APPENDIX 1 REPORT DEVELOPMENT PROCESS

The National Climate Assessment (NCA) supports the U.S. Global Change Research Program (USGCRP) and its Strategic Plan[1] in multiple ways. The Strategic Plan focuses on climate science that informs societal objectives; the USGCRP program and the NCA help build an information base to support climate-related decisions, including decisions to reduce human contributions to future climate change, and to adapt to changes that are occurring now and are projected in the future. In order to facilitate the integration of federal science investments with academic, public, and private sector climate change research, the Third NCA process focused on building strong relationships with stakeholders and experts outside the government. Early in the process, the National Climate Assessment and Development Advisory Committee (NCADAC) and NCA Coordination Office developed a strategy to engage a broad range of the American public. Open participation, communication, and feedback have been integral to the preparation of this far-reaching assessment.[2]

NCA Goal and Vision

As established by the NCADAC,[3] the overarching goal of the NCA process is to enhance the ability of the United States to anticipate, mitigate, and adapt to changes in the global environment that are increasingly linked to human activities.

The vision is to advance an inclusive, broad-based, and sustained process for developing, assessing, and communicating scientific knowledge of the impacts, risks, vulnerabilities, and response options associated with a changing global climate, and to support informed decision-making across the United States.

Legislative Foundations

The NCA is conducted under the auspices of the Global Change Research Act (GCRA) of 1990.[4] The mandate for the U.S. Global Change Research Program as a whole is: "To provide for development and coordination of a comprehensive and integrated United States research program which will assist the Nation and the world to understand, assess, predict, and respond to human-induced and natural processes of global change."

Section 106 of the GCRA requires a report to the President and the Congress every four years that integrates, evaluates, and interprets the findings of the USGCRP; analyzes the effects of global change on the natural environment, agriculture, energy production and use, land and water resources, transportation, human health and welfare, human social systems, and biological diversity; and analyzes current trends in global change, both human-induced and natural, and projects major trends for the subsequent 25 to 100 years.

Institutional Foundations

U.S. Global Change Research Program

USGCRP is a federation of the research components of 13 federal departments and agencies that supports the largest investment in climate and global change research in the world. USGCRP coordinates research activities across agencies and establishes joint funding priorities for research. USGCRP's Strategic Plan, adopted in 2012, focuses on four major goals: advance science, inform decisions, conduct sustained assessments, and communicate and educate.[1] The USGCRP agencies maintain and develop observations, monitoring, data management, analysis, and modeling capabilities that support the nation's response to global change. The agencies that comprise the USGCRP are:

U.S. Department of Agriculture
U.S. Department of Commerce
U.S. Department of Defense
U.S. Department of Energy
U.S. Department of Health & Human Services
U.S. Department of the Interior
U.S. Department of State
U.S. Department of Transportation
U.S. Environmental Protection Agency
National Aeronautics and Space Administration
National Science Foundation
The Smithsonian Institution
U.S. Agency for International Development

The Subcommittee on Global Change Research (SGCR) oversees USGCRP's activities. SGCR operates under the direction of the National Science and Technology Council's (NSTC) Committee on Environment, Natural Resources, and Sustainability (CENRS) and is overseen by the White House Office of Science and Technology Policy (OSTP). The SGCR coordinates interagency activities through the USGCRP National Coordination Office (NCO) and interagency working groups (IWGs).

National Climate Assessment (NCA) Components

The **Interagency NCA Working Group (INCA)** is comprised of representatives of the 13 government agencies listed above, plus additional agencies that have chosen to engage in supporting the NCA activities. INCA is responsible for coordinating, developing, and implementing interagency activities for the NCA, providing critical input to identify and support future NCA products, and developing interagency assessment capacity at the national and regional scales. Through INCA, the agencies have supported the development of the 30 chapters and the process to create the Third NCA report in a variety of ways.

The **National Climate Assessment and Development Advisory Committee (NCADAC)** is a 60-member federal advisory committee established by the Department of Commerce on behalf of USGCRP. Forty-four non-federal NCADAC members represent the public, private, and academic sectors; 16 non-voting ex-officio members represent the USGCRP agencies, the Department of Homeland Security, the SGCR, and the White House Council on Environmental Quality. The NCADAC charter charges the group with developing the Third NCA report and with providing recommendations about how to sustain an ongoing assessment process. The NCADAC selected the authors of the individual chapters and coordinated many of the assessment activities leading to this report. This included NCADAC meetings and more than 20 NCADAC subcommittee working groups on specific assessment needs (for example, regional and sectoral integration, engagement and communication, indicators, and international linkages). An Executive Secretariat of 12 individuals (a subset of the full committee) helps to coordinate the activities of the full committee.

The **NCA Coordination Office** is a part of the USGCRP National Coordination Office in Washington, D.C. The office is supported and funded through an interagency agreement with the University Corporation for Atmospheric Research (UCAR). A team of UCAR staff and federal detailees (agency employees as-

Organization of NCA components

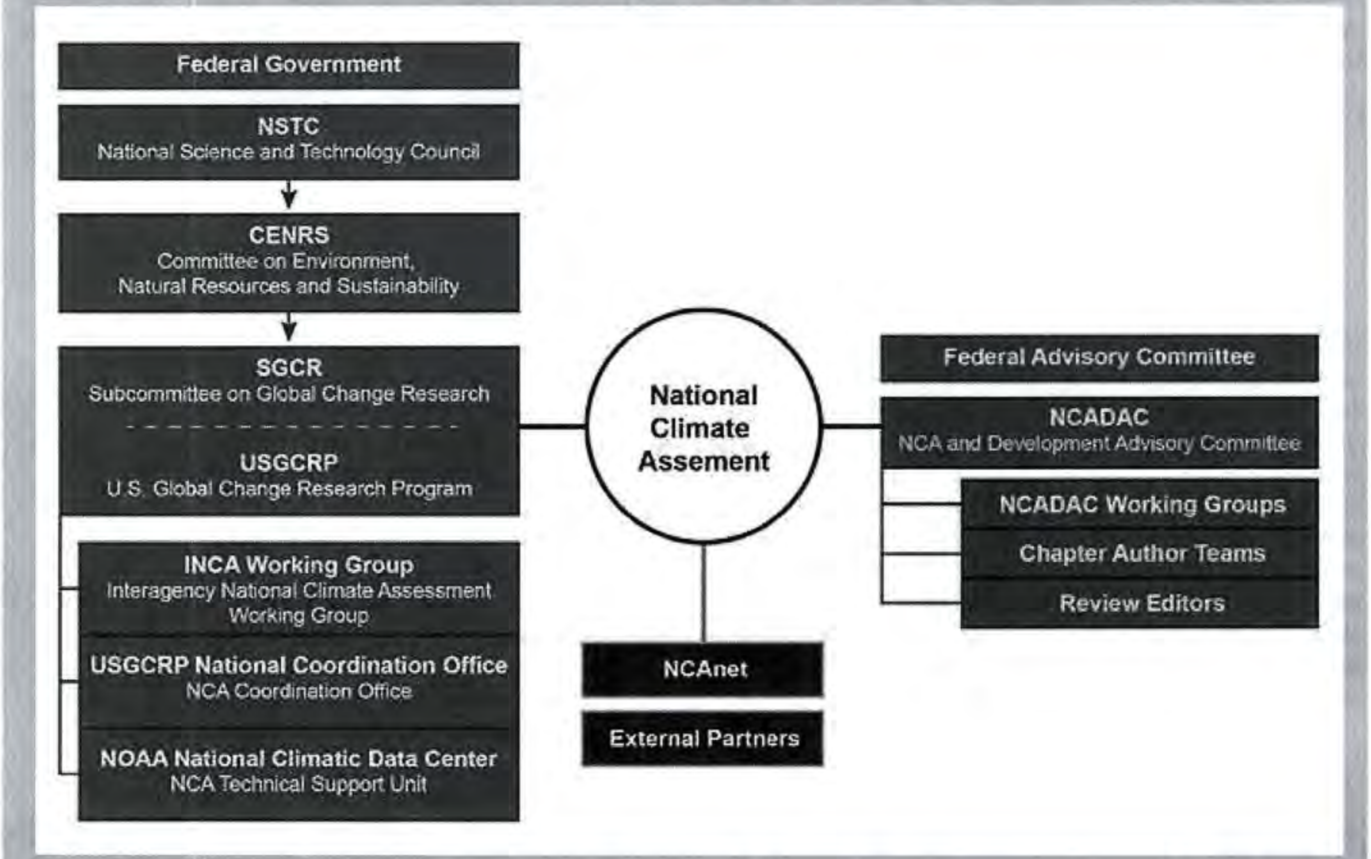


Figure 1.

signed to the NCA Coordination Office) with expertise in planning, writing, and coordinating collaborative climate and environmental science and policy activities provides support for the development of the NCA report and sustained assessment.

The **NCA Technical Support Unit (TSU)** is funded by the National Oceanic and Atmospheric Administration (NOAA) and is located at NOAA's National Climatic Data Center in Asheville, NC. The TSU staff provides multiple kinds of support to the NCA, including climate science research, data management, web design, graphic design, technical and scientific writing and editing, publication production, and meeting support.

The **National Climate Assessment Network (NCAnet)** consists of more than 100 partner organizations that work with the NCA Coordination Office, NCADAC, report authors, and USGCRP agencies to engage producers and users of assessment information.[5] Partners extend the NCA process and products to a broad audience through the development of assessment-related capacities and products, such as collecting and synthesizing data or other technical and scientific inputs into the NCA, disseminating NCA report findings to a wide range of users, engaging producers and users of assessment information, supporting NCA events, and producing communications materials related to the NCA and its report findings.

Creating the Third NCA Report

Process Development

The NCA Engagement Strategy provides a vision for participation, outreach, communication, and education processes that help make the NCA process and products accessible and useful to a wide variety of audiences. The overall goal of engagement is to create a more effective and successful NCA – improving the processes and products of the effort so that they are credible, salient, and legitimate and building the capacity of participants to engage in the creation and use of NCA products in decision-making.[2] The strategy describes a number of mechanisms through which scientific and technical experts, decision-makers, and members of the general public might learn about and participate in the NCA process.

As part of the assessment process, a series of 14 process workshops helped establish consistent assumptions and methodologies. The resulting reports provide a consistent foundation for the technical input teams and chapter authors.

The NCA Coordination Office organized listening sessions, symposia, and sessions at professional society meetings during the development of the NCA report and sustained assessment process. These sessions provided updates on the NCA process, solicited broad input from subject matter experts, and collected feedback on the approach, topics, and methodologies under consideration.

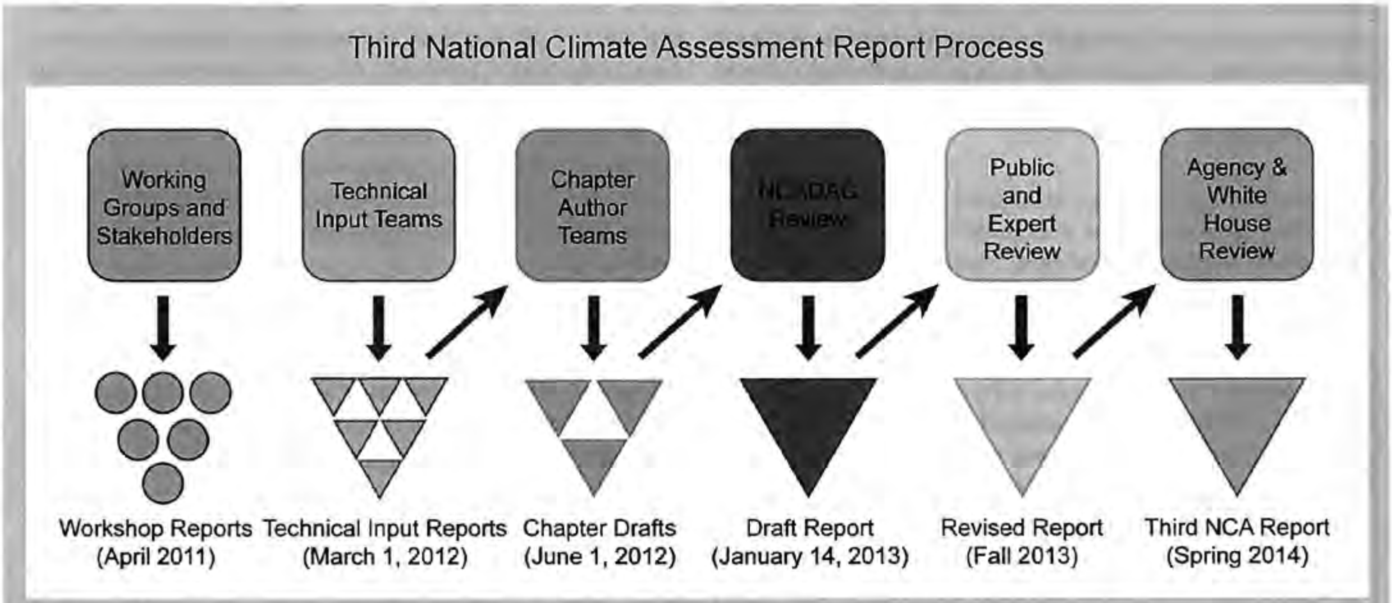


Figure 2. This graphic illustrates the activities and products that were developed during the Third NCA report development process.

Technical Input Reports

A public Request for Information[6] resulted in submission of more than 500 technical input documents authored by more than 800 individuals from academia, industry, and government, including 25 technical inputs[7] sponsored by USGCRP agencies. These inputs included documents and data sets for review and consideration by the author teams that developed the NCA report. Technical input authors used a variety of mechanisms to engage stakeholders in the scoping, writing, and review of their documents, including workshops, web-based seminars, and public comment periods, among other methods.

In addition, the Technical Support Unit climate science team developed nine peer-reviewed regional climate scenario documents (one for each of the eight regions and one for the contiguous United States),[8] providing a scientific consensus view of historical climate trends and projections under the IPCC Special Report on Emissions Scenarios (SRES) A2 and B1 scenarios.[9] A separate interagency committee developed four peer-reviewed sea level rise scenarios.[10] These scenarios were used by chapter authors as underpinnings for their impact assessments.

Third NCA Report Draft Development and Review

The NCADAC selected two to three convening lead authors and approximately six lead authors for each chapter, based on criteria that included expertise, experience, geography, and ensuring a variety of perspectives. They included authors from the public and private sectors, non-governmental organizations, and universities. Beginning in December 2011, each of the author teams met multiple times by phone, web, and in person to produce and refine drafts of their chapters. Traceable accounts developed for each chapter provide transparent information about the authors' decision processes, scientific certainty, and their level of confidence related to the key findings of their respective chapters. All authors served in a volunteer capacity.

After reviewing the draft Third NCA report, the NCADAC released it for public review and comment on January 14, 2013.[11] Concurrently, the NCA underwent an independent expert review by the National Research Council, a part of the National Academies. A three-month review period allowed individuals and groups to examine the draft and provide comments aimed at improvement. The comments were provided using a secure online comment system to ensure that all comments were captured and appropriately addressed.

Regional town hall meetings, conducted by the NCA Coordination Office (one per region, plus coasts) and by NCAnet partners (three additional meetings), brought together authors, NCADAC members, and members of the public to discuss the NCA process and encourage participants to submit comments on the draft report. Report authors, NCADAC members, NCA staff, and NCAnet partners organized, spoke at, and participated in sessions at professional society meetings, web-based seminars, community meetings, and other events similarly aimed at providing an overview of the draft report and encouraging comments.[12]

By the time the public comment period closed on April 12, 2013, the online comment system received 4,161 comments from 644 government, non-profit, and commercial sector employees, educators, students, and the general public. Chapter author teams and the NCADAC amended the draft report in response to comments and prepared written responses to each comment received, and external review editors evaluated the adequacy of the responses to the comments on each chapter. As the result of a NCADAC consensus decision, the entire review process was "blind", that is, NCADAC members and authors did not know the identity of commenters when responding to each comment. The public comments (including commenters' identities) and the chapter authors' responses to those comments were posted online with the final report.
The National Research Council provided a second review of the report, and the NCADAC considered this review in developing a final draft for submission to federal agencies for review in fall 2013.

NCA Final Report

Any adjustments to the NCADAC's Fall 2013 draft as a result of the government review process were made with the authors' approval, and the NCADAC approved the final form of the report in Spring 2014. Having been accepted and finalized following government review, the report is now provided as the assessment by the Federal Government of the United States, pursuant to the requirements of the Global Change Research Act. A number of products derived from the report support the outreach activities following the report release.

Engagement Activities

What follows is a sample of activities convened in support of the development of the Third NCA Report. A full list of activities is available online at http://assessment.globalchange.gov.
NCADAC Meetings: All meetings were open the public. The presentations, documents, and minutes for each NCADAC meeting are available online at http://www.nesdis.noaa.gov/NCADAC/Meetings.html.

- April 4-6, 2011, Washington, DC http://www.nesdis.noaa.gov/NCADAC/April_4_Meeting.html
- May 20, 2011, Teleconference
- August 16-18, 2011, Arlington, VA

- November 16-17, 2011, Boulder, CO
- April 10, 2012, Teleconference
- June 14-15, 2012, Washington, DC
- August 15, 2012, Teleconference
- September 27, 2012, Teleconference
- November 14-15, 2012, Silver Spring, MD
- January 11, 2013, Teleconference
- May 13, 2013, Teleconference
- July 9-10, 2013, Washington, DC
- November 18, 2013, Teleconference
- February 20-21, 2014, Washington, DC
- Spring 2014, Final approval of the Third NCA via teleconference

Process and Methodology Workshops: Reports from these workshops are available online at http://www.globalchange.gov/what-we-do/assessment/nca-activities/workshop-and-meeting-reports.

- Midwest Regional Workshop, February 2010, Chicago, IL
- Strategic Planning Workshop, February 2010, Chicago, IL
- Scoping the Product(s) and Work Plan for the Third National Assessment, June 2010, Washington, DC [no report available]
- Communications Scoping Meeting, July 2010, Washington, DC [no report available]
- International Scoping Meeting, August 2010, Washington, DC [no report available]
- Knowledge Management Workshop, September 2010, Reston, VA
- Regional Sectoral Workshop, November 2010, Reston, VA
- Ecological Indicators Workshop, November 2010, Washington, DC
- Scenarios Workshop, December 2010, Arlington, VA
- Climate Change Modeling and Downscaling Workshop, December, 2010, Arlington, VA
- Valuation Techniques and Metrics Workshop, January 2011, Arlington, VA
- Vulnerability Assessments Workshop, January 2011, Atlanta, GA
- Physical Climate Indicators Workshop, March 2011, Washington, DC
- Societal Indicators Workshop, April 2011, Washington, DC

Agency-Sponsored Technical Input Development Workshops

- Monitoring Changes in Extreme Storm Statistics: State of Knowledge, July 2011, Asheville, NC
- Forestry Sector Stakeholder Workshop, July 2011, Atlanta, GA
- Land Use and Land Cover Stakeholder Workshop, November 1011, Salt Lake City, UT
- Energy Supply and Use Workshop, November 2011, Washington, DC
- Energy, Water, Land Planning Meeting, November 2011, Washington, DC
- Urban Infrastructure and Vulnerabilities Workshop, November 2011, Washington, DC
- Trends and Causes of Observed Changes in Heat Waves, Cold Waves, Floods, and Drought, Nov. 2011, Asheville, NC
- Trends in Extreme Winds, Waves, and Extratropical Storms along the Coasts, January 2012, Asheville, NC
- Ecosystems, Biodiversity, and Ecosystem Services Workshop, January 2012, Palo Alto, CA
- Water Sector Technical Input Workshop, January 2012, Washington, DC
- Coastal Zone Stakeholders Meeting, January 2012, Charleston, SC
- Climate Change and Health Workshop - Southeast, February 2012, Charleston, SC
- Rural Communities Workshop, Feb. 2012, Charleston SC
- Climate Change and Health Workshop - Northwest, February 2012, Seattle, WA

Listening Sessions

- Annual Meeting of the Association of American Geographers, April 2011, Seattle, WA
- American Water Resource Association Spring Specialty Conference, April 2011, Baltimore, MD
- International Symposium on Society and Resource Management, June 2011, Madison, WI
- Annual Soil and Water Conservation Society Conference, July 2011, Washington, DC
- Ecological Society of America Annual Meeting, August 2011, Austin, TX
- American Meteorological Society Annual Meeting, January 2012, New Orleans, LA

Regional Town Hall Meetings

- Hawai'i & Pacific Islands Town Hall, December 2012, Honolulu, HI
- Southwest Regional Town Hall, January 2013, San Diego, CA
- Northeast Regional Town Hall, January 2013, Syracuse, NY
- Great Plains Regional Town Hall, February 2013, Lincoln, NE
- Alaska Regional Town Hall, February 2013, Anchorage, AK
- Midwest Regional Town Hall, February 2013, Ann Arbor, MI
- Southeast Regional Town Hall, February 2013, Tampa, FL
- Northwest Regional Town Hall, March 2013, Portland, OR
- Oceans and Coasts Town Hall, April 2013, Washington, DC

NCAnet Partners Activities

The NCAnet Partners meet monthly (since January 2012) in Washington, DC; teleconference and web conference capabilities allow participants to join remotely. NCAnet Partners hosted more than 25 events around the country for the public and stakeholders throughout the NCA process. A list of partners, minutes from meetings, and a list of events and resulting products is available at http://ncanet.usgcrp.gov.

APPENDIX 1: REPORT DEVELOPMENT PROCESS

REFERENCES

1. USGCRP, 2012: The National Global Change Research Plan 2012–2021: A Strategic Plan for the U.S. Global Change Research Program. 132 pp., The U.S. Global Change Research Program, Washington, D.C. [Available online at http://downloads.globalchange.gov/strategic-plan/2012/usgcrp-strategic-plan-2012.pdf]

2. NCADAC, 2011: National Climate Assessment (NCA) Engagement Strategy, 27 pp., National Climate Assessment and Development Advisory Committee, Washington, DC. [Available online at http://www.globalchange.gov/images/NCA/nca-engagement-strategy_5-20-11.pdf]

3. ——, 2011: National Climate Assessment Strategy – Summary, 3 pp., National Climate Assessment and Development Advisory Committee, Washington, DC. [Available online at http://www.globalchange.gov/images/NCA/nca-summary-strategy_5-20-11.pdf]

4. GCRA, 1990: Global Change Research Act (Public Law 101-606, 104 Stat. 3096-3104), signed on November 16, 1990. [Available online at http://www.gpo.gov/fdsys/pkg/STATUTE-104/pdf/STATUTE-104-Pg3096.pdf]

5. USGCRP: NCAnet: Building a network of networks to support the National Climate Assessment. [Available online at http://ncanet.usgcrp.gov/]

6. DOC, 2011: Technical Inputs and Assessment Capacity on Topics Related to 2013 U.S. National Climate Assessment. Wednesday, July 13, 2011, **76,** 41217-41219. [Available online at http://www.gpo.gov/fdsys/pkg/FR-2011-07-13/html/2011-17379.htm]

7. USGCRP, cited 2013: National Climate Assessment: Available Technical Inputs. [Available online at http://www.globalchange.gov/what-we-do/assessment/nca-activities/available-technical-inputs]

8. ——, cited 2013: Scenarios for Climate Assessment and Adaptation: Climate. [Available online at http://scenarios.globalchange.gov/scenarios/climate]

9. IPCC, 2000: *Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge University Press, 570 pp. [Available online at http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0]

10. USGCRP, cited 2013: Scenarios for Climate Assessment and Adaptation: Sea Level. [Available online at http://scenarios.globalchange.gov/scenarios/sea-level]

11. NCADAC: Federal Advisory Committee Draft Climate Assessment. National Climate Assessment and Development Advisory Committee. [Available online at http://ncadac.globalchange.gov]

12. USGCRP: National Climate Assessment: Opportunities for Engagement. [Available online at http://www.globalchange.gov/what-we-do/assessment/nca-activities]

APPENDIX 2 INFORMATION QUALITY ASSURANCE PROCESS

Summary of Information Quality Assurance Process for the Third National Climate Assessment Report

Throughout the process of drafting this National Climate Assessment, guidance was provided to contributors, authors, federal advisory committee members, and staff regarding the requirements of the Information Quality Act (IQA).

In September 2011, *Preliminary Guidance on Information Quality Assurance in Preparing Technical Input for the National Climate Assessment (NCA)*[1] was made available on the U.S. Global Change Research Program's (USGCRP) website along with other information for those interested in submitting technical input to the NCA in response to the Request for Information posted in the Federal Register on July 13, 2011.[2] This frequently asked questions-style document provided preliminary guidance regarding information quality for use by teams who submitted Expressions of Interest and Technical Inputs for use in the NCA.

In November 2011, the National Climate Assessment and Development Advisory Committee (NCADAC) approved the *General Principles Used in the Development of Guidance for Assuring Information Quality in the National Climate Assessment.*[3] The *Principles* were used by the NCADAC to draft guidance for all Convening Lead Authors (CLAs), Lead Authors, Review Editors, NCADAC, and Government Agencies and Reviewers to assure that information used in the NCA production was of appropriate quality relative to its intended use.

Two tools were developed – a set of questions and a flowchart – to assist the authors and reviewers in determining whether and how to use potential source material in the NCA within the requirements of the IQA. These tools (collectively, *Guidance on Information Quality Assurance to Chapter Authors of the National Climate Assessment: Question Tools*) were approved by the NCADAC and introduced to the CLAs at workshops. They have been available on the USGCRP website since February 2012.[4] The *Guidance* requires consideration of the following criteria for each source of information used in the Third NCA Report:

- Utility: Is the particular source important to the topic of your chapter?
- Transparency and traceability: Is the source material identifiable and publicly available?
- Objectivity: Why and how was the source material created? Is it accurate and unbiased?
- Information integrity and security: Will the source material remain reasonably protected and intact over time?

APPENDIX 2: INFORMATION QUALITY ASSURANCE PROCESS

REFERENCES

1. USGCRP, 2011: Frequently Asked Questions – Sept 2011; Preliminary Guidance on Information Quality Assurance in Preparing Technical Input for the National Climate Assessment, 5 pp., U.S. Global Change Research Program. [Available online at http://globalchange.gov/images/NCA/nca-info-quality-assurance-faq.pdf]
2. DOC, 2011: Technical Inputs and Assessment Capacity on Topics Related to 2013 U.S. National Climate Assessment. Wednesday, July 13, 2011, **76,** 41217-41219. [Available online at http://www.gpo.gov/fdsys/pkg/FR-2011-07-13/html/2011-17379.htm]
3. USGCRP, 2011: General Principles; Used in the Development of Guidance for Assuring Information Quality in the National Climate Assessment, 2 pp., U.S. Global Change Research Program. [Available online at http://www.globalchange.gov/images/NCA/Information-Quality-Principles-Draft_2011-11-16.pdf]
4. USGCRP, 2012: Guidance on Information Quality Assurance to Chapter Authors of the National Climate Assessment: Question Tools, 5 pp., U.S. Global Change Research Program. [Available online at http://downloads.usgcrp.gov/NCA/Question-Tools---2-21-12.pdf]

APPENDIX 3 CLIMATE SCIENCE SUPPLEMENT

Convening Lead Authors

John Walsh, University of Alaska Fairbanks
Donald Wuebbles, University of Illinois

Lead Authors

Katharine Hayhoe, Texas Tech University
James Kossin, NOAA National Climatic Data Center
Kenneth Kunkel, CICS-NC, North Carolina State Univ., NOAA National Climatic Data Center
Graeme Stephens, NASA Jet Propulsion Laboratory
Peter Thorne, Nansen Environmental and Remote Sensing Center
Russell Vose, NOAA National Climatic Data Center
Michael Wehner, Lawrence Berkeley National Laboratory
Josh Willis, NASA Jet Propulsion Laboratory

Contributing Authors

David Anderson, NOAA National Climatic Data Center
Viatcheslav Kharin, Canadian Centre for Climate Modelling and Analysis, Environment Canada
Thomas Knutson, NOAA Geophysical Fluid Dynamics Laboratory
Felix Landerer, Jet Propulsion Laboratory
Tim Lenton, Exeter University
John Kennedy, UK Meteorological Office
Richard Somerville, Scripps Institution of Oceanography, Univ. of California, San Diego

Recommended Citation for Chapter

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Appendix 3: Climate Science Supplement. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 735-789. doi:10.7930/J0KS6PHH.

On the Web: http://nca2014.globalchange.gov/report/appendices/climate-science-supplement

First published May 2014. PDF revised October 2014. See errata (available at http://nca2014.globalchange.gov/downloads) for details.

INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON

APPENDIX 3 CLIMATE SCIENCE

SUPPLEMENTAL MESSAGES

1. **Although climate changes in the past have been caused by natural factors, human activities are now the dominant agents of change. Human activities are affecting climate through increasing atmospheric levels of heat-trapping gases and other substances, including particles.**
2. **Global trends in temperature and many other climate variables provide consistent evidence of a warming planet. These trends are based on a wide range of observations, analyzed by many independent research groups around the world.**
3. **Natural variability, including El Niño events and other recurring patterns of ocean-atmosphere interactions, influences global and regional temperature and precipitation over timescales ranging from months up to a decade or more.**
4. **Human-induced increases in atmospheric levels of heat-trapping gases are the main cause of observed climate change over the past 50 years. The "fingerprints" of human-induced change also have been identified in many other aspects of the climate system, including changes in ocean heat content, precipitation, atmospheric moisture, and Arctic sea ice.**
5. **Past emissions of heat-trapping gases have already committed the world to a certain amount of future climate change. How much more the climate will change depends on future emissions and the sensitivity of the climate system to those emissions.**
6. **Different kinds of physical and statistical models are used to study aspects of past climate and develop projections of future change. No model is perfect, but many of them provide useful information. By combining and averaging multiple models, many clear trends emerge.**
7. **Scientific understanding of observed temperature changes in the United States has greatly improved, confirming that the U.S. is warming due to heat-trapping gas emissions, consistent with the climate change observed globally.**
8. **Many other indicators of rising temperatures have been observed in the United States. These include reduced lake ice, glacier retreat, earlier melting of snowpack, reduced lake levels, and a longer growing season. These and other indicators are expected to continue to reflect higher temperatures.**
9. **Trends in some types of extreme weather events have been observed in recent decades, consistent with rising temperatures. These include increases in heavy precipitation nationwide, especially in the Midwest and Northeast; heat waves, especially in the West; and the intensity of Atlantic hurricanes. These trends are expected to continue. Research on climate change's effects on other types of extreme events continues.**
10. **Drought and fire risk are increasing in many regions as temperatures and evaporation rates rise. The greater the future warming, the more these risks will increase, potentially affecting the entire United States.**

11. Summer Arctic sea ice extent, volume, and thickness have declined rapidly, especially north of Alaska. Permafrost temperatures are rising and the overall amount of permafrost is shrinking. Melting of land- and sea-based ice is expected to continue with further warming.

12. Sea level is already rising at the global scale and at individual locations along the U.S. coast. Future sea level rise depends on the amount of warming and ice melt around the world as well as local processes like changes in ocean currents and local land subsidence or uplift.

This appendix provides further information and discussion on climate science beyond that presented in Ch. 2: Our Changing Climate. Like the chapter, the appendix focuses on the observations, model simulations, and other analyses that explain what is happening to climate at the national and global scales, why these changes are occurring, and how climate is projected to change throughout this century. In the appendix, however, more information is provided on attribution, spatial and temporal detail, and physical mechanisms than could be covered within the length constraints of the main chapter.

As noted in the main chapter, changes in climate, and the nature and causes of these changes, have been comprehensively discussed in a number of other reports, including the 2009 assessment: *Global Climate Change Impacts in the United States*[1] and the global assessments produced by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. National Academy of Sciences. This appendix provides an updated discussion of global change in the first few supplemental messages, followed by messages focusing on the changes having the greatest impacts (and potential impacts) on the United States. The projections described in this appendix are based, to the extent possible, on the CMIP5 model simulations. However, given the timing of this report relative to the evolution of the CMIP5 archive, some projections are necessarily based on CMIP3 simulations. (See Supplemental Message 5 for more on these simulations and related future scenarios).

Supplemental Message 1.

Although climate changes in the past have been caused by natural factors, human activities are now the dominant agents of change. Human activities are affecting climate through increasing atmospheric levels of heat-trapping gases and other substances, including particles.

The Earth's climate has long been known to change in response to natural external forcings. These include variations in the energy received from the sun, volcanic eruptions, and changes in the Earth's orbit, which affects the distribution of sunlight across the world. The Earth's climate is also affected by factors that are internal to the climate system, which are the result of complex interactions between the atmosphere, ocean, land surface, and living things (see Supplemental Message 3). These internal factors include natural modes of climate system variability, such as the El Niño/Southern Oscillation.

Natural changes in external forcings and internal factors have been responsible for past climate changes. At the global scale, over multiple decades, the impact of external forcings on temperature far exceeds that of internal variability (which is less than 0.5°F).[2] At the regional scale, and over shorter time periods, internal variability can be responsible for much larger changes in temperature and other aspects of climate. Today, however, the picture is very different. Although natural factors still affect climate, human activities are now the primary cause of the current warming: specifically, human activities that increase atmospheric levels of carbon dioxide (CO_2) and other heat-trapping gases and various particles that, depending on the type of particle, can have either a heating or cooling influence on the atmosphere.

The greenhouse effect is key to understanding how human activities affect the Earth's climate. As the sun shines on the Earth, the Earth heats up. The Earth then re-radiates this heat back to space. Some gases, including water vapor (H_2O), carbon dioxide (CO_2), ozone (O_3), methane (CH_4), and nitrous oxide (N_2O), absorb some of the heat given off by the Earth's surface and lower atmosphere. These heat-trapping gases then radiate energy back toward the surface, effectively trapping some of the heat inside the climate system. This greenhouse effect is a natural process, first recognized in 1824 by the French mathematician and physicist Joseph Fourier[3] and confirmed by British scientist John Tyndall in a series of experiments starting in 1859.[4] Without this natural greenhouse effect (but assuming the same albedo, or reflectivity, as today), the average surface temperature of the Earth would be about 60°F colder.

Today, however, the natural greenhouse effect is being artificially intensified by human activities. Burning fossil fuels (coal,

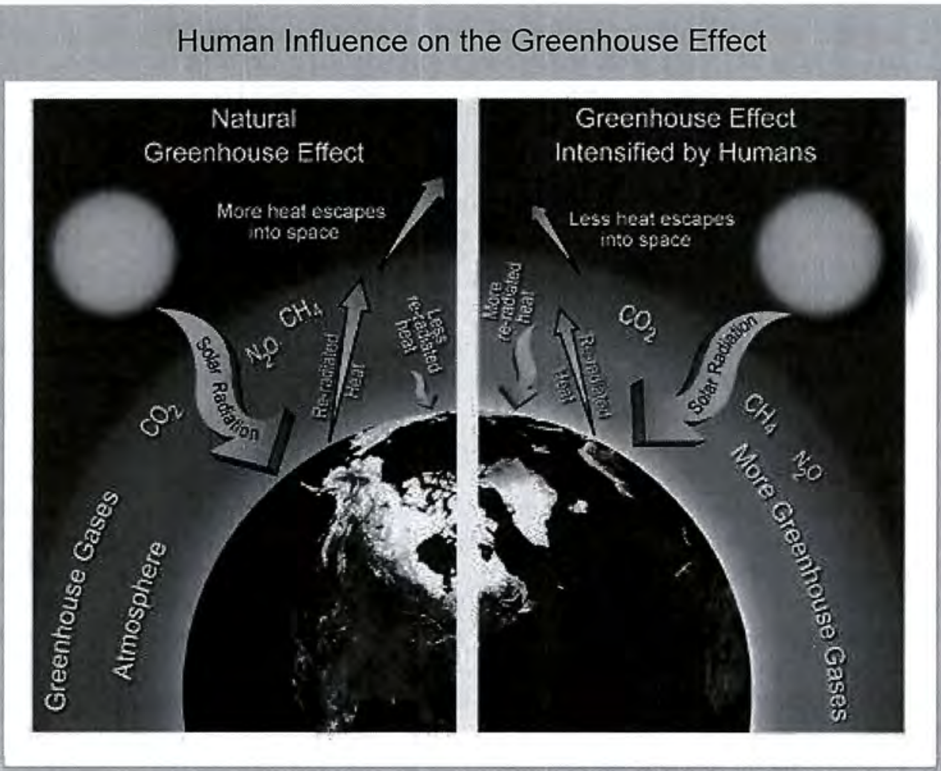


Figure 1. Left: A stylized representation of the natural greenhouse effect. Most of the sun's radiation reaches the Earth's surface. Naturally occurring heat-trapping gases, including water vapor, carbon dioxide, methane, and nitrous oxide, do not absorb the short-wave energy from the sun but do absorb the long-wave energy re-radiated from the Earth, keeping the planet much warmer than it would be otherwise. **Right**: In this stylized representation of the human-intensified greenhouse effect, human activities, predominantly the burning of fossil fuels (coal, oil, and gas), are increasing levels of carbon dioxide and other heat-trapping gases, increasing the natural greenhouse effect and thus Earth's temperature. (Figure source: modified from National Park Service[5]).

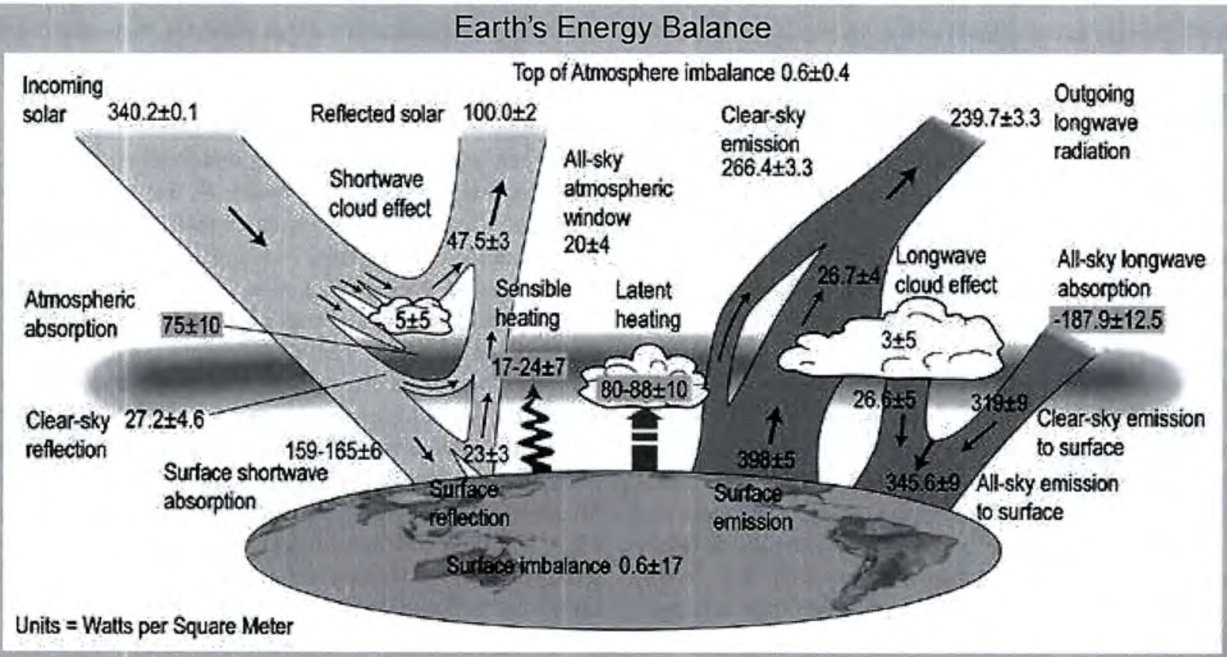


Figure 2. This figure summarizes results of measurements taken from satellites of the amount of energy coming in to and going out of Earth's climate system. It demonstrates that our scientific understanding of how the greenhouse effect operates is, in fact, accurate, based on real world measurements. (Figure source: modified from Stephens et al. 2012[6]).

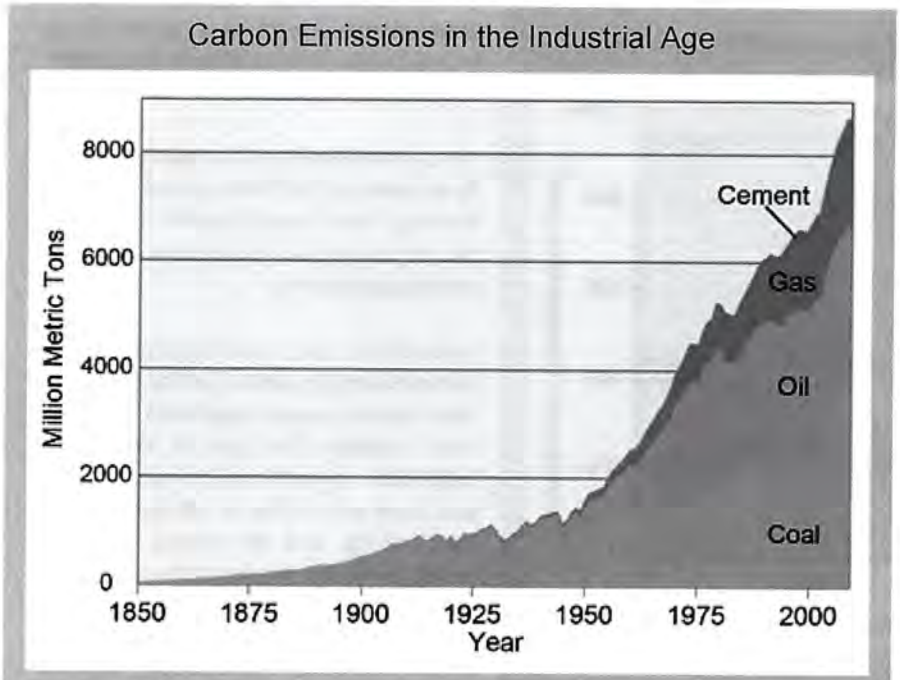


Figure 3. Global carbon emissions from burning coal, oil, and gas and producing cement (1850-2009). These emissions account for about 80% of the total emissions of carbon from human activities, with land-use changes (like cutting down forests) accounting for the other 20% in recent decades (Data from Boden et al. 2012[7]).

oil, and natural gas), clearing forests, and other human activities produce heat-trapping gases. These gases accumulate in the atmosphere, as natural removal processes are unable to keep pace with increasing emissions. Increasing atmospheric levels of CO_2, CH_4, and N_2O (and other gases and some types of particles like soot) from human activities increase the amount of heat trapped inside the Earth system. This human-caused intensification of the greenhouse effect is the primary cause of observed warming in recent decades.

Carbon dioxide has been building up in the Earth's atmosphere since the beginning of the industrial era in the mid-1700s. Emissions and atmospheric levels, or concentrations, of other important heat-trapping gases – including methane, nitrous oxide, and halocarbons – have also increased because of human activities. While the atmospheric concentrations of these gases are relatively small compared to those of molecular oxygen or nitrogen, their ability to trap heat is extremely strong. The human-induced increase in atmospheric levels of carbon dioxide and other heat-trapping gases is the main reason the planet has warmed over the past 50 years and has been an important factor in climate change over the past 150 years or more.

Carbon dioxide levels in the atmosphere are currently increasing at a rate of 0.5% per year. Atmospheric levels measured at Mauna Loa in Hawai'i and at other sites around the world reached 400 parts per million in 2013, higher than the Earth has experienced in over a million years. Globally, over the past several decades, about 78% of carbon dioxide emissions has come from burning fossil fuels, 20% from deforestation and other agricultural practices, and 2% from cement production. Some of the carbon dioxide emitted to the atmosphere is absorbed by the oceans, and some is absorbed by vegetation.

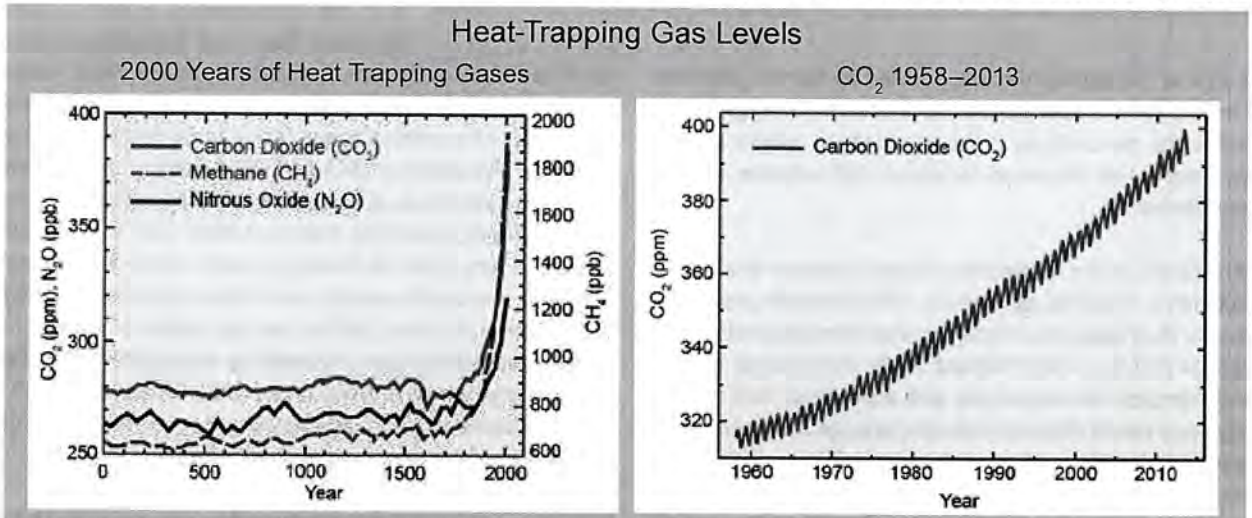


Figure 4. Present-day atmospheric levels of carbon dioxide, methane, and nitrous oxide are notably higher than their pre-industrial averages of 280, 0.7, and 0.27 parts per million (ppm) by volume, respectively (left). Air sampling data from 1958 to 2013 show long-term increases due to human activities as well as short-term variations due to natural biogeochemical processes and seasonal vegetation growth (right). (Figure sources: (left) Forster et al. 2007;[8] (right) Scripps Institution of Oceanography and NOAA Earth Systems Research Laboratory).

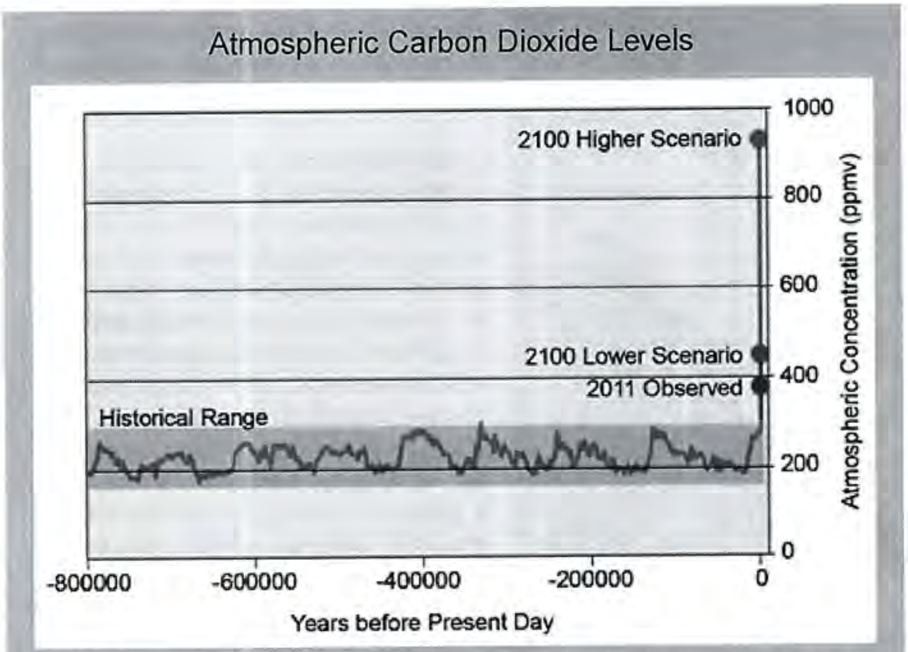


Figure 5. Air bubbles trapped in an Antarctic ice core extending back 800,000 years document the atmosphere's changing carbon dioxide concentration. Over long periods, natural factors have caused atmospheric CO_2 concentrations to vary between about 170 to 300 parts per million (ppm). As a result of human activities since the Industrial Revolution, CO_2 levels have increased to 400 ppm, higher than any time in at least the last one million years. By 2100, additional emissions from human activities are projected to increase CO_2 levels to 420 ppm under a very low scenario, which would require immediate and sharp emissions reductions (RCP 2.6), and 935 ppm under a higher scenario, which assumes continued increases in emissions (RCP 8.5). This figure shows the historical composite CO_2 record based on measurements from the EPICA (European Project for Ice Coring in Antarctica) Dome C and Dronning Maud Land sites and from the Vostok station. Data from Lüthi et al. 2008[9] (664-800 thousand years [kyr] ago, Dome C site); Siegenthaler et al. 2005[10] (393-664 kyr ago, Dronning Maud Land); Pépin 2001, Petit et al. 1999, and Raynaud 2005[11] (22-393 kyr ago, Vostok); Monnin et al. 2001[12] (0-22 kyr ago, Dome C); and Meinshausen et al. 2011[13] (future projections from RCP 2.6 and 8.5).

About 45% of the carbon dioxide emitted by human activities in the last 50 years is now stored in the oceans and vegetation. The remainder has built up in the atmosphere, where carbon dioxide levels have increased by about 40% relative to pre-industrial levels.

Methane levels in the atmosphere have increased due to human activities, including agriculture, with livestock producing methane in their digestive tracts, and rice farming producing it via bacteria that live in the flooded fields; mining coal, extraction and transport of natural gas, and other fossil fuel-related activities; and waste disposal including sewage and decomposing garbage in landfills. On average, about 55% to 65% of the emissions of atmospheric methane now come from human activities.[14,15] Atmospheric concentrations of methane leveled off from 1999-2006 due to temporary decreases in both human and natural sources,[14,15] but have been increasing again since then. Since preindustrial times, methane levels have increased by 250% to their current levels of 1.85 ppm.

Other greenhouse gases produced by human activities include ***nitrous oxide, halocarbons, and ozone.***

Nitrous oxide levels are increasing, primarily as a result of fertilizer use and fossil fuel burning. The concentration of nitrous oxide has increased by about 20% relative to pre-industrial times.

Halocarbons are manufactured chemicals produced to serve specific purposes, from aerosol spray propellants to refrigerant coolants. One type of halocarbon, long-lived chlorofluorocarbons (CFCs), was used extensively in refrigeration, air conditioning, and for various manufacturing purposes. However, in addition to being powerful heat-trapping gases, they are also responsible for depleting stratospheric ozone. Atmospheric levels of CFCs are now decreasing due to actions taken by countries under the Montreal Protocol, an international agreement designed to protect the ozone layer. As emissions and atmospheric levels of halocarbons continue to decrease, their effect on climate will also shrink. However, some of the replacement compounds are hydrofluorocarbons (HFCs), which are potent heat-trapping gases, and their concentrations are increasing.

Over 90% of the ozone in the atmosphere is in the stratosphere, where it protects the Earth from harmful levels of ultraviolet radiation from the sun. In the lower atmosphere, however, ozone is an air pollutant and also an important heat-trapping gas. Upper-atmosphere ozone levels have decreased because of human emissions of CFCs and other halocarbons. However, lower-atmosphere ozone levels have increased because of human activities, including transportation and manufacturing. These produce what are known as ozone precursors: air pollutants that react with sunlight and other chemicals to produce ozone. Since the late 1800s, average levels of ozone in the lower atmosphere have increased by more than 30%.[16] Much higher increases have been observed in areas with high levels of air pollution, and smaller increases in remote locations where the air has remained relatively clean.

Human activities can also produce tiny atmospheric particles, including dust and soot. For example, coal burning produces sulfur gases that form particles in the atmosphere. These sulfur-containing particles reflect incoming sunlight away from the Earth, exerting a cooling influence on Earth's surface.

Another type of particle, composed mainly of soot, or black carbon, absorbs incoming sunlight and traps heat in the atmosphere, warming the Earth.

In addition to their direct effects, these particles can affect climate indirectly by changing the properties of clouds. Some encourage cloud formation because they are ideal surfaces on which water vapor can condense to form cloud droplets. Some can also increase the number, but decrease the average size of cloud droplets when there is not enough water vapor compared to the number of particles available, thus creating brighter clouds that reflect energy from the sun away from the Earth, resulting in an overall cooling effect. Particles that absorb energy encourage cloud droplets to evaporate by warming the atmosphere. Depending on their type, increasing amounts of particles can either offset or increase the warming caused by increasing levels of greenhouse gases. At the scale of the planet, the net effect of these particles is to offset between 20% and 35% of the warming caused by heat-trapping gases.

The effects of all of these greenhouse gases and particles on the Earth's climate depend in part on how long they remain in the atmosphere. Human-induced emissions of carbon dioxide have already altered atmospheric levels in ways that will persist for thousands of years. About one-third of the carbon dioxide emitted in any given year remains in the atmosphere 100 years later. However, the impact of past human emissions of carbon dioxide on the global carbon cycle will endure for tens of thousands of years. Methane lasts for approximately a decade before it is removed through chemical reactions. Particles, on the other hand, remain in the atmosphere for only a few days to several weeks. This means that the effects of any human actions to reduce particle emissions can show results nearly immediately. It may take decades, however, before the results of human actions to reduce long-lived greenhouse gas emissions can be observed. Some recent studies[17] examine various means for reducing near-term changes in climate, for example, by reducing emissions of short-lived gases like methane and particles like black carbon (soot). These approaches are being explored as ways to reduce the rate of short-term warming while more comprehensive approaches to reducing carbon dioxide emissions (and hence the rate of long-term warming) are being implemented.

In addition to emissions of greenhouse gases, air pollutants, and particles, human activities have also affected climate by changing the land surface. These changes include cutting and burning forests, replacing natural vegetation with agriculture or cities, and large-scale irrigation. These transformations of the land surface can alter how much heat is reflected or absorbed by the surface, causing local and even regional warming or cooling. Globally, the net effect of these changes has probably been a slight cooling influence over the past 100 years.

Considering all known natural and human drivers of climate since 1750, a strong net warming from long-lived greenhouse gases produced by human activities dominates the recent climate record. This warming has been partially offset by increases in atmospheric particles and their effects on clouds. Two important natural external drivers also influence climate: the sun and volcanic eruptions. Since 1750, these natural external drivers are estimated to have had a small net warming influence, one that is much smaller than the human influence. Natural internal climate variations, such as El Niño events in

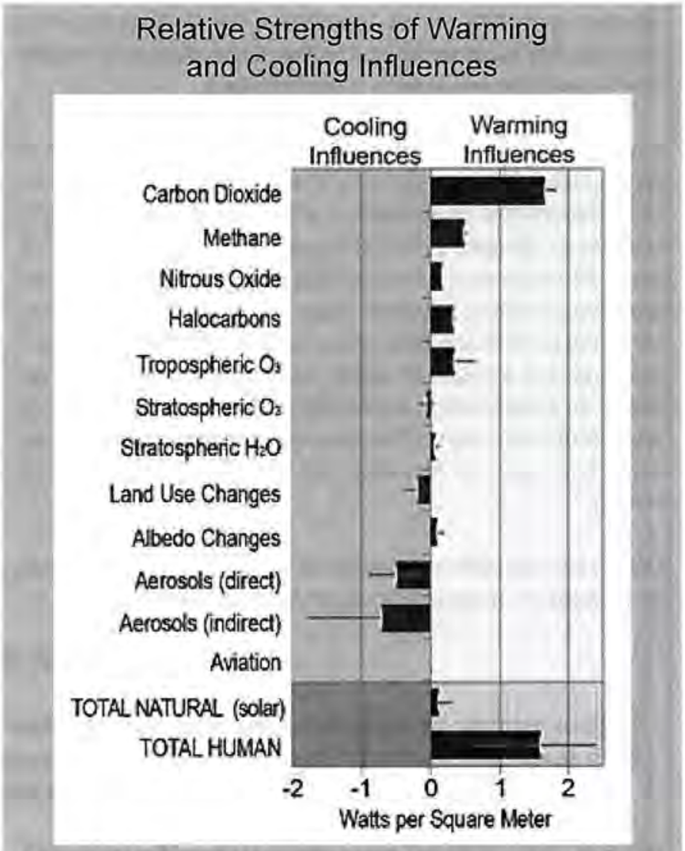


Figure 6. Different factors have exerted a warming influence (red bars) or a cooling influence (blue bars) on the planet. The warming or cooling influence of each factor is measured in terms of the change in radiative forcing in watts per square meter by 2005 relative to 1750. This figure includes all the major human-induced factors as well as the sun, the only major natural factor with a long-term effect on climate. The cooling effect of individual volcanoes is also natural, but is relatively short-lived and so is not included here. Aerosols refer to tiny particles, with their direct effects including, for example, the warming influence of black carbon (soot) and cooling influence of sulfate particles from coal burning. Indirect effects of aerosols include their effect on clouds. The net radiative influence from natural and human influences is a strong warming, predominantly from human activities. The thin lines on each bar show the range of uncertainty. (Figure source: adapted from *Climate Change 2007: The Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Figure 2.20 (A), Cambridge University Press[15]).

the Pacific Ocean, have also influenced regional and global climate. Several other modes of internal natural variability have been identified, and their effects on climate are superimposed on the effects of human activities, the sun, and volcanoes.

During the last three decades, direct observations indicate that the sun's energy output has decreased slightly. The two major volcanic eruptions of the past 30 years have had short-term cooling effects on climate, lasting two to three years. Thus, natural factors cannot explain the warming of recent decades; in fact, their net effect on climate has been a slight cooling influence over this period. In addition, the changes occurring now are very rapid compared to the major changes in climate over at least the last several thousand years.

It is not only the direct effects from human emissions that affect climate. These direct effects also trigger a cascading set of feedbacks that cause indirect effects on climate – acting to increase or dampen an initial change. For example, water vapor is the single most important gas responsible for the natural greenhouse effect. Together, water vapor and clouds account for between 66% and 80% of the natural greenhouse effect.[18] However, the amount of water vapor in the atmosphere depends on temperature; increasing temperatures increase the amount of water vapor. This means that the response of water vapor is an internal feedback, not an external forcing of the climate.

Observational evidence shows that, of all the external forcings, an increase in atmospheric CO_2 concentration is the most important factor in increasing the heat-trapping capacity of the atmosphere. Carbon dioxide and other gases, such as methane and nitrous oxide, do not condense and fall out of the atmosphere, whereas water vapor does (for example, as rain or snow). Together, heat-trapping gases other than water vapor account for between 26% and 33% of the total greenhouse effect,[18] but are responsible for most of the changes in climate over recent decades. This is a range, rather than a single number, because some of the absorption effects of water vapor overlap with those of the other important gases. Without the heat-trapping effects of carbon dioxide and the other non-water vapor greenhouse gases, climate simulations indicate that the greenhouse effect would not function, turning the Earth into a frozen ball of ice.[19]

The average conditions and the variability of the Earth's climate are critical to all aspects of human and natural systems on the planet. Human society has become increasingly complex and dependent upon the climate system and its behavior. National and global infrastructures, economies, agriculture, and ecosystems are adapted to the present climate state, which from a geologic timescale perspective has been remarkably stable for the past several thousand years. Any significant perturbation, in either direction, would have substantial impacts upon both human society and the natural world. The magnitude of the human influence on climate and the rate of change raise concerns about the ability of ecosystems and human systems to successfully adapt to future changes.

Supplemental Message 2.

Global trends in temperature and many other climate variables provide consistent evidence of a warming planet. These trends are based on a wide range of observations, analyzed by many independent research groups around the world.

There are many types of observations that can be used to detect changes in climate and determine what is causing these changes. Thermometer and other instrument-based surface weather records date back hundreds of years in some locations. Air temperatures are measured at fixed locations over land and with a mix of predominantly ship- and buoy-based measurements over the ocean. By 1850, a sufficiently extensive array of land-based observing stations and ship-borne observations had accumulated to begin tracking global average temperature. Measurements from weather balloons began in the early 1900s, and by 1958 were regularly taken around the world. Satellite records beginning in the 1970s provide additional perspectives, particularly for remote areas such as the Arctic that have limited ground-based observations. Satellites also provided new capabilities for mapping precipitation and upper air temperatures. Climate "proxies" – biological or physical records ranging from tree rings to ice cores that correlate with aspects of climate – provide further evidence of past climate that can stretch back hundreds of thousands of years.

These diverse datasets have been analyzed by scientists and engineers from research teams around the world in many different ways. The most high-profile indication of the changing climate is the surface temperature record, so it has received the most attention. Spatial coverage, equipment, methods of observation, and many other aspects of the measurement record have changed over time, so scientists identify and adjust for these changes. Independent research groups have looked at the surface temperature record for land[21] and ocean[22] as well as land and ocean combined.[23,24] Each group takes a different approach, yet all agree that it is unequivocal that the planet is warming.

There has been widespread warming over the past century. Not every region has warmed at the same pace, however, Development of Observing Capabilities

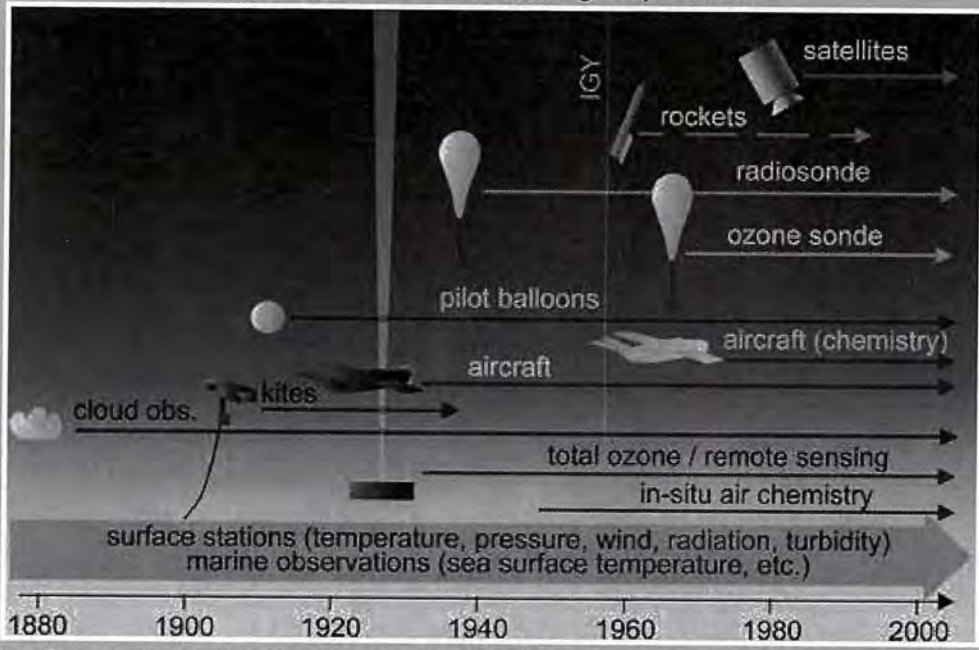


Figure 7. Changes in the mix and increasing diversity of technologies used to observe climate (IGY is the International Geophysical Year). (Figure source: adapted from Brönnimann et al. 2007[20]).

and a few regions, such as the North Atlantic Ocean (Figure 9) and some parts of the U.S. Southeast (Ch. 2: Our Changing Climate, Figure 2.7), have even experienced cooling over the last century as a whole, though they have warmed over recent decades. This is due to the stronger influence of internal variability over smaller geographic regions and shorter time scales, as mentioned in Supplemental Message 1 and discussed in more detail in Supplemental Message 3. Warming during the first half of the last century occurred mostly in the Northern Hemisphere. The last three decades have seen greater warming in response to accelerating increases in heat-trapping gas concentrations, particularly at high northern latitudes, and over land as compared to ocean.

Observed Change in Global Average Temperature

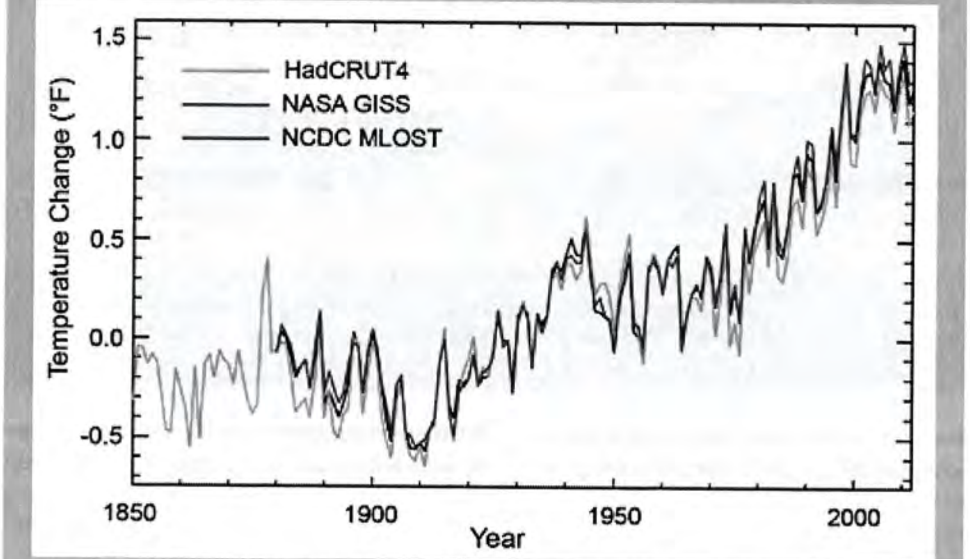


Figure 8. Three different global surface temperature records all show increasing trends over the last century. The lines show annual differences in temperature relative to the 1901-1960 average. Differences among data sets, due to choices in data selection, analysis, and averaging techniques, do not affect the conclusion that global surface temperatures are increasing. (Figure source: NOAA NCDC / CICS-NC).

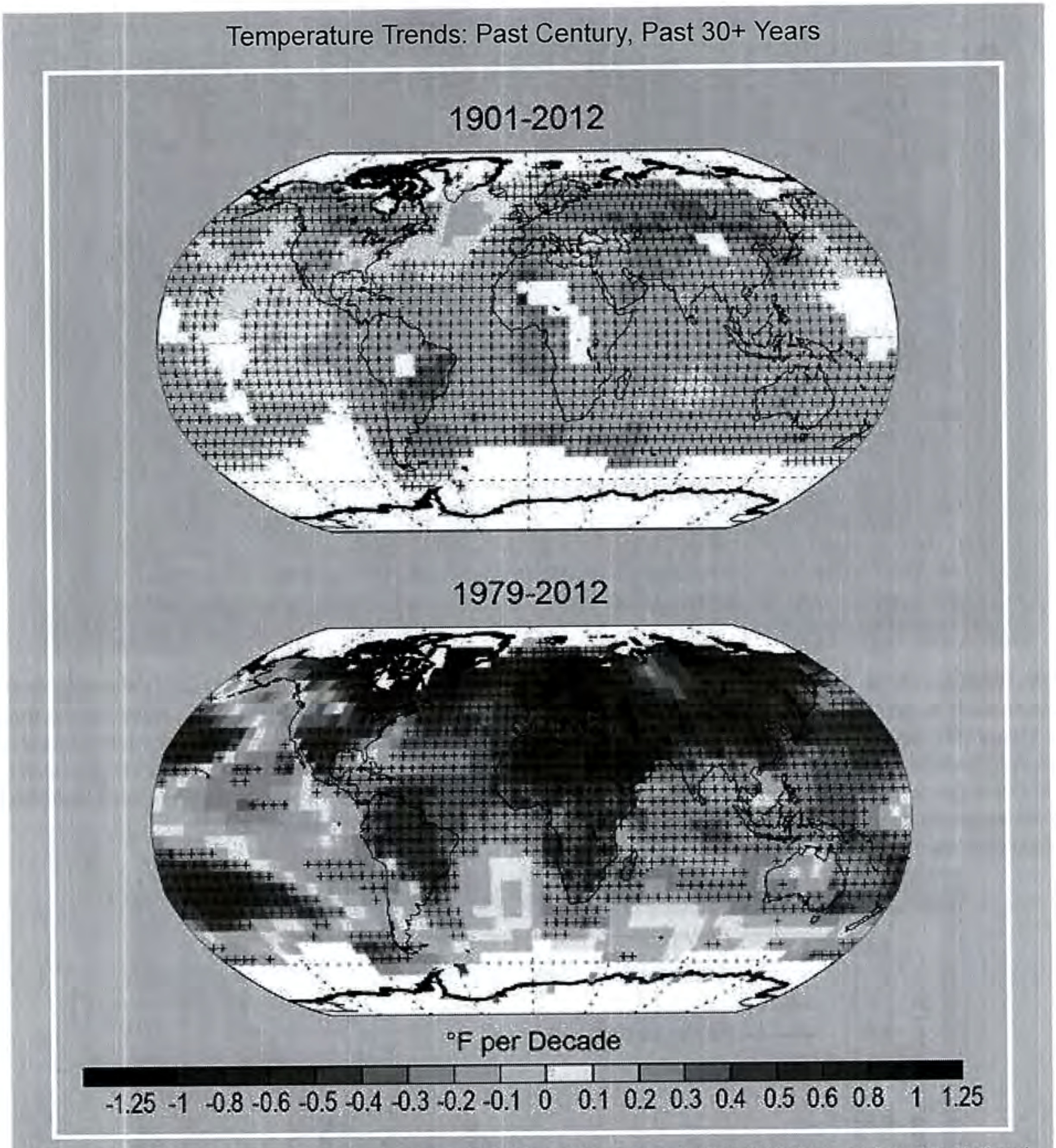


Figure 9. Surface temperature trends for the period 1901-2012 (top) and 1979-2012 (bottom) from the National Climatic Data Center's (NCDC) surface temperature product. The relatively coarse resolution of these maps does not capture the finer details associated with mountains, coastlines, and other small-scale effects. (Figure source: updated from Vose et al. 2012[24]).

Even if the surface temperature had never been measured, scientists could still conclude with high confidence that the global temperature has been increasing because multiple lines of evidence all support this conclusion. Temperatures in the lower atmosphere and oceans have increased, as have sea level and near-surface humidity. Arctic sea ice, mountain glaciers, and Northern Hemisphere spring snow cover have all decreased. As with temperature, multiple research groups have analyzed each of these indicators and come to the same conclusion: all of these changes paint a consistent and compelling picture of a warming world.

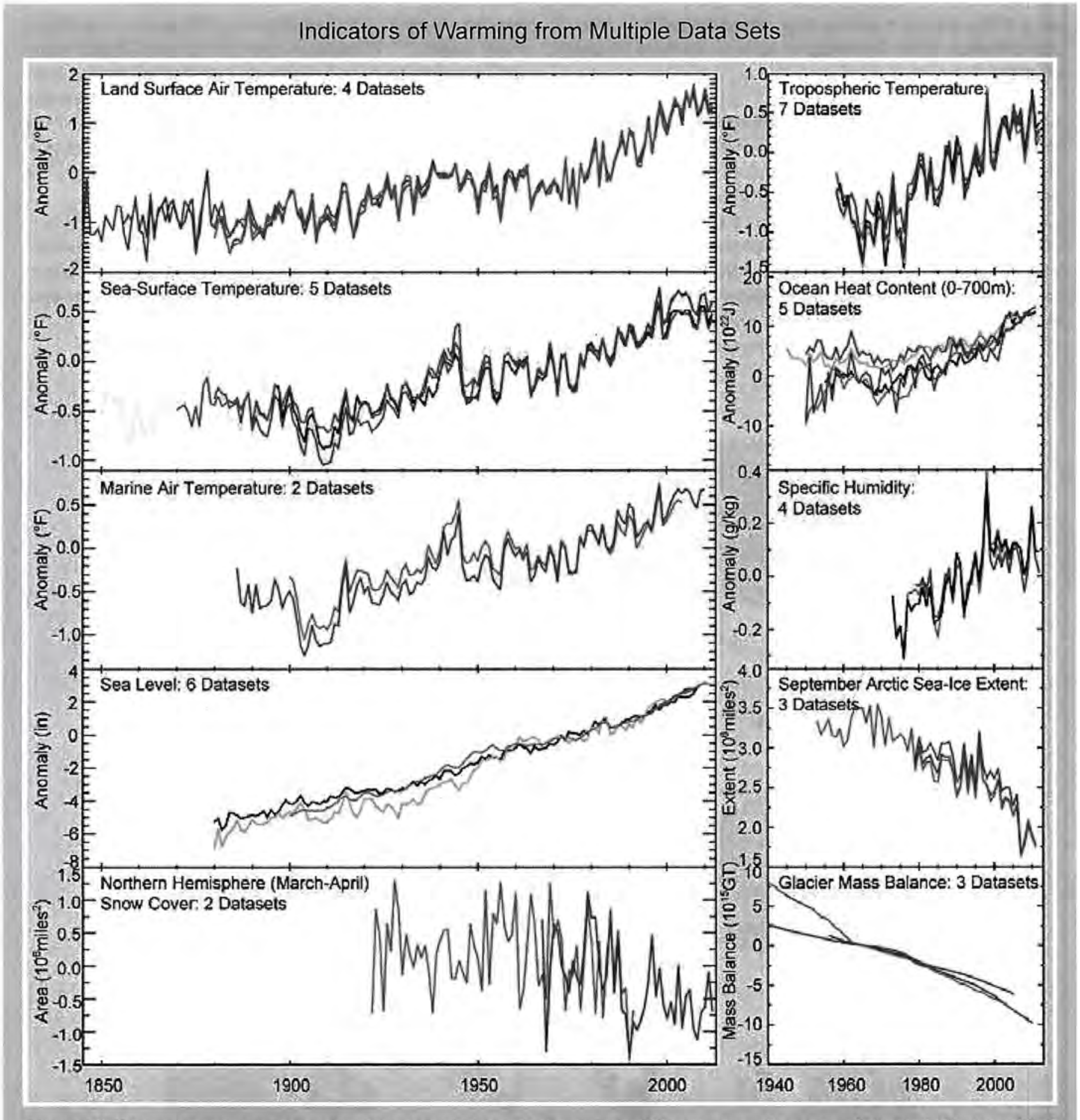


Figure 10. Observed changes, as analyzed by many independent groups in different ways, of a range of climate indicators. All of these are in fact changing as expected in a warming world. Further details underpinning this diagram can be found at http://www.ncdc.noaa.gov/bams-state-of-the-climate/. (Figure source: updated from Kennedy et al. 2010[25]).

Not all of the observed changes are directly related to temperature; some are related to the hydrological cycle (the way water moves cyclically among land, ocean, and atmosphere). Precipitation is perhaps the most societally relevant aspect of the hydrological cycle and has been observed over global land areas for over a century. However, spatial scales of precipitation are small (it can rain several inches in Washington, D.C., but not a drop in Baltimore) and this makes interpretation of the point-measurements difficult. Based upon a range of efforts to create global averages, it is likely that there has been little change in globally averaged precipitation since 1900. However, there are strong geographic trends including a likely increase in precipitation in Northern Hemisphere mid-latitude regions taken as a whole. In general, wet areas are getting wetter and dry areas are getting drier, consistent with an overall intensification of the hydrological cycle in response to global warming.

Analyses of past changes in climate during the period before instrumental records (referred to as paleoclimate) allow current changes in atmospheric composition, sea level, and climate (including extreme events), as well as future projections, to be placed in a broader perspective of past climate variability. A number of different reconstructions of the last 1,000 to 2,000 years[26,27] give a consistent picture of Northern Hemisphere temperatures, and in a few cases, global temperatures, over that time period. The analyses in the Northern Hemisphere indicate that the 1981 to 2010 period (including the last decade) was the warmest of at least the last 1,300 years and probably much longer.[28,29] A reconstruction going back 11,300 years ago[30] suggests that the last decade was warmer than at least 72% of global temperatures since the end of the last ice age 20,000 years ago. The observed warming of the last century has also apparently reversed a long-term cooling trend at mid- to high latitudes of the Northern Hemisphere throughout the last 2,000 years.

Other analyses of past climates going back millions of years indicate that past periods with high levels (400 ppm or greater) of CO_2 were associated with temperatures much higher than today's and with much higher sea levels.[31]

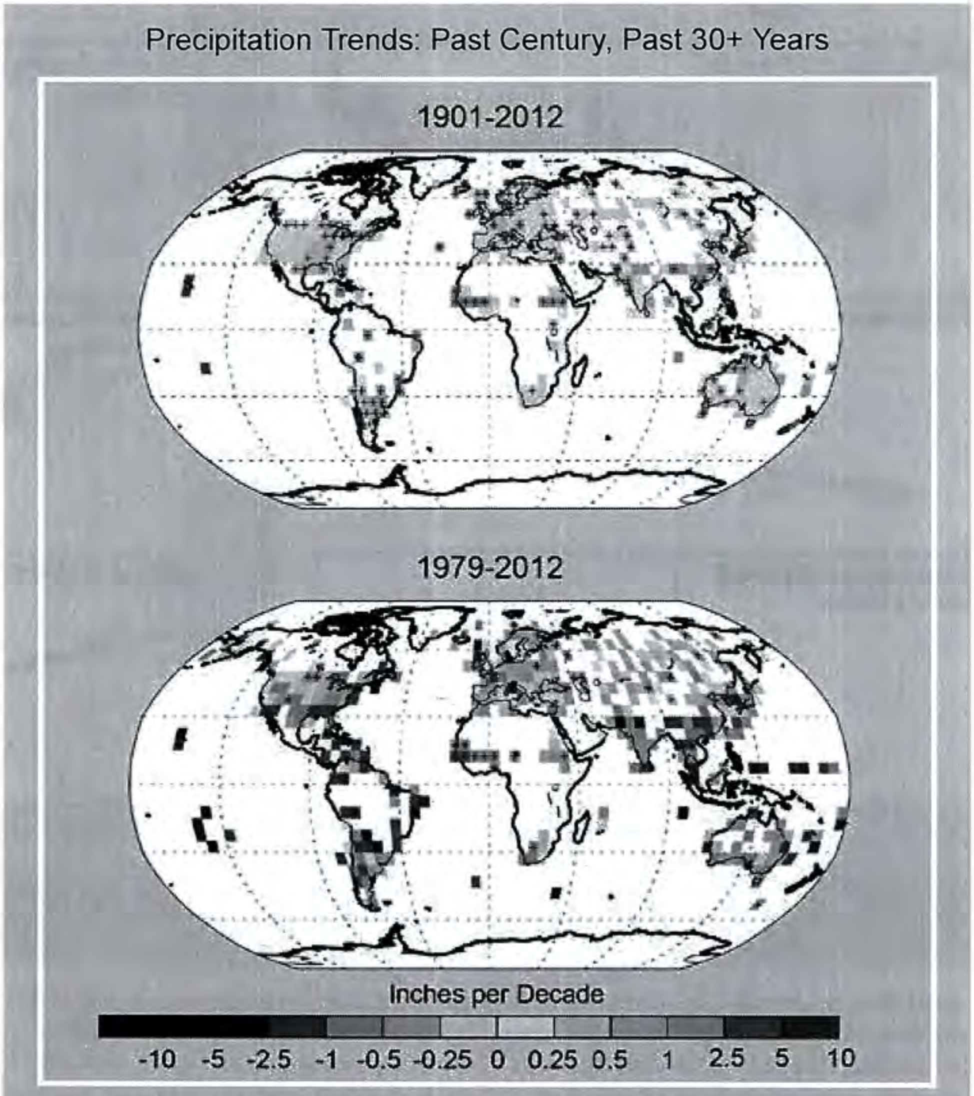


Figure 11. Global precipitation trends for the period 1901-2012 (top) and 1979-2012 (bottom). (Figure source: NOAA NCDC / CICS-NC).

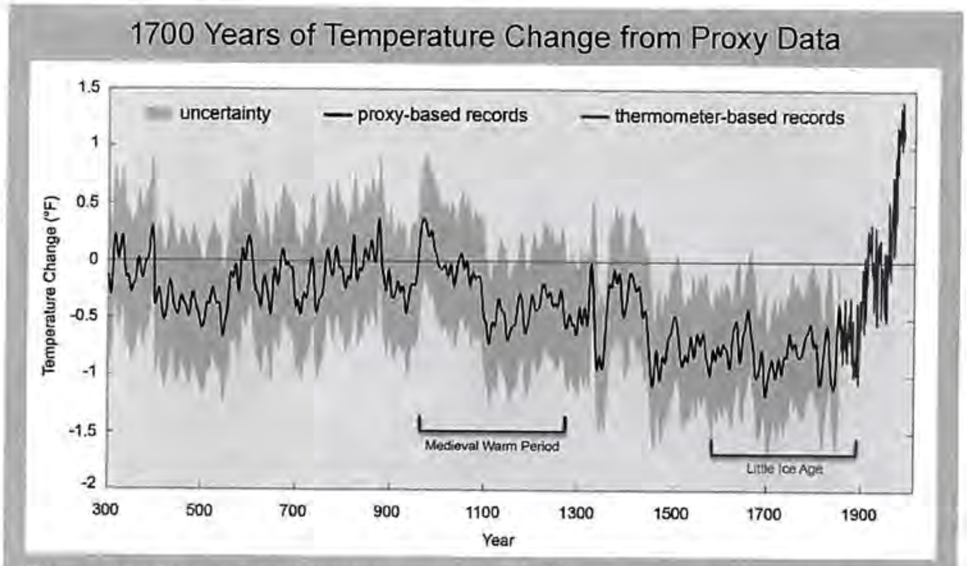


Figure 12. Changes in the temperature of the Northern Hemisphere from surface observations (in red) and from proxies (in black; uncertainty range represented by shading) relative to 1961-1990 average temperature. These analyses suggest that current temperatures are higher than seen globally in at least the last 1700 years, and that the last decade (2001 to 2010) was the warmest decade on record. (Figure source: adapted from Mann et al. 2008[27]).

Supplemental Message 3.

Natural variability, including El Niño events and other recurring patterns of ocean-atmosphere interactions, influences global and regional temperature and precipitation over timescales ranging from months up to a decade or more.

Natural variations internal to the Earth's climate system can drive increases or decreases in global and regional temperatures, as well as affect precipitation and drought patterns around the world. Today, average temperature, precipitation, and other aspects of climate are determined by a combination of human-induced changes superimposed on natural variations in both internal and external factors such as the sun and volcanoes (see Supplemental Message 1). The relative magnitudes of the human and natural contributions to temperature and climate depend on both the time and spatial scales considered. The magnitude of the effect humans are having on global temperature specifically, and on climate in general, has been steadily increasing since the Industrial Revolution. At the global scale, the human influence on climate can be either masked or augmented by natural internal variations over timescales of a decade or so (for example, Tung and Zhou 2013[32]). At regional and local scales, natural variations have an even larger effect. Over longer periods of time, however, the influence of internal natural variability on the Earth's climate system is negligible; in other words, over periods longer than several decades, the net effect of natural variability tends to sum to zero.

There are many modes of natural variability within the climate system. Most of them involve cyclical exchanges of heat and energy between the ocean and atmosphere. They are manifested by recurring changes in sea surface temperatures, for example, or by surface pressure changes in the atmosphere. While many global climate models are able to simulate the spatial patterns of ocean and atmospheric variability associated with these modes, they are less able to capture the chaotic variability in the timescales of the different modes.[33]

The largest and most well-known mode of internal natural variability is the El Niño/Southern Oscillation or ENSO. This natural mode of variability was first identified as a warm current of ocean water off the coast of Peru, accompanied by a shift in pressure between two locations on either side of the Pacific Ocean. Although centered in the tropical Pacific, ENSO affects regional temperatures and precipitation around the world by heating or cooling the lower atmosphere in low latitudes, thereby altering pressure gradients aloft. These pressure gradients, in turn, drive the upper-level winds and the jet stream that dictates patterns of mid-latitude weather, as shown in Figure 13. In the United States, for example, the warm ENSO phase (commonly referred to as El Niño) is usually associated with heavy rainfall and flooding in California and the Southwest, but decreased precipitation in the Northwest.[34] El Niño conditions also tend to suppress Atlantic hurricane formation by increasing the amount of wind shear in the region where hurricanes form.[35] The cool ENSO phase (usually called

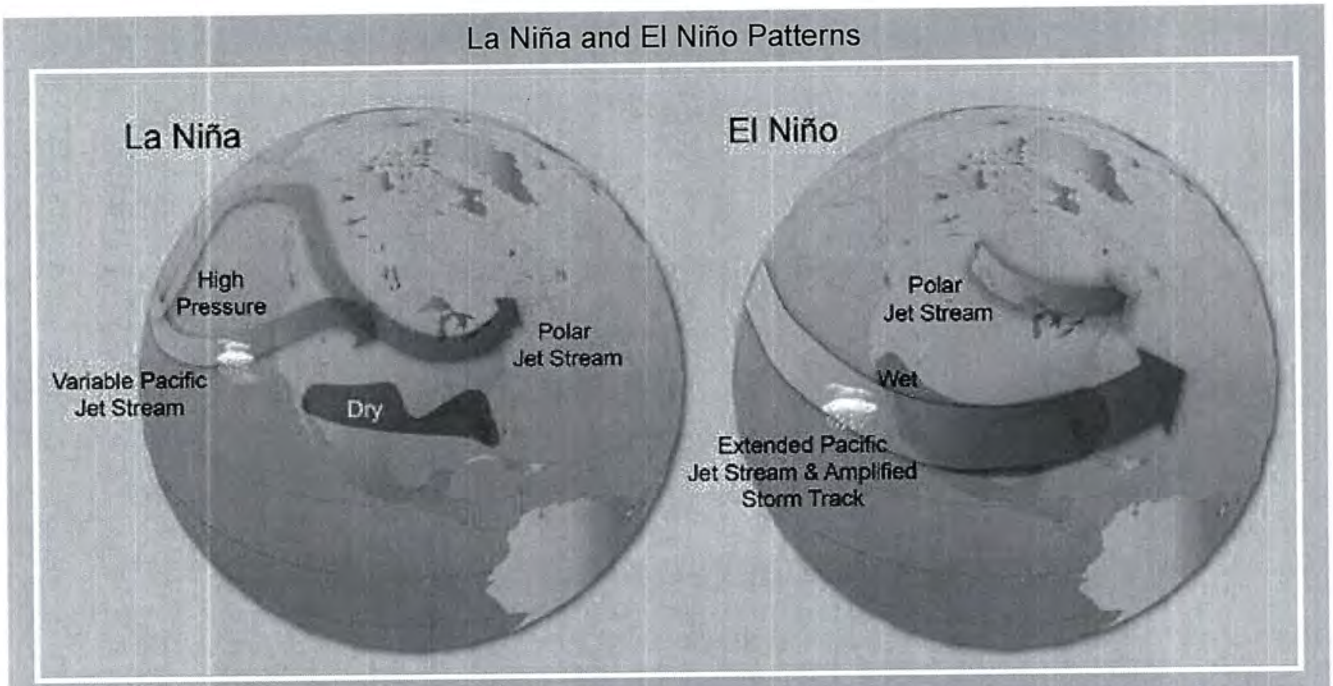


Figure 13. Typical January-March weather conditions and atmospheric circulation (jet streams shown by red and blue arrows) during La Niña and El Niño conditions. Cloud symbols show areas that are wetter than normal. During La Niña, winters tend to be unusually cold in eastern Alaska and western Canada, and dry throughout the southern United States. El Niño leads to unusually warm winter conditions in the northern U.S. and wetter than average conditions across the southern U.S. (Figure source: NOAA).

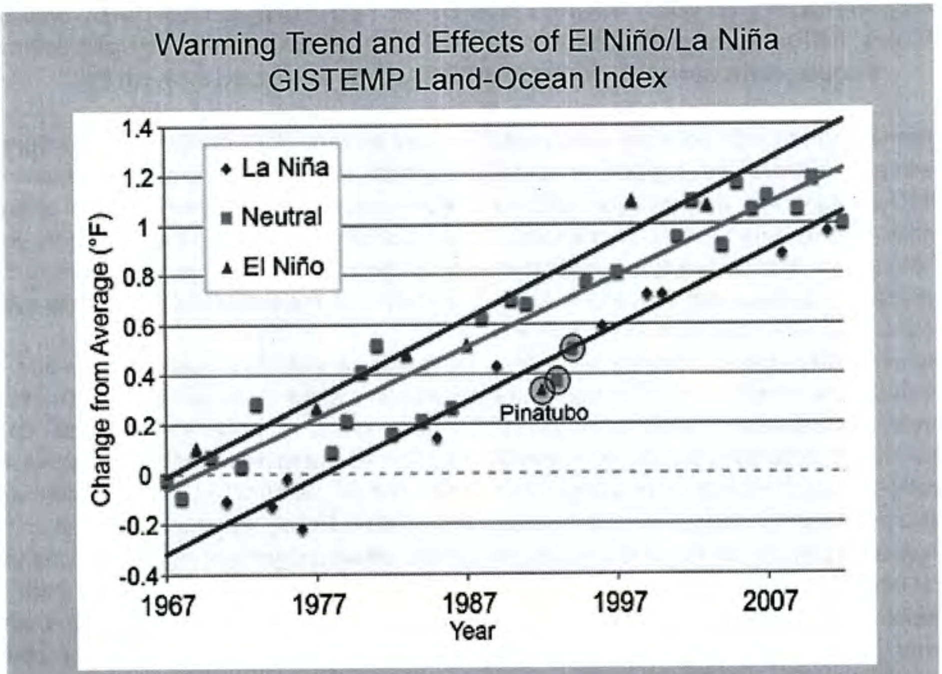


Figure 14. Trends in globally and annually averaged temperature when considering whether it was an El Niño year, a La Niña year, or a neutral year (no El Niño or La Niña event). The average global temperature is 0.4°F higher in El Niño years than in La Niña years. However, all trends show the same significant increase in temperature over the past 45 years. The years for the short-term cooling effect following the Mt. Pinatubo volcanic eruption are not included in the trends. (Figure source: adapted from John Nielsen-Gammon 2012.[38] Data from NASA GISS temperature dataset[39] and Climate Prediction Center Niño 3.4 index[40]).

La Niña) is associated with dry conditions in the Central Plains,[36] as well as a more active Atlantic hurricane season. Although these and other conditions are typically associated with ENSO, no two ENSO events are exactly alike.

Natural modes of variability such as ENSO can also affect global temperatures. In general, El Niño years tend to be warmer than average and La Niña years, cooler. The strongest El Niño event recorded over the last hundred years occurred in 1998. Superimposed on the long-term increase in global temperatures due to human activities, this event caused record high global temperatures. After 1998, the El Niño event subsided, resulting in a slowdown in the temperature increase since 1998. Overall, however, years in which there are El Niño, La Niña, or neutral conditions all show similar long-term warming trends in global temperature (see Figure 14).

Natural modes of variability like ENSO are not necessarily stationary. For example, there appears to have been a shift in the pattern and timing of ENSO in the mid-1970s, with the location of the warm water pool shifting from the eastern to the central Pacific and the frequency of events increasing. Paleoclimate studies using tree rings show that ENSO activity over the last 100 years has been the highest in the last 500 years,[37] and both paleoclimate and modeling studies suggest that global temperature increases may interact with natural variability in ways that are difficult to predict. Climate models can simulate the statistical behavior of these variations in temperature trends. For example, models can project whether some phenomena will increase or decrease in frequency, but cannot predict the exact timing of particular events far into the future.

There are other natural modes of variability in the climate system. For example, the North Atlantic Oscillation is frequently linked to variations in winter snowfall along the Atlantic seaboard. The Pacific Decadal Oscillation was first identified as a result of its effect on the Pacific salmon harvest. The influence of these and other natural variations on global temperatures is generally less than ENSO, but local influences may be large.

A combination of natural and human factors explains regional "warming holes" where temperatures actually decreased for several decades in the middle to late part of the last century at a few locations around the world. In the United States, for example, the Southeast and parts of the Great Plains and Midwest regions did not show much warming over that time period, though they have warmed in recent decades. Explanations include increased cloud cover and precipitation,[41] increased small particles from coal burning, natural factors related to forest re-growth,[42] decreased heat flux due to irrigation,[43] and multidecade variability in North Atlantic and tropical Pacific sea surface temperatures.[44,45] The importance of tropical Pacific and Atlantic sea surface temperatures on temperature and precipitation variability over the central U.S. has been particularly highlighted by many studies. Over the next few decades, as the multi-decadal tropical Pacific Ocean cycle continues its effect on sea surface temperatures, the U.S. Southeast could warm at a rate that is faster than the global average.[45]

At the global scale, natural variability will continue to modify the long-term trend in global temperature due to human activities, resulting in greater and lesser trends over relatively short time scales. Interactions among various components of the Earth's climate system produce patterns of natural variability that can be chaotic, meaning that they are sensitive to the initial conditions of the climate system. Global climate models simulate natural variability with varying degrees of realism, but the timing of these random variations differs among models and cannot be expected to coincide with those of the actual climate system. Over climatological time periods, however, the net effect of natural internal variability on the global climate

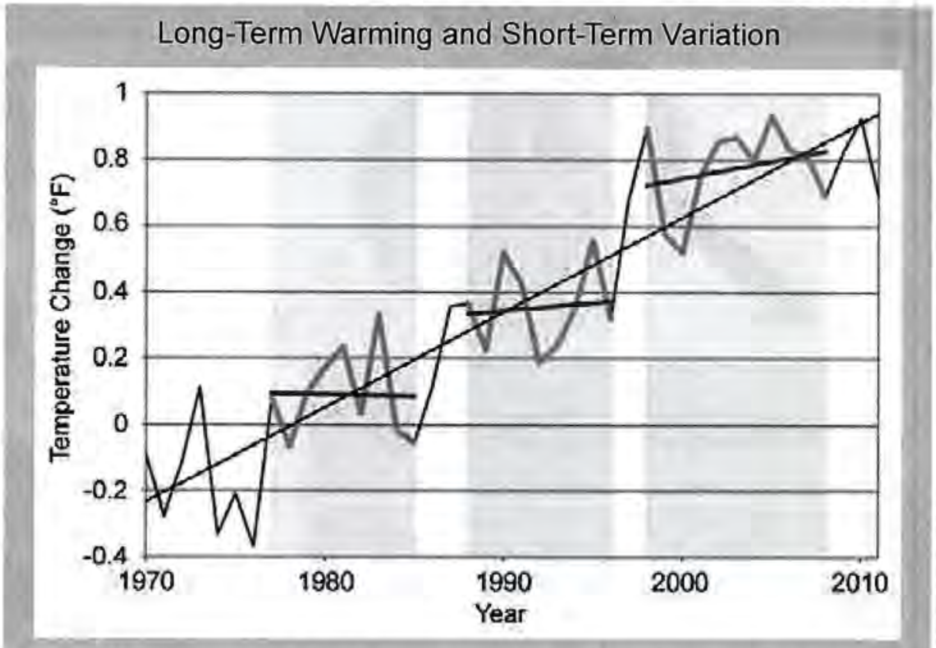


Figure 15. Observations of global mean surface air temperature show that although there can be short periods with little or even no significant upward trend (red trend lines in shaded areas), global temperature continues to rise unabated over long-term climate timescales (black trend line). The recent period, 1998-2012, is another example of a short-term pause embedded in the underlying warming trend. The differences between short-term trends and the underlying (long-term) trend are often associated with modes of natural variability such as El Niño and La Niña that redistribute heat between the ocean and atmosphere. (Data from NOAA NCDC).

tends to average to zero. For example, there can be warmer years due to El Niño (such as 1998) and cooler years due to La Niña (such as 2011), but over multiple decades the net effect of natural variability on uncertainty in global temperature and precipitation projections is small.

Averaging (or compositing) of projections from different models smooths out the randomly occurring natural variations in the different models, leaving a clear signal of the long-term externally forced changes in climate, not weather. In this report, all future projections are averaged over 20- to 30-year time periods.

Supplemental Message 4.

Human-induced increases in atmospheric levels of heat-trapping gases are the main cause of observed climate change over the past 50 years. The "fingerprints" of human-induced change also have been identified in many other aspects of the climate system, including changes in ocean heat content, precipitation, atmospheric moisture, and Arctic sea ice.

Determining the causes of climate changes is a field of research known as "detection and attribution." *Detection* involves identifying a climate trend or event (for instance, long-term surface air temperature trends, or a particularly extreme heat wave) that is strikingly outside the norm of natural variations in the climate system. Similar to conducting forensic analysis on evidence from a crime scene, *attribution* involves considering the possible causes of an observed event or change, and identifying which factor(s) are responsible.

Detection and attribution studies use statistical analyses to identify the causes of observed changes in temperature, precipitation, and other aspects of climate. They do this by trying to match the complex "fingerprint" of the observed climate system behavior to a set of simulated changes in climate that would be caused by different forcings.[46] Most approaches consider not only global but also regional patterns of changes over time.

Climate simulations are used to test hypotheses regarding the causes of observed changes. First, simulations that include changes in both natural and human forcings that may cause climate changes, such as changes in energy from the sun and increases in heat-trapping gases, are used to characterize what

Detection and Attribution as Forensics

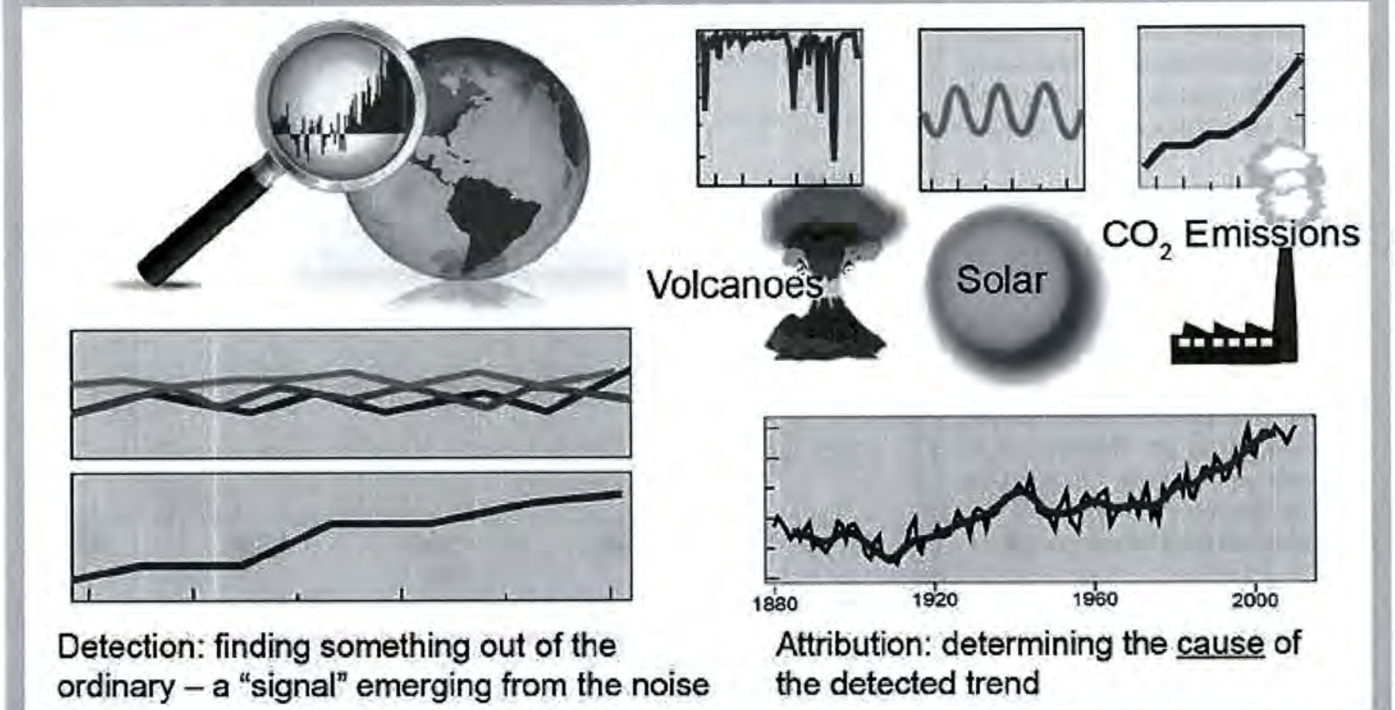


Figure 16. Simplified image of the methodology that goes into detection and attribution of climate changes. The natural factors considered usually include changes in the sun's output and volcanic eruptions, as well as natural modes of variability such as El Niño and La Niña. Human factors include the emissions of heat-trapping gases and particles as well as clearing of forests and other land-use changes. (Figure source: NOAA NCDC / CICS-NC).

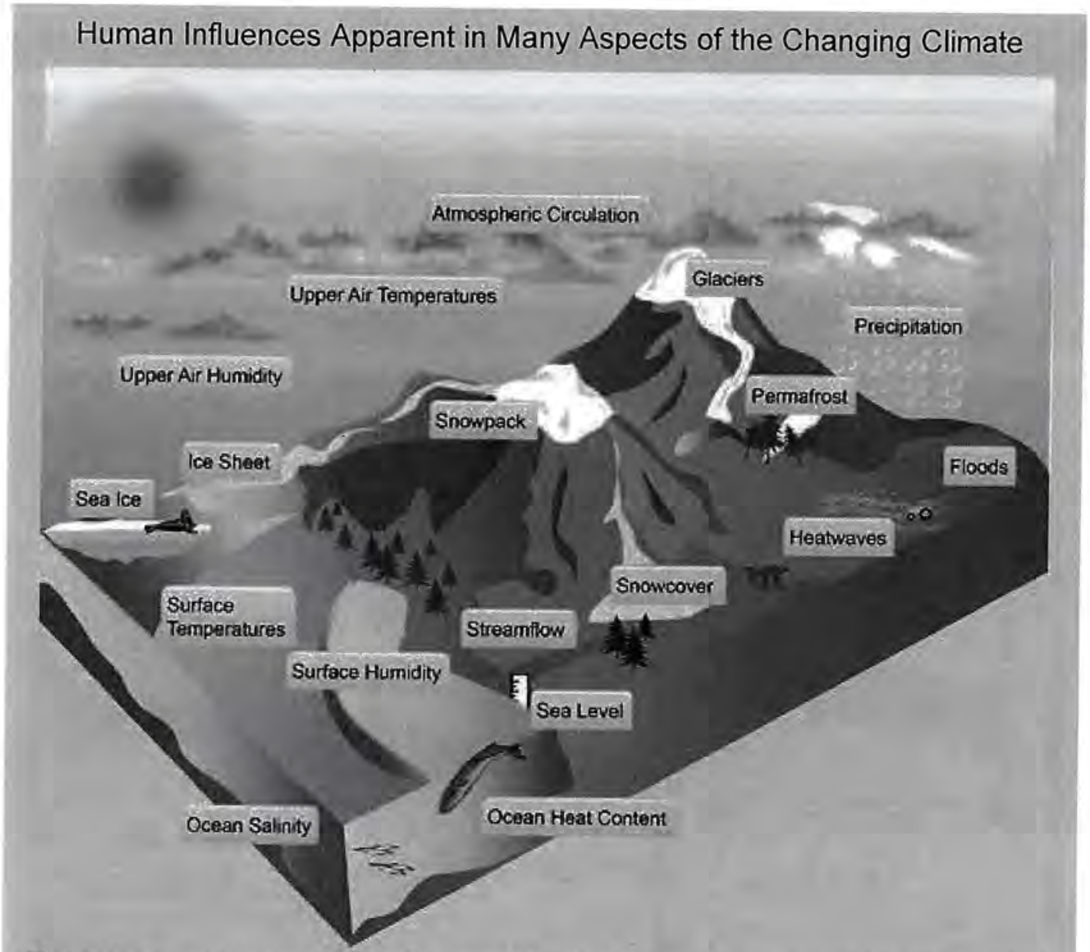
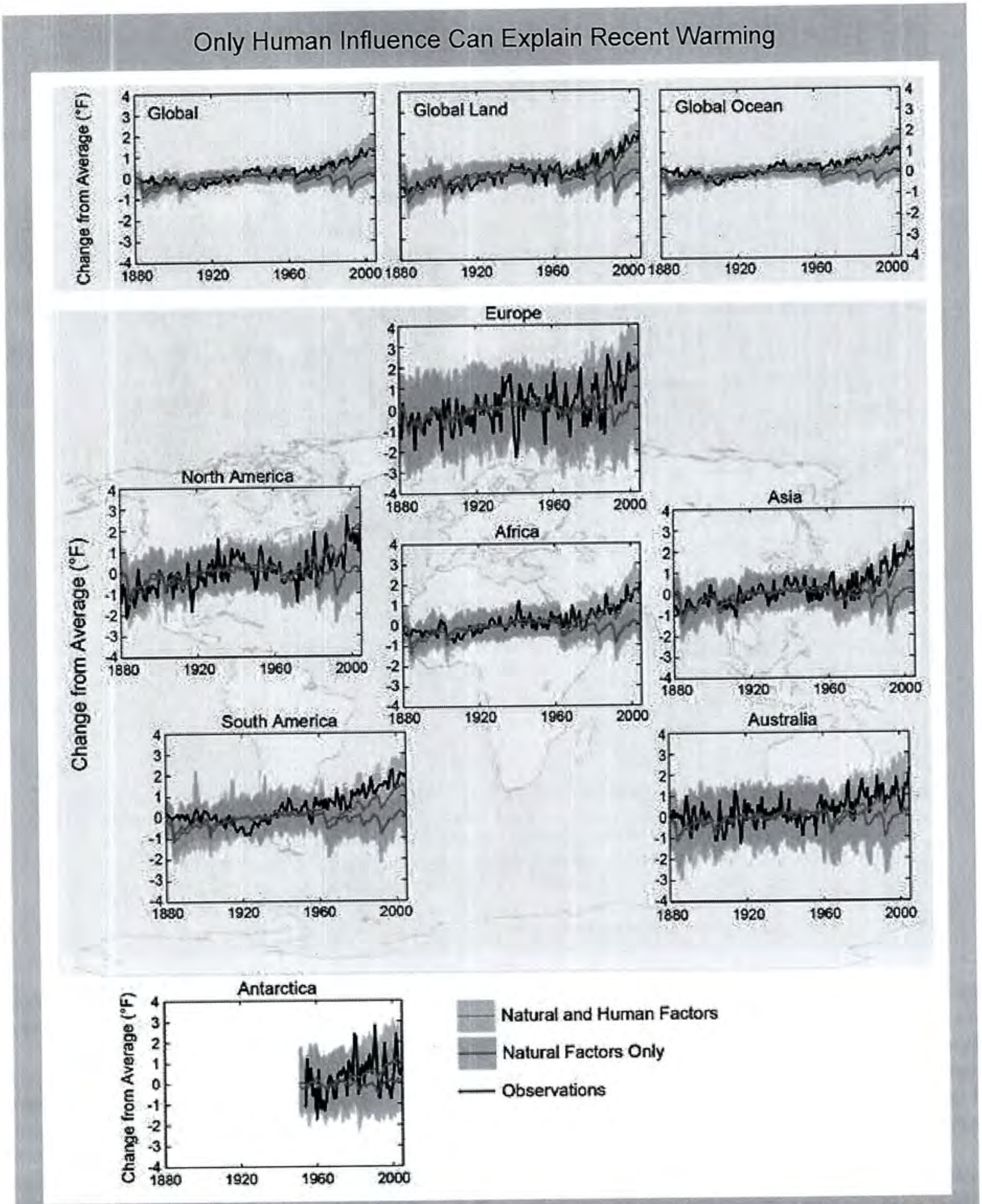


Figure 17. Figure shows examples of the many aspects of the climate system in which changes have been formally attributed to human emissions of heat-trapping gases and particles by studies published in peer-reviewed science literature. For example, observed changes in surface air temperature at both the global and continental levels, particularly over the past 50 years or so, cannot be explained without including the effects of human activities. While there are undoubtedly many natural factors that have affected climate in the past and continue to do so today, human activities are the dominant contributor to recently observed climate changes. (Figure source: NOAA NCDC).

effect those factors would have had working together. Then, simulations with no changes in external forcings, only changes due to natural variability, are used to characterize what would be expected from normal internal variations in the climate. The results of these simulations are compared to observations to see which provides the best match for what has really occurred.

Detection and attribution studies have been applied to study a broad range of changes in the climate system as well as a number of specific extreme events that have occurred in recent years. These studies have found that human influences are the only explanation for the observed changes in climate over the last half-century. Such changes include increases in surface temperatures,[46,47] changes in atmospheric vertical temperature profiles,[48] increases in ocean heat content,[49] increasing atmospheric humidity,[50] increases in intensity of precipitation[51] and in runoff,[52] indirectly estimated through changes in ocean salinity,[53] shifts in atmospheric circulation,[54] and changes in a host of other indices.[46] Taken together these paint a coherent picture of a planet whose climate is changing primarily as a result of human activities.

Detection and attribution of specific events is more challenging than for long-term trends as there are less data, or evidence, available from which to draw conclusions. Attribution of extreme events is especially scientifically challenging.[56] Many extreme weather and climate events observed to date are within the range of what could have occurred naturally, but the probability, or odds, of some of these very rare events occurring[57] has been significantly altered by human influences on the climate system. For example, studies have concluded that there is a detectable human influence in recent heat waves in Europe,[58] Russia,[59] and Texas[60] as well as flooding events in England and Wales,[61] the timing and magnitude of snowmelt and resulting streamflow in some western U.S. states,[62,63] and some specific events around the globe during 2011.[64]



Only Human Influence Can Explain Recent Warming

Figure 18. Changes in surface air temperature at the continental and global scales can only be explained by the influence of human activities on climate. The black line depicts the annually averaged observed changes. The blue shading shows climate model simulations that include the effects of natural (solar and volcanic) forcing only. The orange shading shows climate model simulations that include the effects of both natural and human contributions. These analyses demonstrate that the observed changes, both globally and on a continent-by-continent basis, are caused by the influence of human activities on climate. (Figure source: updated from Jones et al. 2013[55]).

Supplemental Message 5.

Past emissions of heat-trapping gases have already committed the world to a certain amount of future climate change. How much more the climate will change depends on future emissions and the sensitivity of the climate system to those emissions.

A certain amount of climate change is already inevitable due to the build-up of CO_2 in the atmosphere from human activities, most of it since the Industrial Revolution. A decrease in temperature would only be expected if there was an unexpected decrease in natural forcings, such as a reduction in the power of the sun. The Earth's climate system, particularly the ocean, tends to lag behind changes in atmospheric composition by decades, and even centuries, due to the large heat capacity of the oceans and other factors. Even if all emissions of the relevant gases and particles from human activity suddenly stopped, a temperature increase of 0.5°F still would occur over the next few decades,[65] and the human-induced changes in the global carbon cycle would persist for thousands of years.[66]

Global emissions of CO_2 and other heat-trapping gases continue to rise. How much climate will change over this century and beyond depends primarily on: 1) human activities and resulting emissions, and 2) how sensitive the climate is to those changes (that is, the response of global temperature to a change in radiative forcing caused by human emissions). Uncertainties in how the economy will evolve, what types of energy will be used, or what our cities, buildings, or cars will look like in the future all limit scientists' ability to predict the future changes in climate. Scientists can, however, develop scenarios – plausible projections of what might happen, under a given set of assumptions. These scenarios describe possible futures in terms of population, energy sources, technology, heat-trapping gas emissions, atmospheric levels of carbon dioxide, and/or global temperature change.

Over the next few decades, the greater part of the range (or uncertainty) in projected global and regional change is the result of natural variability and scientific limitations in our ability to model and understand the Earth's climate system (natural variability is discussed in Supplemental Message 3 and scientific or model uncertainty in Supplemental Message 6). By the second half of the century, however, scenario uncertainty (that is, uncertainty about what will be the level of emissions from human activities) becomes increasingly dominant in determining the magnitude and patterns of future change, particularly for temperature-related aspects.[67] Even though natural variability will continue to occur, most of the difference between present and future climates will be determined by choices that society makes today and over the next few decades. The further out in time we look, the greater the influence of human choices on the magnitude of future change.

For temperature, it is clear that increasing emissions from human activities will drive consistent increases in global and most regional temperatures and that these rising temperatures will increase with the magnitude of future emissions (see Figure 19 and Ch. 2: Our Changing Climate, Figures 2.8 and 2.9). Uncertainty in projected temperature change is generally smaller than uncertainty in projected changes in precipitation or other aspects of climate.

Future climate change also depends on "climate sensitivity," generally summarized as the response of global temperature to a doubling of CO_2 levels in the atmosphere relative to pre-industrial levels of 280 parts per million. If the only impact of increasing atmospheric CO_2 levels were to amplify the natural greenhouse effect (as CO_2 levels increase, more of the Earth's heat is absorbed by the atmosphere before it can escape to space, as discussed in Supplemental Message 1), it would be relatively easy to calculate the change in global temperature that would result from a given increase in CO_2 levels. However, a series of feedbacks within the Earth's climate system acts to amplify or diminish an initial change, adding some uncertainty to the precise climate sensitivity. Some important feedbacks include:

- Clouds – Will warming increase or decrease cloudiness? Will the changes be to lower-altitude clouds that primarily reflect the sun's energy, or higher clouds that trap even more heat within the Earth system?
- Albedo (reflectivity) – How quickly will bright white reflective surfaces, such as snow and ice that reflect most of the sun's energy, melt and be replaced by a dark ocean or land area that absorbs most of the sun's energy? How will vegetation changes caused by climate change alter surface reflectivity?
- Carbon dioxide absorption by the ocean and the biosphere – Will the rate of uptake increase in the future, helping to remove human emissions from the atmosphere? Or will it decrease, causing emissions to build up even faster than they are now?

Feedbacks are particularly important in the Arctic, where rising temperatures melt ice and snow, exposing relatively dark land and ocean, which absorb more of the sun's energy, heating the region even further. Rising temperatures also thaw permafrost, releasing carbon dioxide and methane trapped in the previously frozen ground into the atmosphere, where they further amplify the greenhouse effect (see Supplemental Message 1). Both of these feedbacks act to further amplify the initial warming due to human emissions of carbon dioxide and other heat-trapping gases.

Together, these and other feedbacks determine the long-term response of the Earth's temperature to an increase in carbon dioxide and other emissions from human activities. Past observations, including both recent measurements and studies that look at climate changes in the distant past, cannot tell us precisely how sensitive the climate system will be to increasing emissions of heat-trapping gases if we are starting from today's conditions. They can tell us, however, that the net effect of these feedbacks will be to increase, not diminish, the direct warming effect. In other words, the climate system will warm by more than would be expected from the greenhouse effect alone.

Quantifying the effect of these feedbacks on global and regional climate is the subject of ongoing data collection and active research. As noted above, one measure used to study these effects is the "equilibrium climate sensitivity," which is an estimate of the temperature change that would result, once the climate had reached an equilibrium state, as a result of doubling the CO_2 concentration from pre-industrial levels. The equilibrium climate sensitivity has long been estimated to be in the range of 2.7°F to 8.1°F. The 2007 IPCC Fourth Assessment Report[15] refined this range based on more recent evidence to conclude that the value is likely to be in the range 3.6°F to 8.1°F, with a most probable value of about 5.4°F, based upon multiple observational and modeling constraints, and that it is very unlikely to be less than 2.7°F. Climate sensitivities determined from a variety of evidence agree well with this range, including analyses of past paleoclimate changes.[68,69] This is substantially greater than the increase in temperature from just the direct radiative effects of the CO_2 increase (around 2°F).

Some recent studies (such as Fasullo and Trenberth 2012[70]) have suggested that climate sensitivities are at the higher end of this range, while others have suggested values at the lower end of the range.[71,72] Some recent studies have even suggested that the climate sensitivity may be less than 2.7°F based on analyses of recent temperature trends.[72] However, analyses based on recent temperature trends are subject to significant uncertainties in the treatment of natural variability,[69] the effects of volcanic eruptions,[73] and the effects of recent accelerated penetration of heat to the deep ocean.[74]

The equilibrium climate sensitivity is sometimes confused with the "transient climate response," defined as the temperature change for a 1% per year CO_2 increase, and calculated using the difference between the start of the experiment and a 20-year period centered on the time of CO_2 doubling. This value is generally smaller than the equilibrium climate sensitivity because of the slow rate at which heat transfers between the oceans and the atmosphere due to transient heat uptake of the ocean. The transient climate response is better constrained than the equilibrium climate sensitivity.[15] It is very likely larger than 1.8°F and very unlikely to be greater than 5.4°F. This transient response includes feedbacks that respond to global temperature change over timescales of years to decades. These "fast" feedbacks include increases in atmospheric water vapor, reduction of ice and snow, warming of the ocean surface, and changes in cloud characteristics. The entire response of the climate system will not be fully seen until the deep ocean comes into balance with the atmosphere, a process that can take thousands of years.

Combining the uncertainty due to climate sensitivity with the uncertainty due to human activities produces a range of future temperature changes that overlap over the first half of this century, but begins to separate over the second half of the century as emissions and atmospheric CO_2 levels diverge.

Emissions, Concentrations, and Temperature Projections

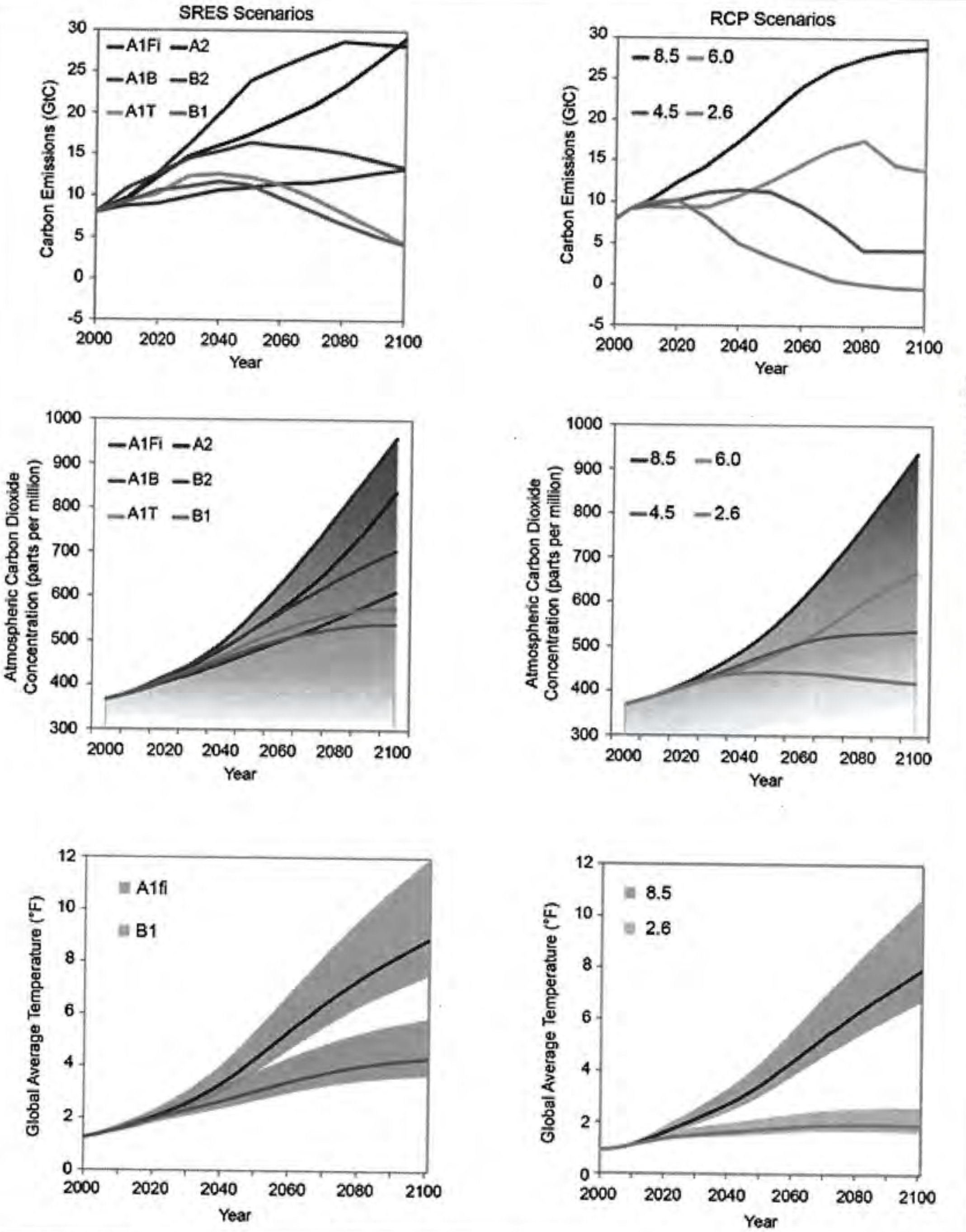


Figure 19. Two families of scenarios are commonly used for future climate projections: the 2000 Special Report on Emission Scenarios (SRES, left) and the 2010 Representative Concentration Pathways (RCP, right). The SRES scenarios are named by family (A1, A2, B1, and B2), where each family is designed around a set of consistent assumptions: for example, a world that is more integrated or more divided. In contrast, the RCP scenarios are simply numbered according to the change in radiative forcing (from +2.6 to +8.5 watts per square meter) that results by 2100. This figure compares SRES and RCP annual carbon emissions (top), carbon dioxide equivalent levels in the atmosphere (middle), and temperature change that would result from the central estimate (lines) and the likely range (shaded areas) of climate sensitivity (bottom). At the top end of the range, the older SRES scenarios are slightly higher. Comparing carbon dioxide concentrations and global temperature change between the SRES and RCP scenarios, SRES A1fI is similar to RCP 8.5; SRES A1B to RCP 6.0 and SRES B1 to RCP 4.5. The RCP 2.6 scenario is much lower than any SRES scenario because it includes the option of using policies to achieve net negative carbon dioxide emissions before end of century, while SRES scenarios do not. (Data from CMIP3 and CMIP5).

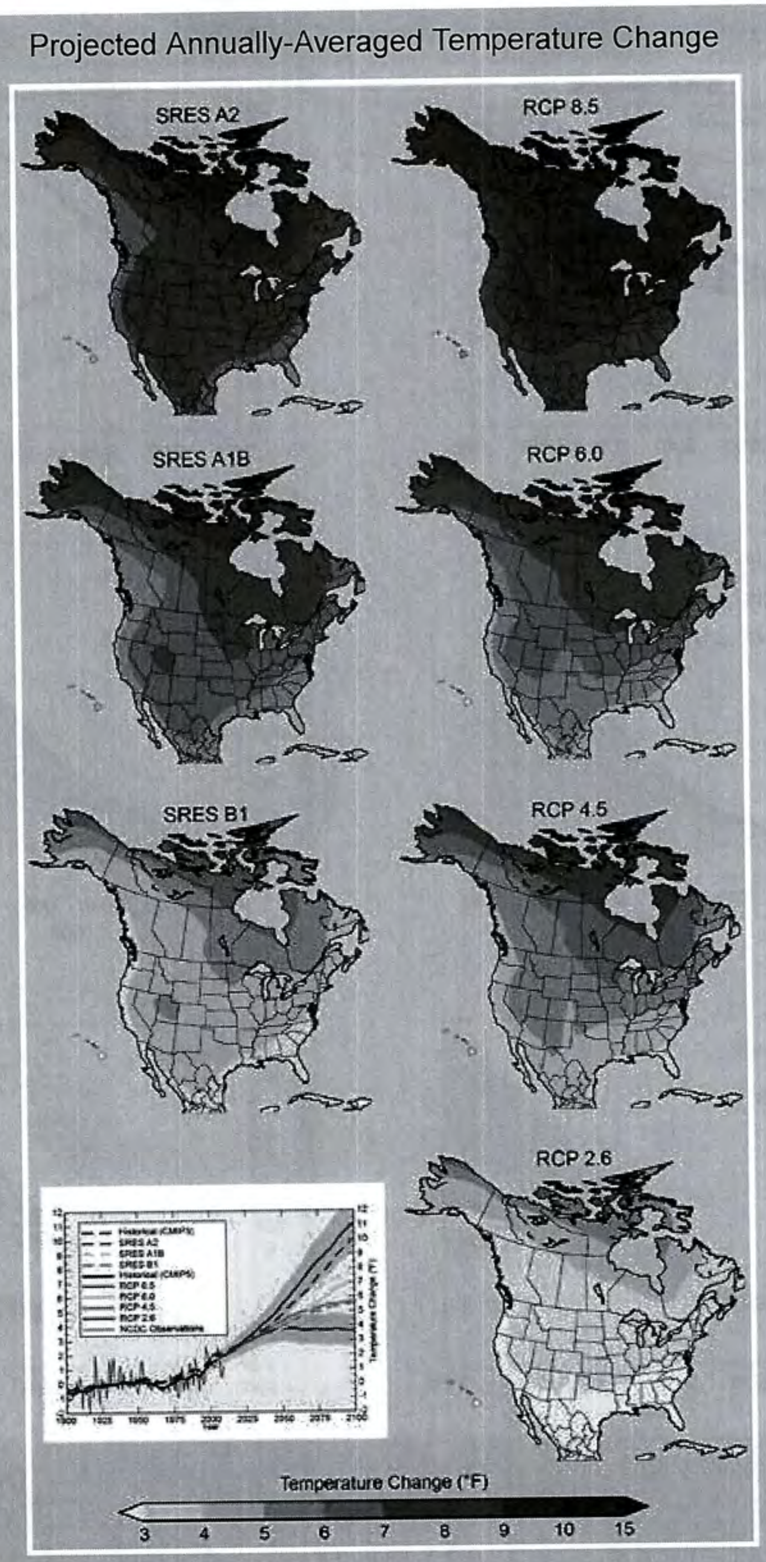


Figure 20. Projected change in surface air temperature at the end of this century (2071-2099) relative to the end of the last century (1970-1999). The older generation of models (CMIP3) and SRES emissions scenarios are on the left side; the new models (CMIP5) and scenarios are on the right side. The scenarios are described under Supplemental Message 5 and in Figure 19. Differences between the old and new projections are mostly a result of the differences in the scenarios of the emission of heat-trapping gases rather than the increased complexity of the new models. None of the new scenarios are exactly the same as the old ones, although at the end of the century SRES B1 and RCP 4.5 are roughly comparable, as are SRES A1B and RCP 6.0. (Figure source: NOAA NCDC / CICS-NC).

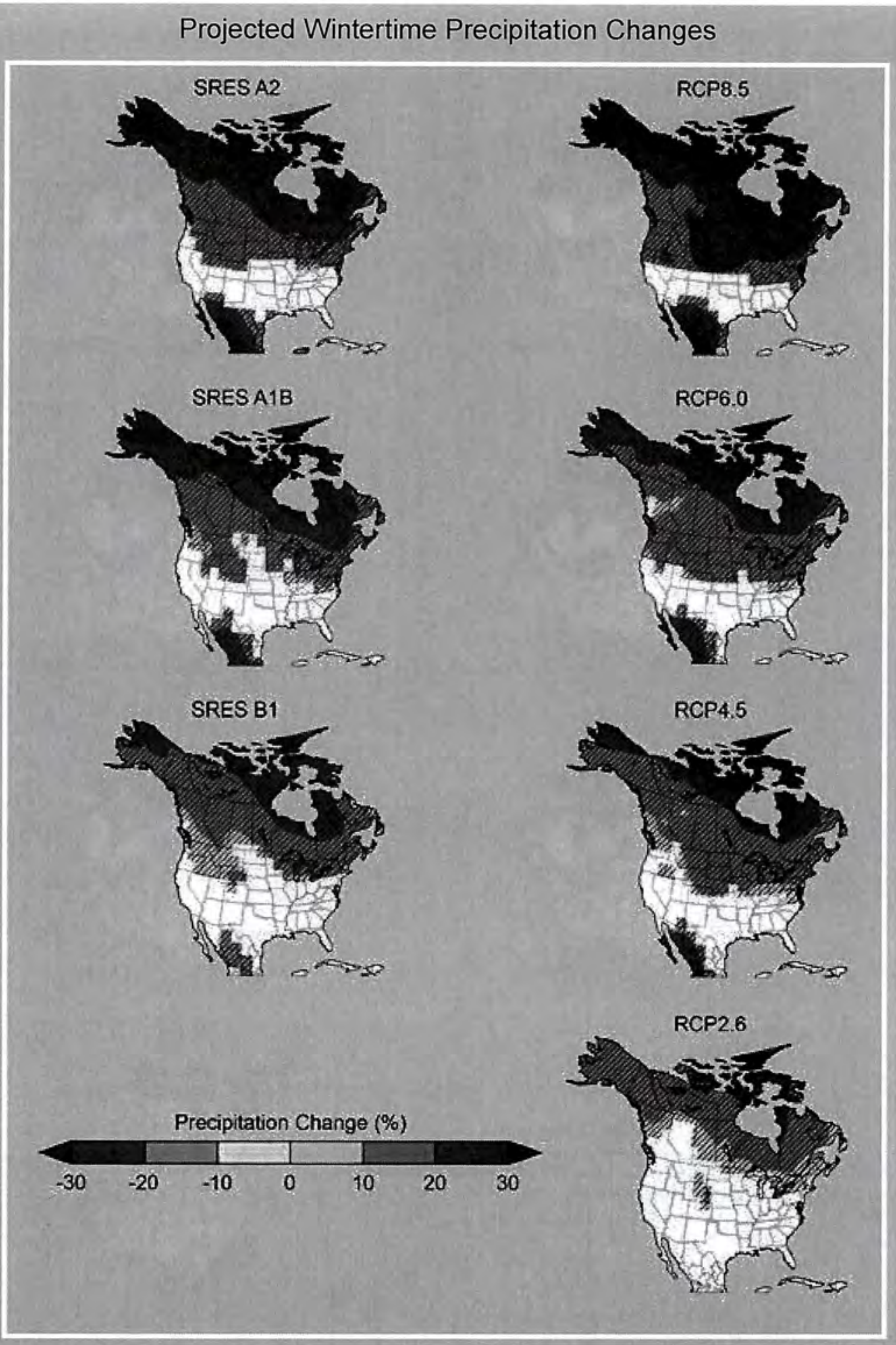


Figure 21. Projected changes in wintertime precipitation at the end of this century (2071-2099) relative to the average for 1970-1999. The older generation of models (CMIP3) and emissions scenarios are on the left side; the new models (CMIP5) and scenarios are on the right side. Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate that the changes are not projected to be larger than could be expected from natural variability. In both sets of projections, the northern parts of the U.S. (and Alaska) become wetter. Increases in both the amount of precipitation change and the confidence in the projections go up as the projected temperature rises. In the farthest northern parts of the U.S., much of the additional winter precipitation will still fall as snow. This is not likely to be the case farther south. (Figure source: NOAA NCDC / CICS-NC).

Projected Summertime Precipitation Changes

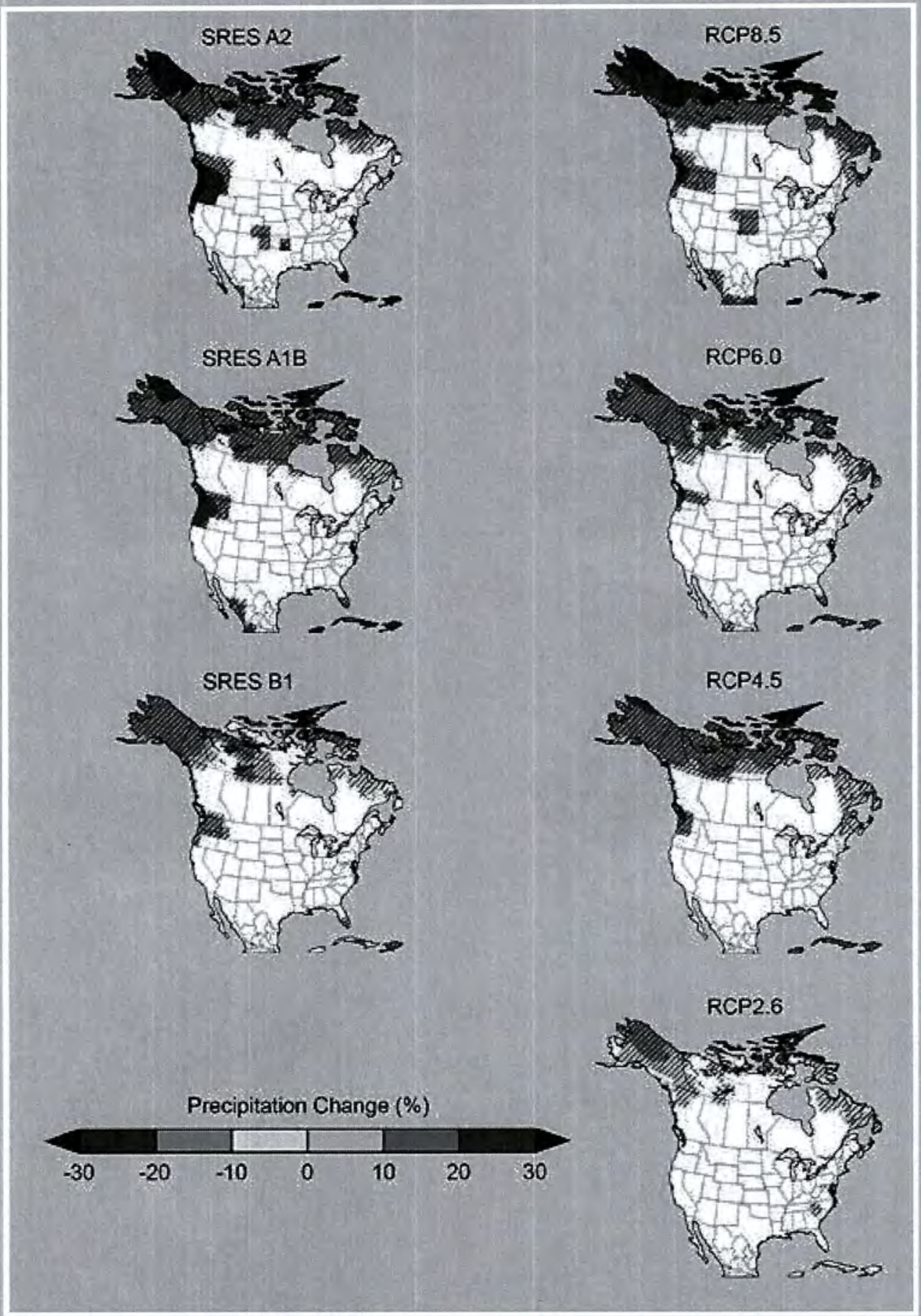


Figure 22. Projected changes in summertime precipitation toward the end of this century (2071-2099) relative to the average for 1970-1999. The older generation of models (CMIP3) and emissions scenarios are on the left side; the new models (CMIP5) and scenarios are on the right side. Hatched areas indicate that the projected changes are significant and consistent among models. White areas indicate confidence that the changes are not projected to be larger than could be expected from natural variability. In most of the contiguous U.S., decreases in summer precipitation are projected, but not with as much confidence as the winter increases. When interpreting maps of temperature and precipitation projections, readers are advised to pay less attention to small details and greater attention to the large-scale patterns of change. (Figure source: NOAA NCDC / CICS-NC).

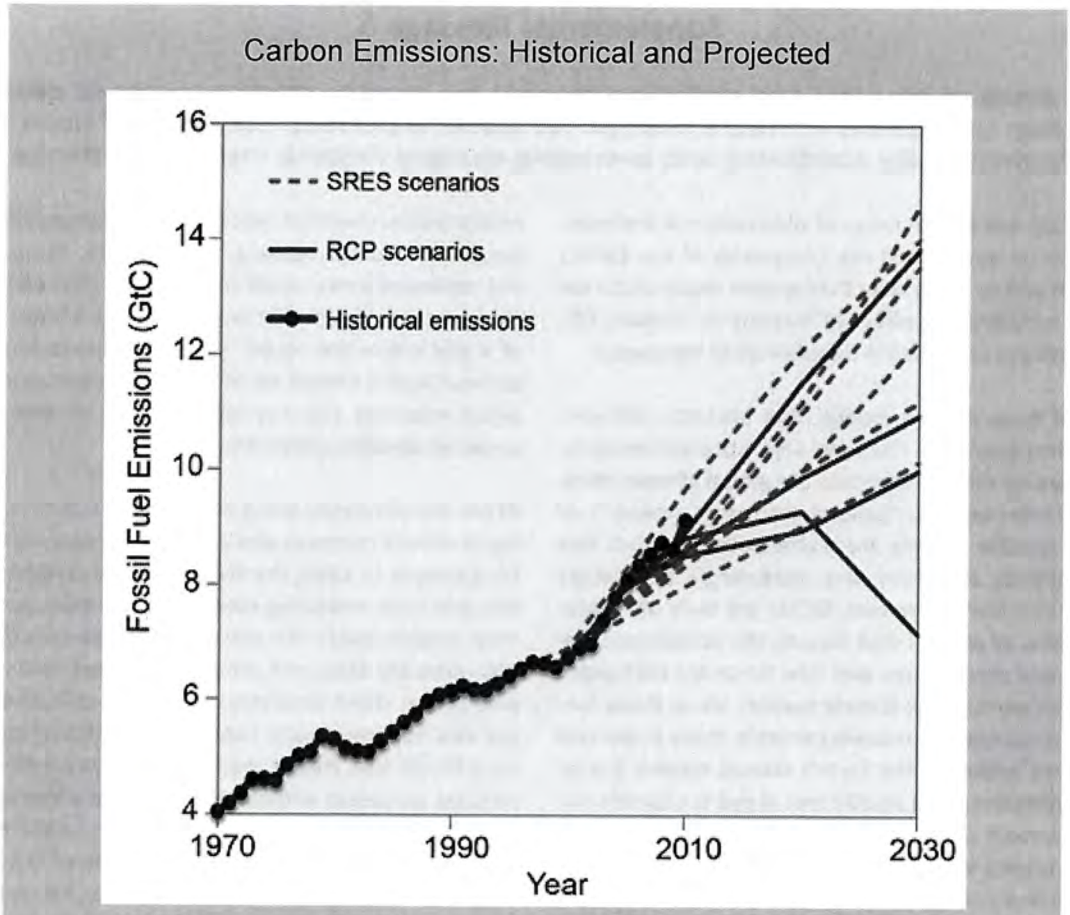


Figure 23. Historical emissions of carbon from fossil fuel (coal, oil, and gas) combustion and land-use change (such as deforestation) have increased over time. The growth rate was nearly three times greater during the 2000s as compared to the 1990s. This figure compares the observed historical (black dots) and projected future SRES (orange dashed lines) and RCP (blue solid lines) carbon emissions from 1970 to 2030. (Data from Boden et al. 2011[75] plus preliminary values for 2009 and 2010 based on BP statistics and U.S. Geological Survey cement data).

Supplemental Message 6.

Different kinds of physical and statistical models are used to study aspects of past climate and develop projections of future change. No model is perfect, but many of them provide useful information. By combining and averaging multiple models, many clear trends emerge.

Climate scientists use a wide range of observational and computational tools to understand the complexity of the Earth's climate system and to study how that system responds to external forces, including the effect of humans on climate. Observational tools are described in Supplemental Message 2.

Computational tools include models that simulate different parts of the climate system. The most sophisticated computational tools used by climate scientists are **global climate models** (previously referred to as "general circulation models"), or GCMs. Global climate models are mathematical models that simulate the physics, chemistry, and, increasingly, the biology that influence the climate system. GCMs are built on fundamental equations of physics that include the conservation of energy, mass, and momentum, and how these are exchanged among different parts of the climate system. Using these fundamental relationships, the models generate many important features that are evident in the Earth's climate system: the jet stream that circles the globe 30,000 feet above the Earth's surface; the Gulf Stream and other ocean currents that transport heat from the tropics to the poles; and even, when the models can be run at a fine enough spatial resolution to capture these features, hurricanes in the Atlantic and typhoons in the Pacific.

GCMs and other physical models are subject to two main types of uncertainty. First, because scientific understanding of the climate system is not complete, a model may not include an important process. This could be because that process is not yet recognized, or because it is known but is not yet understood well enough to be modeled accurately. For example, the models do not currently include adequate treatments of dynamical mechanisms that are important to melting ice sheets. The existence of these mechanisms is known, but they are not yet well enough understood to simulate accurately at the global scale. Also, observations of climate change in the distant past suggest there might be "tipping points," or mechanisms of abrupt changes in climate change, such as shifts in ocean circulation, that are not adequately understood.[76] These are discussed further in Appendix 4: FAQ T.

Second, many processes occur at finer temporal and spatial (time and space) scales than models can resolve. Models instead must approximate what these processes would look like at the spatial scale that the model can resolve using empirical equations, or parameterizations, based on a combination of observations and scientific understanding. Examples of important processes that must be parameterized in climate models include turbulent mixing, radiational heating/cooling, and small-scale physical processes such as cloud formation and precipitation, chemical reactions, and exchanges between the biosphere and atmosphere. For example, these models cannot represent every raindrop. However, they can simulate the total amount of rain that would fall over a large area the size of a grid cell in the model. These approximations are usually derived from a limited set of observations and/or higher resolution modeling and may not hold true for every location or under all possible conditions.

GCMs are constantly being enhanced as scientific understanding of climate improves and as computational power increases. For example, in 1990, the average model divided up the world into grid cells measuring more than 300 miles per side. Today, most models divide the world up into grid cells of about 60 to 100 miles per side, and some of the most recent models are able to run short simulations with grid cells of only 15 miles per side. Supercomputer capabilities are the primary limitation on grid cell size. Newer models also incorporate more of the physical processes and components that make up the Earth's climate system. The very first global climate models were designed to simulate only the circulation of the atmosphere. Over time, the ocean, clouds, land surface, ice, snow, and other features were added one by one. Most of these features were new modules that were developed by experts in those fields and then added into an existing GCM framework. Today, there are more than 35 GCMs created and maintained by more than 20 modeling groups around the world. Some of the newest models are known as Earth System Models, or ESMs, which include all the previous components of a typical GCM but also incorporate modules that represent additional aspects of the climate system, including agriculture, vegetation, and the carbon cycle.

Some models are more successful than others at reproducing observed climate and trends over the past century,[77] or the large-scale dynamical features responsible for creating the average climate conditions over a certain region (such as the Arctic[78] or the Caribbean[79]). Evaluation of models' success often depends on the variable or metric being considered in the analysis, with some models performing better than others for certain regions or variables.[80] However, all future simulations agree that both global and regional temperatures will increase over this century in response to increasing emissions of heat-trapping gases from human activities.[15]

Differences among model simulations over several years to several decades arise from natural variability (as discussed in Supplemental Message 3) as well as from different ways models characterize various small-scale processes. Averaging simulations from multiple models removes the effects of randomly occurring natural variations. The timing of natural variations is largely unpredictable beyond several seasons (although such predictability is an active research area). For this reason, model simulations are generally averaged (as the last stage in any analysis) to make it easier to discern the impact of external forcing (both human and natural). The effect of averaging on the systematic errors depends on the extent to which models have similar errors or offsetting errors.

Despite their increasing resolution, most GCMs cannot simulate fine-scale changes at the regional to local scale. For that reason, **downscaling** is often used to translate GCM projections into the high-resolution information required as input to impact analyses. There are two types of models commonly used for downscaling: dynamical and statistical.

Dynamical downscaling models are often referred to as regional climate models since they include many of the same physical processes that make up a global climate model, but simulate these processes at higher resolution and over a relatively small area, such as the Northwest or Southeast United States. At their boundaries, regional climate models use output from GCMs to simulate what is going on in the rest of the world. Regional climate models are computationally intensive, but provide a broad range of output variables including atmospheric circulation, winds, cloudiness, and humidity at spatial scales ranging from about 6 to 30 miles per grid cell. They are also subject to the same types of uncertainty as a global model, such as not fully resolving physical processes that occur at even smaller scales. Regional climate models have additional uncertainty related to how often their boundary conditions are updated and where they are defined. These uncertainties can have a large impact on the precipitation simulated by the models at the local to regional scale. Currently, a limited set of regional climate model simulations based on one future scenario and output from five CMIP3 GCMs is available from the North American Regional Climate Change Assessment Program (these are the "NARCCAP" models used in some sections of this report). These simulations are useful for examining certain impacts over North America. However, they do not encompass the full range of uncertainty in future projections due to both human activities and climate sensitivity described in Supplemental Message 5.

Statistical downscaling models use observed relationships between large-scale weather features and local climate to translate future projections down to the scale of observations. Statistical models are generally very effective at removing errors in historical simulated values, leading to a good match between the average (multi-decadal) statistics of observed and statistically downscaled climate at the spatial scale and over the historical period of the observational data used to train the statistical model. However, statistical models are based on the key assumption that the relationship between large-scale weather systems and local climate will remain constant over time. This assumption may be valid for lesser amounts of change, but could lead to errors, particularly in precipitation extremes, with larger amounts of climate change.[81] Statistical models are generally flexible and less computationally demanding than regional climate models. A number of databases provide statistically downscaled projections for a continuous period from 1960 to 2100 using many global models and a range of higher and lower future scenarios (for example, the U.S. Geological Survey database described by Maurer et al. 2007[82]).[83,84] Statistical downscaling models are best suited for analyses that require a range of future projections that reflect the uncertainty in emissions scenarios and climate sensitivity, at the scale of observations that may already be used for planning purposes.

Ideally, climate impact studies could use both statistical and dynamical downscaling methods. Regional climate models can directly simulate the response of regional climate processes to global change, while statistical models can better remove any biases in simulations relative to observations. However, rarely (if ever) are the resources available to take this approach. Instead, most assessments tend to rely on one or the other type of downscaling, where the choice is based on the needs of the assessment. If the study is more of a sensitivity analysis, where using one or two future simulations is not a limitation, or if it requires many climate variables as input, then regional climate modeling may be more appropriate. If the study needs to resolve the full range of projected changes under multiple models and scenarios or is more constrained by practical resources, then statistical downscaling may be more appropriate. However, even within statistical downscaling, selecting an appropriate method for any given study depends on the questions being asked. The variety of techniques ranges from a simple "delta" (change or difference) approach (subtracting historical simulated values from future values, and adding the resulting delta to historical observations, as used in the first national climate assessment[85]) to complex clustering and neural network techniques that rival dynamical downscaling in their demand for computational resources and high-frequency model output (for example, Kostopoulou and Jones 2007[86]; Vrac et al. 2007[81]). The delta approach is adequate for studies that are only interested in changes in seasonal or annual average temperature. More complex methods must be used for studies that require information on how climate change may affect the frequency or timing of precipitation and climate extremes.

Modeling the Climate System

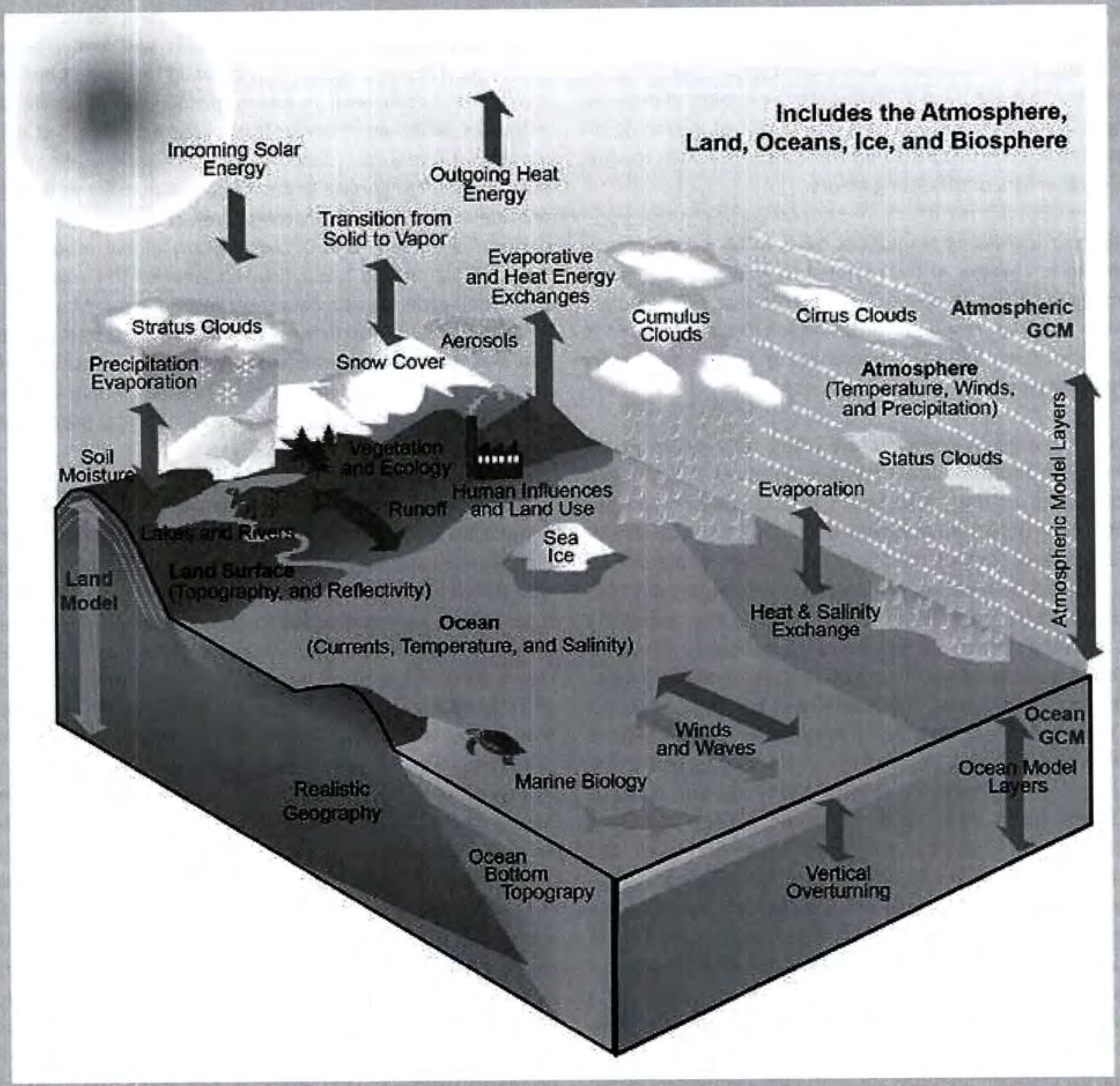


Figure 24. Some of the many processes often included in models of the Earth's climate system. (Figure source: Karl and Trenberth 2003[87]).

Increasing Model Resolution

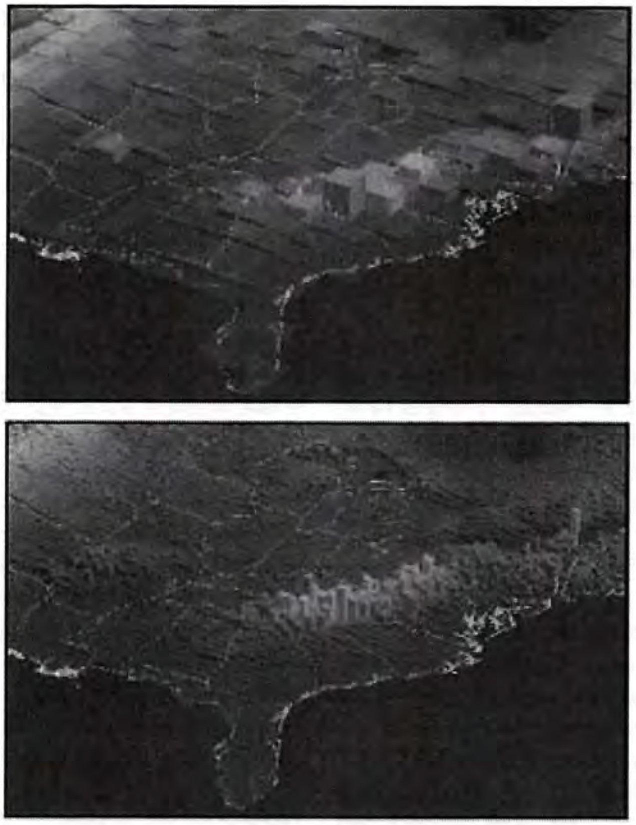
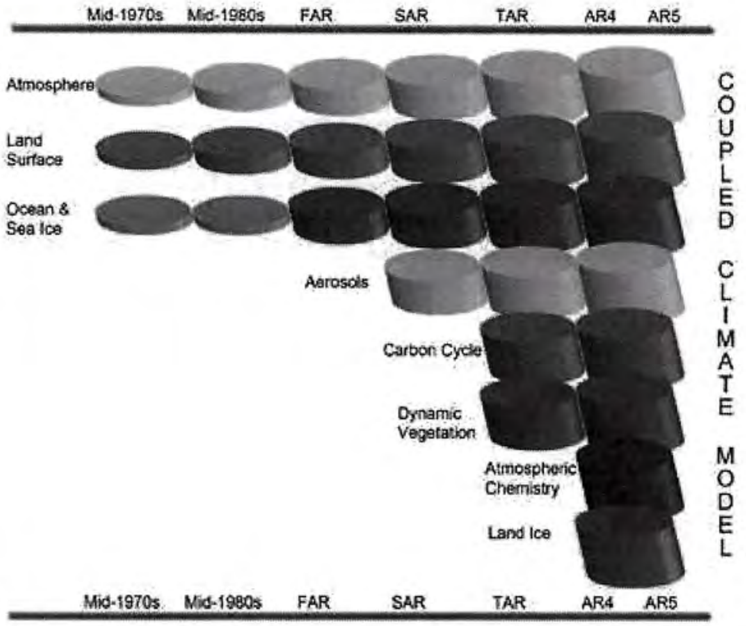


Figure 25. Top: Illustration of the eastern North American topography in a resolution of 68 x 68 miles (110 x 110 km). Bottom: Illustration of the eastern North American topography in a resolution of 19 x 19 miles (30 x 30 km).

Increasing Climate Model Components



Intergovernmental Panel on Climate Change Reports	
FAR	1990
SAR	1995
TAR	2001
AR4	2007
AR5	2013

Figure 26. The development of climate models over the last 35 years showing how the different components were coupled into comprehensive climate models over time. In each aspect (for example, the atmosphere, which comprises a wide range of atmospheric processes) the complexity and range of processes has increased over time (illustrated by growing cylinders). Note that during the same time the horizontal and vertical resolution has increased considerably. (Figure source: adapted from Cubasch et al. 2013[88]).

Supplemental Message 7.

Scientific understanding of observed temperature changes in the United States has greatly improved, confirming that the U.S. is warming due to heat-trapping gas emissions, consistent with the climate change observed globally.

There have been substantial recent advances in our understanding of the continental U.S. temperature records. Numerous studies have looked at many different aspects of the record.[28,89,90,91,92,93] These studies have increased confidence that the U.S. is warming, and refined estimates of how much.

Historical temperature data are available for thousands of weather stations. However, for a variety of practical and often unavoidable reasons, there have been frequent changes to individual stations and to the network as a whole. Two changes are particularly important. The first is a widespread change in the time at which observers read their thermometers. Second, most stations now use electronic instruments rather than traditional glass thermometers.

Extensive work has been done to document the effect of these changes on historical temperatures. For example, the change from afternoon to morning observations resulted in systematically lower temperatures for both maximum and minimum, artificially cooling the U.S. temperature record by about 0.5°F.[93,94] The change in instrumentation was equally important but more complex. New electronic instruments generally recorded higher minimum temperatures, yielding an artificial warming of about 0.25°F, and lower maximum temperatures, resulting in an artificial cooling of about 0.5°F. This has been confirmed by extended period side-by-side instrument comparisons.[95] Confounding this, as noted by a recent citizen science effort, the new instruments were often placed nearer buildings or other man-made structures.[96] Analyses of the changes in siting indicate that this had a much smaller effect than the change in instrumentation across the network as a whole.[89,91,93]

Extensive work has been done to develop statistical adjustments that carefully remove these and other non-climate elements that affect the data. To confirm the efficacy of the adjustments, several sensitivity assessments have been undertaken. These include:

- a comparison with the U.S. Climate Reference Network;[91,97]
- analyses to evaluate biases and uncertainties;[93]
- comparisons to a range of state-of-the-art meteorological data analyses;[92] and
- in-depth analyses of the potential impacts of urbanization.[90]

These assessments agree that the corrected data do not overestimate the rate of warming. Rather, because the average effect of these issues was to reduce recorded temperatures, adjusting for these issues tends to reveal a larger long-term warming trend. The impact is much larger for maximum temperature as compared to minimum temperature because the adjustments account for two distinct artificial cooling signals: the change in observation time and the change in instrumentation. The impact is smaller for minimum temperature because the artificial signals roughly offset one another (the change in observation time cooling the record, the change in instrumentation warming the record). Even without these adjustments, however, both maximum and minimum temperature records show increases over the past century.

Geographically, maximum temperature has increased in most areas except in parts of the western Midwest, northeastern Great Plains, and the Southeast regions. Minimum temperature exhibits the same pattern of change with a slightly greater area of increases. The causes of these slight differences between maximum and minimum temperature are a subject of ongoing research.[98] In general, the uncorrected data exhibit more extreme trends as well as larger spatial variability; in other words, the adjustments have a smoothing effect.

The corrected temperature record also confirms that U.S. average temperature is increasing in all four seasons. The heat that occurred during the Dust Bowl era is prominent in the summer record. The warmest summer on record was 1936, closely followed by 2012. However, twelve of the last fourteen summers have been above average. Temperatures during the other seasons have also generally been above average in recent years.

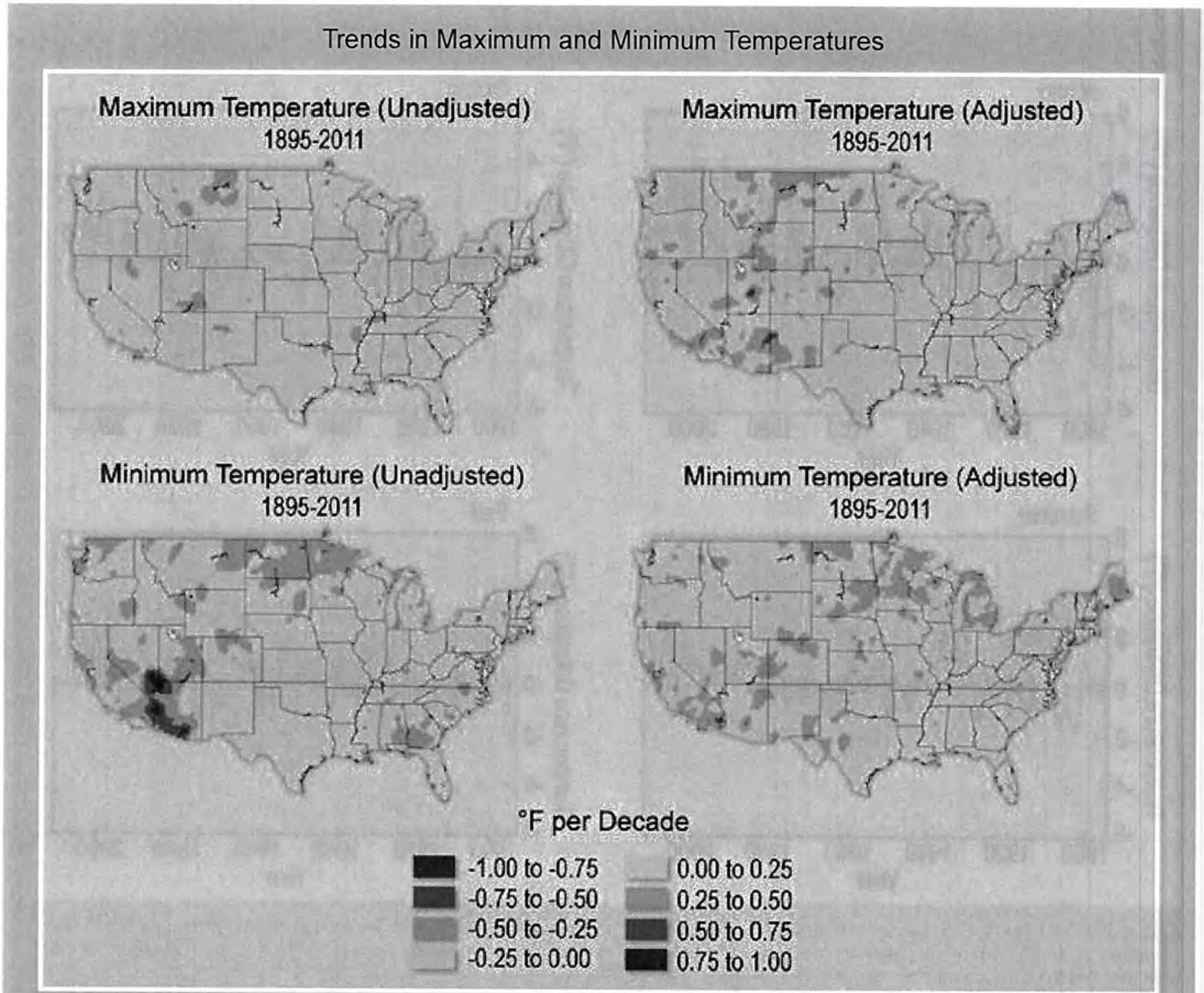


Figure 27. Geographic distribution of linear trends in the U.S. Historical Climatology Network for the period 1895-2011. (Figure source: updated from Menne et al. 2009[91]).

U.S. Seasonal Temperatures

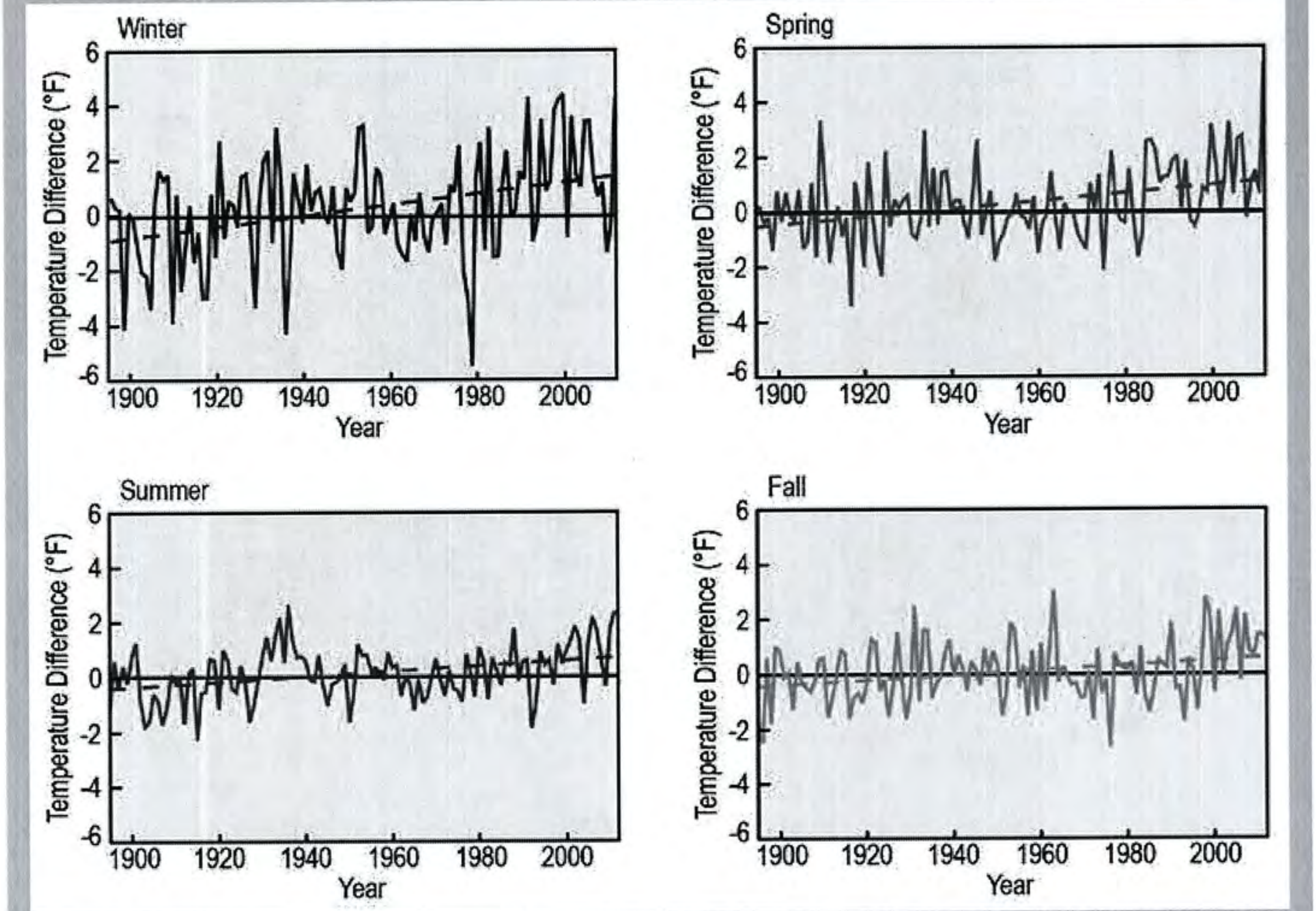


Figure 28. Continental U.S. seasonal temperatures (relative to the 1901-1960 average) for winter, spring, summer, and fall all show evidence of increasing trends. Dashed lines show the linear trends. Stronger trends are seen in winter and spring as compared to summer and fall. (Figure source: updated from Kunkel et al. 2013[99]).

Supplemental Message 8.

Many other indicators of rising temperatures have been observed in the United States. These include reduced lake ice, glacier retreat, earlier melting of snowpack, reduced lake levels, and a longer growing season. These and other indicators are expected to continue to reflect higher temperatures.

While surface air temperature is the most widely cited measure of climate change, other aspects of climate that are affected by temperature are often more directly relevant to both human society and the natural environment. Examples include shorter duration of ice on lakes and rivers, reduced glacier extent, earlier melting of snowpack, reduced lake levels due to increased evaporation, lengthening of the growing season, and changes in plant hardiness zones. Changes in these and many other variables are consistent with the recent warming over much of the United States. Taken as a whole, these changes provide compelling evidence that increasing temperatures are affecting both ecosystems and human society.

Striking decreases in the coverage of ice on the Great Lakes have occurred over the last few decades (see Ch 2: Our Changing Climate, Key Message 11). The annual average ice cover area for the Great Lakes, which typically shows large year-to-year variability, has sharply declined over the last 30+ years.[100] Based on records covering the winters of 1972-1973 through 2010-2011, 12 of the 19 winters prior to 1991-1992 had annual average ice cover greater than 20% of the total lake area while 15 of the 20 winters since 1991-1992 have had less than 20% of the total lake area covered with ice. This includes the three lowest ice extent winters of 1997-1998, 2001-2002, and 2005-2006. A reduction in ice leading to more open water in winter raises concerns about possible increases in lake effect snowfall, although future trends will also depend on the difference between local air and water temperatures.

Smaller lakes in other parts of the country show similar changes. For example, the total duration of ice cover on Lake Mendota in Madison, Wisconsin, has decreased from about 120 days in the late 1800s to less than 100 days in most years since 1990.[101] Average dates of spring ice disappearance on Minnesota lakes show a trend toward earlier melting over the past 60 years or so. These changes affect the recreational and commercial activities of the surrounding communities.

A long-term record of the ice-in date (the first date in winter when ice coverage closes the lake to navigation) on Lake Champlain in Vermont shows that the lake now freezes approximately two weeks later than in the early 1800s and over a week later than 100 years ago.[102] Later ice-in dates are an indication of higher lake temperatures, as it takes longer for the warmer water to freeze in winter. Prior to 1950, the absence of winter ice cover on Lake Champlain was rare, occurring just three times in the 1800s and four times between 1900 and 1950. By contrast, it remained ice-free during 42% of the winters between 1951 and 1990, and since 1991, Lake Champlain has remained ice-free during 64% of the winters. One- to two-week advances of ice breakup dates and similar length delays of freeze-up dates are also typical of lakes and rivers in Canada, Scandinavia, and northern Asia.[15]

While shorter durations of lake ice enhance navigational opportunities during winter, decreasing water levels in the Great Lakes present risks to navigation, especially during the summer. Water levels on Lakes Superior, Michigan, and Ontario have been below their long-term (1918-2008) averages for much of the past decade.[103] The summer drought of 2012 left Lakes Michigan and Ontario approximately one foot below their long-term averages. As noted in the second national climate assessment,[1] projected water level reductions for this century in the Great Lakes range from less than a foot under lower emissions scenarios to between 1 and 2 feet under high-

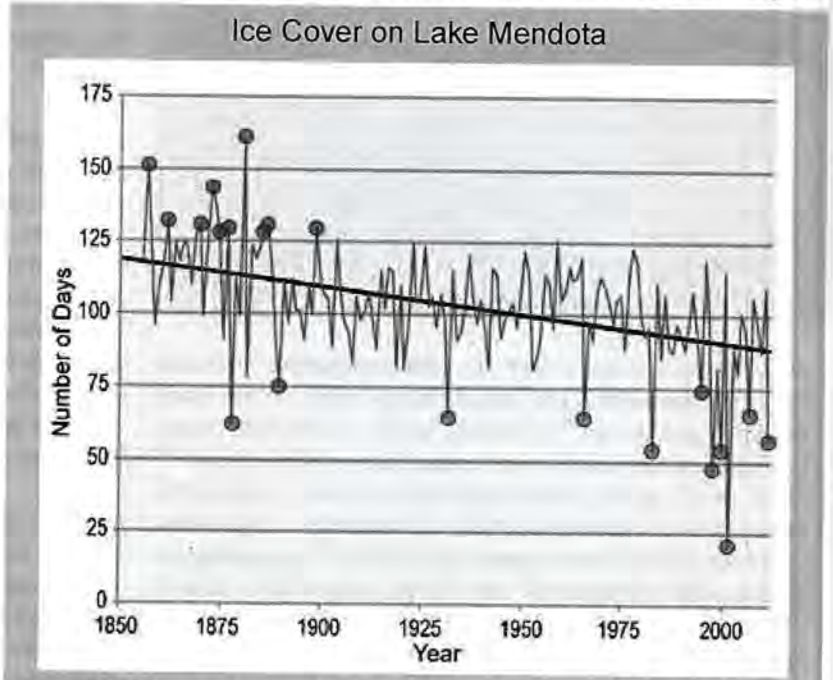


Figure 29. The duration, or number of days, of ice cover on Lake Mendota, Wisconsin, has decreased over time. The 10 longest ice seasons are marked by blue circles, and the 11 shortest ice seasons are marked by red circles. Seven of the 10 shortest ice cover seasons have occurred since 1980. (Figure source: Kunkel et al. 2013[107]).

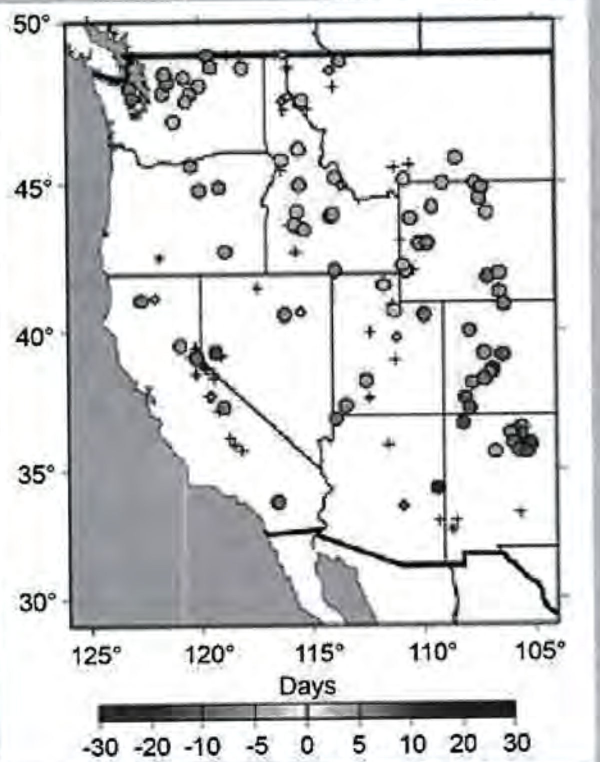

Streamflow from Snowmelt Coming Earlier in the Year

Figure 30. At many locations in the western U.S., the timing of streamflow in rivers fed by snowpack is shifting to earlier in the year. Red dots indicate stream gauge locations where half of the annual flow is now arriving anywhere from 5 to 20 days earlier each year for 2001-2010, relative to the 1951-2000 average. Blue dots indicate locations where the annual flow is now arriving later. Crosses indicate locations where observed changes are not statistically different from the past century baseline at 90% confidence levels, diamonds indicate gauges where the timing difference was significantly different at 90% confidence, and dots indicate gauges where timing was different at 95% confidence level. (Updated from Stewart et al. 2005[110]).

er emissions scenarios, with the smallest changes projected for Lake Superior and the largest change projected for Lakes Michigan and Huron.[83] A notable feature is the large range (several feet) of water level projections among models.[104] More recent studies have indicated that earlier approaches to computing evapotranspiration estimates from temperature may have overestimated evaporation losses.[105] Accounting for land-atmosphere feedbacks may further reduce the estimates of lake level declines.[106] These recent studies, along with the large spread in models, indicate that projections of Great Lakes water levels represent evolving research and are still subject to considerable uncertainty.

In the U.S. Southwest, indications of a changing climate over the last five decades include decreases in mountain snowpack,[108] earlier dates of snowmelt runoff,[109,110] earlier onset of spring (as indicated by shifts in the timing of plant blooms and spring snowmelt-runoff pulses),[111] general shifts in western hydroclimatic seasons,[112] and trends toward more precipitation falling as rain instead of snow over the West.[113] The ratio of precipitation falling as rain rather than snow, the amount of water in snowpack, and the timing of peak stream flow on snowmelt-fed rivers all changed as expected with warming over the past dozen years, relative to the last century baselines.[62]

Changing temperatures affect vegetation through lengthening of the frost-free season and the corresponding growing season, and changing locations of plant tolerance thresholds. The U.S. average frost-free season length (defined as the number of days between the last and first occurrences of 32°F in spring and autumn, respectively) increased by about two weeks during the last century.[114] The increase was much greater in the western than in the eastern United States. Consistent with the recent observed trends in frost-free season length, the largest projected changes in growing season length are in the mountainous regions of the western United States, while smaller changes are projected for the Midwest, Northeast, and Southeast. Related plant and animal changes include a northward shift in the typical locations of bird species[115] and a shift since the 1980s toward earlier first-leaf dates for lilac and honeysuckle.[116]

Plant hardiness zones are determined primarily by the extremes of winter cold.[117] Maps of plant hardiness have guided the selection of plants for both ornamental and agricultural purposes, and these zones are changing as climate warms. Plant hardiness zones for the U.S. have recently been updated using the new climate normals (1981-2010), and these zones show a northward shift by up to 100 miles relative to the zones based on the older (1971-2000) normals. Even greater northward shifts, as much as 200 miles, are projected over the next 30 years as warming increases. Projected shifts are largest in the major agricultural regions of the central United States.

Evidence of a warming climate across the U.S. is based on a host of indicators: hydrology, ecology, and physical climate. Most of these are changing in ways consistent with increasing temperatures, and are expected to continue to change in the future as a result of ongoing increases in human-induced heat-trapping gas emissions.

Shifts in Plant Hardiness Zones

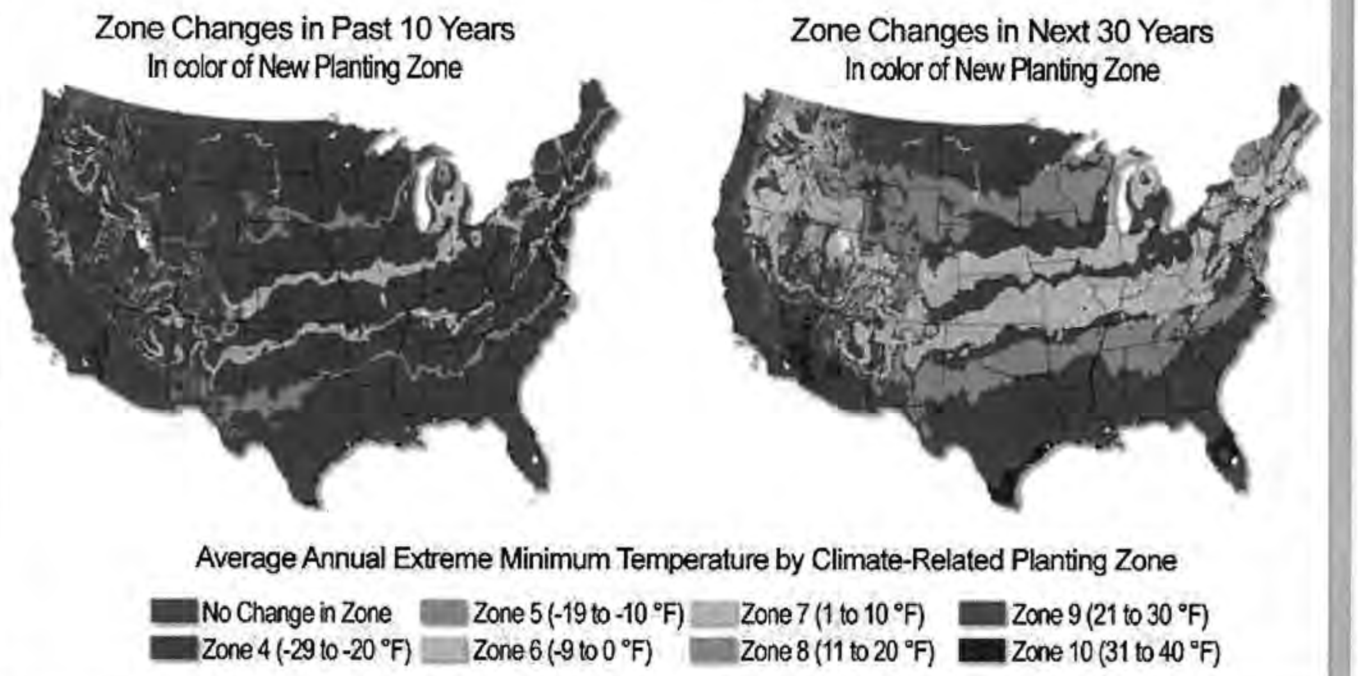


Figure 31. The map on the left shows the change in Plant Hardiness Zones calculated from those based on the 1971-2000 climate to those based on the 1981-2010 climate. Even greater changes are projected over the next 30 years (right). (Figure source: NOAA).

Supplemental Message 9.

Trends in some types of extreme weather events have been observed in recent decades, consistent with rising temperatures. These include increases in heavy precipitation nationwide, especially in the Midwest and Northeast; heat waves, especially in the West; and the intensity of Atlantic hurricanes. These trends are expected to continue. Research on climate change's effects on other types of extreme events continues.

High impact, large-scale extreme events are complex phenomena involving various factors that can vcreate a "perfect storm." Such extreme weather occurs naturally. However, the influence of human activities on global climate is altering the frequency and/or severity of many of these events.

Observations show that heavy downpours have already increased nationally. Regional and global models project increases in extreme precipitation for every U.S. region.[118] Precipitation events tend to be limited by available moisture. For the heaviest, most rare events, there is strong evidence from observations[119] and models[118,120] that higher temperatures and the resulting moister atmosphere are the main cause of these observed and projected increases. Other factors that may also have an influence on observed U.S. changes in extreme precipitation are land-use changes (for example, changes in irrigation[121,122]) and a shift in the number of El Niño events versus La Niña events.

Climate change can also alter the characteristics of the atmosphere in ways that affect weather patterns and storms. In the mid-latitudes, where most of the continental U.S. is located, there is an increasing trend in extreme precipitation in the vicinity of fronts associated with mid-latitude storms (also referred to as extra-tropical [outside the tropics] cyclones[123]). There is also a northward shift in storms over the U.S.[124] that are often associated with extreme precipitation. This shift is consistent with projections of a warming world.[125] No change in mid-latitude storm intensity or frequency has been detected.

In the tropics, the most important types of storms are tropical cyclones, referred to as hurricanes when they occur in the Atlantic Ocean. Over the 40 years of satellite monitoring, there has been a shift toward stronger hurricanes in the Atlantic, with fewer Category 1 and 2 hurricanes and more Category 4 and 5 hurricanes. There has been no significant trend in the global number of tropical cyclones[126] nor has any trend been identified in the number of U.S. landfalling hurricanes.[1] Two

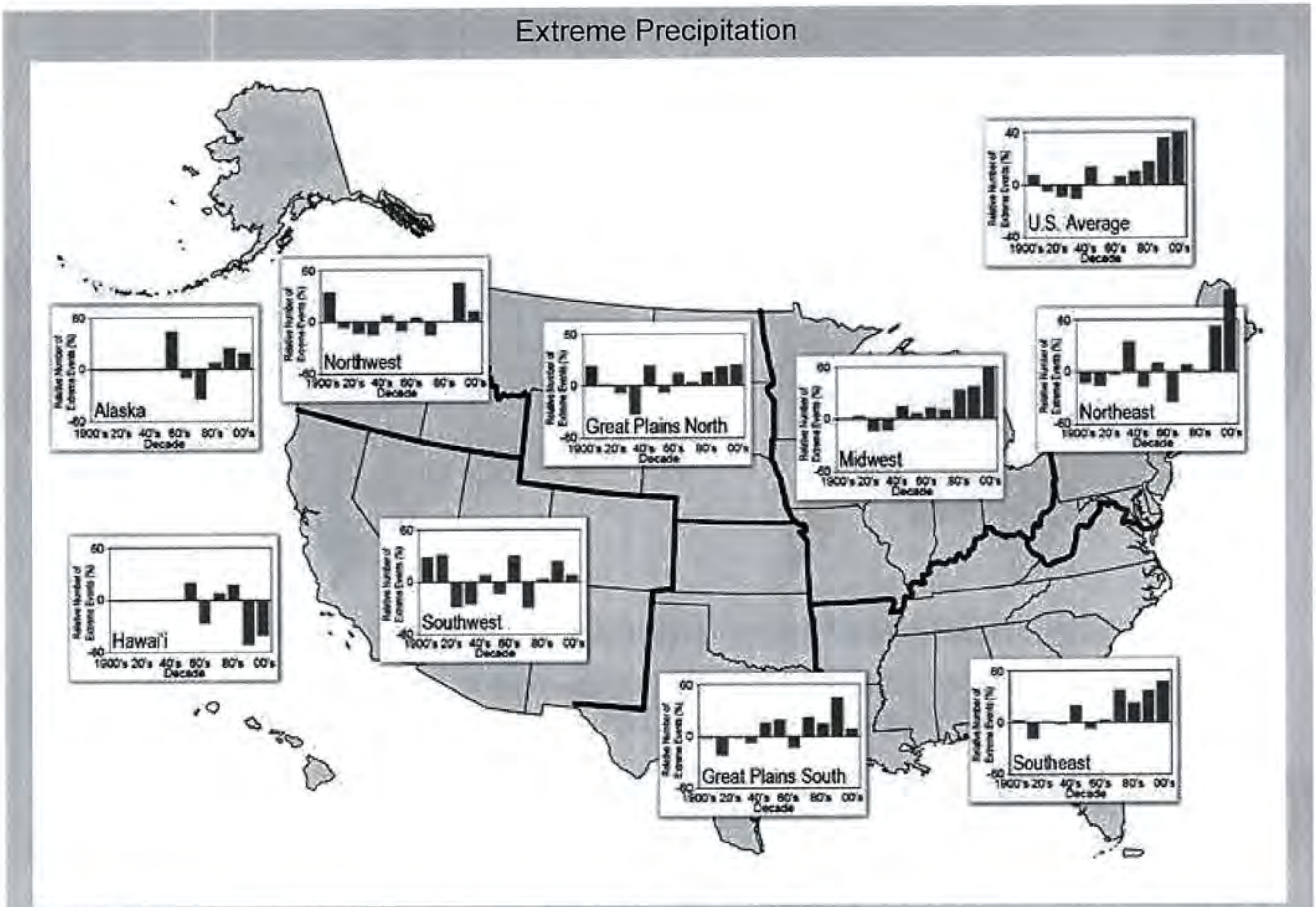


Figure 32. Heavy downpours are increasing nationally, with especially large increases in the Midwest and Northeast.[99] Despite considerable decadal-scale natural variability, indices such as this one based on 2-day precipitation totals exceeding a threshold for a 1-in-5-year occurrence exhibit a greater than normal occurrence of extreme events since 1991 in all U.S. regions except Alaska and Hawai'i. Each bar represents that decade's average, while the far right bar in each graph represents the average for the 12-year period of 2001-2012. Analysis is based on 726 long-term, quality-controlled station records. This figure is a regional expansion of the national index in Figure 2.16 of Chapter 2. (Figure source: updated from Kunkel et al. 2013[99]).

studies have found an upward trend in the number of extreme precipitation events associated with tropical cyclones,[127] but significant uncertainties remain.[122] A change in the number of Atlantic hurricanes has been identified, but interpreting its significance is complicated both by multi-decadal natural variability and the reliability of the pre-satellite historical record.[128] The global satellite record shows a shift toward stronger tropical cyclones,[126,129] but does not provide definitive evidence of a long-term trend. Nonetheless, there is a growing consensus based on scientific understanding and very-high-resolution atmospheric modeling that the strongest tropical cyclones, including Atlantic hurricanes, will become stronger in a warmer world.[130]

The number of heat waves has been increasing in recent years. On a decadal basis, the decade of 2001-2010 had the second highest number since 1901 (first is the 1930s). This trend has continued in 2011 and 2012, with the number of intense heat waves being almost triple the long-term average. Regionally, the Northwest, Southwest, and Alaska had their highest number of heat waves in the 2000s, while the 1930s were the highest in the other regions (note that the Alaskan time series begins in the 1950s). For the number of intense cold waves, the national-average value was highest in the 1980s and lowest in the 2000s. The lack of cold waves in the 2000s was prevalent throughout the contiguous U.S. and Alaska. Climate model simulations indicate that the recent trends toward increasing frequency of heat waves and decreasing frequency of cold waves will continue in the future.

The data on the number and intensity of severe thunderstorm phenomena (including tornadoes, thunderstorm winds, and hail) are not of sufficient quality to determine whether there have been historical trends.[119] This scarcity of high-quality data, combined with the fact that these phenomena are too small to be directly represented in climate models,[131] makes it difficult to project how these storms might change in the future.

Supplemental Message 10.

Drought and fire risk are increasing in many regions as temperatures and evaporation rates rise. The greater the future warming, the more these risks will increase, potentially affecting the entire United States.

As temperatures rise, evaporation rates increase, which (all else remaining equal) would be expected to lead to increased drying.[131] The Palmer Drought Severity Index (PDSI),[132] a widely used indicator of dryness that incorporates both precipitation and temperature-based evaporation estimates, does not show any trend for the U.S. as a whole over the past century.[133] However, drought intensity and frequency have been increasing over much of the western United States, especially during the last four decades. In the Southeast, western Great Lakes, and southern Great Plains, droughts have increased during the last 40 years, but do not show an increase when examined over longer periods encompassing the entire last century. In the Southwest, drought has been widespread since 2000; the average value of the PDSI during the 2000s indicated the most severe average drought conditions of any decade. The severity of recent drought in the Southwest reflects both the decade's low precipitation and high temperatures.

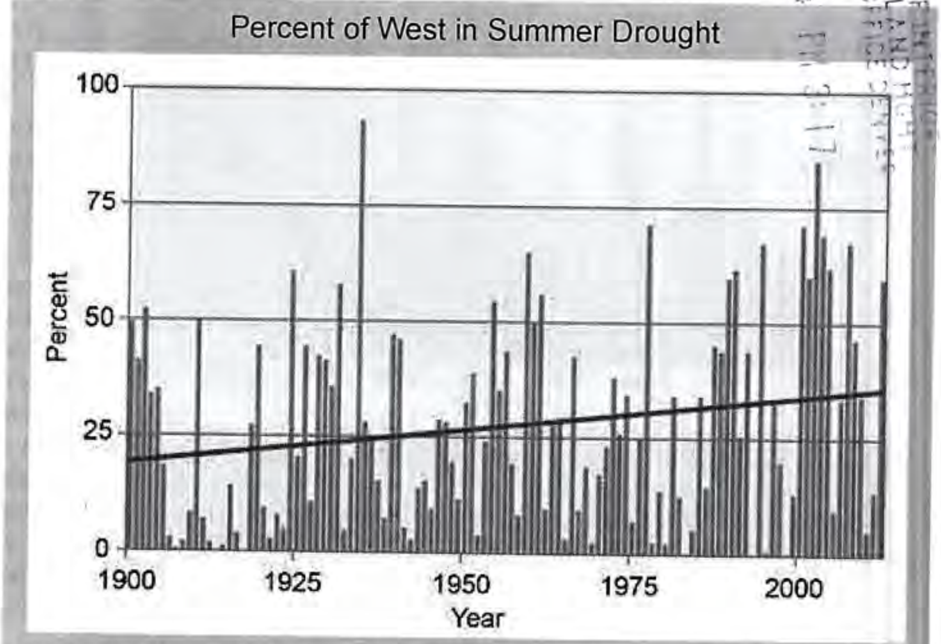


Figure 33. The area of the western U.S. in moderately to extremely dry conditions during summer (June-July-August) varies greatly from year to year but shows a long-term increasing trend from 1900 to 2012. (Data from NOAA NCDC State of the Climate Drought analysis).

Seasonal and multi-year droughts affect wildfire severity.[134] For example, persistent drought conditions in the Southwest, combined with wildfire suppression and land management practices,[135] have contributed to wildfires of unprecedented size since 2000. Five western states (Arizona, Colorado, Utah, California, and New Mexico) have experienced their largest fires on record at least once since 2000. Much of the increase in fires larger than 500 acres occurred in the western United States, and the area burned in the Southwest increased more than 300% relative to the area burned during the 1970s and early 1980s.[136]

Droughts on a duration and scale that affect agriculture are projected to increase in frequency and severity in this century due to higher temperatures. Projections of the Palmer Drought Severity Index at the end of this century indicate that the normal state for most of the nation will be what is considered moderate to severe drought today.[137,138] The PDSI is used by several states for monitoring drought and for triggering certain actions.[139] It is also one component of the U.S. Drought Monitor.[140] The closely related Palmer Hydrological Index is the most

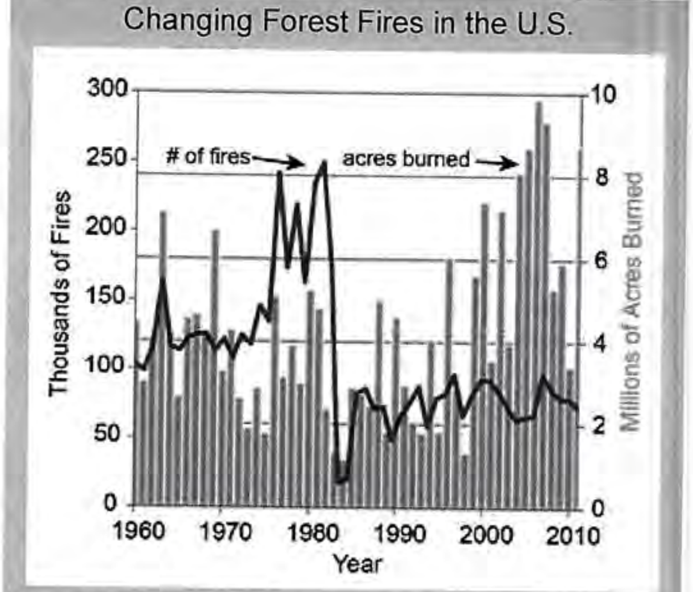


Figure 34. Although the average number of wildfires per year (black line) has decreased over time, the total area burned by wildfires (orange bars) in the continental U.S. (primarily in the western states) has nearly doubled since 2000 relative to the long-term 1960-1999 average (data shown are for 1960-2011). (Data from the National Interagency Fire Center).

Extreme Drought in the U.S. and Mexico, Past and Future

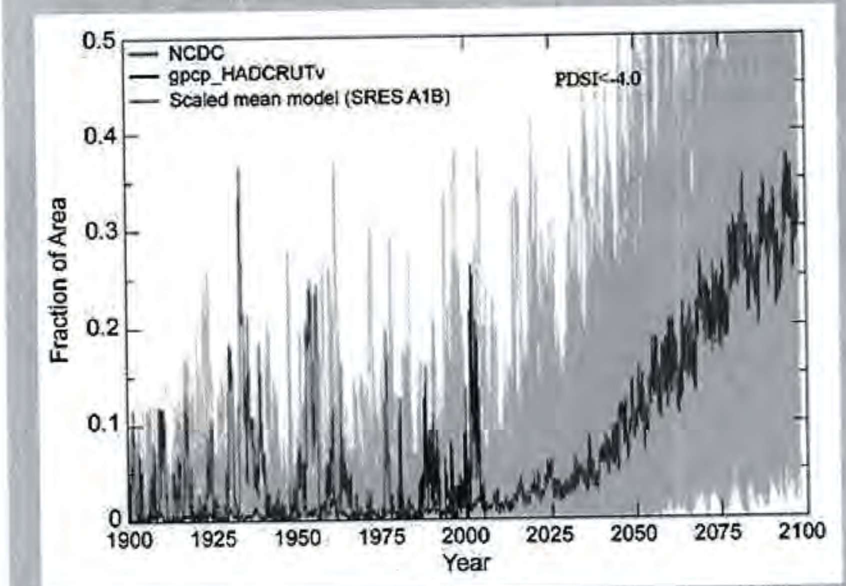


Figure 35. The fractional areal extent of the contiguous U.S. and Mexico in extreme drought according to projections of the Palmer Drought Severity Index under an intermediate emissions scenario (SRES A1B, in between the B1 and A2 scenarios used elsewhere in this report) (Supplemental Message 5 and Ch. 2: Our Changing Climate, Key Message 3). The Palmer Drought Severity Index is the most widely used measure of drought, although it is more sensitive to temperature than other drought indices and may over-estimate the magnitude of drought increases. The red line is based on observed temperature and precipitation. The blue line is from the average of 19 different climate models. The gray lines in the background are individual results from over 70 different simulations from these models. These results suggest an increasing probability of agricultural drought over this century throughout most of the U.S. (Figure source: Wehner et al. 2011[138]).

important component of NOAA's Objective Long-term Drought Indicator Blend,[141] which is used by the U.S. Department of Agriculture to identify counties that are eligible to participate in certain Federal Government drought relief programs. The U.S. Drought Monitor is used by some states for similar purposes.

Despite its widespread usage, the PDSI may be overly sensitive to future temperature increases.[142] As temperatures increase during this century, these PDSI-based monitoring tools may over-estimate the intensity of drought during anomalous warm periods, so statutory adjustments to these tools may be warranted. However, the projection of increased drought risk is reinforced by a direct examination of future soil moisture content projections, which reveals substantial drying in most areas of the western U.S (Ch. 2: Our Changing Climate, Key Message 3).

Provided the wood and ground litter has dried out, the area of forest burned in many mid-latitude areas, including the western United States, may increase substantially as temperature and evapotranspiration increase, exacerbating drought.[143] Under even relatively modest amounts of warming, significant increases in area burned are projected in the Sierra Nevada, southern Cascades, and coastal California; in the mountains of Arizona and New Mexico; on the Colorado Plateau; and in the Rocky Mountains.[144] Other studies, examining a broad range of climate change and development scenarios, find increases in the chance of large fires for much of northern California's forests.[145]

Long periods of consecutive days with little or no precipitation also can lead to drought. The average annual maximum number of consecutive dry days are projected to increase for the higher emissions scenarios in areas that are already prone to little precipitation by mid-century and increase thereafter (Ch. 2: Our Changing Climate, Key Message 5). Much of the western and southwestern U.S. is projected to experience statistically significant increases in the annual maximum number of consecutive dry days, on average up to 10 days above present-day values for parts of the contiguous U.S. by the end of this century under high emissions scenarios. Hence, some years are projected to experience substantially longer dry seasons.

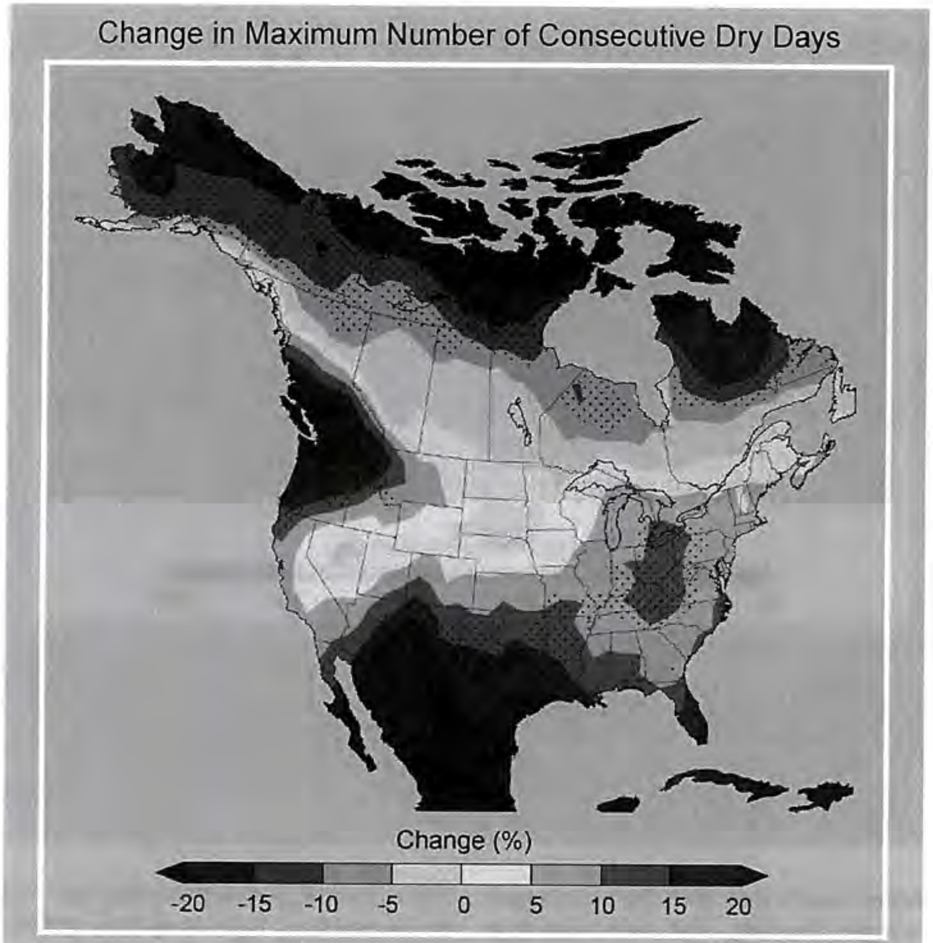


Figure 36. Change in the number of consecutive dry days (days receiving less than 0.04 inches (1 mm) of precipitation) at the end of this century (2070-2099) relative to the end of last century (1971-2000) under the higher scenario, RCP 8.5. Stippling indicates areas where changes are consistent among at least 80% of the 25 models used in this analysis. (Supplemental Message 5 and Ch. 2: Our Changing Climate, Key Message 3). (Figure source: NOAA NCDC / CICS-NC).

Supplemental Message 11.

Summer Arctic sea ice extent, volume, and thickness have declined rapidly, especially north of Alaska. Permafrost temperatures are rising and the overall amount of permafrost is shrinking. Melting of land- and sea-based ice is expected to continue with further warming.

Increasing temperatures and associated impacts are apparent throughout the Arctic, including Alaska. Sea ice coverage and thickness, permafrost on land, mountain glaciers, and the Greenland Ice Sheet all show changes consistent with higher temperatures.

The most dramatic decreases in summer sea ice have occurred along the northern coastline of Alaska and Russia. Since the satellite record began in 1979, September (summer minimum) sea ice extent has declined by 13% per decade in the Beaufort Sea and 32% per decade in the Chukchi Sea,[146] leaving the Chukchi nearly ice-free in the past few Septembers. Longer-term records based on climate proxies suggest that pan-Arctic ice extent in summer is the lowest it has been in at least the past 1,450 years.[147] Winter ice extent has declined less than summer ice extent (see Ch. 2: Our Changing Climate, Key Message 11), indicative of a trend toward seasonal-only (as opposed to year-round) ice cover, which is relatively thin and vulnerable to melt in the summer. Recent work has indicated that the loss of summer sea ice may be affecting the atmospheric circulation in autumn and early winter. For example, there are indications that a weakening of subpolar westerly winds during autumn is an atmospheric response to a warming of the lower troposphere of the Arctic.[148] Extreme summer ice retreat also appears to be increasing the persistence of associated mid-latitude weather patterns, which may lead to an increased prob-

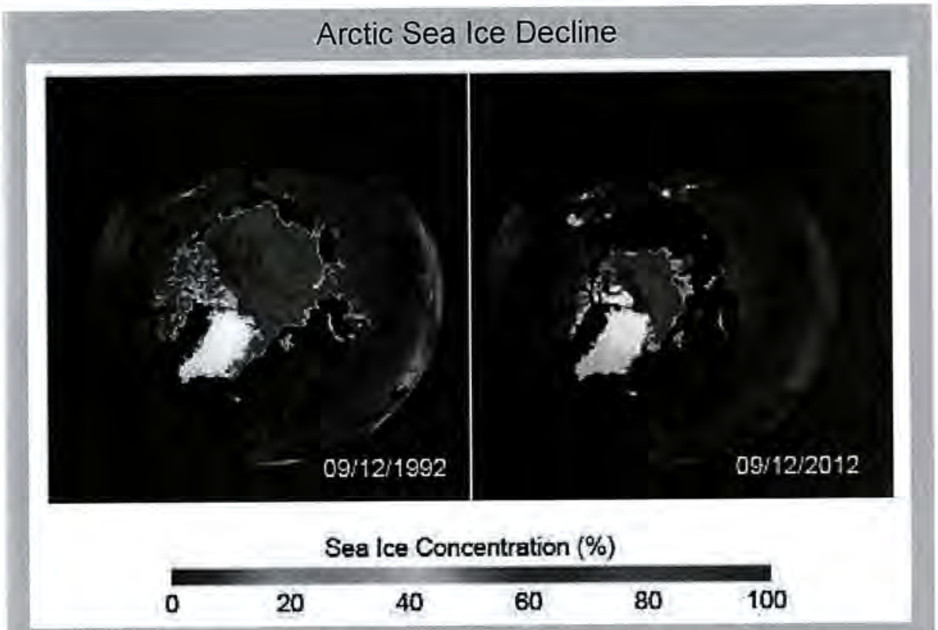


Figure 37. The spatial extent of Arctic sea ice cover in September has decreased substantially in the past two decades, as shown in this pair of satellite images depicting sea ice concentrations. The reduction of September sea ice extent from 1992 (left) to 2012 (right) has been nearly 50%, or about 1.2 million square miles (3 million square kilometers), which is nearly one-third the area of the contiguous United States. (Figure source: University of Illinois, The Cryosphere Today;[150] Data from the National Snow and Ice Data Center).

ability of extreme weather events that result from prolonged conditions, such as drought, flooding, cold spells, and heat waves.[149] However, the combination of interannual variability and the small sample of years with extreme ice retreat make it difficult to identify a geographically consistent atmospheric response pattern in the middle latitudes.

On land, changes in permafrost provide compelling indicators of a warming climate, as they tend to reflect long-term average changes in climate. Borehole measurements are particularly useful, as they provide information from levels below about 10-meter depth where the seasonal cycle becomes negligible. Increases in borehole temperatures over the past several decades are apparent at various locations, including Alaska, northern Canada, Greenland, and northern Russia. The increases are about 3.6°F at the two stations in northern Alaska (Deadhorse and West Dock). In northern Alaska and northern Siberia, where permafrost is cold and deep, thaw of the entire permafrost layer is not imminent. However, in the large areas of discontinuous permafrost of Russia, Alaska, and Canada, average annual temperatures are sufficiently close to freezing that permafrost thaw is a risk within this century. Thawing of permafrost can release methane into the atmosphere, amplifying warming (see Supplemental Message 5), as well as potentially causing infrastructure and environmental damages.

There is evidence that the active layer (the near-surface layer of seasonal thaw, typically up to three feet deep) may be thickening in many areas of permafrost, including in northern Russia and Canada.[152] Permafrost thaw in coastal areas increases the vulnerability of coastlines to erosion by ocean waves, which in turn are exacerbated by the loss of sea ice from coastal areas affected by storms.

Increased melt is reducing both the mass and areal extent of glaciers over much of the Northern Hemisphere. Over the past decade, the contribution to sea level rise from glaciers and small ice caps (excluding Greenland) has been comparable to the contributions from the Greenland Ice Sheet.[153]

Projections of future mass loss by glaciers and small ice caps indicate a continuation of current trends, although these projections are based only on the changes in temperature and precipitation projected by global climate models; they do not include the effects of dynamical changes (for example, glacier movement). While there is a wide range among the projections derived from different global climate models, the models are consistent in indicating that the effects of melting will outweigh the effects of increases in snowfall. The regions from which the contributions to sea level rise are projected to be largest are the Canadian Arctic, Alaska, and the Russian Arctic.[151]

Permafrost Temperatures Rising

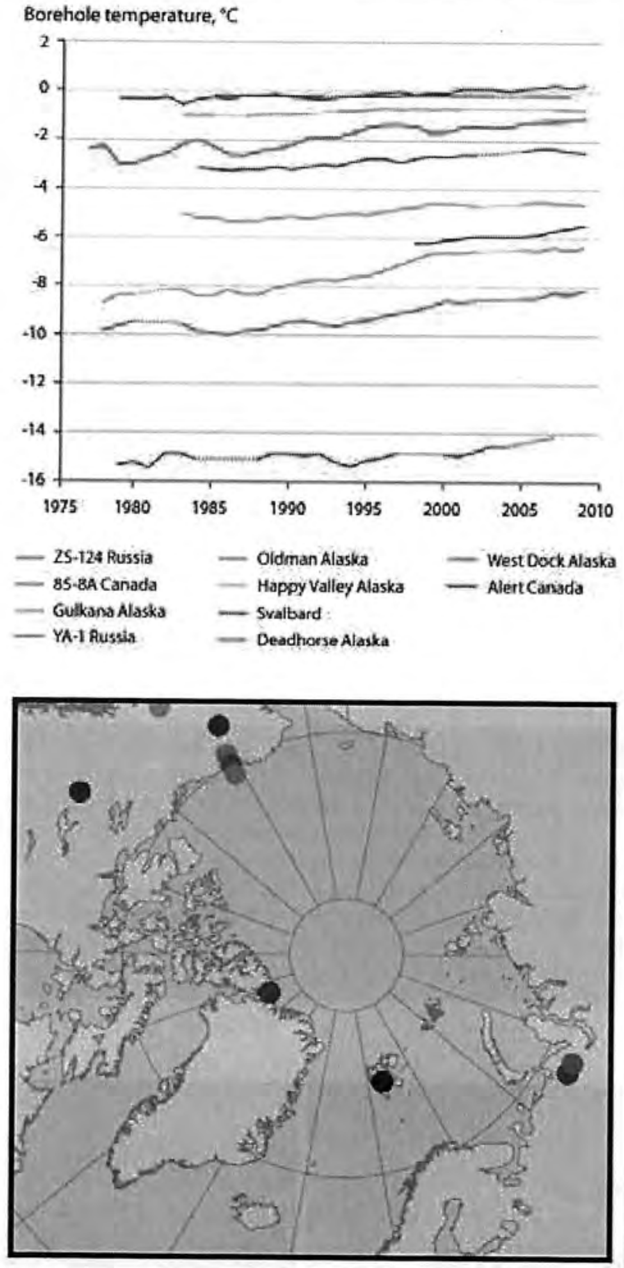


Figure 38. Ground temperatures at depths between 33 and 66 feet (10 and 20 meters) for boreholes across the circumpolar northern permafrost regions. Lower panel shows locations of measurement sites in colors corresponding to lines in upper panel (Figure source: AMAP 2011[151]).

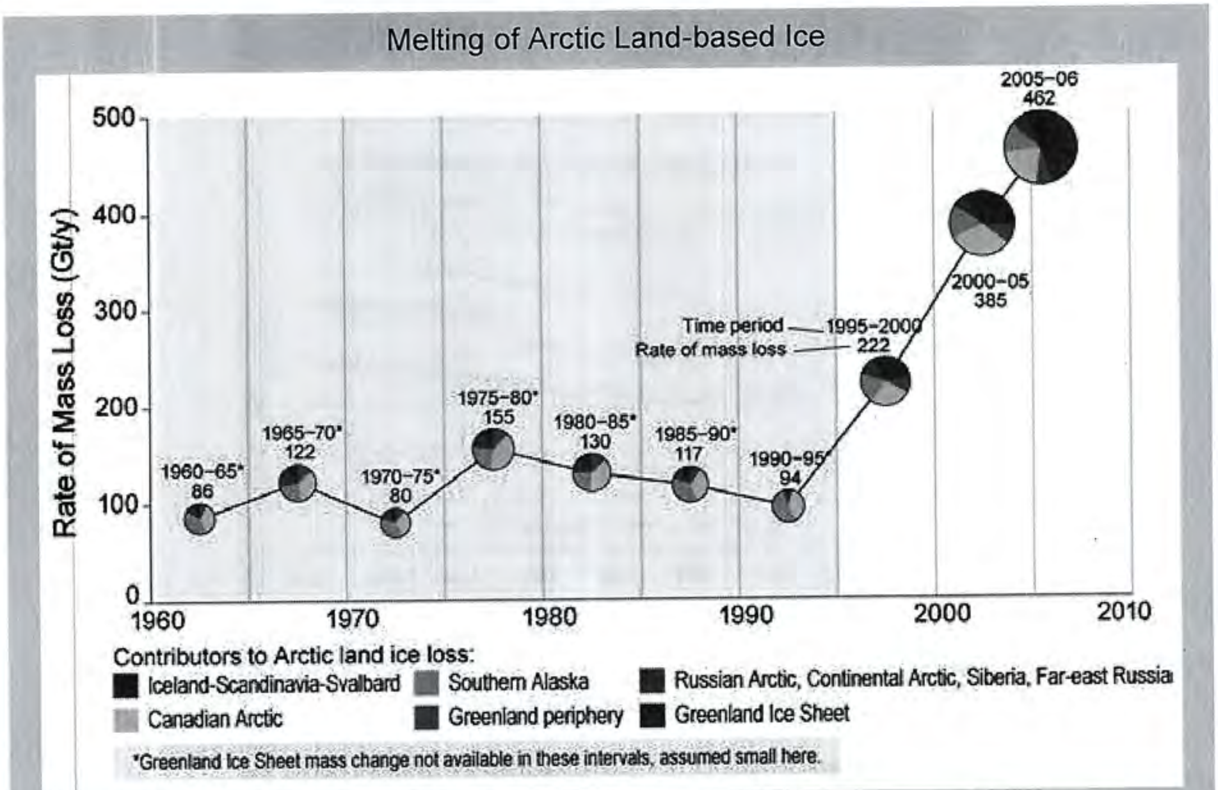


Figure 39. Inputs of freshwater to the ocean from mountain glaciers, small ice caps, and the Greenland Ice Sheet have increased dramatically in the past two decades. The size of the circles in the figure is proportional to the five-year average freshwater contributions to the ocean from melting of land-based ice. The coloring indicates the relative contributions from the Greenland Ice Sheet (brown) and mountain glaciers from the Greenland periphery (orange), Iceland-Scandinavia-Svalbard (dark blue), the Canadian Arctic (yellow), southern Alaska (light blue), and the Russian Arctic (medium blue). The largest contributions from mountain glaciers have been from the Canadian Arctic and southern Alaska. Note that contributions from mass changes of the Greenland Ice Sheet are not available prior to the mid-1990s, but they are assumed to have been small during this earlier period because annual snow accumulation was in approximate balance with annual meltwater discharge. (Figure source: AMAP 2011[151]).

On the left is a photograph of Muir Glacier in Alaska taken on August 13, 1941; on the right, a photograph taken from the same vantage point on August 31, 2004. Total glacial mass has declined sharply around the globe, adding to sea level rise. (Left photo by glaciologist William O, Field; right photo by geologist Bruce F. Molnia of the United State Geological Survey.)

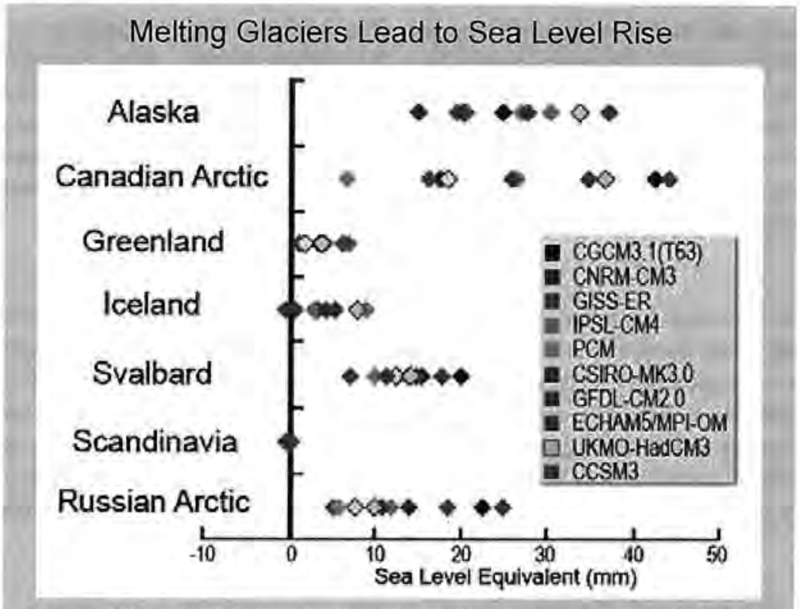


Figure 40. Projections of contributions to sea level rise by 2100 for seven regions that include all Arctic glaciers. Projections are based on temperature and precipitation simulated by ten different global climate models from CMIP3. For each region, the estimates are shown in different colors corresponding to the ten different models. (Figure source: adapted from Radić and Hock 2011[154]).

Supplemental Message 12.

Sea level is already rising at the global scale and at individual locations along the U.S. coast. Future sea level rise depends on the amount of warming and ice melt around the world as well as local processes like changes in ocean currents and local land subsidence or uplift.

The rising global average sea level is one of the hallmarks of a warming planet. It will also be one of the major impacts of human-caused global warming on both human society and the natural environment.

Global sea level is increasing as a result of two different processes. First, the oceans absorb more than 90% of the excess heat trapped by human interference with the climate system, and this warms the oceans.[155] Like mercury in a thermometer, the warmer ocean water expands, contributing to global sea level rise. Second, the warmer climate also causes melting of glaciers and ice sheets. This meltwater eventually runs off into the ocean and contributes to sea level rise as well. A recent synthesis of surface and satellite measurements of the ice sheets shows that the rate at which the Greenland and Antarctic ice sheets contribute to sea level rise has been increasing rapidly and has averaged 0.02 inches (plus or minus 0.008) per year since 1992, with Greenland's contribution being more than double that of Antarctica.[156] In addition, local sea level change can differ from the global average sea level rise due to changes in ocean currents, local land movement, and even changes in the gravitational pull of the ice sheets and changes in Earth's rotation.

There is high confidence that global sea level will continue to rise over this century and beyond and that most coastlines will see higher water levels. The rates of sea level rise along individual coastlines are difficult to predict, as they can vary depending on the region. For example, globally averaged sea level has risen steadily by about 2.4 inches over the past two decades. But during that time, many regions have seen much more rapid rise while some have experienced falling sea levels. These complicated patterns are caused by changes in ocean currents and movement of heat within the oceans. Many of these patterns are due in part to natural, cyclic changes in the oceans. On the West Coast of the United States, sea level has fallen slightly since the early 1990s. Recent work suggests that a natural cycle known as the Pacific Decadal Oscillation has counteracted most or all of the global sea level signal there. This means that in coming decades the West Coast is likely to see faster than average sea level rise as this natural cycle changes phase.[157]

Along any given coastline, determining the rate of sea level rise is complicated by the fact that the land may be rising or sinking. Along the Gulf Coast, for example, local geological factors including extraction of oil, natural gas, and water from under-ground reservoirs are causing the land to sink, which could increase the effect of global sea level rise by several inches by the end of this century.[158] In some other locations, coastlines are rising as they continue to rebound from glaciation during the last glacial maximum. Predicting the future of any single coastline requires intimate knowledge of the local geology as well as the processes that cause sea levels to change at both the local and global scale.

Greenland and Antarctica hold enough ice to raise global sea levels by more than 200 feet if they were to melt completely. While this is very unlikely over at least the next few centuries, studies suggest that meltwater from ice sheets could contribute anywhere from several inches to 4.5 feet to global sea levels by the end of this century.[159] Because their behavior in a warming climate is still very difficult to predict, these two ice sheets are the biggest wildcards for potential sea level rise in the coming decades. What is certain is that these ice sheets are already responding to the warming of the oceans and the atmosphere. Satellites that measure small changes in the gravitational pull of these two regions have proven that both Greenland and Antarctica are currently losing ice and contributing to global sea level rise.[160]

In the United States, an estimated 5 million people currently live within 4 feet of current high tide lines, which places them at increasing risk of flooding in the coming decades.[161] Although sea level rise is often thought of as causing a slow inundation, the most immediate impacts of sea level rise are increases in high tides and storm surges. A recent assessment of flood risks in the United States found that the odds of experiencing a "100-year flood" are on track to double by 2030.

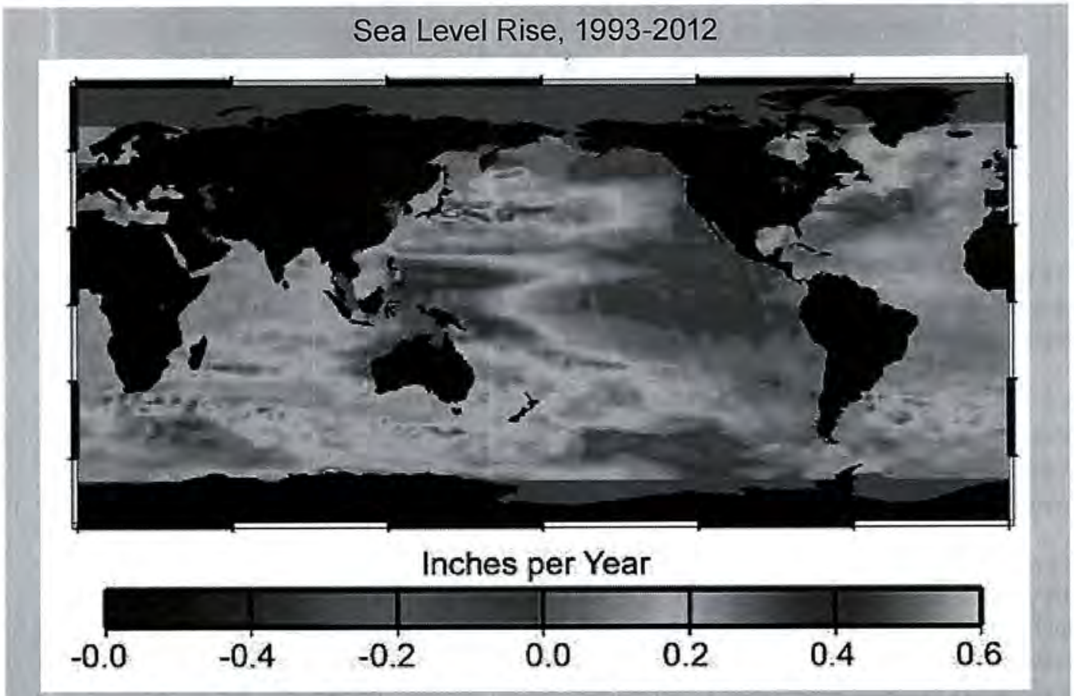


Figure 41. The patterns of sea level rise between 1993 and 2012 as measured by satellites. The complicated patterns are a reminder that sea levels do not rise uniformly.[162] (Figure source: University of Colorado, Sea Level Research Group).

Ice Loss from Greenland and Antarctica

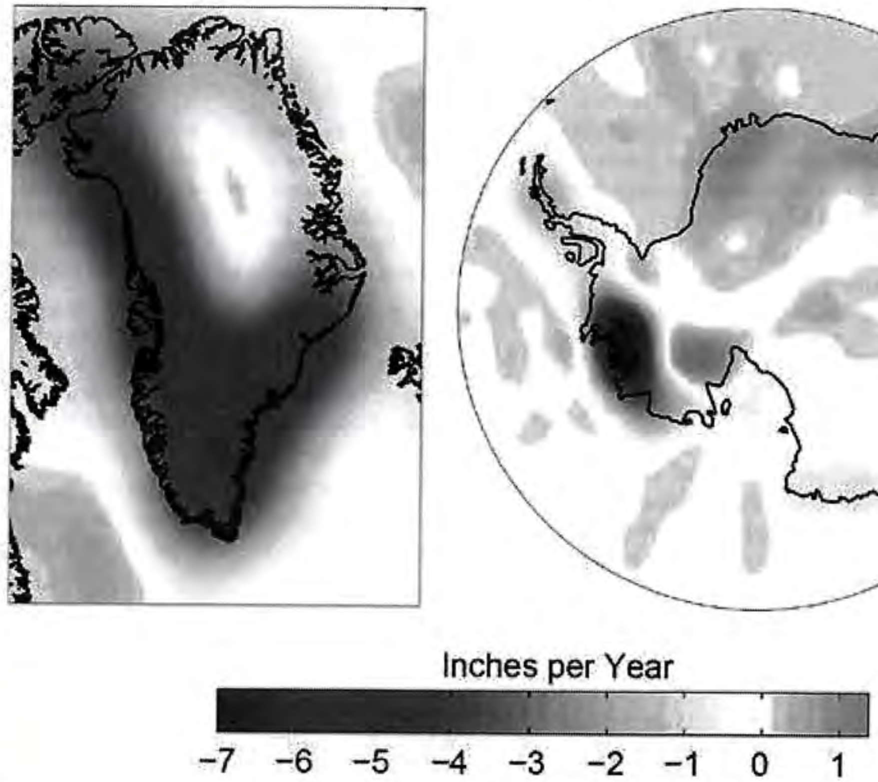


Figure 42. Rate of local ice sheet mass loss (in inches of water-equivalent-height per year) from Greenland (left) and Antarctica (right) from 2003 to 2012. The GRACE (Gravity Recovery and Climate Experiment) satellites measure changes in the pull of gravity over these two regions. As they lose ice to the oceans, the gravitational pull of Greenland and Antarctica is reduced. Analyses of GRACE data have now proven that both of the major ice sheets are currently contributing to global sea level rise due to ice loss. Over the periods plotted here, Greenland lost enough ice to raise sea level at a rate of 0.028 inches per year (0.72 mm/yr), and Antarctica lost ice at a rate that caused 0.0091 inches of sea level rise per year (0.24 mm/yr). (Figure source: NASA Jet Propulsion Laboratory, (left) updated from Velicogna and Wahr 2013;[163] (right) updated from Ivins et al. 2013[164]).

APPENDIX 3: CLIMATE SCIENCE

REFERENCES

1. Karl, T. R., J. T. Melillo, and T. C. Peterson, Eds., 2009: *Global Climate Change Impacts in the United States*. Cambridge University Press, 189 pp. [Available online at http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf]

2. Swanson, K. L., G. Sugihara, and A. A. Tsonis, 2009: Long-term natural variability and 20th century climate change. *Proceedings of the National Academy of Sciences*, **106,** 16120-16123, doi:10.1073/pnas.0908699106.

3. Fourier, J.-B. J., 1824: Remarques générales sur les températures du globe terrestre et des espaces planétaires. *Annales de Chimie et de Physique, 2e série*, **27,** 136-167.

4. Tyndall, J., 1861: The Bakerian Lecture: On the absorption and radiation of heat by gases and vapours, and on the physical connexion of radiation, absoprtion, and conduction. *Philosophical Transactions of the Royal Society of London*, **151,** 1-36. [Available online at http://www.jstor.org/stable/108724]

5. NPS, cited 2012: What is Climate Change? U.S. Department of the Interior, National Park Service. [Available online at http://www.nps.gov/goga/naturescience/climate-change-causes.htm]

6. Stephens, G. L., J. Li, M. Wild, C. A. Clayson, N. Loeb, S. Kato, T. L'Ecuyer, P. W. Stackhouse, M. Lebsock, and T. Andrews, 2012: An update on Earth's energy balance in light of the latest global observations. *Nature Geoscience*, **5,** 691-696, doi:10.1038/ngeo1580.

7. Boden, T., G. Marland, and B. Andres, 2012: *Global CO_2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2009.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. [Available online at http://cdiac.ornl.gov/ftp/ndp030/global.1751_2009.ems]

8. Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D. W. Fahey, J. Haywood, J. Lean, D. C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz, and R. Van Dorland, 2007: Ch. 2: Changes in atmospheric constituents and in radiative forcing. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Eds., Cambridge University Press. [Available online at http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2.html]

9. Lüthi, D., M. Le Floch, B. Bereiter, T. Blunier, J. M. Barnola, U. Siegenthaler, D. Raynaud, J. Jouzel, H. Fischer, K. Kawamura, and T. F. Stocker, 2008: High-resolution carbon dioxide concentration record 650,000–800,000 years before present. *Nature*, **453,** 379-382, doi:10.1038/nature06949. [Available online at http://www.nature.com/nature/journal/v453/n7193/pdf/nature06949.pdf]

10. Siegenthaler, U., E. Monnin, K. Kawamura, R. Spahni, J. Schwander, B. Stauffer, T. F. Stocker, J. Barnola, and H. Fischer, 2005: Supporting evidence from the EPICA Dronning Maud Land ice core for atmospheric CO_2 changes during the past millennium. *Tellus B*, **57,** 51-57, doi:10.1111/j.1600-0889.2005.00131.x. [Available online at http://www.climate.unibe.ch/~spahni/papers/siegenthaler05tellb.pdf]

11. Pépin, L., D. Raynaud, J.-M. Barnola, and M. F. Loutre, 2001: Hemispheric roles of climate forcings during glacial-interglacial transitions as deduced from the Vostok record and LLN-2D model experiments. *Journal of Geophysical Research*, **106,** 31,885-831,892, doi:10.1029/2001JD900117. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2001JD900117/pdf]

    Petit, J. R., J. Jouzel, D. Raynaud, N. I. Barkov, J.-M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, M. Delmotte, V. M. Kotlyakov, M. Legrand, V. Y. Lipenkov, C. Lorius, L. Pépin, C. Ritz, E. Saltzman, and M. Stievenard, 1999: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, **399,** 429-436, doi:10.1038/20859.

    Raynaud, D., J.-M. Barnola, R. Souchez, R. Lorrain, J.-R. Petit, P. Duval, and V. Y. Lipenkov, 2005: Palaeoclimatology: The record for marine isotopic stage 11. *Nature*, **436,** 39-40, doi:10.1038/43639b.

12. Monnin, E., A. Indermühle, A. Dällenbach, J. Flückiger, B. Stauffer, T. F. Stocker, D. Raynaud, and J. M. Barnola, 2001: Atmospheric CO_2 concentrations over the last glacial termination. *Science*, **291,** 112-114, doi:10.1126/science.291.5501.112.

13. Meinshausen, M., S. J. Smith, K. Calvin, J. S. Daniel, M. L. T. Kainuma, J. F. Lamarque, K. Matsumoto, S. A. Montzka, S. C. B. Raper, K. Riahi, A. Thomson, G. J. M. Velders, and D. P. P. van Vuuren, 2011: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*, **109,** 213-214, doi:10.1007/s10584-011-0156-z. [Available online at http://link.springer.com/content/pdf/10.1007%2Fs10584-011-0156-z]

14. Dlugokencky, E. J., E. G. Nisbet, R. Fisher, and D. Lowry, 2011: Global atmospheric methane: Budget, changes and dangers. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **369,** 2058-2072, doi:10.1098/rsta.2010.0341. [Available online at http://rsta.royalsocietypublishing.org/content/369/1943/2058.full.pdf+html]

15. IPCC, 2007: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Eds. Cambridge University Press, 996 pp. [Available online at http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm]

16. Lamarque, J. F., P. Hess, L. Emmons, L. Buja, W. Washington, and C. Granier, 2005: Tropospheric ozone evolution between 1890 and 1990. *Journal of Geophysical Research: Atmospheres*, **110,** D08304, doi:10.1029/2004JD005537. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2004JD005537/pdf]

17. Shindell, D., J. C. I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S. C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluvegi, L. Pozzoli, K. Kupiainen, L. Hoglund-Isaksson, L. Emberson, D. Streets, V. Ramanathan, K. Hicks, N. T. K. Oanh, G. Milly, M. Williams, V. Demkine, and D. Fowler, 2012: Simultaneously mitigating near-term climate change and improving human health and food security. *Science*, **335,** 183-189, doi:10.1126/science.1210026.

18. Schmidt, G. A., R. A. Ruedy, R. L. Miller, and A. A. Lacis, 2010: Attribution of the present-day total greenhouse effect. *Journal of Geophysical Research*, **115,** 1-6, doi:10.1029/2010JD014287. [Available online at ftp://spacegrant.hawaii.edu/coastal/Climate%20Articles/CO2%20role%20modern%20warming%202010.pdf]

19. Lacis, A. A., G. A. Schmidt, D. Rind, and R. A. Ruedy, 2010: Atmospheric CO_2: Principal control knob governing Earth's temperature. *Science*, **330,** 356-359, doi:10.1126/science.1190653.

20. Brönnimann, S., T. Ewen, J. Luterbacher, H. F. Diaz, R. S. Stolarski, and U. Neu, 2007: A focus on climate during the past 100 years. *Climate Variability and Extremes during the Past 100 Years*, 1-25.

21. Jones, P. D., D. H. Lister, T. J. Osborn, C. Harpham, M. Salmon, and C. P. Morice, 2012: Hemispheric and large-scale land surface air temperature variations: An extensive revision and an update to 2010. *Journal of Geophysical Research*, **117**, doi:10.1029/2011JD017139. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2011JD017139/pdf]

Lawrimore, J. H., M. J. Menne, B. E. Gleason, C. N. Williams, D. B. Wuertz, R. S. Vose, and J. Rennie, 2011: An overview of the Global Historical Climatology Network monthly mean temperature data set, version 3. *Journal of Geophysical Research*, **116,** D19121, doi:10.1029/2011JD016187.

Rohde, R., R. Muller, R. Jacobsen, S. Perlmutter, A. Rosenfeld, J. Wurtele, J. Curry, C. Wickham, and S. Mosher, 2013: Berkeley Earth Temperature Averaging Process. *Geoinformatics & Geostatistics: An Overview*, **1,** 1-13, doi:10.4172/gigs.1000103. [Available online at http://www.scitechnol.com/2327-4581/2327-4581-1-103.pdf]

22. Kennedy, J. J., N. A. Rayner, R. O. Smith, D. E. Parker, and M. Saunby, 2011: Reassessing biases and other uncertainties in sea surface temperature observations measured in situ since 1850: 2. Biases and homogenization. *Journal of Geophysical Research: Atmospheres*, **116,** D14104, doi:10.1029/2010JD015220.

Smith, T. M., and R. W. Reynolds, 2002: Bias corrections for historical sea surface temperatures based on marine air temperatures. *Journal of Climate*, **15,** 73-87, doi:10.1175/1520-0442(2002)015<0073:BCFHSS>2.0.CO;2.

23. Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010: Global surface temperature change. *Reviews of Geophysics*, **48,** RG4004, doi:10.1029/2010RG000345.

Morice, C. P., J. J. Kennedy, N. A. Rayner, and P. D. Jones, 2012: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 dataset. *Journal of Geophysical Research: Atmospheres*, doi:10.1029/2011JD017187. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2011JD017187/pdf]

24. Vose, R. S., D. Arndt, V. F. Banzon, D. R. Easterling, B. Gleason, B. Huang, E. Kearns, J. H. Lawrimore, M. J. Menne, T. C. Peterson, R. W. Reynolds, T. M. Smith, C. N. Williams, and D. L. Wuertz, 2012: NOAA's Merged Land-Ocean Surface Temperature Analysis. *Bulletin of the American Meteorological Society*, **93,** 1677-1685, doi:10.1175/BAMS-D-11-00241.1.

25. Kennedy, J. J., P. W. Thorne, T. C. Peterson, R. A. Reudy, P. A. Stott, D. E. Parker, S. A. Good, H. A. Titchner, and K. M. Willett, 2010: How do we know the world has warmed? [in "State of the Climate in 2009"]. *Bulletin of the American Meteorological Society*, **91,** S26-27, doi:10.1175/BAMS-91-7-StateoftheClimate. [Available online at http://journals.ametsoc.org/doi/abs/10.1175/BAMS-91-7-StateoftheClimate]

26. Diaz, H. F., R. Trigo, M. K. Hughes, M. E. Mann, E. Xoplaki, and D. Barriopedro, 2011: Spatial and temporal characteristics of climate in medieval times revisited. *Bulletin of the American Meteorological Society*, **92,** 1487-1500, doi:10.1175/bams-d-10-05003.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-10-05003.1]

Hegerl, G. C., T. J. Crowley, M. Allen, W. T. Hyde, H. N. Pollack, J. Smerdon, and E. Zorita, 2007: Detection of human influence on a new, validated 1500-year temperature reconstruction. *Journal of Climate*, **20,** 650-666, doi:10.1175/jcli4011.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/JCLI4011.1]

Juckes, M. N., M. R. Allen, K. R. Briffa, J. Esper, G. C. Hegerl, A. Moberg, T. J. Osborn, and S. L. Weber, 2007: Millennial temperature reconstruction intercomparison and evaluation. *Climate of the Past*, **3,** 591-609, doi:10.5194/cp-3-591-2007. [Available online at http://www.clim-past.net/3/591/2007/cp-3-591-2007.pdf]

Loehle, C., and J. H. McCulloch, 2008: Correction to: A 2000-year global temperature reconstruction based on non-tree ring proxies. *Energy & Environment*, **19,** 93-100, doi:10.1260/095830508783563109.

Mann, M. E., Z. Zhang, S. Rutherford, R. S. Bradley, M. K. Hughes, D. Shindell, C. Ammann, G. Faluvegi, and F. Ni, 2009: Global signatures and dynamical origins of the Little Ice Age and Medieval Climate Anomaly. *Science*, **326,** 1256-1260, doi:10.1126/science.1177303.

Shi, F., B. Yang, A. Mairesse, L. von Gunten, J. Li, A. Bräuning, F. Yang, and X. Xiao, 2013: Northern Hemisphere temperature reconstruction during the last millennium using multiple annual proxies. *Climate Research*, **56,** 231-244, doi:10.3354/cr01156. [Available online at http://www.int-res.com/articles/cr2013/56/c056p231.pdf]

27. Mann, M. E., Z. Zhang, M. K. Hughes, R. S. Bradley, S. K. Miller, S. Rutherford, and F. Ni, 2008: Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proceedings of the National Academy of Sciences*, **105,** 13252-13257, doi:10.1073/pnas.0805721105. [Available online at http://www.jstor.org/stable/pdfplus/25464030.pdf]

28. Menne, M. J., and C. N. Williams, Jr., 2009: Homogenization of temperature series via pairwise comparisons. *Journal of Climate*, **22,** 1700-1717, doi:10.1175/2008JCLI2263.1. [Available online at http://journals.ametsoc.org/doi/abs/10.1175/2008JCLI2263.1]

29. PAGES 2K Consortium, 2013: Continental-scale temperature variability during the past two millennia. *Nature Geoscience*, **6,** 339-346, doi:10.1038/ngeo1797.

30. Marcott, S. A., J. D. Shakun, P. U. Clark, and A. C. Mix, 2013: A reconstruction of regional and global temperature for the past 11,300 years. *Science*, **339,** 1198-1201, doi:10.1126/science.1228026.

31. Brigham-Grette, J., M. Melles, P. Minyuk, A. Andreev, P. Tarasov, R. DeConto, S. Koenig, N. Nowaczyk, V. Wennrich, P. Rosén, E. Haltia, T. Cook, C. Gebhardt, C. Meyer-Jacob, J. Snyder, and U. Herzschuh, 2013: Pliocene warmth, polar amplification, and stepped Pleistocene cooling recorded in NE Arctic Russia. *Science*, **340,** 1421-1427, doi:10.1126/science.1233137.

Melles, M., J. Brigham-Grette, P. S. Minyuk, N. R. Nowaczyk, V. Wennrich, R. M. DeConto, P. M. Anderson, A. A. Andreev, A. Coletti, T. L. Cook, E. Haltia-Hovi, M. Kukkonen, A. V. Lozhkin, P. Rosén, P. Tarasov, H. Vogel, and B. Wagner, 2012: 2.8 million years of Arctic climate change from Lake El'gygytgyn, NE Russia. *Science*, **337,** 315-320, doi:10.1126/science.1222135.

32. Tung, K.-K., and J. Zhou, 2013: Using data to attribute episodes of warming and cooling in instrumental records. *Proceedings of the National Academy of Sciences*, doi:10.1073/pnas.1212471110. [Available online at http://www.pnas.org/content/early/2013/01/22/1212471110.full.pdf+html]

33. Stoner, A. M. K., K. Hayhoe, and D. J. Wuebbles, 2009: Assessing general circulation model simulations of atmospheric teleconnection patterns. *Journal of Climate*, **22,** 4348-4372, doi:10.1175/2009JCLI2577.1.

Deser, C., A. Phillips, V. Bourdette, and H. Teng, 2012: Uncertainty in climate change projections: The role of internal variability. *Climate Dynamics*, **38,** 527-546, doi:10.1007/s00382-010-0977-x.

34. Larkin, N. K., and D. E. Harrison, 2005: On the definition of El Niño and associated seasonal average U.S. weather anomalies. *Geophysical Research Letters*, **32,** doi:10.1029/2005GL022738. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2005GL022738/pdf]

——, 2005: Global seasonal temperature and precipitation anomalies during El Niño autumn and winter. *Geophysical Research Letters*, **32,** doi:10.1029/2005GL022860. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2005GL022860/pdf]

Hoerling, M. P., and A. Kumar, 2002: Atmospheric response patterns associated with tropical forcing. *Journal of Climate*, **15,** 2184-2203, doi:10.1175/1520-0442(2002)015<2184:ARPAWT>2.0.CO;2. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/1520-0442%282002%29015%3C2184%3AARPAWT%3E2.0.CO%3B2]

35. Bell, G. D., and M. Chelliah, 2006: Leading tropical modes associated with interannual and multidecadal fluctuations in North Atlantic hurricane activity. *Journal of Climate*, **19,** 590-612, doi:10.1175/JCLI3659.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/JCLI3659.1]

36. Wang, Z., C. P. Chang, and B. Wang, 2007: Impacts of El Niño and La Niña on the U.S. climate during northern summer. *Journal of Climate*, **20,** 2165-2177, doi:10.1175/JCLI4118.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/JCLI4118.1]

37. Fowler, A. M., G. Boswijk, A. M. Lorrey, J. Gergis, M. Pirie, S. P. J. McCloskey, J. G. Palmer, and J. Wunder, 2012: Multi-centennial tree-ring record of ENSO-related activity in New Zealand. *Nature Climate Change*, **2,** 172-176, doi:10.1038/nclimate1374.

38. Nielsen-Gammon, J., 2012: Climate Abyss: About the lack of Warming.... *Houston Chronicle*. [Available online at http://blog.chron.com/climateabyss/2012/04/about-the-lack-of-warming/]

39. NASA, 2012: GISS Surface Temperature Analysis (GISTEMP), National Aeronautics and Space Administration Goddard Institute for Space Studies, New York, NY. [Available online at http://data.giss.nasa.gov/gistemp/tabledata_v3/GLB.Ts+dSST.txt]

40. CPC, cited 2012: Historical El Nino/La Nina Episodes (1950-Present). National Weather Service, Climate Prediction Center. [Available online at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml]

41. Pan, Z., R. W. Arritt, E. S. Takle, W. J. Gutowski, Jr., C. J. Anderson, and M. Segal, 2004: Altered hydrologic feedback in a warming climate introduces a "warming hole". *Geophysical Research Letters*, **31,** L17109, doi:10.1029/2004GL020528. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2004GL020528/pdf]

42. Portmann, R. W., S. Solomon, and G. C. Hegerl, 2009: Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States. *Proceedings of the National Academy of Sciences*, **106,** 7324-7329, doi:10.1073/pnas.0808533106. [Available online at http://www.pnas.org/content/106/18/7324.full.pdf+html]

43. Puma, M. J., and B. I. Cook, 2010: Effects of irrigation on global climate during the 20th century. *Journal of Geophysical Research*, **115,** D16120, doi:10.1029/2010JD014122. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2010JD014122/pdf]

44. Kunkel, K. E., X.-Z. Liang, J. Zhu, and Y. Lin, 2006: Can CGCMS simulate the twentieth-century "warming hole" in the central United States? *Journal of Climate*, **19,** 4137-4153, doi:10.1175/JCLI3848.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/JCLI3848.1]

Robinson, W. A., R. Reudy, and J. E. Hansen, 2002: General circulation model simulations of recent cooling in the east-central United States. *Journal Of Geophysical Research*, **107,** ACL 4-1 - ACL 4-14, doi:10.1029/2001JD001577. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2001JD001577/pdf]

45. Meehl, G. A., J. M. Arblaster, and G. Branstator, 2012: Mechanisms contributing to the warming hole and the consequent US east-west differential of heat extremes. *Journal of Climate*, **25,** 6394-6408, doi:10.1175/JCLI-D-11-00655.1. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2009GL040736/pdf]

46. Stott, P. A., N. P. Gillett, G. C. Hegerl, D. J. Karoly, D. A. Stone, X. Zhang, and F. Zwiers, 2010: Detection and attribution of climate change: A regional perspective. *Wiley Interdisciplinary Reviews: Climate Change*, **1,** 192-211, doi:10.1002/wcc.34.

47. Jones, G. S., and P. A. Stott, 2011: Sensitivity of the attribution of near surface temperature warming to the choice of observational dataset. *Geophysical Research Letters*, **38,** L21702, doi:10.1029/2011GL049324. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2011GL049324/pdf]

48. Lott, F., P. A. Stott, D. Mitchell, N. Christidis, N. Gillett, L. Gray, L. Haimberger, J. Perlwitz, and P. Thorne, 2013: Models versus radiosondes in the free atmosphere: A new detection and attribution analysis of temperature. *Journal of Geophysical Research*, **118**, 2609-2619, doi:10.1002/jgrd.50255.

Santer, B. D., J. F. Painter, C. A. Mears, C. Doutriaux, P. Caldwell, J. M. Arblaster, P. J. Cameron-Smith, N. P. Gillett, P. J. Gleckler, J. Lanzante, J. Perlwitz, S. Solomon, P. A. Stott, K. E. Taylor, L. Terray, P. W. Thorne, M. F. Wehner, F. J. Wentz, T. M. L. Wigley, L. J. Wilcox, and C.-Z. Zou, 2013: Identifying human influences on atmospheric temperature. *Proceedings of the National Academy of Sciences*, **110,** 26-33, doi:10.1073/pnas.1210514109. [Available online at http://www.pnas.org/content/110/1/26.full.pdf+html]

49. AchutaRao, K. M., B. D. Santer, P. J. Gleckler, K. E. Taylor, D. W. Pierce, T. P. Barnett, and T. M. L. Wigley, 2006: Variability of ocean heat uptake: Reconciling observations and models. *Journal of Geophysical Research*, **111,** 20, doi:10.1029/2005jc003136.

AchutaRao, K. M., M. Ishii, B. D. Santer, P. J. Gleckler, K. E. Taylor, T. P. Barnett, D. W. Pierce, R. J. Stouffer, and T. M. L. Wigley, 2007: Simulated and observed variability in ocean temperature and heat content. *Proceedings of the National Academy of Sciences*, **104,** 10768-10773, doi:10.1073/pnas.0611375104.

50. Santer, B. D., C. Mears, F. J. Wentz, K. E. Taylor, P. J. Gleckler, T. M. L. Wigley, T. P. Barnett, J. S. Boyle, W. Brüggemann, N. P. Gillett, S. A. Klein, G. A. Meehl, T. Nozawa, D. W. Pierce, P. A. Stott, W. M. Washington, and M. F. Wehner, 2007: Identification of human-induced changes in atmospheric moisture content. *Proceedings of the National Academy of Sciences*, **104,** 15248-15253, doi:10.1073/pnas.0702872104. [Available online at http://sa.indiaenvironmentportal.org.in/files/file/PNAS-2007-Santer-15248-53.pdf]

Willett, K. M., N. P. Gillett, P. D. Jones, and P. W. Thorne, 2007: Attribution of observed surface humidity changes to human influence. *Nature*, **449,** 710-712, doi:10.1038/nature06207.

51. Min, S. K., X. Zhang, F. W. Zwiers, and G. C. Hegerl, 2011: Human contribution to more-intense precipitation extremes. *Nature*, **470,** 378-381, doi:10.1038/nature09763. [Available online at http://www.nature.com/nature/journal/v470/n7334/abs/nature09763.html]

52. Gedney, N., P. M. Cox, R. A. Betts, O. Boucher, C. Huntingford, and P. A. Stott, 2006: Detection of a direct carbon dioxide effect in continental river runoff records. *Nature*, **439,** 835-838, doi:10.1038/nature04504.

53. Durack, P. J., S. E. Wijffels, and R. J. Matear, 2012: Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. *Science*, **336,** 455-458, doi:10.1126/science.1212222.

54. Gillett, N. P., and P. A. Stott, 2009: Attribution of anthropogenic influence on seasonal sea level pressure. *Geophysical Research Letters*, **36,** L23709, doi:10.1029/2009GL041269. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2009GL041269/pdf]

55. Jones, G. S., P. A. Stott, and N. Christidis, 2013: Attribution of observed historical near surface temperature variations to anthropogenic and natural causes using CMIP5 simulations. *Journal of Geophysical Research*, **118,** 4001-4024, doi:10.1002/jgrd.50239. [Available online at http://onlinelibrary.wiley.com/doi/10.1002/jgrd.50239/pdf]

56. Allen, M., 2011: In defense of the traditional null hypothesis: Remarks on the Trenberth and Curry *WIREs* opinion articles. *Wiley Interdisciplinary Reviews: Climate Change*, **2,** 931 pp., doi:10.1002/wcc.145.

Curry, J., 2011: Nullifying the climate null hypothesis. *Wiley Interdisciplinary Reviews: Climate Change*, **2,** 919-924, doi:10.1002/wcc/141.

Trenberth, K. E., 2011: Attribution of climate variations and trends to human influences and natural variability. *Wiley Interdisciplinary Reviews: Climate Change*, **2,** 925-930, doi:10.1002/wcc.142.

57. Stott, P. A., M. R. Allen, N. Christidis, R. Dole, M. Hoerling, C. Huntingford, P. Pall, J. Perlwitz, and D. Stone, 2011: Attribution of weather and climate-related extreme events. World Climate Research Programme report. *World Meteorological Organization. WCRP OSC Climate Research in Service to Society*, Sheraton Denver Downtown Hotel, Denver, CO, WMO, 44 pp. [Available online at http://library.wmo.int/pmb_ged/wcrp_2011-stott.pdf]

Stott, P. A., N. Christidis, and R. A. Betts, 2011: Changing return periods of weather-related impacts: The attribution challenge. *Climatic Change*, **109,** 263-268, doi:10.1007/s10584-011-0265-8.

58. Christidis, N., P. A. Stott, G. S. Jones, H. Shiogama, T. Nozawa, and J. Luterbacher, 2012: Human activity and anomalously warm seasons in Europe. *International Journal of Climatology*, **32,** 225-239, doi:10.1002/joc.2262.

Stott, P. A., D. A. Stone, and M. R. Allen, 2004: Human contribution to the European heatwave of 2003. *Nature*, **432,** 610-614, doi:10.1038/nature03089.

59. Dole, R., M. Hoerling, J. Perlwitz, J. Eischeid, P. Pegion, T. Zhang, X. W. Quan, T. Xu, and D. Murray, 2011: Was there a basis for anticipating the 2010 Russian heat wave? *Geophysical Research Letters*, **38,** L06702, doi:10.1029/2010GL046582.

Otto, F. E. L., N. Massey, G. J. van Oldenborgh, R. G. Jones, and M. R. Allen, 2012: Reconciling two approaches to attribution of the 2010 Russian heat wave. *Geophysical Research Letters*, **39,** L04702, doi:10.1029/2011GL050422. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2011GL050422/pdf]

Rahmstorf, S., and D. Coumou, 2011: Increase of extreme events in a warming world. *Proceedings of the National Academy of Sciences*, **108,** 17905-17909, doi:10.1073/pnas.1101766108. [Available online at http://www.pnas.org/content/108/44/17905.full.pdf+html]

60. Hoerling, M., M. Chen, R. Dole, J. Eischeid, A. Kumar, J. W. Nielsen-Gammon, P. Pegion, J. Perlwitz, X.-W. Quan, and T. Zhang, 2013: Anatomy of an extreme event. *Journal of Climate*, **26,** 2811–2832, doi:10.1175/JCLI-D-12-00270.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-12-00270.1]

61. Pall, P., T. Aina, D. A. Stone, P. A. Stott, T. Nozawa, A. G. J. Hilberts, D. Lohmann, and M. R. Allen, 2011: Anthropogenic greenhouse gas contribution to flood risk in England and Wales in autumn 2000. *Nature*, **470,** 382-385, doi:10.1038/nature09762. [Available online at http://www.nature.com/nature/journal/v470/n7334/abs/nature09762.html]

62. Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan, and M. D. Dettinger, 2008: Human-induced changes in the hydrology of the western United States. *Science*, **319,** 1080-1083, doi:10.1126/science.1152538. [Available online at http://www.sciencemag.org/cgi/content/abstract/1152538]

63. Hidalgo, H. G., T. Das, M. D. Dettinger, D. R. Cayan, D. W. Pierce, T. P. Barnett, G. Bala, A. Mirin, A. W. Wood, C. Bonfils, B. D. Santer, and T. Nozawa, 2009: Detection and attribution of streamflow timing changes to climate change in the western United States. *Journal of Climate*, **22,** 3838-3855, doi:10.1175/2009jcli2470.1. [Available online at http://journals.ametsoc.org/doi/abs/10.1175/2009JCLI2470.1]

Pierce, D. W., T. P. Barnett, H. G. Hidalgo, T. Das, C. Bonfils, B. D. Santer, G. Bala, M. D. Dettinger, D. R. Cayan, A. Mirin, A. W. Wood, and T. Nozawa, 2008: Attribution of declining western US snowpack to human effects. *Journal of Climate*, **21,** 6425-6444, doi:10.1175/2008JCLI2405.1. [Available online at http://journals.ametsoc.org/doi/abs/10.1175/2008JCLI2405.1]

64. Peterson, T. C., P. A. Stott, and S. Herring, 2012: Explaining extreme events of 2011 from a climate perspective. *Bulletin of the American Meteorological Society*, **93,** 1041-1067, doi:10.1175/BAMS-D-12-00021.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-12-00021.1]

65. Matthews, H. D., and K. Zickfeld, 2012: Climate response to zeroed emissions of greenhouse gases and aerosols. *Nature Climate Change*, **2,** 338-341, doi:10.1038/nclimate1424. [Available online at http://www.nature.com/nclimate/journal/v2/n5/full/nclimate1424.html]

66. NRC, 2011: *Climate Stabilization Targets: Emissions, Concentrations, and Impacts over Decades to Millennia.* National Research Council. The National Academies Press, 298 pp. [Available online at http://www.nap.edu/catalog.php?record_id=12877]

67. Hawkins, E., and R. Sutton, 2009: The potential to narrow uncertainty in regional climate predictions. *Bulletin of the American Meteorological Society*, **90,** 1095-1107, doi:10.1175/2009BAMS2607.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/2009BAMS2607.1]

    ——, 2011: The potential to narrow uncertainty in projections of regional precipitation change. *Climate Dynamics*, **37,** 407-418, doi:10.1007/s00382-010-0810-6.

68. Hansen, J. E., and M. Sato, 2012: Paleoclimate Implications for Human-Made Climate Change. *Climate Change. Inferences from Paleoclimate and Regional Aspects*, A. Berger, F. Mesinger, and D. Sijacki, Eds., Springer Vienna, 21-47.

    Knutti, R., and G. C. Hegerl, 2008: The equilibrium sensitivity of the Earth's temperature to radiation changes. *Nature Geoscience*, **1,** 735-743, doi:10.1038/ngeo337.

    PALAEOSENS Project Members, 2012: Making sense of palaeoclimate sensitivity. *Nature*, **491,** 683-691, doi:10.1038/nature11574.

69. Olson, R., R. Sriver, M. Goes, N. M. Urban, H. D. Matthews, M. Haran, and K. Keller, 2012: A climate sensitivity estimate using Bayesian fusion of instrumental observations and an Earth System model. *Journal of Geophysical Research: Atmospheres*, **117,** D04103, doi:10.1029/2011jd016620. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2011JD016620/pdf]

70. Fasullo, J. T., and K. E. Trenberth, 2012: A less cloudy future: The role of subtropical subsidence in climate sensitivity. *Science*, **338,** 792-794, doi:10.1126/science.1227465. [Available online at http://www.sciencemag.org/content/338/6108/792.abstract]

71. Hargreaves, J. C., J. D. Annan, M. Yoshimori, and A. Abe-Ouchi, 2012: Can the Last Glacial Maximum constrain climate sensitivity? *Geophysical Research Letters*, **39,** L24702, doi:10.1029/2012gl053872. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2012GL053872/pdf]

    Libardoni, A. G., and C. E. Forest, 2011: Sensitivity of distributions of climate system properties to the surface temperature dataset. *Geophysical Research Letters*, **38,** L22705, doi:10.1029/2011gl049431. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2011GL049431/pdf]

    ——, 2013: Correction to "Sensitivity of distributions of climate system properties to the surface temperature data set". *Geophysical Research Letters*, **40,** 2309-2311, doi:10.1002/grl.50480. [Available online at http://onlinelibrary.wiley.com/doi/10.1002/grl.50480/pdf]

    Ring, M. J., D. Lindner, E. F. Cross, and M. E. Schlesinger, 2012: Causes of the global warming observed since the 19th century. *Atmospheric and Climate Sciences*, **2,** 401-415, doi:10.4236/acs.2012.24035. [Available online at http://www.scirp.org/journal/PaperDownload.aspx?paperID=24283]

    Schmittner, A., N. M. Urban, J. D. Shakun, N. M. Mahowald, P. U. Clark, P. J. Bartlein, A. C. Mix, and A. Rosell-Melé, 2011: Climate sensitivity estimated from temperature reconstructions of the last glacial maximum. *Science*, **334,** 1385-1388, doi:10.1126/science.1203513. [Available online at http://www.sciencemag.org/content/334/6061/1385.abstract]

72. Lewis, N., 2013: An objective Bayesian, improved approach for applying optimal fingerprint techniques to estimate climate sensitivity. *Journal of Climate*, **26,** 7414-7429, doi:10.1175/jcli-d-12-00473.1. [Available online at http://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-12-00473.1]

73. Neely, R. R., III, O. B. Toon, S. Solomon, J.-P. Vernier, C. Alvarez, J. M. English, K. H. Rosenlof, M. J. Mills, C. G. Bardeen, J. S. Daniel, and J. P. Thayer, 2013: Recent anthropogenic increases in SO$_2$ from Asia have minimal impact on stratospheric aerosol. *Geophysical Research Letters*, **40,** 999-1004, doi:10.1002/grl.50263. [Available online at http://onlinelibrary.wiley.com/doi/10.1002/grl.50263/pdf]

74. Balmaseda, M. A., K. E. Trenberth, and E. Källén, 2013: Distinctive climate signals in reanalysis of global ocean heat content. *Geophysical Research Letters*, **40,** 1754-1759, doi:10.1002/grl.50382. [Available online at http://onlinelibrary.wiley.com/doi/10.1002/grl.50382/pdf]

75. Boden, T., G. Marland, and B. Andres, 2011: *Global CO$_2$ Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2008.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. [Available online at http://cdiac.ornl.gov/ftp/ndp030/global.1751_2008.ems]

76. NRC, 2002: *Abrupt Climate Change: Inevitable Surprises.* National Rearch Council. The National Academies Press, 244 pp. [Available online at http://www.nap.edu/catalog.php?record_id=10136]

77. Randall, D. A., R. A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R. J. Stouffer, A. Sumi, and K. E. Taylor, 2007: Ch. 8: Climate models and their evaluation. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Eds., Cambridge University Press, 589-662. [Available online at www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter8.pdf]

78. Walsh, J. E., W. L. Chapman, V. E. Romanovsky, J. H. Christensen, and M. Stendel, 2008: Global climate model performance over Alaska and Greenland. *Journal of Climate*, **21,** 6156-6174, doi:10.1175/2008JCLI2163.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/2008JCLI2163.1]

    Overland, J. E., M. Wang, N. A. Bond, J. E. Walsh, V. M. Kattsov, and W. L. Chapman, 2011: Considerations in the selection of global climate models for regional climate projections: The Arctic as a case study. *Journal of Climate*, **24,** 1583-1597, doi:10.1175/2010JCLI3462.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/2010JCLI3462.1]

79. Ryu, J.-H., and K. Hayhoe, 2013: Understanding the sources of Caribbean precipitation biases in CMIP3 and CMIP5 simulations. *Climate Dynamics*, 1-20, doi:10.1007/s00382-013-1801-1.

80. Reichler, T., and J. Kim, 2008: How well do coupled models simulate today's climate? *Bulletin of the American Meteorological Society*, **89,** 303-311, doi:10.1175/BAMS-89-3-303. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-89-3-303]

81. Vrac, M., M. L. Stein, K. Hayhoe, and X. Z. Liang, 2007: A general method for validating statistical downscaling methods under future climate change. *Geophysical Research Letters*, **34,** L18701, doi:10.1029/2007GL030295.

82. Maurer, E. P., 2007: Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios. *Climatic Change*, **82,** 309-325, doi:10.1007/s10584-006-9180-9.

83. Hayhoe, K., J. VanDorn, T. Croley, II, N. Schlegal, and D. Wuebbles, 2010: Regional climate change projections for Chicago and the US Great Lakes. *Journal of Great Lakes Research*, **36,** 7-21, doi:10.1016/j.jglr.2010.03.012. [Available online at http://www.bioone.org/doi/pdf/10.1016/j.jglr.2010.03.012]

84. Hayhoe, K., C. P. Wake, T. G. Huntington, L. Luo, M. D. Schwartz, J. Sheffield, E. Wood, B. Anderson, J. Bradbury, A. DeGaetano, T. Troy, and D. Wolfe, 2007: Past and future changes in climate and hydrological indicators in the US Northeast. *Climate Dynamics*, **28,** 381-407, doi:10.1007/s00382-006-0187-8.

85. NAST, 2000: Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change, Report for the US Global Change Research Program, 163 pp., U.S. Global Climate Research Program, National Assessment Synthesis Team, Cambridge, UK. [Available online at http://library.globalchange.gov/downloads/download.php?id=124]

86. Kostopoulou, E., and P. D. Jones, 2007: Comprehensive analysis of the climate variability in the eastern Mediterranean. Part II: Relationships between atmospheric circulation patterns and surface climatic elements. *International Journal of Climatology*, **27,** 1351-1371, doi:10.1002/joc.1466. [Available online at http://onlinelibrary.wiley.com/doi/10.1002/joc.1466/pdf]

87. Karl, T. R., and K. E. Trenberth, 2003: Modern global climate change. *Science*, **302,** 1719-1723, doi:10.1126/science.1090228.

88. Cubasch, U., D. Wuebbles, D. Chen, M. C. Facchini, D. Frame, N. Mahowald, and J.-G. Winther, 2013: Introduction. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, Eds., Cambridge University Press, 119-158. [Available online at http://www.climatechange2013.org/images/report/WG1AR5_Chapter01_FINAL.pdf]

89. Fall, S., A. Watts, J. Nielsen-Gammon, E. Jones, D. Niyogi, J. R. Christy, and R. A. Pielke, Sr., 2011: Analysis of the impacts of station exposure on the US Historical Climatology Network temperatures and temperature trends. *Journal of Geophysical Research*, **116,** D14120, doi:10.1029/2010JD015146.

90. Hausfather, Z., M. J. Menne, C. N. Williams, T. Masters, R. Broberg, and D. Jones, 2013: Quantifying the effect of urbanization on U.S. historical climatology network temperature records. *Journal of Geophysical Research - Atmospheres*, **118,** 481-494, doi:10.1029/2012JD018509.

91. Menne, M. J., C. N. Williams, Jr., and R. S. Vose, 2009: The US Historical Climatology Network monthly temperature data, version 2. *Bulletin American Meteorological Society*, **90,** 993-1007, doi:10.1175/2008BAMS2613.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/2008BAMS2613.1]

92. Vose, R. S., S. Applequist, M. J. Menne, C. N. Williams, Jr., and P. Thorne, 2012: An intercomparison of temperature trends in the US Historical Climatology Network and recent atmospheric reanalyses. *Geophysical Research Letters*, **39,** 6, doi:10.1029/2012GL051387. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2012GL051387/pdf]

93. Williams, C. N., M. J. Menne, and P. W. Thorne, 2012: Benchmarking the performance of pairwise homogenization of surface temperatures in the United States. *Journal of Geophysical Research*, **117,** 16, doi:10.1029/2011JD016761.

94. Karl, T. R., C. N. Williams, Jr, P. J. Young, and W. M. Wendland, 1986: A model to estimate the time of observation bias associated with monthly mean maximum, minimum and mean temperatures for the United States. *Journal of Climate Applied Meteorology*, **25,** 145-160, doi:10.1175/1520-0450(1986)025<0145:AMTETT>2.0.CO;2. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/1520-0450%281986%29025%3C0145%3AAMTETT%3E2.0.CO%3B2]

95. Quayle, R. G., D. R. Easterling, T. R. Karl, and P. Y. Hughes, 1991: Effects of recent thermometer changes in the cooperative station network. *Bulletin of the American Meteorological Society*, **72,** 1718-1723, doi:10.1175/1520-0477(1991)072<1718:EORTCI>2.0.CO;2. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/1520-0477%281991%29072%3C1718%3AEORTCI%3E2.0.CO%3B2]

96. Surfacestations.org, cited 2013: A Resource for Climate Station Records and Surveys. [Available online at http://www.surfacestations.org/]

97. Diamond, H. J., T. R. Karl, M. A. Palecki, C. B. Baker, J. E. Bell, R. D. Leeper, D. R. Easterling, J. H. Lawrimore, T. P. Meyers, M. R. Helfert, G. Goodge, and P. W. Thorne, 2013: U.S. climate reference network after one decade of operations: Status and assessment. *Bulletin of the American Meteorological Society*, **94,** 485-498, doi:10.1175/BAMS-D-12-00170.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-12-00170.1]

98. McNider, R. T., G. J. Steeneveld, A. A. M. Holtslag, R. A. Pielke Sr, S. Mackaro, A. Pour-Biazar, J. Walters, U. Nair, and J. Christy, 2012: Response and sensitivity of the nocturnal boundary layer over land to added longwave radiative forcing. *Journal of Geophysical Research*, **117,** D14106, doi:10.1029/2012JD017578. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2012JD017578/pdf]

99. Kunkel, K. E., L. E. Stevens, S. E. Stevens, L. Sun, E. Janssen, D. Wuebbles, and J. G. Dobson, 2013: Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 9. Climate of the Contiguous United States. NOAA Technical Report NESDIS 142-9. 85 pp., National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Washington, D.C. [Available online at http://www.nesdis.noaa.gov/technical_reports/NOAA_NESDIS_Tech_Report_142-9-Climate_of_the_Contiguous_United_States.pdf]

100. Wang, J., X. Bai, G. Leshkevich, M. Colton, A. Clites, and B. Lofgren, 2010: Severe ice cover on Great Lakes during winter 2008–2009. *Eos, Transactions, American Geophysical Union*, **91,** 41-42, doi:10.1029/2010EO050001.

101. Magnuson, J., 2010: History and heroes: The thermal niche of fishes and long-term lake ice dynamics. *Journal of Fish Biology*, **77,** 1731-1744, doi:10.1111/j.1095-8649.2010.02781.x. [Available online at http://onlinelibrary.wiley.com/doi/10.1111/j.1095-8649.2010.02781.x/pdf]

102. NWS, cited 2012: Dates of Lake Champlain Closing. National Weather Service Forecast Office, Burlington, VT. [Available online at http://www.erh.noaa.gov/btv/climo/lakeclose.shtml]

103. NOAA, cited 2012: Great Lakes Environmental Research Laboratory. [Available online at www.glerl.noaa.gov/data/now/wlevels/levels.html]

104. Angel, J. R., and K. E. Kunkel, 2010: The response of Great Lakes water levels to future climate scenarios with an emphasis on Lake Michigan-Huron. *Journal of Great Lakes Research*, **36**, 51-58, doi:10.1016/j.jglr.2009.09.006.

105. Lofgren, B. M., T. S. Hunter, and J. Wilbarger, 2011: Effects of using air temperature as a proxy for potential evapotranspiration in climate change scenarios of Great Lakes basin hydrology. *Journal of Great Lakes Research*, **37**, 744-752, doi:10.1016/j.jglr.2011.09.006.

106. MacKay, M., and F. Seglenieks, 2012: On the simulation of Laurentian Great Lakes water levels under projections of global climate change. *Climatic Change*, **117**, 55-67, doi:10.1007/s10584-012-0560-z.

107. Kunkel, K. E., L. E. Stevens, S. E. Stevens, L. Sun, E. Janssen, D. Wuebbles, S. D. Hilberg, M. S. Timlin, L. Stoecker, N. E. Westcott, and J. G. Dobson, 2013: Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 3. Climate of the Midwest U.S. NOAA Technical Report NESDIS 142-3. 103 pp., National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Washington, D.C. [Available online at http://www.nesdis.noaa.gov/technical_reports/NOAA_NESDIS_Tech_Report_142-3-Climate_of_the_Midwest_U.S.pdf]

108. Mote, P. W., A. F. Hamlet, M. P. Clark, and D. P. Lettenmaier, 2005: Declining mountain snowpack in western North America. *Bulletin of the American Meteorological Society*, **86**, 39-49, doi:10.1175/BAMS-86-1-39. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-86-1-39]

109. Dettinger, M. D., and D. R. Cayan, 1995: Large-scale atmospheric forcing of recent trends toward early snowmelt runoff in California. *Journal of Climate*, **8**, 606-623, doi:10.1175/1520-0442(1995)008<0606:LSAFOR>2.0.CO;2. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/1520-0442%281995%29008%3C0606%3ALSAFOR%3E2.0.CO%3B2]

110. Stewart, I. T., D. R. Cayan, and M. D. Dettinger, 2005: Changes toward earlier streamflow timing across western North America. *Journal of Climate*, **18**, 1136-1155, doi:10.1175/JCLI3321.1.

111. Cayan, D. R., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, and D. H. Peterson, 2001: Changes in the onset of spring in the western United States. *Bulletin of the American Meteorological Society*, **82**, 399-416, doi:10.1175/1520-0477(2001)082<0399:citoos>2.3.co;2.

112. Regonda, S. K., B. Rajagopalan, M. Clark, and J. Pitlick, 2005: Seasonal cycle shifts in hydroclimatology over the western United States. *Journal of Climate*, **18**, 372-384, doi:10.1175/JCLI-3272.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/JCLI-3272.1]

113. Knowles, N., M. D. Dettinger, and D. R. Cayan, 2006: Trends in snowfall versus rainfall in the western United States. *Journal of Climate*, **19**, 4545-4559, doi:10.1175/JCLI3850.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/JCLI3850.1]

114. Kunkel, K. E., D. R. Easterling, K. Hubbard, and K. Redmond, 2004: Temporal variations in frost-free season in the United States: 1895 - 2000. *Geophysical Research Letters*, **31**, L03201, doi:10.1029/2003gl018624. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2003GL018624/full]

115. National Audubon Society: Northward shifts in the abundance of North American birds in the early winter: A response to warmer winter temperatures? [Available online at www.audubon.org/bird/back/techreport.html]

116. EPA, 2010: Leaf and Bloom Dates. U.S. Environmental Protection Agency, Washington, D.C. [Available online at http://www.epa.gov/climatechange/pdfs/print_leaf-bloom-dates.pdf]

117. Daly, C., M. P. Widrlechner, M. D. Halbleib, J. I. Smith, and W. P. Gibson, 2012: Development of a new USDA plant hardiness zone map for the United States. *Journal of Applied Meteorology and Climatology*, **51**, 242-264, doi:10.1175/2010JAMC2536.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/2010JAMC2536.1]

118. Wehner, M. F., 2013: Very extreme seasonal precipitation in the NARCCAP ensemble: Model performance and projections. *Climate Dynamics*, **40**, 59-80, doi:10.1007/s00382-012-1393-1.

119. Kunkel, K. E., T.R. Karl, H. Brooks, J. Kossin, J. Lawrimore, D. Arndt, L. Bosart, D. Changnon, S.L. Cutter, N. Doesken, K. Emanuel, P.Ya. Groisman, R.W. Katz, T. Knutson, J. O'Brien, C. J. Paciorek, T. C. Peterson, K. Redmond, D. Robinson, J. Trapp, R. Vose, S. Weaver, M. Wehner, K. Wolter, and D. Wuebbles, 2013: Monitoring and understanding trends in extreme storms: State of knowledge. *Bulletin of the American Meteorological Society*, **94**, doi:10.1175/BAMS-D-11-00262.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-11-00262.1]

120. Gutowski, W. J., G. C. Hegerl, G. J. Holland, T. R. Knutson, L. O. Mearns, R. J. Stouffer, P. J. Webster, M. F. Wehner, and F. W. Zwiers, 2008: Ch. 3: Causes of observed changes in extremes and projections of future changes. *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and US Pacific Islands. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*, T. R. Karl, G. A. Meehl, C. D. Miller, S. J. Hassol, A. M. Waple, and W. L. Murray, Eds., 81-116. [Available online at http://library.globalchange.gov/products/assessments/sap-3-3-weather-and-climate-extremes-in-a-changing-climate]

    Li, L., W. Li, and Y. Kushnir, 2012: Variation of the North Atlantic subtropical high western ridge and its implication to Southeastern US summer precipitation. *Climate Dynamics*, **39**, 1401-1412, doi:10.1007/s00382-011-1214-y. [Available online at http://link.springer.com/article/10.1007%2Fs00382-011-1214-y]

121. DeAngelis, A., F. Dominguez, Y. Fan, A. Robock, M. D. Kustu, and D. Robinson, 2010: Evidence of enhanced precipitation due to irrigation over the Great Plains of the United States. *Journal of Geophysical Research*, **115**, D15115, doi:10.1029/2010JD013892.

122. Groisman, P. Y., R. W. Knight, and T. R. Karl, 2012: Changes in intense precipitation over the central United States. *Journal of Hydrometeorology*, **13**, 47-66, doi:10.1175/JHM-D-11-039.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/JHM-D-11-039.1]

123. Kunkel, K. E., D. R. Easterling, D. A. Kristovich, B. Gleason, L. Stoecker, and R. Smith, 2012: Meteorological causes of the secular variations in observed extreme precipitation events for the conterminous United States. *Journal of Hydrometeorology*, **13**, 1131-1141, doi:10.1175/JHM-D-11-0108.1.

124. Vose, R. S., S. Applequist, M. A. Bourassa, S. C. Pryor, R. J. Barthelmie, B. Blanton, P. D. Bromirski, H. E. Brooks, A. T. DeGaetano, R. M. Dole, D. R. Easterling, R. E. Jensen, T. R. Karl, R. W. Katz, K. Klink, M. C. Kruk, K. E. Kunkel, M. C. MacCracken, T. C. Peterson, K. Shein, B. R. Thomas, J. E. Walsh, X. L. Wang, M. F. Wehner, D. J. Wuebbles, and R. S. Young, 2013: Monitoring and understanding changes in extremes: Extratropical storms, winds, and waves. *Bulletin of the American Meteorological Society*, **in press**, doi:10.1175/BAMS-D-12-00162.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-12-00162.1]

Wang, X. L., F. W. Zwiers, V. R. Swail, and Y. Feng, 2009: Trends and variability of storminess in the Northeast Atlantic region, 1874–2007. *Climate Dynamics*, **33,** 1179-1195, doi:10.1007/s00382-008-0504-5.

125. Bengtsson, L., K. I. Hodges, and N. Keenlyside, 2009: Will extratropical storms intensify in a warmer climate? *Journal of Climate*, **22,** 2276-2301, doi:10.1175/2008JCLI2678.1.

Neu, U., 2009: Influence of Global Warming on Extratropical Cyclones, 14 pp. [Available online at http://media.swissre.com/documents/Influence+of+extratropical+storms+factsheet.pdf]

126. IPCC, 2012: *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change.* C. B. Field, V. Barros, T.F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P. M. Midgley, Eds. Cambridge University Press, 582 pp. [Available online at http://ipcc-wg2.gov/SREX/images/uploads/SREX-All_FINAL.pdf]

127. Knight, D. B., and R. E. Davis, 2009: Contribution of tropical cyclones to extreme rainfall events in the southeastern United States. *Journal of Geophysical Research*, **114,** D23102, doi:10.1029/2009JD012511. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2009JD012511/pdf]

Kunkel, K. E., D. R. Easterling, D. A. R. Kristovich, B. Gleason, L. Stoecker, and R. Smith, 2010: Recent increases in U.S. heavy precipitation associated with tropical cyclones. *Geophysical Research Letters*, **37,** L24706, doi:10.1029/2010GL045164. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2010GL045164/pdf]

128. Holland, G. J., and P. J. Webster, 2007: Heightened tropical cyclone activity in the North Atlantic: Natural variability or climate trend? *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, **365,** 2695-2716, doi:10.1098/rsta.2007.2083. [Available online at http://rsta.royalsocietypublishing.org/content/365/1860/2695.full.pdf+html]

Landsea, C. W., 2007: Counting Atlantic tropical cyclones back to 1900. *Eos, Transactions, American Geophysical Union*, **88,** 197-202, doi:10.1029/2007EO180001. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2007EO180001/pdf]

Mann, M. E., T. A. Sabbatelli, and U. Neu, 2007: Evidence for a modest undercount bias in early historical Atlantic tropical cyclone counts. *Geophysical Research Letters*, **34,** L22707, doi:10.1029/2007GL031781. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2007GL031781/pdf]

129. Elsner, J. B., J. P. Kossin, and T. H. Jagger, 2008: The increasing intensity of the strongest tropical cyclones. *Nature*, **455,** 92-95, doi:10.1038/nature07234.

Kossin, J. P., K. R. Knapp, D. J. Vimont, R. J. Murnane, and B. A. Harper, 2007: A globally consistent reanalysis of hurricane variability and trends. *Geophysical Research Letters*, **34,** L04815, doi:10.1029/2006GL028836. [Available online at http://www.agu.org/pubs/crossref/2007/2006GL028836.shtml]

130. Emanuel, K. A., 2000: A statistical analysis of tropical cyclone intensity. *Monthly Weather Review*, **128,** 1139-1152, doi:10.1175/1520-0493(2000)128<1139:ASAOTC>2.0.CO;2. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/1520-0493%282000%29128%3C1139%3AASAOTC%3E2.0.CO%3B2]

Knutson, T. R., J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. K. Srivastava, and M. Sugi, 2010: Tropical cyclones and climate change. *Nature Geoscience*, **3,** 157-163, doi:10.1038/ngeo779.

131. Peterson, T. C., R. R. Heim, R. Hirsch, D. P. Kaiser, H. Brooks, N. S. Diffenbaugh, R. M. Dole, J. P. Giovannettone, K. Guirguis, T. R. Karl, R. W. Katz, K. Kunkel, D. Lettenmaier, G. J. McCabe, C. J. Paciorek, K. R. Ryberg, S. Schubert, V. B. S. Silva, B. C. Stewart, A. V. Vecchia, G. Villarini, R. S. Vose, J. Walsh, M. Wehner, D. Wolock, K. Wolter, C. A. Woodhouse, and D. Wuebbles, 2013: Monitoring and understanding changes in heat waves, cold waves, floods and droughts in the United States: State of knowledge. *Bulletin American Meteorological Society*, **94,** 821-834, doi:10.1175/BAMS-D-12-00066.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-D-12-00066.1]

132. Alley, W. M., 1984: The Palmer Drought Severity Index - limitations and assumptions. *Journal of Climate and Applied Meteorology*, **23,** 1100-1109, doi:10.1175/1520-0450(1984)023<1100:TPDSIL>2.0.CO;2.

Palmer, W. C. 1965: *Meteorological Drought. Research Paper No. 45.* U.S. Department of Commerce, Weather Bureau, 65 pp. [Available online at http://ncdc.noaa.gov/temp-and-precip/drought/docs/palmer.pdf]

133. Dai, A., K. E. Trenberth, and T. Qian, 2004: A global dataset of Palmer Drought Severity Index for 1870-2002: Relationship with soil moisture and effects of surface warming. *Journal of Hydrometeorology*, **5,** 1117-1130, doi:10.1175/JHM-386.1.

134. Brown, P. M., E. K. Heyerdahl, S. G. Kitchen, and M. H. Weber, 2008: Climate effects on historical fires (1630–1900) in Utah. *International Journal of Wildland Fire*, **17,** 28-39, doi:10.1071/WF07023.

Littell, J. S., D. McKenzie, D. L. Peterson, and A. L. Westerling, 2009: Climate and wildfire area burned in western US ecoprovinces, 1916-2003. *Ecological Applications*, **19,** 1003-1021, doi:10.1890/07-1183.1.

Schoennagel, T., R. L. Sherriff, and T. T. Veblen, 2011: Fire history and tree recruitment in the Colorado Front Range upper montane zone: Implications for forest restoration. *Ecological Applications*, **21,** 2210–2222, doi:10.1890/10-1222.1. [Available online at http://frontrangeroundtable.org/uploads/Schoennagel_et_al_Front_Range_Upper_Montane_EA_2011.pdf]

Westerling, A. L., A. Gershunov, T. J. Brown, D. R. Cayan, and M. D. Dettinger, 2003: Climate and wildfire in the western United States. *Bulletin of the American Meteorological Society*, **84,** 595-604, doi:10.1175/BAMS-84-5-595. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/BAMS-84-5-595]

135. Allen, C. D., M. Savage, D. A. Falk, K. F. Suckling, T. W. Swetnam, T. Schulke, P. B. Stacey, P. Morgan, M. Hoffman, and J. T. Klingel, 2002: Ecological restoration of southwestern ponderosa pine ecosystems: A broad perspective. *Ecological Applications*, **12,** 1418-1433, doi:10.1890/1051-0761(2002)012[1418:EROSPP]2.0.CO;2.

136. Westerling, A. L., H. G. Hidalgo, D. R. Cayan, and T. W. Swetnam, 2006: Warming and earlier spring increase western U.S. forest wildfire activity. *Science*, **313,** 940-943, doi:10.1126/science.1128834.

137. Schwalm, C. R., C. A. Williams, K. Schaefer, D. Baldocchi, T. A. Black, A. H. Goldstein, B. E. Law, W. C. Oechel, K. T. Paw, and R. L. Scott, 2012: Reduction in carbon uptake during turn of the century drought in western North America. *Nature Geoscience*, **5,** 551-556, doi:10.1038/ngeo1529. [Available online at http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/33148/LawBeverlyForestryReductionCarbonUptake.pdf?sequence=1]

138. Wehner, M., D. R. Easterling, J. H. Lawrimore, R. R. Heim Jr, R. S. Vose, and B. D. Santer, 2011: Projections of future drought in the continental United States and Mexico. *Journal of Hydrometeorology*, **12,** 1359-1377, doi:10.1175/2011JHM1351.1. [Available online at http://journals.ametsoc.org/doi/abs/10.1175/2011JHM1351.1]

139. NDMC, cited 2012: Directory of Drought and Management Plans. National Drought Mitigation Center, University of Nebraska–Lincoln. [Available online at http://drought.unl.edu/Planning/PlanningInfobyState/DroughtandManagementPlans.aspx]

140. U.S. Drought Monitor, cited 2013: U.S. Drought Monitor. University of Nebraska-Lincoln, U.S. Department of Agriculture, National Oceanic and Atmospheric Administration. [Available online at http://droughtmonitor.unl.edu/]

141. NOAA, cited 2013: Objective Long-term Drought Indicator Blend U.S. Department of Commerce, National Oceanic and Atmospheric Administration. [Available online at http://www.cpc.ncep.noaa.gov/products/predictions/tools/edb/lbfinal.gif]

142. Hoerling, M. P., J. K. Eischeid, X.-W. Quan, H. F. Diaz, R. S. Webb, R. M. Dole, and D. R. Easterling, 2012: Is a transition to semi-permanent drought conditions imminent in the Great Plains? *Journal of Climate*, **25,** 8380–8386, doi:10.1175/JCLI-D-12-00449.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-12-00449.1]

143. Moritz, M. A., M. A. Parisien, E. Batllori, M. A. Krawchuk, J. Van Dorn, D. J. Ganz, and K. Hayhoe, 2012: Climate change and disruptions to global fire activity. *Ecosphere*, **3,** 1-22, doi:10.1890/ES11-00345.1. [Available online at http://www.esajournals.org/doi/pdf/10.1890/ES11-00345.1]

144. Spracklen, D. V., L. J. Mickley, J. A. Logan, R. C. Hudman, R. Yevich, M. D. Flannigan, and A. L. Westerling, 2009: Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *Journal of Geophysical Research*, **114,** D20301, doi:10.1029/2008JD010966.

145. Westerling, A. L., and B. P. Bryant, 2008: Climate change and wildfire in California. *Climatic Change*, **87,** 231-249, doi:10.1007/s10584-007-9363-z.

146. Meier, W. N., S. Gerland, M. A. Granskog, J. R. Key, C. Haas, G. K. Hovelsrud, K. Kovacs, A. Makshtas, C. Michel, D. Perovich, J. D. Reist, and B. E. H. van Oort, 2012: Ch. 9: Sea ice. *Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP)*, SWIPA, Ed., Arctic Monitoring and Assessment Programme (AMAP).

147. Kinnard, C., C. M. Zdanowicz, D. A. Fisher, E. Isaksson, A. de Vernal, and L. G. Thompson, 2011: Reconstructed changes in Arctic sea ice over the past 1,450 years. *Nature*, **479,** 509-512, doi:10.1038/nature10581.

148. Overland, J. E., and M. Wang, 2009: Large-scale atmospheric circulation changes are associated with the recent loss of Arctic sea ice. *Tellus A*, **62,** 1-9, doi:10.1111/j.1600-0870.2009.00421.x. [Available online at http://onlinelibrary.wiley.com/doi/10.1111/j.1600-0870.2009.00421.x/pdf]

149. Francis, J. A., and S. J. Vavrus, 2012: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, **39,** L06801, doi:10.1029/2012GL051000. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2012GL051000/pdf]

150. University of Illinois, cited 2012: The Cryosphere Today. [Available online at http://igloo.atmos.uiuc.edu/cgi-bin/test/print.sh?fm=09&fd=12&fy=1992&sm=09&sd=12&sy=2012]

151. AMAP, 2011: *Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere.* Arctic Monitoring and Assessment Programme, 538 pp. [Available online at http://www.amap.no/documents/download/968]

152. Callaghan, T. V., M. Johansson, R. D. Brown, P. Y. Groisman, N. Labba, V. Radionov, M. Allard, F. S. Chapin, III, T. R. Christensen, B. Etzelmuller, S. Fronzek, D. Gilichinsky, L. Hinzman, H. W. Hubberten, O. Humlum, M. T. Jorgensen, P. Kuhry, A. Lewkowicz, S. S. Marchenko, A. D. McGuire, J. Murton, N. G. Oberman, P. Overduin, M. Parsons, S. A. Reneva, E. A. G. Schuur, I. Semiletov, N. Shakhova, N. I. Shiklomanov, A. A. Velichko, and Y. Zhang, 2012: Ch. 5: Changing permafrost and its impacts. *Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere. Arctic Monitoring and Assessment Programme (AMAP)*, SWIPA, Ed., Arctic Monitoring and Assessment Programme (AMAP), 538. [Available online at http://amap.no/documents/index.cfm?dirsub=%2FSnow%2C%20Water%2C%20Ice%20and%20Permafrost%20in%20the%20Arctic%20(SWIPA)]

153. Cogley, J. G., 2009: Geodetic and direct mass-balance measurements: Comparison and joint analysis. *Annals of Glaciology*, **50,** 96-100, doi:10.3189/172756409787769744.

Romanovsky, V. E., S. L. Smith, and H. H. Christiansen, 2010: Permafrost thermal state in the polar Northern Hemisphere during the international polar year 2007-2009: A synthesis. *Permafrost and Periglacial Processes*, **21,** 106-116, doi:10.1002/ppp.689. [Available online at http://onlinelibrary.wiley.com/doi/10.1002/ppp.689/pdf]

154. Radić, V., and R. Hock, 2011: Regionally differentiated contribution of mountain glaciers and ice caps to future sea-level rise. *Nature Geoscience*, **4,** 91-94, doi:10.1038/ngeo1052. [Available online at http://www.nature.com/ngeo/journal/v4/n2/full/ngeo1052.html]

155. Church, J. A., N. J. White, L. F. Konikow, C. M. Domingues, J. G. Cogley, E. Rignot, J. M. Gregory, M. R. van den Broeke, A. J. Monaghan, and I. Velicogna, 2011: Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. *Geophysical Research Letters*, **38,** L18601, doi:10.1029/2011GL048794.

156. Shepherd, A., E. R. Ivins, A. Geruo, V. R. Barletta, M. J. Bentley, S. Bettadpur, K. H. Briggs, D. H. Bromwich, R. Forsberg, N. Galin, M. Horwath, S. Jacobs, I. Joughin, M. A. King, J. T. M. Lenaerts, J. Li, S. R. M. Ligtenberg, A. Luckman, S. B. Luthcke, M. McMillan, R. Meister, G. Milne, J. Mouginot, A. Muir, J. P. Nicolas, J. Paden, A. J. Payne, H. Pritchard, E. Rignot, H. Rott, L. S. Sørensen, T. A. Scambos, B. Scheuchl, E. J. O. Schrama, B. Smith, A. V. Sundal, J. H. v. Angelen, W. J. v. d. Berg, M. R. v. d. Broeke, D. G. Vaughan, I. Velicogna, J. Wahr, P. L. Whitehouse, D. J. Wingham, D. Yi, D. Young, and H. J. Zwally, 2012: A reconciled estimate of ice-sheet mass balance. *Science*, **338,** 1183-1189, doi:10.1126/science.1228102. [Available online at http://xa.yimg.com/kq/groups/18383638/836588054/name/Science-2012-Shepherd-1183-9.pdf]

157. Bromirski, P. D., A. J. Miller, R. E. Flick, and G. Auad, 2011: Dynamical suppression of sea level rise along the Pacific coast of North America: Indications for imminent acceleration. *Journal of Geophysical Research*, **116,** C07005, doi:10.1029/2010JC006759. [Available online at http://www.agu.org/pubs/crossref/2011/2010JC006759.shtml]

158. Ivins, E. R., R. K. Dokka, and R. G. Blom, 2007: Post-glacial sediment load and subsidence in coastal Louisiana. *Geophysical Research Letters*, **34,** L16303, doi:10.1029/2007gl030003. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2007GL030003/pdf]

159. Willis, J. K., and J. A. Church, 2012: Regional sea-level projection. *Science*, **336,** 550-551, doi:10.1126/science.1220366.

160. Chen, J. L., C. R. Wilson, D. Blankenship, and B. D. Tapley, 2009: Accelerated Antarctic ice loss from satellite gravity measurements. *Nature Geoscience*, **2,** 859-862, doi:10.1038/ngeo694.

Khan, S. A., J. Wahr, M. Bevis, I. Velicogna, and E. Kendrick, 2010: Spread of ice mass loss into northwest Greenland observed by GRACE and GPS. *Geophysical Research Letters*, **37,** L06501, doi:10.1029/2010GL042460. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2010GL042460/pdf]

161. Strauss, B. H., R. Ziemlinski, J. L. Weiss, and J. T. Overpeck, 2012: Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States. *Environmental Research Letters*, **7,** 014033, doi:10.1088/1748-9326/7/1/014033.

162. Nerem, R. S., D. P. Chambers, C. Choe, and G. T. Mitchum, 2010: Estimating mean sea level change from the TOPEX and Jason altimeter missions. *Marine Geodesy*, **33,** 435-446, doi:10.1080/01490419.2010.491031. [Available online at http://www.tandfonline.com/doi/pdf/10.1080/01490419.2010.491031]

163. Velicogna, I., and J. Wahr, 2013: Time-variable gravity observations of ice sheet mass balance: Precision and limitations of the GRACE satellite data. *Geophysical Research Letters*, **40,** 3055-3063, doi:10.1002/grl.50527. [Available online at http://onlinelibrary.wiley.com/doi/10.1002/grl.50527/pdf]

164. Ivins, E. R., T. S. James, J. Wahr, E. J. O. Schrama, F. W. Landerer, and K. M. Simon, 2013: Antarctic contribution to sea level rise observed by GRACE with improved GIA correction. *Journal of Geophysical Research: Solid Earth*, **118,** 3126-3141, doi:10.1002/jgrb.50208. [Available online at http://onlinelibrary.wiley.com/doi/10.1002/jgrb.50208/pdf]

Climate Change Impacts in the United States

APPENDIX 4
FREQUENTLY ASKED QUESTIONS

Convening Lead Authors

John Walsh, University of Alaska Fairbanks
Donald Wuebbles, University of Illinois

Lead Authors

Katharine Hayhoe, Texas Tech University
James Kossin, NOAA National Climatic Data Center
Kenneth Kunkel, CICS-NC, North Carolina State Univ., NOAA National Climatic Data Center
Graeme Stephens, NASA Jet Propulsion Laboratory
Peter Thorne, Nansen Environmental and Remote Sensing Center
Russell Vose, NOAA National Climatic Data Center
Michael Wehner, Lawrence Berkeley National Laboratory
Josh Willis, NASA Jet Propulsion Laboratory

Contributing Authors

David Anderson, NOAA National Climatic Data Center
Viatcheslav Kharin, Canadian Centre for Climate Modelling and Analysis, Environment Canada
Thomas Knutson, NOAA Geophysical Fluid Dynamics Laboratory
Felix Landerer, NASA Jet Propulsion Laboratory
Tim Lenton, Exeter University
John Kennedy, UK Meteorological Office
Richard Somerville, Scripps Institution of Oceanography, Univ. of California, San Diego

Recommended Citation for Chapter

Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Appendix 4: Frequently Asked Questions. *Climate Change Impacts in the United States: The Third National Climate Assessment*, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 790-820. doi:10.7930/J0G15XS3.

On the Web: http://nca2014.globalchange.gov/report/appendices/faqs

FAQ **INFORMATION DRAWN FROM THIS CHAPTER IS INCLUDED IN THE HIGHLIGHTS REPORT AND IS IDENTIFIED BY THIS ICON**

APPENDIX 4 FREQUENTLY ASKED QUESTIONS

This section answers some frequently asked questions about climate change. The questions addressed range from those purely related to the science of climate change to those that extend to some of the issues being faced in consideration of mitigation and adaptation measures. The author team selected these questions based on those often asked in presentations to the public. The answers are based on peer-reviewed science and assessments and have been confirmed by multiple analyses.

A. How can we predict what climate will be like in 100 years if we can't even predict the weather next week?

B. Is the climate changing? How do we know?

C. Climate is always changing. How is recent change different than in the past?

D. Is the globally averaged surface temperature still increasing? Isn't there recent evidence that it is actually cooling?

E. Is it getting warmer at the same rate everywhere? Will the warming continue?

F. How long have scientists been investigating human influences on climate?

G. How can the small proportion of carbon dioxide in the atmosphere have such a large effect on our climate?

H. Could the sun or other natural factors explain the observed warming of the past 50 years?

I. How do we know that human activities are the primary cause of recent climate change?

J. What is and is not debated among climate scientists about climate change?

K. Is the global surface temperature record good enough to determine whether climate is changing?

L. Is Antarctica gaining or losing ice? What about Greenland?

M. Weren't there predictions of global cooling in the 1970s?

N. How is climate projected to change in the future?

O. Does climate change affect severe weather?

P. How are the oceans affected by climate change?

Q. What is ocean acidification?

R. How reliable are the computer models of the Earth's climate?

S. What are the key uncertainties about climate change?

T. Are there tipping points in the climate system?

U. How is climate change affecting society?

V. Are there benefits to warming?

W. Are some people more vulnerable than others?

X. Are there ways to reduce climate change?

Y. Are there advantages to acting sooner rather than later?

Z. Can we reverse global warming?

A. How can we predict what climate will be like in 100 years if we can't even predict the weather next week?

Predicting how climate will change in future decades is a different scientific issue from predicting weather a few weeks from now. Weather is short term and chaotic, largely determined by whatever atmospheric system is moving through at the time, and thus it is increasingly difficult to predict day-to-day changes beyond about two weeks into the future. Climate, on the other hand, is a long-term statistical average of weather and is determined by larger-scale forces, such as the level of heat-trapping gases in the atmosphere and the energy coming from the sun. Thus it is actually easier to project how climate will change in the future. By analogy, while it is impossible to predict the age of death of any individual, the average age of death of an American can be calculated. In this case, weather is like the individual, while climate is like the average. To extend this analogy into the realm of climate change, we can also calculate the life expectancy of the average American who smokes. We can predict that on average, a smoker will not live as long as a non-smoker. Similarly, we can project what the climate will be like if we emit less heat-trapping gas, and what it will be like if we emit more.

Weather is the day-to-day variations in temperature, precipitation, and other aspects of the atmosphere around us. Weather prediction using state-of-the-art computer models can be very accurate for a few days to more than a week in advance. Because weather forecasts are based on the initial conditions of the atmosphere and ocean at the time the prediction is made, accuracy decays over time. After about two weeks, the effects of small errors in defining these initial conditions grow so large that meteorologists can no longer discern what the weather will be like on any specific day or place.

Climate is long-term average weather – the statistics of weather over long time scales, typically of 30 years or more. Climate is primarily the result of the effects of local geography, such as distance from the equator, distance from the ocean, and local topography and elevation, combined with larger scale climate factors that can change over time. These include the amount of energy from the sun and the composition of the atmosphere, including the amount of greenhouse gases and tiny particles suspended in the atmosphere. Knowing all these factors enables scientists to quantify the climate at a given place and time. Climate change occurs when these large-scale climate factors change over time.

Using our understanding of the physics of how the atmosphere works, we can estimate how climate will change in the future – in response to human activities, which are now changing Earth's atmospheric composition faster than at any time in at least the last 800,000 years. It is also possible to estimate changes in the statistics of certain types of weather events, such as heat waves or heavy precipitation events, especially when we know what is causing them to change.

We know how climate has changed in the recent past, and often we know why those changes have occurred. For example, the increase in global temperature, or global warming, that has occurred over the last 150 years can only be explained if we include the impact of increasing levels of heat-trapping gases in the atmosphere caused by human activities. The present generation of climate models can successfully reproduce the past warming and therefore provide an essential tool to peer into the future.

The role of human activities in driving recent change is discussed in FAQ I. (In the context of a changing climate, the term "human activities" is used throughout these frequently asked questions to refer specifically to activities, such as extracting and burning fossil fuels, deforestation, agriculture, waste treatment, and so on, that produce heat-trapping gases like carbon dioxide, methane, and nitrous oxide and/or emissions of black carbon, sulfate, and other particles.) Other human activities, like changes in land use, can also alter climate, especially on local or regional scales, such as that which occurs with urban heat islands.

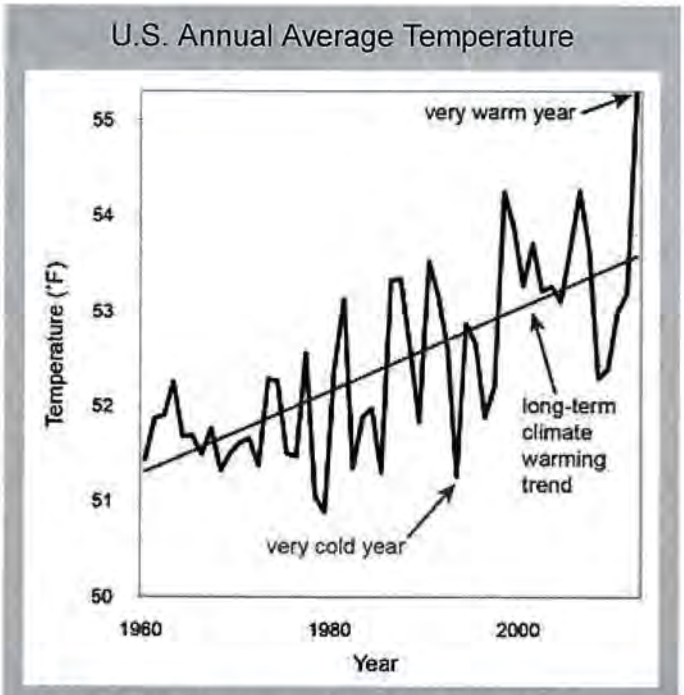


Figure 1. Climate change refers to the changes in average weather conditions that persist for an extended period of time, over multiple decades or even longer. Year-to-year and even decade-to-decade conditions do not necessarily tell us much about long-term changes in climate. One cold year, or even a few cold years in a row, does not contradict a long-term warming trend, even as one hot year does not prove it. (Figure source: adapted from Kunkel et al. 2013[1]).

B. Is the climate changing? How do we know?

Yes. The world has warmed over the last 150 years, and that warming has triggered many other changes to the Earth's climate. Evidence for a changing climate abounds, from the top of the atmosphere to the depths of the oceans. Changes in surface, atmospheric, and oceanic temperatures; melting glaciers, snow cover, and sea ice; rising sea level; and increase in atmospheric water vapor have been documented by hundreds of studies conducted by thousands of scientists around the world. Rainfall patterns and storms are changing and the occurrence of droughts is shifting.

Documenting climate change often begins with global average temperatures recorded near Earth's surface, where people live. But these temperatures, recorded by weather stations, are only one indicator of climate change. Additional evidence for a warming world comes from a wide range of consistent measurements of the Earth's climate system. It is the sum total of these indicators that lead to the conclusion that warming of our planet is unequivocal.

Evidence for a changing climate is not confined to the Earth's surface. Measurements by weather balloons and satellites consistently show that the temperature of the troposphere – the lowest layer of the atmosphere – has increased. The temperature of the upper atmosphere, particularly the stratosphere, has cooled, consistent with expectations of changes due to increasing concentrations of CO_2 and other greenhouse gases. The upper ocean has warmed, and more than 90% of the additional energy absorbed by the climate system since the 1960s has been stored in the oceans. As the oceans warm, seawater expands, causing sea level to rise.

As the troposphere warms, Arctic ice and glaciers melt, also causing sea level to rise. About 90% of the glaciers and land-based ice sheets worldwide are melting as the Earth warms, adding further to the sea level rise. Spring snow cover has decreased across the Northern Hemisphere since the 1950s. There have been substantial losses in sea ice in the Arctic Ocean, particularly at the end of summer when sea ice extent is at a minimum (see FAQ L for discussion of Antarctic sea ice).

Warmer air, on average, contains more water vapor. Globally, the amount of water vapor in the atmosphere has increased over the land and the oceans over the last half century. In turn, many parts of the planet have seen increases in heavy rainfall events. All of these indicators and all of the independent data sets for each indicator unequivocally point to the same conclusion: from the ocean depths to the top of the troposphere, the world has warmed and the climate has reacted to that warming.

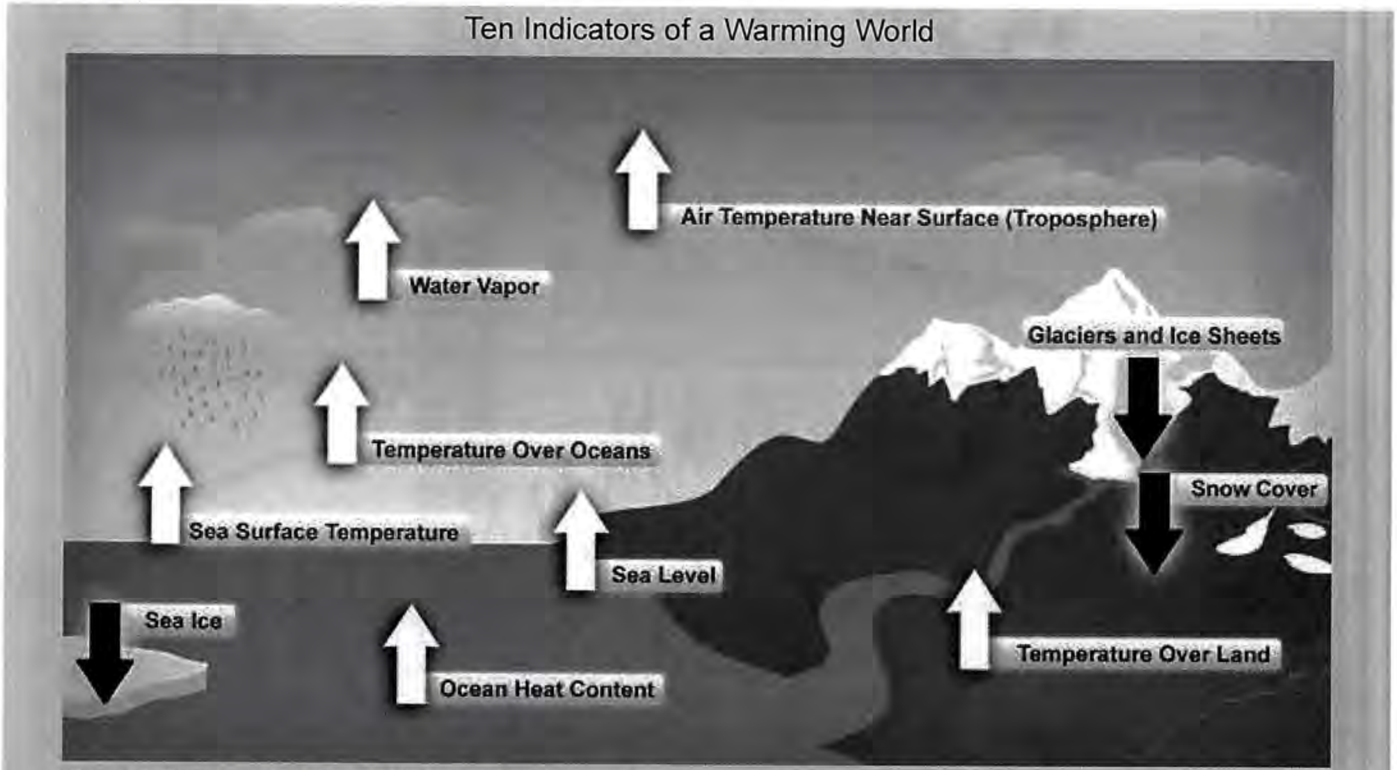


Figure 2. These are just some of the many indicators measured globally over many decades that demonstrate that the Earth's climate is warming. White arrows indicate increases, and black arrows show decreases. All the indicators expected to increase in a warming world are increasing, and all those expected to decrease in a warming world are decreasing. See Figure 3 for measurements showing these trends. (Figure source: NOAA NCDC; based on data updated from Kennedy et al. 2010[2]).

In summary, the evidence that climate is changing comes from a multitude of independent observations. The evidence that climate is changing because of human activity, as discussed in FAQ I and in more detail in Chapter 2: Our Changing Climate and Appendix 3: Climate Science Supplement, comes from observations, basic physics, and analyses from modeling studies.

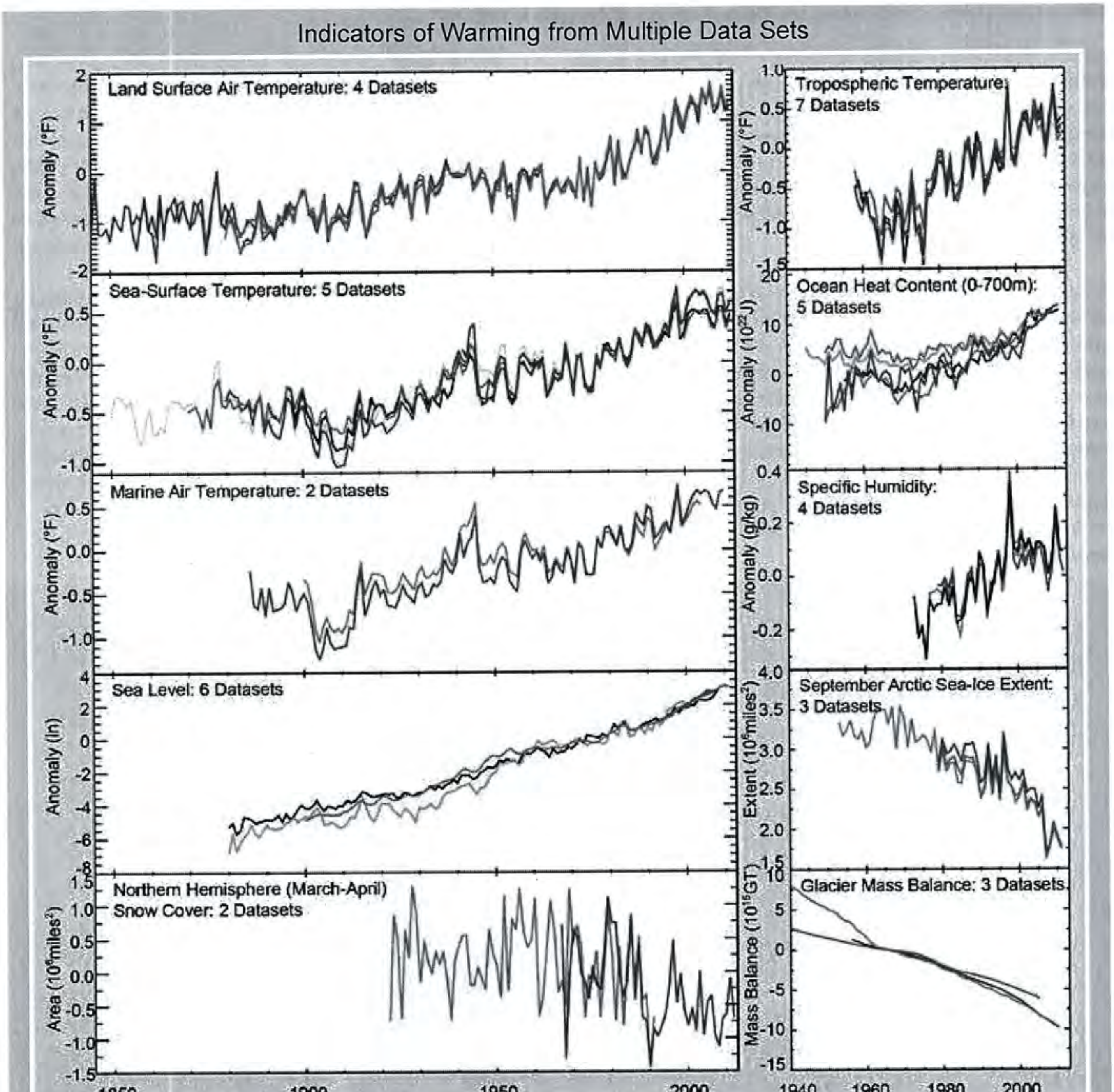


Figure 3. This figure summarizes some of the many datasets documenting changes in the Earth's climate, all of which are consistent with a warming planet. In all figures except the lower two in the right column, data are plotted relative to averages over the period 1960-1999 (Figure source: updated from Kennedy et al. 2010[2]).

C. Climate is always changing. How is recent change different than in the past?

The Earth has experienced many large climate changes in the past. However, current changes in climate are unusual for two reasons: first, many lines of evidence demonstrate that these changes are primarily the result of human activities (see Question I for more info); and second, these changes are occurring (and are projected to continue to occur) faster than many past changes in the Earth's climate.

In the past, climate change was driven exclusively by natural factors: explosive volcanic eruptions that injected reflective particles into the upper atmosphere, changes in energy from the sun, periodic variations in the Earth's orbit, natural cycles that transfer heat between the ocean and the atmosphere, and slowly changing natural variations in heat-trapping gases in the atmosphere. All of these natural factors, and their interactions with each other, have altered global average temperature over periods ranging from months to thousands of years. For example, past glacial periods were initiated by shifts in the Earth's orbit, and then amplified by resulting decreases in atmospheric levels of carbon dioxide and subsequently by greater reflection of solar radiation by ice and snow as the Earth's climate system responded to a cooler climate. Some periods in the distant past were even warmer than what is expected to occur from human-induced global warming. But these changes in the distant past generally occurred much more slowly than current changes.

Natural factors are still affecting the planet's climate today. The difference is that, since the beginning of the Industrial Revolution, humans have been increasingly affecting global climate, to the point where we are now the primary cause of recent and projected future change.

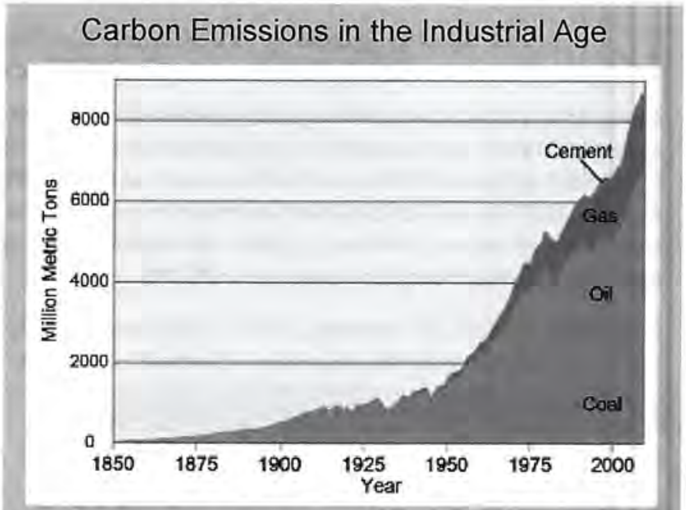


Figure 4. Global carbon emissions from burning coal, oil, and gas and from producing cement (1850-2009). These emissions account for about 80% of the total emissions of carbon from human activities, with land-use changes (like cutting down forests) accounting for the other 20% in recent decades. (Data from Boden et al. 2012[3]).

Records from ice cores, tree rings, soil boreholes, and other forms of "natural thermometers," or "proxy" climate data, show that recent climate change is unusually rapid compared to past changes. After a glacial maximum, the Earth typically warms by about 7°F to 13°F over thousands of years (with periods of rapid warming alternating with periods of slower warming, and even cooling, during that time). The observed rate of warming over the last 50 years is about eight times faster than the average rate of warming from a glacial maximum to a warm interglacial period.

Global temperatures over the last 100 years are unusually high when compared to temperatures over the last several thousand years. Atmospheric carbon dioxide levels are currently higher than any time in at

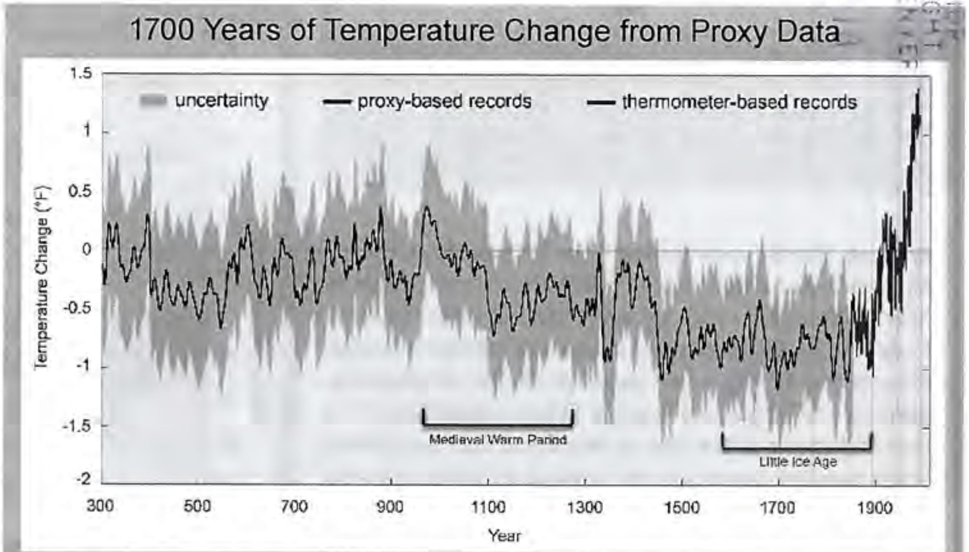


Figure 5. Changes in the temperature of the Northern Hemisphere from surface observations (in red) and from proxies (in black; uncertainty range represented by shading) relative to 1961-1990 average temperature. These analyses suggest that current temperatures are higher than seen globally in at least the last 1700 years and that the last decade (2001 to 2010) was the warmest decade on record. (Figure source: adapted from Mann et al. 2008[4]).

least the last 800,000 years. Paleoclimate studies indicate that temperature and atmospheric carbon dioxide levels have been higher in the distant past, millions of years ago, when the world was very different than it is today. But never before have such rapid, global-scale changes occurred during the history of human civilization.

Our societies have not been built to withstand the changes that are anticipated in the relatively near future, and thus are not prepared for the effects they are already experiencing: higher temperatures, sea level rise, and other climate change related impacts.

D. Is the globally averaged surface air temperature still increasing? Isn't there recent evidence that it is actually cooling?

Global temperatures are still rising. Climate change is defined as a change in the average conditions over periods of 30 years or more (see FAQ A). On these time scales, global temperature continues to increase. Over shorter time scales, natural variability (due to the effects of El Niño and La Niña events in the Pacific Ocean, for example, or volcanic eruptions or changes in energy from the sun) can reduce the rate of warming or even create a temporary reduction in average surface air temperature. These short-term variations in no way negate the reality of long-term warming. The most recent decade was the warmest since instrumental record keeping began around 1880.

From 1970 to 2010, for example, global temperature trends taken at five-year intervals show both decreases and sharp increases. The five-year period from 2005 to 2010, for example, included a period in which the sun's output was at a low point, oceans took up more than average amounts of heat, and a series of small volcanoes exerted a cooling influence by adding small particles to the atmosphere. These natural factors are thought to have contributed to a recent slowdown in the rate of increase in average surface air temperature caused by the buildup of human-induced greenhouse gases. But while there has been a slowdown in the rate of increase, temperatures are still increasing.

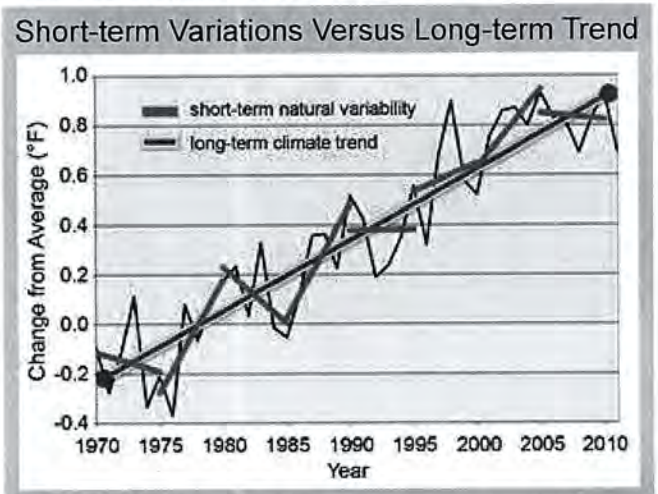


Figure 6. Short-term trends in global temperature (blue lines show temperature trends at five-year intervals from 1970 to 2010) can range from decreases to sharp increases. The evidence of climate change is based on long-term trends over 20-30 years or more (red line). (Data from NOAA NCDC).

In addition, satellite and ocean observations indicate that most of the increased energy in the Earth's climate system from the increasing levels of heat-trapping gases has gone into the oceans. These observations indicate that the Earth-atmosphere climate system has continued to gain heat energy.

In the United States, there has been considerable decade-to-decade variability superimposed on the long-term warming trend. In most seasons and regions, the 1930s were relatively warm and the 1960s/1970s relatively cool. The most recent decade of the 2000s was the warmest on record throughout the United States and globally.

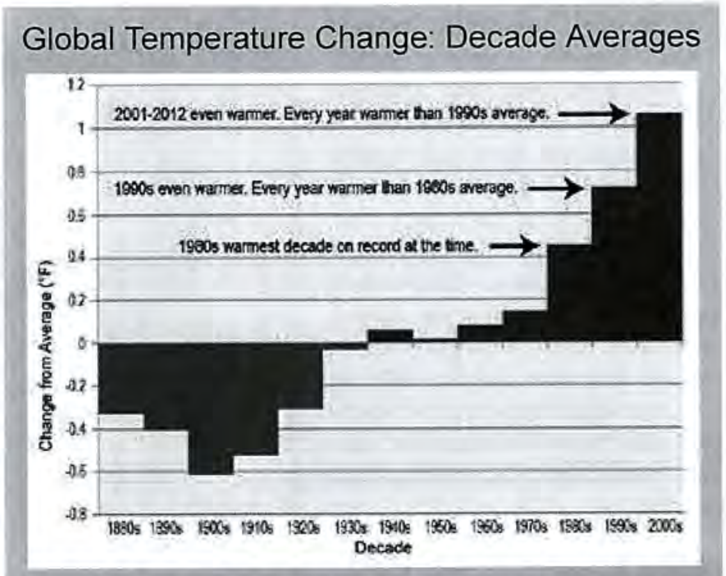


Figure 7. The last five decades have seen a progressive rise in Earth's average surface temperature. Bars show the difference between each decade's average temperature and the overall average for 1901 to 2000. The far right bar includes data for 2001-2012. (Figure source: NOAA NCDC).

E. Is it getting warmer at the same rate everywhere? Will the warming continue?

Temperatures are not increasing at the same rate everywhere, because temperature changes in a given location depend on many factors. However, average global temperatures are projected to continue increasing throughout the remainder of this century due to heat-trapping gas emissions from human activities.

The planet is warming overall (see FAQ I), but some locations could be cooling due to local factors. Temperature changes in a given location are a function of multiple factors, including global and local forces, and both human and natural influences. In some places, including the U.S. Southeast, temperatures actually declined over the last century as a whole (although they have risen in recent decades). Possible causes of the observed lack of warming in the Southeast during the 20th century include increased cloud cover and precipitation,[5] increases in the presence of fine particles called aerosols in the atmosphere (including those produced by burning fossil fuels and by natural sources), expanding forests in the Southeast over this period,[6] decreases in the amount of heat conducted from land to the atmosphere as a result of increases in irrigation,[7] and multi-decadal variability in sea surface temperatures in both the North Atlantic[8] and the tropical Pacific[9] Oceans. At smaller geographic scales, and during certain time intervals, the relative influence of natural variations in climate compared to the human contribution is larger than at the global scale. An observed decrease in temperature at an individual location does not negate the fact that, overall, the planet is warming.

In terms of impacts, "global warming" is probably not the most immediate thing most people would notice. A changing climate affects our lives in many more obvious ways, for example, by increasing the risk of severe weather events such as heat waves, heavy precipitation events, strong hurricanes, and many other aspects of climate discussed throughout this report.

Temperature Trends, 1900-2012

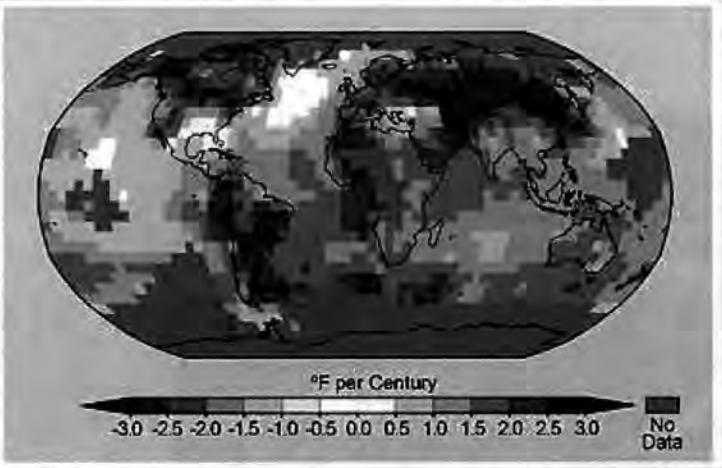


Figure 8. Observed trend in temperature from 1900 to 2012; yellow to red indicates warming, while shades of blue indicate cooling. Gray indicates areas for which there are no data. There are substantial regional variations in trends across the planet, though the overall trend is warming. (Figure source: NOAA NCDC).

For these reasons, many scientists prefer the term "climate change," which connotes a much larger picture: broad changes in what are considered "normal" conditions. This term encompasses both increases and decreases in temperature, as well as shifts in precipitation, changing risk of certain types of severe weather events, and other features of the climate system.

At the global scale, some future years will be cooler than the preceding year; some decades could even be cooler than the preceding decade (though that has not happened for more than six decades; see Figure 7). Brief periods of faster temperature increases and also temporary decreases in global temperature can be expected to continue into the future. Nonetheless, each successive decade in the last 30 years has been the warmest in the period of reliable instrumental records (going back to 1850). Based on this historical record and plausible scenarios for future increases in heat-trapping gases, we expect that future global temperatures, averaged over climate timescales of 30 years or more, will be higher than preceding periods as a result of carbon dioxide and other heat-trapping gas emis-

Decade-Scale Changes in Average Temperature for U.S. Regions

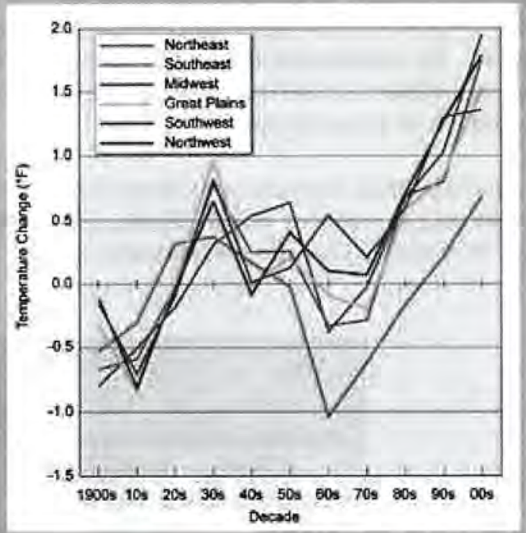


Figure 9. Change in decadal-averaged annual temperature relative to the 1901-1960 average for the six National Climate Assessment regions in the contiguous United States. This figure shows how regional temperatures can be much more variable than global temperatures, going up and down from decade to decade; all regions, however, show warming over the last two decades or more. In the figure, 00s refers to the 12-year period of 2001-2012. (Figure source: NOAA NCDC / CICS-NC).

sions from human activities. A portion of the carbon dioxide emissions from human activities will remain in the atmosphere for hundreds of years and continue to affect the global carbon cycle for thousands of years. Year-to-year projections of regional and local temperatures are more variable than global temperatures, and even at a particular location, future warming becomes increasingly likely over longer periods of time.[1]

F. How long have scientists been investigating human influences on climate?

The scientific basis for understanding how heat-trapping gases affect the Earth's climate dates back to the French scientist Joseph Fourier, who established the existence of the natural greenhouse effect in 1824. The heat-trapping abilities of greenhouse gases were corroborated by Irish scientist John Tyndall with experiments beginning in 1859. Since then, scientists have developed more tools to refine their understanding of human influences on climate, from the invention of the thermometer, to the development of computerized climate models, to the launching of Earth observing satellites that, together, provide global data coverage.

The greenhouse effect is caused by heat-trapping gases, such as water vapor, carbon dioxide, and methane, in the Earth's atmosphere. These gases are virtually transparent to the visible and ultraviolet wavelengths that comprise most of the sun's energy, allowing nearly all of it to reach Earth's surface. However, they are relatively opaque to the heat energy the Earth radiates back outward at infrared wavelengths. Other more abundant gases in the atmosphere like nitrogen and oxygen are largely transparent to the Earth's infrared energy. Greenhouse gases trap some of the Earth's energy inside the atmosphere and prevent it from escaping to space by absorbing and re-emitting that energy in all directions, rather than just upwards. Some of the trapped energy is re-radiated back down to the Earth's surface. This natural trapping effect makes the average temperature of the Earth nearly 60°F warmer than what it would be otherwise. On other planets, like Venus, where there are much higher concentrations of heat-trapping gases in the atmosphere, the greenhouse effect has a much stronger influence on surface temperature, making conditions far too hot for life as we know it.

By the late 1800s, scientists were aware that burning coal, oil, or natural gas produced carbon dioxide, a key heat-trapping gas. They were also aware that methane, another heat-trapping gas, was released during coal mining and other human activities. And they knew that, since the Industrial Revolution, humans were producing increasing amounts of these gases. It was clear that humans were increasing the natural greenhouse effect and that this would warm the planet.

In 1890, Svante Arrhenius, a Swedish chemist, calculated the effect of increasing fossil fuel use on global temperature. This climate model, computed by hand, took two years to complete. Arrhenius' results were remarkably similar to those produced by the most up-to-date global climate models today, although he did not anticipate that atmospheric levels of carbon dioxide would increase as quickly as they have.

In 1938, a British engineer, Guy Callendar, connected rising carbon dioxide levels to the observed increase in the Earth's temperature that had occurred to date. In 1958, Charles David Keeling began to precisely measure atmospheric levels of carbon dioxide in the relatively unpolluted location of Mauna Loa on Hawai'i. Today, those data provide a clear record of the effect of human activities on the chemical composition of the global atmosphere. Many more sources of data corroborate the work of these early pioneers in the field of climate science.

Figure 10. Scientists whose research was key to understanding the greenhouse effect and the impact of human activities on climate.

G. How can the small proportion of carbon dioxide in the atmosphere have such a large effect on our climate?

The reason heat-trapping gases like carbon dioxide, methane, and nitrous oxide have such a powerful influence on Earth's climate is their potency: although they are transparent to visible and ultraviolet solar energy, allowing the sun's energy to come in, they are very strong absorbers of the Earth's infrared heat energy, blanketing the Earth and preventing some of the energy to escape to space.

Before the Industrial Revolution, natural levels of carbon dioxide in the atmosphere averaged around 280 parts per million (ppm), that is, 280 molecules of CO_2 per million molecules of air (which is mostly nitrogen and oxygen). In other words, carbon dioxide made up about 0.028% of the volume of the atmosphere. Methane and nitrous oxide, other heat-trapping gases, made up even less, about 700 parts per billion (ppb) and 270 ppb, respectively. Over the last few centuries, emissions from human activities have increased carbon dioxide levels to about 400 ppm, or more than 3,000 billion tons – more than a 40% increase. Over the same time period, methane and nitrous oxide levels in the atmosphere have risen to around 1800 ppb and 320 ppb, respectively.

As the concentrations in the atmosphere of these heat-trapping gases increase due to human activities, they are absorbing greater and greater amounts of infrared heat energy emitted from the Earth's surface. As discussed in FAQ F, the gases then re-radiate some of this heat back to the surface, effectively trapping the heat inside the Earth's climate system and warming the Earth's surface.

These heat-trapping gases do not absorb energy equally across the infrared spectrum. Carbon dioxide absorption is very strong at certain wavelengths of infrared radiation, whereas water vapor absorbs more broadly across most of the spectrum. Water vapor is the most important naturally occurring heat-trapping greenhouse gas, but small increases in heat energy absorption by carbon dioxide and other heat-trapping gases trigger increases in water vapor that amplify the infrared trapping, leading to further warming. As a result, water vapor is considered a "feedback" rather than a direct forcing on climate.

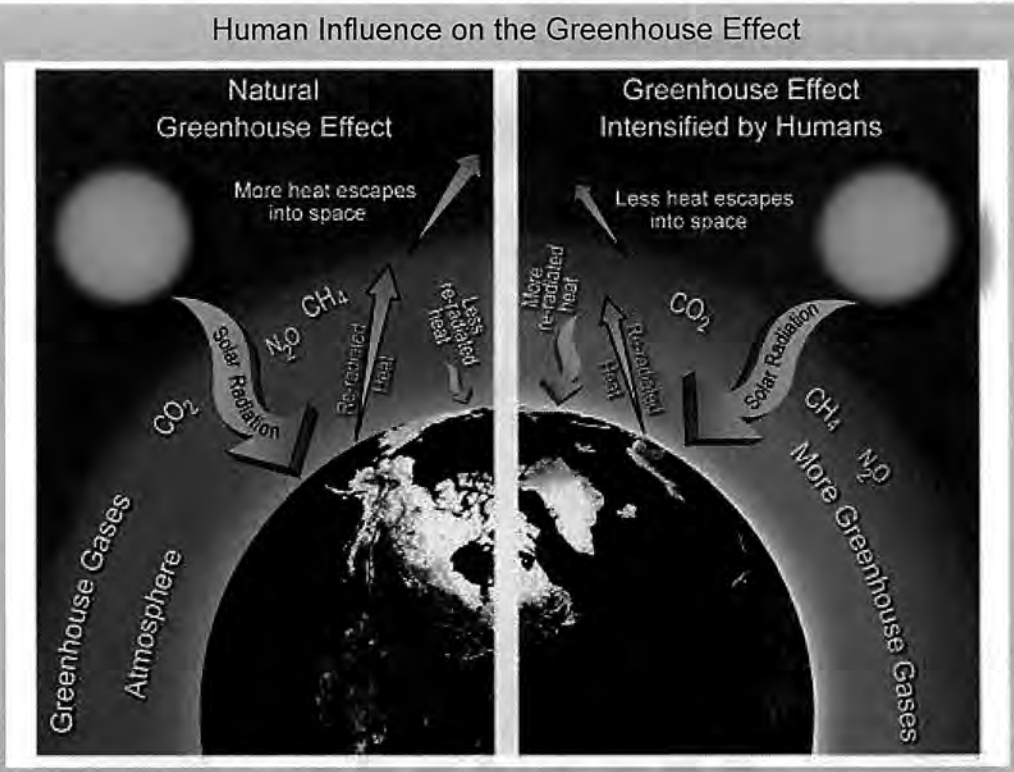


Figure 11. (left) A stylized representation of the natural greenhouse effect. Most of the sun's radiation reaches the Earth's surface. Naturally occurring heat-trapping gases, including water vapor, carbon dioxide, methane, and nitrous oxide, do not absorb the short-wave energy from the sun but do absorb the long-wave energy re-radiated from the Earth, keeping the planet much warmer than it would be otherwise. (right) In this stylized representation of the human-intensified greenhouse effect, human activities, predominantly the burning of fossil fuels (coal, oil, and gas), are increasing levels of carbon dioxide and other heat-trapping gases, increasing the natural greenhouse effect and thus Earth's temperature. (Figure source: modified from National Park Service[10]).

H. Could the sun or other natural factors explain the observed warming of the past 50 years?

No. Since accurate satellite-based measurements of solar output began in 1978, the amount of the sun's energy reaching Earth has slightly decreased, which should, on its own, result in slightly lower temperatures; but the Earth's temperature has continued to rise. The sun can explain less than 10% of the increase in temperature since 1750, and none of the increase in temperature since 1960.

Patterns of vertical temperature change (from the Earth's surface to the upper atmosphere) provide further evidence that the sun cannot be responsible for the observed changes in climate. An increase in solar output would warm the atmosphere consistently from top to bottom. Warming from increasing heat-trapping gases, on the other hand, should be concentrated in the lower atmosphere (troposphere), while the upper atmosphere (stratosphere) would cool. Satellite measurements and weather balloon records reveal that the troposphere has warmed, and the stratosphere has cooled. This observed pattern of vertical temperature change matches what we would expect from the increase in heat-trapping gases, not an increase in solar output.

Changes in the sun's magnetic field are known to affect the intensity of cosmic rays reaching Earth's atmosphere and there is some suggestion that this could affect cloud formation; however, observations indicate that the magnitude of this effect is much smaller than the effects from the human-related changes in heat-trapping gases and from particle emissions on clouds and the changes in climate.

Large explosive volcanic eruptions can cool climate for a few years after an eruption, if the eruption is powerful enough to send particles far up into the atmosphere. In the atmosphere, sulfur dioxide from volcanoes is converted into sulfuric acid particles that can scatter sunlight, cooling the Earth's surface. Particles from exceptionally large eruptions like Mount Pinatubo in 1991 or Krakatoa in 1883 can reach all the way into the stratosphere, where they can stay for several years. Eventually, they fall back into the troposphere where they are rapidly removed by precipitation. Volcanoes also emit carbon dioxide, but this amount is less than 1% annually of the emissions occurring from human activities.

Thus, natural factors cannot explain recent warming. In fact, observed solar and volcanic activity would have tended to slightly cool the Earth, and other natural variations are too small to account for the amount of warming over the last 50 years.

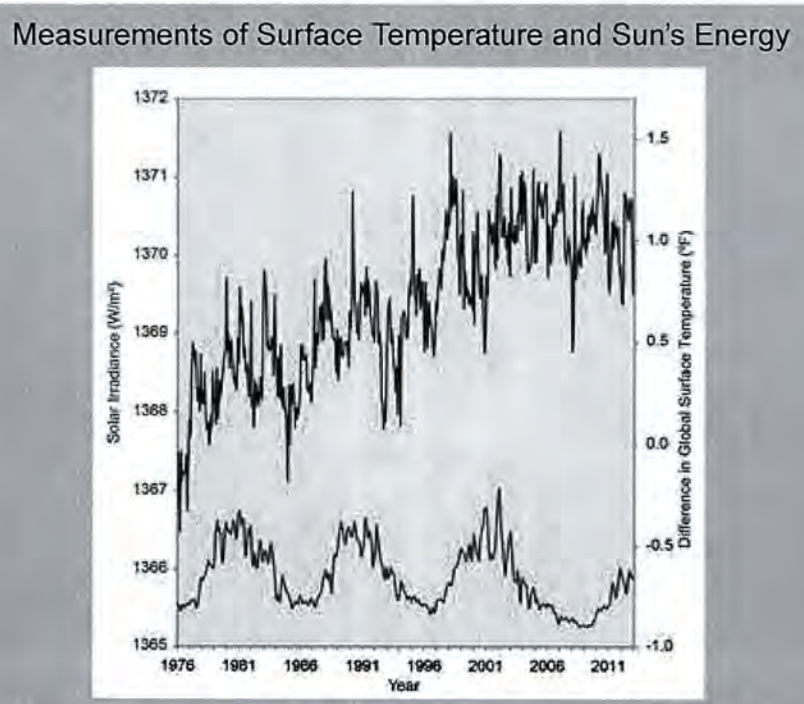


Figure 12. Changes in the global surface temperature (top) and the solar flux (bottom) since 1900 (temperatures are relative to 1961-1990). The temperatures are based on thermometer observations of the Earth's surface temperature, while the solar flux at the top of Earth's atmosphere is based on satellite observations starting in 1978 and on proxy observations before then. (Figure source: NOAA NCDC / CICS-NC).

I. How do we know that human activities are the primary cause of recent climate change?

Many lines of evidence demonstrate that human activities are primarily responsible for recent climate changes. First, basic physics dictates that increasing the concentration of CO_2 and other heat-trapping gases in the atmosphere will cause the climate to warm. Second, modeling studies show that when human influences are removed from the equation, climate would actually have cooled slightly over the past half century. And third, the pattern of warming through the layers of atmosphere demonstrates that human-induced heat-trapping gases are responsible, rather than some natural change.

Scientists are continually designing experiments to test whether observed climate changes are unusual and then to determine their causes. This field of study is known as "detection and attribution." Detection involves looking for evidence of changes or trends. Attribution attempts to identify the causes of these changes from a line-up of "suspects" that include changes in energy from the sun, powerful volcanic eruptions – and today, human-induced emissions of heat-trapping gases.

Detection and attribution analyses have confirmed that recent changes cannot have been caused either by internal climate system variations or by solar and volcanic influences (see FAQs C and H). Human influences on the climate system – including heat-trapping gas emissions, atmospheric particulates, and land-use and land-cover change – are required to explain recent changes (see Figure 14).

Detection and attribution has been used to analyze the contribution of human influences to changes in global average conditions, in extreme events, and even in the change in risk of specific types of events, such as the 2003 European heat wave. Such analyses have found that it is virtually certain that observed changes in many aspects of the climate system are the result of influences of human activities. Scientific analyses also provide extensive evidence that the likelihood of some types of extreme events (such as heavy rains and heat waves) is now significantly higher due to human-induced climate change.

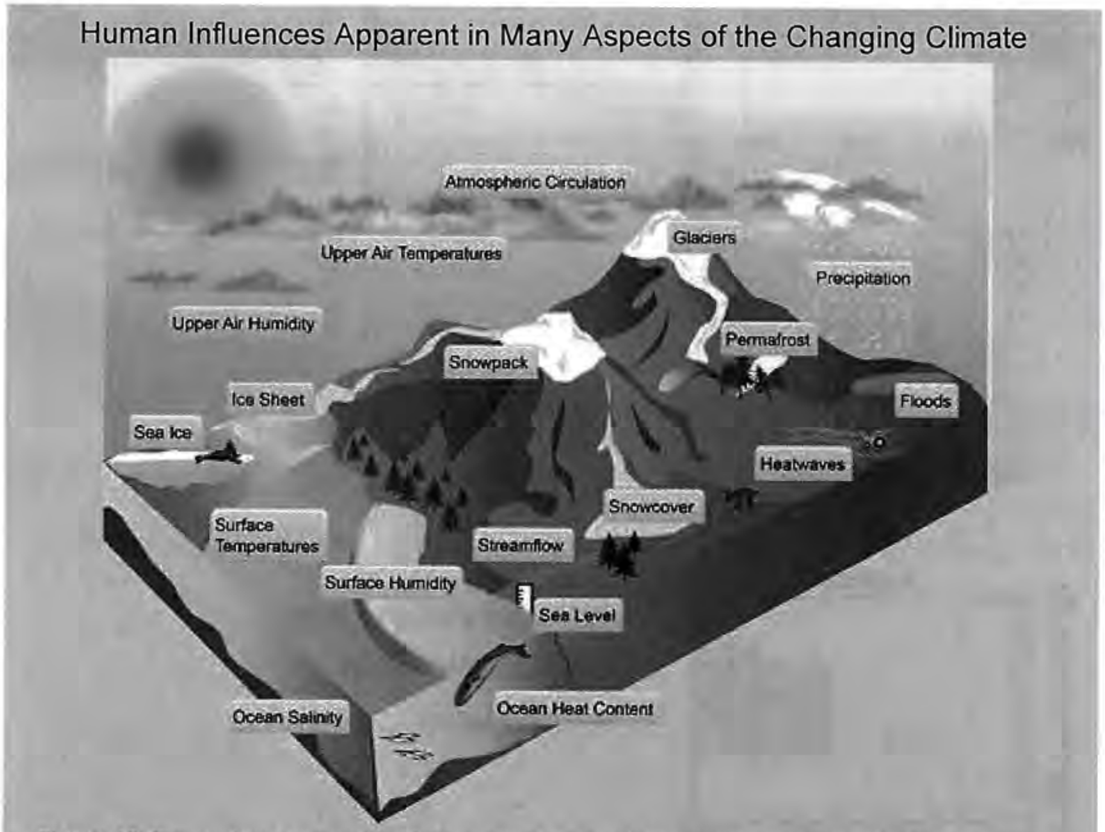

Human Influences Apparent in Many Aspects of the Changing Climate

Figure 13. Figure shows examples of the many aspects of the climate system in which changes have been formally attributed to human emissions of heat-trapping gases and particles by studies published in peer-reviewed science literature. For example, observed changes in surface air temperature at both the global and continental levels, particularly over the past 50 years or so, cannot be explained without including the effects of human activities. While there are undoubtedly many natural factors that have affected climate in the past and continue to do so today, human activities are the dominant contributor to recently observed climate changes. (Figure source: NOAA NCDC).

Only Human Influence Can Explain Recent Warming

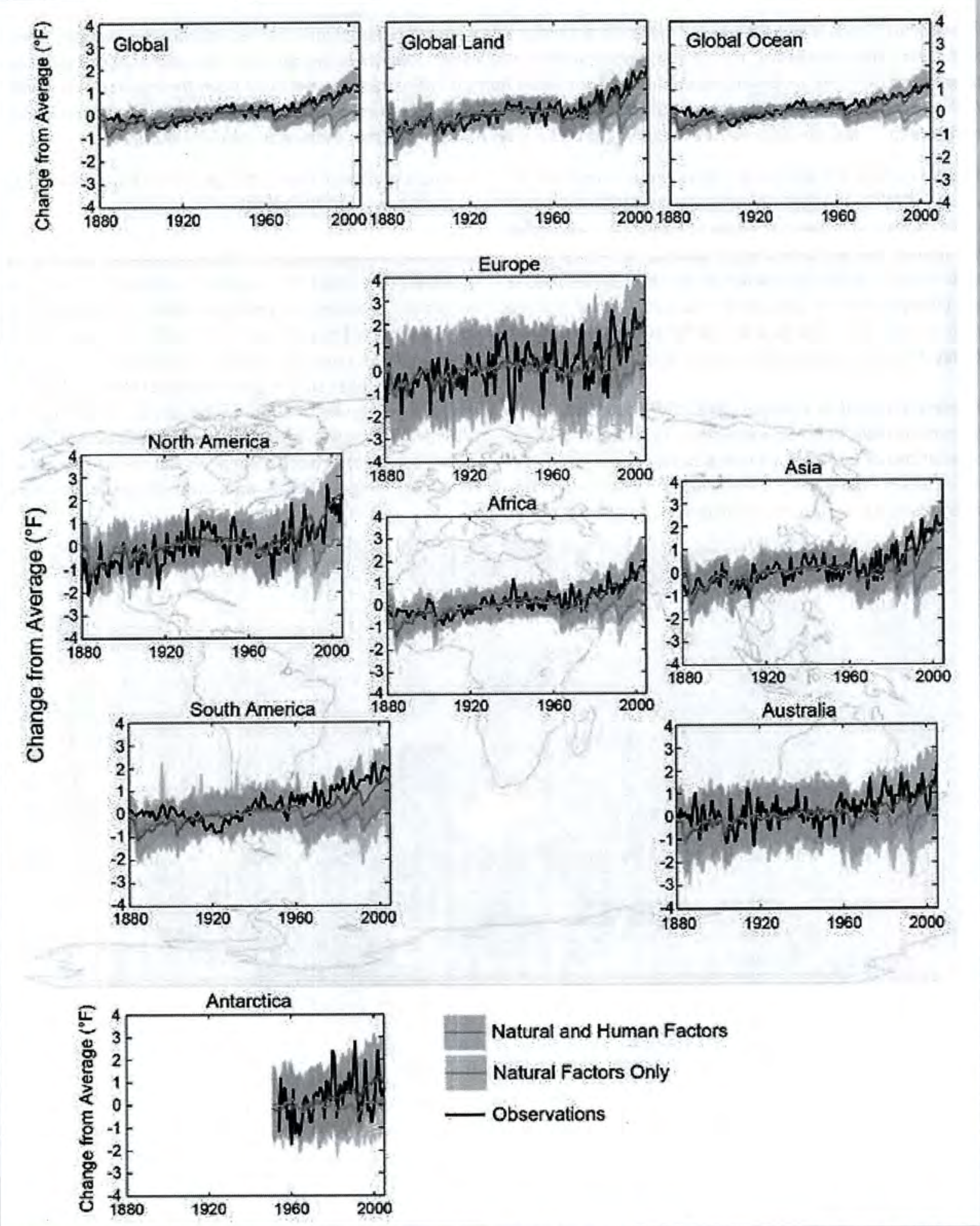


Figure 14. Changes in surface air temperature at the continental and global scales can only be explained by the influence of human activities on climate. The black line depicts the annually averaged observed changes. The blue shading represents estimates from a broad range of climate simulations including solely natural (solar and volcanic) changes in forcing. The orange shading is from climate model simulations that include the effects of both natural and human contributions. These analyses demonstrate that the observed changes, both globally and on a continent-by-continent basis, are caused by the influence of human activities on climate. (Figure source: updated from Jones et al. 2013[11]).

J. What is and is not debated among climate scientists about climate change?

Multiple analyses of the peer-reviewed science literature have repeatedly shown that more than 97% of scientists in this field agree that the world is unequivocally warming and that human activity is the primary cause of the warming experienced over the past 50 years. Spirited debates on some details of climate science continue, but these fundamental conclusions are not in dispute.

The scientific method is built on scrutiny and debate among scientists. Scientists are rigorously trained to conduct experiments to test a question, or hypothesis, and submit their findings to the scrutiny of other experts in their field. Part of that scrutiny, known as "peer review," includes independent scientists examining the data, analysis methods, and findings of a study that has been submitted for publication. This peer review process provides quality assurance for scientific results, ensuring that anything published in a scientific journal has been reviewed and approved by other independent experts in the field and that the authors of the original study have adequately responded to any criticisms or questions they received.

However, peer review is only the first step in the long process of acceptance of new ideas. After publication, other scientists will often undertake new studies that may support or reject the findings of the original study. Only after an exhaustive series of studies over many years, by many different research groups, are new ideas widely accepted.

Given that new scientific understanding emerges from this exhaustive process, the widespread agreement in the scientific community regarding the reality of climate change and the leading role of human activities in driving this change is striking. This consensus includes agreement on the fundamental scientific principles that underlie this phenomenon, as well as the weight of empirical evidence that has been accumulated over decades, and even centuries, of research (see FAQ F).

The conclusion that the world is warming, and that this is primarily due to human activity, is based on multiple lines of evidence, from basic physics to the patterns of change through the climate system (including the atmosphere, oceans, land, biosphere, and cryosphere). The warming of global climate and its causes are not matters of opinion; they are matters of scientific evidence, and that evidence is clear. Scientists do not "believe" in human-induced climate change; rather, the widespread agreement among scientists is based on the vast array of evidence that has accumulated over the last 200 years. When all of the evidence is considered, the conclusions are clear.

There is more work to be done to fully understand the many complex and interacting aspects of climate change, and important questions remain. Scientific debate continues on questions such as: Exactly how sensitive is the Earth's climate to human emissions of heat-trapping gases? How will climate change affect clouds? How will climate change affect snowstorms in Chicago, tornadoes in Oklahoma, and droughts in California? How do particle and soot emissions affect clouds? How will climate change be affected by changes in clouds and the oceans? These detailed questions, and more, serve as healthy indicators that the scientific method is alive and well in the field of climate science. But the fact that climate is changing, that this is primarily in response to human activities, and that climate will continue to change in response to these activities, is not in dispute (see FAQ I).

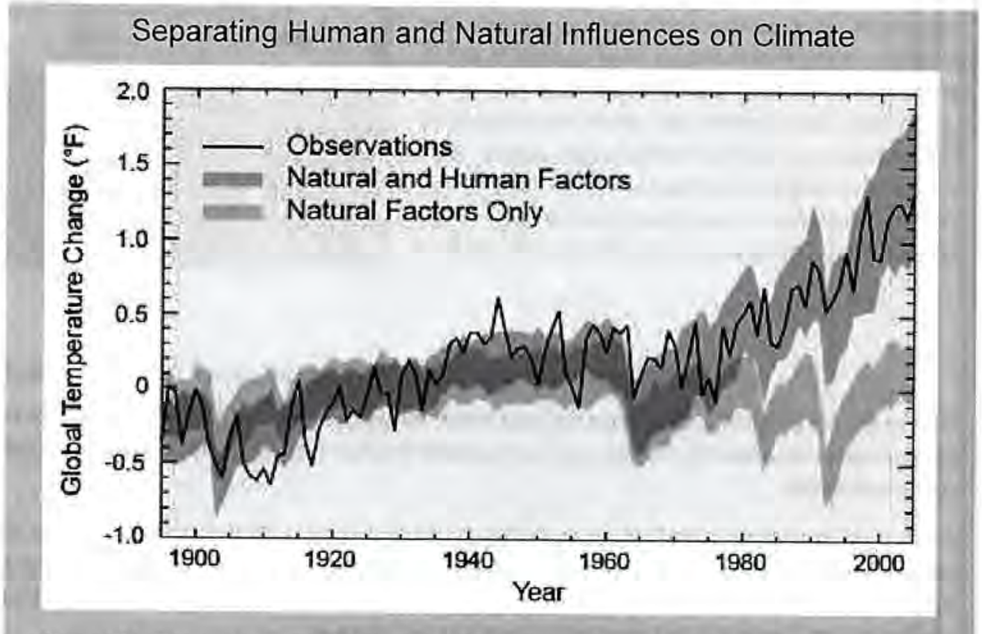


Figure 15. The green band shows how global average temperature would have changed due to natural forces only, as simulated by climate models. The blue band shows model simulations of the effects of human and natural factors combined. The black line shows observed global average temperatures. As indicated by the green band, without human influences, temperature over the past century would actually have cooled slightly over recent decades. The match up of the blue band and the black line illustrate that only the inclusion of human factors can explain the recent warming. (Figure source: adapted from Huber and Knutti, 2012[12]).

K. Is the global surface temperature record good enough to determine whether climate is changing?

Yes. There have been a number of studies that have examined the U.S. and global temperature records in great detail. These have used a variety of methods to study the effects of changes in instruments, time of observations, station siting, and other potential sources of error. All studies reinforce high confidence in the reality of the observed upward trends in temperature.

Global surface temperatures are measured by weather stations over land and by ships and buoys over the ocean. These records extend back regionally for over 300 years in some locations and near-globally to the late 1800s.

Scientists have undertaken painstaking efforts to obtain, digitize, and collate these records. Because of the way these measurements have been taken, many of the records contain results that are skewed by, for example, a change of instrument or a station move. It is essential to carefully examine the data to identify and adjust for such effects before the data can be used to evaluate climate trends.

A number of different research teams have taken up this challenge. Some have spent decades carefully analyzing the data and continually reassessing their approaches and refining their records. These independently produced estimates are in very good agreement at both global and regional scales.

Scientists have also considered other influences that could contaminate temperature records. For example, many thermometers are located in urban areas that could have warmed over time due to the urban heat island effect (in which heat absorbed by buildings and asphalt makes cities warmer than the surrounding countryside). At least three different research teams have examined how this might affect U.S. temperature trends. All have found that this effect is adequately accounted for by the data corrections. At the global scale, if all of the urban stations are removed from the global temperature record, the evidence of warming over the past 50 years remains intact. Other studies have shown that the temperature *trends* of rural and urban areas in close proximity essentially match, even though the urban areas may have higher temperatures overall.

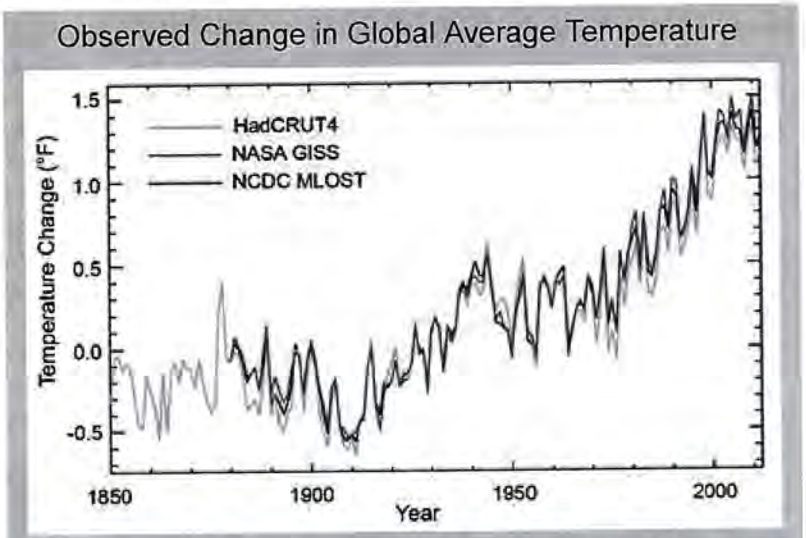


Figure 16. Three different global surface temperature records all show increasing trends over the last century. The lines show annual differences in temperature relative to the 1901-1960 average. Differences among data sets, due to choices in data selection, analysis, and averaging techniques, do not affect the conclusion that global surface temperatures are increasing. (Figure source: NOAA NCDC / CICS-NC).

L. Is Antarctica gaining or losing ice? What about Greenland?

The ice sheets on both Greenland and Antarctica, the largest areas of land-based ice on the planet, are losing ice as the atmosphere and oceans warm. This ice loss is important both as evidence that the planet is warming, and because it contributes to rising sea levels.

One way that scientists are evaluating ice loss is by observing changes in the gravitational fields over Greenland and Antarctica. Fluctuations in the pull of gravity over these major ice sheets reflect the loss of ice over time. Over the last decade, the GRACE (Gravity Recovery and Climate Experiment) satellites have measured changes in the gravitational pull of the continents and revealed that, on the whole, both Greenland and Antarctica are losing ice. It is clear that these ice sheets are already losing mass as a result of human-induced climate change, and the evidence suggests that Greenland and Antarctica are likely to continue to lose ice mass for centuries. How rapidly the Greenland and Antarctic Ice Sheets will melt as warming continues represents the largest uncertainty in projections of future sea level rise.

Paleoclimate records show that the giant ice sheets of Greenland and Antarctica (as well as others, such as the Laurentide Ice Sheet that covered much of North America during the last glacial maximum) have expanded and contracted as the Earth cooled or warmed in the past. As temperature increases and precipitation patterns shift in response to human-induced climate change, scientists expect the ice sheets of Greenland and

Ice Loss from the Two Polar Ice Sheets

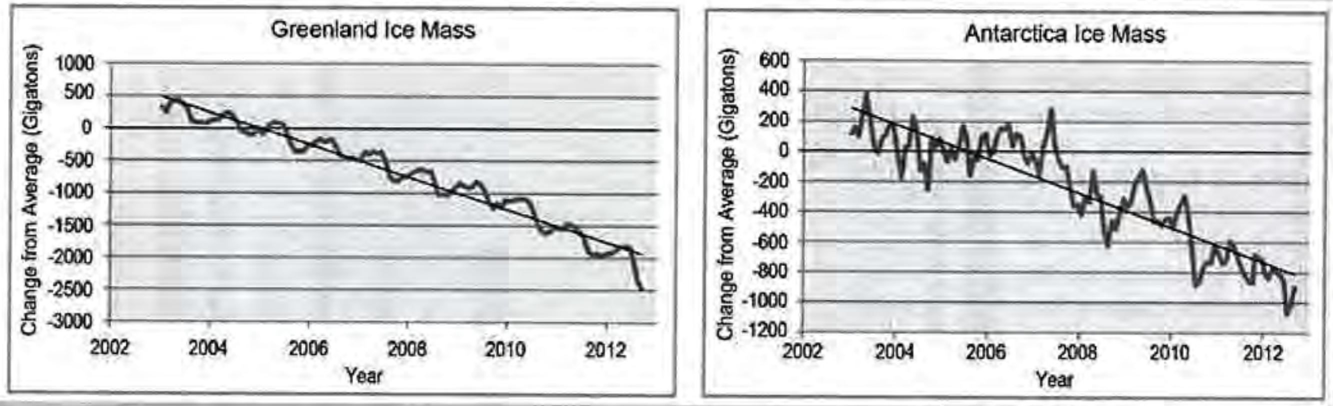


Figure 17. GRACE (Gravity Recovery and Climate Experiment) satellite measurements show that both Greenland and Antarctica are, on the whole, losing ice as the atmosphere and oceans warm. (Figure source: adapted from Wouters et al. 2013[13]).

Antarctica to continue responding in a similar way. Over time horizons of hundreds to thousands of years, a general melting and reduction in the extent of both of these ice sheets is expected to occur in response to global warming. Over shorter time frames of years to decades, however, the response of these ice sheets is more complicated.

The Antarctic Ice Sheet is up to three miles deep and contains enough water to raise sea level about 200 feet. Because Antarctica is so cold, there is little melt of the ice sheet in the summer. However, the ice on the continent slowly flows down the mountains and through the valleys toward the ocean. Some parts of the ice sheet extend out into the ocean as "ice shelves." Here, above-freezing ocean water speeds up the process called "calving" that breaks the ice into free floating icebergs. Melting and calving and the flow of ice into the oceans around Antarctica has accelerated in recent decades and is now contributing about 0.005 to 0.010 inches per year to sea level rise. It is possible that the West Antarctic Ice Sheet, which contains enough ice to raise global sea levels by 10 feet, could begin to lose ice much more quickly if ice shelves in the region begin to disintegrate at the edges.

Greenland contains only about one tenth as much ice as the Antarctic Ice Sheet, but if Greenland's ice were to entirely melt, global sea level would rise 23 feet. Greenland is warmer than Antarctica, so unlike Antarctica, melting occurs over large parts of the surface of Greenland's ice sheet each summer. Greenland's melt area has increased over the past several decades. Satellite measurements indicate that the Greenland Ice Sheet is presently thinning at the edges (especially in the south) and slowly thickening in the interior, increasing the steepness of the ice sheet, which causes the ice to flow toward the ocean. Several of the major outlet glaciers that drain the Greenland Ice Sheet have sped up in the past decade. Recent scientific studies suggest that warming of the ocean at the edges of the outlet glaciers may contribute to this speed-up. Greenland's ice loss has increased substantially in the past decade or two, and is now contributing 0.01 to 0.02 inches per year to sea level rise (about twice the rate of Antarctica's mass loss). This increased rate of ice loss means that Greenland's contribution to global sea level rise is now similar to the effect from smaller glaciers worldwide and from Antarctica.

M. Weren't there predictions of global cooling in the 1970s?

No. An enduring myth about climate science is that in the 1970s the climate science community supposedly predicted "global cooling" and an "imminent" ice age. A review of the scientific literature shows that this was not the case. On the contrary, even then, discussions of human-related warming dominated scientific publications on climate and human influences.

Where did all the discussion about global cooling come from? First, temperature records from about 1940 to 1970 showed a slight global cooling trend, intensified by temporary increases in snow and ice cover across the Northern Hemisphere. Short-term natural variations in the Earth's climate (see FAQ A) and increasing emissions of sulfur and other particles from coal-burning power plants, which reflect solar energy and have a net cooling effect on the Earth, likely contributed to cooler temperatures during that time period. Several unusually severe winters in Asia and parts of North America in the 1970s raised people's concerns about cold weather. The popular press, including *Time*, *Newsweek*, and *The New York Times*, carried a number of articles about cooling at that time.

Second, climate scientists study both natural and human-induced changes in climate. Over the last century, scientists have learned a great deal about what drives Earth's ice ages. Scientific understanding of what are called the Milankovitch cycles (cyclical changes in the Earth's orbit that can explain the onset and ending of ice ages) led a few scientists in the 1970s to suggest that the current warm interglacial period might be ending soon, plunging the Earth into a new ice age over the next few centuries. Scientists continue to study this issue today; the latest information suggests that, if the Earth's climate were being controlled primarily by natural factors, the next cooling cycle would begin sometime in the next 1,500 years. However, humans have so altered the composition of the atmosphere that the next glaciation has now been delayed.

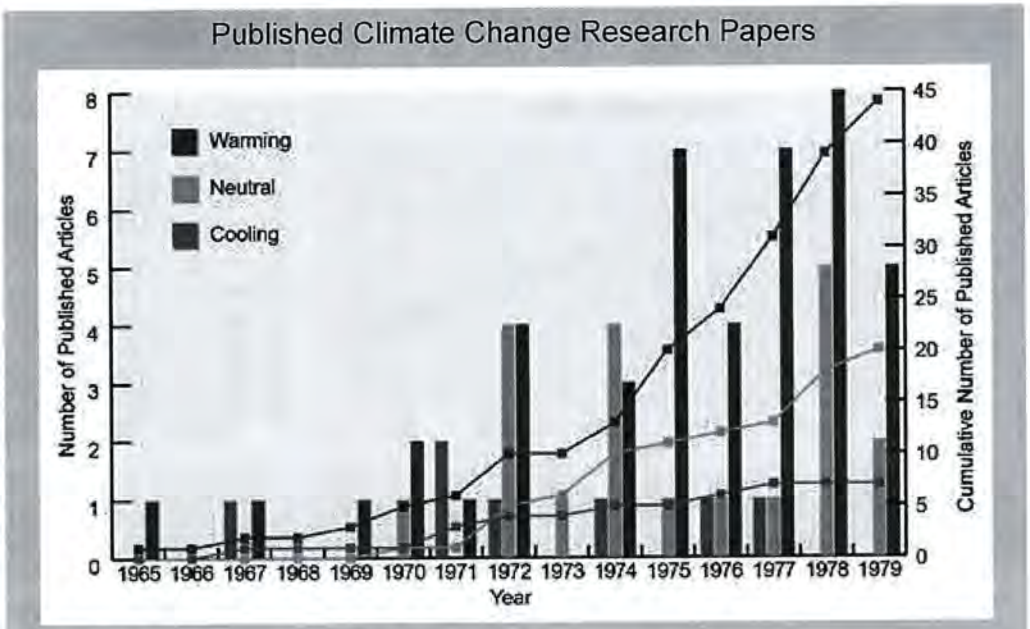


Figure 18. The number of papers classified as predicting, implying, or providing supporting evidence for future global cooling, warming, and neutral categories. Bars indicate number of articles published per year. Squares indicate cumulative number of articles published. For the period 1965 through 1979, the literature survey found seven papers suggesting further cooling, 20 neutral, and 44 warming. Even in the early years of the study of climate change, more science studies were discussing concerns about global warming than global cooling. (Figure source: Peterson et al. 2008[14]).

N. How is climate projected to change in the future?

Climate is projected to continue to warm, with the amount of future warming ranging from another 3°F to another 12°F by 2100, depending primarily on the level of emissions from human activities, principally the burning of fossil fuels. For precipitation, wet areas are generally projected to get wetter while dry areas get drier. More precipitation is expected to fall in heavy downpours. Natural variability will still play a role in year-to-year changes.

Future climate cannot be "predicted" because human activities are currently the most important driver of climate change and we cannot predict what society will choose to do with regard to emissions. Rather, we can *project* the climate change that would result from a given set of assumptions, or future scenarios, regarding human activities (including changes in population, technology, economics, energy, and policy). Future changes also have some uncertainty due to natural variability, particularly over shorter time scales (see FAQ A) and limitations in scientific understanding of exactly how the climate system will respond to human activities (see FAQ S).

The relative importance of these three sources of uncertainty changes over time. Which type of uncertainty is most important also depends on what type of change is being projected: whether, for example, it is for average conditions or extremes, or for temperature or precipitation trends (see FAQ S).

Over the next few decades, global average temperature over 30-year climate timescales is expected to continue to increase (see FAQ D), while natural variability still plays a significant role in year-to-year changes (see FAQ A). The amount of climate change expected over this time period is unlikely to be significantly altered by reducing current heat-trapping gas emissions alone or even by stabilizing atmospheric levels of carbon dioxide and other gases. This is because near-term warming will be caused primarily by emissions that have already occurred, due to the lag in the temperature response to changes in atmospheric composition. This lag is primarily the result of the very large heat storage capacity of the world's oceans and the length of time required for that heat to be transferred to the deep ocean. At smaller geographical scales, temperatures are projected to increase in most regions in the next few decades, but a few regions could experience flat or even decreasing temperatures. Any climate change always represents the net effect of multiple global and local factors, both human-related and natural (see FAQ E).

Beyond the middle of this century, global and regional temperature changes will be determined primarily by the rate and amount of various emissions released by human activities, as well as by the response of the Earth's climate system to those emissions. Efforts to rapidly and significantly reduce emissions of heat-trapping gases can still limit the global temperature increase to 3.6°F (2°C) relative to the 1901-1960 time period. However, significantly greater temperature increases are expected if emissions follow higher scenarios associated with continuing growth in the use of fossil fuels; in that case, the increase in U.S. average air temperature is likely to exceed 11°F by the end of this century. This amount of temperature increase would reshape human societies in ways that are almost unthinkable to us today.

Precipitation patterns are also expected to continue to change throughout this century and beyond. In general, wet areas are projected to get wetter and dry areas, drier. In some areas, located in between wetter and drier areas, the total amount of precipitation falling over the course of a year is not expected to significantly change. Following the observed trends over recent decades, more precipitation is expected to fall as heavier precipitation events. In many mid-latitude regions, including the United States, there will be fewer days with precipitation but the wettest days will be wetter. Large-scale shifts towards wetter or drier conditions and the projected increases in heavy precipitation are expected to be greater under higher emissions scenarios as compared to lower ones.

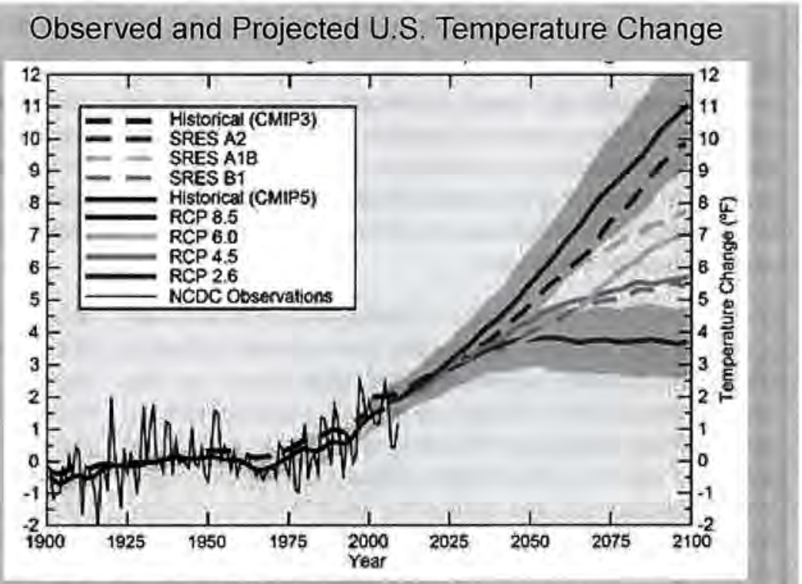


Figure 19. Projected average annual temperature changes over the contiguous United States for multiple future scenarios relative to the 1901-1960 average temperature. The dashed lines are results from the previous generation of climate models and scenarios, while solid lines show the most recent generation of climate model simulations and scenarios. Changes in temperature over the U.S. are expected to be higher than the change in global average temperatures (Figure 23). Differences in these projections are principally a result of differences in the scenarios. (Data from CMIP3, CMIP5, and NOAA NCDC).

O. Does climate change affect severe weather?

Yes, climate change can and has altered the risk of certain types of extreme weather events. The harmful effects of severe weather raise concerns about how the risk of such events might be altered by climate change. An unusually warm month, a major flood or a drought, a series of intense rainstorms, an active tornado season, landfall of a major hurricane, a big snowstorm, or an unusually severe winter inevitably lead to questions about possible connections to climate change.

For example, more extreme high temperatures and fewer extreme cold temperatures occur in a warmer climate (although extreme cold events can and do still occur – just less frequently). In the United States, more than twice as many high temperature records as compared to low temperature records were broken in the period of 2001-2012.

Also, in many areas, heavy rainfall events have already, and will continue to become more frequent and severe as climate continues to change. The intensity and rainfall rates of Atlantic hurricanes are projected to increase, with the strongest storms getting stronger. Recent research has shown how climate change can alter atmospheric circulation and weather patterns such as the jet stream, affecting the location, frequency, and duration of these and other extremes. While there have always been extreme events due to natural causes, scientific evidence indicates that the probability and severity of some types of events has increased due to climate change.

For other types of extreme weather events important to the United States, such as tornadoes and severe thunderstorms, more research is needed to understand how climate change will affect them. These events occur over much smaller scales, which makes observations and modeling more challenging. Projecting the future influence of climate change on these events can also be complicated by the fact that some of the risk factors for these events may increase with climate change, while others may decrease.

P. How are the oceans affected by climate change?

The oceans cover more than two-thirds of the Earth's surface and play a very important role in regulating the Earth's climate and in climate change. Today, the world's oceans absorb more than 90% of the heat trapped by increasing levels of carbon dioxide and other greenhouse gases in the atmosphere due to human activities. This extra energy warms the ocean, causing it to expand. This in turn causes sea level to rise. Of the global rise in sea level observed over the last 35 years, about 40% is due to this warming of the water. Most of the rest is due to the melting of glaciers and ice sheets. Ocean levels are projected to rise another 1 to 4 feet over this century, with the precise number largely depending on the amount of global temperature rise and polar ice sheet melt.

Observations from past climate combined with climate model projections of the future suggest that over the next 100 years the Atlantic Ocean's overturning circulation (known as the "Ocean Conveyor Belt") could slow down as a result of climate change. These ocean currents carry warm water northward across the equator in the Atlantic Ocean, warming the North Atlantic (and Europe) and cooling the South Atlantic. A slowdown of the Conveyor Belt would increase regional sea level rise along the east coast of the United States and change patterns of temperature in Europe and rainfall in Africa and the Americas, but would not lead to global cooling.

Warming ocean waters also affect marine ecosystems like coral reefs, which can be very sensitive to temperature changes. When water temperatures become too high, coral expel the algae (called zooxanthellae) which help nourish them and give them their vibrant color. This is known as coral bleaching. If the high temperatures persist, the coral die.

In addition to the warming, the acidity of seawater is increasing as a direct result of increasing atmospheric carbon dioxide (see FAQ Q). The oceans are now absorbing about a quarter of the carbon dioxide produced by human activities every year. The dissolved carbon dioxide reacts with seawater to form carbonic acid, which makes the water more acidic, making it more difficult for shellfish, corals, and other living things to grow their shells or skeletons. Both the increased acidity and higher temperature of the oceans are expected to negatively affect corals and other living things over the coming decades and beyond.

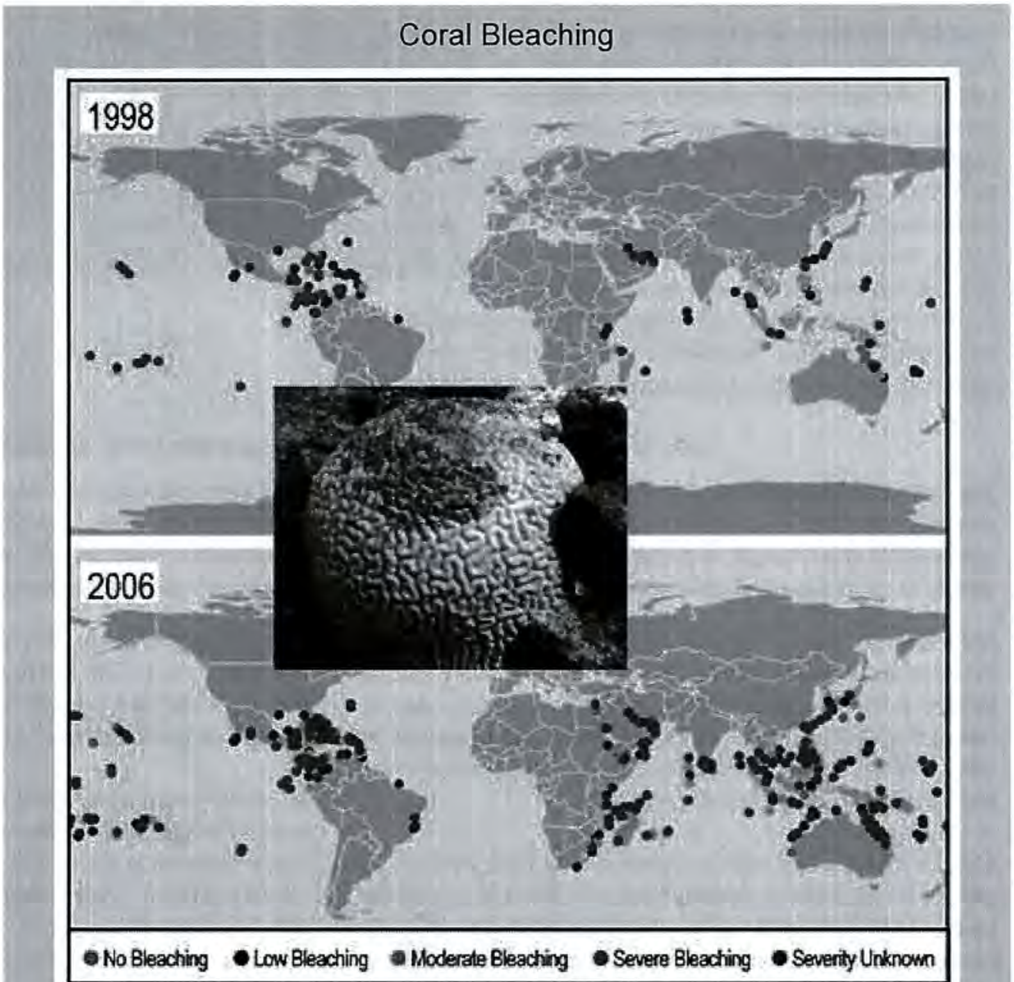


Figure 20. (Photo) Bleached brain coral; (Maps) The global extent and severity of mass coral bleaching have increased worldwide over the last decade. Red dots indicate severe bleaching. (Figure source: Marshall and Schuttenberg 2006;[15] Photo credit: NOAA).

Q. What is ocean acidification?

As human-induced emissions of carbon dioxide build up in the atmosphere, excess carbon dioxide dissolves into the oceans, where it reacts with seawater to form carbonic acid, which makes ocean waters more acidic and corrosive. These changes to ocean chemistry can affect many living things, and possibly the entire food web.

Dissolved calcium and carbonate ions are the building blocks for the skeletons and shells of many living things in the oceans. Ocean acidification lowers the availability of carbonate ions in many parts of the ocean, affecting the ability of some marine life to produce and maintain their shells.

Since the beginning of the Industrial Revolution, the pH of surface ocean waters has fallen by 0.1 pH units, representing approximately a 30% increase in acidity. The oceans will continue to absorb carbon dioxide produced by human activities and become even more acidic in the future. Projections of carbon dioxide levels indicate that by the end of this century the surface waters of the ocean could be as much as 150% more acidic, resulting in a pH that the oceans have not experienced for more than 20 million years and effectively transforming marine life as we know it.

Ocean acidification is expected to affect ocean species to varying degrees. Some photosynthetic algae and seagrass species may benefit from higher CO_2 conditions in the ocean, as they require CO_2 to live, as do plants on land. On the other hand, studies have shown that a more acidic environment has dramatic negative effects on some calcifying species, including pteropods, oysters, clams, sea urchins, shallow water corals, deep sea corals, and calcareous plankton. When shelled species are at risk, the entire food web may also be at risk.

Ocean Acidification and the Food Web

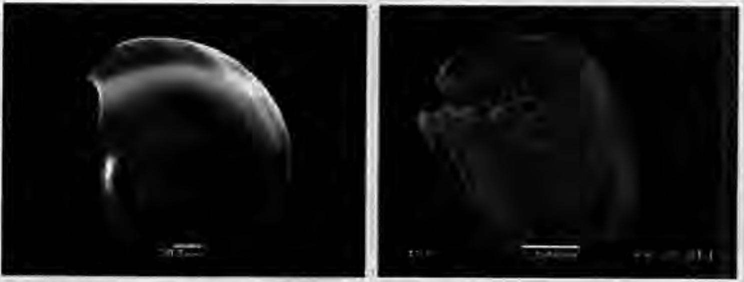


Figure 21. Pteropods, or "sea butterflies," are sea creatures about the size of a small pea. Pteropods are eaten by organisms ranging in size from tiny krill to whales, and are an important source of food for North Pacific juvenile salmon. The photos above show what happens to a pteropod's shell when it encounters seawater that is too acidic. The left panel shows a shell collected from a live pteropod from a region in the Southern Ocean where acidity is not too high. The shell on the right is from a pteropod collected in a region with higher acidity (Photo credits: (left) Bednaršek et al. 2012;[16] (right) Nina Bednaršek).

R. How reliable are the computer models of the Earth's climate?

Climate models are used to analyze past changes in the long-term averages and variations in temperature, precipitation, and other climate indicators, and to make projections of how these trends may change in the future. Today's climate models do a good job at reproducing the broad features of the present climate and changes in climate, including the significant warming that has occurred over the last 50 years. Hence, climate models can be useful tools for testing the effects of changes in the factors that drive changes in climate, including heat-trapping gases, particulates from human and volcanic sources, and solar variability.

Scientists have amassed a vast body of knowledge regarding the physical world. Unlike many areas of science, however, scientists who study the Earth's climate cannot build a "control Earth" and conduct experiments on this Earth in a lab. To experiment with the Earth, scientists instead use this accumulated knowledge to build climate models, or "virtual Earths." In studying climate change, these virtual Earths serve as an important way to integrate different kinds of knowledge of how the climate system works. These models can be used to test scientific understanding of the response of the Earth's climate to past changes (such as the transition from the last glacial maximum to our current warm interglacial period) as well as to develop projections of future changes (such as the response of the Earth's climate to human activities).

Climate models are based on mathematical and physical equations representing the fundamental laws of nature and the many processes that affect the Earth's climate system. When the atmosphere, land, and ocean are divided up into small grid cells and these equations are applied to each grid cell, the models can capture the evolving patterns of atmospheric pressures, winds, temperatures, and precipitation. Over longer timeframes, these models simulate wind patterns, high and low pressure systems, and other weather characteristics that make up climate.

Some important physical processes are represented by approximate relationships because the processes are not fully understood, or they are at a scale that a model cannot directly represent. Examples include clouds, convection, and turbulent mixing of the atmosphere, for which important processes are much smaller than the resolution of current models. These approximations lead to uncertainties in model simulations of climate.

Climate models require enormous computing resources, especially to capture the geographical details of climate. Today's most powerful supercomputers are enabling climate scientists to more thoroughly examine effects of climate change in ways that were impossible just five years ago. Over the next decade, computer speeds are predicted to increase another 100 fold or more, permitting even more details of the climate system to be explored.

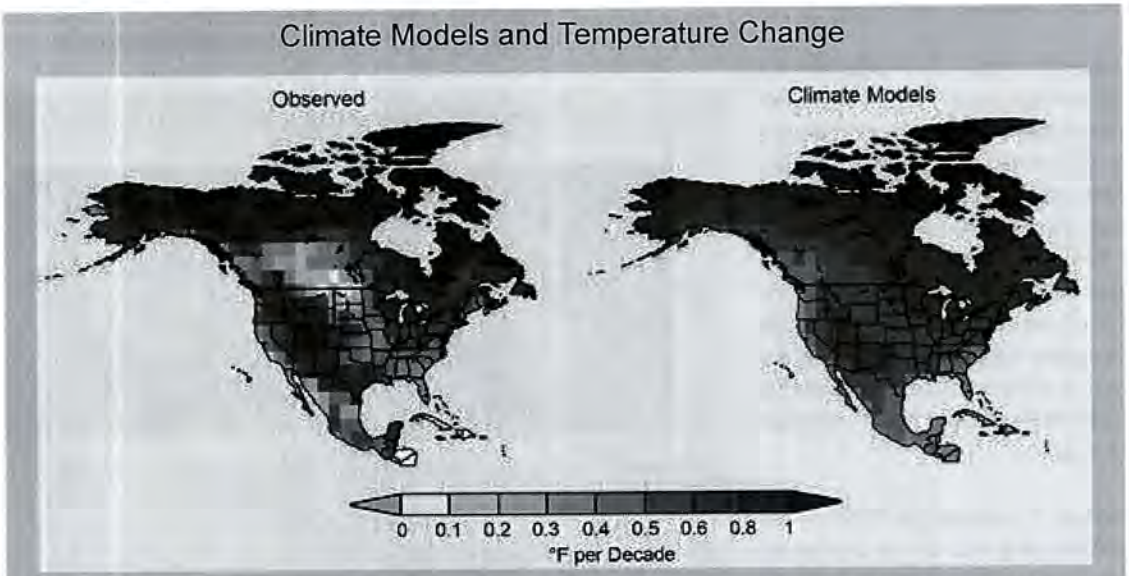


Figure 22. The large-scale geographical patterns and approximate magnitude of the surface air temperature trend from 1980 to 2005 from observational data (left) is approximately captured by computer models of the climate system (right). The pattern from the computer models is an average based on 43 different global climate models (CMIP5) used in the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report. The observations are a combination of both the human contribution to recent warming as well as the natural temperature variations. Averaging these model simulations suppresses the natural variations and thus shows mainly the human contribution, which is the reason that the smaller-scale details are different between the two maps. (Figure source: NOAA NCDC / CICS-NC).

S. What are the key uncertainties about climate change?

Available evidence gives scientists confidence that humans are having a significant effect on climate and will continue to do so over this century and beyond. In particular, continued use of fossil fuels and resulting emissions will significantly alter climate and lead to a much warmer world. Of course, it is impossible to predict the future with absolute certainty. The precise amount of future climate change that will occur over the rest of this century is uncertain for several reasons.

First, projections of future climate changes are usually based on scenarios (or sets of assumptions) regarding how future emissions may change as a result of population, energy, technology, and economics. Society may choose to reduce emissions or to continue to increase them. The differences in projected future climate under different scenarios are generally small for the next few decades. By the second half of the century, however, human choices, as reflected in these scenarios, become the key determinant of future climate change. And human choices are nearly impossible to predict.

A second source of uncertainty is natural variability, which affects climate over timescales from months to decades. These natural variations are largely unpredictable and are superimposed on the warming from increasing heat-trapping gases. Uncertainty in the sun's future output is another source of variability that is independent of human actions. Estimates of past changes in solar variability over the last several millennia suggest that the magnitude of solar effects over this century are likely to be small compared to the magnitude of the climate change effects projected from human activities.

A third source of uncertainty involves limitations to our current scientific knowledge. The Earth's climate system is complex, and continues to challenge scientists' understanding of exactly how it may respond to human influences. Observa-

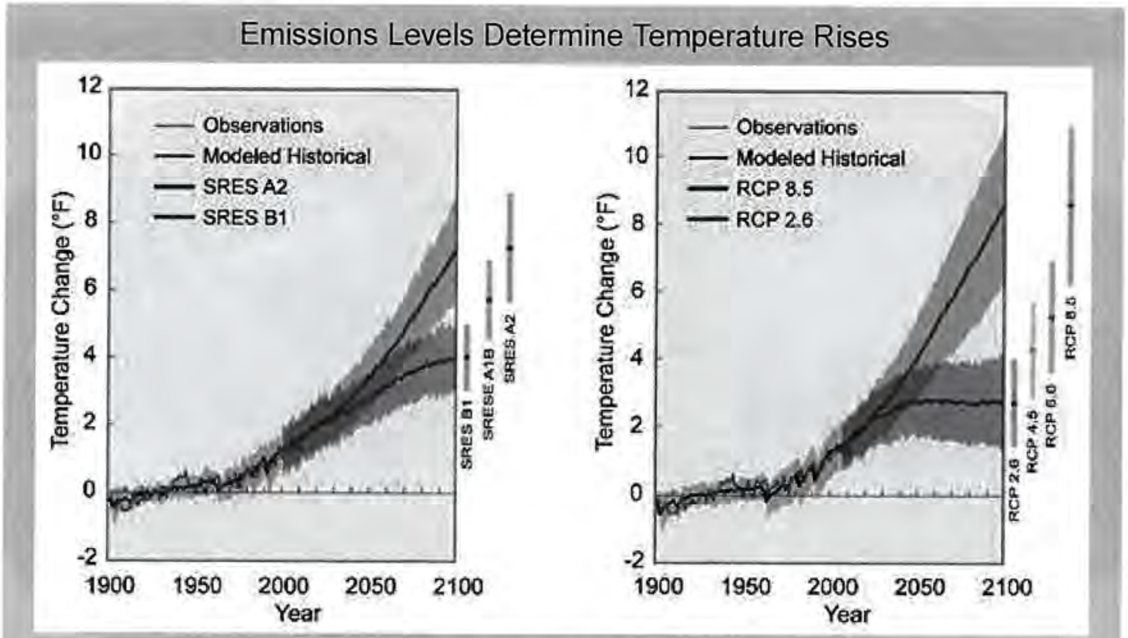


Figure 23. Projected global average annual temperature changes for multiple future scenarios relative to the 1901-1960 average temperature. Each line represents a central estimate of global average temperature rise for a specific emissions pathway. Shading indicates the range (5th to 95th percentile) of results from a suite of climate models. The left panel shows results from the previous generation of climate models (CMIP3), and the right panel shows results from the most recent generation of climate models (CMIP5). Projections in 2099 for additional emissions pathways are indicated by the bars to the right of each panel. In all cases, temperatures are expected to rise, although the difference between lower and higher emissions pathways is substantial. (Data from CMIP3, CMIP5, and NOAA NCDC).

tions of the climate system have expanded substantially since the beginning of the satellite era, but are still limited. Climate models differ in the way they represent various processes (for example, cloud properties, ocean circulation, and turbulent mixing of air). As a result, different models produce slightly different projections of change, even when the models use the same scenarios. Scientists often use multiple models in order to represent this range of projected outcomes.

Finally, there is always the possibility that there are processes and feedbacks not yet being included in future projections. For example, as the Arctic warms, carbon trapped in permafrost may be released into the atmosphere, increasing the initial warming due to human emissions of heat-trapping gases (see FAQ T).

However, for a given future scenario, the amount of future climate change can be specified within plausible bounds, determined not only from the differences in the "climate sensitivity" among models but also from information about climate changes in the past.

T. Are there tipping points in the climate system?

Most climate studies have considered only relatively gradual, continuous changes in the Earth's climate system. However, there are a number of potential "tipping points" in the climate system – points where a threshold is crossed, resulting in a substantial change in the future state of the climate system, regionally and/or globally.

Scientists have identified several aspects of the climate system that could pass a tipping point and/or change substantially under projected climate change (see Figure 24 for key examples). These tipping points have been identified based on observations of past abrupt climate changes, recent observations showing abrupt changes underway (for example, in the Arctic), process-based understanding of the dynamics of the climate system, and climate simulations showing tipping points in future projections. There is no clear scientific consensus at this time as to whether major tipping points, other than loss of the Arctic sea ice in summer, will be reached during this century.

Some tipping points are more imminent, and some would have larger impacts than others. For example, the rapid decline of Arctic sea ice exposes the darker ocean surface which absorbs increasing amounts of heats and reduces the amount of new seasonal ice formed. This drastic reduction in sea ice can tip the Arctic Ocean into a permanent, nearly ice-free state in summer (Ch.2: Our Changing Climate, Key Message 11). There is some

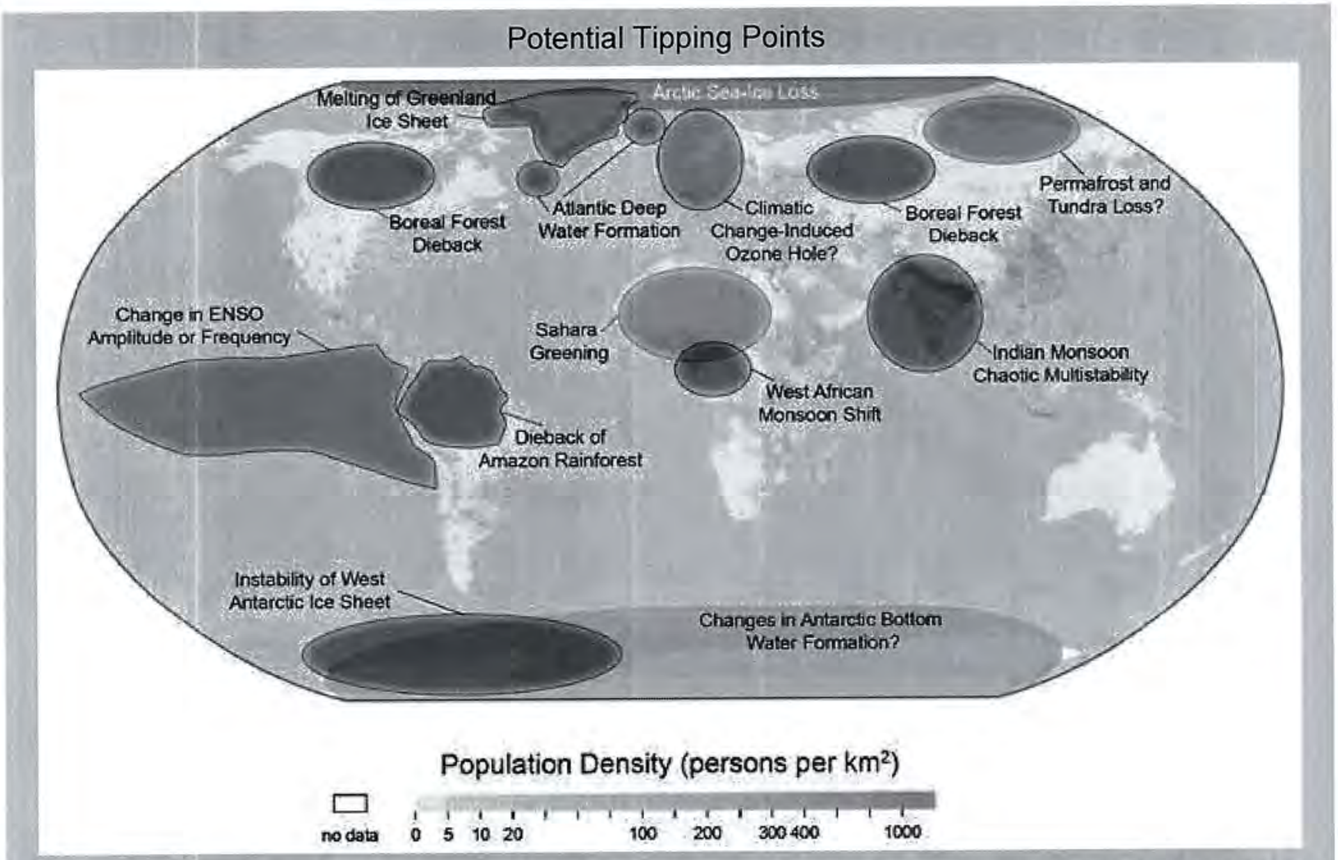


Figure 24. Stylized map of potential policy-relevant tipping elements in the Earth's climate system overlain on population density. Question marks indicate systems whose status as tipping elements is particularly uncertain. (Figure source: adapted from Lenton et al. 2008[17])

evidence that reductions in ice cover are already leading to changes in weather patterns affecting the U.S. and Europe.

Currently, the proximity, rate, and reversibility of tipping points are usually assessed through a mixture of climate modeling, literature review, and expert elicitation. However, there is a need for more research in this area. Climate scientists cannot predict when tipping points will be crossed because of uncertainties in the climate system and because we do not know what pathway future emissions will take. But an absence of certainty does not indicate an absence of risk. To use a medical analogy, just because your doctor cannot tell you the precise date and time that you will have a heart attack does not mean you should ignore medical advice to reduce your risk by taking preventative measures like exercising more, losing weight, and changing your diet. Medical science is imperfect, just like climate science, but it can provide very useful advice regarding the risks of our actions and choices – and the benefits of preventative measures.

U. How is climate change affecting society?

Multiple lines of evidence show that climate change is happening as a result of human activities. Climate change is altering the world around us, and these changes will become increasingly evident with each passing decade. Climate change is already leading to more intense rainfall events and other extreme weather patterns. It will lead to more droughts in some areas, more floods in others, and more frequent heat waves in many areas. Changing temperature and precipitation patterns, as well as increasing sea level, are important factors affecting various parts of the United States. For example, the risks associated with wildfires in the western U.S. are increasing, and coastal inundation is becoming a common occurrence in low-lying areas. Water supply availability is changing in many parts of the United States.

Many people are already being affected by the changes that are occurring, and more will be affected as these changes continue to unfold. To limit risks and maximize opportunities associated with the changes, it would be helpful for people to understand how climate change could affect them and what they can do to adapt, as well as what can be done to reduce future climate change by reducing global emissions.

Taking actions to reduce the emissions that cause climate change has costs. Not taking those actions has much greater costs.[18]

Climate change will affect ecosystems and human systems – such as agricultural, transportation, water resources, and health-related infrastructure – in ways we are only beginning to understand. Moreover, climate change interacts with other stressors, such as population increase, land-use change, and economic and political changes, in ways that we may not be able to anticipate, compounding the risks.

In general, the larger and faster the changes in climate, the more difficult it is for human and natural systems to adapt. The climate system has been relatively stable during the time that human civilizations have existed. Essentially, today's built infrastructure has been developed based on the assumption that future climate will be like that of the past. This assumption is no longer valid.

Since climate change is already occurring, adaptation in some form is inevitable. The choice is between proactive adaptation (planning ahead to limit impacts) or reactive adaptation (where responses occur only after damages are already incurred). The *America's Climate Choices* reports from the U.S. National Academy of Sciences discuss these issues in details.

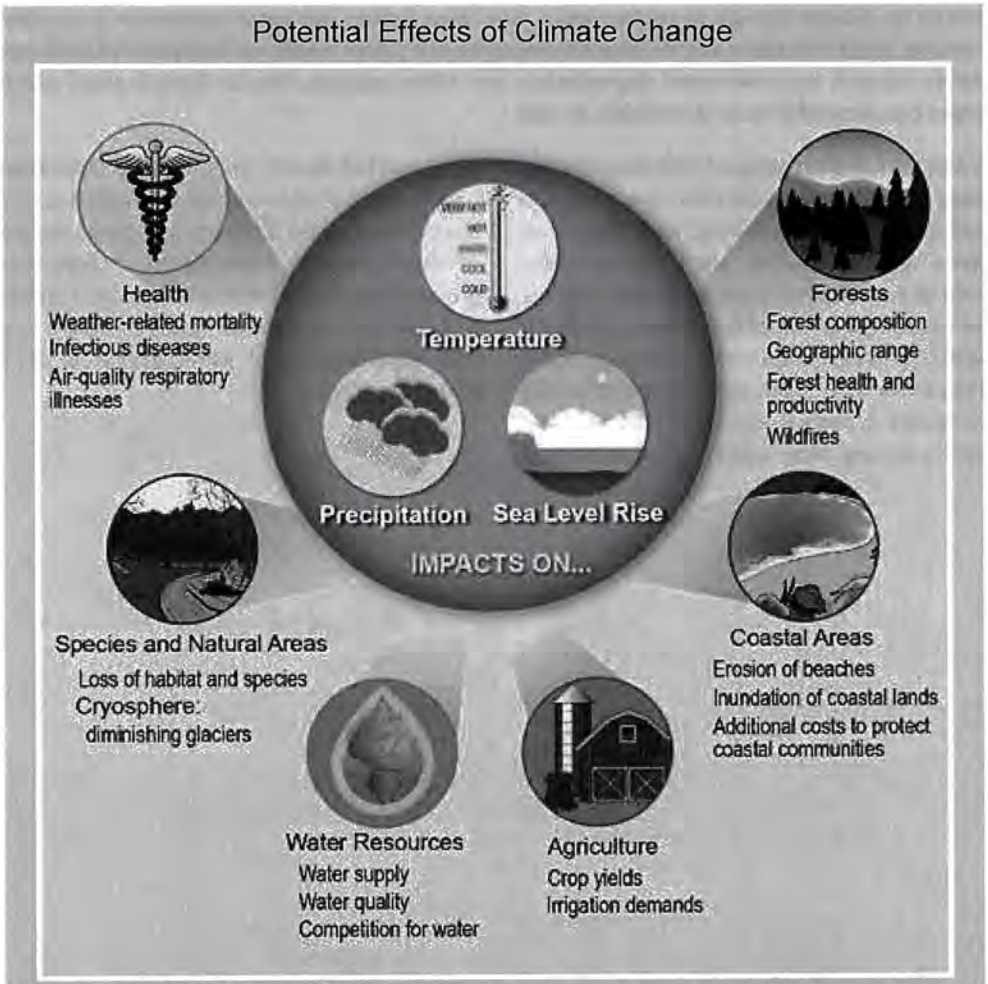


Figure 25. Climate change is likely to affect human society and the natural environment in many ways. The National Climate Assessment's sectoral impacts chapters examine these impacts by category in detail. (Figure source: adapted from Phillipe Rekacewicz UNEP/GRID-Arendal 2012, "Vital Climate Graphics" collection[19]).

V. Are there benefits to warming?

Some climate changes currently have beneficial effects for specific sectors or regions. For example, current benefits of warming include longer growing seasons for agriculture and longer ice-free periods for shipping on the Great Lakes. At the same time, however, longer growing seasons, along with higher temperatures and carbon dioxide, can increase pollen production, intensifying and lengthening the allergy season. Longer ice-free periods on the Great Lakes can result in more lake-effect snowfalls.

Many analyses of this question have concluded that there will be more negative effects than positive ones. This is largely because our society and infrastructure have been built for the climate of the past, and any rapid change from that climate imposes difficulties and costs. For example, many major cities are located on the coasts where they are now vulnerable to sea level rise. And there has been rapid population growth in the U.S. Southwest, where increasing heat and drought threaten water supplies and cause increased wildfires. In addition, ecosystems that we rely on for our food and water are adapted to the cooler climate that our planet has experienced over recent centuries.

W. Are some people more vulnerable than others?

People will be affected by climate change in various ways, but some groups are more vulnerable than others. For example, the poor, the very young, and some older people have less mobility and fewer resources to cope with extremely high temperatures, increased water scarcity, environmental degradation, and other impacts. People living in flood plains, coastal zones, and some urban areas are generally more vulnerable as well.

Children, primarily because of physiological and developmental factors, will disproportionately suffer from the effects of heat waves, air pollution, infectious illness, and trauma resulting from extreme weather events. The country's older population also could be harmed more as the climate changes. Older people are at much higher risk of dying during extreme heat events. Pre-existing health conditions also make older adults susceptible to cardiac and respiratory impacts of air pollution and to more severe consequences from infectious diseases. Limited mobility among older adults can also increase flood-related health risks. Limited resources and an already high burden of chronic health conditions, including heart disease, obesity, and diabetes, will place the poor at higher risk of health impacts from climate change than higher income groups. Potential increases in food cost and limited availability of some foods will exacerbate current dietary inequalities and have significant health ramifications for the poorer segments of our population.

X. Are there ways to reduce climate change?

The most direct way to significantly reduce the magnitude of future climate change is to reduce the emissions of heat-trapping gases. Emissions can be reduced in many ways, and increasing the efficiency of energy use is an important component of many potential strategies. For example, because about 28% of the energy used in the U.S. is used for transportation, developing and driving more efficient vehicles and changing to fuels that do not contribute significantly to heat-trapping gas emissions over their lifetimes would result in fewer emissions per mile driven. A large amount of energy in the U.S. is also used to heat and cool buildings, so changes in building design could dramatically reduce energy use. While there is no single silver bullet that will solve all the challenges posed by climate change, there are many options that can reduce our emissions and help prevent some of the potentially serious impacts of climate change. There will be some costs to these changes, but even very ambitious emissions reductions targets have relatively small costs over the decades it will take to implement them.

Because impacts are already occurring and anticipated to increase, adaptation to the impacts of climate change will be required. Adaptation decisions range from being better prepared for extreme events such as floods and droughts, to identifying economic opportunities that come from investments in adaptation and mitigation strategies and technologies, to integrating considerations of new climate-related risks into city planning, public health and emergency preparedness, and ecosystem management.

Technological fixes such as "geoengineering" may be possible, but at least some such proposals would do nothing to slow ocean acidification, and would need to be done indefinitely. There are a wide variety of potential risks of geoengineering schemes, which are very poorly understood (see FAQ Z).

Multiple Pathways for Reducing U.S. Emissions

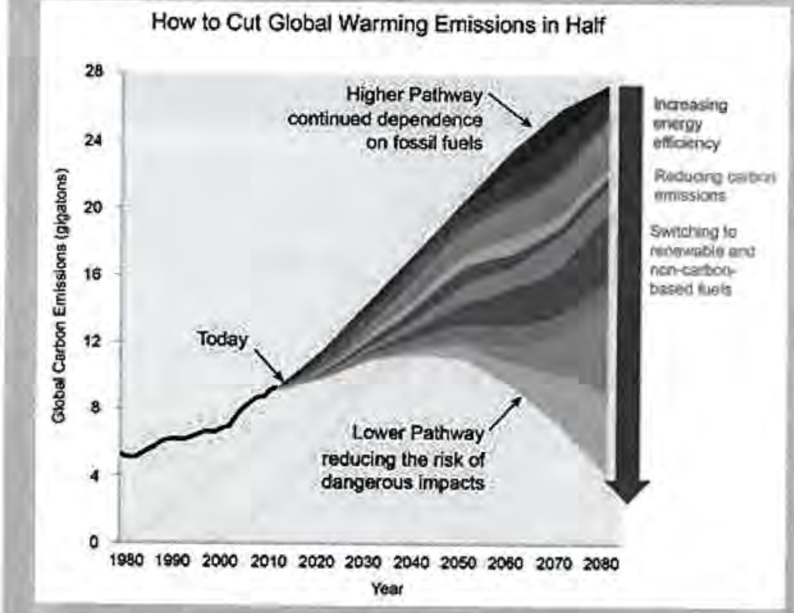


Figure 26. Reducing carbon emissions from a higher pathway (here, RCP 8.5) to a lower pathway (here, RCP 4.5) can be accomplished with a combination of many technologies and policies, illustrated here based on the "wedges" concept pioneered by Pacala and Socolow in 2004.[20] These wedges could include increasing the energy efficiency of appliances, vehicles, buildings, electronics, and electricity generation (orange wedges); reducing carbon emissions from fossil fuels by switching to lower-carbon fuels or capturing and storing carbon (blue wedges); and switching to renewable and non-carbon emitting sources of energy, including solar, wind, wave, biomass, tidal, and geothermal (green wedges). The shapes and sizes of the wedges shown here are illustrative only. (Data from Boden et al. 2012[21]).

Y. Are there advantages to acting sooner rather than later?

The effects of current emissions of carbon dioxide and other heat-trapping gases on climate can take decades to fully manifest themselves. The resulting change in climate and the impacts of those changes can then persist for a long time. The longer these changes in climate continue, the greater the resulting impacts. It will become increasingly costly to adapt, and some systems will not be able to adapt if the change is too much or too fast. Thus it is not surprising that recent reports from the U.S. National Academy of Sciences, including America's Climate Choices[22] and America's Energy Future,[23] have concluded that the environmental, economic, and humanitarian risks posed by climate change indicate a pressing need for substantial action to limit the magnitude of climate change and to prepare to adapt to its impacts. They also concluded that substantial reductions of heat-trapping gas emissions should be among the nation's highest priorities.

The National Academy of Sciences and others have concluded that acting now will reduce the risks posed by climate change and the pressure to make larger, more rapid, and potentially more expensive reductions later. Actions taken to reduce vulnerability to climate change impacts can be considered as investments that can make sense economically, especially if they also offer protection against natural climate variations and extreme events. In addition, investment decisions made now about equipment and infrastructure can "lock in" emissions of heat-trapping gases for decades to come. Finally, while it may be possible to alter our responses to climate change, it is difficult or impossible to "undo" climate change once it has occurred.

Current efforts at local and state levels, and by the private sector, are important, but are insufficient to limit warming to the lower scenarios described throughout this report. Thus, numerous analyses have called for policies that establish coherent national and international goals and incentives, and that promote strong U.S. engagement in international-level response efforts. The National Academy of Sciences found that the inherent complexities and uncertainties of climate change will be best met by applying a risk management approach and by making efforts to significantly reduce heat-trapping gas emissions; prepare for adapting to impacts; invest in scientific research, technology development, and information systems; and facilitate engagement between scientific and technical experts and the many types of people making America's climate choices.

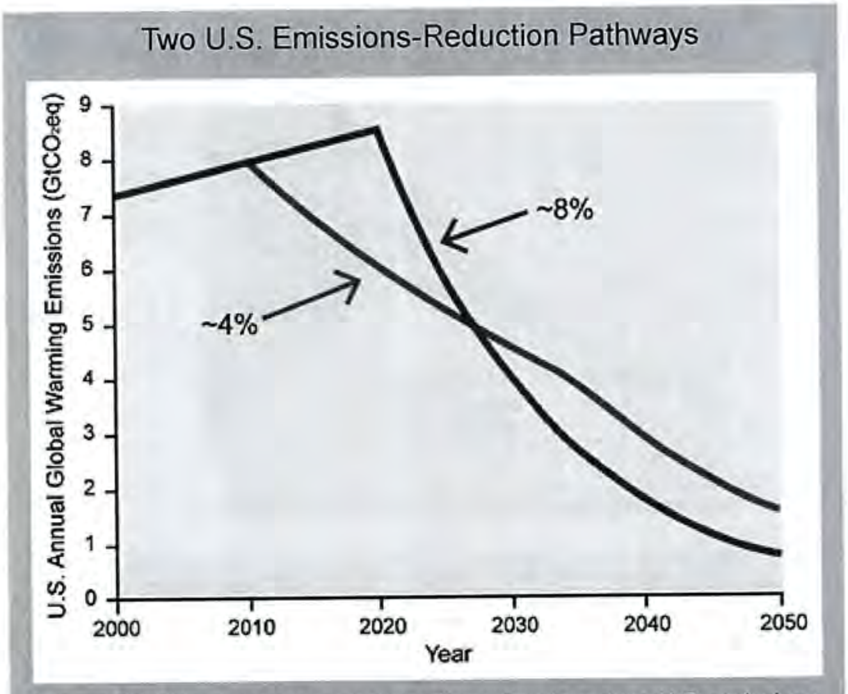


Figure 27. This graph shows how earlier action to reduce U.S. emissions would be less difficult than delayed action. Two pathways show how a cumulative carbon emissions budget of 265 gigatons of CO_2 could be maintained by 2050. By initiating reduced emissions efforts in 2010 (blue line), a 4% per year reduction would have been required; waiting until 2020 to reduce emissions (red line) doubles the rate at which emissions must be reduced. (Figure source: Luers et al. 2007[24])

Z. Can we reverse global warming?

While we can't stop climate change in its tracks, we can limit it to less dangerous levels by reducing our emissions. Even if all human-related emissions of carbon dioxide and the other heat-trapping gases were to stop today, Earth's temperature would continue to rise for a number of decades and then slowly begin to decline. However, focusing on short-lived types of emissions, such as methane and black carbon (soot), can reduce the rate of change in the near term. Because of the complex processes controlling carbon dioxide concentrations in the atmosphere, even after more than a thousand years, the global temperature would still be higher than it was in the pre-industrial period. As a result, without technological intervention, it will not be possible to totally reverse climate change. We do face a choice between a little more warming and lot more warming, however. The amount of future warming will depend on our future emissions.

In theory, it may be possible to reverse global warming through technological interventions called geoengineering. Three types of geoengineering approaches have been proposed to alter the climate system: 1) enhancing the natural processes that remove carbon dioxide from the atmosphere; 2) altering the amount of the sun's energy that reaches the Earth (referred to

Emissions Reductions and Carbon Dioxide Concentrations

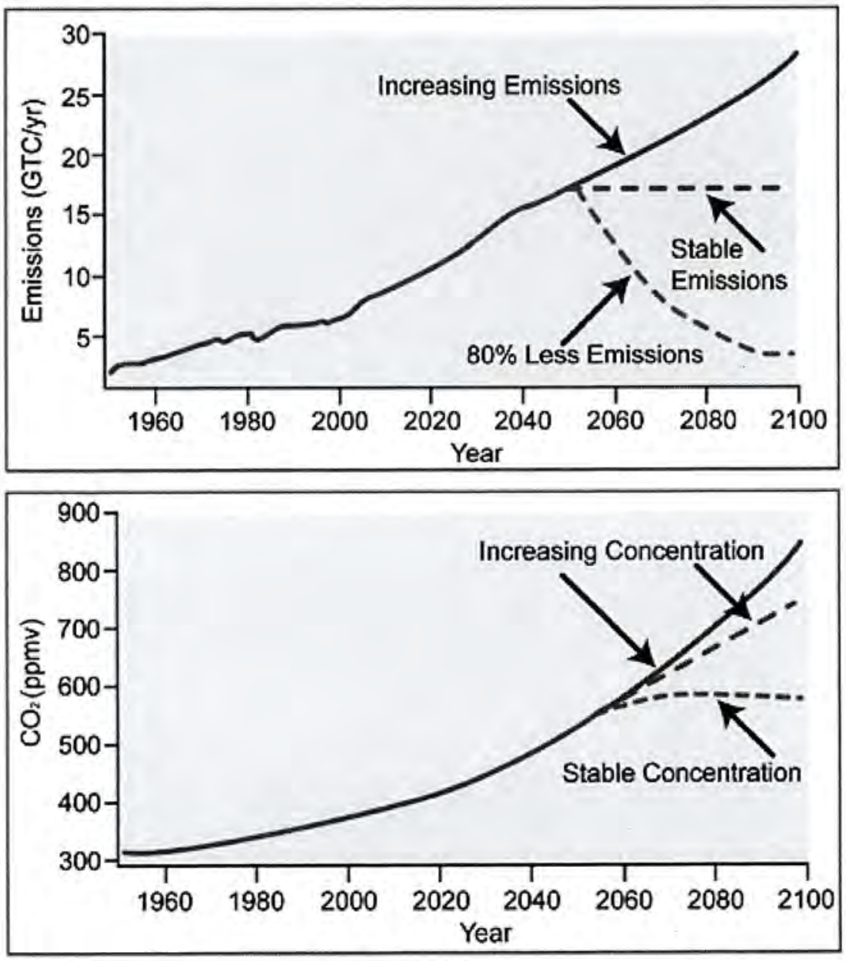


Figure 28. To reduce the changes occurring in climate, we would need to stabilize atmospheric levels of carbon dioxide, not simply stabilize current emission levels of carbon dioxide. Just stabilizing emissions still leads to increasing amounts of carbon dioxide in the atmosphere, because emissions are greater than the sinks that remove it (blue lines). To stabilize levels of atmospheric carbon dioxide, emissions would need to be reduced significantly, on the order of 80% or more compared to the present day (green lines). The lower graph shows how carbon dioxide concentrations would be expected to evolve depending upon emissions for one illustrative case, but this applies for any chosen target. (Figure source: NRC 2011[25]).

as "solar radiation management"); and 3) direct capture and storage of CO_2 from the atmosphere.

Various techniques for removal of carbon dioxide from the atmosphere have been proposed. At this time, however, there is no indication that any of them could be implemented on a large enough scale to have a significant effect. Investments in limiting emissions, combined with capturing and storing carbon, could possibly reverse the warming trend, but it remains to be seen if this is feasible.

Artificial injection of stratospheric particles and cloud brightening are two examples of "solar radiation management" techniques. The cooling effect that some types of particles have on the atmosphere has led to the proposal of an array of possible geoengineering projects, especially with the goal of offsetting the warming until more non-fossil fuel energy is put into place. However, the climate system is complex and experimenting without complete understanding could result in unintended and potentially dangerous side effects on our health, ecosystems, agricultural yields, and even the climate itself. Even if such engineering approaches were economically feasible, the potential impacts on the environment need to be better understood. One important consideration regarding solar radiation management is that ocean acidification would still continue even if warming could otherwise be reduced by reflecting light away from our atmosphere. Much more research is needed to see if such approaches could be environmentally feasible. In the meantime, there are significant concerns about ecological and other side effects of some of these technologies.

APPENDIX 4: FREQUENTLY ASKED QUESTIONS

REFERENCES

1. Kunkel, K. E., L. E. Stevens, S. E. Stevens, L. Sun, E. Janssen, D. Wuebbles, and J. G. Dobson, 2013: Regional Climate Trends and Scenarios for the U.S. National Climate Assessment: Part 9. Climate of the Contiguous United States. NOAA Technical Report NESDIS 142-9. 85 pp., National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, Washington, D.C. [Available online at http://www.nesdis.noaa.gov/technical_reports/NOAA_NESDIS_Tech_Report_142-9-Climate_of_the_Contiguous_United_States.pdf]

2. Kennedy, J. J., P. W. Thorne, T. C. Peterson, R. A. Reudy, P. A. Stott, D. E. Parker, S. A. Good, H. A. Titchner, and K. M. Willett, 2010: How do we know the world has warmed? [in "State of the Climate in 2009"]. *Bulletin of the American Meteorological Society*, **91,** S26-27, doi:10.1175/BAMS-91-7-StateoftheClimate. [Available online at http://journals.ametsoc.org/doi/abs/10.1175/BAMS-91-7-StateoftheClimate]

3. Boden, T., G. Marland, and B. Andres, 2012: *Global CO_2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2009.* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. [Available online at http://cdiac.ornl.gov/ftp/ndp030/global.1751_2009.ems]

4. Mann, M. E., Z. Zhang, M. K. Hughes, R. S. Bradley, S. K. Miller, S. Rutherford, and F. Ni, 2008: Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia. *Proceedings of the National Academy of Sciences*, **105,** 13252-13257, doi:10.1073/pnas.0805721105. [Available online at http://www.jstor.org/stable/pdfplus/25464030.pdf]

5. Pan, Z., R. W. Arritt, E. S. Takle, W. J. Gutowski, Jr., C. J. Anderson, and M. Segal, 2004: Altered hydrologic feedback in a warming climate introduces a "warming hole". *Geophysical Research Letters*, **31,** L17109, doi:10.1029/2004GL020528. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2004GL020528/pdf]

6. Portmann, R. W., S. Solomon, and G. C. Hegerl, 2009: Spatial and seasonal patterns in climate change, temperatures, and precipitation across the United States. *Proceedings of the National Academy of Sciences*, **106,** 7324-7329, doi:10.1073/pnas.0808533106. [Available online at http://www.pnas.org/content/106/18/7324.full.pdf+html]

7. Puma, M. J., and B. I. Cook, 2010: Effects of irrigation on global climate during the 20th century. *Journal Of Geophysical Research*, **115,** D16120, doi:10.1029/2010JD014122. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2010JD014122/pdf]

8. Kunkel, K. E., X.-Z. Liang, J. Zhu, and Y. Lin, 2006: Can CGCMS simulate the twentieth-century "warming hole" in the central United States? *Journal of Climate*, **19,** 4137-4153, doi:10.1175/JCLI3848.1. [Available online at http://journals.ametsoc.org/doi/pdf/10.1175/JCLI3848.1]

9. Robinson, W. A., R. Reudy, and J. E. Hansen, 2002: General circulation model simulations of recent cooling in the east-central United States. *Journal Of Geophysical Research*, **107,** ACL 4-1 - ACL 4-14, doi:10.1029/2001JD001577. [Available online at http://onlinelibrary.wiley.com/doi/10.1029/2001JD001577/pdf]

10. NPS, cited 2012: What is Climate Change? U.S. Department of the Interior, National Park Service. [Available online at http://www.nps.gov/goga/naturescience/climate-change-causes.htm]

11. Jones, G. S., P. A. Stott, and N. Christidis, 2013: Attribution of observed historical near surface temperature variations to anthropogenic and natural causes using CMIP5 simulations. *Journal of Geophysical Research*, **118,** 4001-4024, doi:10.1002/jgrd.50239. [Available online at http://onlinelibrary.wiley.com/doi/10.1002/jgrd.50239/pdf]

12. Huber, M., and R. Knutti, 2012: Anthropogenic and natural warming inferred from changes in Earth's energy balance. *Nature Geoscience*, **5,** 31-36, doi:10.1038/ngeo1327. [Available online at http://www.nature.com/ngeo/journal/v5/n1/pdf/ngeo1327.pdf]

13. Wouters, B., J. L. Bamber, M. R. van den Broeke, J. T. M. Lenaerts, and I. Sasgen, 2013: Limits in detecting acceleration of ice sheet mass loss due to climate variability. *Nature Geoscience*, **6,** 613-616, doi:10.1038/ngeo1874.

14. Peterson, T. C., D. M. Anderson, S. J. Cohen, M. Cortez-Vázquez, R. J. Murnane, C. Parmesan, D. Phillips, R. S. Pulwarty, and J. M. R. Stone, 2008: Ch. 1: Why weather and climate extremes matter. *Weather and Climate Extremes in a Changing Climate. Regions of Focus: North America, Hawaii, Caribbean, and U.S. Pacific Islands. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*, T. R. Karl, G. A. Meehl, C. D. Miller, S. J. Hassol, A. M. Waple, and W. L. Murray, Eds., Department of Commerce, NOAA's National Climatic Data Center, 11-34. [Available online at http://library.globalchange.gov/downloads/download.php?id=22]

15. Marshall, P., and H. Schuttenberg, 2006: *A Reef Manager's Guide to Coral Bleaching*. Great Barrier Reef Marine Park Authority, IUCN Global Marine Programme, and U.S. National Oceanic and Atmospheric Administration, 163 pp. [Available online at http://data.iucn.org/dbtw-wpd/edocs/2006-043.pdf]

16. Bednaršek, N., G. A. Tarling, D. C. E. Bakker, S. Fielding, E. M. Jones, H. J. Venables, P. Ward, A. Kuzirian, B. Lézé, R. A. Feely, and E. J. Murphy, 2012: Extensive dissolution of live pteropods in the Southern Ocean. *Nature Geoscience*, **5,** 881-885, doi:10.1038/ngeo1635.

17. Lenton, T. M., H. Held, E. Kriegler, J. W. Hall, W. Lucht, S. Rahmstorf, and H. J. Schellnhuber, 2008: Tipping elements in the Earth's climate system. *Proceedings of the National Academy of Sciences*, **105,** 1786-1793, doi:10.1073/pnas.0705414105. [Available online at http://www.pnas.org/content/105/6/1786.full.pdf+html]

18. Nordhaus, W., 2013: *The Climate Casino: Risk. Uncertainty. and Economics for a Warming World*. Yale University Press, 392 pp.

19. UNEP/GRID-Arendal, cited 2012: Potential climate change impacts GRID-Arendal and United Nations Environment Programme. [Available online at http://www.grida.no/publications/vg/climate/page/3073.aspx]

20. Pacala, S., and R. Socolow, 2004: Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science*, **305,** 968-972, doi:10.1126/science.1100103.

21. Boden, T., G. Marland, and B. Andres, 2012: *Global CO_2 Emissions from Fossil-Fuel Burning. Cement Manufacture. and Gas Flaring: 1751-2009*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. [Available online at http://cdiac.ornl.gov/ftp/ndp030/global.1751_2009.ems]

22. NRC, 2011: *America's Climate Choices*. National Research Council. The National Academies Press, 144 pp. [Available online at http://www.nap.edu/catalog.php?record_id=12781]

23. ——, 2010: *Overview and Summary of America's Energy Future: Technology and Transformation* National Research Council. The National Academies Press, 58 pp. [Available online at http://www.nap.edu/catalog.php?record_id=12943]

24. Luers, A. L., M. D. Mastrandrea, K. Hayhoe, and P. C. Frumhoff 2007: How to Avoid Dangerous Climate Change: A Target for U.S. Emissions Reductions, 34 pp., Union of Concerned Scientists, Cambridge, MA. [Available online at http://www.ucsusa.org/assets/documents/global_warming/emissions-target-report.pdf]

25. NRC, 2011: *Climate Stabilization Targets: Emissions. Concentrations. and Impacts over Decades to Millennia*. National Research Council. The National Academies Press, 298 pp. [Available online at http://www.nap.edu/catalog.php?record_id=12877]