment Reports[10] and the

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[8] See p. 34 in Bhatia, Pankaj, et al.

[9] About Carbon Majors." *Carbon Majors*, Perma | Carbon Majors Home. Accessed 19 Oct. 2025.

[10] IPCC Physical Science Sixth Assessment Report (AR6), at 108-110, 204-206, 1522-1527, 1541-1542, 1552-1553. Note that this type of analysis is distinct from the long-established research attributing global warming to anthropogenic greenhouse gas emissions and broader body of research projecting climate impacts from rising temperatures and ocean acidification. *Id. See also* Bulletin of the American Meteorological Society, Explaining Extreme Events of 2021 and 2022 from a Climate

US Global Change Research Program National Climate Assessment[11])[12] to link company-level emissions to in-state harms by calculating (1) how the warming from those emissions alter cumulative greenhouse gas concentrations, (2) how those concentrations altered hazards (such as the likelihood or magnitude[13] of extreme heat), and (3) how much impact those greenhouse gas-driven changes in those hazards generate economic burdens on subnational regions, like New York.[14]

22. I am not offering an opinion on how the New York State Department of Environmental Conservation will or should determine a responsible party's share of

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Perspective (2022), https://www.ametsoc.org/ams/publications/bulletin-of-the-american-meteorological-society-bams/explaining-extreme-events-from-a-climate-perspective/explaining-extreme-events-of-2021-from-a-climate-perspective/

[11] Marvel, K. et al., 2023: Ch. 2. Climate trends. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. Perma | toolkit.climate.gov.

[12] It is important to note that these syntheses of the state-of-the-science are massive undertakings by hundreds upon hundreds of scientists. The Working Group I contribution to the IPCC's 6th Assessment Report synthesized findings from more than 14,000 peer-reviewed studies. "In-depth Q&A: The IPCC's Sixth Assessment Report on Climate Science." *Carbon Brief*, 9 Aug. 2021, Perma | In-depth Q&A: The IPCC's sixth assessment report on climate science - Carbon Brief. Accessed 19 Oct. 2025. The 5th National Climate Assessment synthesized over 8,200 references. U.S. Environmental Protection Agency. *EPA Tools and Resources Webinar: 5th National Climate Assessment – Resources and Interactive Atlas*. U.S. EPA, 20 Nov. 2024. PDF file, Perma | www.epa.gov. Accessed 19 Oct. 2025.

[13] Quilcaille, Y. et al., Systematic attribution of heatwaves to the emissions of carbon majors, *Nature* 645, 392–398 (2025). Perma | Systematic attribution of heatwaves to the emissions of carbon majors | Nature; Burke, M. et al., Quantifying climate change loss and damage consistent with a social cost of greenhouse gases, *NBER Working Paper*, 31658 (2023) DOI: 10.3386/w31658 Perma | Quantifying Climate Change Loss and Damage Consistent with a Social Cost of Greenhouse Gases | NBER; Callahan, C. & J.S. Mankin, Globally unequal effect of extreme heat on economic growth, *Science Advances* 8, eadd3726 (2022) Perma | www.science.org; Callahan, C. & J. S. Mankin, National attribution of historical climate damages, *Climatic Change* 172 40 (2022). Perma | National attribution of historical climate damages | Climatic Change

[14] Callahan and Mankin, "Callahan, C. & J.S. Mankin, "Globally unequal effect of extreme heat on economic growth."

the costs imposed by the Act. Instead, I explain how end-to-end climate damage attributions have emerged scientifically and how they work to determine a company's contribution to climate hazards and their documented harms.

23. *Climate attribution is the science to assess causality in a complex Earth system.*[15] Myriad mechanisms can coalesce to account for any given weather or climate phenomena, whether a cloudless summer day, a devastating flood event, or a slowly unfolding warming trend in the ocean. Because of societal demands to inform climate risk mitigation, adaptation, and policy, attribution science is most often concerned with how human activities (in particular greenhouse gas emissions from fossil fuel use and patterns of development like agriculture, deforestation, and other land-use and land cover changes) contribute to both long- and short-term changes in weather and climate phenomena.

24. Attribution science assesses causality by comparing the observed world to a counterfactual one absent some potential explanatory factor, much in the way a controlled medical drug trial compares individuals in a treatment group to those in a control group to assess drug efficacy. In climate science, we rely on observational data and physics-based models to compare the world as it has been (i.e., the treatment group) to a counterfactual one absent an explanatory factor (i.e., the control group). In the counterfactual world, we use physics-based models or statistical approaches to remove one (or more) potential explanatory factor(s), for the outcome, like observed

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[15] *What Is Attribution?* National Oceanic and Atmospheric Administration Physical Sciences Laboratory, Perma | Interpreting Climate Conditions: What is Attribution: NOAA Physical Sciences Laboratory. Accessed 15 Oct. 2025.

greenhouse gas emissions. The counterfactual thus asks, how would the climate or this event have been different *but for* this factor? The difference between the world how it has been (the treatment) and the counterfactual world absent some explanatory factor (the control) is a measure of the causal contribution of that factor to the outcome.

25. Attribution science can take many forms, a function of the question at hand and the portions of the Earth system the attribution is considering. But generally, all attribution requires the use of observational data alongside physical and statistical models to disentangle the contributions of various drivers of weather and climate phenomena, often focusing on separating factors that are "internal" to the climate system (termed *internal variability*) from those "external" to it (termed *forcings*, as they *force* a change in planetary energy balance).

26. A canonical example of "internal" variability is El Niño—when interannual ocean temperatures in the eastern tropical Pacific are anomalously warm. El Niño is a feature of the climate system, meaning it and its impacts on extreme weather globally would occur in absence of people and their combustion of fossil fuels. Another example of internal variability is a randomly occurring high pressure system that sits off the California coast, acting like a boulder in a stream, steering storms north to Washington state. We term these kinds of oscillations in the ocean and atmosphere internal variability because they are an innate characteristic that is a natural feature *internal* to the climate system.

27. Consider the challenge of assessing a causal role for global warming on a heatwave. Addressing this question requires that we isolate the contributions from internal variability to the heatwave—we ask, 'could this observed heatwave have occurred simply from the randomness in weather?' Because of that task, climate scientists work to identify why internal variability emerges, and where possible, characterize recurrent patterns (or *modes*) of variability, and how they can act to shape the weather and climate people experience locally. Internal variability tells us that there are many weather patterns in any one place consistent with the same planetary temperature or greenhouse gas emissions at any one time. And, to the extent that scientists can identify a recurrent pattern of internal variability, it provides a source of predictability as well. When we expect an El Niño, for example, we know it will influence set patterns of weather around the world, such as increasing risks of flood in California or bushfires in Australia. From a climate attribution standpoint, it is essential to identify the contributions of internal variability to weather and climate phenomena.

28. "External" climate drivers are those that exist outside of the climate system. These can be naturally occurring ones like changes in the sun's energy or volcanic eruptions that block sunlight; both can alter climatic behavior by forcing changes in global-scale energy balance. But external drivers can also be human-caused or *anthropogenic*, such as that from land use and land cover changes or from greenhouse gases, like carbon dioxide, methane, and nitrous oxide emitted as by-products from human activities, such as the production and sale of fossil fuels.

29. The energy from the Sun that enters Earth's atmosphere must be balanced by the energy Earth sends back out to space (this is the first law of thermodynamics). As such, changes in the composition of Earth's atmosphere, like from greenhouse gases—even in small amounts—can disrupt Earth's energy balance, preventing Earth from shedding its heat back out to space. This is akin to the way a lid on a pot of water put onto the stove to boil traps more heat than one without. If Earth cannot shed its heat energy as efficiently, it must heat up, raising its temperature to reattain energy balance. This is because hotter objects emit much more energy than cooler ones. For example, if you double the temperature of an object, it emits 16 times more energy. This heating is the global warming we are experiencing.

30. The charge of attribution science is to separate the contributions of internal variability and external forcings of weather and climate phenomena, both to advance the science of Earth system prediction, but also to answer the question of how human activities, particularly the combustion of fossil fuels, have altered weather and climate. There is a long history of attribution science; in fact, the IPCC was awarded the Nobel Prize in 2007 in large part for definitively identifying the fingerprint of human activities on warming temperatures in the climate system—a physical attribution of human-caused changes in greenhouse gas concentrations to global temperature changes (see "physical attribution" link in **Figure 1**).

31. In the last several decades, attribution science has become much more expansive, considering not just planetary scale changes unfolding over many decades from measured changes in greenhouse gas concentrations, but small-scale changes happening over shorter time periods, to include rapid advances in the ability to assess how human activities have altered the likelihood and magnitude of individual extreme weather and climate events, called extreme event attribution (see "event attribution" link in **Figure 1**).

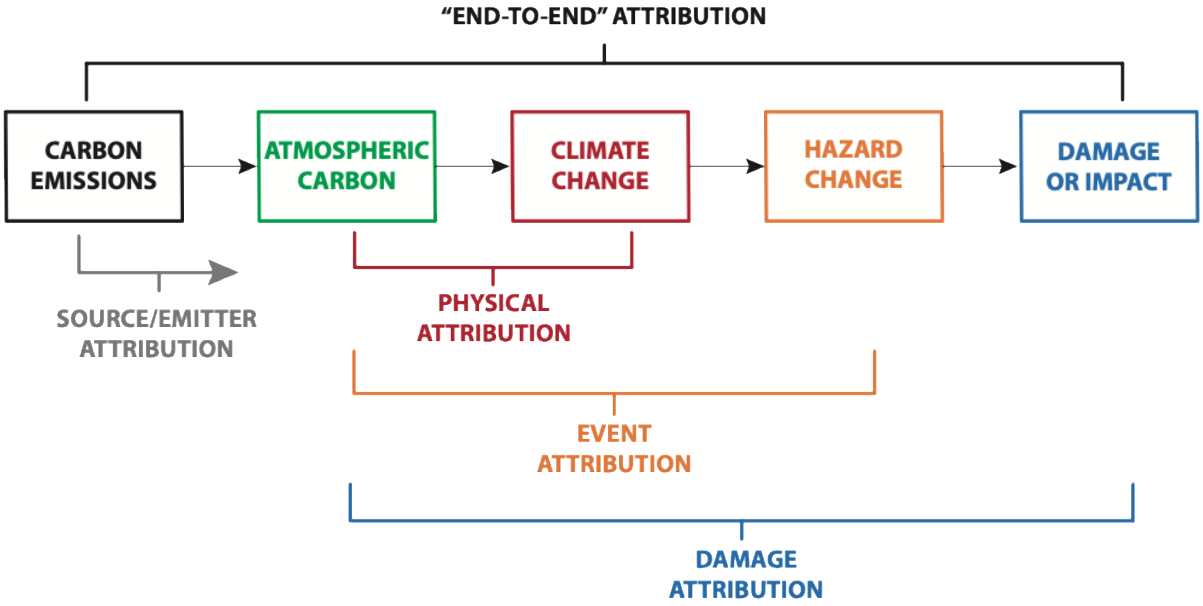

Figure 1| The attribution chain to assess causality. Climate attribution can take many forms, depending on the question at hand. It can consider any linkages in the chain of causality diagramed here, from how measures of carbon dioxide concentrations influence climate change writ large (a physical attribution), to how such concentrations shape weather or climate hazards, like a heatwave (an event attribution), to how such hazards select for impacts like homes washed away or lives lost (a damage attribution). Should any of these attribution linkages include the upstream emissions rather than the concentrations, that is a source or emitter-based attribution. If the entire chain of causality is considered from emissions through damages, that is an end-to-end attribution.

32. Extreme event attribution research identifies how various physical drivers, such as greenhouse gas emissions, alter the likelihood or intensity of extreme weather or climate events, such as heatwaves, extreme rainfall, droughts, wildfires, and floods.[16] The field has rapidly expanded and streamlined its approaches since it was first attempted in 2004, when scientists showed how anthropogenic warming had doubled the likelihood of the 2003 European heatwave that killed 70,000 people.[17] Since that time, extreme event attribution has advanced to become a scientific standard, with scientists fingerprinting anthropogenic contributions to hot and cold temperature extremes, to heavy precipitation events, to droughts, to tropical cyclones. Per the NCA5,[18] "climate change made the record-breaking Pacific Northwest heatwave of June 2021 2° to 4°F hotter,[19] and in 2017, Hurricane Harvey's rainfall was estimated to be about 15%–20% heavier than it would have been without

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[16] *Extreme Event Attribution,* National Oceanic and Atmospheric Administration, Perma | Extreme event attribution: the climate versus weather blame game | NOAA Climate.gov. Accessed 18 Oct. 2025.

[17] Stott et al. "Human contribution to the European heatwave of 2003." *Nature* 432, 610–614 (2004). https://www.nature.com/articles/nature03089

[18] See page 2-4 of Marvel, K. et al., 2023: Ch. 2. Climate trends. In: *Fifth National Climate Assessment*. Crimmins, A.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, B.C. Stewart, and T.K. Maycock, Eds. U.S. Global Change Research Program, Washington, DC, USA. Perma | toolkit.climate.gov

[19] Philip, S.Y. et al., 2021: Rapid attribution analysis of the extraordinary heat wave on the Pacific coast of the US and Canada in June 2021. *Earth System Dynamics*, 13 (4), 1689–1713. Perma | ESD - Rapid attribution analysis of the extraordinary heat wave on the Pacific coast of the US and Canada in June 2021

human-caused warming.[20]" Both the Sixth Assessment Report of the IPCC and the NCA5 note that attribution science has advanced to the point where we can confidently quantify the role of climate change in altering the likelihood or magnitude of extreme events in near-real time,[21] as is done by *World Weather Attribution*, an organization that since its formation in 2014, has used peer-reviewed science to attribute the causal role of human-caused climate change on more than 100 extreme weather and climate events around world.[22]

33. Beyond event attribution, the science has advanced to consider more linkages in the chain of causality that connects changes in emissions to changes in greenhouse gas concentrations; changes in such concentrations to changes in warming; changes in warming to changes in extremes and hazards; and changes in hazards to consequent damages (**Figure 1**)—how emissions through warming lead to, for example, homes washed away, agricultural yield losses, depressed economies, or heatstroke in people. As such, attribution science is now well-positioned to provide assessments of how particular sets of emissions, such as those emerging from the

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[20] Risser, M.D. and M.F. Wehner, 2017: Attributable human-induced changes in the likelihood and magnitude of the observed extreme precipitation during Hurricane Harvey. Geophysical Research Letters, 44 (24), 12457–12464. [Perma | agupubs.onlinelibrary.wiley.com]

[21] Seneviratne, Sonia I., et al. "Weather and Climate Extreme Events in a Changing Climate." *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Valérie Masson-Delmotte et al., Cambridge University Press, 2021, pp. 1513–1766. [Perma | Weather and Climate Extreme Events in a Changing Climate (Chapter 11) - Climate Change 2021 – The Physical Science Basis]; and Marvel, Kate, et al. "Climate Trends." *Fifth National Climate Assessment*, edited by Allison R. Crimmins et al., U.S. Global Change Research Program, 2023. [Perma | toolkit.climate.gov].

[22] World Weather Attribution, available at [Perma | World Weather Attribution – Exploring the contribution of climate change to extreme weather events]. Accessed 18 Oct. 2025.

activities of a single nation or firm like a fossil fuel company, contribute to particular damages, such as the economic losses New York suffers from extreme heat cumulatively over a time period, or from an individual heat wave.[23] These kinds of attributions are called *end-to-end climate damage attributions*, as they resolve the full chain of causality from specific emissions to specific damages (**Figure 1**): *but for* the extreme heat impacts of these emissions, New York's economy would look like this. Such end-to-end climate damage attribution analyses are grounded in observations of what has already occurred: What are the observed changes in weather and climate extremes? What is the observed relationship between such extremes and socioeconomic outcomes? These end-to-end attributions are retrospective, documentary assessments of the world as it has been, the losses that have already occurred, not predictions of a far off and contingent future.

34. Causal inference approaches, which are statistical tools used to mimic a controlled experiment on observed data,[24] can then be used to determine the causal

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[23] Quilcaille, Y. et al., Systematic attribution of heatwaves to the emissions of carbon majors, *Nature* 645, 392–398 (2025). Perma | Systematic attribution of heatwaves to the emissions of carbon majors | Nature; Burke, M. et al., Quantifying climate change loss and damage consistent with a social cost of greenhouse gases, *NBER Working Paper*, 31658 (2023). DOI: 10.3386/w31658 Perma | Systematic attribution of heatwaves to the emissions of carbon majors | Nature; Callahan, C. & J.S. Mankin, Globally unequal effect of extreme heat on economic growth, *Science Advances* **8**, eadd3726 (2022) Perma | www.science.org; Callahan, C. & J. S. Mankin, National attribution of historical climate damages, *Climatic Change* 172 40 (2022). Perma | National attribution of historical climate damages | Climatic Change

[24] Angrist and Pischke. *Mostly Harmless Econometrics: An Empiricist's Companion*. Princeton University Press, 2009.

relationship between the intensity of that extreme and its harms, such as flood-[25] or heatwave-driven[26] mortality[27], property[28] or crop[29] damages, or reductions in economic growth.[30] Such relationships are formalized as 'dose-response' models, and are often called 'marginal effects' or 'damage functions.' Such *damage functions* relate a unit change in the magnitude of a weather or climate hazard, like a 1°C change in a heatwave (the dose), to a unit change in some socioeconomic outcome of interest, like changes in annual-scale economic growth in New York (the response). Combining the quantification of company-level emissions contributions to local climate hazards, like heatwaves, with the observed socioeconomic consequences of such hazards, like depressed economic growth, allows for an assessment of local scale (i.e., at the level of a U.S. state) climate damages traceable to a company's emissions.

35. End-to-end attribution of climate damages at the level of a U.S. state begins with the greenhouse gas emissions to be considered. This can be a fossil fuel

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[25] Lynch et al. "Large floods drive changes in cause-specific mortality in the United States." *Nature Medicine*, vol. 31, no. 2, Feb. 2025, pp. 663-671, Perma | Large floods drive changes in cause-specific mortality in the United States | Nature Medicine; Carleton et al. "Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits." *The Quarterly Journal of Economics*, vol. 137, no. 4, 2022, pp. 2037–2105, Perma | academic.oup.com.

[26] Carleton et al. "Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits."

[27] U.S. Environmental Protection Agency. "Climate Change Indicators: Heat-Related Deaths." *EPA*, 26 Feb. 2025, Perma | Climate Change Indicators: Heat-Related Deaths | US EPA

[28] Davenport et al. "Contribution of Historical Precipitation Change to U.S. Flood Damages." *Proceedings of the National Academy of Sciences of the United States of America*, vol. 118, no. 4, 26 Jan. 2021, e2017524118, Perma | www.pnas.org.

[29] Diffenbaugh et al. "Historical Warming Has Increased U.S. Crop Insurance Losses." *Environmental Research Letters*, vol. 16, no. 8, 2021, article 084025, https://perma.cc/UXA8-HNVT.

[30] Callahan and Mankin, "Globally unequal impact of extreme heat on economic growth."

producer's or refiner's historical greenhouse gas emissions; it could also be a state's emissions, or emissions from a sector of the economy, like the power or transport sectors.[31] This can be presented as a time series of annual emissions in metric tons of carbon or carbon dioxide equivalent (if considering methane and other greenhouse gas emissions), or it can be a percentage of some total set of emissions considered, whether it is all anthropogenic emissions over a given time period, or some other covered period, as considered by the New York Climate Change Superfund Act.

36. A company's emissions can be determined based on data provided by the company through self-reporting, through publicly available datasets, or some combination therein. Currently, there are at least two publicly available datasets of emissions inventories associated with Scope 1 and Scope 3 emissions[32]. In all cases, however, the State is dependent on corporate disclosures from the companies themselves. Self-reported data come with sizable reporting gaps, are rarely audited, and provide companies with wide latitude over the boundaries of the emission Scopes they consider. As such, self-reported data from fossil fuel companies very likely understates the true emissions associated with company activities, particularly for Scope 3 and non-CO_2 gases. Moreover, because Scope 3 emissions are typically

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[31] Mankin et al. (2025), Climate damages to the U.S. economy from U.S. power sector emissions, Perma | Climate damages to the U.S. economy from U.S. power sector emissions; and Mankin et al. (2025), Climate damages to the U.S. economy from U.S. transportation emissions, Perma | Climate damages to the U.S. economy from U.S. transportation emissions.

[32] *Carbon Majors Database Downloads.* Carbon Majors, Perma | Carbon Majors Downloads. Accessed 15 Oct. 2025; Chen et al., "How Much Have the Oil Supermajors Contributed to Climate Change? The Carbon Footprint of the Oil Refining and Petroleum Products Sales Sectors," *Columbia Center on Sustainable Investment*, Mar. 2022, Perma | ccsi.columbia.edu

estimated from fossil fuel production volumes by removing non-energy uses of those fuels (e.g., petrochemicals), and then applying widely-accepted "emissions factors,"[33] which estimate the total emissions released when those fuels are combusted, such values are inherently conservative.[34] Scope 1 emissions from flaring, venting, fugitive methane emissions, and companies' own fuel use are similarly estimated using such emissions factors.[35] Because of the conservatism in both the reporting and in the estimates of emissions using emissions factors, I must emphasize that emissions inventories from fossil fuel companies represent minimum estimates of corporate emissions, rather than complete totals. As such, any attributions of climate damages to New York associated with such emissions will tend to be conservative.

37. Once a fossil fuel producer or refiner's total emissions have been determined, the next step is to determine how those emissions contributed to cumulative greenhouse gas concentrations, consequent global warming, and local hazards. That determination requires a means of estimating the counterfactual

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[33] Emissions factors translate activities—such as burning a gallon of gasoline—into emissions values, expressed as the mass of greenhouse gases (e.g., kilograms of CO_2, CH_4, or N_2O released). When emissions factors are reported in CO_2e (carbon dioxide equivalent) they already incorporate a global warming potential (GWP) to convert each gas into an equivalent amount of CO_2 based on its warming impact over a specified time horizon (typically 100 years).

[34] Note that this only captures Scope 3 Category 11 ("use of sold products") emissions and thus represents a lower-bound on total Scope 3 emissions.

[35] Note that this method applies a global emissions factor based on the state-of-the-science to all companies' production data. Standardized emissions factors are conservative by construction, erring on the side of understating emissions. Constructing global emissions factors requires smoothing high carbon intensity outlying fuels and regions, it means excluding methane or black carbon, fuel leaks, flaring inefficiencies, and/or incomplete combustion (which interestingly increases GHG forcing by increasing methane and black carbon contributions). So, while modeled estimates of Scope 3 emissions based on cautious IPCC emissions factors produce internally consistent estimates of GHG emissions, this is another reason these inventories should be considered conservative.

climate without the considered emissions (i.e., the control): "what might global temperatures have been absent a party's emissions?" Climate or Earth System Models[36] which simulate the global temperature response to greenhouse gas emissions and other climate forcings, provide a means of estimating these counterfactuals. Such models can be run (a) with all historical emissions and (b) with all historical emissions minus those of a particular emitter over a particular time period or a leave-one-emitter-out framework. The difference between these two scenarios—the world as it has been versus the world without one company's emissions—represents the contribution of that company's emissions to warming.

38. Linking the temperature changes from a company's emissions to a local scale climate hazard can be done a number of ways. A spatially explicit Earth System Model explicitly simulates changes in extreme heat, drought, flood, and tropical cyclone changes within a region like New York state. It can also be done by chaining a series of models together, whether based on well-vetted and understood statistical relationships between global temperature changes and local hazard changes,[37] or by using secondary physics-based models, such as a tropical cyclone model[38] run with

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[36] Climate or Earth System Models are computer programs that use physics, chemistry, and biology to simulate how components of our planet—oceans, atmosphere, land, and ice, interact to shape weather and climate over time and space. See, for example, McSweeney & Hausfather, "Q&A: How Do Climate Models Work?" *Carbon Brief*, 16 Jan. 2018, Perma | Q&A: How do climate models work? - Carbon Brief. Accessed 19 Oct. 2025.

[37] Quilcaille, Y. et al., "Systematic attribution of heatwaves to the emissions of carbon majors."

[38] Reed et al. "Attribution of 2020 Hurricane Season Extreme Rainfall to Human-Induced Climate Change." *Nature Communications*, vol. 13, no. 1, Dec. 2022, Article 1905, Perma | Attribution of 2020 hurricane season extreme rainfall to human-induced climate change | Nature Communications.

different experimental treatments many times, such as one with observed temperatures, and one with the temperatures absent a single emitter. In general, however, current peer-reviewed practice is to use consensus-based tools like pattern scaling.[39] Pattern scaling takes the estimate of global warming attributable to an emitter and translates it into local-scale changes in climate hazards. The physical basis for the relationship between global temperatures and climate extremes has been known for decades (e.g., for extreme precipitation,[40] extreme heat,[41] sea level rise[42]). Coupled with longer observational records and advances in modeling, scientists can quantify with increasing precision how global warming alters the likelihood or intensity of these extreme events. Combining the steps above provides an answer to the question: "How has the warming resulting from the emissions of a particular party affected the local risk of climate hazards?"

39. Climate attribution science allows New York to assess the in-state climate harms it has endured over a covered period traceable to the emissions from individual fossil fuel companies. Peer-reviewed, consensus-based end-to-end climate damage attributions can provide estimates of how sets of emissions have contributed to cumulative emissions, warming, and by extension, local extreme weather and

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[39] IPCC, 2021, AR6 WG1, Chapter 4, Section 4.2.4.2 ("Pattern Scaling"), p. 4-35. Perma | www.ipcc.ch

[40] Trenberth et al., "The Changing Character of Precipitation." *Bulletin of the American Meteorological Society*, vol. 84, no. 9, Sept. 2003, pp. 1205-1217, Perma | journals.ametsoc.org.

[41] Stott et al. "Human contribution to the European heatwave of 2003."

[42] Schneider, S. H., and R. S. Chen. "Carbon Dioxide Warming and Coastline Flooding: Physical Factors and Climatic Impact." *Annual Review of Energy and the Environment*, vol. 5, 1980, pp. 107-140, https://doi.org/10.1146/annurev.eg.05.110180.000543.

climate hazards. Climate damage attributions can then link changes in such hazards to their documented economic harms.

Dated: October 27, 2025
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MANKIN EXHIBIT A

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ACADEMIC APPOINTMENTS

Dartmouth College **Hanover, NH**

2023 - Associate Professor, Department of Geography
Adjunct Associate Professor, Department of Earth Sciences
2018 - 2023 Assistant Professor, Department of Geography
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Adjunct Assistant Professor, Department of Earth Sciences

Lamont-Doherty Earth Observatory (LDEO) of Columbia University **Palisades, NY**

2018 - Adjunct Associate Research Scientist, Division of Ocean & Climate Physics
2015 - 2018 Earth Institute Postdoctoral Fellow, Division of Ocean & Climate Physics

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2015 - 2017 Postdoctoral Research Fellow, Joint Appointment with LDEO

EDUCATION

Ph.D., Stanford University **Stanford, CA**
Environment & Resources, September 2015

M.P.A., Columbia University **New York, NY**
Environmental Science & Policy, May 2010

M.Sc., The London School of Economics **London, UK**
Global Politics & Development Economics, October 2008

B.A., Columbia University **New York, NY**
Political Science, May 2004

PROFESSIONAL SOCIETIES

American Geophysical Union (AGU); American Meteorological Society (AMS); American Association of Geographers (AAG); American Association for the Advancement of Science (AAAS)

PUBLICATIONS

⋆ Denotes research where Mankin is lead or senior author (i.e., last author, per Vancouver Protocol); underlined are: PI-advised (P)ostdoc, (G)rad student, (U)ndergrad, and (R)esearch Assistant

Total peer-reviewed papers published: 65. Total citations: ~7700; h-/i-10 index: 39/54 (based on Google Scholar)

MANUSCRIPTS UNDER REVIEW

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for snow to supply human water demand in the present and future, *Environmental Research Letters* (2015) 10.1088/1748-9326/10/11/114016.

3. ⋆**Mankin, J. S.**, N. S. Diffenbaugh, Influence of temperature and precipitation variability on near-term snow trends, *Climate Dynamics* (2015) 10.1007/s00382-014-2357-4.

2. Siegfried, T., T. Bernauer, R. Guiennet, S. Sellars, A. W. Robertson, **J. S. Mankin**, P. Bauer-Gottwein, Will Climate Change Exacerbate or Mitigate Water Stress in Central Asia?, *Climatic Change*, **112** (3-4) 881 (2012) DOI 10.1007/s10584-011-0253-z.

1. ⋆**Mankin, J. S.**, Gaming the system: how Afghan opium underpins local power, *Journal of International Affairs*, **63** (1) 195 (2009).

PEER-REVIEWED BOOK CHAPTERS

1. Moore, F., **J. S. Mankin**, A. H. Becker, Disciplines: Integrating Climate and Social Sciences, Chapter 4 in *Climate Cultures: Anthropological Perspectives on Climate Change*. Jessica Barnes and Michael Dove (eds). New Haven: Yale University Press (2015).

DATASETS

1. National-scale attribution of historical climate damages, (2022) 10.1007/s10584-022-03387-y. Available at: `https://rcweb.dartmouth.edu/CMIG/national_attribution_2022/prod/`. These data are being used in ongoing climate litigation by Our Children's Trust in their national court case (Juliana v. United States) and international cases (e.g., in Canada's LaRose v. Her Majesty, among others in development). Also is the basis of an advising opinion being written by the International Court of Justice for the UN on questions of Loss & Damage.

REPORTS

3. ⋆**Mankin, J.S.**, A. Gottlieb, C. Callahan, National climate damages traceable to emissions from the U.S. transport sector, September 2025, https://zenodo.org/records/17080804.

2. ⋆**Mankin, J.S.**, A. Gottlieb, C. Callahan,ational climate damages traceable to emissions from the U.S. power sector, June 2025, https://doi.org/10.5281/zenodo.16874810.

1. ⋆**Mankin, J.S.**, Response to Request for Information Development of a Climate Superfund Cost Recovery Program for the State of Vermont, October, 2024.

OTHER WRITING

15. ⋆Lesk, C. (P), S. Shukla, W. B. Anderson, B. I. Cook, & **J. S. Mankin**, Continental drying unlikely to explain recent sea-level rise,Reply to Seo et al., Abrupt sea level rise and Earth's gradual pole shift reveal permanent hydrological regime changes in the 21st century, *Science e-letter*.

14. ⋆**Mankin, J. S.**, The people have a right to climate data, *The New York Times*, Section A, Page 22, 20 January 2024.

13. ⋆Lesk, C. (P), **J.S. Mankin** & National Center for Atmospheric Research Staff (Eds), The Climate Data Guide: Making sense of data from Land Surface Models (LSMs), September 2023.

12. ⋆**Mankin, J. S.** & C. Callahan (G), The other climate change, *The Los Angeles Times*, page A11, 25 May 2023.

11. ⋆C. Callahan (G) & **Mankin, J. S.**, MLB home run counts are rising and global warming is playing a role, *The Conversation*, 7 April 2023.

10. ⋆**Mankin, J. S.** & C. Callahan (G), The Scientific Case for Climate Liability and Loss and Damage Claims, *Lawfare*, 2022.

9. ⋆**Mankin, J. S.**, The American West's drought isn't a disaster. It's our new, permanently arid normal, *The Washington Post*, 2021.

8. Fu, R., I. Simpson, **J. S. Mankin**, A. Hoell, D. Barrie, Fueled by climate change, costly Southwest drought isn't going away, *The Washington Post*, 2021.

7. ⋆Coffel, E. (P) & **J. S. Mankin**, Thermal power generation disadvantaged under global warming, *Carbon Brief*, 2021.

6. Fu, R., A. Hoell, **J. S. Mankin**, I. Simpson, Addressing drought-heatwave-wildfire interactions, *EOS*, 2021.

5. ⋆Coffel, E. (P) & **J. S. Mankin**, More rain but less water in the Nile Basin, *The Conversation*, 13 January 2020.

4. ⋆**Mankin, J. S.**, et al., Will plants help make the planet wetter or drier in a changing climate?, *Carbon Brief*, 5 November 2019.

3. Schultz, K. & **J. S. Mankin**, The weather stations that monitor climate change are at risk. This is why, *The Washington Post*, 22 April 2019.

2. **Mankin, J. S.**, Rotten to the core, *Foreign Policy*, (2011).

1. **Mankin, J. S.**, Preventive semantics, *Foreign Policy*, 146 (2005).

Academic honors and awards

MIT & Woods Hole Oceanographic Institution, H. Burr Steinbach Visiting Scholar, 2025.

American Geophysical Union, Global Environmental Change Early Career Award, 2024.

World Climate Research Programme & Future Earth: Callahan & Mankin, *Science* (2023) named one of the 10 New Insights in Climate Science (10NICS), 2024.

Keynote Lecture, National Academies of Sciences, Climate Change and Human Migration, 2024.

AGU Editors' Highlight: Li et al., "Emergent trends complicate the interpretation of the United States Drought Monitor," 2024.

Nature Editors' Highlight: Gottlieb & Mankin, "Evidence of human influence on Northern Hemisphere snow loss," 2024.

Nature Cover Article: Gottlieb & Mankin, "Evidence of human influence on Northern Hemisphere snow loss," 2024.

AMS Editors' Highlight: Callahan et al., "Global warming, home runs, and the future of America's pastime," 2024.

Science Editors' Highlight, Callahan & Mankin, "Persistent effect of El Niño on global economic growth," 2024.

Climate Science Leader, Climate Judiciary Project, Environmental Law Institute, 2023.

Science Editors' Highlight: Callahan et al., "Global warming, home runs, and the future of America's pastime," 2023.

IOP Editors, Outstanding Reviewer Award, 2022.

AMS Editors' Highlight: Gottlieb & Mankin, "Observing, measuring, and assessing the consequences of snow drought," 2022.

Nature Editors' Highlight: Callahan & Mankin, "Globally unequal effect of extreme heat on economic growth," 2022.

IOP Editors, Outstanding Reviewer Award, 2021.

AGU Editors' Highlight: Mankin et al., "The value of initial condition large ensembles to robust adaptation decision-making," 2020.

Nature Editors' Highlight: Qin et al., "Agricultural risks from changing snowmelt," 2020.

Named Co-Lead, National Oceanic and Atmospheric Administration (NOAA) Drought Task Force IV, 2020.

Nature Editors' Highlight: Schultz & Mankin, "Is temperature exogenous? Conflict related uncertainty in the instrumental climate record in Sub-Saharan Africa," 2019.

Nature Climate Change Editors' Highlight: Mankin et al. "The potential for snow to supply human water demand in the present and future," 2018.

IOP Editors, Outstanding Reviewer Award, 2016.

IOP Editors' Highlight: Mankin et al.,"The potential for snow to supply human water demand in the present and future," 2016.

Nature Editors' Highlight: Mankin et al., "The potential for snow to supply human water demand in the present and future," 2015.

IOP Editors Annual "Select" Article, Mankin et al., "The potential for snow to supply human water demand in the present and future," 2015.

Environmental Research Letters Monthly Highlights Collection, November 2015.

Andrew Wellington Cordier Essay Winner, Columbia University, 2009.

Distinction, MSc. Thesis, London School of Economics, 2008.

FELLOWSHIPS

Scialog Fellow, Research Corporation for Science Advancement (RCSA), 2025-2026.

Petitt Family Fellowship, Dartmouth College, 2023-2024.

Junior Faculty Fellowship, Dartmouth College, 2021-2022.

Earth Institute Postdoctoral Fellowship, Columbia University, 2015-2017.

Northeast Climate Science Center Fellowship, The Center for Climate Systems Research & University of Massachusetts, Amherst, 2015-2017.

Predoctoral Science Fellowship, Center for International Security and Cooperation (CISAC), Stanford University, tuition and stipend, 2014-2015.

Stanford Center on International Conflict and Negotiation (SCICN) Fellowship, Stanford Law School, 2012-2013.

Rising Environmental Leadership Program (RELP) Fellowship, Woods Institute for the Environment, Stanford University, 2012-2013.

Margaret Jonsson Family Foundation Fellowship, School of Earth Sciences, Stanford University, tuition and stipend, 2010-2014.

Environmental Science Academic Fellowship, Columbia University, 2010.

ACADEMIC SERVICE

PROFESSIONAL

Member, National Academies of Sciences, The Future of Drought in the United States Consensus Study, 2025-2026

Member, US CLIVAR Working Group on Accelerating Research on the Scientific Foundations of

Regional Climate Risk Information, 2025-2028

Co-lead, 'Drought' Water Cycle Priorities, NASA Decadal Survey, 2024-2025

Member, British Institute of International and Comparative Law (BIICL) Global Perspectives on Corporate climate Legal Tactics Core Group, 2025-present

Graphics Lead Author, Sixth National Climate Assessment (NCA6), Chapter 12, 2024-2027

Media Lead, World Climate Research Programme & Future Earth 10 New Insights in Climate Science, 2024

Editor, *Earth's Future*, American Geophysical Union, 2024-present

Associate Editor, *Journal of Climate*, American Meteorological Society, 2023-present

Associate Editor, *Earth's Future*, American Geophysical Union, 2022-2024

Co-Chair, 37th Conference on Climate Variability and Change at the 104th American Meteorological Society (AMS) Annual Meeting, 2023-2024

Member, The Corporation of the Montshire Museum of Science, 2024-present

Member, American Meteorological Society Committee on Climate Variability and Change (AMS CVC), 2020-present

Committee Member, *Earth's Future* Editor-in-Chief Search Committee, 2023

Committee Member, Conference on Attribution Science and Climate Law Advisory Committee, Columbia University, 2024-present

Chair, American Meteorological Society CVC Scientific and Technological Activities Commission (STAC) Awards Committee, 2021-2023

Member, American Meteorological Society CVC STAC Awards Committee, 2023-present

Co-lead, National Oceanic and Atmospheric Administration Drought Task Force (NOAA DTF), 2020-2023

Member Representative, University Corporation for Atmospheric Research (UCAR) for Dartmouth College, 2020-present

Senior Anti-Corruption Advisor, NATO International Security Assistance Force (ISAF), 2011

Advisor, U.S. House of Representatives, Subcommittee on Environment of the House Committee on Science, Space, and Technology Majority, 2022

Proposal referee for National Science Foundation (Climate & Large Scale Dynamics; Geoinformatics; Human-Environment and Geographical Sciences; Paleo Perspectives on Climate Change; Human Networks and Data Science), National Oceanic and Atmospheric Administration, Department of Energy, Human Frontier Science Program, Swiss National Science Foundation

Guest Editor for Proceedings of the National Academy of Sciences (2025)

Journal referee for Journal of Climate, Geophysical Research Letters, Journal of Hydrology, Nature, Science, Water Resources Research, Earth's Future, Biogeosciences, Climate Dynamics, Climatic Change, Climate of the Past, Frontiers in Climate Science, Environmental Research Letters, Earth Science Reviews, Nature Climate Change, Agricultural and Forest Meteorology, Proceedings of the National Academy of Sciences, Nature Communications, Sustainability, Nature Water, Journal of Geophysical Research-Atmospheres, npj Climate Science, PlosOne, Science Advances, Springer Publishing, Cambridge University Press

Session Convener, American Geophysical Union (AGU) 2024, 'Advances in understanding water-energy-carbon interactions I and II'; American Geophysical Union (AGU) 2023, 'Drought: Mechanisms and Impacts in the Past, Present, and Future'; American Geophysical Union (AGU) 2022, 'Drought: Mechanisms and Impacts in the Past, Present, and Future'; American Meteorological Society (AMS) 2022, 'Land-Atmosphere Interactions'; American Geophysical Union (AGU) 2021, 'Drought: Mechanisms and Impacts in the Past, Present, and Future'; American Meteorological Society (AMS) 2021, 'Downscaling and Regional Climate Change'; American Geophysical Union (AGU) 2020, 'Understanding the Terrestrial Hydrological Response to Atmospheric CO_2: Constraints from the Geologic Past and Insights into the Future'; American Meteorological Society (AMS) 2020, 'The use of large ensembles in understanding climate variability and change', January 2020

Seminar organizer, Dartmouth's 'Critical Data' seminar series, 2019-2020; Lamont-Doherty Earth Observatory Division of Ocean & Climate Physics Seminar, 2016-2017

Conference organizer, Co-Chair of the 37th Conference on Climate Variability and Change at AMS 2024; Columbia Sabin Center Climate and Law Workshop planning committee, January 2025; AGCI Workshop Chair "The Future of Terrestrial Water Availability" October 2024; PAGES2k PMIP3 Workshop planning committee, Lamont-Doherty Earth Observatory, June 1-3 2016

OSPA Judge, AGU 2016 Fall Meeting; AMS 2020 Annual Meeting; AMS 2021 Annual Meeting; AGU 2021 Annual Meeting; AMS 2022 Annual Meeting

DARTMOUTH

Member, Joint Economics-Irving Institute Faculty Search Committee, 2025-present

Team Faculty Advisor, Dartmouth Women's & Men's Lacrosse teams, 2025-present

Chair, Dartmouth Climate Futures Initiative Research Colloquium, 2024

Member, Dartmouth Climate Collaborative Advisory Council, 2024-present

Member, Committee on Standards (COS), 2023-present

Member, Committee on the Faculty (COF), Dartmouth, 2020-2021

Member, Provost's Strategic Working Group to the Irving Institute, 2024

Chair, Curriculum Committee, Department of Geography, 2024-present

Member, Curriculum Committee, Department of Geography, 2023-present

Member, Departmental Seminar Committee, Department of Geography, 2024-present

Co-chair, Departmental Seminar Committee, Department of Geography, 2019-2020

Member, Dartmouth Climate Solutions Working Group Organizing Committee, 2023-2024

Member, Search Committee, Department of Geography, 2022-2023

Chair, Curriculum Committee, Dartmouth EEES PhD program, 2020-2022

Member, Curriculum Committee, Dartmouth EEES PhD program, 2022-present

Member, Program Chair Selection Committee, Dartmouth EEES PhD program, 2021-2023

Advisory Board Member, Irving Institute Faculty Advisory Board, 2022-2024

Member, Ad Hoc Group on Energy for Dartmouth Sustainability Office, 2022-2023

Member, Design Initiative at Dartmouth (DIAD) Steering Committee, 2022-present

Faculty Advisor, Center for Environmental Leadership Training (CELT), 2022-present

ADVISEES

POSTDOCTORAL FELLOWS

Coffel, Ethan, Postdoctoral Fellow, Neukom Institute, Dartmouth, lead advisor (2018-2020), now Asst. Prof. at Syracuse University

Fofrich, Robert, Postdoctoral Fellow, Silicon Valley Family Foundation, lead advisor (2026-2028)

Gottlieb, Alex, Postdoctoral Fellow, Rockefeller Family Fund, lead advisor (2024-2026)
He, Yaqian, Postdoctoral Fellow, Department of Geography, Dartmouth, lead advisor (2018-2020), now Asst. Prof. at University of Arkansas
Lesk, Corey, Postdoctoral Fellow, Neukom Institute, Dartmouth, lead advisor (2022-2025), now Asst. Prof. at UQAM
Li, Zhiying, Postdoctoral Fellow, Department of Geography, Dartmouth, lead advisor (2021-2024), now Asst. Prof. at Indiana University
von Fromm, Sophie, Postdoctoral Fellow, Neukom Institute, Dartmouth, co-advisor (2023-2025), now Asst. Prof. at Montana State University

Graduate students

Burks, Junior, PhD student, EEES program, Dartmouth, committee member (2025-present)
Burns, Madeleine, PhD student, EEES program, Dartmouth, NDSEG funded, lead advisor (2025-present)
Callahan, Christoper, PhD student, EEES program, Dartmouth, NSF GRFP funded, lead advisor (2018-2023), now Asst. Prof. at Indiana University
Gottlieb, Alex, PhD candidate, EEES program, Dartmouth, DOE funded, lead advisor (2019-2024), now Postdoctoral Scholar, Dartmouth
Lane, Erin, PhD candidate, EEES program, Dartmouth, committee member (2021-2025)
Perlmutter, Flora, PhD candidate, EEES Program, Dartmouth, NSF GRFP funded, lead advisor (2022-present)
Potemkin, Stella, PhD student, EEES program, Dartmouth, SVCF Foundation funded, lead advisor (2025-present)
O'Shea, Maggie, PhD student , EEES program, Dartmouth, Changing Horizons Foundation funded, lead advisor (2023-present)
Savage, Joseph, PhD student, EEES program, Dartmouth, committee member (2025-present)
Wang, Chunmeng, PhD student, EEES program, Dartmouth , committee member (2025-present)

Undergraduate students

Liu, Joanne, Women in Science Program Fellow (WISP), Dartmouth undergraduate (2019-2019)
Martinez, Emily, Junior Research Fellow, Neukom Scholar, Dartmouth undergraduate (2019-2022)
Rust, Elise, Senior Honors Thesis QSS, Dartmouth undergraduate (2020-2021)
Zamora Castillo, Santiago, Dartmouth undergraduate (2020-2020)
Siegert, Noel, Dartmouth undergraduate (2020-2023)
Pronichenko, Katya, Dartmouth Sophomore Research Scholar (2021-present)
Adobamen, Anna, Women in Science Program Fellow (WISP), Dartmouth undergraduate (2021-2021)
Kulasingham-Poon, Meghan, Women in Science Program Fellow (WISP), Dartmouth undergraduate (2021-present)
Yildirim, Ulgen, Women in Science Program Fellow (WISP), Dartmouth undergraduate (2021-2021)
Gerber, Annabel, Women in Science Program Fellow (WISP), Dartmouth undergraduate (2021-present)
Moon, Zoe, Women in Science Program Fellow (WISP), Dartmouth undergraduate (2022-present)
Bryant, Grace, Senior Honors Thesis Student, Earth Sciences, Dartmouth undergraduate (2022-2023)
Simon, Erica, Neukom Scholar, Dartmouth undergraduate (2022-present)
Lertbunnaphongs, Buntida "Beam", ENVS scholar, Dartmouth undergraduate (2023-2024)
Pogue, Lily Senior Honors Thesis Student, Geography, Dartmouth undergraduate (2024)
Colgan, May URAD researcher, Geography, Dartmouth undergraduate (2024-present)
Ding, Gary EPS scholar, Dartmouth undergraduate (2025-present)

GRANTS

EXTERNAL AGENCIES AND FOUNDATIONS, PENDING (TOTAL: $5M)

6. **Frontiers Planet Prize**, sole-PI, *limited submission, pending*, End-to-end climate attribution (2026).

5. **Bassi Fellowship**, University of Venice, Euro-Mediterranean Center on Climate Change (CMCC), sole PI, *invited submission, pending*, The costs of climate to reinsurance (2026-2027).

4. **Guggenheim Foundation**, sole PI, *pending, 9/2026-8/2027*, Expanding the end-to-end climate attribution ecosystem.

3. **Keck Foundation**, co-PI, with K. Reed (Stony Brook University), *invited submission, pending, 01/2026-12/2028*, Physically linking climate change to flood impacts. ($500k to Dartmouth)

2. **Larsen Lam Climate Change Foundation**, PI, *invited submission, pending 9/2025-8/2027*, Assessing insured losses from individual emitters. ($2.6M to Dartmouth)

1. **Ikea Foundation**, lead PI, with B. Franta (Oxford University), C. Rodriguez-Garavito (NYU Law), *pending, 10/2025-08/2027*, Democratizing Climate Data: The Climate Damage Attribution Library. ($1.6M to Dartmouth)

EXTERNAL AGENCIES AND FOUNDATIONS, CURRENT, CANCELLED, & COMPLETED
Total to Dartmouth: $2.37M

10. **Changing Horizons Fund**, sole PI, unrestricted gift, *6/2025* ($50k to Dartmouth)

9. **Silicon Valley Community Foundation**, sole PI, unrestricted gift, *5/2025*. ($800,000 to Dartmouth)

8. **Rockefeller Family Fund**, sole PI, *9/2024-8/2026*, Transparent, reproducible, and rational estimates of climate damages to Vermont from particular emissions. ($ 450,000 to Dartmouth)

7. **NOAA Climate Variability & Predictability**, co-I, with Y. Jiang, J. Smerdon, and R. Seager (Columbia University), *recommended, but remains unfunded, 1/2025 - 1/2028,* The impact of land surface conditions on the evolution and predictability of ocean-driven hydroclimate extremes in the western U.S. ($77k to Dartmouth)

6. **NOAA NIDIS**, co-PI with Z. Li (Indiana), Y. Jiang, J. Smerdon, R. Seager (Columbia), Contextualizing Drought Severity in a Changing Climate to Support Drought Monitoring and Management, *selected, remains unfunded, 1/2026-08/2028.* ($52k to Dartmouth)

5. **NSF Climate & Large Scale Dynamics**, co-PI, with Syracuse University,*9/2023-8/2026*, Agriculture as a driver of regional climate extremes. ($128,075 to Dartmouth)

4. **Aspen Global Change Institute**, co-PI, with Cornell *awarded*, Future resilience and risk of terrestrial water availability: towards an integrated perspective on water, plants, and climate.

3. **Department of Energy**, co-PI, with J. Smerdon and R. Seager of Columbia University, *9/2021 - 8/2025,* The Role of Vegetation in Past and Future Global Hydroclimatic Change. ($332,560 to Dartmouth)

2. **NSF Human-Environment and Geographical Sciences**, co-PI, *7/2021 - 6/2024,*The Crop-Climate Feedback Cycle and its Implications for Global Food Production.($26,600 to Dartmouth)

1. **NOAA Modeling, Analysis, Predictions and Projections**, lead PI, with J. Smerdon, B. Cook, and R. Seager of Columbia University, *9/2020 - 8/2024,* Regional Influences of Vegetation on Complex Droughts in North America. ($421,334 to Dartmouth)

INTERNAL, CURRENT & COMPLETED

Rockefeller Center, lead PI, Future Terrestrial Water Availability: Towards an Integrated Perspective on Water, Plants, and Climate, Dartmouth, 2024.

Neukom Institute CompX, lead PI, Geophysical Data Poverty in Climate Damage Assessments, Dartmouth, 2024-25.

Wright Center for the Study of Computation and Just Communities, lead PI, National Attribution of Historical Climate Damages: Data in Service of Climate Litigation, Dartmouth, 2022.

Neukom Institute CompX, lead PI, Assessing adaptation feedbacks to present and future climate extremes, Dartmouth, 2020-21.

Rockefeller Center, lead PI, Estimating the time of emergence and distribution of climate adaptation benefits for climate decision-making, Dartmouth, 2020-21

Walter and Constance Burke Research Initiation Award, lead-PI, The role of vegetation in shaping present and future aridity and drought, 2018

Earth Institute lead PI, Columbia University, 2015-2017.

Earth Institute Cross-Cutting Initiative, co-I, Columbia University, 2016-2017.

E-IPER Graduate Summer Research Grant, 2012.

McGee Grant, Stanford University, School of Earth Sciences, 2011.

Academic certifications

National Center for Atmospheric Research (NCAR), Boulder, CO, USA
Community Land Model Workshop **September 2016**

National Centre of Competence in Research, Climate (NCCR), Grindewald, Switzerland
NCCR Swiss Climate Research Summer School **Summer 2013**

National Center for Atmospheric Research (NCAR), Boulder, CO, USA
Community Earth System Model (CESM) Workshop **Summer 2012**

Teaching

⋆ Denotes an original course developed by Mankin for Dartmouth students

1. ⋆GEOG 01.01: Introduction to Earth System Science
   Lower-division course that introduces students to the study of the physical environment using a systems approach. The lab-based course examines how energy, mass, and momentum are exchanged through physical world, the sets of feedbacks a processes such exchange generates, and how those determine the varied forms of life on Earth. Offered SP 21, F 22, F 23, F 24, F 25, every year.
2. ⋆ GEOG 16.01: A Climate for Human Security
   Mid-division course that examines how the biogeophysics of the climate system shape human welfare and security; assumes a knowledge of the physics of global warming (e.g., GEOG 5) and statistics. Topics include climate projections, climate variability, climate uncertainty, climate sensitivity, and the carbon budget, the consumptive and paradoxical dimensions of the climate problem, the differences between 1.5°C and 2°C worlds, climate and political violence, mitigation, adaptation, and geoengineering. Offered SU 19, SP 21, SP 23, SP 24, W 26, offered most years.
3. ⋆ GEOG 18.01/EEES 140: Climate Extremes on a Warming Planet
   Mid-division course on the physics, impacts, and future of extreme weather and climate with a parallel graduate-level offering (EEES 140). The cloud-based python notebook problem sets developed by Mankin for the class led GEOG 18.01 to be selected as the pilot class for Dartmouth's Data Science Infused for Undergraduate STEM Education Project (DIFUSE), which is an NSF-funded project to develop data science applications in Dartmouth undergraduate classrooms. Assumes no prior knowledge of atmospheric science or programming. Offered SP 19, SP 20, SU 20, SP 23, SP 24, W 25, F 25, offered most years.

4. ⋆ GEOG 60.01/EEES 160: Earth System Modeling
Upper division course with a parallel graduate-level offering (EEES 160) introduces the concepts (theory and practicalities) related to the science and art of numerical modeling generally, and process-based modeling for climate science, specifically. Students build and work with a range of models, from simple, zero-dimensional radiation balance models to compiling and running fully-coupled global-scale Earth System Model experiments on a supercomputer (NCAR's Cheyenne cluster). Students learn the potentials and pitfalls of modeling more generally, while positioning a rational evaluation of models and their place in society, especially around predictions of climate change. Assumes knowledge of scientific computing, linear algebra, vector calculus, statistics, and differential equations. Offered W 23, SP 25, and every other year.
5. ⋆ GEOG 63.01: Decarbonize Your Life
An action-biased, transformative course designed to empower students with a comprehensive understanding of the imperative and practice of individual-level decarbonization. Grounded in an interdisciplinary approach, the course integrates insights from philosophy, critical social science, climate science, engineering, economics, medicine, and public policy. By the end of the term, students will be equipped with the knowledge and tools to critically analyze their carbon footprints and develop actionable, informed strategies to reduce their personal environmental impact where they live, now. Offered F 26.
6. ⋆ EEES 162/EARS 204/GEOG 90.03: Advanced Topics in Climate Science
During this course, students use primary literature and reviews to explore and interrogate seminal, retired, and new findings in climate science. Topics include climate forcings and feedbacks, land-atmosphere interactions, tipping elements, emergent constraints, climate projections, detection and attribution, climate impacts, integrated assessment, climate extremes, adaptation, and mitigation. Students will situate findings within their broader scientific experience and pursuits, tracing the evolution of ideas over time and pinpointing open questions for future research. Offered F 26.

TESTIMONY AND BRIEFINGS

7. Legislative testimony to Massachusetts Joint Committee on Energy & the Environment for H.1014/S.588, *September 2, 2025.*

6. Legislative testimony to Maine Committee on Committee on Environment and Natural Resources Testimony for LD 1870, *May 5, 2025.*

5. Briefing to Vermont Secretary for Natural Resources on S.259, *April 9, 2024.*

4. Briefing to the California Attorney General's Office, *June 26, 2024.*

3. Senate Testimony to Vermont Senate Natural Resources & Energy Committee on S.259, Montpelier, VT *March 21, 2024.*

2. Senate Testimony to Vermont Senate Judiciary Committee on S.259, Montpelier, VT *February 22, 2024.*

1. Congressional Briefing to Subcommittee on Environment, Committee on Science, Space, and Technology on Hydrologic Outlooks for the Western U.S., U.S. House of Representatives, Washington, D.C. *July 14, 2022.*

INVITED WORKSHOPS

17. Continental Weather and Climate Workshop III, Harvard University, Cambridge, MA, USA *May 22-23, 2025.*

16. Examining State Climate Superfund Bills, Environmental Law Institute, Washington, D.C., USA *March 19, 2025.*

15. Law and Climate Science Workshop, Climate Litigation Accelerator New York University, New York, NY, USA *April 4, 2025.*

14. Attribution Science and Climate Law Conference, Columbia University, New York, NY, USA *January 9-10, 2025.*

13. World Climate Research Programme Safe Landings Group, Geneva, Switzerland *could not attend, November 18-20, 2024.*

12. JPL Climate Risk Science Workshop, JPL Pasadena, CA, USA *October 28-30, 2024.*

11. Aspen Global Change Institute, Future of Terrestrial Water, Aspen, CO USA October 20-25, 2024.

10. Continental Weather and Climate Workshop II, Harvard University, Cambridge, MA, USA *June 14-16, 2024.*

9. National Academies Workshop on Climate Change and Human Migration: An Earth Systems Science Perspective, National Academies of Sciences, Engineering, and Medicine, Washington, D.C., USA *March 18-19, 2024.*

8. Continental Weather and Climate Workshop I, Harvard University, Cambridge, MA, USA *June 14-16, 2023.*

7. Assessing Drought in a Changing Climate, National Integrated Drought Information System (NIDIS) and the USDA Climate Hubs, Boulder, CO, USA,*February 28, 2023.*

6. Environmental Law Institute, Climate Leaders Judiciary Project, Washington, D.C., USA,*February 27, 2023.*

5. Rapid Attribution Workshop, National Oceanic and Atmospheric Administration, Boulder, CO, USA, *May 24-25, 2022.*

4. Continental Climate Change: Simple Models to Understand the Future, University of St. Andrews, Scotland, UK,*June 15, 2022.*

3. United States Climate Modeling Summit (US-CMS) on Land-Atmosphere Interactions and Extremes, NOAA Center for Weather and Climate Prediction, College Park, MD, USA, *April 4, 2018.*

2. NSF-EASM Workshop on Surviving peak drought and warming in the Southwest, University of Arizona, Tucson, AZ, USA, *March 29-30, 2018.*

1. PAGES2K / PMIP3 Hydroclimate Workshop, Lamont-Doherty Earth Observatory, Palisades, NY, USA, *June 1-3, 2016.*

PRESENTATIONS

INVITED TALKS (SELECTED)

64. *upcoming,* American Geophysical Union (two invited talks), New Orleans, LA., USA *December 8-10, 2025.*

63. *upcoming,* Program in Atmospheres, Oceans, & Climate (PAOC) Colloquium, Department of Earth, Atmospheric, and Planetary Sciences, MIT, Cambridge, MA, USA *December 1, 2025.*

62. *upcoming,* GundxChange, Gund Institute for the Environment, University of Vermont, Burlington, VT, USA *November 7, 2025.*

61. MIT-WHOI, Steinbach Scholar Colloquium (two talks), Woods Hole Oceanographic Institution, Woods Hole, MA, USA *August 2/3, 2025.*

60. Harvard University Center for the Environment, Harvard University, Cambridge, MA, USA *May 23, 2025.*

59. US Climate Alliance, Washington, D.C., USA *May 21, 2025.*

58. Rockefeller Family Fund, New York, NY, USA *May 20, 2025.*

57. Department of Geography Colloquium, UCLA, Los Angeles, CA, USA *May 12, 2025.*

56. Larsen Lam Climate Change Foundation, *May 8, 2025.*

55. New York University School of Law, New York, NY, USA *April 4, 2025.*

54. Thayer School of Engineering Ice+Climate Seminar, Hanover, NH, USA *March 28, 2025.*

53. Environmental Law Institute, Washington, D.C., USA *March 19, 2025.*

52. Department of Earth Sciences, University of Oxford, Oxford, England, UK *March 14, 2025.*

51. Ocean & Climate Physics Seminar, Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, USA *January 24, 2025.*

50. Columbia Law School, Climate Accountability Workshop, New York, NY, USA *January 10, 2025.*

49. American Geophysical Union, Washington, D.C., USA *December 13, 2024.*

48. Jet Propulsion Laboratory, Caltech, Pasadena, CA, USA *October 28, 2024.*

47. Aspen Global Change Institute, Aspen, CO, USA *October 22, 2024.*

46. Franklin Environmental Center at Hilcrest Climate Action Program, Middlebury College, Middlebury, VT, USA *September 10, 2024.*

45. Rockefeller Family Fund, New York, NY, USA *June 13, 2024.*

44. Harvard University Center for the Environment, Harvard University, Cambridge, MA, USA *June 14, 2024.*

43. Columbia Climate School, Columbia University, New York, NY, USA *June 5, 2024.*

42. New York University School of Law, Climate Litigation Accelerator, New York, NY, USA *March 20, 2023.*

41. National Academies of Sciences, Engineering, and Medicine, Washington, D.C., USA *March 18, 2024.*

40. Grantham Institute, London School of Economics, London, England, UK *November 20, 2023.*

39. Smith School of Enterprise and the Environment, University of Oxford, Oxford, UK *October 12, 2023.*

38. Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA *15 June 2023.*

37. Earth Research Institute, University of California, Santa Barbara, Santa Barbara, CA, USA *19 May 2023.*

36. K. Douglas Nelson Seminar, Department of Earth and Environmental Sciences, Syracuse University, Syracuse, NY, USA *April 6, 2023.*

35. Advances in Climatology, American Association of Geographers Annual Meeting, Denver, CO, USA *March 23, 2023.*

35. Environmental Law Institute, Washington, D.C., USA *February 28, 2023.*

34. Irving Energy Institute, Faculty Seminars on Energy and Climate, Dartmouth College, Hanover, NH, USA *February 17, 2023.*

33. Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY, USA *October 19, 2022.*

32. Department of Atmospheric Sciences, Texas A&M, College Station, TX, USA *September 21, 2022.*

31. NOAA-CIRES Rapid Attribution Workshop, Boulder, CO, USA *May 24, 2022.*

30. School of Earth and Environmental Sciences, University of St. Andrews, Fife, Scotland, UK *June 15, 2022.*

29. School of Ocean and Earth Science and Technology (SOEST), University of Hawaii, Manoa *November 19, 2021.*

28. Science Pub of Vermont, Brandon, VT, USA *November 7, 2021.*

27. Department of Earth System Science, University of California, Irvine, Irvine, CA, USA *April 12, 2021.*

26. NOAA Drought Task Force Monthly Meeting, Teleconference, USA *January 8, 2021.*

25. Department of Earth, Environmental and Planetary Sciences, Rice University, Houston, TX, USA *February 20, 2020.*

24. Department of Environmental Science, University of Virginia, Charlottesville, VA, USA *13 February 2020.*

23. Department of Environmental, Earth and Atmospheric Sciences, University of Massachusetts-Lowell, Lowell, MA, USA *October 17, 2019.*

22. American Geophysical Union, Washington, D.C., USA, *December 12, 2018.*

21. American Geophysical Union, New Orleans, LA, USA, *December 13, 2017.*

20. Center for Lifetime Study, Marist College, Poughkeepsie, NY, USA, *October 3, 2017.*

19. Pacala lab, Princeton University, Princeton, NJ, USA, *May 3, 2017.*

18. Department of Earth & Planetary Sciences, Brown University, Providence, RI, USA, *May 1, 2017.*

17. Sustainable Development Program (*guest lecture*), Columbia University, New York, NY, USA, *May 24, 2017.*

16. School of the Environment, Washington State University, Vancouver, WA, USA,*February 9, 2017.*

15. Department of Earth Sciences, University of Minnesota, Minneapolis, MN, USA, *February 6, 2017.*

14. Department of Environmental Science, American University, Washington, DC, USA, *January 31, 2017.*

13. Department of Geography, Dartmouth College, Hanover, NH, USA, *January 16, 2017.*

12. Society, Water, and Climate, The University of Utah, Salt Lake City, Utah, USA, *November 29, 2016.*

11. Urban Ecology Studio, Graduate School of Architecture, Planning, and Preservation, Columbia University, New York, NY, USA, *June 30, 2016.*

10. Department of Earth & Planetary Sciences Seminar, Northwestern University, Evanston, IL, USA, *February 19, 2016.*

9. Earth Matters Series,“A Matter of Degrees”, School of Continuing Education, Stanford University, Stanford, CA, USA, *February 24, 2015.*

8. Ocean & Climate Physics Seminar, Lamont-Doherty Earth Observatory, Palisades, NY, *February 20, 2015.*

7. Center for International Security and Cooperation (CISAC), Freeman Spogli Institute (FSI), Stanford, CA, USA, *January 15, 2015.*

6. Stanford Center on International Conflict and Negotiation (SCICN), Stanford, CA, *May 28, 2013.*

5. Knowledge transfer program (KTP), University of Reading, Reading, UK, *May 8, 2012.*

4. Policy & Economic Research Roundtable (PERR), Stanford University, Stanford, CA, USA, 27 January 2012.

3. National Conference on Science, Policy and the Environment (NCSE): Environment and Security, Washington, DC, USA, *January 18, 2012*.

2. Center for International Security and Cooperation (CISAC), Hewlett Foundation, CA, USA, *January 17, 2012*.

1. NATO ISAF HQ CJIATF-Shafafiyat, Kabul, Afghanistan, *January 30, 2011*.

CONTRIBUTED TALKS (SELECT 1^{st} AUTHOR ONLY)

9. **Mankin, J.S.**, Nonlinear plant responses to carbon dioxide and climate diminish water availability, American Geophysical Union Annual Meeting, Chicago, IL, USA, 12 December 2022.

8. **Mankin, J.S.**, The causes, consequences, and future of the ongoing Western U.S. drought, American Association of Geographers, New York, NY, USA 27 February 2022.

7. **Mankin, J.S.**, H. Singh, J. E. Smerdon, B. I. Cook, R. Seager, Impact of vegetation on historical North American droughts and the implications for a future greenhouse world, American Geophysical Union Annual Meeting, Washington, D.C., USA, 7 December 2020.

6. **Mankin, J.S.**, R. Seager, J. E. Smerdon, B. I. Cook, A. P. Williams, Will plants ameliorate or amplify drought risks under global warming? American Geophysical Union Annual Meeting, Washington, D.C., USA, 10 December 2018.

5. **Mankin, J. S.**, Blue water tradeoffs with ecosystems in a CO2-enriched climate, American Association of Geographers, New Orleans, LA, USA 11 April 2018.

4. **Mankin, J. S.**, J. E. Smerdon, B. I. Cook, A. P. Williams, R. Seager, Transpiration-driven aridification of the American West in 21st century model projections, American Geophysical Union Annual Meeting, San Francisco, CA, USA, 12 December 2016.

3. **Mankin, J. S.**, Climate certainty, uncertainty and human water availability in a warming world, Stanford University, Stanford, CA, USA, 12 June 2015.

2. **Mankin, J. S.**, D. Viviroli, M. M. Mekonnen, A. Y. Hoekstra, and N. S. Diffenbaugh, Quantifying the crucial role of snow in supplying human water demand. American Geophysical Union Annual Meeting, San Francisco, CA, USA, 15 December 2014.

1. **Mankin, J. S.**, M. Scherer, and N. S. Diffenbaugh, Diagnosing the inter-model spread in snow water equivalent over Central and Southwest Asia. Stanford School of Earth Sciences Review, CA, USA, 12 April 2013.

SKILLS & MISCELLANY

Technical: Unix/Linux shell, Python/Jupyter, NCL, R, Matlab, ArcGIS, ENVI, git, HTML, CSS LaTeX
Clearance: Top Secret (TS/SCI) clearance, granted 2004; NATO Secret as of 2011

SCIENTIFIC COMMUNICATION & OUTREACH

Media interviews and coverage of research (truncated): The New York Times, The Washington Post, The Los Angeles Times, The Guardian, AP, Reuters, AFP, CNN, CBS, NPR, PBS, Bloomberg, BBC, Scientific American, Nature, Accuweather, CNBC, National Geographic, The Atlantic, The Weather Channel, FSRN, Axios, The Christian Science Monitor, Phys.org, CarbonBrief, Environmental Research News, Salon, USA Today.

Documentary films: Climate in Therapy (2023) `https://www.imdb.com/title/tt18163368`

Podcasts: Living on Earth, September 2025, America Adapts, March 2024; On Point, February 2024, British Institute of International and Comparative Law, June 2025; Harvard Kennedy School Journalist's Resource "Unlocked," June 2025

Last updated: October 23, 2025 •

`http://jsmankin.github.io`

MANKIN EXHIBIT B

Mankin Exhibit B-1 — Stott et al. (2004)

Methods

A set of speckle-tracking algorithms[5] was used to determine the 1992, 1994, 1995 and 2000 velocities from 1–24-day image pairs. Speckle tracking uses the displacements of the correlated speckle patterns in pairs of SAR images to derive ice motion estimates. Individual errors were up to a few hundred metres per year (see Fig. 2), but errors on averages (for example, Fig. 3) are below 100 m yr^{-1}. We did not tide-correct the speckle-tracked data, so there are biases on the floating ice that do not spatially average out. To assess this error, we estimated velocity for five 1992 InSAR pairs, each with different tidal errors. The standard deviation for these estimates was 69 m yr^{-1}. Our 1992 and 1994 estimates are temporal averages of multiple (2 to 5) same-year pairs, which further reduces this error. The 2001 through 2003 estimates were derived using the IMCORR[25] feature-tracking software applied to 16-to-64-day Landsat image pairs. Established methods[26] were applied to passive microwave data to determine the 2002 melt extent.

Received 7 July; accepted 8 October 2004; doi:10.1038/nature03130.

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Acknowledgements This work was supported by the Cryospheric Sciences Program of NASA's Earth Science Enterprise. I.J. performed his contribution at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. We thank H. Brecher for the 1985 velocity data and B. Csatho, K. In Huh and S. Manizade for acquiring and orthorectifying the Landsat imagery. Radarsat data were provided by CSA through ASF and ERS SAR data were provided by ESA through the VECTRA project.

Author contributions All authors contributed equally to this work.

Competing interests statement The authors declare that they have no competing financial interests.

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Human contribution to the European heatwave of 2003

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The summer of 2003 was probably the hottest in Europe since at latest AD 1500[1–4], and unusually large numbers of heat-related deaths were reported in France, Germany and Italy[5]. It is an ill-posed question whether the 2003 heatwave was caused, in a simple deterministic sense, by a modification of the external influences on climate—for example, increasing concentrations of greenhouse gases in the atmosphere—because almost any such weather event might have occurred by chance in an unmodified climate. However, it is possible to estimate by how much human activities may have increased the risk of the occurrence of such a heatwave[6–8]. Here we use this conceptual framework to estimate the contribution of human-induced increases in atmospheric concentrations of greenhouse gases and other pollutants to the risk of the occurrence of unusually high mean summer temperatures throughout a large region of continental Europe. Using a threshold for mean summer temperature that was exceeded in 2003, but in no other year since the start of the instrumental record in 1851, we estimate it is very likely (confidence level >90%)[9] that human influence has at least doubled the risk of a heatwave exceeding this threshold magnitude.

Temperatures near the Earth's surface are rising globally[10], and evidence is mounting that most of the warming observed in recent decades has been caused by increasing atmospheric concentrations of greenhouse gases[9,11,12]. Anthropogenic increases in annual-mean temperatures have also been detected on continental scales, in Europe, North America and other land regions[13–15]. We first investigate the origins of long-term changes in decadal-mean European summer (June–August) temperatures, determining the changes attributable to anthropogenic drivers of the climate system and changes attributable to natural drivers. We then estimate how the risk of mean June–August temperatures exceeding a particular extreme threshold in any individual summer has changed as a result of this anthropogenic interference in the climate system.

Over the course of the twentieth century, June–August temperatures in Europe exhibited an overall increase, and a distinctive temporal pattern of temperature change, including cooling in the 1950s and 1960s (Fig. 1). We focus on the region bounded by 10° W and 40° E and 30–50° N (Fig. 1 inset), this being one of the regions chosen in previous studies[13,16] to represent climatically coherent regions sufficiently large to exhibit climate change signals above the noise of natural internal variability. We use a pre-selected region in order to minimize any bias that could result from selecting our region already knowing where the most extreme temperatures occurred. Even in such a large domain, 2003 was the warmest summer on record. The history of temperature change averaged over this region is well reproduced by simulations of the HadCM3 climate model[17], even at the model's relatively low spatial resolution (3.75° longitude by 2.5° latitude), when driven with both anthropogenic and natural drivers of climate change (Fig. 1; see red, green, blue and turquoise lines). Four simulations (denoted ALL) were made with different initial conditions[18], each with the same combination of well mixed greenhouse gases, sulphate aerosols and changes in tropospheric and stratospheric ozone, as well as natural changes in solar output and explosive volcanic eruptions[12]. A calculation of the temperature changes due to natural drivers alone (obtained by combining a simulation with solar forcing and

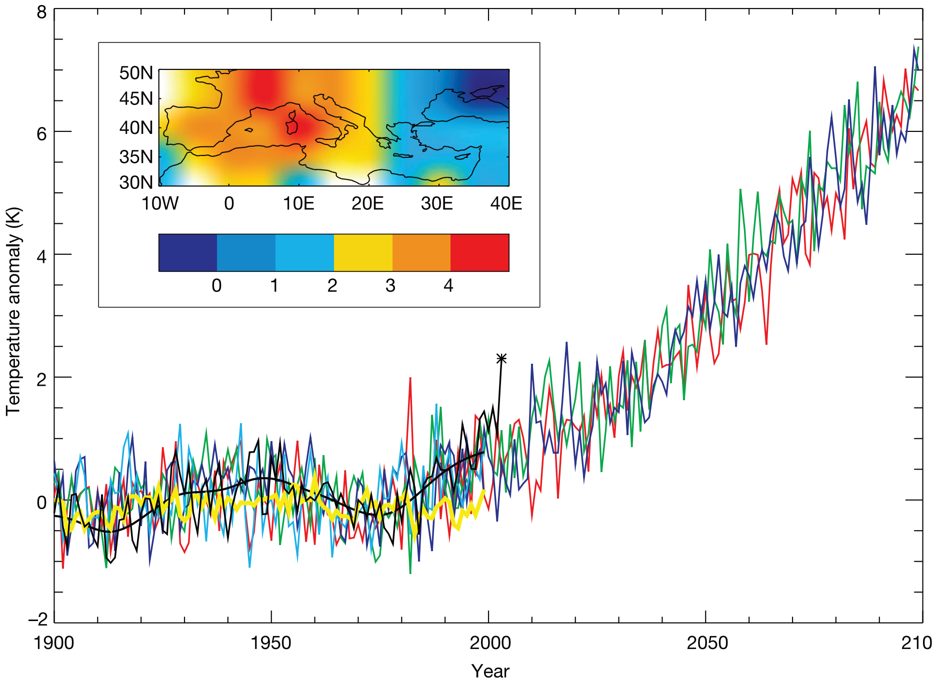

Figure 1 June–August temperature anomalies (relative to 1961–90 mean, in K) over the region shown in inset. Shown are observed temperatures (black line, with low-pass-filtered temperatures as heavy black line), modelled temperatures from four HadCM3 simulations including both anthropogenic and natural forcings to 2000 (red, green, blue and turquoise lines), and estimated HadCM3 response to purely natural natural forcings (yellow line). The observed 2003 temperature is shown as a star. Also shown (red, green and blue lines) are three simulations (initialized in 1989) including changes in greenhouse gas and sulphur emissions according to the SRES A2 scenario to 2100[22]. The inset shows observed summer 2003 temperature anomalies, in K.

a simulation with volcanic forcing, and denoted NAT) shows no warming in the latter part of the century (Fig. 1, yellow line).

A necessary requirement for any detection of significant warming is that HadCM3 adequately represents the natural internal variability of European summer temperatures. A quantitative test, in which an estimate of the forced response calculated from the ALL ensemble mean is subtracted from the observations and the residual compared with HadCM3 simulated internal variability, shows no significant discrepancy in variance on either interdecadal or 2- to 10-year timescales (Fig. 2). If anything, the model appears to be overestimating observed variability in this season and region, making our estimates of attributable risk relatively conservative. We also find no evidence of a secular change in variance on subdecadal timescales in either model or observations: over the twenty-first century, the standard deviation of the forced simulations under the SRES A2 scenario (Fig. 1), when a second-order polynomial trend has been removed, increases by an insignificant 0.01 K from the first 40 years (1990–2030) to the last 40 years (2060–2100). This contrasts with the conclusions of ref. 2, although their results applied to a much smaller region.

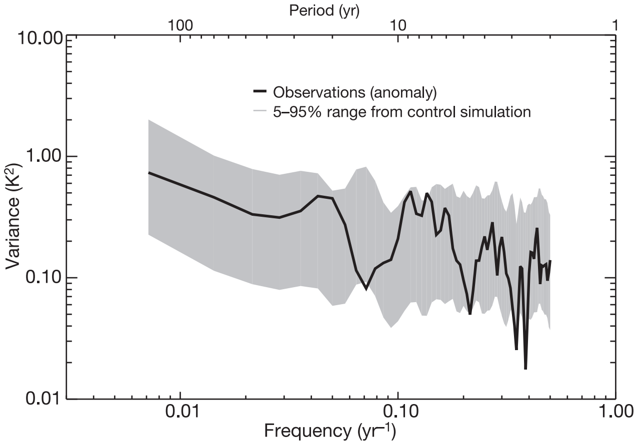

Figure 2 Power spectra of European mean summer temperature. Solid line, observed spectrum after removing an independent estimate of the externally forced response provided by the ensemble mean of the ALL simulations. Shaded region, 5 to 95 percentile region of the estimated range of spectra of natural internal variability estimated from segments taken from the HadCM3 control run of the same length as the observations. Model spectral densities have been inflated by a factor of 1.25 to allow for sampling uncertainty in the ALL ensemble mean.

We now apply a standard optimal detection analysis to European summer temperatures, similar to those applied to global scale patterns of temperature change[11,12,19]. The analysis is a regression between decadal-mean seasonal-mean observations over 1920–99 and simulated temperature changes over the same period from both anthropogenic and natural forcings (ALL) and from natural forcings alone (NAT), and is in most respects identical to that of ref. 13 (see Methods). Figure 3a shows the estimated likelihood functions for the factors by which we could scale up or down the amplitudes of the model-simulated responses to anthropogenic forcing (red curve) and natural forcing (green curve) while remaining consistent with the observations. As the fifth percentile of the scaling factor on the anthropogenic response (red curve in Fig. 3a) is greater than zero, an anthropogenic influence on decadal-mean European summer temperature is detected at the 5% significance level (that is, the hypothesis that there is no positive anthropogenic influence can be rejected at the 5% level). We conclude from this investigation of decadal-mean summer temperatures that it is very likely that past anthropogenic forcing is responsible for a significant fraction of the observed European summer warming.

We now calculate the changed risk of extremely hot summers that can be attributed to past anthropogenic emissions, allowing for uncertainty in the anthropogenic warming. Averaged over the region of interest (Fig. 1 inset), summer temperatures in 2003 exceeded the 1961–90 mean by 2.3 K (Fig. 1, black star). To quantify changes in risk, we need an objective definition of the event in question. Using 2.3 K itself is problematic for three reasons: first, relying too closely on the details of what actually occurred when defining what we are looking for introduces a selection bias in our attribution procedure; second, temperature anomalies in 2003 may have been amplified by soil-moisture feedbacks[2] or interactions with the North Atlantic[20], both of which may be under-estimated, although we do observe similar magnitude spikes in model summer temperatures in Fig. 1; third, given the length of model-simulated variability we have available, inferring the statistics of temperature excursions over 2 K requires extrapolation of extreme value distributions, which introduces further uncertainties. 2003 was the first year to reach or exceed a threshold of 1.6 K (2001 being the second-warmest European summer, at 1.5 K). We therefore consider how the probability of exceeding this threshold has changed, by comparing this estimated late-twentieth-century probability with the estimated probability of exceeding the same absolute threshold if there had been no anthropogenic influence on climate. Increasing this threshold to any value up to 2.3 K strengthens our conclusions regarding attributable risk; hence using a threshold that only just exceeds the second warmest summer is relatively conservative.

Assuming that sub-decadal continental-scale variability is stationary and adequately represented by HadCM3, we estimate possible distributions of temperatures in individual summers in the presence and absence of anthropogenic influence. We do this by adding HadCM3 control variability to reconstructions of 1990s decadal-mean temperatures both with all external factors included, and with anthropogenic factors removed, allowing for uncertainty in these decadal-mean temperatures from the detection analysis (Fig. 3b). Figure 4a shows the estimated likelihood of the risk (probability) of exceeding a 1.6 K threshold in the presence of anthropogenic climate change (red line) and in the absence of anthropogenic change (green line), expressed both as a frequency (number of occurrences per thousand years, bottom axis) and as a return period (top axis). The clear shift from the green to the red distribution implies that an appreciable fraction of the risk of such hot summers can be attributed to human influence on climate. Even in the presence of anthropogenic warming, we conclude that the estimated probability of exceeding 1.6 K appears to be low (best estimate is a 1 in 250 year event (Fig. 4a, red curve) but this risk may be increasing rapidly).

The fraction attributable risk (FAR) is estimated in Fig. 4b (see Methods). In certain circumstances, the figure of relevance in establishing possible liability for compensation has been FAR = 0.5, corresponding to a doubling of risk over natural conditions[21] (meaning that one event in two would have happened naturally). According to our calculation, there is a greater than 90% chance that over half the risk of European summer temperatures exceeding a threshold of 1.6 K is attributable to human influence on climate. Although there is a large spread, reflecting the remaining uncertainties in the effects of climate change on this spatial scale, the anthropogenic FAR could be substantially greater than 0.5. Also marked on Fig. 4b is a vertical line representing an overall 'best estimate' of the human contribution to the increased risk of these very hot European summers[7], given the information that we have available at present. On this basis, human influence is to blame for 75% of the increased risk of such a heatwave.

Our analysis shows that European summers are warming owing to anthropogenic climate change. Under un-mitigated emissions scenarios, summers like 2003 are likely to be experienced more

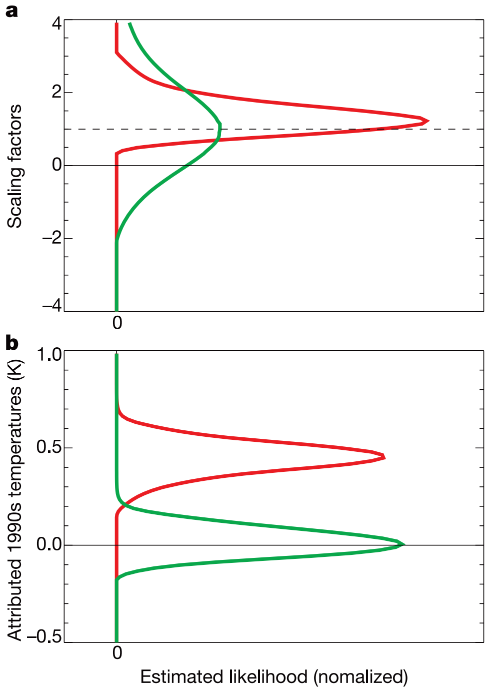

Figure 3 Estimated likelihood functions for anthropogenic and natural contributions to European summer temperature changes. The curves show estimated distributions of anthropogenic (red) and natural (green) scaling factors on model-simulated responses (**a**). 1990s summer temperatures (relative to pre-industrial climate) including all external drivers of climate change (red) and with anthropogenic drivers removed (green) (**b**). A scaling factor of zero (horizontal solid line in **a**) implies no contribution to observed 1990s temperatures from this driver, while unity (horizontal dashed line in **a**) implies no systematic under- or over-estimate by the model of the observed response to this driver. The width of these distributions reflects the uncertainties for these probabilities.

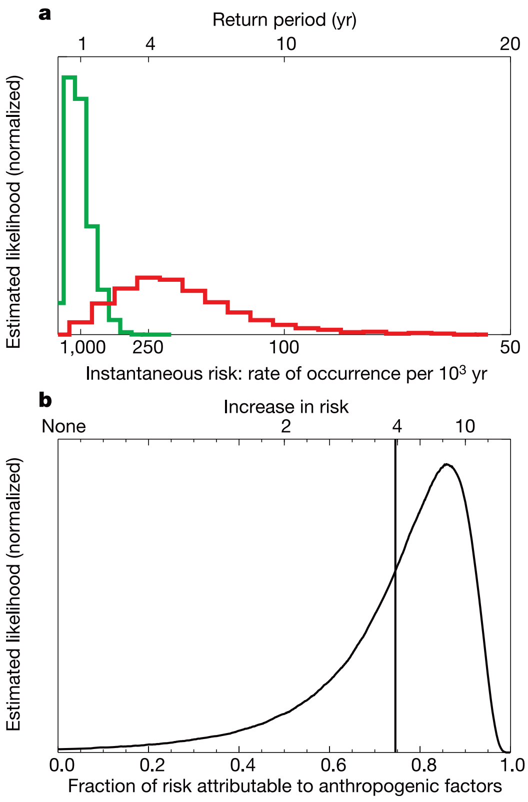

Figure 4 Change in risk of mean European summer temperatures exceeding the 1.6 K threshold. **a**, Histograms of instantaneous return periods under late-twentieth-century conditions in the absence of anthropogenic climate change (green line) and with anthropogenic climate change (red line). **b**, Fraction attributable risk (FAR). Also shown, as the vertical line, is the 'best estimate' FAR, the mean risk attributable to anthropogenic factors averaged over the distribution.

frequently in future; HadCM3 projections (Fig. 1) indicate that the probability of European mean summer temperatures exceeding those of 2003 increases rapidly under the SRES A2 scenario[22], with more than half of years warmer than 2003 by the 2040s. By the end of this century, Fig. 1 shows that 2003 would be classed as an anomalously cold summer relative to the new climate, for the scenario and model under consideration.

We may have underestimated the FAR of a heatwave in 2003 by using 1990s figures for attributable background warming. Conversely, the FAR may have been overestimated by selecting an area that has recently been subject to extreme temperatures, although this effect should be alleviated by our use of an independently specified region. Modelling and forcing uncertainties, and any errors in the variability characteristics of the model, could mean that our assessment of the likelihood of the FAR exceeding 0.5 is in error. Including a different combination of the available natural HadCM3 simulations changes the results quoted by less than 5%, but a systematic exploration of both modelling and forcing uncertainty would require a very large multi-model ensemble, varying model parameters across their range of possible values and exploring the range of potential forcing estimates[23,24].

Anthropogenic warming trends in Europe imply an increased probability of very hot summers. Given the effects of the 2003 heatwave, this suggests a greater risk of associated adverse impacts, although to make a quantitative attribution assessment of any specific social, economic or ecological impact will require detailed modelling of both local meteorological conditions and their relationships with the impact in question. Nevertheless, it seems likely that past human influence has more than doubled the risk of European mean summer temperatures as hot as 2003, and with the likelihood of such events projected to increase 100-fold over the next four decades, it is difficult to avoid the conclusion that potentially dangerous anthropogenic interference in the climate system is already underway. The FAR provides a potential measure for redistributing the associated costs of such extreme events[21]. ☐

Methods

Attribution of decadal-mean seasonal-mean changes

In a natural extension of previous work[12,13,25], observed decadal-mean summer near-surface temperature changes, **y**, over land for 1920–99 are constructed from monthly-mean values extracted from the CRUTEM2(v) data set[10] for the region 10° W-40° E, 30–50° N, requiring data for at least two out of three months (June–August) in at least half the years. They are regressed against the mean response over the observational data-mask of a four-member ensemble of HadCM3 simulations driven with both anthropogenic and natural forcings ($\mathbf{x}_1$, ALL, red, green, blue and turquoise lines in Fig. 1) and a second set of simulations of the response to solar and volcanic forcing alone ($\mathbf{x}_2$, NAT, yellow line in Fig. 1) plus noise:

$$\mathbf{y} = (\mathbf{x}_1 - \nu_1)\beta_1 + (\mathbf{x}_2 - \nu_2)\beta_2 + \nu_0 \qquad (1)$$

where β_1, β_2 are the unknown scaling factors to be estimated in the regression, ν_0 is the noise in the observations, and ν_1 and ν_2 account for sampling uncertainty introduced by estimating model-simulated responses from a finite ensemble[26]. A scaling factor of 1 would imply that the response in the model simulations is identical to the observed changes, while a factor of 0 implies no correspondence between modelled and observed responses. Likelihood functions for scaling factors obtained from the regression account only for sampling variability that arises from natural internal climate variability as represented by HadCM3. They do not account for systematic errors in the shapes of the modelled patterns or uncertainties due to missing forcings (for example, land use changes or fossil-fuel black carbon emissions). If we assume a uniform prior in these scaling factors, these likelihoods can be thought of as probability distributions.

The combined effects of solar and volcanic forcings are estimated from a simulation with volcanic forcing amplified by a factor of 10 and solar forcing amplified by a factor of 5, multiplied by 0.1 and 0.2, respectively, and added. This approach was taken in order to obtain the clearest possible climate signal from a weak forcing and a limited number of climate simulations. Previous work showed that the large-scale temperature responds linearly to increasing these forcings[27]. Including an additional four simulations with unamplified natural forcings in the analysis makes little difference to the results.

We use the HadCM3 control run and intra-ensemble variability to estimate internal variability, ν_0, ν_1 and ν_2, taking into account the enhanced signal-to-noise from averaging over the ALL ensemble and inflating the solar and volcanic forcing[13]. This gives scaling factors for the combined effects of all forcings and for natural forcings, from which the anthropogenic and natural scaling factors can be calculated by linear transformation[27] (Fig. 3a). Where the 5 to 95 percentile uncertainty range does not include zero scaling factor, this indicates that the relevant signal has been detected at the 5% significance level, that is, there is less than 5% chance that the relevant forcing has had no effect. From the scaling factors and their uncertainties, we derive likelihood functions of 1990s temperature anomalies attributable to the combined effects of all forcings and attributable to natural factors alone (Fig. 3b).

Attribution of change in risk of exceeding a threshold

The distribution of attributed anthropogenic decadal-mean warming in the 1990s is used to calculate the FAR for an individual European summer exceeding the 1.6 K threshold as follows. We estimate the probability of exceeding the 1.6 K threshold from the generalized Pareto distribution (GPD) fitted to the HadCM3 control run temperatures[28]. The spectral analysis shown in Fig. 2 indicates that HadCM3 provides an adequate representation of internal variability. We calculate the probability, P_0, of the 1.6 K threshold being exceeded without anthropogenic climate change (shown by the green curve in Fig. 4a, expressed as return period, top axis, and instantaneous risk: rate of occurrence per 10^3 yr, bottom axis) and the probability, P_1, of exceeding the threshold with anthropogenic climate change (red curve in Fig. 4a). In estimating the green curve, the chance of exceeding the 1.6 K threshold is re-estimated using the GPD with the mean summer temperature adjusted to each percentile of the estimated distribution of decadal-mean temperature anomalies attributable to natural forcing and internal variability. For the red curve, the response to anthropogenic forcing is also included. A bootstrap resampling method is used to allow for uncertainty in GPD parameters. From these distributions, we calculate the distribution of attributable increase in risk (P_1/P_0) and the FAR ($(P_1 - P_0)/P_1$)[8], as shown in Fig. 4b, whose spread reflects uncertainty in the magnitude of the forced decadal-mean response and in the estimation of the extreme value distribution parameters due to limited sample size.

Received 21 May; accepted 5 October 2004; doi:10.1038/nature03089.

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Acknowledgements P.A.S. was supported by the Department for Environment, Food and Rural Affairs, D.A.S. by a Wellcome Trust Showcase Award, and M.R.A. received partial support from the NOAA/DoE International Detection and Attribution Group.

Competing interests statement The authors declare that they have no competing financial interests.

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Evidence for cultivar adoption and emerging complexity during the mid-Holocene in the La Plata basin

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Multidisciplinary investigations at the Los Ajos archaeological mound complex in the wetlands of southeastern Uruguay challenge the traditional view that the La Plata basin was inhabited by simple groups of hunters and gatherers for much of the pre-Hispanic era[1–4]. Here we report new archaeological, palaeoecological and botanical data indicating that during an increasingly drier mid-Holocene, at around 4,190 radiocarbon (^{14}C) years before present (BP), Los Ajos became a permanent circular plaza village, and its inhabitants adopted the earliest cultivars known in southern South America. The architectural plan of Los Ajos during the following Ceramic Mound Period (around 3,000–500 ^{14}C yr BP) is similar to, but earlier than, settlement patterns demonstrated in Amazonia[5–10], revealing a new and independent architectural tradition for South America.

Research on the emergence of complex societies in South America has mainly concentrated on Andean coastal and highland valleys[11–14], and more recently in the lowland forest and riverine regions of Amazonia[5–10]. The La Plata basin (Fig. 1a) is a large and little explored river system that is beginning to reveal an early and long sequence of unique and complex cultural trajectories. The natural environment of the study area is dominated by subtropical grasslands interspersed with vast extensions of wetlands. In strategic locations circumscribed to wetland floodplains, archaeological mound complexes are large and numerous. They have mounded architecture geometrically arranged in circular, elliptical and horseshoe formats that surround a central communal space (Fig. 1b).

The first excavations at the multi-mound site called Los Ajos, by Bracco[15], in the early 1990s consisted of a block excavation in Mound Alfa, a test unit in Mound Beta and a few opportunistic test units in off-mound areas. This work established the mid-Holocene age of the earthen mounds in the area. The Preceramic Mound Period (PMP) component at Los Ajos yielded five dates between 3,950 and 3,350 ^{14}C yr BP (4,580 and 3,380 calibrated (cal.) yr BP)[16]. Closely comparable dates from the deeper PMP components of the Puntas de San Luis, Isla Larga and Potrerillo sites collectively ascertained the antiquity of the PMP[17–19] (Table 1).

Our new excavation programme consisted of the placement of a block excavation in Mound Gamma, a test unit in Mound Delta, two trench transects articulating mound and off-mound areas and a 50-m systematic interval transect sampling strategy of test units to target off-mound areas (Fig. 2) totalling an excavated area of 305 m^2 (ref. 20). Our work revealed that Los Ajos is one of the largest and most formally laid out sites in the study area and covers about 12 ha (Fig. 2a). Its Inner Precinct includes six flat-topped, quadrangular platform mounds (called 6, Alfa, Delta, Gamma, 4 and 7) closely arranged in a horseshoe formation and with a height above ground level of 1.75 to 2.5 m (Fig. 2a, b). Two dome-shaped mounds (called Beta and 8) frame the central, oval plaza with a size of 75 × 50 m (Supplementary Fig. 1a). The formal and compact Inner Precinct contrasts with more dispersed and informally arranged peripheral sectors, which include two crescent-shaped rises (named TBN (Supplementary Fig. 1b) and TBS), five circular and three elongated lower dome-shaped mounds, borrow pits and a vast off-mound area bearing subsurface occupational refuse.

A series of major social and economic changes took place at Los Ajos during the PMP. The broad contemporaneity of radiocarbon dates (Table 1), artefact content and similarities in Preceramic Mound Component (PMC) stratigraphy among mounds Alfa, Delta and Gamma suggest that the Los Ajos inhabitants began to live in a circular household-based community, partitioning the site into a number of discrete functional areas characterized by the placement of residential units around a central plaza area. Charcoal from the basal level of Mound Gamma, 270–275 cm deep (arbitrary depth), dates the beginning of the PMC at 4,190 ± 40 ^{14}C yr BP (4,840–4,580 cal. yr BP). Another radiocarbon assay at 205–210 cm deep yielded a date of around 3,460 ^{14}C yr BP (3,980–3,470 cal. yr BP). The upper portion of the PMC in Mound Delta yielded a date of around 2,960 ± 120 ^{14}C yr BP. Taken together, the eight dates from Los Ajos place the PMC occupation between 4,190 ± 40 and 2,960 ± 40 ^{14}C yr BP. The two oldest dates from the basal levels of the PMC at Mound Gamma and Alfa suggest that mound-building began between around 4,190 and 3,950 ^{14}C yr BP (4,840–4,160 cal. yr BP). Mounds grew as a result of multiple overlapping of domestic occupations where a wide range of activities associated with food preparation, consumption, stone tool production and maintenance took place. The PMC Layer 4 is characterized by a ~85-cm-thick compact, very dark brown silty loam organic sediment (Fig. 3) consisting of relatively undifferentiated deposits composed of lithic debitage and tools, small fragments of charred bone, ash and soot lenses, and small pieces of burned clay.

Our associated palaeoecological data[20] indicate that, similar to other regions in the Americas[21], the mid-Holocene (between 6,620 ± 40 ^{14}C yr BP (7,580–7,440 cal. yr BP) and 4,020 ± 40 ^{14}C yr BP (4,570–4,410 cal. yr BP)) was a period of significant environmental flux marked by increasing aridity. At around 4,020 ^{14}C yr BP (4,570–4,410 cal. yr BP) a maximum drying episode occurred, as evidenced by a massive spike of Amaranthaceae/Chenopodiaceae coupled with a sharp drop in wetland species (Supplementary Fig. 2). These changes probably caused a decrease in the surface water recharge to the inland wetlands and waterways. Although reduced in extent, wetlands probably became attractive places for pre-Hispanic populations by providing abundant, now more highly circumscribed plant and animal resources and a stable source of water. The mid-Holocene drying trend may thus have acted as an important catalyst for the reorientation of settlements towards the topographically higher freshwater wetlands, where permanent communities were established.

Despite the application of an intensive flotation program, seeds, roots and nuts were not recovered; however, phytoliths and starch grains were abundant (Methods are available as Supplementary Information). Phytoliths diagnostic of maize cobs[22] (Fig. 4c) record their earliest appearance in the level from 255–260 cm deep, 15 cm

CORRIGENDUM

doi:doi:10.1038/nature04100

Magnetic carbon

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Nature 413, 716–718 (2001)

In this Letter, there was a mistake in the presentation of the synthesis conditions of the reported samples. The actual range of the temperatures of synthesis for the four rhombohedral samples was 975–1,025 K. One of the five reported samples was wrongly characterized in relation to the polymerization type: the sample was actually prepared at 2.5 GPa (synthesis temperature, 1,125 K), representing a mixture of the rhombohedral and tetragonal phases with some hard carbon. The error in characterization of this sample weakens our attribution of the ferromagnetism to defects in the rhombohedral phase (Rh-C_{60}) but does not influence our main conclusion concerning the observation of magnetism in a carbon solid based on polymerized fullerenes, although its origin and the actual magnitude remain an open question. Also, we were unaware of earlier work on magnetism in polymerized fullerenes[1], that should have been cited.

T.L.M. takes full responsibility for the misidentification of the sample preparation conditions. We thank A. V. Talyzin for alerting us to this mistake.

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CORRIGENDUM

doi:10.1038/nature04099

Human contribution to the European heatwave of 2003

P. A. Stott, D. A. Stone & M. R. Allen

Nature 432, 610–614 (2004)

The description of the method used for the calculation of the fraction attributable risk (FAR) shown in Fig. 4b is incorrect. The corresponding sentence in the Methods section should read "For the red curve, the response to anthropogenic forcing is also included, and a normal distribution is used to estimate the chance of exceeding the 1.6 K threshold."

ERRATUM

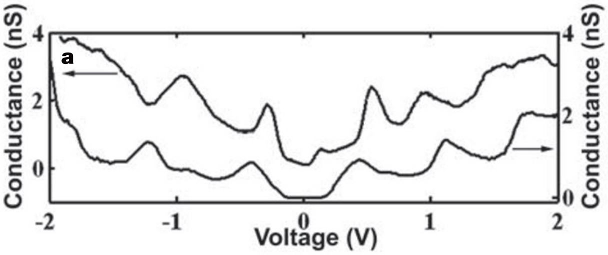
doi:10.1038/nature04102

Measurement of the conductance of single conjugated molecules

Tali Dadosh, Yoav Gordin, Roman Krahne, Ilya Khivrich, Diana Mahalu, Veronica Frydman, Joseph Sperling, Amir Yacoby & Israel Bar-Joseph

Nature 436, 677–680 (2005)

In Fig. 4a of this Letter, in which the spectra of two BPD dimmers are compared, the scaling on the two y axes should have been shifted relative to one another in order to illustrate the point made in the text. The corrected Fig. 4a is shown here.



Mankin Exhibit B-2 — Stephen H. Schneider & Robert S. Chen (1980)

Ann. Rev. Energy. 1980. 5:107-40

CARBON DIOXIDE WARMING AND COASTLINE FLOODING: Physical Factors and Climatic Impact

◆11078

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INTRODUCTION

Carbon dioxide concentration is known to be increasing in the atmosphere, and some calculations project about a 20% increase over present levels by 2000 AD and a doubling by the middle of the next century (1–9). CO_2 increases are associated with increasing use of fossil fuels (10, 11) and possibly also from a net decrease in the pools of biospheric carbon, primarily from deforestation of tropical woodlands (12–16). If such increases in CO_2 do materialize, as is widely believed (6, 17), then theoretical equilibrium calculations with climatic models suggest some 1°C global warming near 2000 AD and a few degrees centigrade global warming by the middle of the twenty-first century (18–22). Both theoretical and observational arguments have been given which suggest that such global warming estimates could be substantially amplified (perhaps by a factor as large as 5) in polar regions (18, 21). Thus a warming of about 5°C is quite possible in polar regions over several decades if present estimates of CO_2 increases and climatic equilibrium responses prove correct. However, recently the neglect of transient effects has been noted (23). These imply that the climatic response to CO_2 increases could be delayed up to several decades relative to the equilibrium calculations. Also, the nature of the climate changes during the transient period could be of significantly different character than the equilibrium responses.

It is against this background that some glaciologists have expressed grave concern that a CO_2-induced polar warming could lead to the disintegration of the West-Antarctic floating ice shelf, which could trigger a deglaciation

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[2] Sponsored by the National Science Foundation.

0362-1626/80/1010-0107$01.00

or "surge" of the land ice in that region and result in a sea level rise averaging some 5 m globally. (24–27). This rise could be distributed a few meters more or less in some areas (28). Depending on the nature of the physical processes governing such a deglaciation, the hypothesized sea level rise could take place over time scales as rapid as a few decades or as slow as a few centuries.

Considerable scientific uncertainty surrounds estimates of all three of these physical links in the argument: CO_2 concentration increases, resultant climatic effects, and the likelihood, timing, and magnitude of a CO_2-induced, West Antarctic deglaciation. It is not our purpose to assess in more than summary detail the evidence for each of these links, since this has been done extensively elsewhere (1–30). Nor do we wish to suggest that other processes, natural or anthropogenic, may not enhance or oppose the projected CO_2-induced warming trend (9). Finally, we do not suggest that a deglaciation is necessarily the most likely or even the most deleterious possible impact on society of a possible CO_2-induced warming. Changes in agricultural productivity, water supply, and energy demand are examples of other possible impacts which, although difficult to quantify, may well be the most likely and significant consequences of climatic changes (31–35). But we do believe that (*a*) plausible physical arguments can be given to support the possibility of a deglaciation from CO_2-induced warming and (*b*) it could well take decades of research to narrow considerably the wide range of uncertainties inherent in present estimates of the magnitude and timing of these three potential physical changes—approximately the time frame in which the climate system will "perform the experiment" of proving many of these present estimates too high or too low.

Before one can seriously consider actions to mitigate the potential risks of CO_2-induced climatic changes, some comparison will be necessary between the distribution of potential costs of CO_2 abatement policies and the distribution of potential costs for society of such climatic changes. In most cases, the latter are quite difficult to assess, especially in light of the extreme uncertainty in predictions of the regional distribution of changes in climatic parameters (9, 19). However, in the case of a West Antarctic deglaciation, order of magnitude estimates of the demographic and economic consequences of a 5 m rise in global mean sea level are possible. Such estimates have been derived by the authors (manuscript in preparation) for several coastal regions of the United States. These provide a preliminary look at the magnitude of the costs that may be associated with climatic changes and are thus an early step toward a more complete global climatic impact assessment of CO_2 buildup. A complete assessment would, of course, need to go well beyond the issue of a possible sea level rise.

To trace the process of making an integrated climatic impact assessment, it is useful to list five points, each a subcomponent of such an assessment:

1. climatic prediction (or scenario);
2. the physical effect of the climatic scenario on some environmental factor of interest (e.g. crop yield or sea level);
3. the social, economic, and political impacts of physical effects of the climatic scenario;
4. the *interactions* among these; and
5. an analysis to assess the influence of a variety of policy options on the relative distribution of impacts; that is, how policy options can alter the impact of the climatic scenario on various political or economic sectors of society.

Although our ability to carry out this type of assessment is currently quite limited (36), it is nevertheless useful to trace the sea level rise example through each subcomponent in order to identify strengths, weaknesses, and gaps in our knowledge. We begin by reviewing briefly the basic elements of the climatic prediction, including some discussion of the many uncertainties and a list of references. [A very thorough review is provided by Marland & Rotty (29).] We then examine points *2* and *3* by presenting the results of our preliminary analysis of the potential geographic extent of inundation and the associated economic losses of real property and income. We skim over some speculations on social or political impacts and their interactions, since these have been treated elsewhere. Finally, we present a short discussion of alternative policy responses. Our chief purpose is to encourage (by concrete, quantitative example) vastly expanded efforts at integrated climatic impact assessments so that policy options can be viewed more rationally than is possible at today's levels of knowledge.

PHYSICAL FACTORS: A BRIEF REVIEW

CO_2 Concentration Projections

Hypothesized changes in atmospheric CO_2 concentration and its effect on climate have been suggested since at least the late nineteenth century (37). The principal evidence for an increasing trend of CO_2 in the air comes from the continuous Mauna Loa record of the past two decades (38–40). It shows a secular increase of CO_2 from 1958 to the present of some 20 parts per million (ppm) by volume above the 315 ppm value in 1958. Superimposed on this trend are an annual oscillation of about 5 ppm and an interannual variation of some 1 ppm. The annual oscillation in this record is widely believed to be primarily a result of the expansion and contraction of the seasonal biosphere in the northern hemisphere, with a decrease of atmospheric CO_2 from photosynthesis increase in the warm season succeeded by an increase in the concentration of CO_2 in the cold season, when respiration and decay rates exceed photosynthesis rates. The interannual variation in CO_2 increase is small compared either with the amplitude of the seasonal oscillation or the secular trend over a few years or more. It has been hypothesized that the former coincide with ocean surface temperature anomalies associated with the climatic phenomena known as the Southern Oscillation (8, 41, 42).

Several other CO_2 records taken in both hemispheres confirm the secular trend in the Mauna Loa record, although the annual and interannual fluctuations differ with latitude and hemisphere (43–46). Thus, while some quantitative doubt as to the local magnitude of both annual and interannual fluctuations remains, there is little controversy over the existence of a secular trend showing an increase in CO_2 of almost 7% in the two decades since the late 1950s.

Until recently, it has been generally believed that the secular trend in CO_2 concentration reflects the anthropogenic effect of burning fossil fuels (47). Roughly one half of the CO_2 produced by the combustion of fossil fuels over the past two decades can account for the observed secular trend. The remaining 50% was assumed to have been absorbed largely by the oceans, and possibly in the biosphere [since an increase in atmospheric CO_2 would cause an increase of photosynthetic CO_2 uptake in some plants not limited by other nutrient deficiencies (6, 48)]. This leads to the conclusion that the "airborne fraction" of inputed CO_2 is 50%. Recently, however, a number of investigators have argued that biospheric reservoirs of carbon (in both the standing crop forests and soil humus) have been *decreasing* through deforestation of tropical woodlands and agriculture (13–15). One large estimate from Woodwell et al (13) would put the rate of biospheric CO_2 injection as comparable to that of fossil fuel combustion. If that estimate is correct, then the sinks for CO_2 would need to be twice as active as previously assumed to account for the observed secular trend, and the airborne fraction for injected CO_2 would be half as large, only 25%. The airborne fraction is important because it is needed to project future CO_2 concentrations, whether inputs are from fossil fuel or biospheric origins.

Since the isotopic composition of CO_2 is fractionated differently among the fossil, biospheric, and atmospheric reservoirs, some attempts have been made to trace the recent secular increase in CO_2 to its respective source by isotopic decomposition (14). Although this approach is promising, it is still quantitatively uncertain because of the large sampling errors inherent, for example, in the ^{13}C record in tree rings. Very recently there have been suggestions that charcoal is a principal sink for biospheric carbon in areas where deforestation is accomplished by burning (12). These, or similar, suggestions are likely to be welcomed by chemical oceanographers who cannot explain uptake of CO_2 by the oceans in amounts much larger than

50% of the fossil fuel injection (6, 49). However, it has also been suggested that the role of the ocean as a CO_2 sink may have been underestimated (19).

Although resolution to the debate over past sources and sinks of CO_2 does bear significantly on the quantitative estimation of the airborne fraction, and hence projections of future CO_2 concentrations, it is very likely that sufficient fossil fuels (primarily coal) remain unused, so that a several-fold increase in CO_2 in the atmosphere over the next century or so would occur should the decisions to burn them be made (50, 51). It is upon this foundation of debate and uncertainty over the biogeochemistry of the carbon cycle that we forge the next physical link in our argument: the potential climatic response to an increase in CO_2.

Estimating Climatic Effects of CO_2 Increase

CO_2 is one of the principal absorbers of terrestrial infrared radiation (IR), leading to the well-known (and somewhat misnamed) term "greenhouse effect." Calculations made with climatic models based on a doubling of CO_2 have been critically reviewed (19, 21). These models suggest, for a CO_2 doubling, a global surface temperature increase, ΔT_S, of roughly 1.5–4.5°C, with an amplification of up to a factor of five in the surface temperature increase in polar regions (21, 52). The radiative calculations are generally based on absorption of IR in the 15 μ band of CO_2, and the different ΔT_S estimates of different models is thus primarily a result of different assumptions of how the climatic system reacts to a global radiative energy perturbation like a CO_2 doubling. Recently, Augustsson & Ramanathan (20) have demonstrated that CO_2 absorption of IR by "hot bands," in addition to the classical 15 μ band, can be significant in the calculation of IR changes for large increases in CO_2. Nevertheless, the principal controversy in estimating the global surface temperature increase from the CO_2 trend projections (up to a doubling or two) comes not from the radiative calculations, but rather from the assumptions used in climatic models about the relative importance of various interactive physical processes or climatic feedback mechanisms. These processes could either amplify or damp by several times the calculation of a global surface temperature response to a given CO_2 increase relative to that of a calculation that otherwise excluded such processes (or treated them partially or incorrectly). It is not clear whether the sum of all climatic feedback mechanisms would act to increase or decrease present estimates of ΔT_S, as has been discussed in detail elsewhere (10, 19, 21, 53, 54).

But, despite their uncertainties, climatic models are the only available tools to estimate the relative magnitude of the effect of an unprecedented[3]

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[3] It is unprecedented only in the sense that we have no reliable measurements of historic CO_2 concentrations from which to scale future climatic changes.

perturbation, like a CO_2 increase, to the global energy budget. Thus, when the computed estimates of T_S from CO_2 projections become as large as the inherent fluctuations in historical temperature records, they attract considerable controversy. If a global surface temperature change of about 1°C can be taken as a rough measure of the range of natural interannual variation in T_S over the past few centuries, then some time around 2000 AD an equilibrium temperature change (ΔT_S) of about 1°C (several times larger at the poles) is typically projected by present generation climate models, assuming about a 20% increase in CO_2 by 2000 AD.

Finally, we must recognize that a "global surface temperature" increase is not the only dimension of a climatic change. Not only could regional responses in T_S to a CO_2 increase be different in magnitude from the global value, but they could even be different in sign. Furthermore, precipitation changes would probably result from any atmospheric circulation adjustments that might accompany a change in large-scale thermal forcing (i.e. ΔT_S or the spatial distribution of ΔT_S arising from CO_2 increase). Again, such changes could be large in some regions and negligible in others. The general circulation model experiments of Manabe & Wetherald (18) exhibit such regionally asymmetric responses. Also, Kellogg has shown that the regional distribution in precipitation about 8,000 years ago (when the earth was about 2 K warmer than today—but not necessarily from anthropogenic CO_2 increase) was different from today's (55). This again suggests that a global average is merely one possible measure of when human influences grow to be comparable to natural variations on a global scale. Although regional changes can be anticipated when global estimates become large (greater than about 1°C), a specific regional forecast cannot be very reliably estimated with state-of-the-art climatic models.

This problem is complicated further by the fact that most estimates of CO_2 effects have been made with equilibrium assumptions. That is, the response of, say, the global average or zonal average temperature distribution, is made to a given (usually a doubling) fixed increase in CO_2 concentrations. Thompson & Schneider (23) showed that mixing of upper layer waters with deeper oceanic reservoirs can vastly increase the effective heat capacity of the climatic system on longer time scales, resulting in delays of up to several decades before the actual climatic response would approach that made with equilibrium assumptions. More recently, these authors showed (56) that because of the latitudinal variations in oceanic heat reservoirs (and other factors), the response of different regions of the globe to a CO_2 perturbation could proceed at different rates toward its equilibrium value at different places. Thus, the character of transient response (for example, local or regional climatic changes) could be very different from the ultimate equilibrium response to a fixed CO_2 increase. In fact, the actual increase of CO_2 in the atmosphere is more closely approximated by an exponential function than by a step function; the latter is generally used in CO_2 equilibrium calculations.

Although a variety of physical, economic, social, and political impacts are plausible (in crop yields or water supplies, for example), should there be a change in accustomed climatic conditions with an increase in CO_2 (31–36), we review quantitatively here the impact assessment of only one such possibility: a rise in global mean sea level of some 5 m.

Glacial Volume Change

The plausibility of a significant and rapid rise in mean sea level (should the surface temperature at the poles increase) is based on the possibility that a huge mass of glacial ice, the West-Antarctic Ice Sheet (WIS), could collapse into the surrounding ocean. We discuss this possibility in some detail, highlighting as much as possible the assumptions and points of contention; however, we do not attempt to judge the probability of such an event, a task better left to experienced glaciologists, who presently disagree materially among themselves (57).

Before we proceed, a few definitions are necessary.

> An ice sheet is a continent-sized mass of ice and snow . . . consisting of terrestrial portions grounded on continental shields that are above sea level when unglaciated, marine portions grounded on continental shelves that are below sea level when unglaciated, and floating portions called ice shelves. . . . Ice shelves form from thickening sea ice and from the coalescence of ice streams, which are fast-flowing currents of ice in marine ice caps or the marine portion of an ice sheet. Outlet glaciers are ice streams that flow in fjords through coastal mountains (58).

The junction between grounded marine ice, ice shelves, and sea water is termed the "grounding line." The particular ice sheet in question has four major drainage areas, two of which are ice shelves and two of which contain outlet glaciers.

The possible instability of the WIS has been discussed by several authors, primarily because of its role in one theory of climatic change (24–27, 59–64). The principal contention is that the ice sheet is now unstable, as evidenced by a concave surface profile, decreasing glacial extent (i.e. a retreating grounding line), extensive basal melting, and the overall thinning of the interior ice (27, 58, 64). These conditions could lead to a "surge" of the ice streams, in which the glacial ice advances at a relatively high velocity [perhaps 110 m per day or more according to Hollin (60)]. Such a surge, augmented by powerful calving processes, could then result in the rapid disintegration of the interior of the ice sheet (58).

However, Budd & McInnes (65) disagree that the ice sheet is in danger of imminent disintegration. They state that "the present (surface) profile is one typical of the post-surge slow build-up phase," citing evidence that the interior may be increasing in mass (thickening) rather than decreasing (thinning) (65, 66). In addition, although the major ice shelves could surge, the calculated rates of ice outflow may be too low for any rapid advances. This controversy has yet to be resolved.

Surges in the ice streams may now be prevented by the ice shelves which slow up the outflow of ice (67) and which may establish a relatively stable equilibrium at the grounding line, depending largely on the bottom slope and depth (68). Outlet glaciers may be further restrained by high sills in the underlying bedrock (58). According to Mercer (24), the protective ice shelves are quite sensitive to warming at their upper surface, since the resulting meltwater can help disrupt the cold internal ice and accelerate melting at their base. Moreover, Hughes (58) suggests that the "shelves exist in metastable equilibrium; their calving margins are stable for small temperature perturbations but become unstable when a critical temperature perturbation is exceeded."

Air temperatures during the warmest month (January) at the northern edges of the Ross and Filchner shelves average some –4° to –5°C (69). Therefore, a temperature rise greater than about 5°C could initiate the rapid destruction of these ice shelves and lead to a catastrophic surge of the ice sheet. The small ice shelves of the Pine Island and Thwaites outlet glaciers may be even more susceptible and could perhaps already be collapsing (25). Thus a rise in global mean surface air temperature of a degree or two, magnified several times near the poles, could cause the removal of the ice shelves and the subsequent disintegration of much of the WIS. However, the surface temperature over polar waters is a complicated result of many factors, not just the radiative balance. The salinity of the surface waters is a major factor in determining the stability of the upper oceanic layers. Heat transport from lower layers in the ocean toward the surface depends on this stability. How the stability and thus the heat transport would be affected by CO_2-induced warming or possible associated precipitation changes is still difficult to establish.

Some evidence suggests that the ice shelves may already be receding, perhaps in conjunction with a detectable Antarctic warming trend [Mercer (70) reviews the observations]. For example, analysis of LANDSAT satellite photographs tentatively indicates that the fronts of several small ice shelves underwent major recessions from 1972 to 1975 (71). Although some measurements show that the grounding line at the Ross Ice Shelf may be advancing, Thomas (72) feels that this may not be inconsistent with a general retreat. Such a retreat may also explain part of the observed eustatic sea level rise of slightly over a millimeter annually (73).

The extent of a WIS disintegration is of particular interest. Budd & McInnes (65) imply that the drainage basins would surge independently from each other in the absence of a common initiation, as indicated by bedrock elevations and ice flowlines for Antarctica (74). Thus, the entire WIS might not collapse all at once if each drainage basin were to respond differently to its local temperature change. Furthermore, should one portion collapse, the resulting isostatic uplift (the response of the underlying bedrock to the substantial decrease in weight) might affect the collapse in another portion. It does seem likely, nevertheless, that if a surge were to begin, most of the WIS ice now above sea level would enter the ocean (75). Additional ice might also flow out through outlet glaciers across the mountains from East Antarctica (64).

Only general limits can be placed on the likely timing of a WIS disintegration. Hollin (61, 62) discusses a catastrophic collapse that might occur in a week and examines the possibility of sedimentary evidence of waves or tsunamis which might accompany such a rapid event. The Laurentide Ice Sheet is thought by some to have undergone a collapse of its Hudson Bay ice dome by calving processes in 200 years or less (76–78), based on relative dates derived from carbon-14 analysis. Thomas et al (25) have recently derived estimates for the retreat times of grounding lines of ice streams in the Ross Ice Shelf region, obtaining values of 50–200 years which depend critically on the bottom topography and the presence of ice rises. They also suggest that the destruction of the ice shelves might not begin for several centuries due to an assumed slow thermal response of the ocean; however, this seems inconsistent with estimates of the sensitivity of sea surface temperatures to the CO_2-perturbed radiation balance and the recently reported active circulation and melting beneath the Ross Ice Shelf (79–81). In any case, the Pine Island and Thwaites outlet glaciers may already be collapsing, a process that could take as little as 40 yr (25). In summary, although many uncertainties remain, a WIS disintegration could begin within a few years of an Antarctic warming and could take between a few decades and a few centuries to proceed significantly toward completion.

Sea Level Variations

The rise in global mean sea level due to the deglaciation of the West Antarctic Ice Sheet (WIS) would result directly from the redistribution of ice now above sea level, approximately half of the total WIS volume. A 4–5 m overall rise could be expected. Uncertainty exists in the amount of ice above sea level, the extent of WIS disintegration, and the potential contribution of ice from the East Antarctic or Greenland ice sheets. This global mean rise may be unevenly distributed due to the redistribution of mass [isostatic uplift in Antarctica, isostatic depression in the tropics and northern hemisphere, and a reduction in the gravitational attraction of WIS on the surrounding ocean (28)]. In other words, local values of the rise in mean sea level may be substantially different (tens of percent) from the global average change in mean sea level; and the local patterns could change as the disintegration progressed.

Several researchers have reviewed evidence of a global mean sea level about 6 m higher than the present level during a warm interglacial period some 120,000 years ago (61, 62, 70, 82–83). Of particular interest are the apparently higher values of sea level in the northern hemisphere, consistent at first glance with the suggestion of Clark & Lingle (28) that sea level changes may be unevenly distributed geographically. For example, Florida, North and South Carolina, Virginia, Washington DC, and northwest Alaska all have evidence of sea levels some 5–20 m higher than the present (62, 70). Evidence also exists that such a past higher sea level was most likely the result of a WIS deglaciation rather than a Greenland one and of greater ocean volumes than at present rather than tectonic or other factors (24).

IMPACT ASSESSMENT OF A CO_2-INDUCED SEA LEVEL RISE

Geographic Changes from a Sea Level Rise

The geographic changes due to a sea level rise of approximately 5 m have been analyzed for the United States using US Geological Survey topographic maps, usually the 7½-min series (scale 1:24000). The 15- and 25-foot (4.6–7.6 m) contours for land elevation above mean sea level were used to derive approximate areas flooded within individual counties. These estimates may be somewhat conservative since the effects of tides, storm surges, coastal erosion, and land subsidence have been ignored. However, they provide simple yet reasonably accurate (to within a few percent) values for flooded areas.

Dramatic changes in coastal geography would result from a sea level rise of 4.6–7.6 m. As can be seen from Figure 1, as much as one fourth of Florida may be submerged by a 4.6 m local rise and one third by a 7.6 m rise, including all but four of its cities of over 25,000 people (in 1970) in the latter case. Louisiana would be subject to inundation of comparable magnitude. New Orleans is of particular note since much of the city is already several feet below below sea level, protected only by extensive levees. Large portions of the Texas coast, including the cities of Galveston, Corpus Christi, Beaumont, and Port Arthur, already very susceptible to hurricane flooding because of the flat terrain, would be inundated permanently. In the mid-Atlantic region, a 25-ft rise would submerge Savannah, Georgia; Charleston, South Carolina; four out of the eight Virginia cities with populations over 100,000 (in 1970); one fourth of Delaware; and portions of Washington DC, including much of the Smithsonian Institution. One could launch a boat from the west steps of the United States Capitol, should such a flooding occur, and row to the White House South Lawn (Figure 2). Along the north Atlantic Coast, although only small land areas are involved compared with the previous regions, well-developed coastal lowlands in several major cities such as New York, Atlantic City, and Boston, (including most of the Massachusetts Institute of Technology and Harvard University) would be inundated by a 15- to 25-ft rise in local mean sea level. Along the West Coast, with the exception of the Sacramento River flood plain (and the state capitol), only relatively minor losses would be expected. All in all, for the continental United States, about 1.5% and 2.1% of the total land area would be covered for each respective level of rise (Table 1).

Demographic and Economic Impacts

The geographic analysis of the previous section can be combined with demographic and property value data from United States censuses (84, 85) to yield quantitative estimates of the impacts of the hypothesized sea level rise. By assuming that population, income, and wealth are distributed evenly within a county, initial estimates of the numbers of people displaced and the immobile wealth destroyed can be obtained. Table 1 summarizes the results for the continental United States. For a 15-ft rise, over 11 million people (about 6% of the 1970 continental United States population) plus some 110 billion 1971 dollars in non-removable, taxable property value (about 6% of the total) are affected; for the 25-ft case, these values increase to about 16 million people (8%) and 150 billion 1971 dollars (8%). Since an estimated one third of the United States property is not taxed (86), these figures can be increased by 50%, yielding 160 and 220 billion 1971 dollars for the 15- and 25-ft cases, respectively (or about 4% and 6% of the 1971 Net National Wealth). On a regional scale, the impacts are yet more severe: some 40% of Florida's population and about half of both its income and immobile wealth (44% of its total 1971 locally taxable wealth of about 75 billion dollars) are affected in the 15-ft case and an additional 10–15% of each in the 25-ft case. (In 1980 dollars these estimates are probably several times too low.)

It is important to note that these values are only first-order estimates based on census data that are frequently limited and somewhat uncertain because of averaged adjustment factors. Moreover, we have not made any attempt to estimate secondary economic effects, which may at the least equal direct losses (87), nor actual replacement costs after a major economic perturbation of this kind. We have ignored potential environmental consequences for wetlands, inland ecosystems, and even low-lying nuclear

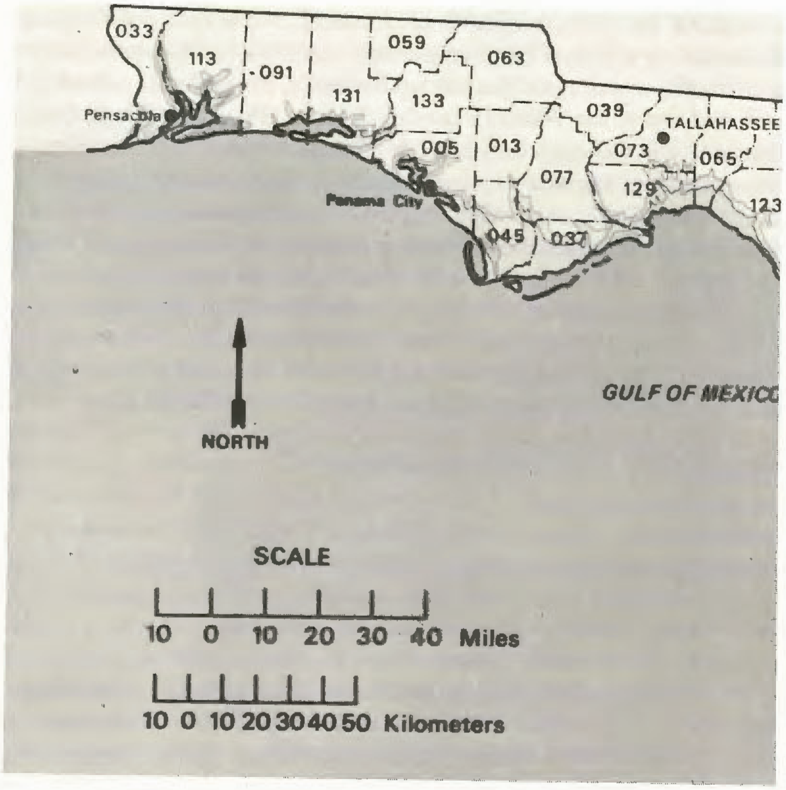

Figure 1. Approximate areas flooded by a 15–25 foot (4.6–7.6 meter) rise in mean sea level: Florida. The darkest shading is sea level (ocean or lake). The next lighter shade is 0-15 ft., and the next lighter 15-25 ft. above sea level.


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Titusville
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Tampa
Lakeland
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Melbourne
Clearwater
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Fort Pierce
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West Palm Beach
Fort Myers
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Boca Raton
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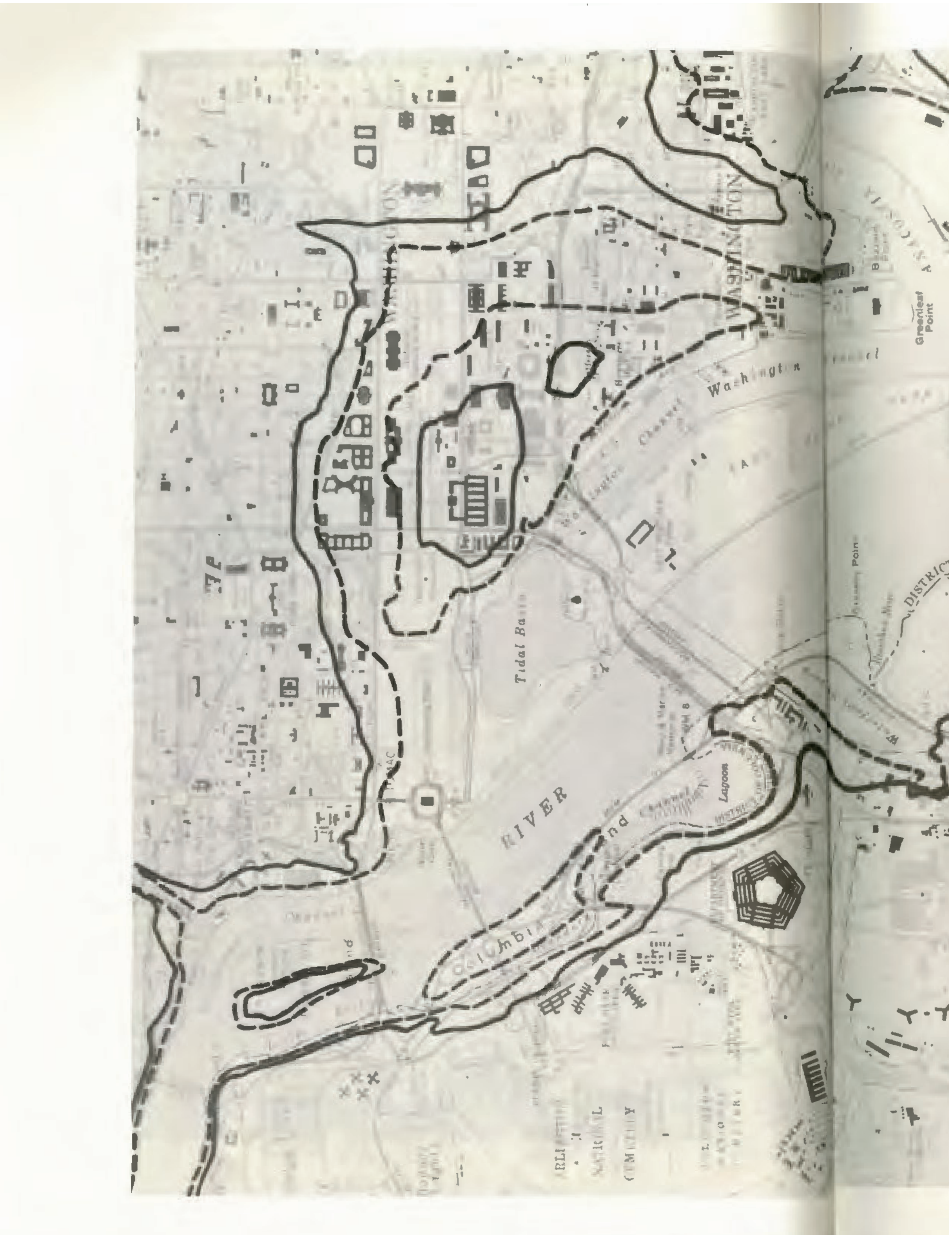
WASHINGTON
Tidal Basin
RIVER
Washington Channel
Lagoon
Greenleaf Point
ARLINGTON NATIONAL CEMETERY
DISTRICT

Figure 2. Approximate areas flooded by a 15–25 foot (4.6–7.6 meter) rise in mean sea level: Washington DC.

Table 1 Summary of estimated geographic, demographic, and economic impacts of 15- and 25-ft (4.6- and 7.6- m) rises in sea level for the
tinental United States[a]

	15-ft case					25-ft case				
Region/state	Percentage flooded	Population (millions)	Approx. percentage of state	EMV [b] (bill. $)	Approx. percentage of state	Percentage flooded	Population (millions)	Approx. percentage of state	EMV [b] (bill. $)	App perce of s
Florida	24.1	2.9	43	33.4	52	35.5	3.8	55	41.7	6
Gulf Coast	4.7	2.7	—	21.3	—	5.8	3.3	—	26.9	-
Texas	2.2	0.9	8	14.3	14	3.2	1.3	11	19.2	1
Louisiana	27.5	1.7	46	6.5	51	31.4	1.8	50	7.0	5
Mississippi	1.0	c	2	0.2	3	1.5	0.1	4	0.3	
Alabama	0.8	c	2	0.3	2	1.1	0.1	2	0.4	
Mid-Atlantic	5.3	1.8	—	11.6	—	7.6	2.5	—	16.6	-
Georgia	2.4	0.2	4	0.8	4	4.0	0.3	6	1.2	
South Carolina	6.7	0.3	10	1.6	12	10.2	0.3	13	2.2	1
North Carolina	7.9	0.2	3	1.4	4	9.8	0.2	4	1.9	
Virginia	3.1	0.7	16	4.1	12	4.8	1.0	21	5.8	1
Maryland	12.3	0.2	6	1.5	5	17.3	0.4	10	2.6	
Dist. of Col.	15.0	0.1	15	1.2	15	20.0	0.2	20	1.6	2
Delaware	16.0	0.1	19	1.0	18	25.0	0.1	25	1.3	2

North-Atlantic	0.9	3.6	—	33.3	—	1.3	5.0	—	47.6
New Jersey	9.5	0.7	9	6.2	9	13.1	0.9	12	8.4
Pennsylvania	0.1	0.4	3	2.0	3	0.2	0.5	4	2.8
New York	0.6	2.1	12	22.0	12	0.8	3.0	16	30.9
Connecticut	1.2	c	2	0.6	2	2.2	0.1	3	1.1
Rhode Island	3.5	c	3	0.2	3	7.0	0.1	6	0.4
Massachusetts	2.1	0.3	4	2.2	5	3.4	0.4	8	3.7
New Hampshire	0.1	c	0	c	1	0.4	c	1	0.1
Maine	0.2	c	1	0.1	2	0.4	c	1	0.2
West Coast	0.6	0.8	—	7.8	—	1.2	1.4	—	14.2
California	1.0	0.7	4	7.3	3	1.7	1.2	6	12.7
Oregon	0.1	c	1	0.3	1	0.4	0.1	3	0.6
Washington	0.4	c	1	0.2	1	7.1	0.1	2	0.9
All regions	—	11.6	—	107.5	—	—	15.7	—	146.9
Percentage of continental US	1.5	5.7	—	6.2	—	2.1	7.8	—	8.4

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[a] Totals may not add exactly due to rounding errors.

[b] Estimated Market Value derived by dividing the "locally assessed taxable real property" in each county by the "aggregate assessment price ratio," which is based on a sample of market values (85).

[c] Less than 0.1.

reactors [of which at least 10 may be affected by a 25-ft rise (88)]. Furthermore, future population growth, migration patterns, or economic trends may well change the value of coastal land and structures (84, 89–92). Actions, such as the building of levees or dams, could also be taken to reduce damage or to redistribute losses across the entire country (89).

Experience with such huge displacements of population and losses of wealth is extremely limited. Other natural hazards are qualitatively different and quantitatively less damaging (a few billion dollars annually in the United States). Only coastal erosion, which for the entire United States costs about 300 million dollars per year, results in permanent loss of land. Damage from hurricanes, earthquakes, windstorms, lightning, and so forth are measured in hundreds of millions of dollars at most, rather than the tens of billions of losses estimated for areas such as the Texas coast (Table 1). Furthermore, such hazards are characterized by such complications as extensive loss of life (89).

The seriousness of damage would certainly depend on the time frame of a sea level rise. For example, if the rise were to occur in only one year, the logistic problems of housing and feeding people and of salvaging household property, equipment, and inventories would become formidable. They would be compounded by the difficulty of absorbing rapidly the costs of relocation and reconstruction and the immediate losses of productive capacity. On the other hand, were the rise spread over a decade or longer, the migration of people (say, 1–1.5 million per year) could be considerably easier and the macroeconomic effects less of a shock. For instance, housing construction exceeded 2 million units per year for the three years 1971–1973 (92). An annual direct loss of 15–20 billion dollars would be economically serious, but perhaps not catastrophic [on the order of past and present "losses" to members of the Organization of Petroleum Exporting Countries (93)]. Moreover, an accurate prediction or warning a few years in advance could reduce and distribute impacts even further.

Some Speculations on Social and Political Impacts

A variety of social and political impacts could result from a sea level rise or from policy actions to reduce risks or damage. Such impacts are more difficult both to quantify and to compare than economic factors, especially since they often involve such important issues as equity, individual and collective responsibilities, risk perceptions, and international development goals. Rather than analyzing these impacts and issues in detail, a task more appropriate for an integrated, multidisciplinary team of researchers, we briefly list some possible consequences and interactions.

One type of impact could result directly from a rise in sea level. For example, a rise would endanger various historical monuments, cemetaries, educational institutions, wildlife preserves, and other cultural and environmental assets such as the Smithsonian Institution, MIT, Harvard University, Plymouth Rock, the Lincoln and Jefferson Memorials, and the Everglades. Although the costs of protecting or transplanting such resources may be calculable, changes in aesthetic, historical, or cultural value may not be.

Even more uncertain, quantitatively, would be the psychological and sociological trauma of disruption and dislocation. The loss of much of an individual's or family's assets, forced relocation, changes in employment, destruction of communities, and severing of "roots" would cause substantial mental stress and anguish. Other complications, such as consumer fraud, racial and income discrimination in the distribution of relief, and housing shortages might also contribute to the hardship (89, 94–96). In areas such as Florida, with its high proportion of elderly, these problems could become even more severe (84). Another interesting possibility is the potential restructuring of political power within a region due to relocation.

A second type of impact results from actions taken in response to an actual or predicted sea level rise. Clearly the extent and conduct of government assistance would influence both the distribution of economic losses and the magnitude of the psychological and sociological shocks (89, 97). A prediction of a sea level rise could severely disrupt the real estate market by causing severe price fluctuations due to speculation and windfall profits. The nature of the prediction, including the source and its credibility, the uncertainty stated, the timing, and the support given by the scientific community would certainly be important in the ensuing situation (98, 99).

The perceived risk of a sea level rise may significantly affect other sociopolitical trends and policies, a third type of impact. The possibility of inundation might impact upon a low-lying area's economic well-being and development, especially if the government were to encourage or enforce land-use controls or a no-growth policy (100). Internationally, proposals to reduce fossil fuel consumption or deforestation may directly conflict with development and energy growth goals, particularly in the less-developed countries where the risk of these impacts seems less important than in the developed nations.

The potential impacts described above are merely an early cut at the issues. Indeed, thorough analyses are needed for all types of climatic change. Such further examination should consider equity issues, problems in the perception of risk, inhomogeneity in both impacts and causal factors, and decision-making processes.

PERSPECTIVE AND CONCLUSIONS

CO_2: An "Externality" of Development

In economic parlance the term "externalities" has been used to describe the cost or benefit of some economic activity to parties not directly involved in (i.e. external to) that economic activity (101). The medical costs to people subjected to health-damaging pollutants are usually external to the economic considerations of the polluters (unless environmental emissions regulations are in force). This is an example of a negative externality (102). On the other hand, the benefit to some fishermen from the delayed freezing of a pond heated by the thermal discharge of a power plant is a positive externality to those fishermen (it could also be negative, of course, depending on the nature of the impact to the fish).

In the case of CO_2 and climate, the potential externalities from CO_2-induced climatic changes are not now being internalized in the economic calculations of activities that can change the concentration of CO_2. No external costs, such as those borne by people whose coasts might be flooded or whose crop yields might be reduced, are included in today's "cost of doing business," for, for example, a deforester or a fossil fuel user. Nor, on the other hand, are external benefits such as potential crop-yield increases from CO_2 fertilization internalized in the balance sheets of CO_2-related economic activities. At least four factors contribute to the neglect of CO_2-related externalities in present economic activities:

1. Widespread recognition of potential CO_2 impacts is lacking.
2. Considerable technical uncertainty remains over the timing and magnitude of physical, economic, social, and political impacts of a given CO_2-induced climatic change (to say nothing of the uncertainty in the CO_2 projections themselves or in present calculations of climatic response).
3. Difficulty exists in identifying specific interests upon whom negative or positive externalities will accrue. In particular, no mechanism exists for resolving conflicts between individual or regional economic activities and a global perspective.
4. Difficulty exists in choosing a discount rate (or perhaps a value rate) at which future costs or benefits should be weighed in today's monetary units. As the first three points have been touched upon in varying degrees of detail to this point, we next discuss point 4, the question of discounting the future.

Consequences of Discounting in the Context of CO_2

Even if we knew (or assumed) a future climatic scenario resulting from CO_2 increases today and could specify in detail what the physical and economic impacts of that scenario would be at some future time, we would still not be able to internalize this externality into today's economic planning until we had assumed some rate at which the future could be discounted (or valued). For example, if offered the opportunity to buy today the option to receive $10 next year, we would be unlikely to offer $10 for that option simply because, in today's economic conditions, we can invest that $10 in a bank and receive both the principal plus an interest payment of at least 7% in one year. Thus, in this example, $10 one year from now is worth only $9.35 today (assuming, of course, no inflation of the dollar, which only exacerbates the devaluation of the future). Clearly then, in many, if not all, of our economic activities we discount the future by such a process. The rate at which we do so is related to the discount rate.

Extending this trivial example to the case of coastal flooding from CO_2 increases requires the use of a discount rate because the costs of mitigating CO_2 impacts will be felt, in general, earlier than the costs of leaving them unabated. Reducing today the economic activities that increase CO_2 will generate costs that, in a classical "cost-benefit" study, need to be weighed against the discounted costs of not reducing those activities (we ignore for the moment the equity issues of who benefits or loses today or in the future).

To be more specific, we generalize our estimate of the real property costs to the United States of a 7.6 m sea level rise (about one quarter of 1 trillion 1971 US dollars) to the rest of the world. For the sake of this example, we assume the total world value (in 1971 US dollars) of inundated areas to be $\$2.5 \times 10^{12}$, ten times greater than estimated US losses. Furthermore, we assume that losses from such flooding occur in 150 years. What then is it "worth" to us today to invest in measures to prevent such a $\$2.5 \times 10^{12}$ catastrophe in 150 years?

If we discount the future at 7% per year, this represents a doubling time for investments of roughly 10 years (and only 7 years for a 10% discount rate). Therefore, a dollar invested at 7% per year today would double roughly 15 times in the next 150 years, and be worth (ignoring inflation) about $30,000.

Similarly, a dollar in 150 years is worth only about 1/30,000 of a dollar today—assuming again that we discount the future at a yearly rate of 7% per year, of course. Thus, a $\$2.5 \times 10^{12}$ inundation cost in 150 years is worth only about $75,000,000, a sum considerably less than the economic value of fossil fuel–related industries or the potential agricultural income from deforested lands. Thus, many people today would not consider it "economically rational" to spend more than 75 million dollars (hardly more than the cost of a few fossil-fueled power plants) now even to prevent a two and one-half trillion-dollar catastrophe 150 years in the future. In other words, this 75 million-dollar sum would presumably increase at about 7% per year, reaching 2.5 trillion in 150 years, exactly enough to compensate in the aggregate for future losses (again ignoring inflation and equity issues). All of this assumes, of course, that discounting the future at 7% per year is a "politically rational" policy.

If the inundation were to occur in only 20 years, though, it would be worth $\$6 \times 10^{11}$, a loss sufficiently serious to warrant dramatic, immediate policy actions. Uncertainties in the timing of potential sea level rises combine with those of estimating the discount rate, thus further complicating our impact assessment. Of course, in the future, population pressures and the desire to live near the oceans could drive up the value of coastal properties relative to now. But such value rate factors (as opposed to discount rate factors) are difficult to assess.

Regardless of the "correct" discount (or, some would argue, value) rate we should use to evaluate the worth of the future, one thing remains clear: discounting at high rates further diminishes the likelihood that this generation will invest heavily to hedge against potential CO_2-induced losses in the future.

Policy Options

Although the process of policy choice is clearly a value-laden activity that rightly belongs in the political, not scientific, arena, experts can still exert considerable influence through policy analyses. That is, expertise is needed to assess the effects of different policy options on changing the magnitude or distribution of, say, economic impacts from climatic changes arising from CO_2 increase. Such assessments can help to clarify political choices.

In the case of the potential climatic consequences of CO_2 increases, several policy options can be listed, progressing from the most passive (i.e. do nothing), up to very active countermeasures that involve complex international regulations—or even climate control schemes. These policy options in response to CO_2 could be:

1. DO NOTHING DIFFERENT Those either (*a*) unaware of the issues, (*b*) perplexed thoroughly by the uncertainties, or (*c*) special interests most likely to be adversely affected by some policy are the most likely to favor this inactive policy. However, at least a few social scientists who have examined this problem believe that adaptation by society to climatic changes may be the best, or at least the most likely, option (103, 104). This does not, however, preclude option 3.

2. STUDY (OR MONITOR) MORE Few who are aware of the potential for global climatic change from CO_2-generating activities wholly dismiss the policy aspect of the problem as premature. Instead, those who are disturbed by the prospect of active policy (e.g. emission regulations) in view of the

large degree of technical uncertainty often favor a "prudent" response: study (or monitor). (We scientists who so frequently suggest this option, in part because of our professional commitment to increased knowledge, must be especially careful to justify our advice, as funding agencies are well aware of our special interest in research.) This choice is of course an active policy, since it commits funds now for research to narrow the uncertainties surrounding the costs and benefits of CO_2-induced climatic changes in the future. In fact, the active efforts of the US Department of Energy and other agencies to invest in climatic research and monitoring with emphasis on CO_2 demonstrates that this policy is favored at the highest levels of government in the United States (40, 105–107).

A troublesome part of this policy is the often implicit feeling that since present estimates of CO_2-induced societal impacts are not "due" to be large for a few decades, then we can safely study the problem for 10 more years or so without risks, thereby avoiding costly and perhaps premature, active CO_2-control policies. The danger of this policy is twofold: (*a*) It could well take decades before the data needed to verify or deny the predictions of state-of-the-art climatic models are in hand; presently the time frame over which the atmosphere itself will "perform the experiment" of proving present estimates too high or low. (*b*) The historic record shows that the time taken for a new energy supply technology to replace a significant fraction of an existing infrastructure (e.g. coal to replace wood or oil to replace coal) is 50–100 yr (108, 109). Although it is possible that nonmarket interventions such as government regulations or incentive programs and the use of modern technological aids (e.g. communications and transportation systems) could significantly reduce this "market penetration time," it would still be hard to replace the bulk of the "standing crop" of fossil fuel energy devices in less than several decades at least. Thus this infrastructural inertia implies that once a decision to curb CO_2 emissions were made, it would likely be decades before the trend of increasing CO_2 concentrations could be reversed. Thus, one cannot delay a decision to curtail CO_2 emissions (or other such active policies) by some 10 yr while experts study, without some risk! That risk, of course, is that the future will be committed to a larger dose of CO_2 and its impacts if such a decision is delayed, relative to the impacts that would be felt if the decision to cut CO_2 emissions were made now. Whether the risk of delay justifies stronger action than research is a value choice that balances the costs of immediate actions versus the potential costs of future CO_2 impacts—all in the face of large uncertainty.

3. BUILD RESILIENCE A more active response than research to the prospect of CO_2-induced environmental changes, but less severe than emission controls, is the policy to build resilience; that is, active efforts are pursued

to minimize the vulnerability of various economic or political sectors of society to climatic changes whether natural or induced by CO_2 or other human influences [what one of us has previously termed a Genesis Strategy (110)]. Examples of policy actions that could be undertaken in advance of CO_2 emission controls, but beyond (and/or in addition to) the more passive policy of research are: food reserves, seed stocks capable of producing plants widely adapted to different growing conditions, soil conservation practices, judicious management of coastal development, water supply networks, food trade agreements, research and development of nonfossil fuel energy alternatives, reduced energy demand, and decoupling of the dependence of economic development (whether GNP or some alternative measure) on energy growth. Not only would the building of resilience (or minimizing vulnerability) help to mitigate the impacts of CO_2-induced climatic changes, should they prove as serious as some estimations, but it could also reduce the economic impacts of curtailed or regulated CO_2-emitting activities by changing the character of the economy slowly enough to prevent sudden disruptions, should new evidence prove CO_2 a more certain threat.

4. REDUCE THE CO_2 INSULT The most active response to the potential impact of CO_2-induced climatic changes [short of CO_2-transfer and climate-control schemes (40, 111, 112)] would be policies to reduce the emissions of CO_2 by curtailing the activities that produce them. At least four steps could be taken, ranging from voluntary conservation up to international regulatory controls.

(a) Conservation Regardless of technologies used, each alternative energy system has risks in rough proportion to the total amount of energy utilized. With fossil fuel energy systems, for example, fuel not consumed will result in diminished CO_2 input to the atmosphere, sulfate pollution, release of heat, strip mining damage, etc.

Conservation itself can be taken in two forms. The form least disruptive in economic terms would be an effort to improve end-use efficiency. Better insulated structures, mass transit systems rather than individual vehicles, more efficient cars, use of less energy-intensive materials, lowered thermostats, etc are all well-known examples of steps that could reduce considerably energy consumption without significant economic losses. In fact, several major studies have recently concluded that conservation in the sense of increased end-use efficiency is the cheapest and cleanest energy alternative (93, 113–116).

The second and more severe form of conservation of energy involves "curtailment" of its usage. Curtailment, it has been argued, can result in job losses in affected industries and thus is likely to be unpopular—or at least controversial. On the other hand, overall employment could increase if an economy were designed to utilize more workers in less energy intensive occupations. In fact, one means of reducing the CO_2 emissions with minimal economic damage is to plan for an economy whose growth rate depends less and less on the growth rate of energy usage. Shifts from industrial to service sectors in employment have already been evolving toward this goal.

Regardless of the degree of conservation chosen by society, it seems clear that most people agree that energy waste cannot be tolerated in view of the broad array of risks from energy use.

(b) Alternatives to fossil fuel energy systems There are many options to reduce the CO_2 insult in the long run without reducing the utilization of energy below some "desirable" level. These include solar, nuclear, wind, geothermal, biomass, and hydroelectric power, among others (113–118). Each offers the chance to provide the same benefit, a unit of energy, but the costs and risks vary widely across these systems. Whether these alternative systems provide more or less risk than fossil fuels is difficult to determine, since their risks are heterogenous and often accompanied by large uncertainties (119).

(c) Land use regulation If deforestation of the tropics or loss of organic carbon in soil from agriculture are, as some biologists suspect, likely sources of CO_2, then control of atmospheric CO_2 concentrations will require land use regulations. Of course, just as fossil fuel burning is an international pursuit, so are land uses with the potential to increase CO_2. Thus, if actions to reduce the insult of increasing CO_2 are to be effective, they will, of necessity, have to be international, and deal with both fossil fuel burning and land usage.

(d) Law of the Air To meet any international desire to keep CO_2 concentrations below some "standard," an international regulatory mechanism would need to be set up, first to negotiate standards and then to inspect for national emissions of CO_2. In essence, what would be required is a multilateral treaty or "Law of the Air" [as suggested by Margaret Mead (120)]. For it to succeed, not only would nations need to assign to such an international mechanism the power to set global CO_2 standards, but they would also have to follow through by agreeing to restrict their individual developmental activities to levels sufficient to prevent CO_2 emissions that were above their national quotas. The possibility of achieving such a "Law of the Air" at this point is, from a political standpoint, next to nil, especially since present emissions of CO_2 are due primarily to the industrialized countries of the world (121). However, if climatic impact assessments can demonstrate

more credibly that the potential risks of CO_2 buildup are sufficiently threatening, then pressures to protect the global atmospheric commons could mount. Moreover, the costs of prevention, though large, could be tenable (122).

On the other hand, once individual special interests have been identified (i.e. who might benefit and who might lose from a CO_2 increase), they will demand protection. We face a predicament: At present, great uncertainties persist as to the magnitude, timing, and distribution of consequences from CO_2-induced climatic changes. These mitigate against aggressive policies of costly preventative measures. Yet, once any benefactors of such changes could be identified, they will likely resist participation in international effort to control CO_2. This argues for early action on a Law of the Air to protect the global climatic commons while all nations still face the *possibility* of harmful changes. This CO_2 predicament is merely a part of the larger issues of the growths of population, use of resources, environmental quality, and rates of development. The balancing of interests in these areas has been termed the human predicament (110, 117, 123–125).

CO_2 as Part of the Human Predicament

A rousing, often bitter, debate has been going on for a decade or so about the problem of providing sufficient amenities (e.g. food, health, education, shelter, energy, environmental quality, etc) to a growing world population. Particularly heated have been questions about the earth's carrying capacity for humans, the desirability of increased technology versus population control as a means to ensure adequate per capita standards for future generations, and the more general questions of "limits to growth." The pessimists have argued that environmental degradation and resource shortages, driven by both population pressures and unrealistic expectations of the benefits of technology, will result in social and environmental catastrophes. The optimists argue that more technology, not less, is needed to help improve global economic conditions—and, they claim, the per capita quality of life—to a sufficient degree such that birth rates will decline naturally (what has been termed the "demographic transition"). They point to increasing use of energy as a major correlate with Gross National Product (GNP), and low birth rates with high GNP per capita. The limits-to-growth advocates respond that such a demographic transition, even if it were to work in the less-developed countries (LDCs) as it has in the developed countried (DCs), would still take many generations, too long to wait since total population levels would be too high to sustain (117).

Others share aspects of each position, arguing that it is not per capita GNP that correlates well with lowered birth rates, but rather per capita measures of the physical quality of life. One index, the physical quality of life index (PQLI), has shown that health care, education, and basic nutrition, not GNP (at least for GNP below about $1000 per capita), are the chief correlates with lowered birth rates in LDCs (126, 127). This argument suggests that increased energy usage, fossil or other, will help solve the world predicament *only to the extent that it helps achieve the rapid spread of these basic human services.*

This brief review of these well-publicized discussions brings us back to the role of CO_2 in the human predicament. If fossil fuel burning and land uses that produce CO_2 are to be minimized, then the total use of fossil fuel and deforestation rates must be kept in check. On the other hand, if greater per capita energy consumption and land usage are needed to improve PQLI in order to bring down birth rates, then more CO_2-producing activities will, at least in the short run, need to be encouraged. But this may raise total CO_2 levels and increase the likelihood of CO_2-induced problems. Since total energy use is the per capita level times the total population, the trade-off becomes clear: energy-use expansion to improve PQLI and thus reduce birth rates (should it prove more than a coincidence) must be accomplished rapidly enough to help create a stable population level so that adequate per capita levels of consumption can be obtained before the total population becomes so large that severe environmental damages, like a sea level rise, occur. The CO_2 issue, then, enters the world predicament debate by suggesting an urgency for minimizing the time in which population growth rates must be reduced, after which further per capita CO_2 production could create such large environmental changes as to negate the benefits the very expansion in fossil fuel energy (or land use) was designed to allow (110, 125).

The Risks of Alternative Energy Systems

Clearly, before a decision to regulate CO_2-producing activities can become less controversial, we need to assess the benefits of energy use (or CO_2-producing land usage) relative to the risks of that usage. Assuming the relative benefits of energy usage can be measured primarily per unit of energy services produced, then the major difference among alternative supply technologies (again, per unit energy service produced) would be the economic, health, environmental, and sociopolitical costs of each alternative. A number of studies (93, 113–119) have shown that no energy system is without risks, and that these risks are of very different characters and affect different segments of society for different energy supply systems. Weighing the potential CO_2 risks from fossil fuels versus the possibility of nuclear weapons proliferation from the spread of nuclear power technology versus the risk of hydroelectric dam failures, to name a few, is a monumentally compex value choice.

Political choices on energy alternatives will partly depend on the technical assessments of both the probability and consequences of various potential energy supply system risks (both of which can be fraught with *inestimable* uncertainties). They will also depend on the public's perception of the acceptability of one kind of risk versus another. Finally, these differently assessed and perceived risks of alternative energy systems will have to be weighed through the political process against the differently assessed and perceived benefits of energy services. The prospect of choosing a mix of energy supplies systems that accommodates differing interests is a staggering challenge to existing political systems. In view of the immensity of the difficulties in choosing the "best" set of supply technologies, punctuated by large uncertainties in already analyzed data—to mention nothing of incomplete risk/benefit inputs—it may well be best to maintain open options (119, 128). The activities listed in the aforementioned policy of building resilience are examples of such options. Even if there were no CO_2 problem, the activities called "build resilience" are important for other reasons. Viewed this way, the CO_2 issue has tie-ins with other problems. In view of the large CO_2 uncertainties, it seems likely that policy responses with tie-ins are the ones that will receive priority attention by decision makers (129).

SUMMARY

We have mentioned that energy increases are likely in the future, and that these can cause both benefits and risks for society. The risks are heterogeneous and often uncertain, making an optimum choice of alternatives difficult. Nevertheless, fossil fuel power is, and is likely for decades at least to continue to be, the dominant energy supply source. Fossil fuel burning and some land uses have led to, and are likely to continue to lead to, increases in the concentration of carbon dioxide (CO_2) in the atmosphere. The increases are projected by state-of-the-art equilibrium climatic models to lead to a global warming of a degree or so Celsius around 2000 AD, with this warming amplified several times near the poles. (Recent transient models suggest that the projected equilibrium signal may be delayed up to several decades. They also suggest that the character of the transient response could be different from equilibrium estimates.) Several glaciologists have hypothesized that such a warming could initiate a breakdown of the West Antarctic ice sheet and a subsequent rise in mean sea level of several meters. The process could be initiated over the next few decades and take anywhere from tens to hundreds of years to complete. Despite the cascade of uncertainties inherent in each link of the logical chain that started with CO_2 production and may end with sea level rise, its possibility remains plausible at present.

We have briefly reviewed the issues of the likelihood and timing of such a coastal flooding, and also have emphasized some demographic, economic, social, and geopolitical consequences of an assumed CO_2-induced rise in sea level of 15–25 ft (4.6–7.6 m). We have restricted our analyses to the continental United States, but conclude, nonetheless, that only in this one country on the order of $2 X 10^{11} (in 1971 US dollars) in private and public land and structures would be inundated by the 7.6 m local rise. (In 1980 dollars these estimates are low by several fold.) Other economic, social, and political repercussions are also likely.

This "externality" of CO_2-producing activities is not now considered in economic development activities. If it were it could alter the present outlook for the expansion of such activities, depending upon the discount rate and other accounting factors used in any risk/benefit study. Moreover, as there are inestimable factors rendering cost/benefit studies perpetually tentative, a final consideration of the CO_2 problem is *ethics*: that is, is it ethical for this generation to allow a long-term buildup of CO_2 with potentially large consequences for posterity, even though the extent of the threat is presently uncertain (130).

The possible rise in sea level is certainly not the most immediate, and perhaps not even the most important potential CO_2-induced environmental effect. For example, alteration to accustomed patterns of rainfall as well as insects, diseases, and weeds could accompany a global warming, thereby affecting the location and productivity of grainbelts or watersheds. Primarily because of its tractability, we choose this sea level example as a quantitative case study to demonstrate the need for increased efforts toward more general climatic impact assessments. That is, although we suspect that assessments of the potential effects of regional climatic variations (CO_2-induced or otherwise) on regional food and water supplies will prove of greater importance to society (at least in the next few decades) than an assessment of a possible sea level rise, the latter is easier to perform quantitatively than the former. Regional climatic alterations, for which reliable estimates are beyond the state-of-the-art of climate theory, would (among other things) be necessary input to any assessment of the food and water supply impacts of a CO_2-induced climatic change.

We recognize that quantitative assessment of a relatively far away problem like the sea level rise case may be less useful for immediate decision making in society than a qualitative assessment of a potentially more significant problem like food production variations. But the general efforts at climatic impact assessment must, we believe, expand considerably, and the quantitative analysis of the potential impacts of a hypothetical, but plausible, sea level rise is a tangible case study. We hope many other studies will follow. At the same time, we believe it is not premature to begin to consider steps to minimize our vulnerability both to CO_2-induced climatic changes and to any future shifts away from fossil fuels. It is in this spirit that we wish our efforts here to be interpreted.

ACKNOWLEDGMENTS

We wish to thank Lester Lave, Robert Kates, and Tom Teisberg for their helpful comments. R. S. Chen gratefully acknowledges the support of the Advanced Study Program of the National Center for Atmospheric Research which administers the Graduate Fellowship Program of the University Corporation of Atmospheric Research. We also thank Holly Howard for her prompt and efficient typing and Justin Kitsutaka and other members of the NCAR graphics group for their drafting of figures.

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NOTE ADDED IN PROOF The authors have become aware of a study which examines a rise of 100m due to a hypothetical melting of all glacial ice (131).