2

Climate Science

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Key Findings

Key findings of this chapter include the following:

Methodology

- The Scientific Method is a series of requirements imposed on scientists to ensure the integrity of their work. The IPCC has not followed established rules that guide scientific research.

- Appealing to consensus may have a place in science, but should never be used as a means of shutting down debate.

- Uncertainty in science is unavoidable but must be acknowledged. Many declaratory and predictive statements about the global climate are not warranted by science.

Observations

- Surface air temperature is governed by energy flow from the Sun to Earth and from Earth back into space. Whatever diminishes or intensifies this energy flow can change air temperature.

- Levels of carbon dioxide (CO_2) and methane (CH_4) in the atmosphere are governed by processes of the carbon cycle. Exchange rates and other climatological processes are poorly understood.

- The geological record shows temperatures and CO_2 levels in the atmosphere have not been stable, making untenable the IPCC's assumption that they would be stable in the absence of human emissions.

- Water vapor is the dominant greenhouse gas owing to its abundance in the atmosphere and the wide range of spectra in which it absorbs radiation. CO_2 absorbs energy only in a very narrow range of the longwave infrared spectrum.

Controversies

- Reconstructions of average global surface temperature differ depending on the methodology used. The warming of the twentieth and early twenty-first centuries has not been shown to be beyond the bounds of natural variability.

- General circulation models (GCMs) are unable to accurately depict complex climate processes. They do not accurately hindcast or forecast the climate effects of anthropogenic greenhouse gas emissions.

- Estimates of equilibrium climate sensitivity (the amount of warming that would occur following a doubling of atmospheric CO_2 level) range widely. The IPCC's estimate is higher than many recent estimates.

- Solar irradiance, magnetic fields, UV fluxes, cosmic rays, and other solar activity may have greater influence on climate than climate models and the IPCC currently assume.

Climate Impacts

- There is little evidence that the warming of the twentieth and early twenty-first centuries has caused a general increase in severe weather events. Meteorological science suggests a warmer world would see milder weather patterns.

- The link between warming and drought is weak, and by some measures drought decreased over the twentieth century. Changes in the hydrosphere of this type are regionally highly variable and show a closer correlation with multidecadal climate rhythmicity than they do with global temperature.

- The Antarctic ice sheet is likely to be unchanged or is gaining ice mass. Antarctic sea ice is gaining in extent, not retreating. Recent trends in the Greenland ice sheet mass and Artic sea ice are not outside natural variability.

- Long-running coastal tide gauges show the rate of sea-level rise is not accelerating. Local and regional sea levels exhibit typical natural variability.

- The effects of elevated CO_2 on plant characteristics are net positive, including increasing rates of photosynthesis and biomass production.

Why Scientists Disagree

- Fundamental uncertainties and disagreements prevent science from determining whether human greenhouse gas emissions are having effects on Earth's atmosphere that could endanger life on the planet.

- Climate is an interdisciplinary subject requiring insights from many fields of study. Very few scholars have mastery of more than one or two of these disciplines.

- Many scientists trust the Intergovernmental Panel on Climate Change (IPCC) to objectively report the latest scientific findings on climate change, but it has failed to produce balanced reports and has allowed its findings to be misrepresented to the public.

- Climate scientists, like all humans, can have tunnel vision. Bias, even or especially if subconscious, can be especially pernicious when data are equivocal and allow multiple interpretations, as in climatology.

Appeals to Consensus

- Surveys and abstract-counting exercises that are said to show a "scientific consensus" on the causes and consequences of climate change invariably ask the wrong questions or the wrong people. No survey data exist that support claims of consensus on important scientific questions.

- Some survey data, petitions, and peer-reviewed research show deep disagreement among scientists on issues that must be resolved before the man-made global warming hypothesis can be accepted.

- Some 31,000 scientists have signed a petition saying "there is no convincing scientific evidence that human release of carbon dioxide, methane, or other greenhouse gases is causing or will, in the foreseeable future, cause catastrophic heating of the Earth's atmosphere and disruption of the Earth's climate."

- Because scientists disagree, policymakers must exercise special care in choosing where they turn for advice.

Introduction

A central issue in climate science today is whether human emissions of carbon dioxide, methane, and other "greenhouse gases" are having effects on Earth's atmosphere that could endanger life on the planet. As the size of recent reports by the Intergovernmental Panel on Climate Change (IPCC, 2013, 2014a, 2014b) and the Nongovernmental International Panel on Climate Change (NIPCC, 2009, 2011, 2013, 2014) suggest, climate science is a complex and highly technical subject. Simplistic claims about the relationship between human activity and climate change are misleading.

This chapter focuses on physical and biological sciences. It does not address the impacts of climate change (or fossil fuels) on human prosperity, health, or security or conduct a cost-benefit analysis of climate change or fossil fuels. Those topics are addressed in subsequent chapters. Sometimes science presentations also appear in other chapters, including "tutorials" on air quality (Chapter 6), energy matters (Chapter 7), and integrated assessment models (Chapter 8), but most of the pure science in this book appears in this chapter.

Section 2.1 offers a tutorial describing some of the methodological issues and observational data involved in efforts to understand the causes and consequences of climate change. Section 2.2 describes controversies over four important topics in climate science: temperature records, general circulation models (GCMs), climate sensitivity, and solar influences on climate. Each of these topics is important for discerning and measuring the human impact on the climate.

Section 2.3 examines observational evidence concerning four climate impacts: severe weather events, melting ice, sea-level rise, and effects on plants. Section 2.4 reviews four reasons why scientists disagree: basic scientific uncertainties, the subject's interdisciplinary nature, the failure of the IPCC to win the confidence of many scientists, and tunnel vision (or bias). Section 2.5 looks at claims that a scientific consensus exists on some or all of these issues. A brief summary and conclusion appear in Section 2.6.

Two previous volumes in the *Climate Change Reconsidered* series produced by NIPCC subtitled *Physical Science* (2013) and *Biological Impacts* (2014) contain exhaustive reviews of the scientific literature conducted by lead authors Craig D. Idso, Sherwood Idso, Robert M. Carter, and S. Fred Singer and an international team of some 100 scientists. Combined, they offer more than 2,000 pages of summaries and abstracts of scientific research, nearly all of it appearing in peer-reviewed science journals. Readers seeking a more in-depth treatment of the topics addressed in this chapter are encouraged to read those volumes.

Two reports written in 2018 by teams of scientists led by Jay Lehr were valuable in providing updated references to the scientific literature (Lehr *et al.*, 2018a, 2018b). Sections 2.4 and 2.5 rely on parts of a book titled *Why Scientists Disagree about Global Warming* published by NIPCC in 2015 and revised in 2016 (NIPCC, 2016). Section 2.3.3, on sea-level rise, draws in part from a previous NIPCC special report titled *Data versus Hype: How Ten Cities Show Sea-level Rise Is a False Crisis* (Hedke, 2017).

This chapter provides a comprehensive and balanced account of the latest science on climate change. While acknowledging the extraordinary scientific accomplishment represented by the IPCC's assessment reports, the authors do not hesitate to identify possible errors and omissions. To the extent that this chapter critiques the IPCC's reports, it does so in the spirit of healthy scientific debate and respect.

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2.1 A ScienceTutorial

Climate science is confusing and often confused because people claiming to be "climate scientists" are usually specialists in one or a few areas -- including physics, mathematics, computer modeling, and oceanography – who study just one part of the complex climate puzzle. Researchers define concepts and measure values differently and interpret the results through different prisms based on their academic discipline and training. The discipline of climatology is quite new and consequently disagreements start early and new discoveries continuously challenge prevailing wisdom.

For example, recent and current global temperatures are disputed (Christy and McNider, 2017) and some physicists doubt whether the concept of a single global temperature should be used in climate research (Essex *et al.*, 2007). The processes by which carbon dioxide (CO_2) enters the atmosphere and is exchanged with other reservoirs are poorly understood (Falkowski *et al.*, 2000). The role of water vapor and clouds (Chou and Lindzen, 2004; Spencer *et al.*, 2007), ocean currents (D'Aleo and Easterbrook, 2016), solar influences (Ziskin and Shaviv, 2012; Harde, 2017), and CO_2 (Lewis and Curry, 2014; Bates, 2016) in regulating global temperature are all areas of controversy and uncertainty. These are hardly peripheral or unimportant issues.

All this disagreement and uncertainty makes explaining even the basic principles of climate science difficult. Declarative statements usually need to be followed by exceptions, cautions, or alternative interpretations. With these caveats in mind, this "tutorial" presents seven key topics in climate science as shown in Figure 2.1. Later sections of this chapter and later chapters in this book revisit the topics addressed only briefly in this section.

Figure 2.1
Topics in the tutorial

2.1.1 Methodology

2.1.1.1 Scientific Method
2.1.1.2 Consensus
2.1.1.3 Uncertainty

2.1.2 Observations

2.1.2.1 Energy Budget
2.1.2.2 Carbon Cycle
2.1.2.3 Geological Record
2.1.2.4 Greenhouse Gases

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2.1.1 Methodology

Science is a search for causal explanations of natural events. It is a search for *why* things are the way they are and act the way they do. In Chapter 1, the economic way of thinking was characterized as asking "and then what?" The question leads to careful study of incentives and unintended consequences. In the chapter following this one, engineers are characterized as always asking "how much?" They are keen on measuring energy inputs, power, and efficiency. Scientists, as this section will demonstrate, ask "how do we know?" Skepticism is at the heart of science.

The growth of scientific knowledge proceeds through a process called the *Scientific Method*. It is different from the process called *consensus*, which may have a role in science but is mainly used in politics to determine public policies. The two methods often come into conflict in discussions of climate change. *Uncertainty,* a third concept involving methodology, is unavoidable in science. How to reduce uncertainty and communicate it to the public and policymakers are major sources of disagreement in the climate science community. All three concepts are addressed in this section.

2.1.1.1 Scientific Method

> *The Scientific Method is a series of requirements imposed on scientists to ensure the integrity of their work. The IPCC has not followed established rules that guide scientific research.*

To find reliable answers, scientists use the Scientific Method. Armstrong and Green (2018a) surveyed the literature, citing Hubbard (2016), Munafo *et al.* (2017), and other previously published reviews, to identify practices that have been consistently endorsed by scientists and learned societies. They found general acceptance that the Scientific Method requires scientists to …

1. study important problems,
2. build on prior scientific knowledge,
3. use objective methods,
4. use valid and reliable data,
5. use valid, reliable, and simple methods,
6. use experiments,
7. deduce conclusions logically from prior knowledge and new findings, and
8. disclose all information needed to evaluate the research and to conduct replications.

Armstrong and Green then developed 24 "guidelines for scientists," which appear in Figure 2.1.1.1.1, to ensure compliance with the eight criteria of the Scientific Method. Failure to comply with the Scientific Method often results in what Armstrong and Green call "advocacy research," which they say is characterized by 10 instruments:

1. ignore cumulative scientific knowledge,
2. test a preferred hypothesis against an implausible null hypothesis,
3. show only evidence favoring the preferred hypothesis,
4. do not specify the conditions associated with the hypothesis,
5. ignore important causal variables,
6. use non-experimental data,
7. use data models,
8. use faulty logic,
9. avoid tests of *ex ante* predictive validity, and
10. use *ad hominem* arguments (attack authors and not their reasoning).

Figure 2.1.1.1.1
Armstrong and Green's guidelines for scientists

Selecting a Problem

1. Seek an important problem.
2. Be skeptical about findings, theories, policies, methods, and data, especially absent experimental evidence.
3. Consider replications and extensions of papers with useful scientific findings.
4. Ensure that you can address the problem impartially.
5. If you need funding, ensure that you will nevertheless have control over all aspects of your study.

Designing a Study

6. Acquire existing knowledge about the problem.
7. Develop multiple reasonable hypotheses with specified conditions.
8. Design experiments with specified conditions that can test the predictive validity of hypotheses.

Collecting Data

9. Obtain all valid data.
10. Ensure that the data are reliable.

Analyzing Data

11. Use methods that incorporate cumulative knowledge.
12. Use multiple validated methods.
13. Use simple methods.
14. Estimate effect sizes and prediction intervals.
15. Draw logical conclusions on the practical implications of findings from tests of multiple reasonable hypotheses.

Writing a Scientific Paper

16. Disclose research hypotheses, methods, and data.
17. Cite all relevant scientific papers when presenting evidence.
18. Ensure that summaries of cited prior findings are necessary, explained, and correct.
19. Explain why your findings are useful.
20. Write clearly and succinctly for the widest audience for whom the findings might be useful.
21. Obtain extensive peer review and editing *before* submitting a paper for publication.

Disseminating Findings

22. Provide responses to journal reviewers, including reasons for ignoring their suggestions, and if rejected, appeal to editors if you have useful scientific findings.
23. Consider alternative ways to publish your findings.
24. Inform those who can use your findings.

Source: Armstrong and Green, 2018a, Exhibit 2, pp. 18–19.

Role of Experimentation

Scientific theories differ from observations by being suppositions about what is not observable directly. Only some of their consequences – logical or causal – can be observed. According to Popper (1965), a theory is scientific only if it can be falsified by observational data or experimentation, if not currently then in principle at some future date when the data or tools for further investigation become available. A famous example is how one of the predictions of Albert Einstein's general theory of relativity, first proposed in 1915, was tested and shown to be correct in 1919 by observations gathered during a total solar eclipse (O'Neill, 2017). Popper justified his stance by arguing that humans are fallible – we lack omniscience and so cannot comprehend a theory that might explain everything – and because future observations or experiments could disprove any current theory. Therefore, the best we can do is try to falsify the hypothesis, and by surviving such tests a hypothesis demonstrates it may be close to the truth. Einstein agreed, writing in 1919,

> A theory can thus be recognized as erroneous if there is a logical error in its deductions, or as inadequate if a fact is not in agreement with its consequences. But the truth of a theory can never be proven. For one never knows that even in the future no experience will be encountered which contradicts its consequences; and still other systems of thought are always conceivable which are capable of joining together the same given facts.

This suggests observations in science are useful primarily to falsify hypotheses and cannot prove one is correct. Objecting to Popper's and Einstein's critique of inductive reasoning, Jaynes (2003) writes, "It is not the absolute status of an hypothesis embedded in the universe of all conceivable theories, but the plausibility of an hypothesis relative to a definite set of specified alternatives, that Bayesian inference determines" (p. 310). In other words, the test of a hypothesis is not the impossible standard of omniscience, but rather how well it performs relative to other hypotheses. Bayesian inference is a way of improving the probability that a theory is correct by using Bayes' theorem. Bayes' theorem reads:

$$\boldsymbol{P(A \backslash B) = \frac{P(B \backslash A)\, P(A)}{P(B)}}$$

where A and B are events and $P(B) \neq 0$.

$P(A\backslash B)$ is the likelihood of event A occurring given that B is true.

$P(B\backslash A)$ is the likelihood of event B occurring given that A is true.

$P(A)$ and $P(B)$ are the probabilities of observing A and B independently of each other; this is known as the marginal probability.

Null Hypothesis

Bayes' theorem demonstrates the importance of alternative or "null" hypotheses. A null hypothesis is negative only in the sense that unless it is rebutted, the original hypothesis remains unproven. Failing to disprove the null hypothesis does not mean it is true, only that it survives as a possible alternative explanation. Null hypotheses also need to make specific predictions and be falsifiable. As Jaynes (2003) writes, "we have not asked any definite, well-posed question until we specify the possible alternatives to H0 [null hypothesis]. Then … probability theory can tell us how our hypothesis fares relative to the alternatives that we have specified" (p. 136). Jaynes goes on to write, "This means that if any significance test is to be acceptable to a scientist, we shall need to examine its rationale to see whether it has … some implied if unstated alternative hypotheses. Only when such hypotheses are identified are we in a position to say what the test accomplishes; i.e. what it is testing" (p. 137).

It is relatively easy to assemble reams of "evidence" in favor of a point of view or opinion while ignoring inconvenient facts that would contradict it, a phenomenon called "confirmation bias" and a practice sometimes called "data dredging." The best way to avoid confirmation bias is to entertain alternative hypotheses. Armstrong and Green (2018a) write, "We use the term advocacy to refer to studies that are designed to 'prove' a given hypothesis, as distinct from arguing in favor of an idea. Advocacy studies can be identified operationally by the absence of fair tests of multiple reasonable hypotheses" (p. 7).

The hypothesis implicit in the IPCC's writings, though rarely explicitly stated, is that dangerous global warming is resulting, or will result, from anthropogenic greenhouse gas emissions. As stated, that hypothesis is falsifiable. The null hypothesis is that the warming found in temperature records and changes in polar ice, sea levels, and various weather indices are instances of natural variability or causes unrelated to anthropogenic (human) greenhouse gas emissions. As long as recent average global temperatures, sea-level rise, polar ice melting, etc. are not much different than earlier times when human greenhouse gas emissions were low, the null hypothesis is very reasonable.

Invalidating this null hypothesis requires, at a minimum, direct evidence of human causation of changes in global mean average surface temperature and that recent trends are unprecedented. ("Direct evidence" is knowledge based on observations which, if true, directly prove or disprove a theory without resorting to any assumption or inference. It is distinguished from "circumstantial evidence," which is knowledge that relies on an inference to connect it to a conclusion of fact.) But the IPCC and many other research and advocacy groups make no effort to falsify the null hypothesis. For example, virtually no research dollars are available to study the causes and consequences of *natural* (or what the IPCC calls "internal") climate variability. Rather than investigate the role of ocean currents, solar influences, cosmic rays, and clouds in a fair and balanced way, IPCC researchers dismiss them out of hand as "poorly understood" or "unlikely to have a major effect." Even modest attention to research in these areas would likely force the IPCC to reconsider some of its postulates. The IPCC has used all 10 of Armstrong and Green's instruments of "advocacy research" to defend, rather than test, its hypothesis.

Why doesn't the IPCC study natural causes of climate change? Article 1.2 of the United Nations' Framework Convention on Climate Change, which gave the IPCC its mandate, defines climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods" (UNFCCC, 1994). Working Group I of the IPCC has interpreted this as a mandate not to study climate change "in the round" but only a possible *human* impact on climate. As Curry (2013) writes,

> The UNFCCC Treaty provides the rationale for framing the IPCC assessment of climate change and its uncertainties, in terms of identifying dangerous climate change and providing input for decision making regarding CO_2 stabilization targets. In the context of this framing, key scientific questions receive little attention. In detecting and attributing 20th century climate change, the IPCC AR4 all but dismisses natural internal multidecadal variability in the attribution argument. The IPCC AR4 conducted no systematic assessment of the impact of uncertainty in 20th century solar variability on attribution, and indirect solar impacts on climate are little known and remain unexplored in any meaningful way.

Interestingly, the IPCC's Working Group II does not also limit its definition of climate change this way, allowing it to include any impact of climate change "regardless of its cause" in its lengthy catalogue of alleged damages (IPCC, 2014, p. 4, fn. 5). Judging the impacts of man-made climate change to be harmful to human well-being or the environment requires, at a minimum, distinguishing those impacts from impacts that would have occurred in the absence of the human presence. Such a finding also requires balancing all costs and benefits, including the known benefits of higher levels of CO_2 in the atmosphere to ecosystems. Since a steep reduction in the use of fossil fuels is the policy recommendation that arises from a finding that anthropogenic climate change is harmful to humanity, then the costs of living without those energy sources must be weighed as well.

Peer Review

Part of the Scientific Method is independent review of a scientist's work by other scientists who do not have a professional, reputational, or financial stake in whether the hypothesis is confirmed or disproven. Peer review distinguishes academic literature from more popular writing and journalism. Tragically, peer review is in a state of crisis in a wide range of disciplines, affecting even or especially some of the most respected academic journals.

In a series of articles published in leading academic journals, Ioannidis (2005a, 2005b, 2012, 2018; Ioannidis and Trikalinos, 2005) revealed most published research in the health care field cannot be replicated or is likely to be contradicted by later publications His most frequently cited work is titled "Why most published research findings are false." Although the problem is not new (see Mayes *et al.*, 1988), Ioannidis's work generated widespread awareness that peer review is no guarantee of the accuracy or value of a research paper. In fact, he found that the likelihood of research being contradicted is highest when it is published in the most prestigious journals, including *JAMA*, *Nature*, and *Science*.

Springer, a major publisher of science journals, retracted 16 papers it had published that were simply gibberish generated by a computer program called SCIgen (*Nature*, 2014). In 2016, more than 70% of 1,576 researchers who replied to a survey conducted by *Nature* reported having tried and failed to reproduce another scientist's experiments, and more than half failed to reproduce their own experiments (Baker, 2016). Fifty-two percent agree there is a significant "crisis" of reproducibility. Camerer *et al.* (2018) attempted to replicate 21 experimental social science studies published in *Nature* and *Science* between 2010 and 2015 and found "a significant effect in the same direction as the original study for 13 (62%) studies," while the rest found no effect or an opposite effect. Random chance would have led to a 50% replication rate, so this is a dismal finding. While Camerer *et al.* looked at studies in the social sciences, similar results have been reported in the physical sciences. See Sánchez and Parott (2017) for a review of studies alleging negative health effects of genetically modified foods.

Some journals and academic institutions claim to be engaged in considerable soul-searching and efforts to reform a peer-review process that is plainly broken. However, journals such as *Nature* seem to take the scandal over peer-review corruption seriously only when it concerns issues other than climate science (e.g., Ferguson *et al.*, 2014; Sarewitz, 2016).

This controversy has particular relevance to the climate change debate due to "Climategate," the release by a whistleblower in 2009 and again in 2011 of thousands of emails exchanged among prominent climate scientists discussing their use of the peer-review process to exclude global warming skeptics from journals, punish editors who allowed skeptics' articles to appear, and rush into publication articles refuting or attempting to discredit scientists who disagree with the IPCC's findings (Montford, 2010; Sussman, 2010; Michaels, 2011, Chapter 2). No scientists were punished for their misbehavior and the practice continues today.

The lessons of the peer-review crisis are several. Just because something appears in a peer-reviewed journal does not mean it is credible or reliable. Research that "fails" peer-review or appears in the so-called secondary literature may in fact be credible and reliable. Review by a small cadre of experts behind closed doors is more likely to lead to publication of research that reinforces a prevailing paradigm and overlooks errors, while transparency and open debate lead to generally higher quality research (Raymond, 1999; Luke *et al.*, 2018). This is relevant to Armstrong and Green's Rule #8: Disclose all information needed to evaluate the research and to conduct replications.

Correlation versus Causation

The correlation of two variables does not establish causation, for it is not at all unusual for two trends to co-vary by accident, or in parallel when both are driven by the same outside force. To infer causation one needs a reasoned argument based on some causal theory that has stood up to tests and sits within a framework of theories and "basic statements."

VanCauwenberge (2016) writes, "Sometimes a correlation means absolutely nothing, and is purely accidental (especially when you compute millions of correlations among thousands of variables) or it can be explained by confounding factors. For instance, the fact that the cost of electricity is correlated to how much people spend on education, is explained by a confounding factor: inflation, which makes both electricity and education costs grow over time. This confounding factor has a bigger influence than true causal factors, such as more administrators/ government-funded student loans boosting college tuition."

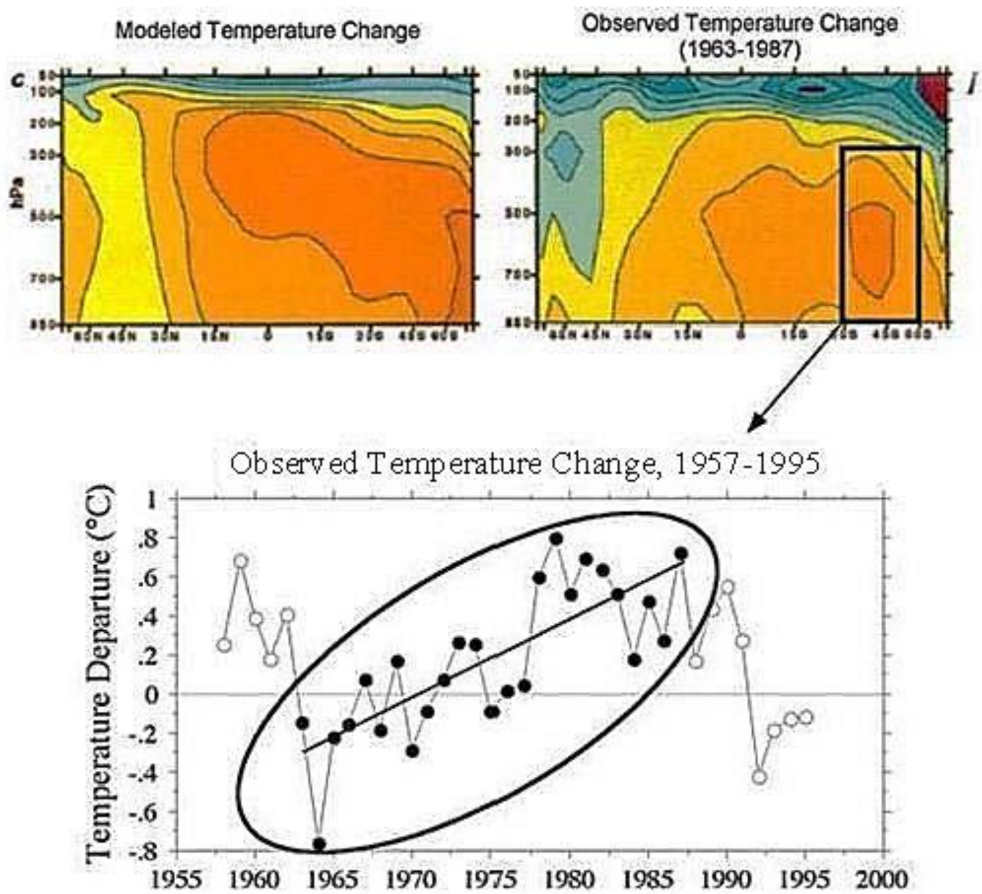
In the climate change debate, data showing a correlation between observed warming in the Southern Hemisphere between 1963 and 1987 and what was projected to occur by models led some scientists to claim, just days before the Second Conference of the Parties to the United Nations Framework Convention on Climate Change, that this was proof that rising atmospheric CO_2 levels *caused* the temperature to rise (Santer *et al.*, 1996). Michaels and Knappenberger (1996) quickly pointed out that the observational record actually begins in 1957 and extended to 1995, and when all of the data are used, the warming trend completely disappears. (See Figure 2.1.1.1.2.) Despite this, the theory gained momentum as millions and then billions of dollars were spent searching for a human influence on the climate (Essex and McKitrick, 2007; Darwall, 2013; Lewin, 2017).

Related to the need to distinguish between correlation and causation is the phenomenon of data dredging, also called "data mining" or "p-hacking," whereby large databases are analyzed repeatedly in hopes of finding a calculated probability or p value ≤ 0.05, and then selectively reporting the positive results as circumstantial evidence in support of a hypothesis (Goldacre, 2016; Gorman *et al.*, 2017). Reporting positive results greatly increases the odds of being published in academic journals, where articles reporting positive findings outnumber those reporting negative findings by 9:1 or greater (Fanelli, 2012). Advances in data collection and computer processing speeds enable researchers to test thousands and even millions of possible relationships in search of the elusive $p \leq 0.05$ and then to seek a publication willing to accept their findings. This practice is especially apparent in the public health arena where exposure to small doses of chemicals is alleged to be "associated" with negative health effects (see Chapter 6), and also in climatology where small changes in temperatures are alleged to be "associated" with almost countless health and environmental impacts. Data dredging violates the Scientific Method by putting the collection and analysis of data ahead of formulating a reasonable hypothesis and one or more alternative hypotheses.

Control for Natural Variability

To discern the impact of a particular variable or process, scientific experiments attempt to control for natural variability in populations or physical phenomena. Sometimes the "background noise" of natural variability is too great to discern an impact or pattern. When the subject of inquiry is Earth's atmosphere, the largest and most complex phenomenon ever studied by man, it is very difficult to meet the requirements of control for designing, conducting, and interpreting experiments or observational programs.

Figure 2.1.1.1.2
Santer *et al.* (1996) claim to have found a "human influence" on climate and Michaels and Knappenberger (1996) demonstrate no trend



Modeled (upper left) and observed (upper right) temperature changes throughout the atmosphere. Lower image shows time series of temperatures in the region of the highlighted box in the upper right panel for years 1957-1995. Filled circles are years reported by Santer *et al.* (1996). Use of all the available data (open circles) reveals no trend. *Source:* Michaels, 2010, Figure 3, citing Santer *et al.,* 1996 and Michaels and Knappenberger, 1996.

The geological record reveals that we live on a dynamic planet. All aspects of the physical and biological environment are in a constant state of flux (including, of course, temperature). It is wrong to assume no changes would occur in the absence of the human presence. Climate, for example, will be different in 100 years regardless of what humans do. This is a point of contention in the climate change debate because the IPCC seems to assume that global temperatures, solar influences, and exchanges among global carbon reservoirs (to name just three) would remain unchanged, decade after decade and century after century, *but for* the human presence.

Related to this matter, many studies of the impact of climate change on wildlife simply assume temperatures in the area under investigation have risen in pace with estimates of *global* surface temperatures, or that severe weather events have become more frequent, etc., without establishing that the relevant *local* temperature and weather records conform to the postulate. Assertions about specific phenomena should not be made based on global averages. An example of research conducted correctly in this regard is a study of infrastructure needs for a city in California conducted by Pontius (2017). Rather than rely on the mean global average surface temperature, the researcher studied temperature data from the City of Riverside, California from 1901 to 2017. "No evidence of significant climate change beyond natural variability was observed in this temperature record," he reports. "Using a Climate Sensitivity best estimate of 2°C, the increase in temperature resulting from a doubling of atmospheric CO_2 is estimated at approximately 0.009°C/yr which is insignificant compared to natural variability."

Postulates Are Not Science

Postulates, commonly defined as "something suggested or assumed as true as the basis for reasoning, discussion, or belief," can stimulate the search for relevant observations or experiments but more often are merely assertions that are difficult or impossible to test (Kahneman, 2011). For example, most parts of the IPCC's very large assessment reports accept without qualification or acknowledgement of uncertainty the following five postulates:

- The warming of the twentieth century cannot be explained by natural variability.
- The late twentieth century warm peak was of greater magnitude than previous natural peaks.
- Increases in atmospheric CO_2 precede, and then force, parallel increases in temperature.
- Solar influences are too small to explain more than a trivial part of twentieth-century warming.
- A future warming of 2°C or more would be net harmful to the biosphere and human well-being.

All five statements may be true. There is evidence that seems to support all of them, but there is also evidence that contradicts them. In their declarative form, all of these statements are misleading at best and probably untrue. The IPCC expresses "great confidence" and even "extreme confidence" in these postulates, but it did not consider alternative hypotheses or evidence pointing to different conclusions. A true high confidence interval, defined in statistics as the probability that a finding falls within the range of values of the entire population being sampled, cannot be given because *these are statements of opinion and not of fact.* Once again, this is a failure to conform to the requirements of the Scientific Method.

* * *

Armstrong and Green (2018b) write, "logical policy requires scientific forecasts of substantive long-term trend in global mean temperatures, major net harmful effects from changing temperatures, and net benefit from proposed policies relative to no action. Failure of any of the three requirements means policy action is unsupported" (p. 29). When they applied a checklist of 20 operational guidelines to the IPCC "business as usual" forecast and to a default no-change model forecast, they found the IPCC scenarios followed none of the guidelines while the no-change model followed 95%. Results like these suggest the IPCC has not been careful to follow the rules of the Scientific Method.

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2.1.1.2 Consensus

> *Appealing to consensus may have a place in science, but should never be used as a means of shutting down debate.*

The meme of "an overwhelming consensus" of scientists favoring one particular view on climate change is very popular, despite its implausibility. For example, Lloyd and Winsberg (2018) write, "While a fair bit of controversy concerning the cause of these phenomena [recent severe weather events] remains in the body politic (especially in the United States), nothing could be further from the truth when it comes to the scientific community. Multiple studies, appearing in peer-reviewed publications, all show similar findings: that roughly 97–98% of actively publishing climate scientists agree with the claim that it is extremely likely that the past century's warming trend is due to human activities" (p. 2). This claim quickly falls apart upon inspection.

That climate change is real or happening is a truism: Climate is always changing. To say it is "due to human activities" begs the questions "how much?" and "how do we know?" Nearly all scientists understand that some of the past century's warming trend was due to natural causes. The issue is how much is natural variability and how much is due to anthropogenic greenhouse gases and changes in land use (mostly agriculture and forestry). Some scientists believe it is difficult or meaningless to ascribe a single temperature to the globe and then to attribute changes to that statistical abstraction to human causes. And whether climate change is dangerous or not is a subjective and political decision, not a scientific concept. Who is at risk? When? And how do the risks created by climate change compare to other risks we face every day?

If the scientific debate were truly over, the range of uncertainty over the impact of carbon dioxide on climate would be smaller than it was in 1979, instead of being virtually the same. Many admissions of uncertainty appear in the IPCC's hefty assessment reports (a topic addressed in the next section and frequently in other chapters), but those reservations and doubts are scrubbed from the often-cited summaries for policymakers (SPMs), an example of scientific malpractice that has been protested by many distinguished scientists (Seitz, 1996; Landsea, 2005; Lindzen, 2012; Tol, 2014; Stavins, 2014). Many scientists look no further than the SPMs and trust them to accurately depict the current state of climate science. They do not. Surveys and abstract-counting exercises purporting to show consensus are critiqued at some length in Section 2.5, so that will not be done here.

Consensus may have a place in science, but only in contexts different than what occur in climate science. It is typically achieved over an extended period of time by independent scientists following the conventions of the Scientific Method, in particular not neglecting the need to entertain competing hypotheses. Consensus emerges from open debate and tolerance of new theories and discoveries; it is not handed down by an international political organization tasked with defending one paradigm. Consensus on basic theories can open up other areas for new research and exploration while leaving the door open to reconsider first principles. Unfortunately, this is not the context in which consensus is invoked in climate science. Curry (2012) wrote,

> The manufactured consensus of the IPCC has had the unintended consequences of distorting the science, elevating the voices of scientists that dispute the consensus, and motivating actions by the consensus scientists and their supporters that have diminished the public's trust in the IPCC. Research from the field of science and technology studies are finding that manufacturing a consensus in the context of the IPCC has acted to hyper-politicize the scientific and policy debates, to the detriment of both. Arguments are increasingly being made to abandon the scientific consensus-seeking approach in favor of open debate of the arguments themselves and discussion of a broad range of policy options that stimulate local and regional solutions to the multifaceted and interrelated issues of climate change, land use, resource management, cost effective clean energy solutions, and developing technologies to expand energy access efficiently.

More recently, Curry (2018) writes, "The IPCC and other assessment reports are framed around providing support for the hypothesis of human-caused climate change. As a result, natural processes of climate variability have been relatively neglected in these assessments."

In his book titled *Why We Disagree about Climate Change*, climate scientist Mike Hulme (2009) defends appealing to consensus in climate science by calling climate change "a classic example of ... 'post-normal science,'" which he defines as "the application of science to public issues where 'facts are uncertain, values in dispute, stakes high and decisions urgent'" (quoting Silvio Funtowicz and Jerry Ravetz). Issues that fall into this category, he says, are no longer subject to the cardinal requirements of true science: skepticism, universalism, communalism, and disinterestedness. Instead of experimentation and open debate, post-normal science says "consensus" brought about by deliberation among experts determines what is true, or at least temporarily true enough to direct public policy decisions.

The merits and demerits of post-normalism have been debated (see Carter, 2010; Lloyd, 2018), but it is plainly a major deviation from the rules of the Scientific Method and should be met with skepticism by the scientific community. Claiming a scientific consensus exists tempts scientists to simply sign on to the IPCC's latest reports and pursue the research topics and employ the methodologies approved by the IPCC and its member governments. The result is too little hypothesis-testing in climate science and too much amassing of data that can be "dredged" to support the ruling paradigm. U.S. President Dwight Eisenhower (1961) famously warned of such an outcome of government funding of scientific research in his farewell address:

> The free university, historically the fountainhead of free ideas and scientific discovery, has experienced a revolution in the conduct of research. Partly because of the huge costs involved, a government contract becomes virtually a substitute for intellectual curiosity ...
>
> Yet, in holding scientific research and discovery in respect, as we should, we must also be alert to the equal and opposite danger that public policy could itself become the captive of a scientific-technological elite. The prospect of domination of the nation's scholars by Federal employment, project allocations, and the power of money is ever present – and is gravely to be regarded.

Some scientists see in this arrangement a license to indulge their political biases. Hulme, for example, writes, "The idea of climate change should be seen as an intellectual resource around which our collective and personal identities and projects can form and take shape. We need to ask not what we can do for climate change, but to ask what climate change can do for us" (*Ibid.*, p. 326). This seems quite distant from the rules of the Scientific Method.

The discipline of climate science is young, leaving many basic questions to be answered. Instead of conforming to a manufactured consensus, climate change science outside the reach of the IPCC is full of new discoveries, new theories, and lively debate. New technologies are bringing new discoveries and surprising evidence. Just a few examples:

- Ilyinskaya *et al.* (2018) estimated CO_2 emissions from Katla, a major subglacial volcanic caldera in Iceland, are "up to an order of magnitude greater than previous estimates of total CO_2 release from Iceland's natural sources" and "further measurements on subglacial volcanoes worldwide are urgently required to establish if Katla is exceptional, or if there is a significant previously unrecognized contribution to global CO_2 emissions from natural sources."

- Martinez (2018) compared changes in electric lights seen from satellites in space coming from free and authoritarian countries to the economic growth rates reported by their governments during the same period. He found "yearly GDP growth rates are inflated by a factor of between 1.15 and 1.3 in the most authoritarian regimes" (see also Ingraham, 2018). The integrated assessment models (IAMs) relied on by the IPCC to estimate the "social cost of carbon" rely on this sort of data being accurate.

- Marbà *et al.* (2018) found seagrass meadows in Greenland could be emerging as a major carbon sink. The meadows "appear to be expanding and increasing their productivity. This is supported by the rapid growth in the contribution of seagrass-derived carbon to the sediment C_{org} [organic carbon] pool, from less than 7.5% at the beginning of 1900 to 53% at present, observed in the studied meadows. Expansion and enhanced productivity of eelgrass meadows in the subarctic Greenland fjords examined here is also consistent with the on average 6.4-fold acceleration of C_{org} burial in sediments between 1940 and present."

- McLean (2018) conducted what is apparently the first ever audit of the temperature dataset (HadCRUT4) maintained by the Hadley Centre of the UK Met Office and the Climatic Research Unit of the University of East Anglia. He identified some 70 "issues" with the database, including "simple issues of obviously erroneous data, glossed-over sparsity of data, [and] significant but questionable assumptions and temperature data that has been incorrectly adjusted in a way that exaggerates warming" (p. i). Simply cleaning up this database, which is relied on by the IPCC for all its analysis, should be a high priority.

- Kirkby *et al*. (2016) reported the CLOUD research conducted by CERN (the European Institute for Nuclear Research) provided experimental results supporting the theory that variations in the number of cosmic rays hitting Earth's atmosphere create more or fewer (depending on the strength of the solar magnetic wind) of the low, wet clouds that deflect solar heat back into space. Subsequent to the CLOUD experiment, four European research institutes collaborated on a new climate model giving cosmic rays a bigger role than the models used by the IPCC (Swiss National Science Foundation, 2017).

Kreutzer *et al.* (2016) write, "The idea that the science of climate change is 'settled' is an absurdity, contrary to the very spirit of scientific enquiry. Climate science is in its infancy, and if its development follows anything resembling the normal path of scientific advancement, we will see in the years ahead significant increases in our knowledge, data availability, and our theoretical understanding of the causes of various climate phenomena."

Disagreements among scientists about methodology and the verity of claimed facts make it difficult for unprejudiced lay persons to judge for themselves where the truth lies regarding complex scientific questions. For this reason, politicians and even many scientists look for and eagerly embrace claims of a "scientific consensus" that would free them of the obligation to look at the science and reach an informed opinion of their own. Regarding climate change, that is a poor decision. As Essex and McKitrick (2007) write, "non-scientists [should] stop looking for shortcuts around the hard work of learning the science, and high-ranking scientists [should] stop resorting to authoritarian grandstanding as an easy substitute for the slow work of research, debate, and persuasion" p. 15).

It is too early, the issues are too complex, and new discoveries are too many to declare the debate over. In many ways, the debate has just begun.

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2.1.1.3 Uncertainty

> *Uncertainty in science is unavoidable but must be acknowledged. Many declaratory and predictive statements about the global climate are not warranted by science.*

Uncertainty in science is unavoidable. Jaynes (2003, p. 54, fn) writes, "incomplete knowledge is the only working material a scientist has!" But uncertainty can be minimized through experimentation and statistical methods such as Bayesian inference. Jaynes continues, "In scientific inference our job is always to do the best we can with whatever information we have; there is no advance guarantee that our information will be sufficient to lead us to the truth. But many of the supposed difficulties arise from an inexperienced user's failure to recognize and use the safety devices that probability theory as logic always provides" (p. 106).

Kelly and Kolstad (1998) report there are two kinds of uncertainty, *stochastic* and *parametric*. The latter can be expected to decline over time as more is learned about the global climate system and the variables and values used for parameters in general circulation models (GCMs) and integrated assessment models (IAMs) are better constrained. Stochastic uncertainty, on the other hand, can increase, decrease, or remain about the same over time. It is a function of various phenomena that impact economic or geophysical processes but are either not included in the models or included incorrectly. Stochastic uncertainties include the effects of earthquakes, volcanic eruptions, or abrupt economic downturns, such as the global financial crisis of 2007–08. A major element of stochastic uncertainty is the fact that we cannot know the future trend of technology or the economy and are, therefore, always susceptible to surprises.

A third source of uncertainty is *epistemic*. Roy and Oberkampf (2011) define this as "[predictive] uncertainty due to lack of knowledge by the modelers, analysts conducting the analysis, or experimentalists involved in validation. The lack of knowledge can pertain to, for example, modeling of the system of interest or its surroundings, simulation aspects such as numerical solution error and computer round-off error, and lack of experimental data." In describing how to treat such error, Helton *et al.* (2010) note, "the mathematical structures used to represent [stochastic] and epistemic uncertainty must be propagated through the analysis in a manner that maintains an appropriate separation of these uncertainties in the final results of interest."

Uncertainties abound in the climate change debate. For example, there is uncertainty regarding pre-modern-era surface temperatures due to reliance on temperature proxies, such as sediment deposition patterns and oxygen isotopes found in ice cores, and in the modern temperature record due to the placement of temperature stations and changes in technology over time. According to Frank (2016),

> Field-calibrations reveal that the traditional Cotton Regional Shelter (Stevenson screen) and the modern Maximum-Minimum Temperature Sensor (MMTS) shield suffer daily average 1σ systematic measurement errors of ±0.44ºC or ±0.32ºC, respectively,

stemming chiefly from solar and albedo irradiance and insufficient windspeed.

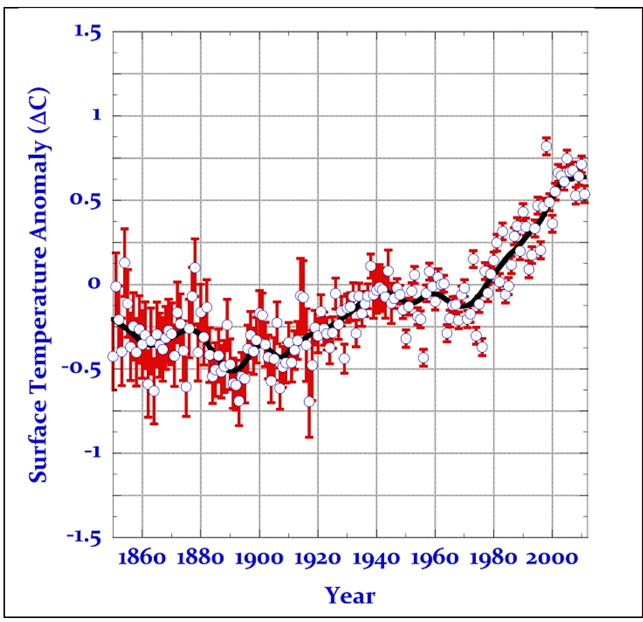
Marine field calibrations of bucket or engine cooling-water intake thermometers revealed typical SST [sea surface temperature] measurement errors of 1σ = ±0.6ºC, with some data sets exhibiting ±1ºC errors. These systematic measurement errors are not normally distributed, are not known to be reduced by averaging, and must thus enter into the global average of surface air temperatures. Modern floating buoys exhibit proximate SST error differences of ±0.16ºC.

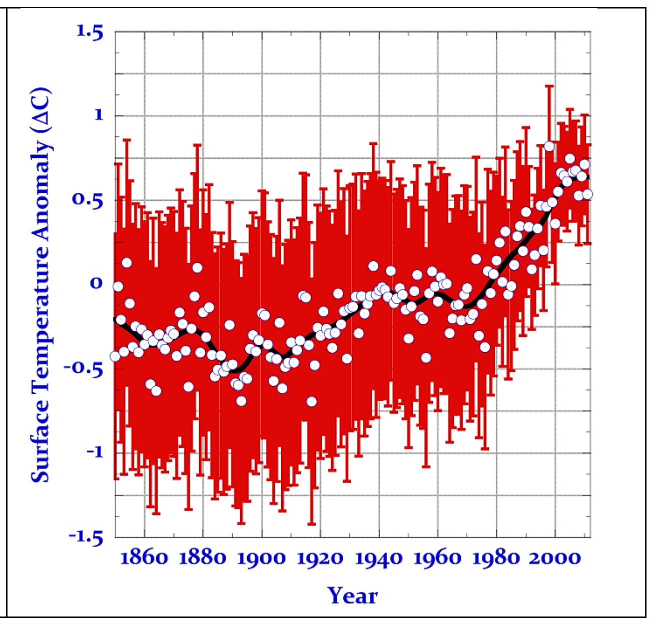
These known systematic errors combine to produce an estimated lower limit uncertainty of 1σ = ±0.5ºC in the global average of surface air temperatures prior to 1980, descending to about ±0.36ºC by 2010 with the gradual introduction of modern instrumentation (abstract).

Frank (2016) observes that when known uncertainties in the temperature record are more properly accounted, reconstruction of the global temperature record reveals so much uncertainty that "at the 95% confidence interval, the rate or magnitude of the global rise in surface air temperature since 1850 is unknowable." He illustrates the point by calculating error bars due to systematic measurement error and adding them to the widely reproduced graph of global temperatures since 1850 created by the Climatic Research Unit at the University of East Anglia. His graphs are reproduced in Figure 2.1.1.3.1. With the measurement uncertainty so great, it is impossible to know whether human emissions of greenhouse gases have had any impact at all on global air temperature.

The human impact on global average temperature is also uncertain due to our incomplete understanding of the carbon cycle (e.g., exchange rates between CO_2 reservoirs) and the atmosphere (e.g., the behavior of clouds), both described in Section 2.1.2 below. Falkowski *et al.* (2000) admitted, "Our knowledge is insufficient to describe the interactions

Figure 2.1.1.3.1
2010 HadCRUT temperature record with error bars due to systematic measurement errors





The 2010 global average surface air temperature record obtained from the website of the Climate Research Unit (CRU), University of East Anglia, UK. Left graph shows error bars following the description provided at the CRU website. Right graph shows error bars reflecting uncertainty width due to estimated systematic sensor measurement errors within the land and sea surface records. *Source*: Frank, 2016, Figure 11, p. 347.

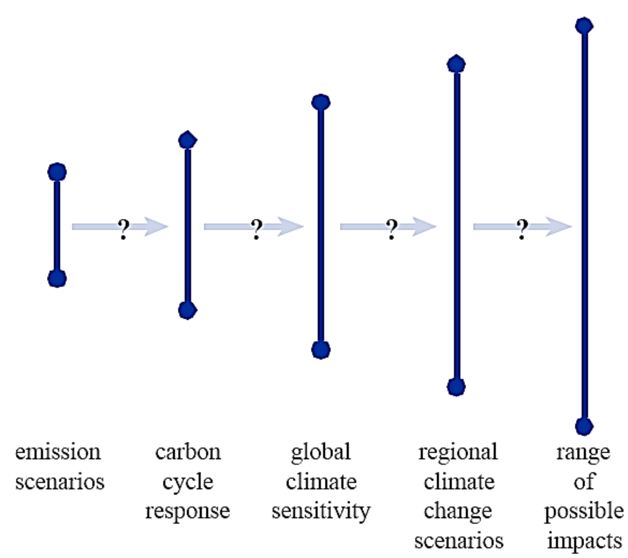
between the components of the Earth system and the relationship between the carbon cycle and other biogeochemical and climatological processes."

Ahlström *et al*. (2017) report "global vegetation models and terrestrial carbon cycle models are widely used for projecting the carbon balance of terrestrial ecosystems. Ensembles of such models show a large spread in carbon balance predictions, ranging from a large uptake to a release of carbon by the terrestrial biosphere, constituting a large uncertainty in the associated feedback to atmospheric CO_2 concentrations under global climate change. … We conclude that climate bias-induced uncertainties must be decreased to make accurate coupled atmosphere-carbon cycle projections."

Skeie *et al.* (2011) describe another source of uncertainty: measuring human emissions of greenhouse gases. They write, "The uncertainties in present day inventories for [fossil fuel and biofuels black carbon and organic carbon] are about a factor of 2 and there are uncertainties in the rate of change of the emissions and the uncertainties differ in different regions, but are not quantified by Bond *et al.* (2007). Smith *et al.* (2011) found that uncertainties in the regional emissions of SO_2 are far higher than the uncertainties in the global emissions. The 5–95% confidence interval for the global emissions is 9% of the best estimate in 2000 and range between 16% and 7% between 1850 and 2005. The regional uncertainties in the emissions in Former Soviet Union were 20% in 1990 and 30% in China for the year 2000. A formal error propagation for the RF time series of short lived components including the uncertainties in the rate of change and spatial distribution of the emissions is not performed in this study or other published studies. The error estimates for all mechanisms (Fig. 1d) are therefore based on spread found in previous studies."

GCMs, described in Section 2.2.2, and IAMs, described at length in Chapter 8 grapple with the problem of "propagation of error," a term used in statistics referring to how errors or uncertainty in one variable, due perhaps to measurement limitations or confounding factors, are compounded (propagated) when that variable becomes part of a function involving other variables that are also uncertain. Error propagation through sequential calculations is widely used in the physical sciences to reveal the reliability of an experimental result or a calculation from theory. As the number of variables or steps in a function increases, uncertainties multiply until there can be no confidence in the outcomes. In academic literature this is sometimes referred to as "cascading uncertainties" or "uncertainty explosions." (See Curry and Webster, 2011; and Curry, 2011, 2018.)The IPCC itself illustrated the phenomenon in Working Group II's contribution to the Third Assessment Report (TAR) in the figure reproduced as Figure 2.1.1.3.2. The caption of the image reads, "Range of major uncertainties that are typical in impact assessments, showing the 'uncertainty explosion' as these ranges are multiplied to encompass a comprehensive range of future consequences, including physical, economic, social, and political impacts and policy responses (modified after Jones, 2000, and 'cascading pyramid of uncertainties' in Schneider, 1983" (IPCC, 2001, p. 130).

Figure 2.1.1.3.2
Illustration of cascading uncertainties in climate science



Source: IPCC, 2001, p. 130.

Frank (2015) writes, "It is very well known that climate models only poorly simulate global cloud fraction, among other observables. This simulation error is due to incorrect physical theory. ... [E]ach calculational step delivers incorrectly calculated climate magnitudes to the subsequent step. ... In a sequential calculation, calculational error builds upon initial error in every step, and the uncertainty accumulates with each step" (p. 393). When systematic error is propagated through a model, uncertainty increases with the projection time. When the uncertainty bars become large, no information remains in the projection.

Recognizing this problem, modelers may make their model relatively unresponsive to changes in data or parameter values, creating the appearance of stability until those restraints are questioned and lifted. Hourdin *et al.* (2017), in an article titled "The Art and Science of Climate Model Tuning," write, "Either reducing the number of models or over-tuning, especially if an explicit or implicit consensus emerges in the community on a particular combination of metrics, would artificially reduce the dispersion of climate simulations. *It would not reduce the uncertainty, but only hide it*" (italics added).

Ranges of uncertainty also apply to how to measure alleged climate effects (e.g., loss of livelihood, loss of personal property, forced migration) and how much of the effect to attribute to a specific weather-related event (e.g., flood, drought, hurricane) or to some other non-climate variable (e.g., poverty, civil war, mismanagement of infrastructure). Although considerable progress has been made in climate science and in the understanding of how human activity interacts with and affects the biosphere and economy, significant uncertainties persist in each step of an IAM. As the model progresses through each of these phases, uncertainties surrounding each variable in the chain of computations are compounded one upon another, creating a cascade of uncertainties that peaks upon completion of the final calculation. Tol (2010, p. 79) writes,

> A fifth common conclusion from studies of the economic effects of climate change is that the uncertainty is vast and right- skewed. For example, consider only the studies that are based on a bench-mark warming of 2.5°C. These studies have an average estimated effect of climate change on average output of -0.7% of GDP, and a standard deviation of 1.2% of GDP. Moreover, this standard deviation is only about best estimate of the economic impacts, given the climate change estimates. It does not include uncertainty about future levels of GHG emissions, or uncertainty about how these emissions will affect temperature levels, or uncertainty about the physical consequences of these temperature changes. Moreover, it is quite possible that the estimates are not independent, as there are only a relatively small number of studies, based on similar data, by authors who know each other well.

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2.1.2 Observations

Science depends on observational data to form and test hypotheses. In climate science, key observational data relate to energy flows in the atmosphere characterized as the energy budget; the movement of carbon among reservoirs, called the carbon cycle; warming and cooling periods seen in the geological and historical records; and sources and behavior of greenhouse gases (GHGs) such as carbon dioxide (CO_2) and methane (CH_4).

2.1.2.1 Energy Budget

> *Surface air temperature is governed by energy flow from the Sun to Earth and from Earth back into space. Whatever diminishes or intensifies this energy flow can change air temperature.*

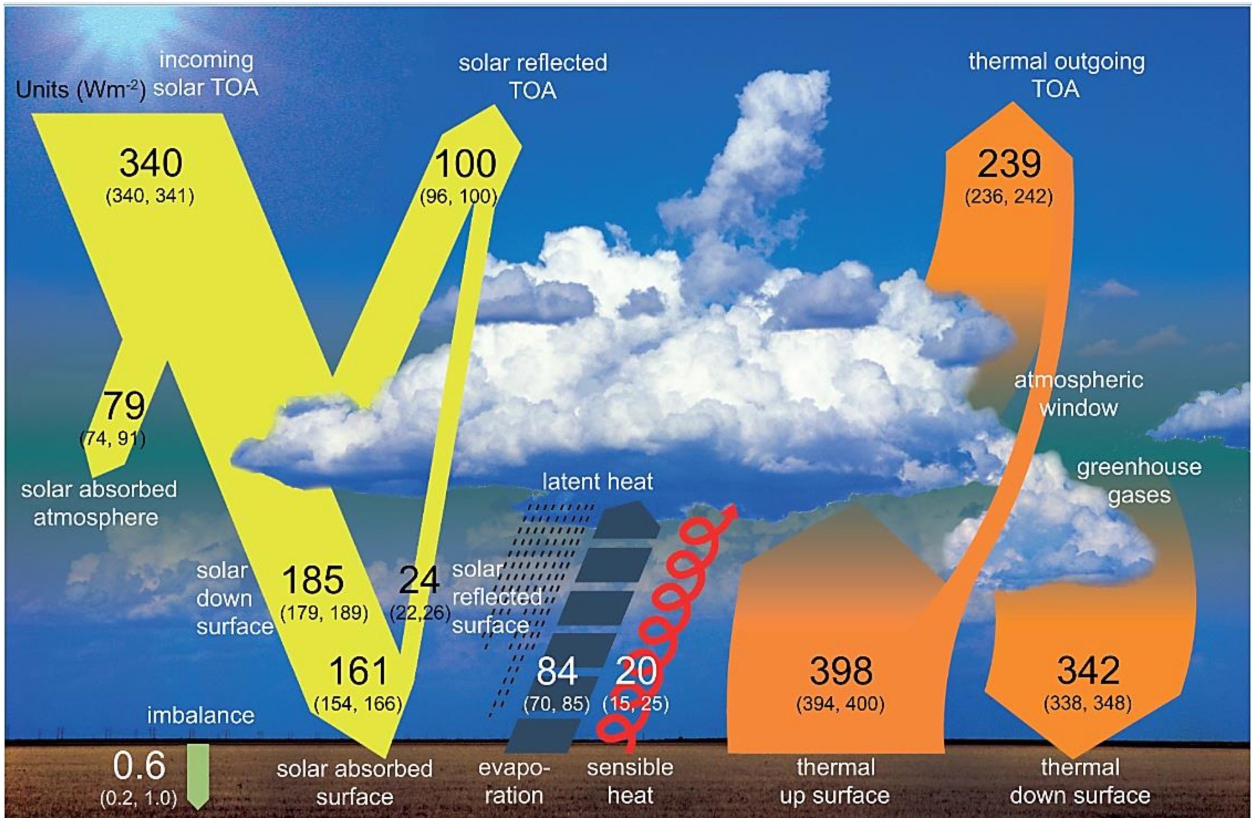
Figure 2.1.2.1.1 presents a recent effort by the Intergovernmental Panel on Climate Change (IPCC) to characterize and quantify heat flows in Earth's atmosphere. Incoming energy must equal outgoing energy for Earth's temperature to be stable over long periods of time, a balance called radiative equilibrium. Hence, the label "energy budget" is applied to the phenomenon.

The principal source of energy entering Earth's atmosphere is the Sun, providing irradiance, solar wind (plasma), and solar magnetism. The amount of energy reaching any particular point at the top of the atmosphere varies dramatically depending on latitude, season, and diurnal phase (daytime or nighttime). A global average of approximately 340 watts of solar power per square meter (Wm^2, one watt is one joule of energy every second) hits the top of the atmosphere, 100 Wm^2 is reflected back into space by clouds, and approximately 240 Wm^2 enters the atmosphere. Approximately 239 Wm^2 leaves Earth's atmosphere as thermal energy, creating a net "imbalance" of 0.6° [0.2°, 1.0°] Wm^2. That imbalance is the first order cause of rising surface temperatures.

Whatever diminishes or intensifies the energy flow from the Sun to Earth and from Earth back into space can change air temperature. However, the dynamics are not straightforward. Natural variation in the planet's energy budget occurs without human influence, some of the mechanisms are non-linear, and the physics is poorly understood. For example, the changing intensity of the Sun, the planet's changing magnetic field, and galactic cosmic rays all affect incoming solar at the top of the atmosphere. Changes to Earth's albedo (reflectivity) due to changes in snow and ice cover and land use can affect the amount of energy leaving the planet.

The amount of energy reflected back into space by clouds is assumed to be (on average) a constant, but even small changes in cloud cover, cloud brightness, and cloud height – all of which are known to vary spatially and over time and none of which is well modeled – could alter this key variable in the energy budget enough to explain the slight warming of the twentieth century (Lindzen, 2015, p. 55; Hedemann *et al.*, 2017). Surface air temperature at any one place on Earth's terrestrial surface is determined by many factors, only one of which is the small change in the global temperature that presumably emerges from the stylized energy flows shown in Figure 2.1.2.1.1. One such factor is turbulence, which Essex and McKitrick call "one of the most basic and intractable research problems facing humanity. You can't compute it. You can't measure it. But rain falls because of it" (Essex and McKitrick, 2007, p. 20).

Figure 2.1.2.1.1
Global mean energy budget of Earth under present-day climate conditions



Source: IPCC, 2013, Table 2.11, p. 181. TOA = top of the atmosphere. Imbalance (0.6° [0.2°, 1.0°] Wm^2 shown at bottom left corner of the image) is thought to be the imbalance causing a net warming of the atmosphere.

Earth's rotation produces gyres and flows in two dynamic fluids – the atmosphere and the oceans. Oceans cover more than 70% of Earth's surface and hold approximately 1,000 times as much heat as the atmosphere. This means Earth's surface temperature does not adjust quickly to changes in the atmosphere "due to the ocean's thermal inertia, which is substantial because the ocean is mixed to considerable depths by winds and convection. Thus it requires centuries for Earth's surface temperature to respond fully to a climate forcing" (Hansen *et al.*, 2012). The fluid dynamics of these systems are not well understood. Coupled with rotation, the flows in these two fluids create internal variability in the climate system. The exchange of energy within or between the oceans and the atmosphere can cause one or the other to warm or cool even without any change in the heat provided by the Sun.

El Niño and La Niña cycles dominate the flux of water and energy in the tropical Pacific over periods of two to seven years. These cyclical episodes normally last between nine and 12 months and are part of a complex cycle referred to as the El Niño-Southern Oscillation (ENSO). El Niño, a winter phenomenon (Northern Hemisphere), refers to a period of anomalously warm water in the Central and Eastern Pacific. La Niña is the cold counterpart to the El Niño phenomenon. Both events can have large impacts on global temperatures, rainfall, and storm patterns.

Long-term changes in solar energy entering the top of the atmosphere are caused by changes in the Sun itself as well as Milankovitch cycles – variations in the Earth's orbit due to eccentricity (the changing shape of the Earth's orbit around the Sun), axial tilt (oscillations in the inclination of the Earth's axis in relation to its plane of orbit around the Sun), and precession (the planet's slow wobble as it spins on its axis) on cycles of approximately 100,000, 41,000, and 23,000 years, respectively. Changes in these orbital characteristics affect the seasonal contrasts experienced on Earth. Minimal seasonal contrasts (i.e., cooler summers, warmer winters) are conducive to cooler periods while greater seasonal contrasts promote warmer climate episodes. The prevailing thinking is that warmer winters result in higher snowfall amounts and cooler summers lead to reduced melting of the winter snowpack. The net effect is to raise the planet's reflectivity (albedo), driving temperatures lower over time. The opposite occurs during periods of high seasonal contrast.

The heat energy of fossil fuel combustion is very small compared to the natural heat flux from the Sun and other processes. It is estimated that the total man-made combustion energy amounts to about 0.031 Wm^2, averaged over the surface of Earth. The Sun provides 340 Wm^2, nearly 11,000 times more. The Sun is responsible for nearly 100% of the heat coming to Earth. A very small fraction is contributed by heat rising through the crust from the molten core.

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2.1.2.2 Carbon Cycle

Levels of carbon dioxide (CO_2) and methane (CH_4) in the atmosphere are governed by processes of the carbon cycle. Exchange rates and other climatological processes are poorly understood.

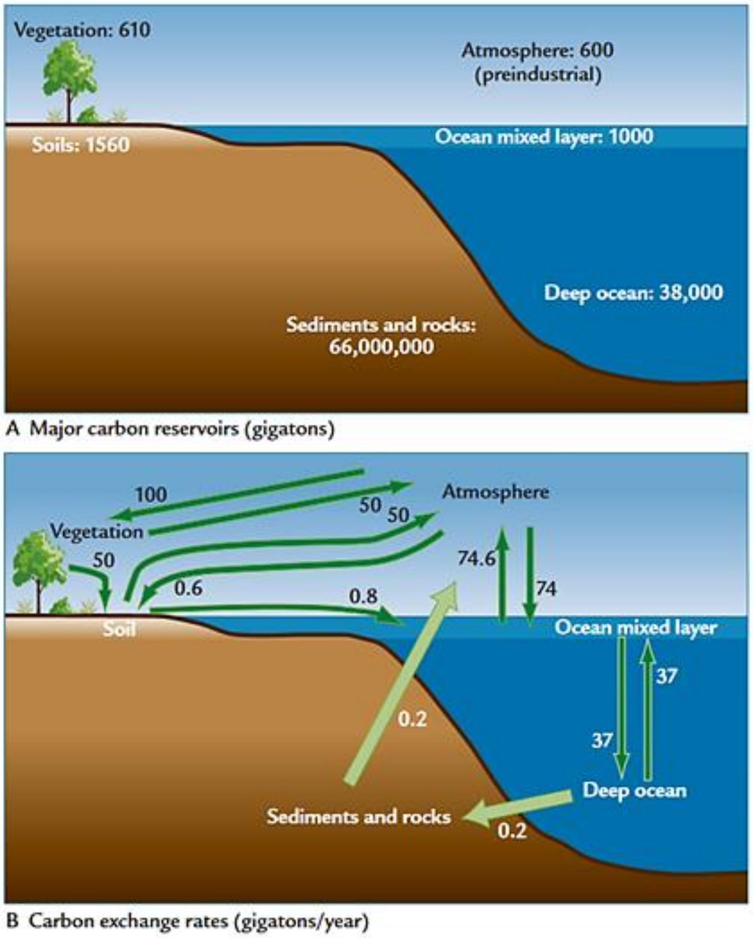
Earth's energy budget only partly explains the natural processes that determine surface temperatures. Carbon dioxide (CO_2) and methane (CH_4) are two gases whose rising presence in the atmosphere contributes to rising temperatures. Their concentration in the atmosphere is a function of complex processes characterized in biology as the "carbon cycle." A typical simplified rendering of the cycle appears in Figure 2.1.2.2.1. The Intergovernmental Panel on Climate Change (IPCC) presents a more detailed but no more accurate rendering of the cycle in Figure 6.2 in the Working Group I contribution to its Fifth Assessment Report (IPCC, 2013, p. 474).

Carbon and hydrogen appear abundantly throughout the universe and on Earth. Carbon's unique function as the base element for Earth's biosphere derives from it being the lightest element capable of forming four covalent bonds with atoms of most elements in many variations. ("Covalent bonds" involve the sharing of electron pairs and are stronger than bonds involving single electrons.) The resulting molecules can contain from one to millions of carbon atoms. Carbon is so abundant and apt to bond with other atoms that the discipline of chemistry is divided into *organic chemistry*, which studies only carbon-based compounds, and *inorganic chemistry*, which studies all other compounds. Carbon-based compounds comprise the overwhelming majority of the tens of millions of compounds identified by scientists.

Carbon Reservoirs

Carbon on Earth is stored in four reservoirs: rocks and sediments (lithosphere), oceans and lakes (hydrosphere), vegetation and soil (biosphere), and the air (atmosphere). Contrary to casual assertions and sometimes feigned certainty, the amount of carbon stored in each reservoir and the exchanges among reservoirs are not known with certainty. There is no way to actually measure things as large as the lithosphere or atmosphere, so all estimates of their sizes depend on measurements performed on small parts and fed into models to generate global estimates. These estimates vary widely depending on assumptions made by models. Predictably, estimates of reservoir sizes vary in the literature. The numbers in Figure 2.1.2.2.1 and below from Ruddiman (2008)

Figure 2.1.2.2.1
Schematic of the global carbon cycle



Source: Modified from Ruddiman, 2008, p. 46. See original for sources.

differ, for example, from those appearing in Falkowski *et al*. (2000), which at the time was thought to be authoritative, and the IPCC's Fifth Assessment Report (IPCC, 2013, pp. 471–4), also thought to be authoritative. According to Ruddiman, carbon is distributed among reservoirs as follows:

Gigatons of Carbon (GtC)	Reservoirs
66,000,000	Rocks and sediment (lithosphere)
39,000	Oceans (hydrosphere)
2,170	Vegetation and soils (biosphere)
600	Air (atmosphere) (preindustrial)

The carbon stored in rocks and sediment dominates the distribution, some 110,000 times as much as the amount in the air. That carbon is mostly in the form of carbonate rocks such as limestone (which is mainly calcium carbonate), marble, chalk, and dolomite. Most of the carbon stored in Earth's mantle was there when Earth formed. Some of the carbon in Earth's crust was deposited there in the form of undecayed biomass produced by the biosphere, buried by the mechanics of plate tectonics, and turned by metamorphism into fossil fuels.

Carbon moves from rocks and sediment into the atmosphere via outgassing from midocean ridges and hotspot volcanoes, leakage of crude oil on the ocean floor, weathering of rocks, upward percolation and migration from deeper in the lithosphere, and human drilling, transporting, and burning of fossil fuels. Just how much carbon is released from the lithosphere in any given year is uncertain since empirical measurements are available for only ~20% of major volcanic gas emission sources. Many researchers suspect computer models of the carbon cycle underestimate the impact of volcanic activity on ocean currents, sea surface temperature, and ice formation and melting (e.g., Viterito, 2017; Smirnov *et al*., 2017; Kobashi *et al.*, 2017; Slawinska and Robock, 2018; and Ilyinskaya *et al.*, 2018). Wylie (2013) reported,

> In 1992, it was thought that volcanic degassing released something like 100 million tons of CO_2 each year. Around the turn of the millennium, this figure was getting closer to 200 [million]. The most recent estimate, released this February, comes from a team led by Mike Burton, of the Italian National Institute of Geophysics and Volcanology [Burton *et al*., 2013] – and it's just shy of 600 million tons. It caps a staggering trend: A six-fold increase in just two decades.

Oceans are the second largest reservoir of carbon, containing about 65 times as much as the air. The IPCC and other political and scientific bodies assume roughly 40% of the CO_2 produced by human combustion of fossil fuels is absorbed and sequestered by the oceans, another 15% by plants and animals (terrestrial as well as aquatic), and what is left remains in the air, contributing to the slow increase in atmospheric concentrations of CO_2 during the modern era.

When CO_2 dissolves into water, it reacts with water molecules to form carbonic acid, which increases concentrations of the hydrogen carbonate (HCO_3-) and carbonate (CO_3-$_2$) ions, which in turn form carbonate rocks, in the process removing CO_2 from the air, a process called weathering. Deep-sea calcium carbonate sediments also neutralize large amounts of CO_2 by reacting with and dissolving it. A hypothetical carbon equilibrium between the atmosphere and the world's oceans would probably show the oceans have assimilated between 80% and 95% of the anthropogenic CO_2 from the atmosphere (World Ocean Review 1, 2010).

Vegetation and soils are the third largest reservoir of carbon, containing approximately 3.6 times as much as the air. The carbon in living matter is derived directly or indirectly from carbon dioxide in the air or dissolved in water. Algae and terrestrial green plants use photosynthesis to convert CO_2 and water into carbohydrates, which are then used to fuel plant metabolism and are stored as fats and polysaccharides. The stored products are then eaten by other organisms, from protozoans to plants to man, which convert them into other forms. CO_2 is added to the atmosphere by animals and some other organisms via respiration. The carbon present in animal wastes and in the bodies of all organisms is also released into the air as CO_2 by decay (DiVenere, 2012).

Uncertainty pervades estimates of the size of the biospheric carbon reservoir. Bastin *et al.* (2017), using high-resolution satellite images covering more than 200,000 plots, found tree-cover and forests in drylands "is 40 to 47% higher than previous estimates, corresponding to 467 million hectares of forest that have never been reported before. This increases current estimates of global forest cover by at least 9%." Their finding, they write, "will be important in estimating the terrestrial carbon sink."

Earth's atmosphere, the fourth carbon reservoir, holds the least carbon – about 600 GtC before human combustion of fossil fuels began to make a measurable contribution. The current best estimate is approximately 870 GtC. Carbon in the atmosphere exists mainly as CO_2 and methane. Pathways for carbon to enter the atmosphere from other reservoirs have already been described. Carbon dioxide leaves the atmosphere by dissolving into bodies of water (oceans, rivers, and lakes), being taken up by plant leaves, branches, and roots during the process of photosynthesis, and being absorbed by the soil.

Carbon dioxide composes approximately 400 parts per million (ppm) of the atmosphere by volume and methane approximately 1,800 parts per billion (ppb). Atmospheric concentrations of both substances have increased since the start of the Industrial Era and both increases are thought to be largely due to human activities, with CO_2 coming from the burning of fossil fuels and methane from agricultural practices and the loss of carbon sinks due to changes in land use. However, uncertainties in measurement and new discoveries cast doubt on this assumption. In any case, compared to natural sources of carbon in the environment, the human contribution is very small.

Exchange Rates

The carbon cycle acts as a buffer to minimize the hypothesized impact of atmospheric CO_2, whether from natural or man-made sources, on surface temperatures. It provides an illustration of Le Chatelier's principle, which states, "when a stress is applied to a chemical system at equilibrium, the equilibrium concentrations will shift in a direction that reduces the effect of the stress" (ChemPRIME, 2011). In the case of CO_2 and the carbon cycle, atmospheric CO_2 is in equilibrium with dissolved CO_2 in the oceans and the biosphere. An increased level of CO_2 in the atmosphere will result in more CO_2 dissolving into water, partly offsetting the rise in atmospheric concentrations as well as forming more carbonic acid, which causes more weathering of rocks, forming calcium ions and bicarbonate ions, which remove more CO_2 from the air. The biosphere will also increase its uptake of CO_2 from the air (the aerial fertilization effect) and sequester some of it in woody plants, roots, peat, and other sediments (Idso, 2018). Atmospheric CO_2 concentrations will then fall, restoring the system to equilibrium.

In contrast to this first order process, where the rate of exchange among reservoirs is directly proportional to the amount of carbon present, the IPCC's carbon cycle model assumes an uptake that scales with the emission rate and not the actual concentration. Such models can never come to a new equilibrium for a slightly increased but constant emission rate due to natural or human influences. The IPCC also contends the time frames on which some parts of the carbon cycle operate, such as the weathering cycle and dissolving into deep oceans, are too long for them to help offset during the twenty-first century the sudden pulse of CO_2 from the combustion of fossil fuels in the twentieth century. But the fact that some exchange processes operate slowly and others rapidly does not mean, *prima facie*, that an entire pulse of CO_2 cannot be absorbed by the faster-acting parts of the carbon cycle. The different sinks for CO_2 act in parallel and add up to a total uptake as a collective effect, determined by the fastest, not the slowest, sinks (Harde, 2017). The rapid response of the biosphere is seen in the widely documented "greening of the Earth" discussed in Chapter 5, Section 5.3.

The IPCC estimates that between 200 and 220 GtC enters Earth's atmosphere each year. Of that total, 8.9 GtC is anthropogenic (7.8 GtC from fossil fuels and 1.1 GtC from net land use change (agriculture)). The total human contribution, then, is only about 4.3% of total annual releases of carbon into the atmosphere (IPCC, 2013, p. 471, Figure 6.1). The IPCC "assessed that about 15 to 40% of CO_2 emitted until 2100 will remain in the atmosphere longer than 1,000 years" and "the removal of all the human-emitted CO_2 from the atmosphere by natural processes will take a few hundred thousand years (high confidence)," citing Archer and Brovkin (2008) and reproducing the table shown in Figure 2.1.2.2.2 (p. 472).

Human use of fossil fuels contributes only about 3.5% (7.8 Gt divided by 220 Gt) of the carbon entering the atmosphere each year and so, with about 0.5% (1.1 Gt divided by 220 Gt) from net land use change, natural sources account for the remaining 96.0%. The residual of the human contribution the IPCC

Figure 2.1.2.2.2
Time required for natural processes to remove CO_2 from atmosphere (IPCC AR5)

Processes	Time scale (years)	Reactions
Land uptake: Photosynthesis–respiration	$1–10^2$	$6CO_2 + 6H_2O + \text{photons} \rightarrow C_6H_{12}O_6 + 6O_2$ $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{heat}$
Ocean invasion: Seawater buffer	$10–10^3$	$CO_2 + CO_3^{2-} + H_2O \rightleftharpoons 2HCO_3^-$
Reaction with calcium carbonate	$10^3–10^4$	$CO_2 + CaCO_3 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$
Silicate weathering	$10^4–10^6$	$CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$

Source: IPCC, 2013, p. 472, Box 6.1, Table 1, citing Archer and Brovkin, 2008.

believes remains in the atmosphere after natural processes move the rest to other reservoirs is as little as 1.17 Gt per year (15% of 7.8 Gt), just 0.53% of the carbon entering the atmosphere each year. This is less than two-tenths of 1% (0.195%) of the total amount of carbon thought to be in the atmosphere, per Ruddiman (2008).

The lasting human contribution of carbon emitted to the atmosphere by the use of fossil fuels, according to the IPCC's own estimates, is minuscule, less than 1% of the natural annual flux among reservoirs. As stated earlier, all estimates of the amount of carbon in the four reservoirs and the exchange rates among them are uncertain and constantly being revised in light of new findings. Yet the IPCC assumes exchange rates are estimated with sufficient accuracy to say "It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together," while "the contribution of natural forcings is likely to be in the range of −0.1°C to 0.1°C and from natural internal variability is likely to be in the range of −0.1°C to 0.1°C" (IPCC, 2013, p. 17). This seems improbable.

The atmospheric CO_2 trend is a minute residual between titanic sources and sinks that mostly cancel out each other. While measurable in ambient air, the residual is likely to be less than the margin of error in measurements of the reservoirs or natural variability in their exchange rates. The IPCC came close to acknowledging this in the Working Group I contribution to its Third Assessment Report (IPCC, 2001, p. 191), writing "Note that the gross amounts of carbon annually exchanged between the ocean and atmosphere and between the land and atmosphere, represent a sizeable fraction of the atmospheric CO_2 content – and are many times larger than the total anthropogenic CO_2 input. In consequence, an imbalance in these exchanges could easily lead to an anomaly of comparable magnitude to the direct anthropogenic perturbation."

Why does the IPCC assume exchange rates will not continue changing to keep pace with human contributions of CO_2 to the atmosphere, as they have accommodated both natural and anthropogenic changes in the past? A case can be made based on chemistry and biological science that keeping pace should be the null hypothesis, instead of the IPCC's apparent assumptions that some reservoirs already are or soon will be saturated, or that some fraction of anthropogenic CO_2 will remain in the atmosphere until only very slow natural processes such as weathering and deep ocean sequestration can remove it.

Residence Time

Regarding residence time (the average time carbon spends in a given reservoir), according to Harde (2017, p. 20), "Previous critical analyses facing the IPCC's favored interpretation of the carbon cycle and residence time have been published," citing Jaworowski *et al.* (1992), Segalstad (1998), Dietze (2001), Rörsch *et al.* (2005), Essenhigh (2009), Salby (2012, 2016), and Humlum *et al.* (2013). "Although most of these analyses are based on different observations and methods, they all derive residence times (in some cases also differentiated between turnover and adjustment times) in part *several orders of magnitude shorter than specified in [the Fifth Assessment Report]*. As a consequence of these analyses also a much smaller anthropogenic influence on the climate than propagated by the IPCC can be expected" (italics added).

Harde (2017) derives a residence time of his own, writing, "for the preindustrial period, for which the system is assumed to be in quasi equilibrium, a quite reliable estimate of the average residence time or lifetime can be derived from the simple relation, that under steady state the emission or absorption rate times the average residence time gives the total CO_2 amount in the atmosphere" (p. 21). He calculates a residence time of just three years. Over the industrial era, using the IPCC's own exchange rate estimates, he finds a residence time of 4.1 years. He notes, "a residence time of 4 years is in close agreement with different other independent approaches for this quantity," identifying tests on the fall-out from nuclear bomb testing and solubility data while referencing Sundquist (1985), Segalstad (1998), and Essenhigh (2009).

While the IPCC says it would take longer than one thousand years for oceans and the biosphere to absorb whatever residue of human-produced CO_2 remains after all use of fossil fuels is somehow halted, Harde finds the IPCC's own accounting scheme shows it would take no more than 47.8 years, this derived from the IPCC's own accounting scheme, which considers a slightly increased absorption rate of 2.4%, forced by the instantaneous anthropogenic emission rate of 4.3%. An even more coherent approach presupposing a first order uptake process and no longer distinguishing between a natural and anthropogenic cycle, this results in a unique time scale, the residence time of only four years.

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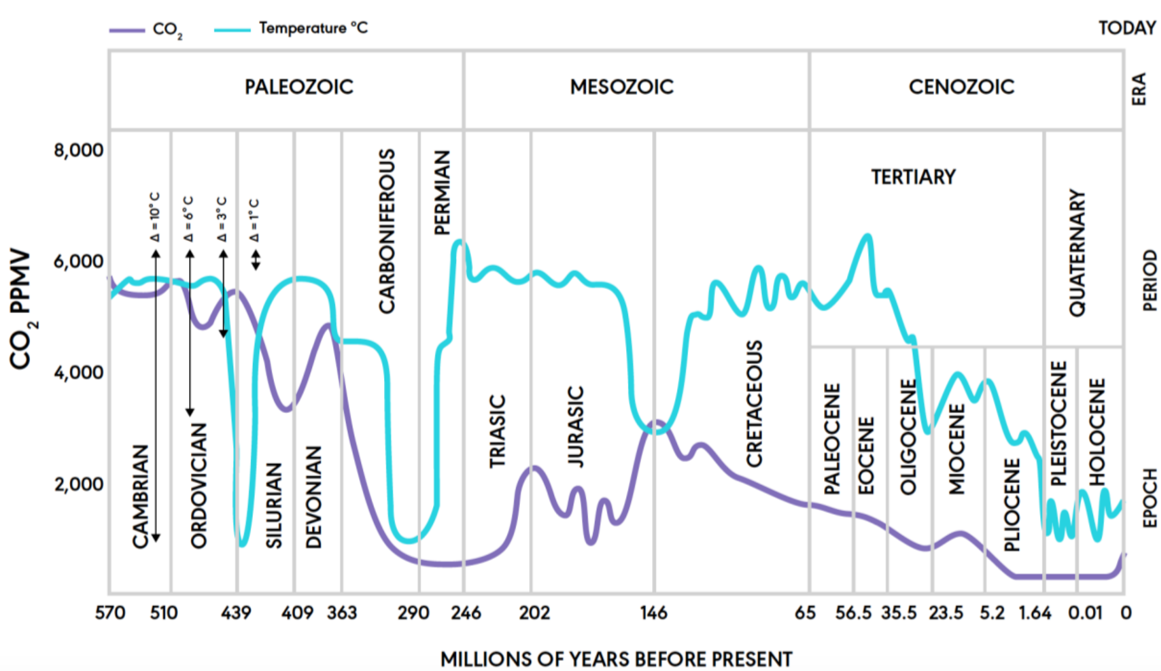
2.1.2.3 Geological Record

The geological record shows temperatures and CO_2 levels in the atmosphere have not been stable, making untenable the IPCC's assumption that they would be stable in the absence of human emissions.

Estimates of CO_2 concentrations in the atmosphere and local surface temperatures in the distant past can be made by extrapolation from proxy data, which the IPCC defines as "a record that is interpreted, using physical and biophysical principles, to represent some combination of climate-related variations back in time. … Examples of proxies include pollen analysis, tree ring records, speleothems, characteristics of corals and various data derived from marine sediments and ice cores" (IPCC, 2013, p. 1460). The most valuable proxy data come from oxygen and hydrogen isotopes in ice and CO_2 in air bubbles preserved in ice cores obtained by drilling in Antarctica and Greenland. Temperature is inferred from the isotopic composition of the water molecules released by melting the ice cores. During colder periods, there will be a higher ratio of ^{16}O to ^{18}O and ^{2}H (also known as deuterium) to ^{1}H in the ice formed than would be found during warm periods. Once again it is important to note that reconstructions of past climatic conditions are not actually data. Like "carbon reservoirs" and "exchange rates," such reconstructions rely on very limited data fed into models and subject to interpretation by scientists.

Proxy data reveal temperatures have varied considerably over the past 600 million years (Lamb, 2011, 2012). Earth's orbital changes, known as Milankovitch cycles and described previously, are the generally accepted explanation for these broad changes in temperatures. Figure 2.1.2.3.1 shows one reconstruction of changes in temperature (blue) and CO_2 levels (purple) for the past 570 million years or

Figure 2.1.2.3.1
Global temperature and atmospheric CO_2 concentration over the past 600 million years



Purple line is CO_2 concentration (ppm); blue line is change in temperature (Δ°C). Horizontal scale is not in constant units. CO_2 scale derived from ratios to levels at around 1911 (300 ppm) calculated by Berner and Kothavala, 2001. *Source*: Adapted from Nahle, 2009 referencing Ruddiman, 2001; Scotese, 2002; and Pagani *et al.,* 2005.

so. Both temperature and and CO_2 are lower today than they have been during most of the era of modern life on Earth since the Cambrian Period. For more than 2.5 million years (the Pleistocene Epoch) the world was in a cold period with long glaciations (ice ages) interrupted by relatively brief warm periods of typically 10,000 to 15,000 years. On this time scale, temperature and CO_2 are completely without correlation. Note "before present" means before 1950, so warming and CO_2 levels since then are not shown.

We have been in the current Holocene Epoch warm period for about 11,500 years. Within the Holocene, there is strong physical evidence for periods of both global warming and cooling, although those periods are less extreme than the Milankovitch-forced glaciation cycles. The current warm period was preceded by the Little Ice Age (1300–1850 AD), which was preceded by the Medieval Warm Period or Medieval Climate Optimum (800–1300 AD), which was preceded by the Dark Ages Cold Period (400–800 AD), which was preceded by the Roman Warm Period or Roman Climate Optimum (250 BC–400 AD). Before that there is evidence of a Minoan Warm Period (~2500 BC) and a thousand-year Holocene Climate Optimum about 6,500 years ago.

Most of the "warm periods" or "climate optimums" are thought to have been at least as warm as Earth's current climate. The Greenland Ice Sheet Project Two (GISP2) used ice cores to estimate temperatures between 1,500 to 10,000 years ago, shown in Figure 2.1.2.3.2 (Alley, 2000). These findings are validated by global glacial advances and retreats, oxygen isotope data from cave deposits, tree ring data, and historic records (Singer and Avery, 2007). Within the past 5,000 years, the Roman Warm Period appears prominently in the GISP2 ice core, about 1,500–1,800 years ago. During that period, ancient Romans wrote of grapes and olives growing farther north in Italy than had been previously thought possible, as well as of there being little or no snow or ice.

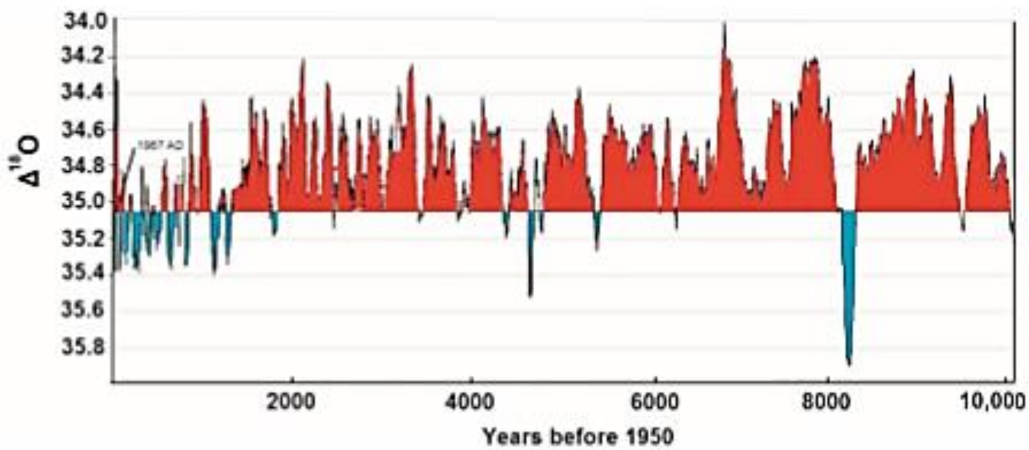
Oxygen isotope data from the GISP2 Greenland ice cores show the prominent Medieval Warm Period (MWP) occurring around 900–1300 AD. The MWP was followed by a period of global cooling and the beginning of the Little Ice Age, which spanned the sixteenth to the eighteenth centuries, though some scientists date its start much earlier. The effects of the MWP are also seen in the reconstructions of sea surface temperature near Iceland by Sicre *et al*. (2008), reproduced as Figure 2.1.2.3.3 below. During the MWP in Europe, grain crops flourished, alpine tree lines rose, and the population more than doubled. The Vikings took advantage of the warmer climate to colonize Greenland. The MWP was a global event with proxy data confirming the warm period found in Africa (Lüning *et al*., 2017), South America (Lüning *et al.*, 2018), North America (McGann, 2008), China (Hong *et al*., 2009), and many other areas (NIPCC, 2011, Chapter 3). More recent temperature records are discussed in Section 2.2.1. Four observations from the geological record of the carbon cycle, as shown by ice core records and other proxy data, should guide any discussion of the human impact on Earth's climate. First, the concentration of CO_2 in the atmosphere today is below levels that existed during most of the geologic record. Figure 2.1.2.3.1 graphs CO_2 and temperature over geological time with temperature in blue, atmospheric CO_2 concentration in purple, and the trend in CO_2 concentration represented by the purple arrow. Moore (2016, p. 8) writes, "Note the uptick [in CO_2 concentrations] at the far right of the graph representing the reversal of the 600 million-year downward trend due primarily to emissions of CO_2 from the use of fossil fuels for energy. Note that even today, at 400 ppm, CO_2 is still far lower than it has been during most of this 600 million-year history." Figure 2.1.2.3.1 also shows the average level of CO_2 in the atmosphere over the geological span encompassing the evolution and spread of plants, about 300 million years before present, was probably approximately 1,000 ppm, more than twice today's level.

The dramatic fall in atmospheric CO_2 concentrations is significant in the climate change discussion because virtually all species of plant and animal life in the world today arose, evolved, and flourished during periods when atmospheric CO_2 levels were much higher than they are today. Moreover, during the Paleocene-Eocene Thermal Maximum, the average global temperature was 16°C (28.8°F) higher than temperature today. This suggests today's species will survive or even thrive if CO_2 levels rise to several times their current levels and if temperatures increase more than 2°C or 3°C (3.6° or 5.4° F), the increase the IPCC claims would result in unacceptable and irreversible ecological harm.

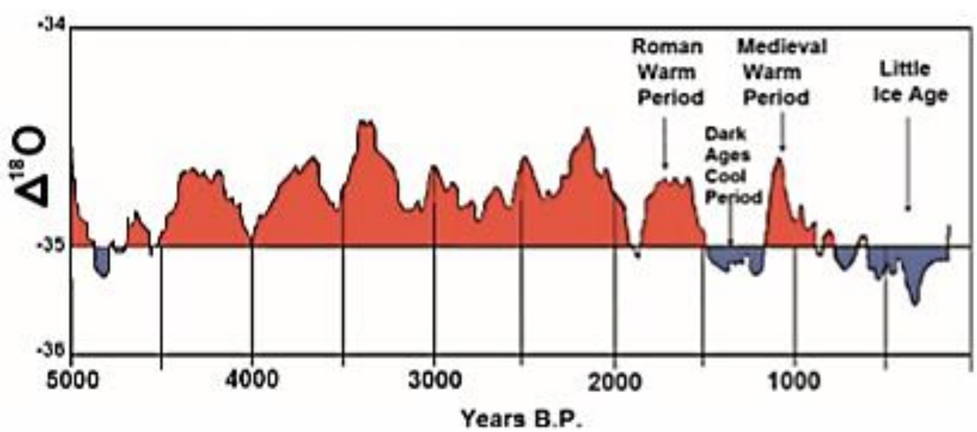
The second observation from the geological record is that CO_2 levels in the atmosphere are not stable, making untenable the IPCC's assumption that they would be stable in the future in the absence of human emissions. The increase in atmospheric CO_2 concentrations in the modern era, while dramatic when viewed as a trend over thousands or even hundreds of thousands of years, is a brief reversal of

Figure 2.1.2.3.2
Temperatures from Greenland ice cores

A. Greenland GISP2 oxygen isotope curve for the past 10,000 years

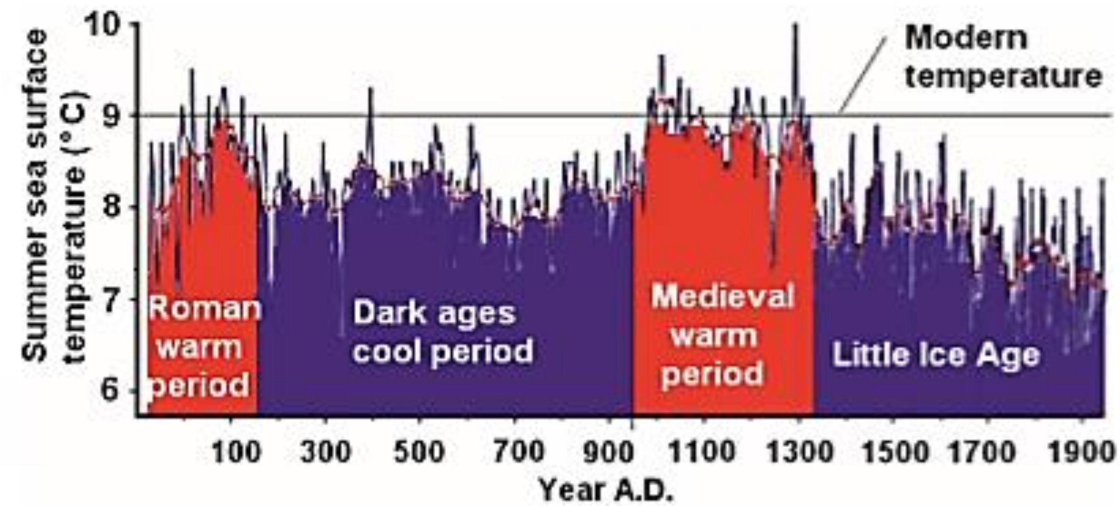


B. Greenland GISP2 oxygen isotope curve for the past 5,000 years.



The vertical axis is $\delta^{18}O$, which is a temperature proxy. Horizontal scale for (a) is 10,000 years before 1950 and for (b) is past 5,000 years. The red areas represent temperatures warmer than present (1950). Blue areas are cooler times. Note the abrupt, short-term cooling 8,200 years ago and cooling from about 1500 A.D. to 1950. *Source*: Alley, 2000, plotted from data by Grootes and Stuiver, 1997.

Figure 2.1.2.3.3
Summer sea surface temperature near Iceland



.
Source: Sicre *et al*., 2008.

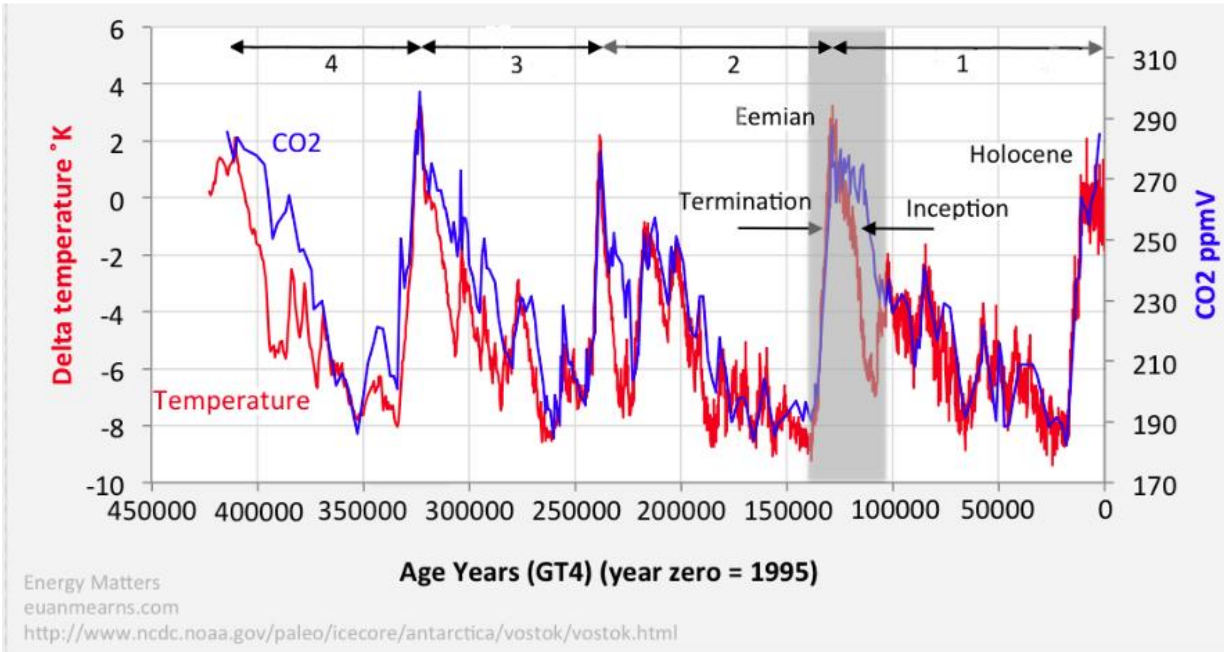
a multi-million-year trend. Today's atmospheric CO_2 concentrations are "unprecedented" only because they are *lower* than at most other points in the record. The third observation from the geological record is that CO_2 concentrations in the atmosphere typically rose several hundred years *after* temperatures rose, indicating temperature increase was not caused by the CO_2 rise (Petit *et al*., 1999; Monnin *et al.*, 2001; Mudelsee, 2001; Caillon *et al.*, 2003). This is shown in Figure 2.1.2.3.4, where carbon dioxide levels appear as a blue line and changes in temperature are plotted in red. The graph, reproduced from Mearns (2014), shows data from the Vostok ice core drilled in 1995. Mearns explains how the record is created:

> [T]he temperature signal is carried by hydrogen: deuterium isotope abundance in the water that makes the ice whilst the CO_2 and CH_4 signals are carried by air bubbles trapped in the ice. The air bubbles trapped by ice are always deemed to be younger than the ice owing to the time lag between snow falling and it being compacted to form ice. In Vostok, the time lag between snow falling and ice trapping air varies between 2000 and 6500 years. There is therefore a substantial correction applied to bring the gas ages in alignment with the ice ages and the accuracy of this needs to be born in mind in making interpretations.

The Vostok ice core is 3,310 meters long and represents 422,766 years of snow accumulation. Mearns writes, "There is a persistent tendency for CO_2 to lag temperature throughout and this time lag is most pronounced at the onset of each glacial cycle '*where CO_2 lags temperature by several thousand years'"* (quoting Pettit *et al.*, 1999). Writing three years later, Mearns (2017) comments, "It is quite clear from the data that CO_2 follows temperature with highly variable time lags depending upon whether the climate is warming or cooling. … The general picture is one of quite strong-co-variance, but in detail there are some highly significant departures where temperature and CO_2 are clearly de-coupled" and "CO_2 in the past played a negligible role [in determining temperature]. It simply responded to bio-geochemical processes caused by changing temperature and ice cover."

For other recent temperature record reconstructions showing the "CO_2 lag" see Soon *et al.* (2015), Davis (2017), and Lüning and Vahrenholt (2017). During periods of glaciation, cooling oceans absorb more CO_2 due to the "solubility pump," which Moore defines as "the high solubility of CO_2 in cold

Figure 2.1.2.3.4
Temperature and CO_2 co-variance in the Vostok ice core



CO_2 and temperature appear well-correlated in a gross sense but there are some significant deviations. At the terminations, the alignment is good but upon descent into the following glaciation there is a time lag between CO_2 and temperature of several thousand years. *Source:* Mearns, 2014.

ocean water at higher latitudes where sinking cold sea-water carries it into the depths of the ocean" (Moore, 2016, p. 10). During warmer inter-glacial periods, oceans absorb less CO_2 or outgas more of it into the air. Plant life absorbs more CO_2 from the air during warm periods than during cold periods, having a countercyclical effect but one that is much smaller given that the ocean reservoir is approximately 65 times as large as the biosphere.

The fourth observation from the geological record is that the rise in CO_2 levels since the beginning of the Industrial Age, whether due to human emissions from the use of fossil fuels and changes to land use or the result of ocean outgassing caused by cyclical warming, could be averting an ecological disaster. As Moore observes, "on a number of occasions during the present Pleistocene Ice Age, CO_2 has dropped during major glaciations to dangerously low levels relative to the requirements of plants for their growth and survival. At 180 ppm, there is no doubt that the growth of many plant species was substantially curtailed" (Moore, 2016, p. 10, citing Ward, 2005).

"If humans had not begun to use fossil fuels for energy," Moore continues, "it is reasonable to assume that atmospheric CO_2 concentration would have continued to drop as it has for the past 140 million years," perhaps to levels so low during the next glaciation period as to cause "widespread famine and likely the eventual collapse of human civilization. This scenario would not require two million years but possibly only a few thousand" (Moore, 2016, pp. 16–17).

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2.1.2.4 Greenhouse Gases

Water vapor is the dominant greenhouse gas owing to its abundance in the atmosphere and *the wide range of spectra in which it absorbs radiation. Carbon dioxide absorbs energy only in a very narrow range of the longwave infrared spectrum.*

A central issue in climate science is how much of the energy flowing through the atmosphere is obstructed by atmospheric gases called, erroneously, "greenhouse gases." (The label is erroneous because greenhouses warm the air inside by preventing convection, a process different than how these gases behave in the atmosphere. But the label was coined in 1963 and is the preferred term today.) Many laboratories have conducted repeated tests on the radiative properties of gases for more than a century, with handbooks reporting the results since the 1920s. All gases absorb energy at various wavelengths.

Carbon dioxide (CO_2), the greenhouse gas at the center of the climate change debate, is an invisible, odorless, tasteless, non-toxic gas that is naturally present in the air and essential for the existence of all plants, animals, and humans on Earth. In the photosynthesis process, plants remove CO_2 from the atmosphere and release oxygen, which humans and animals breathe in. CO_2 in the atmosphere does not harm humans directly. In confined spaces, such as in submarines or spacecraft, CO_2 concentrations can build up and threaten human health and safety – but only at concentrations more than 20 times the current trace levels in our atmosphere. Nuclear submarines commonly contain 5,000 parts per million (ppm) of CO_2 after more than a month below the surface (Persson and Wadsö, 2002). The current level of CO_2 in the atmosphere is approximately 405 ppm.

Radiative Properties

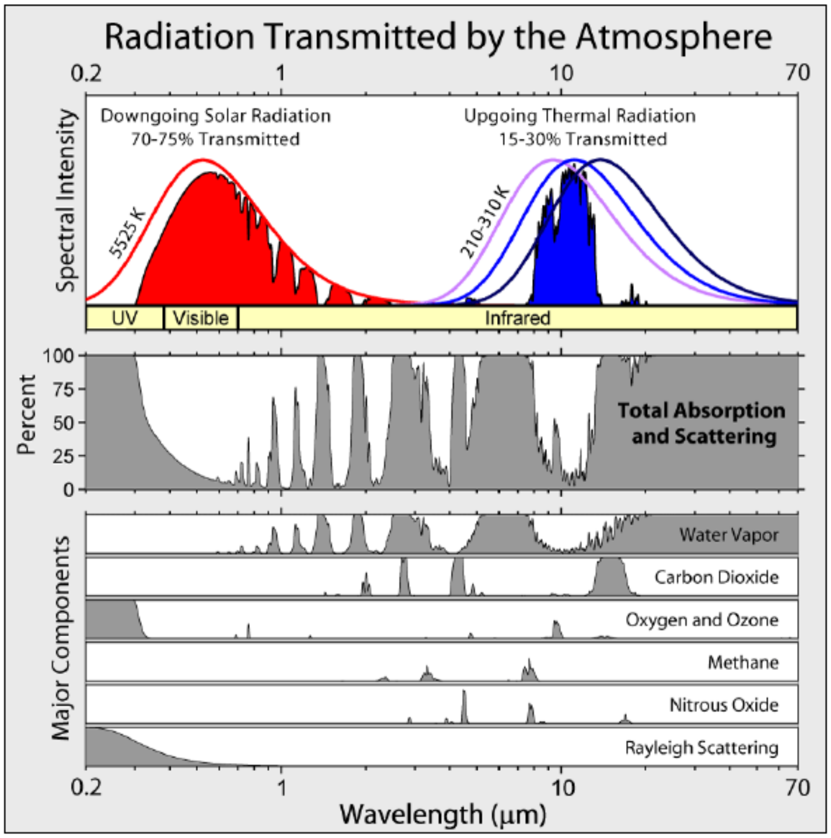
A two-atom molecule can spin and oscillate, while a three-atom molecule can also bend, which adds to the possibilities for interactions with radiation. Oxygen (O_2) and nitrogen (N_2) are symmetrical molecules, meaning they are linear and also include only a single element. The molecular stretches of two identical elements do not involve moving charges, so the molecule cannot bend. The chemical elements in CO_2 are different. The C-O stretches of CO_2 include moving charges because the molecular electrons are not symmetrically distributed. These moving atomic charges induce an oscillating electromagnetic (EM) field around the CO_2 molecule. That field can now couple with the EM field of infrared (IR) radiation. The energy quanta associated with the CO_2 bending mode transition corresponds to a photon of 15 µm longwave infrared radiation (Burch and Williams, 1956; Wilson and Gea-Banacloche, 2012). Similar properties of water vapor explain why it too can absorb radiation in the EM field, but across a much wider range of wavelengths.

When CO_2 absorbs IR radiation, it becomes vibrationally excited. This means the C-O atoms oscillate back-and-forth more quickly and with greater amplitude than they did before the IR was absorbed. The vibrationally excited CO_2 molecule strikes an oxygen (O_2) or nitrogen (N_2) molecule in the air and transfers that vibrational energy to the O_2 or N_2. That energy transfer causes the N_2 or O_2 average velocity – a measure of "translational kinetic energy" – to increase. It is like (to dramatize) slamming a car with a backhoe, causing the car to speed up. That greater translational kinetic energy is also a measure of the "thermal energy" of the gas as measured by its temperature. Water vapor behaves similarly in its respective wavelength spectrum. Briefly put, greenhouse gases transform IR radiation into vibrational energy, and then offload that vibrational energy into air molecules as thermal energy, which is injected into the atmosphere.

Absorption properties vary from gas to gas as shown in Figure 2.1.2.4.1. Some gases, such as nitrogen and oxygen, absorb energy in the ultraviolet spectrum, where wavelengths are shorter than visible light. The greenhouse gases in Earth's atmosphere are mostly transparent to the ultraviolet and visible wavelengths, meaning almost no energy is absorbed by these gases in that part of the spectrum. However, greenhouse gases do absorb energy in the far infrared spectrum (a/k/a longwave infrared or LWIR), at wavelengths much longer than visible light that are invisible to the human eye. If no further radiation of a particular wavelength is absorbed, the wavelength is said to be "saturated."

Figure 2.1.2.4.1 shows how water vapor is the dominant greenhouse gas owing to its abundance in the atmosphere and the wide range of spectra in which it absorbs LWIR radiation. CO_2 absorbs energy only in a very narrow range of the infrared spectrum, a wavelength of 15 µm (micrometers), and is overlapped by the water vapor range. Other greenhouse gases together absorb less than 1% of upgoing LWIR. With increasing altitude water vapor "condenses out" and falls as rain or snow and the concentration of water vapor falls to a few parts per million. When water vapor condenses to liquid water at high altitude, it radiates its excess thermal energy into space. This dynamic process cools and stabilizes

Figure 2.1.2.4.1
Radiation transmitted by the atmosphere and wavelengths absorbed by the five most important greenhouse gases



The data used for these figures are based primarily on Spectral Calculator of GATS, Inc. which implements the LINEPAK system of calculating (Gordley *et al.*, 1994) from the HITRAN2004 (Rothman *et al.*, 2004) spectroscopic database. To aid presentation, horizontal scale is not proportional and the absorption spectra were smoothed. Features with a bandwidth narrower than 0.5% of their wavelength may be obscured. *Source:* Wikipedia Commons, n.d.

the climate. At about 10 km (33,000 feet), CO_2, which does not "condense out," becomes the most abundant greenhouse gas.

The ability of greenhouse gases to absorb energy in the longwave infrared spectrum is important because Earth gives off much more LWIR than it receives, so gases that absorb LWIR have a warming effect by preventing the escape of some of the LWIR radiation to space. As shown in Figure 2.1.2.4.1, water vapor emits and absorbs infrared radiation at many more wavelengths than any of the other greenhouse gases, and there is substantially more water vapor in the atmosphere than any of the other greenhouse gases. While this means water vapor can generate thermal energy, water vapor also has a net *cooling* effect when it forms clouds. Clouds can reflect sunshine back into space during the day, but they can also reflect LWIR downward at night, keeping the surface warmer. Increasing levels of water vapor in the atmosphere, then, by increasing cloud formation, could result in nights getting warmer without increases in day-time high temperatures. Observations confirm this occurred during the twentieth century (Alexander *et al.*, 2006).

The effect of water vapor on surface temperature is especially important because CO_2 is not capable of causing significant warming by itself, due to the narrow range of the spectra it occupies. Scientists aligned with the IPCC claim CO_2 raises global temperature slightly and that rise, in turn, produces an increase in water vapor, which is capable of increasing atmospheric temperature (Chung *et al.*, 2014). But the hydrology of the atmosphere and dynamics of the ocean-atmosphere interface are poorly understood and modeled (Legates, 2014; Christy and McNider, 2017). Whether that effect is large enough to account for the warming of the twentieth century and early twenty-first centuries is a topic of debate and research.

Sources

The greenhouse gases that occur naturally and are also produced by human activities include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Other greenhouse gases produced only by human activities include the fluorinated gases such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs). Water vapor is by far the most prevalent greenhouse gas, with an average global ground-level concentration of approximately 14,615 ppm, about 1.5% of the atmosphere near the surface (less in the deserts, more in the tropics) (Harde, 2017). Carbon dioxide is present in the atmosphere at about 405 ppm, methane at 1.8 ppm, and nitrous oxide at 324 ppb. Fluorinated gases are measured in parts per trillion (IPCC, 2013, pp. 167-168).

As reported earlier, the IPCC estimates that between 200 and 220 GtC enters Earth's atmosphere each year. Of that total, 7.8 GtC comes from the combustion of fossil fuels and 1.1 GtC from net land use change (agriculture). The total human contribution, then, is only about 4.3% of total annual releases of carbon into the atmosphere (IPCC, 2013, p. 471, Figure 6.1). Human use of fossil fuels contributes only about 3.5% (7.8 Gt divided by 220 Gt) of the carbon entering the atmosphere each year and so, with about 0.5% (1.1 Gt divided by 220 Gt) from net land use change, natural sources account for the remaining 96.0%.

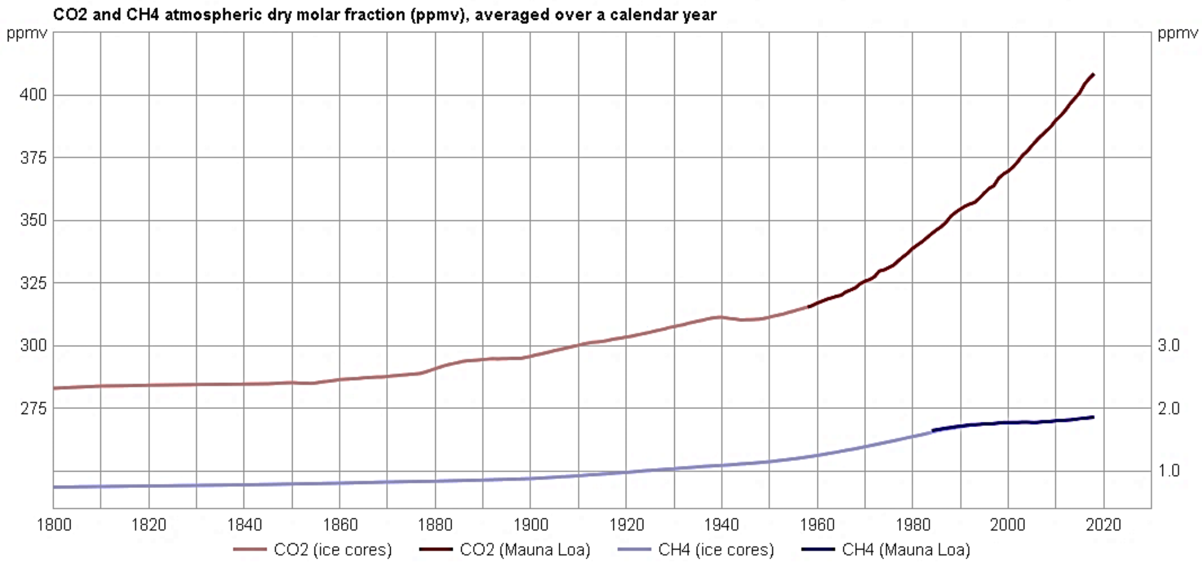
Carbon dioxide is readily absorbed by water (i.e., the oceans and rain). All else being equal, cold water will absorb more CO_2 than warm water. When the oceans cool they absorb more atmospheric CO_2; when they warm they release CO_2, thereby increasing the CO_2 concentration of the atmosphere. Consequently, over the past million years atmospheric CO_2 levels have varied, with warm "interglacials" causing higher atmospheric CO_2 levels due to oceanic outgassing, and colder glacial periods causing lower atmospheric CO_2 levels due to oceanic absorption. This variation in the CO_2 concentration of the atmosphere over the past 800,000 years is evident in the ice core data presented in Section 2.1.2.3.

Over the past million years, changes in atmospheric CO_2 level are believed to have been primarily due to release or absorption by oceans. However, human emissions related to the use of fossil fuels, manufacture of cement, and changes in land use (agriculture and forestry) are likely to be the main cause of the increase from approximately 280 ppm in 1800 to 405 ppm in 2018. Deforestation is often cited as a contributor of CO_2 into the atmosphere, but the well-documented "greening of the Earth" caused by the increase in atmospheric CO_2 appears to have offset any reduction in global biomass due to agriculture and forestry (De Jong *et al*., 2012; NIPCC, 2014, pp. 493–508). Figure 2.1.2.4.2 shows the rising concentrations of CO_2 and CH_4 since 1800.

Approximately 40% of the CO_2 released into the atmosphere by human activities is believed to be absorbed by the oceans. Figure 2.1.2.4.3 shows a recreation by Tans (2009) of "cumulative emissions consistent with observed CO_2 increases in the atmosphere and ocean," with uncertainties identified by horizontal lines through diamonds for the years to which they apply. The net terrestrial emissions (from plants, including aquatic plants) are derived "as a residual from better determined terms in the budget" (p. 29). Tans writes, "the atmospheric increase [in CO_2 concentrations] was primarily caused by land use until the early part of the twentieth century, but the net cumulative emissions from the terrestrial biosphere peaked in the late 1930s at ~45 GtC, dwindling to ~20 GtC in the first decade of the twenty-first century" (p. 30).

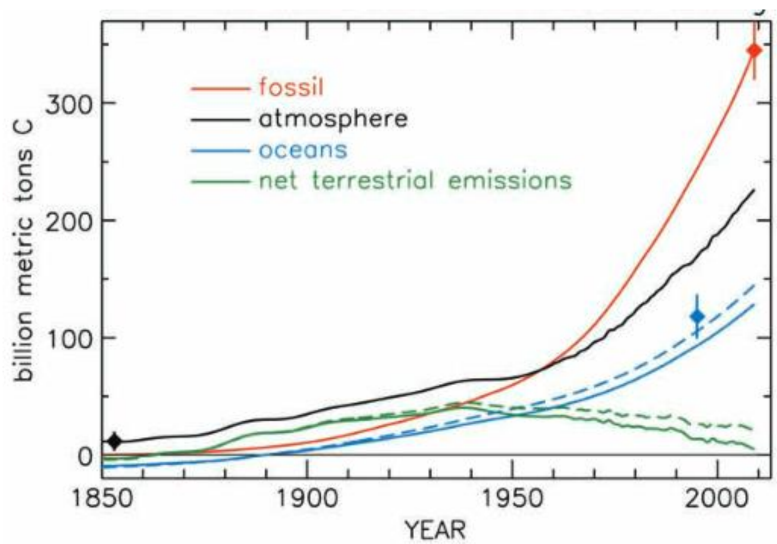
Tans (2009) also calculated the role fossil fuel emissions may play in determining future CO_2 levels in the atmosphere. He writes, "Instead of adopting the common economic point of view, which, through its emphasis on perpetual growth, implicitly assumes infinite Earth resources, or at least infinite substitutability of resources, let us start with an estimate of global fossil fuel reserves" (p. 32). Using data from the World Energy Council (WEC, 2007), Tans estimates there are 640 GtC of proved reserves and 967 GtC of resources (potential reserves when extraction technology improves). Consumption of fossil fuels rises exponentially at first as the easiest to exploit reserves are used but then declines as more

Figure 2.1.2.4.2
Atmospheric carbon dioxide (CO_2) and methane (CH_4) levels, 1800–present



Source: Burton, 2018. See original for data sources.

Figure 2.1.2.4.3
Cumulative emissions and reservoir change



History of cumulative emissions consistent with observed CO_2 increases in the atmosphere and ocean. Uncertainties in the fossil fuel emissions and the accumulations in the atmosphere and ocean are plotted with vertical lines for the years in which they apply. The Hamburg Ocean Carbon Cycle (HAMOCC3) model does not fit the observed cumulative ocean uptake. Therefore, there are two versions of cumulative ocean uptake and net terrestrial emissions: solid lines indicate HAMOCC3 and dashed lines indicate empirical pulse response function. *Source:* Tans, 2009, Figure 2, p. 29.

expensive and energy-intensive methods are needed to extract remaining reserves. Tans applies a logistic model where the rate of extraction is

$$E = dQ/dt = kQ(1 - Q/N)$$

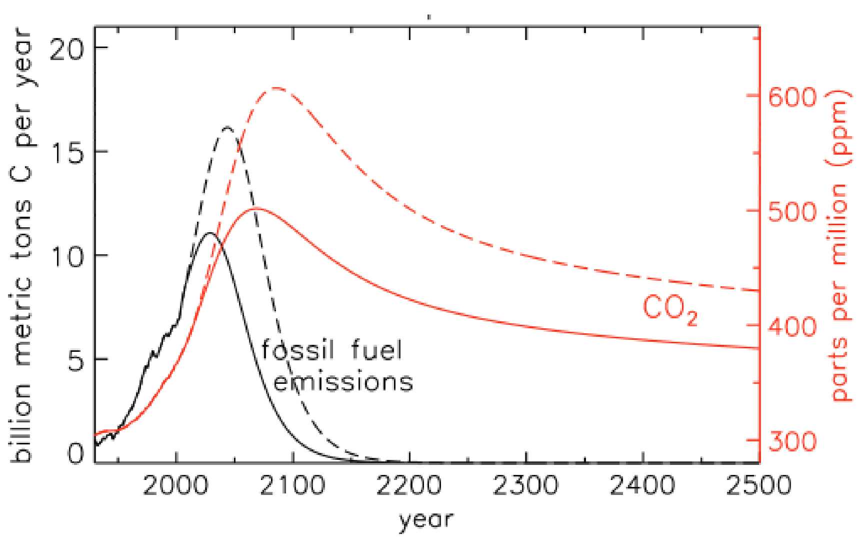
where E is the rate of extraction, Q is cumulative extraction, k is the initial exponential rate of growth, and $(1 - Q/N)$ expresses the increasing difficulty of extraction, which results in slowing of growth. The peak rate of extraction occurs when Q equals half of the total resource. Tans runs the model for two emission scenarios, one assuming 1,000 GtC of fossil fuels will eventually be used and the second, 1,500 GtC. The results are shown in the figure reproduced as Figure 2.1.2.4.4 below.

The Right Climate Stuff

The only scenario presented by the IPCC that does not assume some implementation of worldwide greenhouse gas (GHG) emission controls is RCP8.5, indicating the Representative Concentration Pathway (RCP) scenario would create 8.5 Wm^2 GHG forcing of global temperature in 2100. RCP8.5 is an extreme outlier in the climate science literature, assuming abnormally high estimates of world population growth and energy use and the absence of any technological improvements in energy efficiency that would lower per-capita growth in CO_2 equivalent (CO_{2eq}) emissions. RCP8.5 would result in more greenhouse gas emissions than 90% of any emissions scenarios published in the technical literature (Riahi *et al*., 2011). RCP8.5 also does not take into account the fossil-fuel supply and demand changes modeled by Tans (2009) as remaining reserves become more scarce or expensive to develop or the effects of conservation and fuel substitution as prices rise.

Doiron (2016) observes RCP8.5 assumes that by 2100 there would be 930 ppm of CO_2 in the atmosphere. This is 55% more than the 600 ppm of CO_2 that could be generated by burning all the currently known worldwide reserves of coal, oil, and natural gas, according to the U.S. Energy Information Administration's estimates. Working with The Right Climate Stuff (TRCS), a research team composed of retired NASA scientists and engineers, Doiron developed and validated a simple algebraic model for forecasting global mean surface temperature (GMST)

Figure 2.1.2.4.4
Fossil fuel emissions and atmospheric carbon dioxide concentrations, actual and forecast



Potential emissions in billion metric tons per year (black lines, left axis) and resulting atmospheric concentration in parts per million (red lines, right axis) for two emission scenarios. Solid lines represent Scenario A (emissions totaling 1,000 GtC), dashed lines represent Scenario B (emissions totaling 1,500 GtC. *Source*: Tans, 2009, Figure 4, p. 32.

using a standard transient climate sensitivity (TCS) variable but basing its forecast of atmospheric CO_2 concentration on historical data and known reserves of fossil fuels. Additionally, the TRCS metric includes a constant, β, based on historical data to account for the warming effects of greenhouse gases other than CO_2 and aerosols. In the TRCS model, TCS with the beta variable is TCS x (1 + β) = 1.8°C.

The TRCS research team developed two scenarios, RCP6.0 and RCP6.2, projecting CO_2 concentrations of 585 ppm and 600 ppm, respectively, by the year 2100. These scenarios determined a market-driven transition to alternative energy sources would need to *begin* by 2060 to meet the worldwide demand for energy, which will be growing even as reserves of coal, oil, and natural gas are declining and their prices rising. The RCP6.0 and RCP6.2 scenarios project the transition to alternative fuels would be complete by 2130 or 2100, respectively.

The IPCC's Fifth Assessment Report also presented an RCP6.0 scenario, which assumed implementation of modest CO_2 emission controls before 2100. The IPCC and TRCS RCP6.0 scenarios project similar trajectories of CO_2 concentration in the atmosphere by 2100, but the IPCC assumes worldwide controls on the use of fossil fuels would be required to achieve this RCP while the TRCS attributes falling emissions to market forces and a depleting supply of worldwide reserves of coal, oil, and natural gas. The 25-year forecasts for coal, oil, and natural gas consumption published by ExxonMobil (ExxonMobil, 2016) and British Petroleum (BP, 2016) align closely with the fossil-fuel consumption estimates included in the TRCS RCP6.0 and RCP6.2 scenarios.

Figure 2.1.2.4.5 shows the results of the TRCS model using the RCP6.2 emission scenario. The HadCRUT4 temperature anomaly database, which reaches back to 1850, appears on the left side on the vertical axis. The atmospheric CO_2 concentration in ppm is displayed on the right side on the vertical axis. The CO_2 concentration since 1850 and the RCP6.2 projection for the remainder of this century are represented by the green curve, with the sensitivity metric in the model represented by the blue curve. It was found to provide the best fit of the model to the data's long-term temperature increase trends.

The blue curve, the sensitivity metric, threads the narrow path between upper ranges of the temperature data and anomalous data points known to be associated with Super El Niño weather events. Model results with higher values of the sensitivity metric, represented by the red curve and red dashed curve in Figure 2.1.2.4.5, are clearly too sensitive based on historical CO_2 and temperature measurements. The GMST increase above current conditions for the TRCS model forecasting the RCP6.2 scenario is less than 2°C from 1850 to 2100 and less than 1°C from 2015 to 2100.

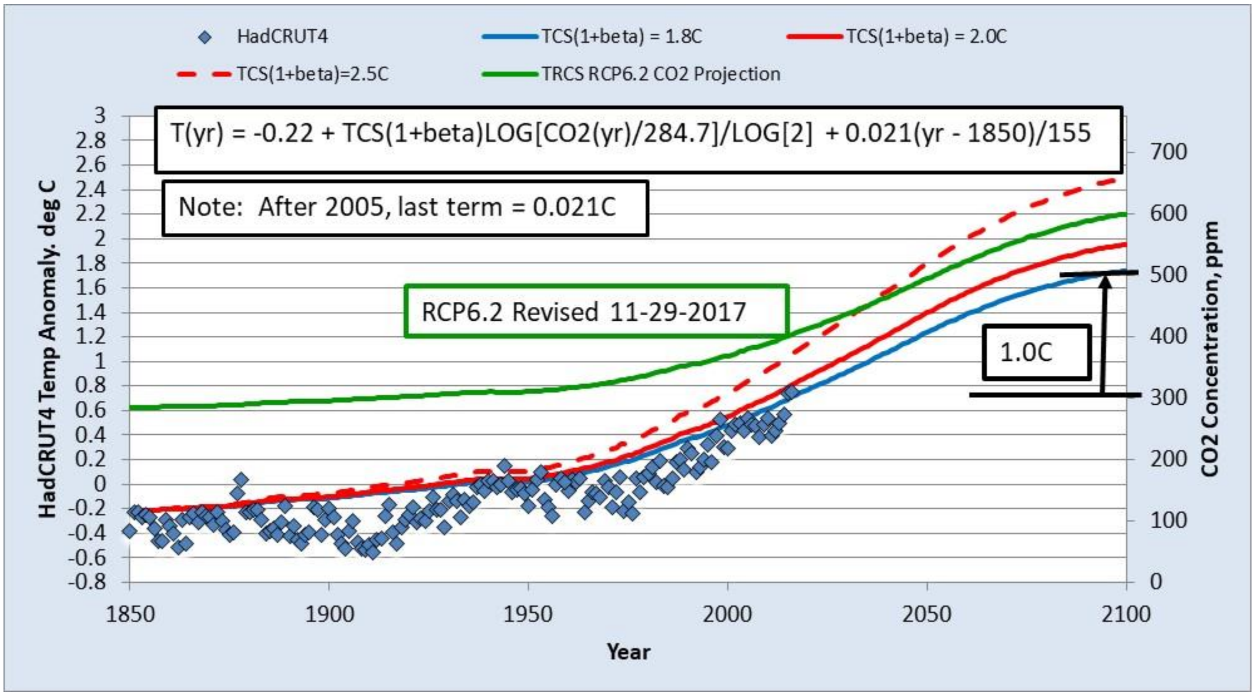
* * *

A basic understanding of the Earth's energy budget, carbon cycle, and geological record, and the chemical and radiative properties of greenhouse gases, helps clarify some of the key issues in climate science. Earth's "energy budget" explains how even a small change in the composition of the planet's atmosphere could lead to a net warming or cooling trend, but it also highlights the enormity of the natural processes and their variability compared to the impacts of the human presence, and therefore the difficulty of discerning a human "signal" or influence. The carbon cycle minimizes the impact of human emissions of CO_2 by reforming it into other compounds and sequestering it in the oceans, plants, and rocks. The exact size of any of these reservoirs is unknown, but they necessarily stay in balance with one another – Le Chatelier's principle – by exchanging huge amounts of carbon. According to the IPCC, the residual of the human contribution of CO_2 that remains in the atmosphere after natural processes move the rest to other reservoirs is as little as 0.53% of the carbon entering the air each year and 0.195% of the total amount of carbon thought to be in the atmosphere.

The geological record shows (a) the concentration of CO_2 in the atmosphere today is below levels that existed during most of the record, (b) CO_2 levels in the atmosphere are not stable in the absence of human emissions, (c) CO_2 concentrations in the atmosphere typically rise several hundred years *after* temperatures rise, and (d) the rise in CO_2 levels since the beginning of the Industrial Age may have averted an ecological disaster.

Understanding the atmospheric concentrations and radiative properties of greenhouse gases reveals the important role water vapor plays in Earth's temperature. Water vapor near the surface is present at concentrations approximately 36 times that of CO_2 (14,615 ppm versus 405 ppm) and it absorbs upgoing thermal radiation on a much wider range of wavelengths. However, water vapor's concentration decreases with altitude, making CO_2 the more powerful greenhouse gas at higher levels of the atmos-

Figure 2.1.2.4.5
TRCS validated model with RCP6.2 greenhouse gas and aerosol projections



See text for notes. *Source:* Doiron, 2016.

phere. Is a small increase in CO_2 enough to trigger an increase in water vapor sufficient to explain the warming of the twentieth and early twenty-first centuries? This is one important question climate scientists are trying to answer.

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2.2 Controversies

Climate science has made great strides in recent decades thanks especially to satellite data and research laboratories such as CERN, the European Organization for Nuclear Research located on the border between France and Switzerland. However, this progress has not ended controversies that prevent general agreement on some key topics. This section looks at controversies in four areas: temperature records, general circulation models, climate sensitivity, and solar influences on the climate.

2.2.1 Temperature Records

> *Reconstructions of average global surface temperature differ depending on the methodology used. The warming of the twentieth and early twenty-first centuries has not been shown to be beyond the bounds of natural variability.*

The IPCC says it is "certain that global mean surface temperature (GMST) has increased since the late 19th century" and estimates the increase from 1850–1900 to 2003–2012 was 0.78°C [0.72 to 0.85] based on the Hadley Center/Climatic Research Unit dataset (HadCRUT4) (IPCC, 2013, p. 37). While this statement may be true, scientists may reasonably ask "how do we know?" Answering this question reveals difficult questions and disagreements.

How Do We Know?

Recall from Section 2.1.1.3 that Frank (2016) added error bars around the HadCRUT4 temperature record, producing the figure reproduced as Figure 2.1.1.3.1. According to Frank, "these known systematic errors combine to produce an estimated lower limit uncertainty of $1\sigma = \pm 0.5$ºC in the global average of surface air temperatures prior to 1980, descending to about ±0.36ºC by 2010 with the gradual introduction of modern instrumentation." The IPCC itself admits its temperature reconstructions are highly uncertain:

> The uncertainty in observational records encompasses instrumental/recording errors, effects of representation (e.g., exposure, observing frequency or timing), as well as effects due to physical changes in the instrumentation (such as station relocations or new satellites). All further processing steps (transmission, storage, gridding, interpolating, averaging) also have their own particular uncertainties. Because there is no unique, unambiguous, way to identify and account for non-climatic artefacts in the vast majority of records, there must be a degree of

uncertainty as to how the climate system has changed (IPCC, 2013, p. 165).

In other words, the IPCC's estimate of 0.78°C [0.72 to 0.85] from 1850–1900 to 2003–2012 is not direct evidence but an estimate based on a long chain of judgements about how to handle data, what data to include and what to leave out, and how to summarize it all into a single "global temperature." The IPCC's temperature estimate cannot be tested because it has no empirical existence. It is a "stylized fact," one of many in climate science.

Serious flaws of the HadCRUT dataset are apparent from emails leaked from the Climatic Research Unit in 2009 (Goldstein, 2009). A file titled "Harry Read Me" contained some 247 pages of email exchanges with a programmer responsible for maintaining and correcting errors in the HadCRUT climate data between 2006 and 2009. Reading only a few of the programmer's comments reveals the inaccuracies, data manipulation, and incompetence that render the database unreliable:

- "Wherever I look, there are data files, no info about what they are other than their names. And that's useless ..." (p. 17).
- "It's botch after botch after botch" (p. 18).
- "Am I the first person to attempt to get the CRU databases in working order?!!" (p. 47).
- "As far as I can see, this renders the [weather] station counts totally meaningless" (p. 57).
- "COBAR AIRPORT AWS [data from an Australian weather station] cannot start in 1962, it didn't open until 1993!" (p. 71).
- "What the hell is supposed to happen here? Oh yeah – there is no 'supposed,' I can make it up. So I have : -)" (p. 98).
- "I'm hitting yet another problem that's based on the hopeless state of our databases. There is no uniform data integrity, it's just a catalogue of issues that continues to grow as they're found" (p. 241).

Also in 2009, after years of denying Freedom of Information Act (FOIA) requests for the HadCRUT dataset on frivolous and misleading grounds (Montford, 2010), Phil Jones, director of the Climatic Research Unit, admitted *the data do not exist.* "We, therefore, do not hold the original raw data but only the value-added (i.e., quality controlled and homogenized) data" (quoted in Michaels, 2009). Recall that "Harry Read Me" was in charge of "quality control" at the time. This means the HadCRUT dataset it is not direct evidence … evidence that does not rely on inference … of the surface temperature record prior to the arrival of satellite data in 1979. Relying on such circumstantial evidence to test hypotheses violates the Scientific Method. As Michaels remarked at the time, "If there are no data, there's no science."

Many researchers have identified serious quality control problems with the surface-based temperature record (Balling and Idso, 2002; Pielke Sr., 2007a, 2007b; Watts, 2009; Fall *et al.*, 2011; Frank, 2015, 2016; Parker and Ollier, 2017). Very recently, Hunziker *et al*. (2018) set out to determine the reliability of data from manned weather stations from the Central Andean area of South America by comparing results using an "enhanced" approach to the standard approach for a sample of stations. They found "about 40% of the observations [using the standard approach] are inappropriate for the calculation of monthly temperature means and precipitation sums due to data quality issues. These quality problems, undetected with the standard quality control approach, strongly affect climatological analyses, since they reduce the correlation coefficients of station pairs, deteriorate the performance of data homogenization methods, increase the spread of individual station trends, and significantly bias regional temperature trends." They conclude, "Our findings indicate that undetected data quality issues are included in important and frequently used observational datasets and hence may affect a high number of climatological studies. It is of utmost importance to apply comprehensive and adequate data quality control approaches on manned weather station records in order to avoid biased results and large uncertainties."

McLean (2018) conducted an audit of the HadCRUT4 dataset and found "more than 70 issues of concern" including failure to check source data for errors, resulting in "obvious errors in observation station metadata and temperature data" (p. 88). According to McLean, grid cell values, hemispheric averages, and global averages were derived from too little data to be considered reliable. "So-called 'global' average temperature anomalies have at times been heavily biased toward certain areas of the world and at other times there is a lack of coverage in specific regions." McLean found adjustments to data that "involve heroic assumptions because the necessary information about the conditions was not recorded. They are likely to be flawed." McLean concludes:

> In the opinion of this author, the data before 1950 has negligible real value and cannot be relied upon to be accurate. The data from individual stations might be satisfactory but only if local environments are unchanged and with no manual adjustments to the temperature data. The many issues with the 1850–1949 data make it meaningless to attempt any comparison between it and later data especially in derived values such as averages and the trends in those averages (p. 90).

McLean (2018) is no more satisfied with the record since 1950:

> It is also the opinion of this author that the HadCRUT4 data since 1950 is likewise not fit for purpose. It might be suitable for single-station studies or even small regional studies but only after being deemed satisfactory regards [sic] the issues raised in this report. It is not suitable for the derivation of global or hemispheric averages, not even with wide error margins that can only be guessed at because there are too many points in the data collection and processing that are uncertain and inconsistent (*Ibid.*).

This is the temperature record relied on by the IPCC and climate scientists who claim to know how much the mean global surface temperature has changed since 1850, and hence to know as well what the human impact on climate has been. How much confidence can be placed in their analysis when it is based on such a flawed premise? Sir Fred Hoyle saw this problem more than two decades ago when he wrote: "To raise a delicate point, it really is not very sensible to make approximations … and then to perform a highly complicated computer calculation, while claiming the arithmetical accuracy of the computer as the standard for the whole investigation" (Hoyle, 1996).

In the introduction to his audit, McLean (2018) writes, "it seems very strange that man-made warming has been a major international issue for more than 30 years and yet the fundamental data has never been closely examined." Indeed.

Compared to What?

The choice of 1850 as the starting point for the timeline IPCC features seems designed to exaggerate the alleged uniqueness of the warming of the twentieth century. The world was just leaving the Little Ice Age, which is generally dated as spanning the sixteenth to the eighteenth centuries. Had the IPCC chosen to start the series before the Little Ice Age, during the Medieval Warm Period (MWP), when temperatures were as warm as they are today (Sicre *et al.*, 2008), there would have been no warming trend to report. The IPCC acknowledges "continental-scale surface temperature reconstruct-tions show with *high confidence*, multidecadal periods during the Medieval Climate Anomaly (950–1250) that were in some regions as warm as the mid-20th century and in others as warm as in the late 20th century" (IPCC, 2013, p. 37). In fact, hundreds of researchers have found the MWP was a global phenomenon (NIPCC, 2011, Chapter 3).

The warming since 1850, if it occurred at all, is meaningful information only if it exceeds natural variability. Proxy temperature records from the Greenland ice core for the past 10,000 years demonstrate a natural range of warming and cooling rates between +2.5°C and -2.5°C/century, significantly greater than rates measured for Greenland or the globe during the twentieth century (Alley, 2000; Carter, 2010, p. 46, Figure 7). The ice cores also show repeated "Dansgaard–Oeschger" events when air temperatures rose at rates of about 10 degrees per century. There have been about 20 such warming events in the past 80,000 years.

Glaciological and recent geological records contain numerous examples of ancient temperatures up to 3°C or more warmer than temperatures as recently as 2015 (Molnár and Végvári, 2017; Ge *et al*., 2017; Lasher *et al*., 2017; Simon *et al*., 2017; Köse *et al*., 2017; Kawahata *et al*., 2017; Polovodova Asteman *et al*., 2018; Badino *et al*., 2018). During the Holocene, such warmer peaks included the Egyptian, Minoan, Roman, and Medieval warm periods. During the Pleistocene, warmer peaks were associated with interglacial oxygen isotope stages 5, 9, 11, and 31 (Lisiecki and Raymo, 2005). During the Late Miocene and Early Pliocene (6–3 million years ago) temperature consistently attained values 2–3°C above twentieth century values (Zachos *et al.*, 2001).

Phil Jones, director of the Climatic Research Unit, when asked in 2010 (in writing) if the rates of global warming from 1860–1880, 1910–1940, and 1975–1998 were identical, wrote in reply "the warming rates for all 4 periods [he added 1975 – 2009] are similar and not statistically significantly different from each other" (BBC News, 2010). When asked "Do you agree that from 1995 to the present there has been no statistically significant global warming?" Jones answered "yes." His replies contradicted claims made by the IPCC at the time as well as the claim, central to the IPCC's hypothesis, that the warming of the late twentieth and early twenty-first centuries was beyond natural variability.

In its Fifth Assessment Report, the IPCC admits the global mean surface temperature stopped rising from 1997 to 2010, reporting the temperature increase for that period was 0.07°C [-0.02 to 0.18] (IPCC, 2013, p. 37). This "pause" extended 18 years before being interrupted by the major El Niño events of 2010–2012 and 2015–2016. (See Figure 2.2.1 below.) During "the pause" humans released approximately one-third of all the greenhouse gases emitted since the beginning of the Industrial Revolution. If CO_2 concentrations drive global temperatures, their impact surely would have been visible during this period. Either CO_2 is a weaker driver of climate than the IPCC assumes, or natural drivers and variation play a bigger role than it realizes.

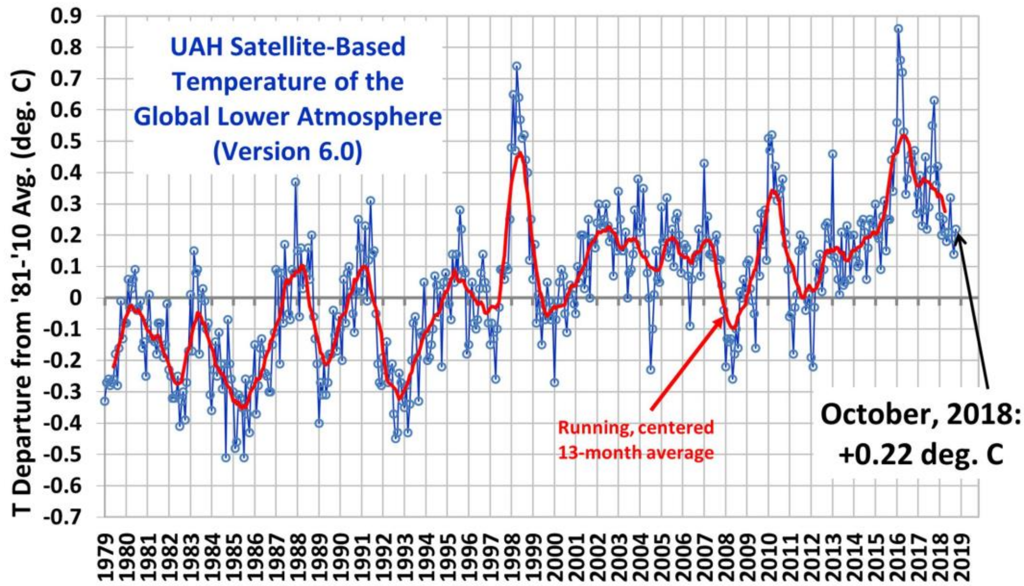
Temperatures quickly fell after each El Niño event, though not to previous levels. This step-function increase in temperature (also seen in 1977 in what is known as the Great Pacific Climate Shift) is not the linear increase in global temperatures predicted by general circulation models tuned to assign a leading role to greenhouse gases (Belohpetsky *et al*., 2017; Jones and Ricketts, 2017). El Niño events are produced by cyclical changes in ocean currents (the El Niño-Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO)) and their known periodicity of 60 to 70 years explains much of the warming and cooling cycles observed in the twentieth century (Douglass and Christy, 2008). The ENSO and AMO are thought to be the result of solar influences (Easterbrook, 2008) dismissed by the IPCC as being too small to have a significant influence on climate. The impact of El Niño events on global temperatures is evidence of natural variability and the strength of natural forcings relative to human greenhouse emissions. (See also D'Aleo and Easterbrook, 2016.)

Satellite Data

NASA research scientists Roy Spencer and John Christy (1990) published a method to use data collected by satellites since December 1978 to calculate global atmospheric temperatures. They now maintain a public database at the University of Alabama – Huntsville (UAH) of nearly 40 years of comprehensive satellite temperature measurements of the atmosphere that has been intensively quality controlled and repeatedly peer-reviewed (Christy and Spencer, 2003a, 2003b; Spencer *et al.*, 2006; Christy *et al.*, 2018). Satellites retrieve data from the entire surface of the planet, something surface-based temperature stations are unable to do, and are accurate to 0.01°C. They are also transparent (available for free on the internet); free from human influences other than greenhouse gas emissions such as change in land use, urbanization, farming, and land clearing, and changing instrumentation and instrument location; and at least somewhat immune to human manipulation. As Santer *et al.* (2014, pp. 185–9) reported, "Satellite TLT [temperature lower troposphere] data have near-global, time-invariant spatial coverage; in contrast, global-mean trends estimated from surface thermometer records can be biased by spatially and temporally non-random coverage changes." Figure 2.2.1.1 presents the latest data from the UAH satellite dataset.

Christy *et al.* (2018) analyzed eight datasets generated by satellites and weather balloons producing bulk tropospheric temperatures beginning in 1979 and ending in 2016, finding the trend is +0.103°C decade^{-1} with a standard deviation among the trends of 0.0109°C. More specifically, they report "a range of near global (+0.07 to +0.13°C decade^{-1}) and tropical (+0.08 to 0.17°C decade^{-1}) trends (1979–2016)." Looking specifically at the tropical (20°S – 20°N) region, where CO_2-forced warming is thought to be most detectable, they find the trend is +0.10 ± 0.03°C decade^{-1}. "This tropical result," they write, "is over a factor of two less than the trend projected from the average of the IPCC climate model simulations for this same period (+0.27°C decade^{-1})." Phrased differently, the only direct evidence available regarding global temperatures since 1979 shows a warming trend of only 0.1°C per decade, or 1°C per century. This is approximately one-third as much as the IPCC's forecast for the twenty-first century, and

Figure 2.2.1.1
Global temperature departure from 1981–2010 average (°C) from 1979 to 2018, UAH satellite-based readings



Source: Spencer, 2018.

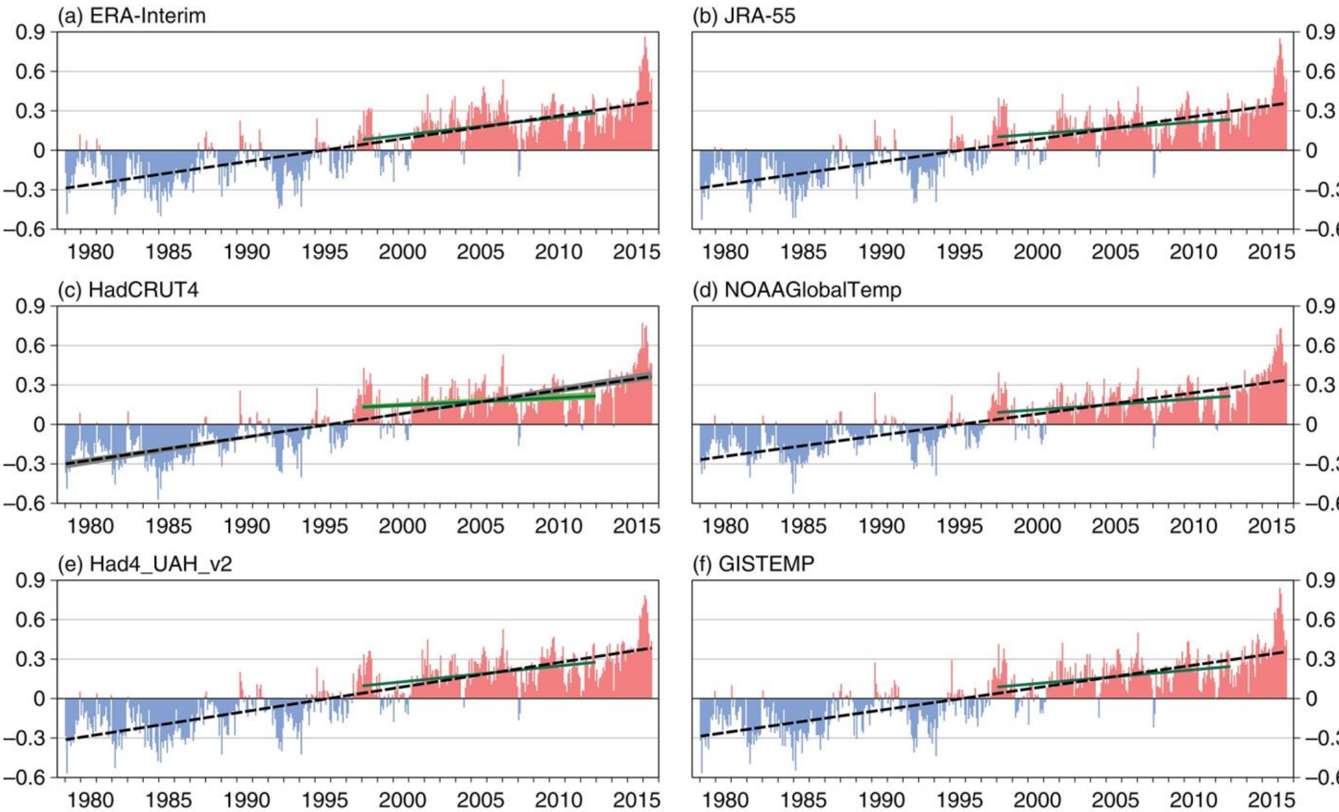
within the range of natural variability. It is not evidence of a human impact on the global climate.

In 2017, Christy and McNider (2017) used satellite data to "identify and remove the main natural perturbations (e.g. volcanic activity, ENSOs) from the global mean lower tropospheric temperatures (T_{LT}) over January 1979 – June 2017 to estimate the underlying, potentially human-forced trend. The unaltered value is +0.155 K dec^{-1} while the adjusted trend is +0.096 K dec^{-1}, related primarily to the removal of volcanic cooling in the early part of the record." While that trend is "potentially human-forced," it is just as likely to be the result of other poorly understood processes such as solar effects.

Despite the known deficiencies in the HadCRUT surface temperature record and the superior accuracy and global reach of satellite temperature records, the IPCC and many government agencies and environmental advocacy groups continue to rely on the surface station temperature record. One reason for this preference is because some credible surface-based records date back to the 1850s and even earlier. (But recall the conclusion of McLean (2018) that "the data before 1950 has negligible real value and cannot be relied upon to be accurate.") Another reason becomes clear if one compares the satellite data in Figure 2.2.1.2 to five surface station records shown in Figure 2.2.1.2. Whereas the satellite record shows only 0.1°C per decade warming since 1979, various surface station records (and surface station + satellite in one case) for approximately the same period shows an average warming of about 0.17°C , about 70% higher (Simmons *et al.*, 2016).

Satellite data are valuable for providing a test of the water vapor amplification theory (reported in the next section), demonstrating the inaccuracy of surface station data (particularly their failure to control for urban heat island effects), and exposing the exaggerated claims of those who say global warming (or "climate change") is "already happening." What warming has occurred in the past four decades was too small or slow to have been responsible for the litany of supposed harms attributed to anthropogenic forcing. However, geologists point to how short a period 40 years or even a century are when studying climate, which is known to respond to internal forcings (e.g., ocean currents and solar influences) with multidecadal, centennial, and longer periodicities. Even a century's

Figure 2.2.1.2
Global temperature departure from 1961–1990 average (°C) from 1979 to 2016



Monthly anomalies in globally averaged surface temperature (°C) relative to 1981–2010, from (a) ERA-Interim, (b) JRA-55, (c) the HadCRUT4 median, (d) NOAAGlobalTemp, (e) Had4_UAH_v2 and (f) GISTEMP, for January 1979 to July 2016. Also shown are least-squares linear fits to the monthly values computed for the full period (black, dashed lines) and for 1998 – 2012 (dark green, solid lines). In the case of HadCRUT4, the corresponding linear fits for each ensemble member are plotted as sets of (overlapping) grey and lighter green lines. *Source:* Simmons *et al.,* 2016.

worth of data would be a mere 1% of the 10,000 years of the Holocene Epoch. How do we know how much of the warming of the twentieth and early twenty-first centuries is due to the human influence?

A Single Global Temperature?

Some scientists challenge the notion that a single temperature can be attributed to the planet's atmosphere. Does it really make sense to create and report the mean average of the temperatures of deserts, corn fields, oceans, and big cities? In a dynamic system where cold weather in one part of the world can mean warmer weather in another, and where poorly understand weather processes have impacts that dwarf decades and even centuries of long-term climate change, what is the point? As Essex *et al.* (2007) explain, the "statistic called 'global temperature' … arises from projecting a sampling of the fluctuating temperature field of the Earth onto a single number at discrete monthly or annual intervals." The authors continue,

> While that statistic is nothing more than an average over temperatures, it is regarded as the temperature, as if an average over temperatures is actually a temperature itself, and as if the out-of-equilibrium climate system has only one temperature. But an

> average of temperature data sampled from a non-equilibrium field is not a temperature. Moreover, it hardly needs stating that the Earth does not have just one temperature. It is not in global thermodynamic equilibrium – neither within itself nor with its surroundings. It is not even approximately so for the climatological questions asked of the temperature field.

Essex *et al.* (2007) conclude, “there is no physically meaningful global temperature for the Earth in the context of the issue of global warming.”

The method of deriving a global average temperature must be arbitrary since there is an infinite number of ways it could be calculated from observational data. Temperatures could be weighed based on the size of the area sampled, but since weather stations are not evenly distributed around the world, the result could be a few dozen stations having more influence on the global or regional “average” than hundreds or thousands of other stations, something McLean (2018) in fact observed in the HadCRUT dataset. Efforts to manipulate and “homogenize” divergent datasets, fill in missing data, remove outliers, and compensate for changes in sampling technology are all opportunities for subjective or just poor decision-making.

The resulting number is an accounting fiction with no real-world counterpart, and therefore is not subject to experimentation or falsification. Essex *et al.* (2007) write, “The resolution of this paradox is not through adoption of a convention. It is resolved by recognizing that it is an abuse of terminology to use the terms ‘warming’ and ‘cooling’ to denote upward or downward trends in averages of temperature data in such circumstances. Statistics might go up or down, but the system itself cannot be said to be warming or cooling based on what they do, outside of special circumstances.”

Why was the attempt made to infer a single temperature to the planet’s atmosphere in the first place? The answer can be found in Chapter 1, where the concept of “seeing like a state” was discussed. Governments need to assign numbers to the things they seek to regulate or tax. Complex realities must be simplified at the cost of misrepresentation and outright falsification to produce the stylized facts that can be used in legislation and then in regulations. Saying the world has a single temperature – 14.9°C (58.82°F) in 2017, according to NASA’s Goddard Institute for Space Studies (Hansen *et al.*, 2018) – violates many of the principles of the Scientific Method, but it fills a need expressed by government officials at the United Nations and in many of the world’s capitols.

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2.2.2 General Circulation Models

> *General circulation models (GCMs) are unable to accurately depict complex climate processes. They do not accurately hindcast or forecast the climate effects of anthropogenic greenhouse gas emissions.*

Working Group III of the IPCC says without mitigation, "global mean surface temperature increases in 2100 from 3.7°C to 4.8°C compared to pre-industrial levels" (IPCC, 2014., p. 8). To arrive at this forecast, the IPCC relies on computer models called general circulation models (GCMs). Relatively few people in the climate science community are experts in building, "tuning," and operating such models, and so the rest of the community accepts their outputs on faith. This is a mistake. Like the history of the flawed HadCRUT temperature record told in the previous section, an examination of how GCMs are created and operate reveals why they are unreliable.

The Map Is Not the Territory

Specialized models, which try to model reasonably well-understood processes like post-glacial rebound (PGR) and radiation transport, are useful because the processes they model are manageably simple and well-understood. Weather forecasting models are also useful, even though the processes they model are very complex and poorly understood, because the models' short-term predictions can be repeatedly tested, allowing the models to be validated and refined. But more ambitious models like GCMs, which attempt to simulate the combined effects of many poorly understood processes, over time periods much too long to allow repeated testing and refinement, are of dubious utility.

Lupo *et al.* (2013) present a comprehensive critique of GCMs in Chapter 1 of *Climate Change Reconsidered II: Physical Science*. The authors write, "scientists working in fields characterized by complexity and uncertainty are apt to confuse the output of models – which are nothing more than a statement of how the modeler believes a part of the world works – with real-world trends and forecasts (Bryson, 1993). Computer climate modelers frequently fall into this trap and have been severely criticized for failing to notice their models fail to replicate real-world phenomena by many scientists, including Balling (2005), Christy (2005), Essex and McKitrick (2007), Frauenfeld (2005), Michaels (2000, 2005, 2009), Pilkey and Pilkey-Jarvis (2007), Posmentier and Soon (2005), and Spencer (2008)."

Confusing models for the real world they are meant to represent is part of the fallacy of a single world temperature discussed by Essex *et al.* (2007) earlier in this section. Similarly, Jaynes (2003) writes,

> Common language, or at least, the English language, has an almost universal tendency to disguise epistemological statements by putting them into a grammatical form which suggests to the unwary an ontological statement. A major source of error in current probability theory arises from an unthinking

> failure to perceive this. To interpret the first kind of statement in the ontological senses is to assert that one's own private thoughts and sensations are realities existing externally in Nature. We call this the "Mind Projection Fallacy," and note the trouble it causes many times in what follows (p. 116).

Mind Projection Fallacy leads to circular arguments. Modelers assume a CO_2 increase causes a temperature increase and so they program that into their models. When asked how they know this happens they say the model shows it, or other models (similarly programmed) show it, or their model doesn't work *unless* CO_2 is assumed to increase temperatures. Modelers may get the benefit of doubt from their colleagues and policymakers owing to the complexity of models and the expense of the supercomputers needed to run them. This does not make them accurate maps of a highly complex territory.

Citing a book by Solomon (2008), Lupo *et al.* (2013) provided the following sample of informed opinion regarding the utility of GCMs:

- Dr. Freeman Dyson, professor of physics at the Institute for Advanced Study at Princeton University and one of the world's most eminent physicists, said the models used to justify global warming alarmism are "full of fudge factors" and "do not begin to describe the real world."

- Dr. Zbigniew Jaworowski, chairman of the Scientific Council of the Central Laboratory for Radiological Protection in Warsaw and a world-renowned expert on the use of ancient ice cores for climate research, said the United Nations "based its global-warming hypothesis on arbitrary assumptions and these assumptions, it is now clear, are false."

- Dr. Hendrik Tennekes, director of research at the Royal Netherlands Meteorological Institute, said "there exists no sound theoretical framework for climate predictability studies" used for global warming forecasts.

- Dr. Antonino Zichichi, emeritus professor of physics at the University of Bologna, and former president of the European Physical Society, said global warming models are "incoherent and invalid."

Dyson (2007) writes, "I have studied the climate models and I know what they can do. The models solve the equations of fluid dynamics, and they do a very good job of describing the fluid motions of the atmosphere and the oceans. They do a very poor job of describing the clouds, the dust, the chemistry, and the biology of fields and farms and forests. They do not begin to describe the real world that we live in."

More recently, Hedemann *et al*. (2017) examined why climate models failed to predict the "surface-warming hiatus" of the early twenty-first century, reporting that other researchers identify model errors in external forcing and heat rearrangements in the ocean. The authors write, "we show that the hiatus could also have been caused by internal variability in the top-of-atmosphere energy imbalance. Energy budgeting for the ocean surface layer over a 100-member historical ensemble reveals that hiatuses are caused by energy-flux deviations as small as 0.08 $W\ m^{-2}$, which can originate at the top of the atmosphere, in the ocean, or both. Budgeting with existing observations cannot constrain the origin of the recent hiatus, because the uncertainty in observations dwarfs the small flux deviations that could cause a hiatus."

Coats and Karnauskas (2018) studied whether climate models could hindcast historical trends in the tropical Pacific zonal sea surface temperature gradient (SST gradient) using 41 climate models (83 simulations) and five observational datasets. They found "None of the 83 simulations have a positive trend in the SST gradient, a strengthening of the climatological SST gradient with more warming in the western than eastern tropical Pacific, as large as the mean trend across the five observational data sets. If the observed trends are anthropogenically forced, this discrepancy suggests that state-of-the-art climate models are not capturing the observed response of the tropical Pacific to anthropogenic forcing, with serious implications for confidence in future climate projections." They conclude, "the differences in SST gradient trends between climate models and observational data sets are concerning and motivate the need for process-level validation of the atmosphere-ocean dynamics relevant to climate change in the tropical Pacific."

Dommenget and Rezny (2017) observe that "state-of-the-art coupled general circulation models (CGCMs) have substantial errors in their simulations of climate. In particular, these errors can lead to large uncertainties in the simulated climate response (both globally and regionally) to a doubling of CO_2." The authors use the Globally Resolved Energy Balance (GREB) model to test the impact of "tuning" and find "While tuning may improve model performance (such as reproducing observed past climate), it will not get closer to the 'true' physics nor will it significantly improve future climate change projections. Tuning will introduce artificial compensating error interactions between submodels that will hamper further model development."

Stouffer *et al.* (2017) present a progress report on the Coupled Model Intercomparison Project (CMIP5), the international partnership created to achieve consensus on GCMs for the IPCC. They offer a frank assessment of the shortcomings of the models: "The quantification of radiative forcings and responses was poor, and thus it requires new methods and experiments to address this gap. There are a number of systematic model biases that appear in all phases of CMIP that remain a major climate modeling challenge. These biases need increased attention to better understand their origins and consequences through targeted experiments. Improving understanding of the mechanisms' underlying internal climate variability for more skillful decadal climate predictions and long-term projections remains another challenge for CMIP6."

Hindcasting Failure

There is a relatively simple test of the accuracy of GCMs: run them over a historical interval to see if they can "hindcast" temperature anomalies (departures from an average) recorded in real-world observations. This should be an easy test to pass since the models are "parameterized" to approximate the historical temperature record. (Parameterization is the topic of the next section.) But when this is done, a large and growing divide between the climate model simulations and real-world observations is observed (Douglass, Pearson, and Singer, 2004; Singer, 2011; Singer, 2013).

Christy (2017) performed a test of 102 model runs conducted by GCMs in the CMIP5 against actual temperature observations for the period 1979–2016. Figure 2.2.2.1 shows his results.

Christy's graph shows the growing distance between computer models and observational data from three independent data sources. Almost without exception, the models "run hot," predicting more warming than satellite and weather balloons observe. Christy (2017) summarizes the findings:

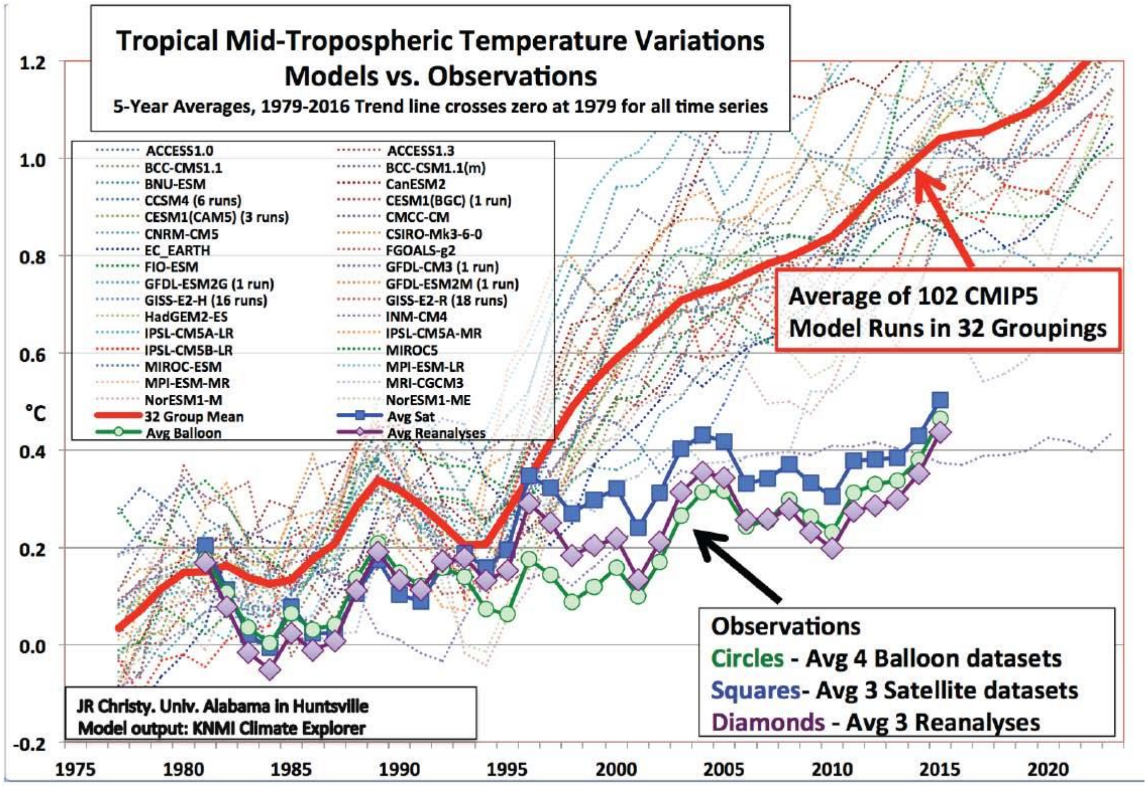
> The scientific conclusion here, if one follows the Scientific Method, is that the average model trend fails to represent the actual trend of the past 38 years by a highly significant amount. As a result, applying the traditional Scientific Method, one would accept this failure and not promote the model trends as something truthful about the recent past or the future.

More recently, McKitrick and Christy (2018) tested the ability of GCMs to predict temperature change in the tropical 200- to 300-hPa layer (hectopascals, or hPa, is a measure of atmospheric pressure) over the past 60 years, saying this constitutes a strong test of the global warming hypothesis because it meets the four criteria of a valid test: measurability, specificity, independence, and uniqueness. The researchers used model runs using the IPCC's Representative Concentration Pathway 4.5, which employs the best estimate of historical forcings through 2006 and anticipated forcings through 2100. (See Section 8.2.1 of Chapter 8 for a discussion of the IPCC's emission scenarios.)

According to McKitrick and Christy (2018), "the models project on average that the total amount of warming in the target zone since 1958 should have been about 2°C by now, a magnitude well within observational capability, and that the trends should be well established, thus specifying both the magnitude and a timescale" (p. 531). They continue, "simulations in the IPCC AR4 Chapter 9 indicate that, within the framework of mainstream GCMs, greenhouse forcing provides the only explanation for a strong warming trend in the target region" (p. 532). They use a 60-year temperature record composed from radiosondes (instruments carried up into the atmosphere by weather balloons that measure pressure, temperature, and relative humidity) for the period 1958–2017. Figure 2.2.2.2 shows their results.

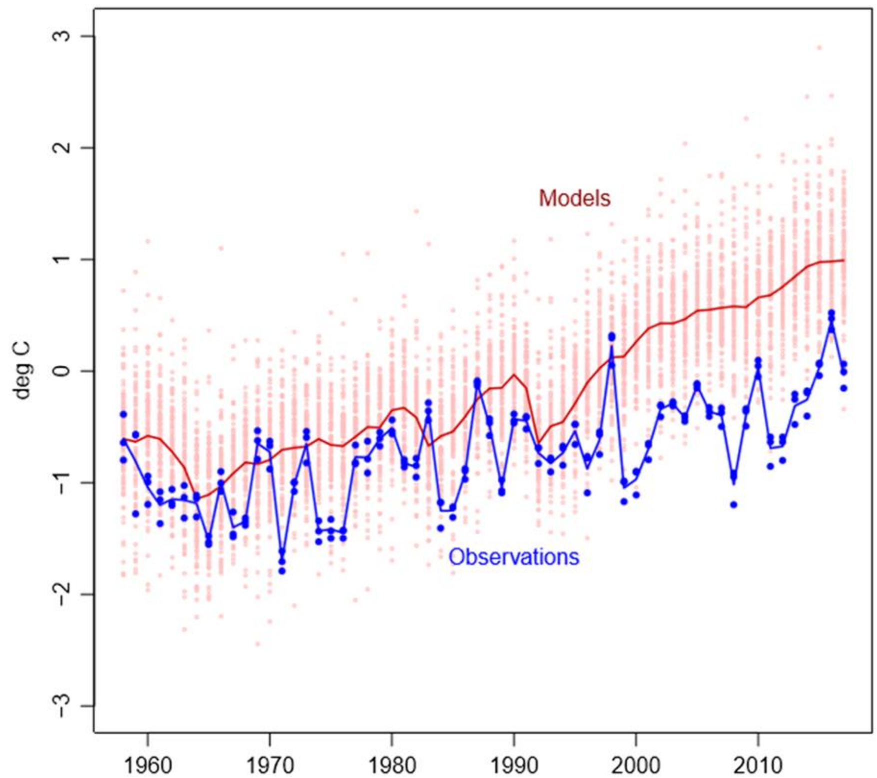
McKitrick and Christy (2018) also conduct a statistical test (the Vogelsang-Frances F-Test) to determine whether the average temperature prediction of the 102 model runs for the 200- to 300 hPa layer of the atmosphere is statistically different from the observational record. The results are reproduced below as Figure 2.2.2.3. The authors summarize their findings: "The mean restricted trend (without a break term) is 0.325 ± 0.132°C per decade in the models and 0.173 ± 0.056°C per decade in the observations. With a break term included they are 0.389 ± 0.173°C per decade (models) and 0.142 ± 0.115°C per decade (observed)." In other words,

Figure 2.2.2.1
Climate model forecasts versus observations, 1979–2016



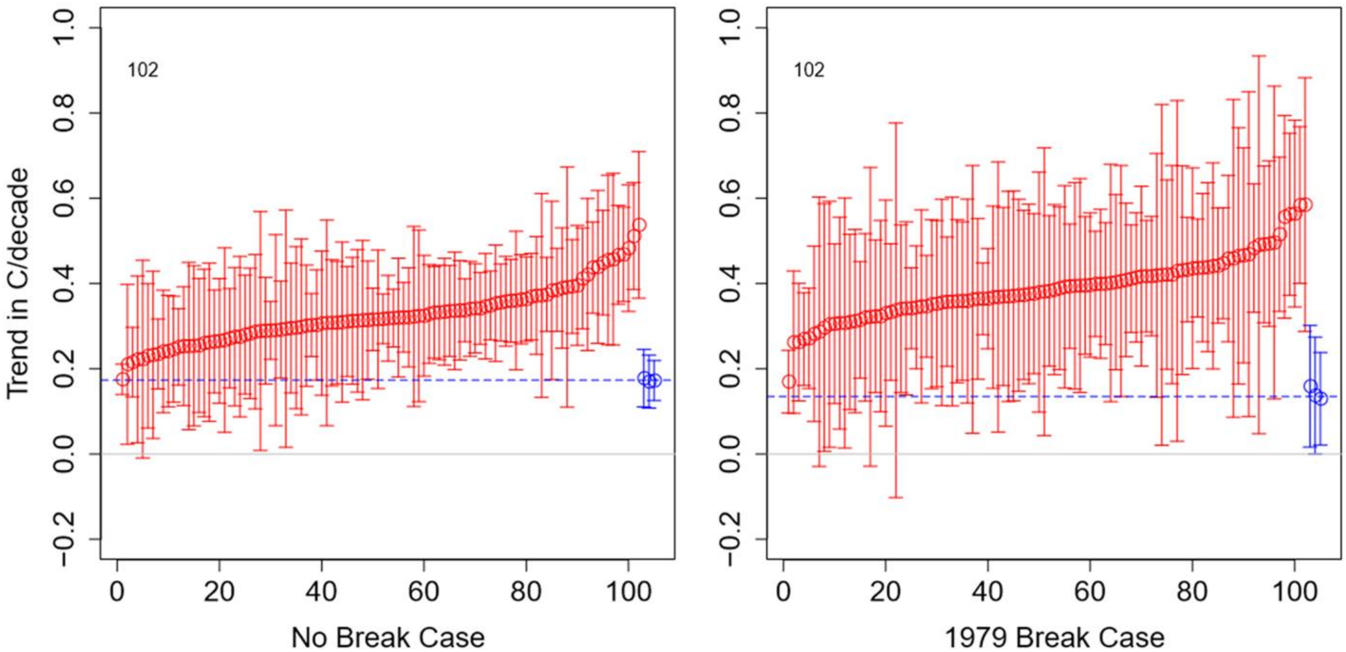
Five-year averaged values of annual mean (1979–2016) tropical bulk T_{MT} as depicted by the average of 102 IPCC CMIP5 climate models (red) in 32 institutional groups (dotted lines). The 1979–2016 linear trend of all time series intersects at zero in 1979. Observations are displayed with symbols: green circles – average of four balloon datasets, blue squares – 3 satellite datasets and purple diamonds – 3 reanalyses. The last observational point at 2015 is the average of 2013–2016 only, while all other points are centered, 5-year averages. *Source*: Christy, 2017.

Figure 2.2.2.2
A test of the tropical 200- to 300-hPa layer of atmosphere warming rate in climate models versus observations



Light red dots show the complete year-by-year array of individual anomaly values from CMIP5. Red line is the annual mean of CMIP5 anomalies. Blue line is the mean of the three observational series, which are shown individually as blue dots. These are positioned so that the year-by-year observational mean starts at the same value as the corresponding model mean. *Source*: McKitrick and Christy, 2018, Figure 3, p. 531.

Figure 2.2.2.3
Test of statistical significance of difference between climate models and observations in tropical 200- to 300-hPa layer of the atmosphere



Trend magnitudes (red circles) and 95% confidence intervals (vertical red lines) for 102 values from CMIP5. Observed average trend (blue dashed line) and confidence intervals (vertical blue lines) for average of three observational series (RAOBCORE, RICH, and RATPAC). Numbers in upper left corner indicate number of model trends (out of 102) that exceed observed average trend. *Source*: McKitrick and Christy, 2018, Figure 4, p. 531.

words, the models run hot by about 0.15°C per decade (0.325 – 0.173) and predict nearly twice as much warming in this area of the atmosphere as actually occurred (0.325 / 0.173) during the past 60 years.

Other scientists have confirmed the failure of GCMs to make accurate hindcasts. Green *et al.* (2009) found that when applied to the period of industrialization from 1850 to 1974, the IPCC projection of 3°C per century of warming from human carbon dioxide emissions resulted in errors that were nearly 13 times larger than those from forecasting no change in global mean temperatures for horizons of 91 to 100 years ahead. Monckton *et al.* (2015) found almost without exception, the models "run hot," predicting more warming than satellite and weather balloons observe. Idso and Idso (2015) write, "we find (and document) a total of 2,418 failures of today's top-tier climate models to accurately hindcast a whole host of climatological phenomena. And with this poor record of success, one must greatly wonder how it is that anyone would believe what the climate models of today project about earth's climate of tomorrow, i.e., a few decades to a century or more from now."

Kravtsov (2017) notes, "identification and dynamical attribution of multidecadal climate undulations to either variations in external forcings or to internal sources is one of the most important topics of modern climate science, especially in conjunction with the issue of human-induced global warming." Using ensembles of twentieth century climate simulations in an attempt to isolate the forced signal and residual internal variability in observed and modeled climate indices, they found "the observed internal variability … exhibits a pronounced multidecadal mode with a distinctive spatiotemporal signature, *which is altogether absent* in model simulations" (italics added).

Roach *et al.* (2018) compared satellite observations with model simulations of the compactness of Antarctic sea ice and the regional distribution of sea ice concentration and found "the simulation of Antarctic sea ice in global climate models often does not agree with observations. … As a fraction of total sea ice extent, models simulate too much loose, low-concentration sea ice cover throughout the year, and too little compact, high-concentration cover in the summer." Scanlon *et al*. (2018) tested the ability of seven GCMs to accurately hindcast land water storage using data from three Gravity Recovery and Climate Experiment (GRACE) satellite solutions in 186 river basins (~60% of global land area). They found "medians of modeled basin water storage trends greatly underestimate GRACE-derived large decreasing (≤ -0.5 km^3/y) and increasing (≥ 0.5 km^3/y) trends. Decreasing trends from GRACE are mostly related to human use (irrigation) and climate variations, whereas increasing trends reflect climate variations." Specifically, the GRACE satellite detected a large increasing trend in the Amazon while most models estimate decreasing trends, and global land water storage trends are positive for GRACE but negative for models. They conclude, "The inability of models to capture large decadal water storage trends based on GRACE indicates that model projections of climate and human-induced water storage changes may be underestimated."

Of the 102 model runs considered by Christy and McKitrick, only one comes close to accurately hindcasting temperatures since 1979: the INM-CM4 model produced by the Institute for Numerical Mathematics of the Russian Academy of Sciences (Volodin and Gritsun, 2018). That model projects only 1.4°C warming by the end of the century, similar to the forecast made by the Nongovernmental International Panel on Climate Change (NIPCC, 2013) and many scientists, a warming only one-third as much as the IPCC forecasts. Commenting on the success of the INM-CM model compared to the others (as shown in an earlier version of the Christy graphic), Clutz (2015) writes,

> (1) INM-CM4 has the lowest CO_2 forcing response at 4.1K for 4xCO_2. That is 37% lower than multi-model mean.
>
> (2) INM-CM4 has by far the highest climate system inertia: Deep ocean heat capacity in INM-CM4 is 317 W yr m^{-2} K^{-1}, 200% of the mean (which excluded INM-CM4 because it was such an outlier).
>
> (3) INM-CM4 exactly matches observed atmospheric H_2O content in lower troposphere (215 hPa), and is biased low above that. Most others are biased high.
>
> So the model that most closely reproduces the temperature history has high inertia from ocean heat capacities, low forcing from CO_2 and less water for feedback. Why aren't the other models built like this one?

Parameterization

Weather is defined as the instantaneous state and/or conditions of the atmosphere. Climate is the long-term mean state of the atmospheric conditions, including the variability, extremes, and recurrence intervals, for at least a 30-year period. While these definitions suggest weather and climate are different, each is governed by the same underlying physical causal factors. These factors are represented by seven mathematical equations referred to as the "primitive equations," which form the dynamic core of computer models that attempt to make both weather forecasts and climate projections. Primitive equations represent physical processes for which there are no precise formulations that allow for accurate predictions – processes such as cloud formation, heat exchange between Earth's surface and the atmosphere, precipitation generation, and solar radiation. Therefore, the variables in the equations must be represented by "parameterizations" or ranges.

Computer modelers "tune" these parameters until they get an answer that matches observations or the expectations of the modelers or their peers or funders. An international team of GCM modelers led by Frédéric Hourdin, senior research scientist at the French National Center for Scientific Research (CNRS), revealed how model tuning works in an extraordinary article published in 2017 (Hourdin *et al.* 2017). The authors are high-ranking modelers and yet are frank about the shortcomings of models. They write,

> Climate model tuning is a complex process that presents analogy with reaching harmony in music. Producing a good symphony or rock concert requires first a good composition and good musicians who work individually on their score. Then, when playing together, instruments must be tuned,

> which is a well-defined adjustment of wave frequencies that can be done with the help of electronic devices. But the orchestra harmony is reached also by adjusting to a common tempo as well as by subjective combinations of instruments, volume levels, or musicians' interpretations, which will depend on the intention of the conductor or musicians.
>
> When gathering the various pieces of a model to simulate the global climate, there are also many scientific and technical issues, and tuning itself can be defined as an objective process of parameter estimation to fit a predefined set of observations, accounting for their uncertainty, and a process that can be engineered. However, because of the complexity of the climate system and of the choices and approximations made in each submodel, and because of priorities defined in each climate center, there is also subjectivity in climate model tuning (Tebaldi and Knutti 2007) as well as substantial know how from a limited number of people with vast experience with a particular model (p. 590).

How does "harmony … reached also by adjusting to a common tempo" comply with Armstrong and Green's (2018) list of requirements imposed on researchers by the Scientific Method? Instead of seeking an important problem and being "skeptical about findings, theories, policies, methods, and data, especially absent experimental evidence," modelers adjust, calibrate, and change their methods and findings to be in "harmony" with others. Engineering a research project to fit a predefined set of observations does not sound like addressing the problem impartially. And rather than "exercising control over all aspects of your study," as Armstrong and Green counsel, modelers play a score written by others, surrendering control over their studies to a leader who has "vast experience with a particular model."

"Once a model configuration is fixed," Hourdin *et al.* (2017) continue, "tuning consists of choosing parameter values in such a way that a certain measure of the deviation of the model output from selected observations or theory is minimized or reduced to an acceptable range" (p. 591). One must ask, who determines the acceptable range? Is that range determined by the IPCC or other political and scientific organizations? What are their conflicts of interest?

"Energy balance tuning," Hourdin *et al.* (2017) write, is "crucial since a change by 1 Wm^2 of the global energy balance typically produces a change of about 0.5 – 1.5 K in the global-mean surface temperature in coupled simulations depending on the sensitivity of the given model" (pp. 592–3). One can only take from this that variables involving the atmosphere's energy balance are tweaked to make sure the resulting surface temperature forecast is in "an acceptable range." Is that range the IPCC's latest estimate of climate sensitivity or future warming?

Information used to support parameterization, Hourdin *et al.* (2017) write, "can come from theory, from a back-of-the-envelope estimate, from numerical experiments … or from observations" (p. 593). Promising theories and hypotheses can be derived from such myriad and sundry sources, but setting the parameters of computer models running on supercomputers and used to set national and international policies is a different matter. Is there really no quality control on such ad hoc justifications for tuning models? The authors admit that "although tuning is an efficient way to reduce the distance between model and selected observations, it can also risk masking fundamental problems and the need for model improvements" (p. 595). Indeed.

Voosen (2016) also reports on the use of tuning in climate models but blames climate "skeptics" for the secrecy surrounding it. He writes, "Climate models render as much as they can by applying the laws of physics to imaginary boxes tens of kilometers a side. But some processes, like cloud formation, are too fine-grained for that, and so modelers use 'parameterizations': equations meant to approximate their effects. For years, climate scientists have tuned their parameterizations so that the model overall matches climate records. But fearing criticism by climate skeptics, they have largely kept quiet about how they tune their models, and by how much." Given the sausage factory-like environment of climate modeling presented by Hourdin *et al.* (2017), the "skeptics" are right to criticize.

If natural climate forcings and feedbacks are not well understood, then GCMs become little more than an exercise in curve-fitting, changing parameters until the outcomes match the modeler's expectations. As John von Neumann is reported to have once said, "with four parameters I can fit an elephant, and with five I can make him wiggle his trunk" (Dyson, 2004). Of course, conscientious modelers try to avoid abusing their control over parameters, but GCMs provide so much room for subjective judgements that even subconscious bias produces big differences in model outputs. The Scientific Method is meant to protect scientists from such temptation.

Other Specific Shortcomings

The key failure of the climate models is the inability to reproduce warm phases that have repeatedly occurred in a natural way over the past 10,000 years. The models do not contain a meaningful natural climatic driver mechanism, as all natural climate drivers (e.g. sun, volcanoes) are deliberately set to nearly zero. Models without significant natural climate drivers are clearly unable to reproduce the natural temperature perturbations of the pre-industrial past 10,000 years. Climate models need to first pass their hindcast calibration test before they can be said to accurately model present and future climate.

Many important elements of the climate system, including atmospheric pressure, wind, clouds, the distribution of water vapor and carbon dioxide, the condensation of water vapor at ground level, the solar wind, aerosol concentration and distribution, dust concentration and distribution, and the reflectivity of snow and ice are highly uncertain. Lupo *et al.* (2013) cite extensive scholarly research on the following specific problems with climate models:

- Climate models underestimate surface evaporation caused by increased temperature by a factor of 3, resulting in a consequential under-estimation of global precipitation.

- Climate models inadequately represent aerosol-induced changes in infrared (IR) radiation, despite studies showing different mineral aerosols (for equal loadings) can cause differences in surface IR flux between 7 and 25 Wm^{-2}.

- Limitations in computing power restrict climate models from resolving important climate processes; low-resolution models fail to capture many important regional and lesser-scale phenomena such as clouds.

- Model calibration is faulty, as it assumes all temperature rise since the start of the Industrial Revolution has resulted from human activities; in reality, major anthropogenic emissions commenced only in the mid-twentieth century and there is no reason to assume the temperature increase since then is entirely due to human activity.

- Internal climate oscillations (AMO, PDO, etc.) are major features of the historic temperature record; climate models simulate them very poorly.

- Climate models fail to incorporate the effects of variations in solar magnetic field or in the flux of cosmic rays, both of which are known to significantly affect climate.

Christy and McNider (2017) observe, "the mismatch since 1979 between observations and CMIP5 model values suggests that excessive sensitivity to enhanced radiative forcing in the models can be appreciable. The tropical region is mainly responsible for this discrepancy suggesting processes that are the likely sources of the extra sensitivity are (a) the parameterized hydrology of the deep atmosphere, (b) the parameterized heat-partitioning at the ocean atmosphere interface and/or (c) unknown natural variations."

According to Legates (2014, p. 1,165),

> GCMs simply cannot reproduce some very important phenomena. For example, hurricanes and most other forms of severe weather (e.g., nor'easters, tornadoes, and thunderstorms) cannot be represented in a GCM owing to the coarse spatial resolution. Other more complex phenomena resulting from interactions among the elements that drive the climate system may be limited or even not simulated at all. Phenomena such as the Pacific Decadal Oscillation, the Atlantic Multidecadal Oscillation, and other complex interrelationships between the ocean and the atmosphere, for example, are inadequately reproduced or often completely absent in climate model simulations. Their absence indicates a fundamental flaw exists in either our understanding of the climate system, the mathematical parameterization of the process, the spatial and temporal limitations imposed by finite computational power, or a combination of all three.

* * *

The outputs of GCMs are only as reliable as the data and theories "fed" into them, which scientists widely recognize as being seriously deficient (Bray and von Storch, 2016; Strengers, *et al.*, 2015). The utility and skillfulness of computer models are dependent on how well the processes they model are understood, how faithfully those processes are simulated in the computer code, and whether the results can be repeatedly tested so the models can be refined (Loehle, 2018). To date, GCMs have failed to deliver on each of these counts.

Clutz (2015), observing how the Russian INM-CM4 climate model most closely reproduces the temperature history since 1850 by incorporating "high inertia from ocean heat capacities, low forcing from CO_2 and less water for feedback," then asked, "Why aren't the other models built like this one?" Why indeed? Unless, as was the case with HadCRUT's flawed temperature record, the purpose of most GCMs is not to accurately model the real climate, but rather to present an image of the climate that meets the needs of the world's political leaders. In this case, the map is definitely not the territory.

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2.2.3 Climate Sensitivity

Estimates of equilibrium climate sensitivity (the amount of warming that would occur following a doubling of atmospheric CO_2 level) range widely. The IPCC's estimate is higher than many recent estimates.

Climate sensitivity is a metric used to characterize the response of the global climate system to a given forcing. A forcing, in turn, is a chemical or physical process that alters Earth's radiative equilibrium, causing temperatures to rise or fall. Equilibrium climate sensitivity (ECS) is broadly defined as the global mean surface temperature change following a doubling of atmospheric CO_2 concentration and following the passage of time (possibly centuries) required for the atmosphere and oceans to return to equilibrium. Transient climate sensitivity (TCS) is surface temperature change occurring at the time of CO_2 doubling over a period of 70 years (IPCC, 2013, p. 82). Both metrics typically assume a pre-industrial level of CO_2 as the basis of the calculation (e.g., 280 ppm x 2 = 560 ppm).

The current controversy over man-made global warming originated in a 1979 report published by the U.S. National Academy of Sciences called the Charney Report (NRC, 1979). The authors conceded the increase in temperatures from a doubling of atmospheric CO_2 would be modest, probably not measurable at that time. However, they speculated that with water vapor feedback, a doubling of CO_2 would increase atmospheric temperatures sufficiently to result in an increase of surface temperatures by 3 ± 1.5°C. The Charney Report overruled the simple physics calculations of Rasool and Schneider (1971) that had estimated an ECS of 0.6°C (upped to 0.8°C with a simple H_2O feedback).

In the Working Group I contribution to the IPCC's Fifth Assessment Report (AR5), the IPCC claims an ECS in "a range of 2°C to 4.5°C, with the CMIP5 model mean at 3.2°C" (IPCC, 2013, p. 83). This is at odds with the Summary for Policymakers of the same volume, which gives an ECS "in the range 1.5°C to 4.5°C" and says in a footnote on the same page, "No best estimate for equilibrium climate sensitivity can now be given because of a lack of agreement on values across assessed lines of evidence and studies" (p. 16). Either estimate is indistinguishable from the one in the Charney report issued three decades earlier, illustrating the lack of progress made on this key issue of climate science.

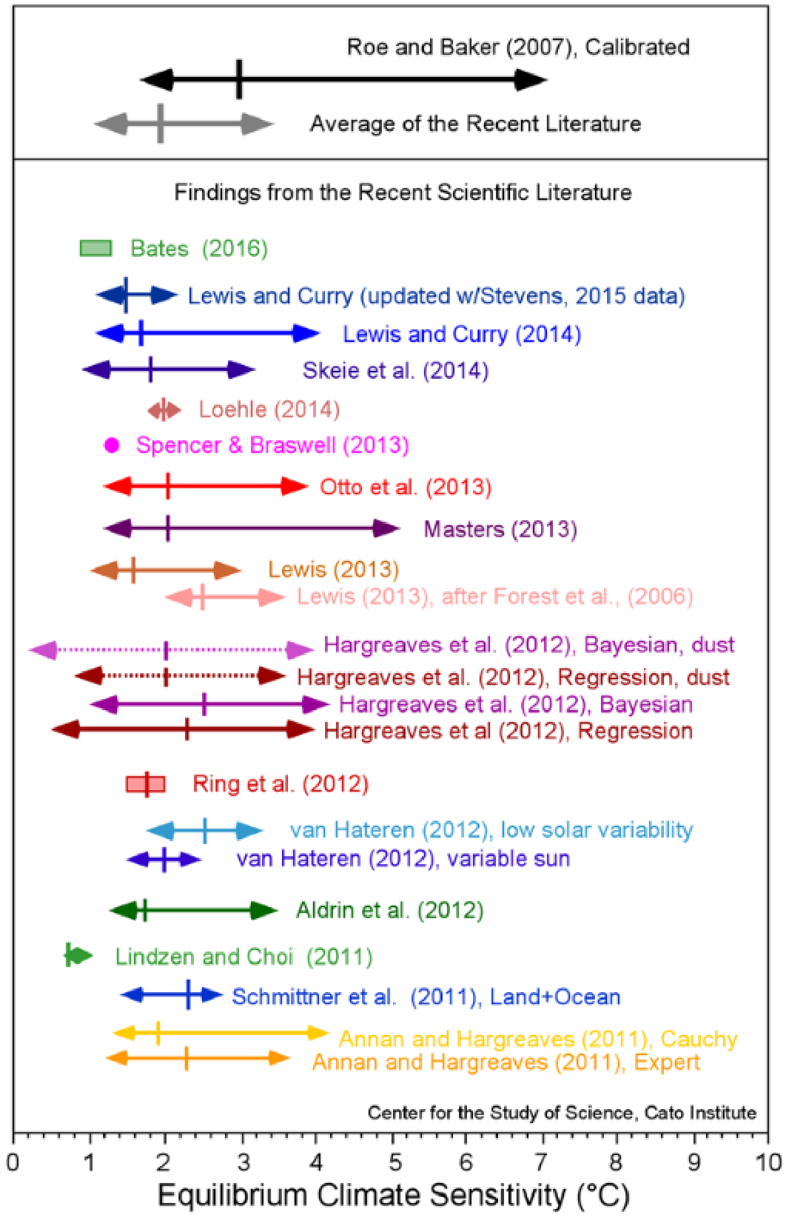
The IPCC's ECS Is Too High

The IPCC's estimate is higher than many estimates appearing in the scientific literature, especially those appearing most recently. Christy and McNider (2017), relying on the latest satellite temperature data, write, "If the warming rate of +0.096 K dec^{-1} represents the net T_{LT} response to increasing greenhouse radiative forcings, this implies that the T_{LT} tropospheric transient climate response (ΔT_{LT} at the time CO_2 doubles) is +1.10 ± 0.26 K which is about half of the average of the IPCC AR5 climate models of 2.31 ± 0.20 K. Assuming that the net remaining unknown internal and external natural forcing over this period is near zero, the mismatch since 1979 between observations and CMIP-5 model values suggests that excessive sensitivity to enhanced radiative forcing in the models can be appreciable."

Figure 2.2.3.1 presents a visual representation of estimates of climate sensitivity appearing in scientific research papers published between 2011 and 2016. According to Michaels (2017), the climate sensitivities reported in the literature average ~2.0°C (median) with a range of ~1.1°C (5th percentile) and ~3.5°C (95th percentile). The median is more than one-third lower than the estimate used by the IPCC.

The IPCC ignores mounting evidence that climate sensitivity to CO_2 is much lower than its models assume. Monckton *et al.* (2015) cited 27 peer-reviewed articles "that report climate sensitivity to be below current central estimates." Their list of sources appears in Figure 2.2.3.2.

Figure 2.2.3.1
Equilibrium climate sensitivity estimates from scientific research since 2011 (colored), compared to Roe and Baker (2007) (black)



Arrows represent the 5% to 95% confidence bounds for estimates of climate sensitivity released since 2011. Colored vertical lines show the best estimate of climate sensitivity (median of each probability density function or the mean of multiple estimates). Ring *et al.* (2012) present four estimates of the climate sensitivity, and the red box encompasses those estimates. Spencer and Braswell (2013) produce a single ECS value best-matched to ocean heat content observations and internal radiative forcing. Keep in mind that all of these confidence bounds represent spreads about a model mean, and are therefore statements of precision rather than of accuracy. Citations to each of these studies appear in the references section below. *Source:* Michaels, 2017, p. 6.

Figure 2.2.3.2
Research finding climate sensitivity is less than assumed by the IPCC

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Source: Monckton *et al.,* 2015, pp. 1378–1390, footnotes 7 to 33. Some corrections to citations have been made.

Uncertainty

No one actually knows the "true" climate sensitivity value because it is, like so many numbers in the climate change debate, a stylized fact: a single number chosen for the sake of convenience by those who make their living modeling climate change or advocating for government action to slow or stop it. The number is inherently uncertain for much the same reason it is impossible to know how much CO_2 is emitted into the atmosphere or how much of it stays there, which is the enormous size of natural processes relative to the "human signal" caused by our CO_2 emissions. Pindyck (2013) offers some insight with respect to the problems posed by climate feedbacks:

> Here is the problem: the physical mechanisms that determine climate sensitivity involve crucial feedback loops, and the parameter values that determine the strength (and even the sign) of those feedback loops are largely unknown, and for the foreseeable future may even be unknowable. This is not a shortcoming of climate science; on the contrary, climate scientists have made enormous progress in understanding the physical mechanisms involved in climate change. But part of that progress is a clearer realization that there are limits (at least currently) to our ability to pin down the strength of the key feedback loops.
>
> … We don't know whether the feedback factor *f* is in fact normally distributed (nor do we know its mean and standard deviation). Roe and Baker [2007] simply assumed a normal distribution. In fact, in an accompanying article in the journal *Science*, Allen and Frame (2007) argued climate sensitivity is in the realm of the "unknowable" (pp. 865, 867).

The IPCC acknowledges there may be natural variability in radiative forcing due to "solar variability and aerosol emissions via volcanic activity" and contends they "are also specified elements in the CMIP5 experimental protocol, but their future time evolutions are not prescribed very precisely" (IPCC, 2013, pp. 1047, 1051). Deferring to the GCMs on which CMIP bases its carbon cycle, the IPCC blandly reports that "some models include the effect" of solar cycles and orbital variations "but most do not." None tries to model volcanic eruptions. "For the other natural aerosols (dust, sea-salt, etc.), no emission or concentration data are recommended. The emissions are potentially computed interactively by the models themselves and many change with climate, or prescribed from separate model simulations carried out in the implementation of CMIP5 experiments, *or simply held constant*" (IPCC, 2013, p. 1051, italics added).

From this description it is likely that most of the GCMs simply assume radiative forcing in the atmosphere would be unchanging for decades or even centuries if not for anthropogenic greenhouse gas emissions. In light of evidence of significant natural variability in global average temperatures on geologic time scales as well as in the modern era, as documented in Section 2.1.2.3, that assumption is unrealistic, and consequently the IPCC's estimate of ECS is also unrealistic.

Earlier in the current chapter, in Section 2.1.1.3, profound uncertainty was documented about re-creations of the global average temperature record since 1850, including a graph by Frank (2015), who added the missing error bars to a graph produced by the Climatic Research Unit at the University of East Anglia. Frank also applied known sources of uncertainty to projections of *future* temperatures, writing, "CMIP5 climate model simulations of global cloud fraction reveal theory-bias error. Propagation of this cloud forcing error uncovers a [root-sum-squared-error] uncertainty 1σ ≈ ±15°C in centennially projected air temperature." This single error is so consequential it means "causal attribution of warming is therefore impossible." Frank then applies error bars to the projection of future global temperatures from NASA's Goddard Institute for Space Studies (GISS). His graphic appears here as Figure 2.2.3.3.

After cataloguing a series of errors and uncertainties in the data leading up to a finding of causation (or "attribution"), Frank (2015, p. 406) summarized his findings as follows:

Figure 2.2.3.3
GISS Model II projections of future global averaged surface air temperature anomalies as presented in 1988, (a) without and (b) with uncertainty bars

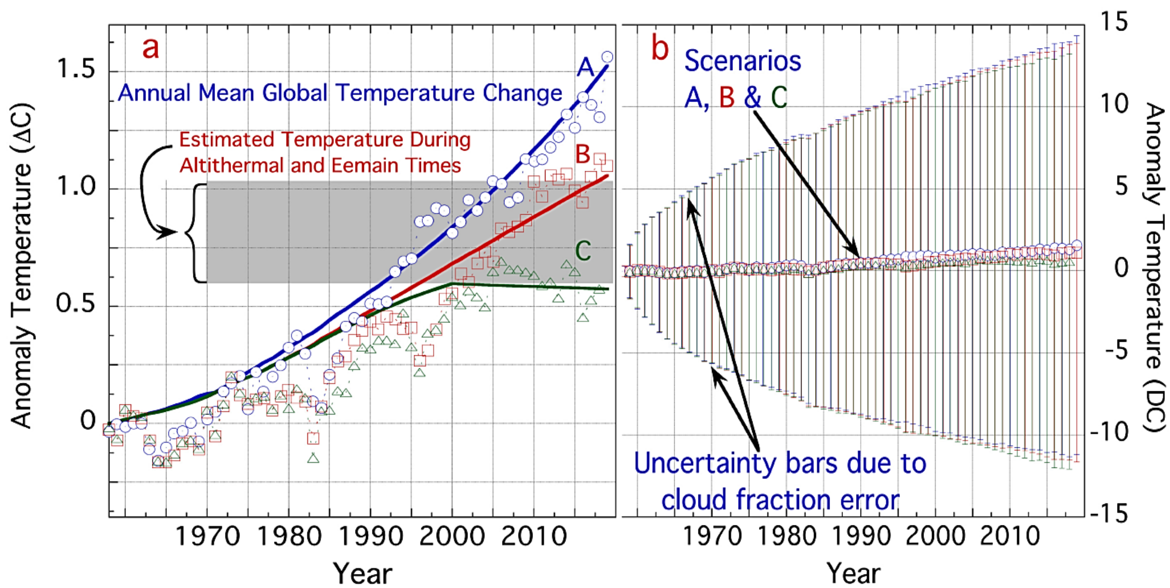

Figure (a) is modified from Hansen, 1988 and Hansen *et al.,*2006; figure (b) has uncertain bars added to account for cloud-forcing error. Note the change in vertical scale to accommodate the uncertainty range of figure (b). *Source:* Frank, 2015, Figure 1, p. 392.

1. The poor resolution of present state-of-the-art CMIP5 GCMs means the response of the terrestrial climate to increased GHGs is far below any level of detection.

2. The poor resolution of CMIP5 GCMs means all past and present projections of terrestrial air temperature can have revealed nothing of future terrestrial air temperature.

3. The lack of any scientific content in consensus proxy paleo-temperature reconstructions means nothing has been revealed of terrestrial paleo-temperatures.

4. The neglected systematic sensor measurement error in the global air temperature record means that neither the rate nor the magnitude of the change in surface air temperatures is knowable. Therefore,

5. Detection and attribution of an anthropogenic cause to climate change cannot have been nor presently can be evidenced in climate observables.

Researchers are continually trying to reduce the uncertainty described by Frank and as they do, estimates of ECS continue to fall. In 2016, the CLOUD research project being conducted by CERN (the European Institute for Nuclear Research) reported the discovery that aerosol particles can form in the atmosphere purely from organic vapors produced naturally by the biosphere (Dunne *et al.*, 2016). In a separate paper (Gordon *et al.*, 2016) CLOUD researchers demonstrated that pure biogenic nucleation was the dominant source of particles in the pristine pre-industrial atmosphere. By raising the baseline aerosol state, this process significantly reduces the estimated aerosol radiative forcing from anthropogenic activities and, in turn, reduces modeled climate sensitivities. The researchers also found evidence of a much bigger role played by cosmic rays in cloud formation than was previously known, a topic covered in the next section.

"This is a huge step for atmospheric science," CLOUD lead-author Ken Carslaw told a writer for the research center's newsletter, the *CERN Courier* (CERN, 2016). "It's vital that we build climate models on experimental measurements and sound understanding, otherwise we cannot rely on them to predict the future. Eventually, when these processes get implemented in climate models, we will have much more confidence in aerosol effects on climate. Already, results from CLOUD suggest that estimates of high climate sensitivity may have to be revised downwards."

Abbot and Marohasy (2017) conducted signal analysis on six temperature proxy datasets and used the resulting component sine waves as input to an artificial neural network (ANN), a form of machine learning. The ANN model was used to simulate the late Holocene period to 1830 CE and then through the twentieth century. The authors report, "the largest deviation between the ANN projections and measured temperatures for six geographically distinct regions was approximately 0.2 °C, and from this an Equilibrium Climate Sensitivity (ECS) of approximately 0.6 °C was estimated. This is considerably less than estimates from the General Circulation Models (GCMs) used by the Intergovernmental Panel on Climate Change (IPCC), and similar to estimates from spectroscopic methods."

If Frank and these other researchers are correct, modelers should not enter into their GCMs or IAMs the IPCC's TCS estimate, since it appears to be too high. But caution is nowhere to be found in the IPCC's discussion of climate sensitivity or in the way it is treated in the popular press or even scholarly research. The IPCC's estimate of equilibrium climate sensitivity of ~3.2°C for a doubling of CO_2 in the atmosphere is accepted as if it were direct evidence or a finding with a high degree of certainty. It is incorporated into IAMs with little debate and no admission of its uncertainty.

* * *

Equilibrium climate sensitivity (ECS) is one of the most important variables in climate science, but it is also the most uncertain and possibly unknowable value. IPCC's estimate of ~3.2°C is not based on direct evidence but on assumptions about Earth's temperature record, the changing composition of its atmosphere, and complex interactions between the atmosphere and oceans that mean discerning the impact of a few trace gases – CO_2 at 405 ppm, CH_4 at only 1.8 ppm, and nitrous oxide at 324 ppb – is likely to be impossible. The current generation of GCMs cannot find a reliable estimate of ECS.

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2.2.4 Solar Activity

> *Solar irradiance, magnetic fields, UV fluxes, cosmic rays, and other solar activity may have greater influence on climate than climate models and the IPCC currently assume.*

Solar influences on Earth's climate are a fourth area of controversy in climate science. According to the IPCC (2013), "changes in solar irradiance are an important driver of climate variability, along with volcanic emissions and anthropogenic factors," but they are considered by the IPCC to be too small to explain global temperature fluctuations of more than approximately 0.1°C between minima and maxima (p. 392). Solar influences, according to the IPCC, "cannot explain the observed increases since the late 1970s" (*Ibid.*).

Usoskin (2017) offers an excellent survey of the literature on solar activity. He explains,

> Although scientists knew about the existence of "imperfect" spots on the sun since the early seventeenth century, it was only in the nineteenth century that the scientific community recognized that solar activity varies in the course of an 11-year solar cycle. Solar variability was later found to have many different manifestations, including the fact that the "solar constant," or the total solar irradiance, TSI, (the amount of total incoming solar electromagnetic radiation in all wavelengths per unit area at the top of the atmosphere) is not a constant. The sun appears much more complicated and active than a static hot plasma ball, with a great variety of nonstationary active processes going beyond the adiabatic equilibrium foreseen in the basic theory of sun-as-star. Such transient nonstationary (often eruptive) processes can be broadly regarded as solar activity, in contrast to the so-called "quiet" sun. Solar activity includes active transient and long-lived phenomena on the solar surface, such as spectacular solar flares, sunspots, prominences, coronal mass ejections (CMEs), etc.

Usoskin (2017) summarizes what he calls the "main features … observed in the long-term evolution of solar magnetic activity":

- Solar activity is dominated by the 11-year Schwabe cycle on an interannual timescale. Some additional longer characteristic times can be found, including the Gleissberg secular cycle, de Vries/Suess cycle, and a quasi-cycle of 2000–2400 years (Hallstatt cycle). However, all these longer cycles are intermittent and cannot be regarded as strict phase-locked periodicities.

- One of the main features of long-term solar activity is that it contains an essential chaotic/stochastic component, which leads to irregular variations and makes solar-activity predictions impossible for a scale exceeding one solar cycle.

- The sun spends about 70% of its time at moderate magnetic activity levels, about 15–20% of its time in a grand minimum, and about 10–15% in a grand maximum.

- Grand minima are a typical but rare phenomena in solar behavior. They form a distinct mode of solar dynamo. Their occurrence appears not periodically, but rather as the result of a chaotic process within clusters separated by 2000–2500 years (around the lows of the Hallstatt cycle). Grand minima tend to be of two distinct types: short (Maunder-like) and longer (Spörer-like).

- The recent level of solar activity (after the 1940s) was very high, corresponding to a prolonged grand maximum, but it has ceased to the normal moderate level. Grand maxima are also rare and irregularly occurring events, though the exact rate of their occurrence is still a subject of debates.

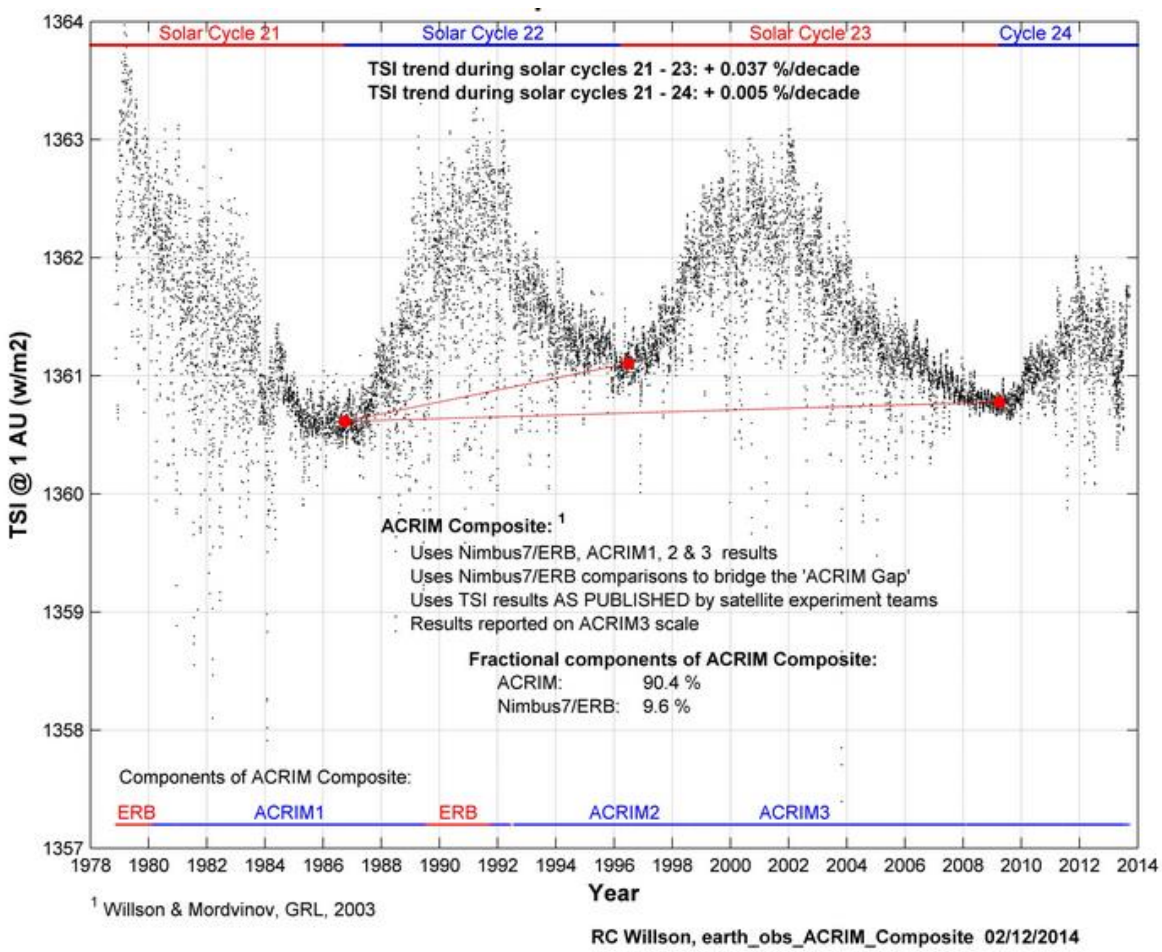
With this background, we can address whether solar activity explains some of the climate changes attributed by the IPCC to anthropogenic forcing.

2.2.4.1 Total Solar Irradiance

Incoming solar radiation is most often expressed as total solar irradiance (TSI), a measure derived from multi-proxy measures of solar activity. Measurements produced from 1979 to 2014 by the now defunct ACRIM satellite, one of 21 observational components of NASA's Earth Observing System, are shown in Figure 2.2.4.1.1. They show TSI rose and fell with solar cycles and ranged between 1,360 and 1,363 Wm^{-2} during the period 1979–2014, a variability of ~3 Wm^{-2} (ACRIM, n.d.). We are currently in the 24th solar cycle since 1755, which began in December 2008 and is expected to end in 2019.

The ACRIM TSI composite shows a small upward pattern from around 1980 to 2000, an increase not acknowledged by the IPCC or incorporated into the models on which it relies (Scafetta and Willson, 2014, Appendix). According to the ACRIM website, "gradual variations in solar luminosity of as little as 0.1% was the likely forcing for the 'Little Ice Age' that persisted in varying degree from the late 14th to the mid-19th centuries." Shapiro *et al.* (2011) estimated the TSI change between the Maunder Minimum and current conditions may have been as large as 6 Wm^{-2}.

Figure 2.2.4.1.1
Satellite measurement of total solar irradiance (TSI), 1978–2013



Source: ACRIM. n.d. Total solar irradiance (TSI) monitoring.

Egorova *et al*. (2018, Figure 8b) provide more recent and reliable estimates of about 3.7 to 4.5 Wm^{-2} for the TSI change between the Maunder Minimum and recent activity minima. Those values are still significantly higher than those provided by the CMIP6 estimates (Matthes *et al*., 2017) expected in the IPCC Sixth Assessment reports forthcoming in 2021–2022.

According to the IPCC, trends in TSI accounted for only +0.05 [-0.01 to +0.10] Wm^{-2} of radiative forcing in 2011 relative to 1750, compared to 1.68 [1.33 to 2.03] Wm^{-2} for CO_2 and 2.29 [1.13 to 3.33] Wm^{-2} for total anthropogenic radiative forcing (IPCC, 2013, p. 14, Figure SPM.5). But changes in solar irradiance and ultraviolet radiation could easily yield a larger influence on global climate than that of CO_2. The absolute forcing of incoming solar radiation is approximately 340 Wm^{-2} at the top of the atmosphere, more than 10 times the forcing of atmospheric CO_2, so even small changes in the absolute forcing of the Sun could result in values larger than the predicted changes in radiative forcing caused by increasing CO_2.

Bond *et al*. (2001) used an accelerator mass spectrometer to study ice-rafted debris found in three North Atlantic deep-sea sediment cores, documenting a characteristic temperature cyclicity with a period of 1,000 to 2,000 years. The climatic oscillations coincided well with solar activity changes as reconstructed based on cosmogenic radionuclides in the Greenland ice cores (beryllium-10, ^{10}Be) and Northern Hemispheric tree rings (carbon-14, ^{14}C). The natural climate cycle occurred throughout the 12,000 years of the Holocene. The last two cold and warm nodes of this oscillation, in the words of Bond *et al*. (2001), were "broadly correlative with the so called 'Little Ice Age' and 'Medieval Warm Period.'" Bond *et al*. concluded, "a solar influence on climate of the magnitude and consistency implied by our evidence could not have been confined to the North Atlantic," suggesting the cyclical climatic effects of the Sun are experienced throughout the world. Soon *et al*. (2014) provide a detailed analysis of the nature of the millennial and bimillennial scales of solar and climatic variability throughout the Holocene.

How do the small changes in solar radiation bring about such significant and pervasive shifts in Earth's global climate? Bond *et al*. (2001) describe a scenario whereby solar-induced changes high in the stratosphere are propagated downward through the atmosphere to Earth's surface, provoking changes in North Atlantic deep water formation that alter the thermohaline circulation of the global ocean. They speculate "the solar signals thus may have been transmitted through the deep ocean as well as through the atmosphere, further contributing to their amplification and global imprint." Concluding their landmark paper, the researchers write the results of their study "demonstrate that the Earth's climate system is highly sensitive to extremely weak perturbations in the Sun's energy output," noting their work "supports the presumption that solar variability will continue to influence climate in the future."

Research linking changes in solar influences to temperature, sea-level change, precipitation patterns, and other climate impacts is extensive; a summary in Chapter 3 of *Climate Change Reconsidered II: Physical Science* (NIPCC, 2013) is more than 100 pages long. We mention only a few recent studies here. One is Beer *et al*. (2006), who presented the various short- and longer-term scales of solar variability over the past 9,000 years. Beer *et al*. conclude that "comparison [of the solar development] with paleoclimatic data provides strong evidence for a causal relationship between solar variability and climate change."

Scafetta and West (2006a) developed two TSI reconstructions for the period 1900–2000, and their results suggest the Sun contributed 46% to 49% of the 1900–2000 warming of Earth, but with uncertainties of 20% to 30% in their sensitivity parameters. They say the role of the Sun in twentieth-century global warming has been significantly underestimated "because of the difficulty of modeling climate in general and a lack of knowledge of climate sensitivity to solar variations in particular." They also note "theoretical models usually acknowledge as solar forcing only the direct TSI forcing," thereby ignoring "possible additional climate effects linked to solar magnetic field, UV radiation, solar flares and cosmic ray intensity modulations." In a second study published that year, Scafetta and West (2006b) found a "good correspondence between global temperature and solar induced temperature curves during the pre-industrial period, such as the cooling periods occurring during the Maunder Minimum (1645–1715) and the Dalton Minimum (1795–1825)." Scafetta has written and coauthored several papers finding additional evidence of a solar effect on climate (Scafetta, 2008, 2010, 2012a, 2012b, 2013a, 2013b, 2016; Scafetta and West, 2003, 2005, 2007, 2008; Scafetta and Willson, 2009, 2014; Scafetta *et al*. 2017a, 2017b).

Shaviv (2008) found a "very clear correlation between solar activity and sea level" including the

11-year solar periodicity and phase, with a correlation coefficient of r = 0.55. He also found "the total radiative forcing associated with solar cycles variations is about 5 to 7 times larger than those associated with the TSI variations, thus implying the necessary existence of an amplification mechanism, though without pointing to which one." Shaviv argues "the sheer size of the heat flux, and the lack of any phase lag between the flux and the driving force further implies that it cannot be part of an atmospheric feedback and very unlikely to be part of a coupled atmosphere-ocean oscillation mode. It must therefore be the manifestation of real variations in the global radiative forcing." This provides "very strong support for the notion that an amplification mechanism exists. Given that the CRF [cosmic ray flux]/climate links predicts the correct radiation imbalance observed in the cloud cover variations, it is a favorable candidate." Additional work by Shaviv and coauthors with similar results includes Shaviv (2005), Shaviv *et al.* (2014), Howard *et al*. (2015), and Benyamin *et al.* (2017).

Raspopov *et al*. (2008), a team of eight researchers from China, Finland, Russia, and Switzerland, found an approximate 200-year cycle in paleoclimate reconstructions in the Central Asian Mountains that matches well with the solar Suess-de Vries cycle, suggesting the existence of a solar-climate connection. After reviewing additional sets of published palaeoclimatic data from various parts of the world, the researchers concluded the same periodicity is evident in Europe, North and South America, Asia, Tasmania, Antarctica, and the Arctic, as well as "sediments in the seas and oceans," citing 20 independent research papers in support of this statement. They conclude there is "a pronounced influence of solar activity on global climatic processes" related to "temperature, precipitation and atmospheric and oceanic circulation."

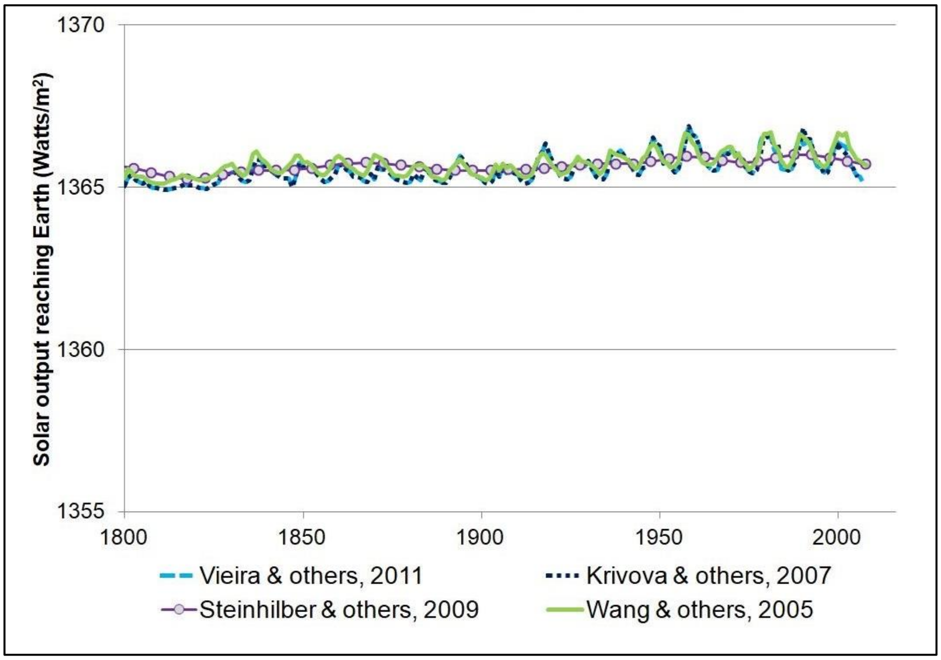
de Jager and Duhau (2009) used "direct observations of proxy data for the two main solar magnetic field components since 1844" to derive "an empirical relation between tropospheric temperature variation and those of the solar equatorial and polar activities." When the two researchers applied this relationship to the period 1610–1995, they found a rising linear association for temperature vs. time, upon which were superimposed "some quasi-regular episodes of residual temperature increases and decreases, with semi-amplitudes up to ~0.3°C," and they note "the present period of global warming is one of them." de Jager and Duhau conclude, "the amplitude of the present period of global warming does not significantly differ from the other episodes of relative warming that occurred in earlier centuries." The late twentieth-century episode of relative warming is merely "superimposed on a relatively higher level of solar activity than the others," giving it the appearance of being unique when it is not.

Qian and Lu (2010) used data from a 400-year solar radiation series based on ^{10}Be data "to analyze their causality relationship" with the periodic oscillations they had detected in the north Pacific sea surface temperature reconstruction. They determined "the ~21-year, ~115-year and ~200-year periodic oscillations in global-mean temperature are forced by and lag behind solar radiation variability," and the "relative warm spells in the 1940s and the beginning of the 21st century resulted from overlapping of warm phases in the ~21-year and other oscillations." They note "between 1994 and 2002 all four periodic oscillations reached their peaks and resulted in a uniquely warm decadal period during the last 1000 years," representing the approximate temporal differential between the current global warming and the prior Medieval Warm Period.

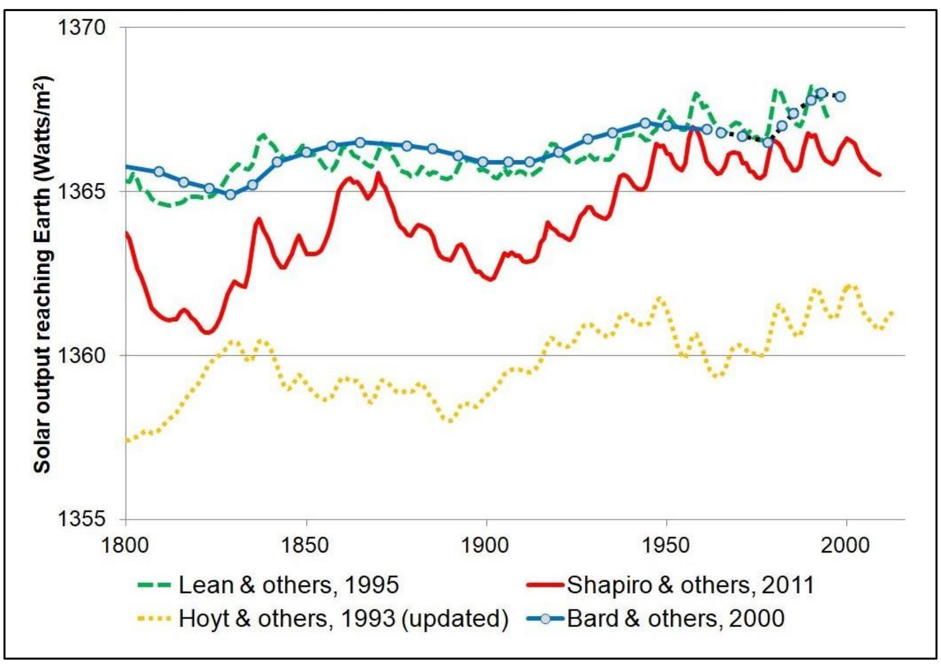
Soon (2005, 2009) and with coauthors (Soon and Baliunas, 2003; Soon and Legates, 2013; Soon *et al.*, 2000, 2011) has shown close correlations between TSI proxy models and many twentieth-century climate records including temperature records of the Arctic and of China, the sunshine duration record of Japan, and the Equator-to-Pole (Arctic) temperature gradient record. Soon *et al.* (2015) show that the solar models used by the IPCC's climate models were only a small and unrepresentative sample of the models published in the scientific literature. Although several plausible models of solar output have been proposed, the climate models considered only those that showed almost no solar variability since the nineteenth century (see Figure 2.2.4.1.2). The authors then show how solar variability reported in one ignored model (by Hoyt and Schatten (1993), updated by Scafetta and Willson (2014)) closely tracks temperatures in the Northern Hemisphere using a newly reconstructed temperature record from 1881 to 2014 based on primarily rural temperature stations. (See Figure 2.2.4.1.3.) This result is especially significant in that Soon *et al*. (2015) were the first to attempt to avoid the known contamination of non-climatic factors in the surface station records around the world.

Figure 2.2.4.1.2
Solar models considered by IPCC AR5 versus other models in the literature

A. Solar models considered by the IPCC

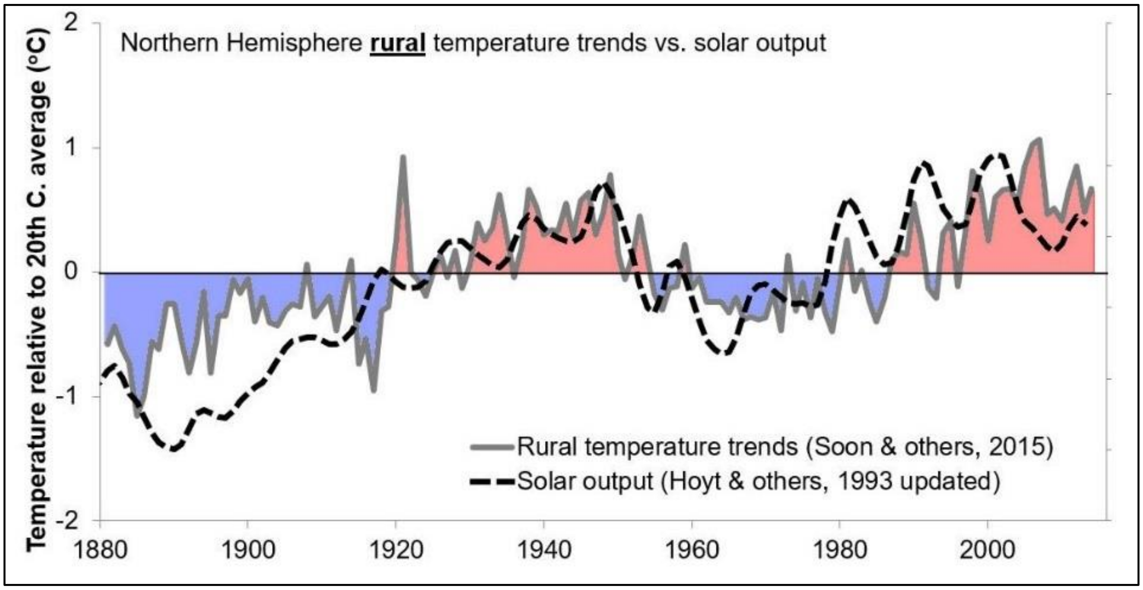


B. Solar models not considered by the IPCC



Source: Adapted from Soon *et al.,* 2015, Figure 8, p. 422. See original source for models cited in the figures.

Figure 2.2.4.1.3
Northern Hemisphere rural temperature trends vs. solar output



Red and blue represent positive and negative temperature anomalies from twentieth-century average for a Northern Hemisphere temperature reconstruction using primarily rural surface stations (to control for urban heat island effect). Dashed line is solar output according to Hoyt and Schatten (1993) as updated by Scafetta and Willson (2014). *Source:* Adapted from Soon *et al.,* 2015, Figure 27, p. 442.

Several researchers using different methodologies have estimated the percentage of global warming in the modern era that could be attributed to solar activity. Ollila (2017) puts the solar contribution to warming in 2015 at 46% and greenhouse gases at 37%. Harde (2017) estimates that CO_2 contributed 40% and the Sun 60% to global warming over the last century. Booth (2018) estimates that 37% of the warming from 1980 to 2001 was due to solar effects.

Some solar scientists are investigating the possibility of the Sun entering a grand solar minimum (GSM), which could manifest itself within two decades (Lockwood *et al*., 2011). How an approaching GSM might affect Earth's climate is being studied extensively. Papers by Shindell *et al*. (2001) and others discussed the impact of past low solar activity on regional and global climate. During the last GSM, known popularly as the Maunder Minimum, Earth's climate underwent what has come to be known in climatic terms as the Little Ice Age (LIA), a period that brought the coldest temperatures of the entire Holocene, or current interglacial, in which we live. Lasting about 200 years (approximately 1650 to 1850), the brunt of the LIA was felt in Europe, which experienced long and extreme winters and cooler summers. Soon and Yaskell (2003) provide a comprehensive discussion of the climatic impact of the Maunder Minimum. Whether the Sun is indeed approaching a new grand solar minimum, however, remains to be seen.

* * *

It is now fairly certain the Sun was responsible for creating multi-centennial global cold and warm periods in the past, and it is quite plausible that modern fluctuations in solar output are responsible for some part of the warming the planet experienced during the past century or so. Besides solar activity changes, other natural climate drivers such as volcanic eruptions and ocean cycles controlled pre-industrial climate change. It is likely that these natural drivers continue to influence modern climate, in addition to yet unquantifiable anthropogenic contributions. A detailed quantitative understanding of the various climatic processes will be possible only once the natural background climate variability is fully understood and successfully calibrated with the known pre-industrial climate change as part of model hindcasts.

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2.2.4.2 Cosmic Rays

According to the IPCC, "cosmic rays enhance new particle formation in the free troposphere, but the effect on the concentration of cloud condensation nuclei is too weak to have any detectable climate influence during a solar cycle or over the last century (*medium evidence, high agreement*). No robust association between changes in cosmic rays and cloudiness has been identified. In the event that such an association existed, a mechanism other than cosmic ray-induced nucleation of new aerosol particles would be needed to explain it" (IPCC, 2013, p. 573). On this matter, new research has proven the IPCC to be wrong.

The field of galactic cosmic ray (GCR) research begins with the original publication of Svensmark and Friis-Christensen (1997) and later developments are summarized well by Svensmark (2007). Svensmark and his colleagues at the Center for Sun-Climate Research of the Danish National Space Center experimentally determined ions released to the atmosphere by GCRs act as catalysts that significantly accelerate the formation of ultra-small clusters of sulfuric acid and water molecules that constitute the building blocks of cloud condensation nuclei. Svensmark also explains the complex chain of expected atmospheric interactions, in particular how, during periods of greater solar activity, greater shielding of Earth occurs associated with a strong solar magnetic field. That shielding results in fewer cosmic rays penetrating to the lower atmosphere of the Earth, resulting in fewer cloud condensation nuclei being produced and thus fewer and less reflective low-level clouds occurring. More solar radiation is thus absorbed at the surface of Earth, resulting in increasing near-surface air temperatures.

Svensmark provides support for key elements of this scenario with graphs illustrating the close correspondence between global low-cloud amount and cosmic-ray counts over the period 1984–2004. He also notes the history of changes in the flux of galactic cosmic rays estimated since 1700, which correlates well with Earth's temperature history over the same time period, starting from the latter portion of the Maunder Minimum (1645–1715), when Svensmark says "sunspots were extremely scarce and the solar magnetic field was exceptionally weak," and continuing on through the twentieth century, over which last hundred-year interval, as noted by Svensmark, "the Sun's coronal magnetic field doubled in strength."

Over the past two decades, several studies have uncovered evidence supporting several of the linkages described by Svensmark (e.g., Lockwood *et al*., 1999; Parker, 1999; Kniveton and Todd, 2001; Carslaw *et al*., 2002; Shaviv and Veizer, 2003; Veretenenko *et al*., 2005; Usoskin *et al*., 2006; Lockwood, 2011; Shapiro *et al.*, 2011; Veretenenko and Ogurtsov, 2012; Georgieva *et al.*, 2012). In 2016, CERN (the European Institute for Nuclear Research) confirmed one of Svensmark's postulates when its large particle beam accelerator, acting on a cloud chamber, revealed that ions from cosmic rays increase the number of cloud condensation nuclei of sizes of at least 50 to 100 nanometers. Kirkby *et al*. (2016) write,

> We find that ions from galactic cosmic rays increase the nucleation rate by one to two orders of magnitude compared with neutral nucleation. Our experimental findings are supported by quantum chemical calculations of the cluster binding energies of representative HOMs [highly oxygenated molecules]. Ion-induced nucleation of pure organic particles constitutes a potentially widespread source of aerosol particles in terrestrial environments with low sulfuric acid pollution.

The CERN experiment documents an important mechanism whereby cosmic rays turn small changes in TSI into larger effects on temperatures. The pre-industrial atmosphere is thought to have been "pristine," without sulfuric acid caused by the combustion of fossil fuels. We now know cosmic rays were seeding clouds then, so their presence or absence due to variation in solar wind explains more of the variability in temperature observed in geological and historical reconstructions than previously thought. Commenting on the finding, Svensmark *et al.* (2017) write, "The mechanism could therefore be a natural explanation for the observed correlations between past climate variations and cosmic rays, modulated by either solar activity or caused by supernova activity in the solar neighborhood on very long time scales where the mechanism will be of profound importance."

An active debate is taking place over the empirical basis for the cosmic ray-low cloud relationship, with scientists raising alternative mechanisms involving the solar wind, aurora, and atmospheric gravity waves (see Soon *et al.,* 2000, 2015; Prikryl *et al*., 2009a; 2009b; Scafetta 2012a, 2012b; Scafetta and Willson, 2013a, 2013b). The flux of galactic cosmic rays clearly wields an important influence on Earth's climate, likely much more so than that exhibited by the modern increase in atmospheric CO_2. At the very least, these research findings invalidate the IPCC's claim that the GCR-ionization mechanism is too weak to influence global temperatures.

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2.2.4.3 Possible Future Impacts

Researchers study the Sun itself as well as the decadal, multidecadal, centennial, and even millennial periods in available climate and solar records in order to extrapolate solar activity into the future. Solheim *et al*. (2012) found significant linear relationships between the average air temperature in a solar cycle and the length of the previous solar cycle for 12 of 13 weather stations in Norway and the North Atlantic, as well as for 60 European stations and for the HadCRUT3N database. For Norway and the other European stations, they found "the solar contribution to the temperature variations in the period investigated is of the order 40%" while "an even higher contribution (63–72%) is found for stations at the Faroe Islands, Iceland and Svalbard," which they note is considerably "higher than the 7% attributed to the Sun for the global temperature rise in AR4 (IPCC, 2007)."

Ludecke *et al.* (2013) considered six periodic components with timescales greater than 30 years in the composite of a six-station temperature record from Central Europe since about 1757, creating a very good reconstruction of the original instrumental records. They project a substantial cooling of the Central European temperature in the next one to two decades but caution their result "does not rule out a warming by anthropogenic influences such as an increase of atmospheric CO_2." In addition, climate system internal oscillations may play a role.

In analyzing the global temperature data records (HadCRUT3 and HadCRUT4, respectively) directly, Loehle and Scafetta (2011) and Tung and Zhou (2013) conclude a large fraction of recent observed warming (60% over 1970–2000 and 40% over the past 50 years) can be accounted for by the natural upswing of the 60-year climatic ocean cycle during its warming phase. Loehle and Scafetta (2011) proffer that "a 21st Century forecast suggests that climate may remain approximately steady until 2030–2040, and may at most warm 0.5–1.0°C by 2100 at the estimated 0.66°C/century anthropogenic warming rate, which is about 3.5 times smaller than the average 2.3°C/century anthropogenic warming rate projected by the IPCC up to the first decades of the 21st century. However, additional multi-secular natural cycles may cool the climate further."

Scafetta (2016) says his 2011 temperature forecast "has well agreed with the global surface temperature data up to August 2016." He then proposes "a semi-empirical climate model able to reconstruct the natural climatic variability since Medieval times. I show that this model projects a very moderate warming until 2040 and a warming less than 2°C from 2000 to 2100 using the same anthropogenic emission scenarios used by the CMIP5 models. This result suggests that climatic adaptation policies, which are less expensive than the mitigation ones, could be sufficient to address most of the consequences of a climatic change during the 21st century."

In an independent analysis of global temperature data from the Climatic Research Unit (CRU) at the University of East Anglia and the Berkeley Earth Surface Temperature consortium, Courtillot *et al*. (2013) arrive at a new view of the significance of the ~60 year oscillation. They interpret the 60-year period found in the global surface temperature record as "a series of ~30-yr long linear segments, with slope breaks (singularities) in ~1904, ~1940, and ~1974 (±3 yr), and a possible recent occurrence at the turn of the 21st century." Courtillot and his colleagues suggest "no further temperature increase, a dominantly negative PDO index and a decreasing AMO index might be expected for the next decade or two."

By extrapolating present solar cycle patterns into the future, several scientists have suggested a planetary cooling may be expected over the next few decades. The Gleissberg and Suess/de Vries cycles will reach their low points between 2020 and 2040 at a level comparable to what was experienced during the Dalton Minimum. At that time, around 1790–1820, global temperatures were nearly 1°C lower than they are today; conservatively, at least half of that cooling was due to a weaker Sun. Moreover, as Courtillot *et al*. (2013) noted, the Pacific Decadal Oscillation (PDO) is expected to be in a cool phase by 2035, and the Atlantic Multidecadal Oscillation (AMO) will begin to drop around 2020. Such internal climate cycles are generally responsible for about 0.2°C to 0.3°C of the temperature dynamic.

Soon *et al.* (2015) use the new surface temperature record for North America they created using rural stations and the TSI reconstruction created by Hoyt and Schatten (1993) as updated by Scafetta and Willson (2014) to estimate a solar radiative forcing of 1 Wm^{-2} on average causes a change of 1.18°C in surface temperature. The warming from 1881 to 2014 is almost entirely explained by this forcing, leaving CO_2 forcing responsible for a minute "residual" of approximately 0.12°C. They calculate a doubling of CO_2 from its current level of about 400 ppm would cause "at most" 0.44°C of warming (Soon *et al.*, 2015, p. 444).

Finally, Cionco *et al*. (2018) recently provided the first comprehensive boundary conditions for incoming solar radiation that fully account for both the correct orbital solutions (based on Cionco and Soon, 2017) and the intrinsic solar irradiance changes (Velasco Herrera *et al*., 2015) for the past 2,000 years as well as a forward projection for about 100 years into the future.

* * *

Effects of solar variations on climate are due to changes in radiation reaching the Earth as well as still poorly understood amplifier effects associated with cosmic rays, cloud cover, and stratospheric temperature changes in combination with the ultraviolet (UV) part of the solar spectrum. The CERN experiment in 2016 provided some proof of the mechanism for which the IPCC asked in its Fifth Assessment Report. Numerous case studies of the last decades to millennia have empirically demonstrated a strong link between solar activity and climate. We now know solar influences play a larger role in average surface temperature and other climate indices than the IPCC assumed in 2013 and most climate modelers still assume today. The cautions about avoiding or eliminating non-climatic factors in the world's surface station records from Soon *et al*. (2015) are also important for IPCC authors to note. Estimates of climate sensitivity to a doubling of CO_2 that take the new research into account are lower, and so too are forecasts of future temperature increases. While forecasts differ and are uncertain, one clear conclusion is that the IPCC's prediction of future warming is too high.

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2.3 Climate Impacts

The Working Group II contribution to the Fifth Assessment Report (AR5) of the United Nations' Intergovernmental Panel on Climate Change (IPCC, 2014) claims climate change causes a "risk of death, injury, and disrupted livelihoods" due to sea-level rise, coastal flooding, and storm surges; food insecurity, inland flooding, and negative effects on fresh water supplies, fisheries, and livestock; and "risk of mortality, morbidity, and other harms during periods of extreme heat, particularly for vulnerable urban populations" (p. 7).

Given the uncertainty that pervades climate science discussed in Section 2.1, and observations showing less warming of the atmosphere than predicted by climate models discussed in Section 2.2, disagreement and uncertainty over the climate impacts of human activity can be expected. This section documents that uncertainty. Observational data on four climate impacts are surveyed here: what the IPCC calls "extreme weather," melting ice, sea-level rise, and effects on plants.

More than two thousand studies on these subjects were reviewed in the Nongovernmental International Panel on Climate Change's *Climate Change Reconsidered II: Physical Science* (NIPCC, 2013) and *Climate Change Reconsidered II: Biological Impacts* (NIPCC, 2014). This section greatly condenses that literature review by leaving out descriptions of research methods and most studies published before 2010. Research is typically presented in chronological order by publication date. Reviews of new research published after 2013 have been added.

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2.3.1 Extreme Weather Events

> *There is little evidence that the warming of the twentieth and early twenty-first centuries has caused a general increase in "extreme" weather events. Meteorological science suggests a warmer world would see milder weather patterns.*

Sutton *et al.* (2018), five British climate scientists, admonished the editors of Nature for repeating the IPCC's claim that climate change is causing extreme weather events, writing in part,

> Attribution depends fundamentally on global climate models that can adequately capture regional weather phenomena – including circulation anomalies such as the weak jet stream and large, persistent planetary-scale atmospheric waves that characterized this summer's weather. Accurate simulation of such extremes remains a challenge for today's models. It is not enough to increase the size of the ensemble of simulations if the models themselves have fundamental limitations. Any statement on attribution should therefore always be accompanied by a scientifically robust demonstration of the model's ability to simulate the global and regional weather patterns and the related weather phenomena that lie at the root of extreme events.

Extensive scientific research supports the view expressed by Sutton *et al*. We address six weather phenomena characterized by the IPCC as "extreme weather events" allegedly caused by human greenhouse emissions: high temperatures and heat waves, wildfires, droughts, floods, storms, and hurricanes. In every case, we find the IPCC exaggerates the possibility that such events have or will become more frequent or more intense due to the human presence.

2.3.1.1 Heat Waves

According to the Summary for Policymakers (SPM) of the Working Group I contribution to the IPCC's Fifth Assessment Report, "It is *virtually certain* that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales as global mean temperatures increase. It is *very likely* that heat waves will occur with a higher frequency and duration" (IPCC, 2013, p. 20). Regarding past trends, the IPCC writes "There is only *medium confidence* that the length and frequency of warm spells, including heat waves, has increased since the middle of the 20th century mostly owing to lack of data or of studies in Africa and South America. However, it is *likely* that heatwave frequency has increased during this period in large parts of Europe, Asia and Australia" (p. 162). The prediction in the SPM has fed the almost hysterical claims about recent and future heat waves appearing in the media and in "documentary" films. But the IPCC's position overstates the possibility that rising temperatures and heat waves pose a threat to human health.

As explained in Section 2.2.1, the surface station temperature record is too flawed to be used as the basis of scientific research. One of many problems it faces is contamination by heat-emitting and -absorbing activities and structures associated with urbanization. Buildings, roads, parking lots, and loss of green space all combine to raise temperatures, and their effects need to be removed if the purpose of a temperature reconstruction is to measure the effect of anthropogenic greenhouse gases. The IPCC claims to control for this "heat island effect," but researchers have found its adjustments are too small (e.g. McKitrick and Michaels, 2007; Soon *et al.* 2015; Quereda Sala *et al.*, 2017). For example, Zhou and Ren (2011) studied the impact of urbanization on extreme temperature indices for the period 1961–2008 using daily temperature records from the China Homogenized Historical Temperature Datasets compiled by the National Meteorological Information Center of the China Meteorological Administration. They discovered "the contributions of the urbanization effect to the overall trends ranged from 10% to 100%, with the largest contributions coming from tropical nights, daily temperature range, daily maximum temperature and daily minimum temperature," adding "the decrease in daily temperature range at the national stations in North China was caused entirely by urbanization."

A second problem affecting forecasts of future warming is that they fail to consider the cooling effects of the Greening of the Earth phenomenon reported in Section 2.1.2 and in greater detail in Chapter 5. Jeong *et al*. (2010) investigated "the impact of vegetation-climate feedback on the changes in temperature and the frequency and duration of heat waves in Europe under the condition of doubled atmospheric CO_2 concentration in a series of global climate model experiments." Their calculations revealed "the projected warming of 4°C over most of Europe with static vegetation has been reduced by 1°C as the dynamic vegetation feedback effects are included," and "examination of the simulated surface energy fluxes suggests that additional greening in the presence of vegetation feedback effects enhances evapo-transpiration and precipitation, thereby limiting the warming, particularly in the daily maximum temperature." The scientists found "the greening also tends to reduce the frequency and duration of heat waves."

Extensive investigation of historical records and proxy data has found many examples of absolute temperature or variability of temperature exceeding observational data from the twentieth and early twenty-first centuries, lending support to the null hypothesis that recent temperature changes are due to natural causes. For example, Dole *et al*. (2011) ask whether a 2010 summer heat wave in western Russia exceeded natural variability and thus could be evidence of an anthropogenic effect on climate. They used climate model simulations and observational data "to determine the impact of observed sea surface temperatures, sea ice conditions and greenhouse gas concentrations." They found "analysis of forced model simulations indicates that neither human influences nor other slowly evolving ocean boundary conditions contributed substantially to the magnitude of the heat wave." They observed the model simulations provided "evidence that such an intense event could be produced through natural variability alone." "In summary," Dole *et al*. observe, "the analysis of the observed 1880–2009 time series shows that no statistically significant long-term change is detected in either the mean or variability of western Russia July temperatures, implying that for this region an anthropogenic climate change signal has yet to emerge above the natural background variability."

Hiebl and Hofstatter (2012) studied the extent to which temperature variability may have increased in Austria since the late nineteenth century. Using air temperature based on 140 years of data from

Vienna-Hohe Warte, Kremsmunster, Innsbruck-University, Sonnblick, and Graz-University, they found a slow and steady rise in variability during the twentieth century. They also reported a "period of persistently high variability levels before 1900," which leads them to conclude the "relatively high levels of temperature variability during the most recent warm decades from 1990 to 2010 are put into perspective by similar variability levels during the cold late 19th century." They add, "when compared to its inter-annual fluctuations and the evolution of temperature itself, high-frequency temperature variability in the course of the recent 117–139 years appears to be a stable climate feature." Hiebl and Hofstatter conclude concerns about "an increasing number and strength of temperature extremes in terms of deviations from the mean state in the past decades cannot be maintained" and "exaggerated statements seem irresponsible."

Bohm (2012) studied climate data for South Central Europe from 1771–1800 and 1981–2010 and found "the overwhelming majority of seasonal and annual sub-regional variability trends is not significant." Regarding temperature, he reports "most of the variability trends are insignificantly decreasing." In a special analysis of the recent 1981–2010 period that may be considered the first "normal period" under dominant greenhouse-gas-forcing, he found all extremes "remaining well within the range of the preceding ones under mainly natural forcing," and "in terms of insignificant deviations from the long-term mean, the recent three decades tend to be less rather than more variable." Bohm concludes "the … evidence [is clear] that climate variability did rather decrease than increase over the more than two centuries of the instrumental period in the Greater Alpine Region, and that the recent 30 years of more or less pure greenhouse-gas-forced anthropogenic climate were rather less than more variable than the series of the preceding 30-year normal period."

Rusticucci (2012) examined the claim global warming will increase climatic variability, reviewing many studies that have explored this subject throughout South America, particularly as it applies to daily maximum and minimum air temperatures. The Buenos Aires researcher found the most significant trends exist in the evolution of the daily minimum air temperature, with "positive trends in almost all studies on the occurrence of warm nights (or hot extremes of minimum temperature)," as well as negative trends in the cold extremes of the minimum temperature. She states this was the case "in almost all studies." By contrast, she writes, "on the maximum temperature behavior there is little agreement, but generally the maximum temperature in South America has decreased." Over most of South America there has been a decrease in the extremeness of both daily maximum and minimum air temperatures, with the maximums declining and the minimums rising. These changes are beneficial, as Rusticucci notes cold waves and frost are especially harmful to agriculture, one of the main economic activities in South America. Cold waves and frost days were on the decline nearly everywhere throughout the continent during the warming of the twentieth century.

Deng *et al*. (2012) used daily mean, maximum, and minimum temperatures for the period 1958–2007 to examine trends in heat waves in the Three Gorges area of China, which comprises the Chongqing Municipality and the western part of Hubei Province, including the reservoir region of the Three Gorges Dam. They found extreme high temperature events showed a U-shaped temporal variation, decreasing in the 1970s and remaining low in the 1980s, followed by an increase in the 1990s and the turn of the twenty-first century, such that "the frequencies of heat waves and long heat waves in the recent years were no larger than the late 1950s and early 1960s." They observe, "coupled with the extreme low frequency in the 1980s, heat waves and long heat waves showed a slight linear decreasing trend in the past 50 years." They note the most recent frequency of heat waves "does not outnumber 1959 or 1961" and "none of the longest heat waves recorded by the meteorological stations occurs in the period after 2003." Deng *et al*. conclude, citing Tan *et al*. (2007), "compared with the 1950s and 1960s, short heat waves instead of long heat waves have taken place more often," which, as they describe it, "is desirable, as longer duration leads to higher mortality."

Sardeshmukh *et al.* (2015) comment on how "it is tempting to seek an anthropogenic component in any recent change in the statistics of extreme weather," but warn fellow scientists that such attribution is likely to be wrong "if the distinctively skewed and heavy-tailed aspects of the probability distributions of daily weather anomalies are ignored or misrepresented." Departures from mean values in temperature record even by "several standard deviations" are "far more common in such a distinctively non-Gaussian world than they are in a Gaussian world. This further complicates the problem of detecting changes in tail probabilities from historical records of limited length and accuracy." Referring to statements in IPCC's AR5 attributing changing extreme weather risks to global warming, the authors write,

> Such statements downplay the fact that there is more to regional climate change than surface warming, and that assessing the changing risks of extreme storminess, droughts, floods, and heat waves requires accurate model representations of multidecadal and longer-term changes in the large-scale modes of natural atmospheric circulation variability and the complex nonlinear climate-weather interactions associated with them. The detection of changes in such modes from the limited observational record is much less clear cut than for surface temperature.

Christy (2012) observed that most of the record highs for heat waves in the United States happened before atmospheric CO_2 levels rose because of human activities. Thirty-eight states set their record highs before 1960, and 23 states' record highs occurred in the 1930s. Also in the United States, the number of days per year during which the temperature broke 100°F (37.8°C) has *declined* considerably since the 1930s, as shown in Figure 2.3.1.1.1. Commenting on this figure, Christy (2016) writes "It is not only clear that hot days have not increased, but it is interesting that in the most recent years there has been a relative dearth of them" (p. 16). The U.S. Environmental Protection Agency's Heat Wave Index confirms the 1930s was the decade in the twentieth century with the most heat waves (EPA, 2016). (See Figure 2.3.1.1.2.)

It is also worth noting that in Canada, the hottest ever recorded temperature of 45°C (113°F) was reached on July 5, 1937 at Yellow Grass, Saskatchewan, on the Canadian Prairies. Also, the deadliest heat wave in Canada occurred July 5–12, 1936, when more than 1,000 people died of heat exhaustion in Manitoba and southern Ontario (Khandekar, 2010). Recent heat waves supposedly "amplified" by higher levels of CO_2 have not reached so high a level or had such tragic consequences.

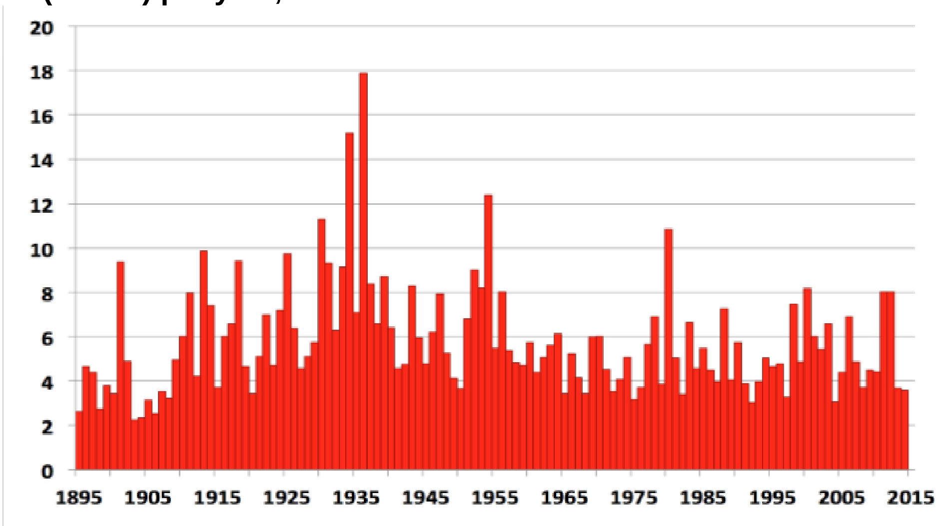
More recently, Köse *et al*. (2017) used a dataset of 23 tree-ring chronologies to provide a high-resolution spring (March–April) temperature reconstruction over Turkey during the period 1800–2002. The authors report, "the reconstruction is punctuated by a temperature increase during the 20th century; yet extreme cold and warm events during the 19th century seem to eclipse conditions during the 20th century." Similarly, Polovodova Asteman *et al*. (2018) used a ca. 8-m long sediment core from Gullmar Fjord (Sweden) to create a 2000-year record of winter temperatures. They report "the record demonstrates a warming during the Roman Warm Period (~350 BCE – 450 CE), variable bottom water temperatures during the Dark Ages (~450 – 850 CE), positive bottom water temperature anomalies during the Viking Age/Medieval Climate Anomaly (~850 – 1350 CE) and a long-term cooling with distinct multidecadal variability during the Little Ice Age (~1350 – 1850 CE)." Significantly, the temperature reconstruction "also picks up the contemporary warming of the 20th century, which does not stand out in the 2500-year perspective and is of the same magnitude as the Roman Warm Period and the Medieval Climate Anomaly."

Cold Weather

According to the IPCC (2013), "It is *virtually certain* that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales as global mean temperatures increase" (p. 20). Contrary to this forecast, many researchers have documented an increase in *cold* weather extremes in many parts of the world since around the beginning of the twenty-first century. Such events confirm the much lower temperature rise revealed by satellite data and rural temperature station records than the unreliable and frequently adjusted HadCRUT surface station record. Cold weather extremes have been observed throughout the Northern Hemisphere and parts of Asia. According to D'Aleo and Khandekar (2016), "Between 1996 and 2015, winter months (January to March) globally have shown no warming in 20 years. Instead, a cooling of 0.9°C (1.5°F)/decade has been identified in the northeastern United States. Cooling of a lesser magnitude has been shown for the lower 48 U.S. states and for winters in the UK for the last 20 years" (p. 107).

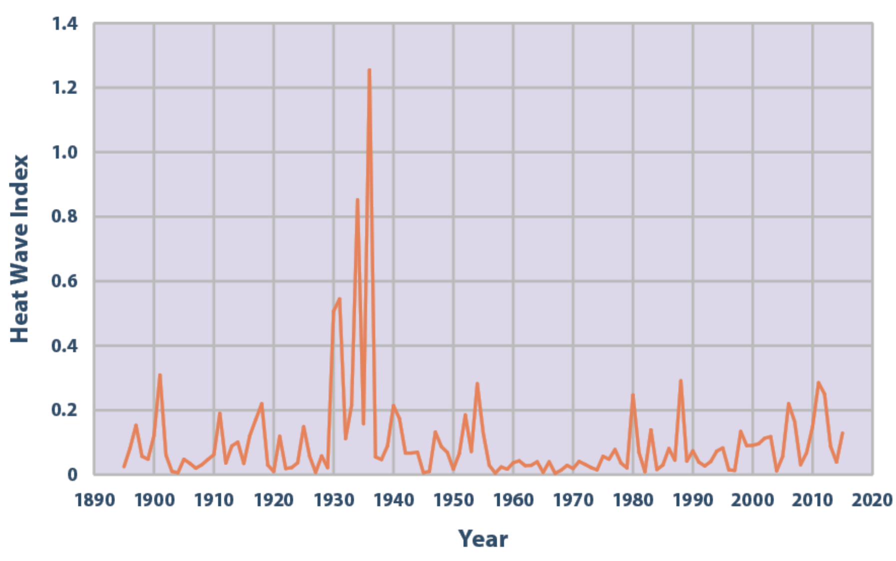
Among the papers published in the scientific literature reporting on the phenomenon are those by Benestad (2010), Cattiaux *et al*. (2010), Haigh (2010), Haigh *et al.* (2010), Wang *et al*. (2010), Woollings *et al*. (2010), Seager *et al*. (2010), Taws *et al*., (2011), Lockwood *et al*. (2011), Sirocko *et al*. (2012), Deser and

Figure 2.3.1.1.1
Average number of daily high temperatures at 982 USHCN stations exceeding 100°F (37.8°C) per year, 1895–2014



Source: Christy, 2016, citing NOAA data.

Figure 2.3.1.1.2
U.S. heat wave index, 1895–2015



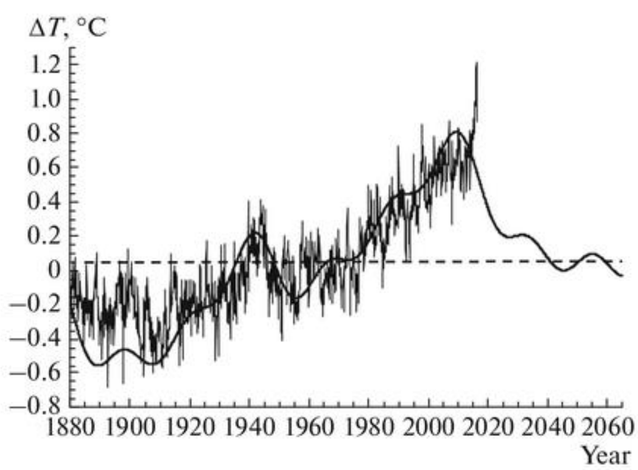
These data cover the contiguous 48 states. An index value of 0.2 could mean that 20% of the country experienced one heat wave, 10% of the country experienced two heat waves, or some other combination of frequency and area resulted in this value. *Source*: EPA, 2016.

Phillips (2015), Li *et al.* (2015), Sun *et al.* (2016), and Xie *et al.* (2016). Many of these papers suggest reduced solar activity played a prominent role in the observed colder winters.

Brown and Luojus (2018) report, "Early 2018 experienced close to record maximum snow accumulations over Northern Hemisphere and Arctic land areas since satellite passive microwave coverage began in 1979. The Finnish Meteorological Institute confirmed that the 2017/2018 winter has been quite exceptional compared to typical recent winters and is one of the snowier winters in the period since 1979 where passive microwave satellite data have been used to monitor the amount of snow on land. While 2017–2018 is not a record – that title belongs to 1993 with 3649 gigatons of peak snow water storage – close to 3500 gigatons of peak snow water storage were estimated, which ranks as the tenth highest peak snow accumulation since 1979."

Garnett and Khandekar (2018) contend "a colder climate awaits us," noting Canada, China, Europe, Japan, the United States, and other regions of the world have seen at least 25 global cold weather extremes since 2000. They write, "The IPCC-espoused science has highlighted [warm weather extremes] like heat waves, droughts, floods and fires while ignoring the 'cold' reality of the Earth's climate since the new millennium" (p. 435). Some Russian scientists predict cooling in the next few decades, as shown in Figure 2.3.1.1.3. See also Page (2017) and Lüdecke and Weiss (2018) for similar forecasts.

Figure 2.3.1.1.3
Changes in global near-surface air temperature from 1880–2015 and forecast after 2015



Thin lines represent monthly average ΔT counted from the average value of the global temperature for the period 1901–2000 (dashed line). The solid heavy curve represents calculations performed using spectral data analysis. *Source:* Stozhkov *et al.,* 2017, Figure 1.

As reported in Section 2.2.4, some solar scientists believe the Sun may be entering a grand solar minimum (GSM), which could manifest itself with cooler temperatures (Shindell *et al*., 2001; Lockwood *et al*., 2010, 2011; Yndestad and Solheim, 2016). During the last GSM, known as the Maunder Minimum, humanity endured the hardships of the Little Ice Age, a period that brought the coldest temperatures of the Holocene (Soon and Yaskell, 2003). Whether the Sun is indeed approaching a new GSM remains to be seen, but recent temperatures suggest cooling may be as much a concern as warming in coming decades.

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2.3.1.2 Wildfires

According to model-based predictions, larger and more intense wildfires will become more frequent because of CO_2-induced global warming. Many scientists have begun to search for a link between fire and climate, often examining past trends to see if they support the models' projections. While some studies find fires were more common during the Medieval Warm Period, and so might well increase if warming resumes in the twenty-first century, others find little or no impact on fires and some even find a declining trend during the twentieth century.

A warmer world with higher levels of CO_2 in the atmosphere produces more vegetation and consequently more fuel for fires. While this could be interpreted as "climate change will cause more forest fires," this hardly supports the meme that this is a net environmental harm, since rising temperatures and CO_2 levels are responsible for the increased mass of trees and other plants being burned. For example, Turner *et al*. (2008) determined "climatically-induced variation in biomass availability was the main factor controlling the timing of regional fire activity during the Last Glacial-Interglacial climatic transition, and again during Mid-Holocene times, with fire frequency and magnitude increasing during wetter climatic phases." In addition, they report spectral analysis of the Holocene part of the record "indicates significant cyclicity with a periodicity of ~1500 years that may be linked with large-scale climate forcing."

Riano *et al*. (2007) conducted "an analysis of the spatial and temporal patterns of global burned area with the Daily Tile US National Oceanic and Atmospheric Administration-Advanced Very High-Resolution Radiometer Pathfinder 8 km Land dataset between 1981 and 2000." For several areas of the world this investigation revealed there were indeed significant upward trends in land area burned. Some parts of Eurasia and western North America, for example, had annual upward trends as high as 24.2 pixels per year, where a pixel represents an area of 64 km^2. These increases in burned area, however, were offset by equivalent decreases in burned area in tropical Southeast Asia and Central America. Consequently, observe Riano *et al*., "there was no significant global annual upward or downward trend in burned area." They also note "there was also no significant upward or downward global trend in the burned area for any individual month." In addition, they found "latitude was not determinative, as divergent fire patterns were encountered for various land cover areas at the same latitude."

Marlon *et al*. (2008) observe "large, well-documented wildfires have recently generated worldwide attention, and raised concerns about the impacts of humans and climate change on wildfire regimes." The authors used "sedimentary charcoal records spanning six continents to document trends in both natural and anthropogenic biomass burning [over] the past two millennia." They found "global biomass burning declined from AD 1 to ~1750, before rising sharply between 1750 and 1870," after which it "declined abruptly." In terms of attribution, they note the initial long-term decline in global biomass burning was due to "a long-term global cooling trend," while they suggest the rise in fires that followed was "linked to increasing human influences." With respect to the final decline in fires that took place after 1870, however, they note it occurred "despite increasing air temperatures and population." As for what may have overpowered the tendency for increased global wildfires that would "normally" have been expected to result from the warming of the Little Ice Age-to-Current Warm Period transition, the nine scientists attribute "reduction in the amount of biomass burned over the past 150 years to the global expansion of intensive grazing, agriculture and fire management."

McAneney *et al*. (2009) assembled a database of building losses in Australia since 1900 and found "the annual aggregate numbers of buildings destroyed by bushfire since 1926 ... is 84," but "most historical losses have taken place in a few extreme fires." Nevertheless, they observe "the most salient result is that the annual probability of building destruction has remained almost constant over the last century," even in the face of "large demographic and social changes as well as improvements in fire fighting technique and resources." McAneney *et al*. conclude, "despite predictions of an increasing likelihood of conditions favoring bushfires under global climate change, we suspect that building losses due to bushfires are unlikely to alter materially in the near future."

Girardin *et al*. (2009) investigated "changes in wildfire risk over the 1901–2002 period with an analysis of broad-scale patterns of drought variability on forested eco-regions of the North American and Eurasian continents." The seven scientists report "despite warming since about 1850 and increased incidence of large forest fires in the 1980s, a number of studies indicated a decrease in boreal fire activity in the last 150 years or so." They find "this holds true for boreal southeastern Canada, British Columbia, northwestern Canada and Russia." With respect to this long-term "diminishing fire activity," Girardin *et al*. observe "the spatial extent for these long-term changes is large enough to suggest that climate is likely to have played a key role in their induction." The authors further note, "the fact that diminishing fire activity has also been detected on lake islands on which fire suppression has never been conducted provides another argument in support of climate control."

Brunelle *et al*. (2010) collected sediments during the summers of 2004 and 2005 from a drainage basin located in southeastern Arizona (USA) and northeastern Sonora (Mexico), from which samples were taken "for charcoal analysis to reconstruct fire history." Their results "show an increase in fire activity coincident with the onset of ENSO, and an increase in fire frequency during the Medieval Climate Anomaly [MCA]." During this latter period, from approximately AD 900 to 1260, "background charcoal reaches the highest level of the entire record and fire peaks are frequent," and "the end of the MCA shows a decline in both background charcoal and fire frequency, likely associated with the end of the MCA-related drought in western North America (Cook *et al*., 2004)." Brunelle *et al*. speculate that if the region of their study warms in the future, "warming and the continuation of ENSO variability will likely increase fire frequency (similar to the MCA) while extreme warming and the shift to a persistent El Niño climate would likely lead to the absence of fires, similar to >5000 cal yr BP."

Wallenius *et al*. (2011) "studied *Larix*-dominated forests of central Siberia by means of high-precision dendro-chronological dating of past fires." They found "in the 18th century, on average, 1.9% of the forests burned annually, but in the 20th century, this figure was only 0.6%," and "the fire cycles for these periods were 52 and 164 years, respectively." In addition, they report "a further analysis of the period before the enhanced fire control program in the 1950s revealed a significant lengthening in the fire cycle between the periods 1650–1799 and 1800–1949, from 61 to 152 years, respectively." They note "a similar phenomenon has been observed in Fennoscandia, southern Canada and the western United States, where the annually burned proportions have decreased since the 19th century (Niklasson and Granstrom, 2000; Weir *et al*., 2000; Heyerdahl *et al*., 2001; Bergeron *et al*., 2004)." They also found "in these regions, the decrease has been mostly much steeper, and the current fire cycles are several hundreds or thousands of years."

Girardin *et al*. (2013) write that many people have supposed that "global wildfire activity resulting from human-caused climatic change is a threat to communities living at wildland-urban interfaces world-wide and to the equilibrium of the global carbon cycle." The eight researchers note "broadleaf deciduous stands are characterized by higher leaf moisture loading and lower flammability and rate of wildfire ignition and initiation than needleleaf evergreen stands," citing the work of Paatalo (1998), Campbell and Flannigan (2000), and Hely *et al*. (2001). And they therefore speculate that the introduction of broadleaf trees into dense needleleaf evergreen landscapes "could decrease the intensity and rate of spread of wildfires, improving suppression effectiveness, and reducing wildfire impacts," citing Amiro *et al*. (2001) and Hirsch *et al*. (2004).

Girardin *et al.* (2013) integrated into a wildfire modeling scheme information about millennial-scale changes in wildfire activity reconstructed from analyses of charred particles found in the sediments of 11 small lakes located in the transition zone between the boreal mixed-wood forests and the dense needle leaf forests of eastern boreal Canada. They report their assessment of millennial-scale variations of seasonal wildfire danger, vegetation flammability, and fire activity suggests "feedback effects arising from vegetation changes are large enough to offset climate change impacts on fire danger."

Asking whether such vegetation changes occur in the real world, the Canadian and French scientists cite the work of McKenney *et al*. (2011) and Terrier *et al*. (2013) suggesting that "future climate warming will lead to increases in the proportion of hardwood forests in both southern and northern boreal landscapes." They note this change in landscapes likely will have other benefits as well, such as "the higher albedo and summer evapotranspiration from deciduous trees, which would cool and counteract regional warming (Rogers *et al*., 2013), and the increase in the resilience of forests to climatic changes (Drobyshev *et al*., 2013)."

Yang *et al.* (2014) note fire is a critical component of the biosphere that "substantially influences land surface, climate change and ecosystem dynamics." To accurately predict fire regimes in the twenty-first century, they write, "it is essential to understand the historical fire patterns and recognize the interactions among fire, human and environmental factors." They "developed a 0.5° x 0.5° data set of global burned area from 1901 to 2007 by coupling the Global Fire Emission Database version 3 with a process-based fire model and conducted factorial simulation experiments to evaluate the impacts of human, climate and atmospheric components."

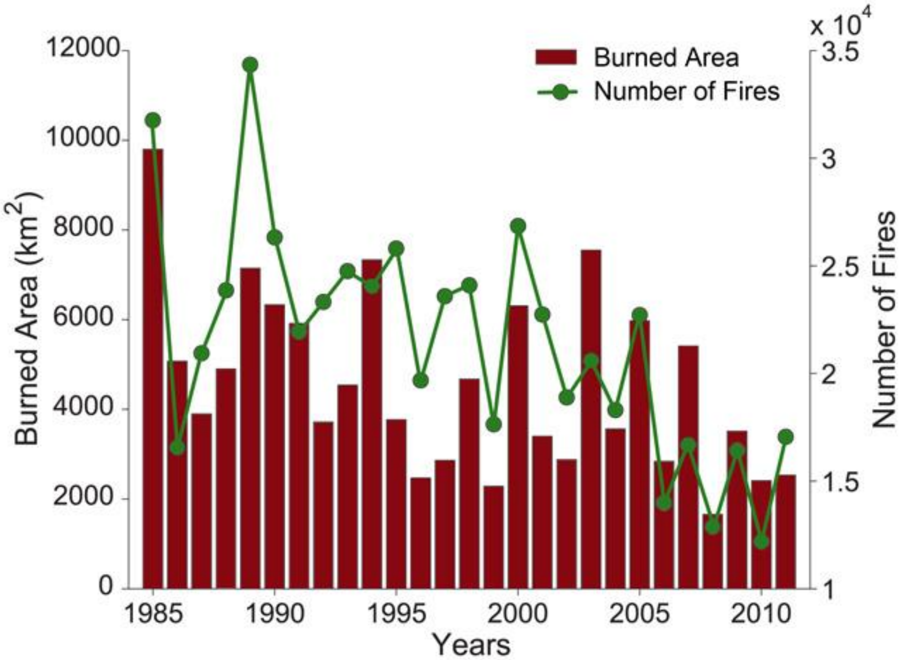
The seven scientists found "the average global burned area was about 442×10^4 km^2/yr during 1901–2007," with "a notable declining rate of burned area globally (1.28×10^4km^2/yr)." They also found "burned area in the tropics and extra-tropics exhibited a significant declining trend, with no significant trend detected at high latitudes." They report "factorial experiments indicated that human activities were the dominant factor in determining the declining trend of burned area in the tropics and extra-tropics" and "climate variation was the primary factor controlling the decadal variation of burned area at high latitudes." They note elevated CO_2 and nitrogen deposition "enhanced burned area in the tropics and southern extra-tropics" but "suppressed fire occurrence at high latitudes."

According to Hanson and Odion (2014), "there is widespread concern about an increase in fire severity in the forests of the western United States," citing Agee and Skinner (2005), Stephens and Ruth (2005), and Littell *et al*. (2009); but they write prior studies of the subject have "provided conflicting results about current trends of high-severity fire," possibly due to the fact that they "have used only a portion of available fire severity data, or considered only a portion of the Sierra Nevada." Using remote sensing data obtained from satellite imagery to assess high-severity fire trends since 1984, Hanson and Odion analyzed the entire region included within the Sierra Nevada Ecosystem Project (SNEP, 1996), which includes all of the Sierra Nevada and the southern Cascade mountains located within California, USA.

The two researchers report they could find "no trend in proportion, area or patch size of high-severity fire," while also noting "the rate of high-severity fire has been lower since 1984 than the estimated historical rate." They conclude that predictions of excessive, high-severity fire throughout the Sierra Nevada in the future "may be incorrect."

Noting "forest fires are a serious environmental hazard in southern Europe," Turco *et al*. (2016) write that "quantitative assessment of recent trends in fire statistics is important for assessing the possible shifts induced by climate and other environmental/ socioeconomic changes in this area." They analyzed "recent fire trends in Portugal, Spain, southern France, Italy and Greece, building on a homogenized fire database integrating official fire statistics provided by several national/EU agencies." The nine researchers from Greece, Italy, and Spain report, "during the period 1985–2011, the total annual burned area (BA) displayed a general decreasing trend" (see Figure 2.3.1.2.1) and "BA decreased by about 3020 km^2 over the 27-year-long study period (i.e. about -66% of the mean historical value)." They note "these results are consistent with those obtained on longer time scales when data were

Figure 2.3.1.2.1
Total annual burned area (BA) and number of fires (NF) in Mediterranean Europe, 1985–2011



Source: Adapted from Turco *et al*., 2016.

available" and "similar overall results were found for the annual number of fires (NF), which globally decreased by about 12,600 in the study period (about -59%)."

Calder *et al*. (2015) used 12 lake-sediment charcoal records taken within and surrounding the Mount Zirkel Wilderness, a mountainous area of subalpine forests in northern Colorado, USA, to reconstruct the history of wildfire in the region over the past two millennia. The researchers found "warming of ~0.5 °C ~1,000 years ago increased the percentage of our study sites burned per century by ~260% relative to the past ~400 y," confirming that wildfires during the Medeival Warm Period were much more frequent and intense than they are in the modern era. The authors report, "only 15% of our study area burned in the past 80 y and only 30% of the area in a 129,600-ha study area in Yellowstone National Park burned from 1890 to 1988. Using Yellowstone National Park fire history as a baseline for comparison, our minimum estimate of 50% of sites burned within a century at the beginning of the MCA (Medieval Climate Anomaly) exceeds any century-scale estimate of Yellowstone National Park burning for the past 750 y."

Zhang *et al.* (2016) studied trends in forest fires and carbon emissions in China from 1988 to 2012. They note, "As one of the largest potential mechanisms for release of carbon from forest ecosystems, fires can have substantial impacts on the net carbon balance of ecosystems through emissions of carbon into the atmosphere and changes in net ecosystem productivity in postfire environments (Li *et al.*, 2014; Liu *et al.*, 2014). For 1960 to 2000, global estimates of approximately 2.07–2.46 Pg carbon emission per year due to fire have been reported (Schultz *et al.*, 2008; van der Werf *et al.*, 2010; Randerson *et al.*, 2012). These emissions represent about 26%–31% of current global CO_2 emissions from fossil fuels and industrial processes (Raupach *et al.*, 2007)." Using data reported in the *China Agriculture Yearbooks* from 1989 to 2013, the researchers were able to identify 169,100 forest fires that occurred in China, an average of 6,764 fires per year. "During the entire period, no significant temporal trends of fire numbers and burned area were observed." The frequency of fires declined during the

1990s, rose during the 2000s, and fell precipitously after 2008. They conclude, "The results indicated that no significant increases in fire occurrence and carbon emissions were observed during the study period at the national level."

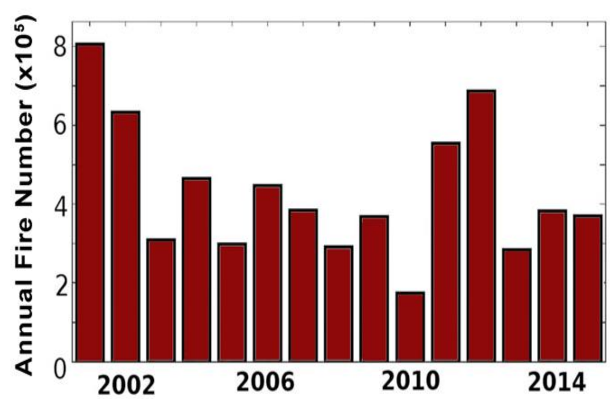
Introducing their study of a somewhat unusual subject, Meigs *et al*. (2016) write "in western North America, recent widespread insect outbreaks and wildfires have sparked acute concerns about potential insect-fire interactions," noting "although previous research shows that insect activity typically does not increase wildfire likelihood, key uncertainties remain regarding insect effects on wildfire severity." The five U.S. researchers developed "a regional census of large wildfire severity following outbreaks of two prevalent bark beetle and defoliator species – mountain pine beetle (*Dendroctonus ponderosae*) and western spruce budworm (*Choristoneura freemani*) – across the U.S. Pacific Northwest." They report, "in contrast to common assumptions of positive feedbacks, we find that insects generally reduce the severity of subsequent wildfires," noting "specific effects vary with insect type and timing," but "both insects decrease the abundance of live vegetation susceptible to wildfire at multiple time lags," so that "by dampening subsequent burn severity, native insects could buffer rather than exacerbate fire regime changes expected due to land use and climate change." In light of these findings, they recommend "a precautionary approach when designing and implementing forest management policies intended to reduce wildfire hazard and increase resilience to global change."

Noting the economic and ecological costs of wildfires in the United States have risen in recent decades, Balch *et al*. (2017) studied more than 1.5 million government records of wildfires that had to be either extinguished or managed by state or federal agencies from 1992 to 2012. The six scientists report "humans have vastly expanded the spatial and seasonal 'fire niche' in the coterminous United States, accounting for 84% of all wildfires and 44% of total area burned." They note "during the 21-year time period, the human-caused fire season was three times longer than the lightning-caused fire season" and humans "added an average of 20,000 wildfires per year across the United States."

Earl and Simmonds (2017) examined the spatial and temporal patterns of fire activity for Australia over the period 2001–2015 using satellite data from the MODerate resolution Imaging Spectroradiometer (MODIS) sensors on the Terra and Aqua satellites, which they write allows for "a more consistent and comprehensive evaluation" of fire trends. They derived fire count numbers from an active fire algorithm, allowing them to calculate seasonal and annual fire activity on a 0.1° x 0.1° grid box scale (~1000 km^2). Results for Australia as a whole are presented in Figure 2.3.1.2.2. Annual fire numbers for Australia have decreased across the past 15 years of study, although the decrease is not statistically significant. Seasonally, the most abundant fire season was in the spring (48% of all fires), followed by winter (21%), summer (16%), and fall (15%). Summer was the only season found to exhibit a statistically significant trend ($p < 0.05$), showing a decline over the period of record.

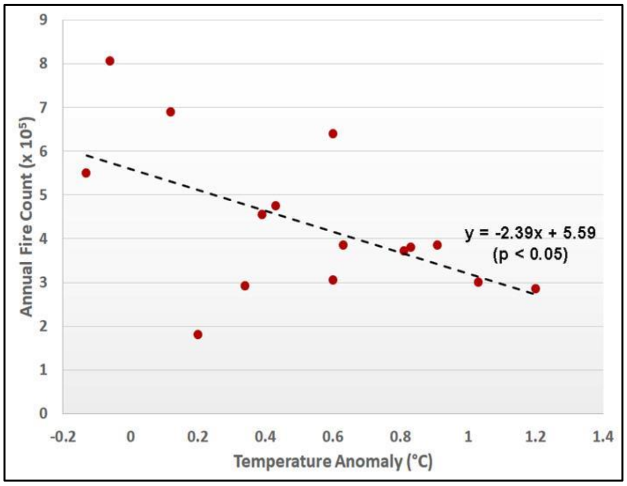
With respect to possible climatic drivers of annual fire number statistics, Earl and Simmonds (2017) conducted a series of analyses to explore their relationship with large-scale climate indices, including ENSO, the Indian Ocean Dipole, and a precipitation dataset covering the continent. Their results revealed some significant relationships across both space and time. The authors did *not* conduct an analysis between the fire records and temperature, which omission we have remedied in Figure 2.3.1.2.3. As illustrated there, a statistically significant relationship exists between Australian temperature and annual fire counts, such that a 1°C temperature increase results in a 2.39 x 10^5 decline in annual fire count. Consequently, these data would appear to contradict claims that rising temperatures will increase fire frequency.

Figure 2.3.1.2.2
Annual number of Australian fires over the period 2001–2015



Source: Adapted from Earl and Simmonds, 2017.

Figure 2.3.1.2.3
Relationship between the annual number of Australian fires and Australian temperature anomalies over the period 2001–2015



Source: Adapted from Earl and Simmonds, 2017.

Stirling (2017) studied the circumstances around the Fort McMurray, Alberta wildfire of 2016, said at the time to be "the costliest [insured] natural disaster in Canadian history," to see if claims that the fire was the result of global warming had a scientific basis. She begins by noting "Wildfires are an expected and essential occurrence in the vast boreal forests of Canada. Fires are essential for the regrowth of certain coniferous species whose seeds can only be released from the pine cones under the intense heat of a wildfire. But unusually dry periods between snow-melt and spring rain, careless campers or reckless intentional activities, and uncontrollable natural conditions like high winds and aging conifers can turn otherwise manageable wildfires into catastrophic, extreme events within hours or days if appropriate personnel, wildfire fighting equipment, and sufficient budget are not immediately available."

Stirling (2017) identifies the proximate causes of the fire and its destructiveness as a dry spring, sparse snow cover, inadequate resources for appropriate management of the fire hazard being "at the ready," and the high ratio of aging conifers. "Aging trees die from the bottom up," she explains, "with lower branches remaining on the stem. These become 'ladder fuels,' literally offering a small fire a way to race up the tree to the crown." Her review of 96 years of Fort McMurray temperature records of the monthly average daytime highs found "no apparent warming trend." (Recall from Section 2.1.1 that a common mistake made in climate research is to assume that global averages and trends accurately describe local and regional circumstances.) Stirling also observes that some 80% of forest fires are caused by human interaction with wilderness, which is "directly proportional to humans building into and extending activity in forested areas." She also notes fossil fuels allow "humans to escape wildfires in mass evacuations by car, truck and plane, and to fight wildfires with fossil-fueled air craft like water bombers, helicopters and motorized water pumps and vehicles."

Wildfires in the United States have been the focus of public attention in recent years due to drought conditions and forest mismanagement mainly in California. Nationally, the average annual number of forest fires did not increase between 1983, the first year for which comparable data are available, and 2017 (NIFC, n.d.). The number of acres burned did increase, though that figure is highly variable and has not increased since 2007. Both trends appear in Figure 2.3.1.2.4 below.

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Figure 2.3.1.2.4
Number of U.S. wildland fires and acres burned per year, 1983–2017

Source: National Interagency Fire Center (NIFC), n.d.

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2.3.1.3 Droughts

> *The link between warming and drought is weak, and by some measures drought decreased over the twentieth century. Changes in the hydrosphere of this type are regionally highly variable and show a closer correlation with multidecadal climate rhythmicity than they do with global temperature.*

Higher surface temperatures are said to result in more frequent, severe, and longer-lasting droughts. The IPCC expresses doubt, however, that this is or will become a major problem. In the Working Group I contribution to the Fifth Assessment Report, the authors write "compelling arguments both for and against significant increase in the land area affected by drought and/or dryness since the mid-20th century have resulted in a *low confidence* assessment of observed and attributable large-scale trends" and "*high confidence* that proxy information provides evidence of droughts of greater magnitude and longer duration than observed during the 20th century in many regions" (IPCC, 2013, p. 112).

The historical record is replete with accounts of megadroughts lasting for several decades to centuries that occurred during the Medieval Warm Period (MWP), dwarfing modern-day droughts (e.g., Seager *et al*., 2007; Cook *et al*., 2010). Atmospheric CO_2 concentrations were more than 100 ppm lower during the Medieval Warm Period than they are today. The clear implication is that natural processes operating during the MWP were responsible for droughts that were much more frequent and lasted much longer than those observed in the twentieth and twenty-first centuries or even forecast for the rest of the twenty-first century by all but the most unrealistic climate models.

Minetti *et al*. (2010) examined a regional inventory of monthly droughts for the portion of South America located south of approximately 22°S latitude, dividing the area of study into six sections (the central region of Chile plus five sections making up most of Argentina). They note "the presence of long favorable tendencies [1901–2000] regarding precipitations or the inverse of droughts occurrence are confirmed for the eastern Andes Mountains in Argentina with its five sub-regions (Northwest Argentina, Northeast Argentina, Humid Pampa, West-Centre Provinces and Patagonia) and the inverse over the central region of Chile." From the middle of 2003 to 2009, however, they report "an upward trend in the occurrence of droughts with a slight moderation over the year 2006." They additionally note the driest single-year periods were 1910–1911, 1915–1916, 1916–1917, 1924–1925, and 1933–1934, suggesting twentieth century warming has not promoted an abnormal increase in droughts in the southern third of South America.

Sinha *et al*. (2011) observed "proxy reconstructions of precipitation from central India, north-central China (Zhang *et al*., 2008), and southern Vietnam (Buckley *et al*., 2010) reveal a series of monsoon droughts during the mid 14th–15th centuries that each lasted for several years to decades," and "these monsoon megadroughts have no analog during the instrumental period." They note "emerging tree ring-based reconstructions of monsoon variability from SE Asia (Buckley *et al*., 2007; Sano *et al*., 2009) and India (Borgaonkar *et al*., 2010) suggest that the mid 14th–15th century megadroughts were the first in a series of spatially widespread megadroughts that occurred during the Little Ice Age" and "appear to have played a major role in shaping significant regional societal changes at that time."

Wang *et al*. (2011) estimated soil moisture and agricultural drought severities and durations in China for the period 1950–2006, identifying a total of 76 droughts. Wang *et al*. report "climate models project that a warmer and moister atmosphere in the future will actually lead to an enhancement of the circulation strength and precipitation of the summer monsoon over most of China (e.g., Sun and Ding, 2010) that will offset enhanced drying due to increased atmospheric evaporative demand in a warmer world (Sheffield and Wood, 2008)." Tao and Zhang (2011) provide some support for this statement, finding the net effect of physiological and structural vegetation responses to expected increases in the atmosphere's CO_2 content will lead to "a decrease in mean evapotranspiration, as well as an increase in mean soil moisture and runoff across China's terrestrial ecosystem in the 21st century," which should act to lessen, or even offset, the "slightly drier" soil moisture conditions modeled by Wang *et al*.

Buntgen *et al*. (2011) "introduce and analyze 11,873 annually resolved and absolutely dated ring-width measurement series from living and historical fir (*Abies alba* Mill.) trees sampled across France, Switzerland, Germany and the Czech Republic, which continuously span the AD 962–2007 period," and which "allow Central European hydroclimatic springtime extremes of the industrial era to be placed against a 1000 year-long backdrop of natural variations." The nine researchers found "a fairly uniform distribution of hydroclimatic extremes throughout the Medieval Climate Anomaly, Little Ice Age and Recent Global Warming." Such findings, Buntgen *et al*. state, "may question the common belief that frequency and severity of such events closely relates to climate mean states."

Kleppe *et al*. (2011) reconstructed the duration and magnitude of extreme droughts in the northern Sierra Nevada region of the Fallen Leaf Lake (California, USA) watershed to estimate paleo-precipitation near the headwaters of the Truckee River-Pyramid Lake watershed of eastern California and northwestern Nevada. The six scientists found "submerged Medieval trees and geomorphic evidence for lower shoreline corroborate a prolonged Medieval drought near the headwaters of the Truckee River-Pyramid Lake watershed," and water-balance calculations independently indicated precipitation was "less than 60% normal." They note these findings "demonstrate how prolonged changes of Fallen Leaf's shoreline allowed the growth and preservation of Medieval trees far below the modern shoreline." In addition, they note age groupings of such trees suggest similar megadroughts "occurred every 600–1050 years during the late Holocene."

Pederson *et al*. (2012) attempt to put the southeastern United States' recent drought variability in a long-term perspective by reconstructing historic drought trends in the Apalachicola-Chattahoochee-Flint river basin over the period 1665–2010 using a dense and diverse tree-ring network. This network, they write, "accounts for up to 58.1% of the annual variance in warm-season drought during the 20th century and captures wet eras during the middle to late 20th century." The 12 researchers found the Palmer Drought Severity Index reconstruction for their study region revealed "recent droughts are not unprecedented over the last 346 years" and "droughts of extended duration occurred more frequently between 1696 and 1820," when most of the world was in the midst of the Little Ice Age. They also found their results "confirm the findings of the first reconstruction of drought in the southern Appalachian Mountain region, which indicates that the mid-18th and early 20th centuries were the driest eras since 1700," citing Stahle *et al*. (1988), Cook *et al*. (1988), and Seager *et al*. (2009).

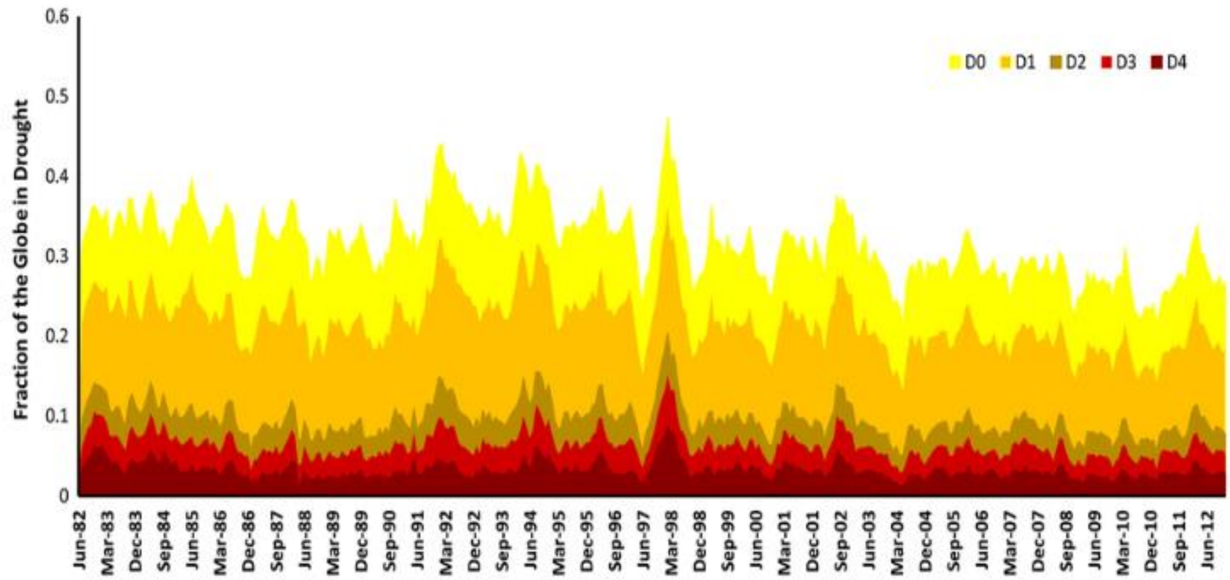
Chen *et al*. (2012) used the standard precipitation index to characterize drought intensity and duration throughout the Southern United States (SUS) over the past century. According to the nine researchers, there were "no obvious increases in drought duration and intensity during 1895–2007." Instead, they found "a slight (not significant) decreasing trend in drought intensity." They note "although reports from IPCC (2007) and the U.S. Climate Report (Karl *et al*., 2009) indicated that it is likely that drought intensity, frequency, and duration will increase in the future for the SUS, we did not find this trend in the historical data." They also note, although "the IPCC (2007) and U.S. Climate Report predicted a rapid increase in air temperature, which would result in a higher evapotranspiration thereby reducing available water," they "found no obvious increase in air temperature for the entire SUS during 1895–2007."

According to Hao *et al.* (2014), the global areal extent of drought fell from 1982 to 2012 across all five levels used to rank drought conditions. A figure illustrating their findings is reproduced as Figure 2.3.1.3.1.

Khandekar (2014) notes the Canadian prairies "are very drought prone, … but since 2005, droughts have been replaced by floods, with 2010 and 2014 ranking among the wettest summers on record" (p. 10, citing Garnett and Khandekar, 2010). And with respect to India, he notes "most climate models have achieved only limited success in simulating and predicting the features of the monsoon, for example extreme rainfall events and the associated flooding or extended monsoon-season dry spells." Noting there is "an urgent need to develop more skillful algorithms for the short-term prediction of regional and localized floods and droughts" (p. 8), he concludes, "Reducing greenhouse gas emissions (to reduce floods or other extreme weather events in future) is a meaningless exercise and will do nothing to influence future climate extremes" (*Ibid*.)

Delworth *et al.* (2015) observe "portions of western North America have experienced prolonged drought over the last decade" and acknowledge "the underlying causes of the drought are not well established in terms of the role of natural variability versus human-induced radiative forcing changes, such as from increasing greenhouse gases." They

Figure 2.3.1.3.1
Global areal extent of five levels of drought for 1982–2012



Fraction of the global land in D0 (abnormally dry), D1 (moderate), D2 (severe), D3 (extreme), and D4 (exceptional) drought condition (Data: Standardized Precipitation Index data derived from MERRA-Land). *Source:* Hao *et al.,* 2014.

further note the drought "has occurred at the same time as the so-called global warming hiatus, a decadal period with little increase in global mean surface temperature." Could the two events be related? The authors pose the hypothesis that the hiatus *caused* the drought, proposing as the mechanism enhanced easterly winds in the Pacific (unrelated to anthropogenic forcing) citing Kosaka and Xie (2013) and England *et al*. (2014). The five authors, all of them affiliated with NOAA, conducted an experiment with three climate models using observational data pertaining to the Pacific winds and the drought, and "find a clear link" between the hiatus and the drought. According to the model results, "tropical wind anomalies account for 92% of the simulated North American drought during the recent decade, with 8% from anthropogenic radiative forcing changes." They predict drought conditions will continue so long as the Pacific wind anomaly continues.

McCabe *et al*. (2017) studied monthly runoff for 2,109 hydrologic units (HUs) in the coterminous United States from 1901–2014, recording the frequency of drought as indicated by the HU runoff percentile dropping to the 20th percentile or lower. A drought was considered to end when the HU runoff percentile exceeded the 20th percentile. Among their findings, and the one most relevant to the current discussion, is "for most of the continental United States, drought frequency appears to have *decreased* during the 1901 through 2014 period" (italic added).

Ault *et al*. (2018) conducted a rare test of a null hypothesis in the global warming debate, that megadroughts in the western United States "are inevitable and occur purely as a consequence of internal climate variability." They test the hypothesis using a linear inverse model (LIM) constructed from global sea surface temperature anomalies and self-calibrated Palmer Drought Severity Index data for North America. They find "Despite being trained only on seasonal data from the late twentieth century, the LIM produces megadroughts that are comparable in their duration, spatial scale, and magnitude to the most severe events of the last 12 centuries. The null hypothesis therefore cannot be rejected with much confidence when considering these features of megadrought, meaning that similar events are possible today, even without any changes to boundary conditions."

Drought conditions in the United States reached their lowest level in 2017 since the United States Drought Monitor (USDM) began keeping records in 2000. (The USDM is a partnership between the University of Nebraska-Lincoln, the U.S. Department of Agriculture, and the U.S. National Oceanic and Atmospheric Administration (NOAA), see USDM, n.d.). The long drought in California ended that year, or at least was interrupted, and more than 100 inches of snow fell in parts of the Sierra Nevada mountain range. However, drought conditions over the entire United States increased their range in 2018, reaching levels last seen in 2014. As shown in Figure 2.3.1.3.2, there has been a generally decreasing trend in drought area in the continental United States for the past 10 years.

The findings of Kleppe *et al*. (2011) and many others whose works they cite suggest the planet during the Medieval Warm Period experienced less precipitation and longer and more severe drought than have been experienced to date in the modern era. In addition, their data suggest such dry conditions have occurred regularly, in cyclical fashion, "every 650–1150 years during the mid- and late-Holocene." These observations suggest there is nothing unusual, unnatural, or unprecedented about the global number or intensity of droughts during the modern era.

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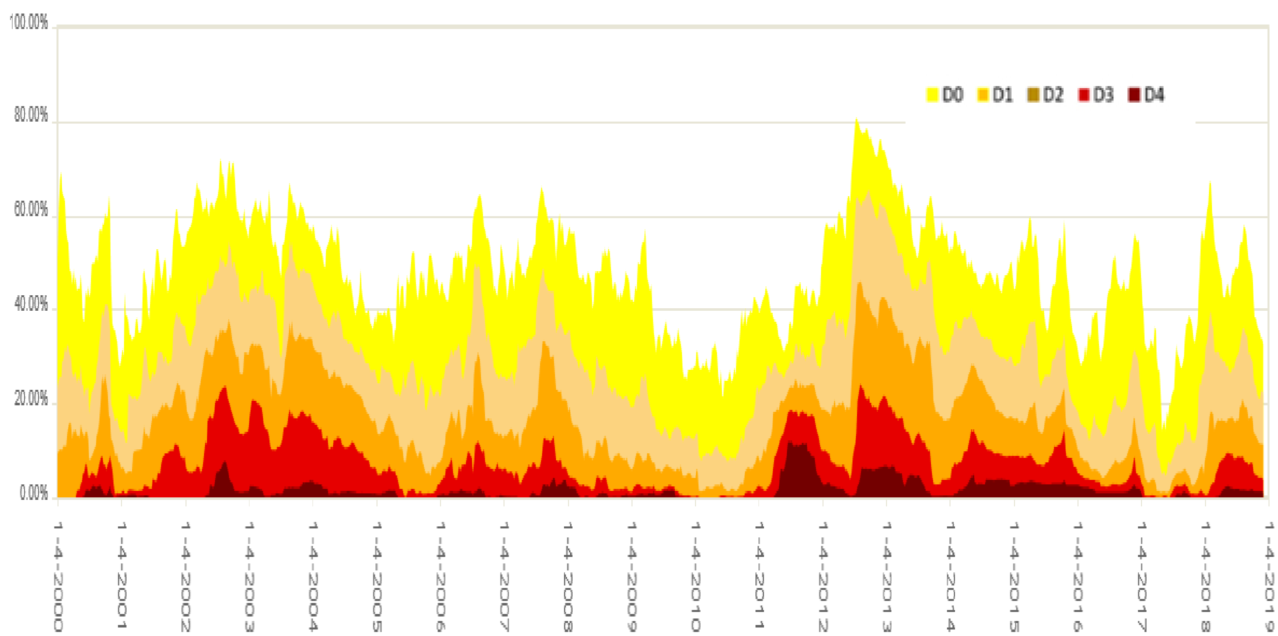
Figure 2.3.1.3.2
United States areal extent of five levels of drought for 2000–2018



Fraction of the United States land area in D0 (abnormally dry), D1 (moderate), D2 (severe), D3 (extreme), and D4 (exceptional) drought condition. *Source:* USDM, n.d.

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2.3.1.4 Floods

Climate model simulations generally predict a future with more frequent and severe floods in response to CO_2-induced global warming. Confirming such predictions has remained an elusive task, according to the Working Group I contribution to the IPCC's Fifth Assessment Report. The authors write, "there continues to be a lack of evidence and thus *low confidence* regarding the sign of trend in the magnitude and/or frequency of floods on a global scale over the instrumental record" (IPCC, 2013, p. 112). That conclusion is not in fact due to a "lack of evidence," but the presence of real-world data contradicting the narrative the IPCC attempts to present. A large body of scientific research shows CO_2-induced global warming has not increased the frequency or magnitude of floods nor is it likely to do so in the future.

Two problems confront those claiming that climate change has caused more flooding in recent decades. The first is the failure to control for increases in impervious surfaces (roads, parking lots, buildings, etc.) near rivers, which result in more, and more rapid, run-off during heavy rains. Bormann *et al*. (2011) studied data from 78 river gauges in Germany and found a significant impact by changes in nearby surfaces. When impervious surfaces increase in area, they note, "runoff generation can be expected to increase and infiltration and groundwater recharge decrease," which can lead to increases in river flow and a potential for more frequent and extreme floods. They conclude these facts "should be emphasized in the recent discussion on the effect of climate change on flooding."

A second problem is controlling for the increasing value and vulnerability of property located near river and lake shorelines, an issue addressed by many scholars including Pielke and Landsea (1998), Crompton and McAneney (2008), Pielke *et al*. (2008), Barredo (2009, 2010), and Neumayer and Barthel (2011). Barredo *et al*. (2012) write "economic impacts from flood disasters have been increasing over recent decades" more often due to the rising value of properties located near water than to climate change. The authors examined "the time history of insured losses from floods in Spain between 1971 and 2008" to see "whether any discernible residual signal remains after adjusting the data for the increase in the number and value of insured assets over this period of time." They found "the absence of a significant positive trend in the adjusted insured flood losses in Spain," suggesting "the increasing trend in the original losses is explained by socio-economic factors, such as the increases in exposed insured properties, value of exposed assets and insurance penetration." "The analysis rules out a discernible influence of anthropogenic climate change on insured losses," they write, a finding that "is consistent with the lack of a positive trend in hydrologic floods in Spain in the last 40 years."

Many researchers have documented past floods that are larger than any in the industrial era, meaning natural variability cannot be ruled out as the cause of even major and unusual floods in the modern era. Zhang *et al*. (2009) found coolings of 160- to 170-year intervals dominated climatic variability in the Yangtze Delta in China over the past millennium, and these cooling periods promoted locust plagues by enhancing temperature-associated drought/flood events. The six scientists state "global warming might not only imply reduced locust plague[s], but also reduced risk of droughts and floods for entire China," noting these findings "challenge the popular view that global warming necessarily accelerates natural and biological disasters such as drought/flood events and outbreaks of pest insects." They contend their results are an example of "benign effects of global warming on the regional risk of natural disasters."

Benito *et al*. (2010) reconstructed flood frequencies of the Upper Guadalentin River in southeast Spain using "geomorphological evidence, combined with one-dimensional hydraulic modeling and supported by records from documentary sources at Lorca in the lower Guadalentin catchment." The combined palaeoflood and documentary records indicate past floods were clustered during particular time periods: AD 950–1200 (10), AD 1648–1672 (10), AD 1769–1802 (9), AD 1830–1840 (6), and AD 1877–1900 (10), where the first time interval coincides with the Medieval Warm Period and the latter four fall within the Little Ice Age. By calculating mean rates of flood occurrence over each of the five intervals, a value of 0.40 floods per decade during the Medieval Warm Period and an average value of 4.31 floods per decade over the four parts of the Little Ice Age can be determined. The latter value is more than ten times greater than the mean flood frequency experienced during the Medieval Warm Period.

Villarini and Smith (2010) "examined the distribution of flood peaks for the eastern United States using annual maximum flood peak records from 572 U.S. Geological Survey stream gaging stations with at least 75 years of observations." This work revealed "only a small fraction of stations exhibited significant linear trends," and "for those stations with trends, there was a split between increasing and decreasing trends." They also note "no spatial structure was found for stations exhibiting trends." Thus, they conclude, "there is little indication that human-induced climate change has resulted in increasing flood magnitudes for the eastern United States."

Villarini *et al*. (2011) similarly analyzed data from 196 U.S. Geological Survey streamflow stations with a record of at least 75 years over the midwestern United States. Most streamflow changes they observed were "associated with change-points (both in mean and variance) rather than monotonic trends," and they indicate "these non-stationarities are often associated with anthropogenic effects," which they identify as including "changes in land use/land cover, changes in agricultural practice, and construction of dams and reservoirs." "In agreement with previous studies (Olsen *et al*., 1999; Villarini *et al*., 2009)," they conclude, "there is little indication that anthropogenic climate change has significantly affected the flood frequency distribution for the Midwest U.S."

Stewart *et al*. (2011) derived "a complete record of paleofloods, regional glacier length changes (and associated climate phases) and regional glacier advances and retreats (and associated climate transitions) … from the varved sediments of Lake Silvaplana (ca. 1450 BC–AD 420; Upper Engadine, Switzerland)," indicating "these records provide insight into the behavior of floods (i.e. frequency) under a wide range of climate conditions." They found "an increase in the frequency of paleofloods during cool and/or wet climates and windows of cooler June–July–August temperatures" and the frequency of flooding "was reduced during warm and/or dry climates." Reiterating that "the findings of this study suggest that the frequency of extreme summer–autumn precipitation events (i.e. flood events) and the associated atmospheric pattern in the Eastern Swiss Alps was not enhanced during warmer (or drier) periods," Stewart *et al*. acknowledge "evidence could not be found that summer–autumn floods would increase in the Eastern Swiss Alps in a warmer climate of the 21st century."

Hirsch and Ryberg (2012) compared global mean carbon dioxide concentration ($GMCO_2$) to a streamflow dataset consisting of long-term (85- to 127-year) annual flood series from 200 stream gauges deployed by the U.S. Geological Survey in basins with little or no reservoir storage or urban development (less than 150 persons per square kilometer in AD 2000) throughout the coterminous United States. The authors determine whether the patterns of the statistical associations between the two parameters were significantly different from what would be expected under the null hypothesis that flood magnitudes are independent of $GMCO_2$. The authors report "in none of the four regions defined in this study is there strong statistical evidence for flood magnitudes increasing with increasing $GMCO_2$." One region, the southwest, showed a statistically significant *negative* relationship between $GMCO_2$ and flood magnitudes. Hirsch and Ryberg conclude "it may be that the greenhouse forcing is not yet sufficiently large to produce changes in flood behavior that rise above the 'noise' in the flood-producing processes." It could also mean the "anticipated hydrological impacts" envisioned by the IPCC and others are simply incorrect.

Zha *et al*. (2012) conducted a paleohydrological field investigation in the central portion of the Jinghe River, the middle and upper reaches of which are located in a semiarid zone with a monsoonal climate, between Binxian county and Chunhua county of Shaanxi Province, China. Their analysis revealed during the mid-Holocene climatic optimum, the climate was warm-humid, the climate system was stable, and "there were no flood records identified in the middle reaches of the Yellow river." Thereafter, however, they report "global climatic cooling events occurred at about 4200 years BP, which was also well recorded by various climatic proxies in China." These observations led them to conclude, "the extraordinary floods recorded in the middle reaches of the Jinghe River were linked to the global climatic events" – all of which were global *cooling* events.

Wilhelm *et al*. (2012) analyzed the sediments of Lake Allos, a 1-km-long by 700-m-wide high-altitude lake in the French Alps (44°14'N, 6°42'35'E), by means of both seismic survey and lake-bed coring, revealing the presence of 160 graded sediment layers over the past 1,400 years. Comparisons of the most recent of these layers with records of historic floods suggest the sediment layers are representative of significant floods that were "the result of intense meso-scale precipitation events." Of special interest is their finding of "a low flood frequency during the Medieval Warm Period and more frequent and more intense events during the Little Ice Age." Wilhelm *et al*. additionally state "the Medieval Warm Period was marked by very low hydrological activity in large rivers such as the Rhone, the Moyenne Durance, and the Tagus, and in mountain streams such as the Taravilla lake inlet." Of the Little Ice Age, they write, "research has shown higher flood activity in large rivers in southern Europe, notably in France, Italy, and in smaller catchments (e.g., in Spain)."

Sagarika *et al*. (2014) examined variability and trends in seasonal and water year (October through September) streamflow for 240 stream gauges considered to be minimally impaired by human influences in the coterminous United States for the years 1951–2010. They report finding positive trends in streamflow for many sites in the eastern United States and negative trends in streamflow for sites in the Pacific Northwest.

McCabe and Wolock (2014) examined "spatial and temporal patterns in annual and seasonal minimum, mean, and maximum daily streamflow values" using a database drawn from 516 reference stream gauges located throughout the coterminous United States for the period 1951–2009. Cluster analysis was used to classify the stream gauges into 14 groups based on similarity in their temporal patterns of streamflow. They found "some small magnitude trends over time" which "are only weakly associated with well-known climate indices. We conclude that most of the temporal variability in flow is unpredictable in terms of relations to climate indices and infer that, for the most part, future changes in flow characteristics cannot be predicted by these indices."

Hao *et al.* (2016) studied trends in floods in China over a 2,000-year record to see if drought and flood events coincided with known warm and cold periods. They begin by observing "there has been no significant trend in the mean precipitation over the whole country" from 1951 to 2009, despite a measured increase in temperature of 1°C during that period. The authors used a 2,000-year temperature series created by Ge *et al.* (2013) using 28 proxies including historical documents, tree rings, ice cores, lake sediments, and stalagmites, producing a record with a time resolution finer than 10 years. A data set of precipitation anomalies and grading system for the severity of droughts and flood disasters created by Zhang (1996) was then compared to the temperature record. The results showed only weak correlations and a random assortment of positive as well as negative associations depending on region. The results "showed that there has been no fixed spatial pattern of precipitation anomalies during either cold or warm periods in Eastern China over the past 2000 years." Which means neither drought conditions nor flooding in China correlate with changes in mean average global temperature.

Macdonald and Sangster (2017) lament that "one of the greatest challenges presently facing river basin managers is the dearth of reliable long-term data on the frequency and severity of extreme floods," and set out to address that challenge by presenting "the first coherent large-scale national analysis undertaken on historical flood chronologies in Britain, providing an unparalleled network of sites (Fig. 1), permitting analysis of the spatial and temporal distribution of high-magnitude flood patterns and the potential mechanisms driving periods of increased flooding at a national scale (Britain) since AD 1750." The authors report, "The current flood-rich period (2000) is of particular interest with several extreme events documented in recent years, though it should be noted from a historical perspective that these are not unprecedented, with several periods with comparable [Flood Index] scores since ca. 1750, it remains unclear at present whether the current period (2000) represents a short or long flood-rich phase." They conclude, "The apparent increase in flooding witnessed over the last decade appears in consideration to the long-term flood record not to be unprecedented; whilst the period since 2000 has been considered as flood-rich, the period 1970–2000 is 'flood poor', which may partly explain why recent floods are often perceived as extreme events. The much publicised (popular media) apparent change in flood frequency since 2000 may reflect natural variability, as there appears to be no shift in long-term flood frequency."

Hodgkins *et al*. (2017) studied major floods (25–100 year return period) from 1961 to 2010 in North America and from 1931 to 2010 in Europe to see if such events had become more frequent over time. More than 1,200 flood gauges were studied in diverse catchments from North America and Europe; only minimally altered catchments were used, and trends were assessed on a variety of flood characteristics and for a variety of specific regions. "Overall," they write, "the number of significant trends in major-flood occurrence across North America and Europe was approximately the number expected due to chance alone. Changes over time in the occurrence of major floods were dominated by multidecadal variability rather than by long-term trends. There were more than three times as many significant relationships between major-flood occurrence and the Atlantic Multidecadal Oscillation than significant long-term trends."

* * *

Summarizing, the historical record suggests no global trend toward increasing flooding events in the modern era, while proxy data give a contradictory picture of major floods due to natural causes, more flooding during cool periods than during warm periods or *vice versa*, or (as in the case of China) no correlation at all between floods and temperature. This being the case, it is unlikely that human CO_2 emissions are currently causing a global increase in floods or that warmer temperatures forecast for the rest of the twenty-first century would trigger such an increase.

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2.3.1.5 Storms

The IPCC writes "it is *likely* that the number of heavy precipitation events over land has increased in more regions than it has decreased in since the mid-20th century, and there is *medium confidence* that anthropogenic forcing has contributed to this increase. … For the near and long term, CMIP5 projections confirm a clear tendency for increases in heavy precipitation events, in the global mean seen in the AR4 [Fourth Assessment Report], but there are substantial variations across regions. Over most of the mid-latitude land masses and over wet tropical regions, extreme precipitation will *very likely* be more intense and more frequent in a warmer world" (IPCC, 2013, p. 112). Climate models generally predict more storms as the human impact on climate increases during the twenty-first century (e.g., Seeley and Romps, 2014).

Referring to extreme or intense storms, Dezileau *et al*. (2011) note the key question is, "are they linked to global warming or are they part of natural climate variability?" They write "it is essential to place such events in a broader context of time, and trace the history of climate changes over several centuries," because "these extreme events are inherently rare and therefore difficult to observe in the period of a human life." Analyzing regional historical archives and sediment cores extracted from two Gulf of Aigues-Mortes lagoons in the northwestern part of the occidental Mediterranean Sea for bio- and geo-indicators of past storm activities there, they were able to assess "the frequency and intensity of [extreme] events during the last 1500 years" as well as "links between past climatic conditions and storm activities." They found evidence of four "catastrophic storms of category 3 intensity or more," which occurred at approximately AD 455, 1742, 1848, and 1893, all before human greenhouse gases could have been a factor.

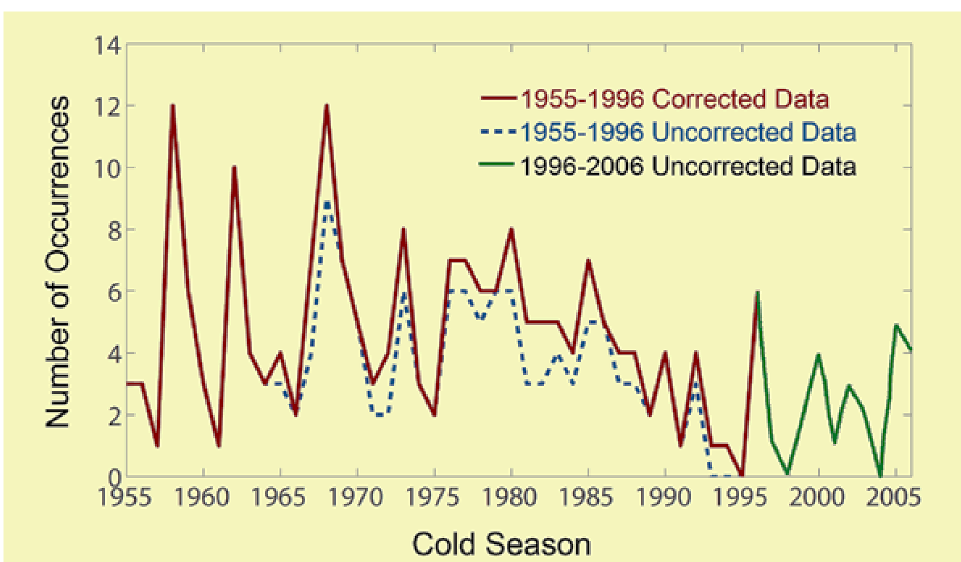
Dezileau *et al*. (2011) write, "the apparent increase in intense storms around 250 years ago lasts to about AD 1900," whereupon "intense meteorological activity seems to return to a quiescent interval after (i.e. during the 20th century AD)." They add, "interestingly, the two periods of most frequent superstorm strikes in the Aigues-Mortes Gulf (AD 455 and 1700–1900) coincide with two of the coldest periods in Europe during the late Holocene (Bond cycle 1 and the latter half of the Little Ice Age.)" The authors suggest "extreme storm events are associated with a large cooling of Europe," and they calculate the risk of such storms occurring during that cold period "was higher than today by a factor of 10," noting "if this regime came back today, the implications would be dramatic."

Barredo (2010) examined large historical windstorm event losses in Europe over the period 1970–2008 for 29 European countries. After adjusting the data for "changes in population, wealth, and inflation at the country level and for inter-country price differences using purchasing power parity," the researcher, employed by the Institute for Environment and Sustainability, European Commission-Joint Research Centre in Ispra, Italy, reports "the analyses reveal no trend in the normalized windstorm losses and confirm increasing disaster losses are driven by society factors and increasing exposure," adding "increasing disaster losses are overwhelmingly a consequence of changing societal factors."

Page *et al*. (2010), working with sediment cores extracted from Lake Tutira on the eastern end of New Zealand's North Island, developed a 7,200-year history of the frequency and magnitude of storm activity based on analyses of sediment grain size, diatom, pollen, and spore types and concentrations, carbon and nitrogen concentrations, and tephra and radiocarbon dating. They report millennial-scale cooling periods tend to "coincide with periods of increased storminess in the Tutira record, while warmer events match less stormy periods." Their research shows the sudden occurrence of a string of years, or even decades, of unusually large storms is something that can happen at almost any time without being driven by human activities such as the burning of fossil fuels.

Gascon *et al*. (2010) conducted a study they describe as "the first to document the climatology of major cold-season precipitation events that affect southern Baffin Island [Canada]." They examined the characteristics and climatology of the 1955–2006 major cold-season precipitation events at Iqaluit, the capital of Nunavut, located on the southeastern part of Baffin Island in the northwestern end of Frobisher Bay, basing their work on analyses of hourly surface meteorological data obtained from the public archives of Environment Canada. The three researchers detected a "non-significant decrease" in autumn and winter storm activity over the period of their study. The authors' results are depicted in Figure 2.3.1.5.1.

Figure 2.3.1.5.1
Cold-season occurrences of major precipitation events at Iqaluit, Nunavut, Canada



Source: Adapted from Gascon *et al.*, 2010.

Alexander *et al*. (2011) analyzed storminess across southeast Australia using extreme (standardized seasonal 95th and 99th percentiles) geostrophic winds deduced from eight widespread stations possessing sub-daily atmospheric pressure observations dating back to the late nineteenth century, finding "strong evidence for a significant reduction in intense wind events across SE Australia over the past century." They note "in nearly all regions and seasons, linear trends estimated for both storm indices over the period analyzed show a decrease," while "in terms of the regional average series," they write, "all seasons show statistically significant declines in both storm indices, with the largest reductions in storminess in autumn and winter."

Mallinson *et al*. (2011) employed optically stimulated luminescence dating of inlet-fill and flood tide delta deposits from locations in the Outer Banks barrier islands of North Carolina, USA to provide a "basis for understanding the chronology of storm impacts and comparison to other paleoclimate proxy data" in the region over the past 2,200 years. Analyses of the cores revealed "the Medieval Warm Period (MWP) and Little Ice Age (LIA) were both characterized by elevated storm conditions as indicated by much greater inlet activity relative to today." They write, "given present understanding of atmospheric circulation patterns and sea-surface temperatures during the MWP and LIA, we suggest that increased inlet activity during the MWP responded to intensified hurricane impacts, while elevated inlet activity during the LIA was in response to increased nor'easter activity." The group of five researchers state their data indicate, relative to climatic conditions of the Medieval Warm Period and Little Ice Age, there has more recently been "a general decrease in storminess at mid-latitudes in the North Atlantic," reflecting "more stable climate conditions, fewer storm impacts (both hurricane and nor'easter), and a decrease in the average wind intensity and wave energy field in the mid-latitudes of the North Atlantic."

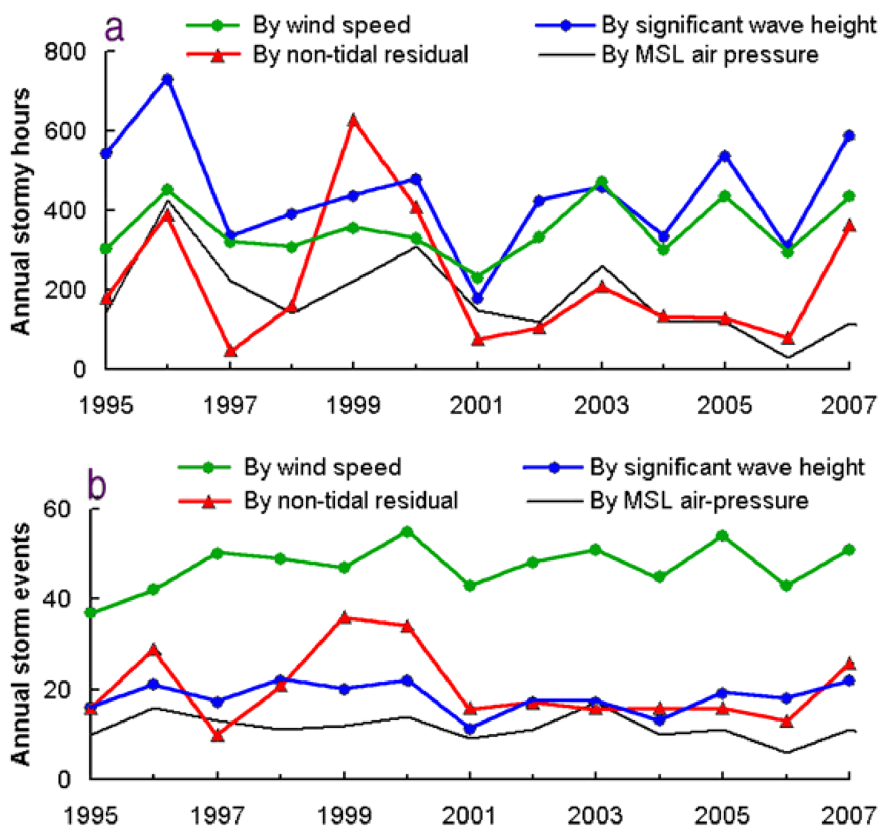
Li *et al*. (2011), citing "unprecedented public concern" with respect to the impacts of climate change, set out to examine the variability and trends of storminess for the Perth, Australia metropolitan coast. They conducted an extensive set of analyses using observations of wave, wind, air pressure, and water level over the period 1994–2008. The results of their analysis, in their view, would serve "to validate or invalidate the climate change hypothesis" that rising CO_2 concentrations are increasing the frequency and severity of storms. As shown in Figure 2.3.1.5.2, all storm indices showed significant interannual variability over the period of record, and "no evidence of increasing (decreasing) trends in extreme storm power was identified to validate the climate change hypotheses for the Perth region."

Sorrel *et al*. (2012) note the southern coast of the English Channel in northwestern France is "well suited to investigate long-term storminess variability because it is exposed to the rapidly changing North Atlantic climate system, which has a substantial influence on the Northern Hemisphere in general." They present "a reappraisal of high-energy estuarine and coastal sedimentary records," finding "evidence for five distinct periods during the Holocene when storminess was enhanced during the past 6,500 years." The six scientists write, "high storm activity occurred periodically with a frequency of about 1,500 years," with the last extreme stormy period "coinciding with the early to mid-Little Ice Age." They note "in contrast, the warm Medieval Climate Optimum was characterized by low storm activity (Sorrel *et al*., 2009; Sabatier *et al*., 2012)."

Khandekar (2013) observed that "many excellent studies on thunderstorm climatology (e.g., Changnon, 2001) have used over 100 years of data to document that 'thunderstorms and related activity in the U.S. peaked during the 1920s and 1930s and since then have declined in the late 1990s.'" See Changnon and Kunkel (2006) and Changnon (2010) for more recent presentations of this research. Khandekar also reports research conducted by Hage (2003), who "extracts data from several thousand Prairie-farm newsletters and reconstructs windstorm activity from 1880 to 1995 for the Canadian Prairies." The study (by Hage) concludes that "severe windstorms and associated thunderstorm activity peaked during the early part of the twentieth century and has since then declined steadily."

Yang *et al*. (2015) report that over the period December 2013–February 2014, "there was a pronounced reduction of extratropical storm (ETS) activity over the North Pacific Ocean and the west coast of the United States of America (USA), and a substantial increase of ETS activity extending from central Canada down to the midwestern USA." In hopes of explaining the "extreme North America winter storm season of 2013/14," they used the Geophysical Fluid Dynamics Laboratory Forecast-Oriented Low Ocean Resolution model to conduct a series of simulations. The authors' modeling exercise found "no statistically significant change" in ETS over mid-America or the Pacific coastal

Figure 2.3.1.5.2
Annual storm trends for Perth, Australia, 1994–2008



Annual storm trends for Perth, Australia defined by (a) stormy hours and (b) number of storm events, as determined by wind speed, significant wave height, non-tidal residual water level, and mean sea level pressure. Adapted from Li *et al., 2011.*

region from 1940–2040 could be attributed to anthropogenic forcing, while a "significant decrease starting [in] 2000" was found for mid-Canada. They conclude, "thus, the impact of antorpogenic forcing prescribed on this model did not contribute to the 2013-14 extreme ETS events over North America."

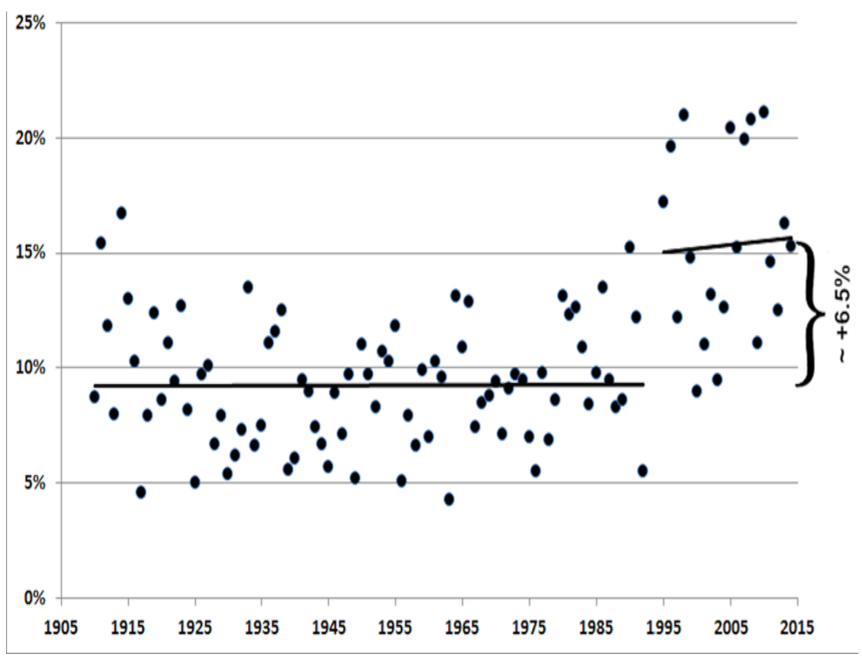
Degeai *et al.* (2015) studied sediments in a lagoon in southern France to find the "sedimentological signature" of ancient storms. The study area is located in the Languedoc region along the continental shelf of the Gulf of Lions in the Northwestern Mediterranean. "The many lagoons in this coastal plain give an excellent opportunity to find sedimentary sequences recording the palaeostorm events," they write. They found "phases of high storm activity occurred during cold periods, suggesting a climatically-controlled mechanism for the occurrence of these storm periods." They also found a "new 270-year solar-driven pattern of storm cyclicity" and 10 major storm periods with a mean duration of 96 ± 54 years. Phases of higher storm activity occurred generally during the cold episodes of the Little Ice Age, the Dark Ages Cold Period, and the Iron Age Cold Period. Extreme storm waves were recorded on the French Mediterranean coast to the East of the Rhone delta during the Little Ice Age. Periods of low storm activity occurred during periods that coincide with the Roman Warm Period and the Medieval Warm Period.

Zhang *et al*. (2017a) note "understanding the trend of localized severe weather under the changing climate is of great significance but remains challenging which is at least partially due to the lack of persistent and homogeneous severe weather observations at climate scales while the detailed physical processes of severe weather cannot be resolved in global climate models." They created a database of "continuous and coherent severe weather reports from over 500 manned stations" across China and discovered "a significant decreasing trend in severe weather occurrence across China during the past five decades. The total number of severe weather days that have either thunderstorm, hail and/or damaging wind decrease about 50% from 1961 to 2010. It is further shown that the reduction in severe weather occurrences correlates strongly with the weakening of East Asian summer monsoon which is the primary source of moisture and dynamic forcing conducive for warm-season severe weather over China."

Turning from China to the United States, the number of extreme rainfall events – defined as a greater-than-normal proportion of one-day precipitation originating from the highest 10th percentile of one-day precipitation – are alleged to be increasing in the United States. A database often cited is Step 4 of the Climate Exchange Index maintained by the National Oceanic and Atmospheric Administration (NOAA, 2018). But most or even all of the increase is likely due to a change in instrumentation and analysis methodology rather than a change in weather. Figure 2.3.1.5.3 plots data from 1910 through 2014 and finds from 1990 through 1992, a near zero slope exists with a percent of explained variance (R^2) of only 0.007%. Then, from 1995 to 2014, another insignificant slope with an R^2 of 0.24% is observed. Thus, the data do not exhibit a trend, but rather a discontinuity occurring between 1992 and 1995.

Climate forcing caused by CO_2 is predicted to produce a linear increase in surface temperature and other climate indices, not sudden discontinuities such as that shown in NOAA's extreme precipitation record. The more likely cause of the jump is that between 1992 and 1995, the National Weather Service (NWS) changed the way it measures precipitation at its "first-order" weather stations network, replacing manual observation gauges with electronic devices that are equipped with wind shields, are closer to the ground, and are "corrected" by

Figure 2.3.1.5.3
Percentage of the contiguous United States with a much greater-than-normal proportion of precipitation derived from extreme 1-day precipitation events



Annual time-series of the proportion of the contiguous United States with a greater-than-normal proportion of its one-day precipitation originating from the highest 10th percentile of one-day precipitation (Climate Extreme Index Step 4). The expected value is 10%. Separate regression lines are plotted for the period from 1910 to 1992 (R^2=7x10^{-5}) and from 1995 to 2014 (R^2=0.0024). *Source:* Adapted from Gleason *et al.,* 2008, Figure 2, p. 2129.

NWS staff to account for some known biases. The sudden jump in extreme precipitation reports is probably just an artifact of this change in data-collection methodology. This is independently confirmed by evidence that the record of floods across the United States shows no evidence of increasing extreme rainfall events since 1950 (Hirsch and Ryberg, 2012; McCabe and Wolock, 2014).

As mentioned at the beginning of this section, climate models generally predict more extreme rainfall events. However, the models do a poor job simulating such events and therefore are unreliable guides to the future. Zhang *et al*. (2017b) note, "meeting the demand for robust projections for extreme short-duration rainfall is challenging, however, because of our poor understanding of its past and future behaviour. The characterization of past changes is severely limited by the availability of observational data. Climate models, including typical regional climate models, do not directly simulate all extreme rainfall producing processes, such as convection." The authors report on efforts to improve the models by focusing on precipitation–temperature relationships, but those relationships are tenuous and of limited use for projecting future precipitation extremes.

* * *

In conclusion, storms, like floods, sometimes appear to be more frequent and more intense during periods of global *cooling*, not warming, and are unrelated to anthropogenic forcing. Climate models are not a reliable guide to the frequency or intensity of future extreme rainfall events. If the human presence is causing the climate to warm, in many parts of the world this may produce weather that is calm, not stormier.

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2.3.1.6 Hurricanes

For many years, nearly all climate model output suggested hurricanes (in the Atlantic and Northeastern Pacific Basin, although the terms typhoon, severe cyclonic storm, or tropical cyclone are used elsewhere) should become more frequent and intense as planetary temperatures rise. Scientists worked to improve the temporal histories of these hurricane characteristics for various ocean basins around the world to evaluate the plausibility of such projections. In nearly all instances, the research revealed such trends do not exist.

As a result of these findings, the IPCC revised its conclusion on hurricanes, stating in the Fifth Assessment Report, "there is *low confidence* in long-term (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities … and there is *low* confidence in attribution of changes in tropical cyclone activity to human influence owing to insufficient observational evidence, lack of physical understanding of the links between anthropogenic drivers of climate and tropical cyclone activity and the low level of agreement between studies as to the relative importance of internal variability, and anthropogenic and natural forcings" (IPCC, 2013, p. 113). Or maybe no relationship exists between the human presence and hurricanes.

The prediction of more frequent or more intense hurricanes is significant due to the destruction they may cause to the environment and homes and businesses in exposed coastal areas. However, much of that damage is likely to be due to continued human migration to coastal areas and not to more hurricanes. According to Pielke *et al*. (2005), by 2050 "for every additional dollar in damage that the Intergovernmental Panel on Climate Change expects to result from the effects of global warming on tropical cyclones, we should expect between \$22 and \$60 of increase in damage due to population growth and wealth," citing the findings of Pielke *et al*. (2000). They state, "the primary factors that govern the magnitude and patterns of future damages and casualties are how society develops and prepares for storms rather than any presently conceivable future changes in the frequency and intensity of the storms." The authors note many continue to claim a significant hurricane–global warming connection for advocating anthropogenic CO_2 emission reductions that "simply will not be effective with respect to addressing future hurricane impacts," additionally noting "there are much, much better ways to deal with the threat of hurricanes than with energy policies (e.g., Pielke and Pielke, 1997)."

Klotzbach *et al*. (2018) updated earlier research by Pielke *et al.*, this time covering trends in hurricanes making landfall in the continental United States (CONUS) since 1990. They "found no significant trends in landfalling hurricanes, major hurricanes, or normalized damage consistent with what has been found in previous studies." They report hurricane activity is influenced by El Niño–Southern Oscillation on the interannual time scale and by the Atlantic Multidecadal Oscillation on the multidecadal time scale. "Despite a lack of trend in observed CONUS landfalling hurricane activity since 1900," they write, "large increases in inflation-adjusted hurricane-related damage have been observed, especially since the middle part of the twentieth century. We demonstrate that this increase in damage is strongly due to societal factors, namely, increases in population and wealth along the U.S. Gulf and East Coasts."

The Scientific Debate

Many of the first major advances in understanding hurricane genesis, tracks, and cyclical patterns were produced by William W. Gray and his many students and colleagues at Colorado State University, located in Fort Collins, Colorado, USA. Klotzbach *et al.* (2017) described Gray's contributions in a tribute published after Gray's death in 2016:

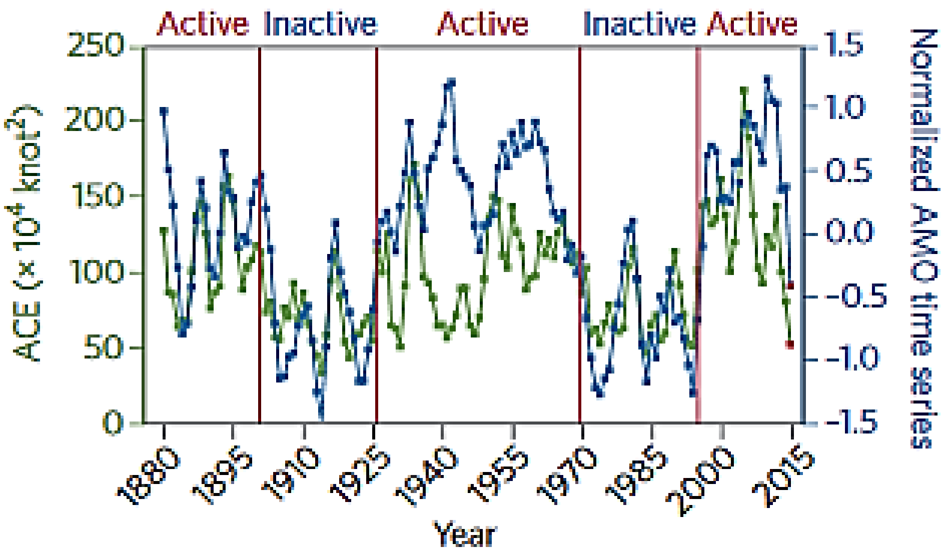
> Gray pioneered the compositing approach to observational tropical meteorology through assembling of global radiosonde datasets and tropical cyclone research flight data. In the 1970s, he made fundamental contributions to knowledge of convective–larger-scale interactions. Throughout his career, he wrote seminal papers on tropical cyclone structure, cyclogenesis, motion, and seasonal forecasts. His conceptual development of a seasonal genesis parameter also laid an important framework for both seasonal forecasting as well as climate change studies on tropical cyclones. His work was a blend of both observationally based studies and the development of theoretical concepts.

In the 1990s, Gray connected the natural cycles in Atlantic basin hurricane activity with variability in air and sea surface temperatures (SST) (Gray, 1990; Gray *et al.*, 1997), and then to variability in the Atlantic Multidecadal Oscillation (AMO) (Goldenberg *et al.*, 2001). Gray identified the source of AMO variability as natural changes in the thermohaline circulation, the large-scale movement of water through Earth's oceans thought to be propelled by changes in temperatures and density and surface winds (Klotzbach and Gray, 2008). When the AMO is in its warm (positive) phase, conditions are more favorable to the formation of hurricanes as characterized by above-average far north and tropical Atlantic SSTs, below-average tropical Atlantic sea-level pressures, and reduced levels of tropical Atlantic vertical wind shear. When the AMO is in its cool phase, the atmosphere is drier, has more inhibiting vertical wind shear, and cannot sustain deep convection as readily. Figure 2.3.1.6.1 shows this natural variability from 1880 to 2015 (Klotzbach *et al.*, 2015). Recent research by Barcikowska *et al.* (2017) confirms many of Gray's observations, with the authors finding "observational SST and atmospheric circulation records are dominated by an almost 65-yr variability component" and "the recently observed (1970s–2000s) North Atlantic warming and eastern tropical Pacific cooling might presage an ongoing transition to a cold North Atlantic phase with possible implications for near-term global temperature evolution."

Gray did not support the theory that human sulfate aerosols in the atmosphere were masking the effect of CO_2 and warmer temperatures on hurricane genesis. Gray's view on this matter was strenghthened by the CERN cloud particle experiment reported in Section 2.2.4, which found "ion-induced nucleation of pure organic particles constitutes a potentially widespread source of aerosol particles in terrestrial environments with low sulfuric acid pollution" (Kirkby *et al.*, 2016). Instead, Gray argued (consistent with the views of the authors of this section) that climate models are unable to distinguish natural from anthropogenic forcings and misrepresent the role of water vapor feedback. He also also argued that rising temperatures from around 1970 to 2000 were due not to anthropogenic causes but to a long-term weakening in the strength of the Atlantic thermohaline circulation possibly due to solar influences (Gray, 2012).

Sobel *et al.* (2016) summarized the views of climate modelers as follows: "Theory and numerical simulations suggest that human emissions of greenhouse gases, acting on their own, should have already caused a small increase in tropical cyclone (TC) intensities globally. The same theory and simulations indicate that we should not expect to be able to discern this increase in recent historical observations because of the confounding influences of aerosol forcing (which acts to oppose greenhouse gas forcing) and large natural variability (which compromises trend detection). Current expectations for the future are that aerosol forcing will remain level or decrease while greenhouse gas forcing continues to increase, leading to considerable increases in TC intensity as the climate warms further." In light of the CERN experiment and other research on cosmic rays described in Section 2.2.4, this expectation is not justified.

Figure 2.3.1.6.1
Tropical cyclone Atlantic multidecadal variability



Three-year-averaged accumulated cyclone energy (ACE) in the Atlantic basin (green line) and three-year-averaged standardized normalized Atlantic multidecadal oscillation (AMO) (blue line) from 1880–2014 with predicted value for 2015 (red squares). The 2015 AMO value is the January–June-averaged value. The year listed is the third year being averaged (for example, 1880 is the 1878–1880 average). Correlation between the two time series is 0.61. *Source:* Klotzbach *et al.*, 2015.

Sobel *et al.* (2016) acknowledge "the validity of data from the earlier periods in the longest-term observational data sets has been strongly questioned," "large natural variability, including substantial components with decadal and longer frequencies, further confounds trend detection in records," and "robustly detectable trends in basin-average PI [potential impact] are found only in the North Atlantic, where both surface warming and, to some extent, tropical tropopause cooling have contributed to an increase in PI between 1980 and 2013." Still, they argue "it would be inappropriate to go on to conclude that there is no human influence on TCs at present. To draw that conclusion would be a type II statistical error, conflating absence of evidence with evidence of absence." But the evidence offered by Gray and others in this section suggests there is indeed "evidence of absence," and hurricane activity is unlikely to be affected by human influences on climate.

Uncertainty in the Hurricane Database

Landsea and Franklin (2013) studied the hurricane database (called HURDAT) used by the National Hurricane Center to report the intensity, central pressure, position, and three measures of radii (size) of Atlantic and eastern North Pacific basin tropical and subtropical cyclones, with the goal of measuring changes in their uncertainty over the past decade. They observe that “given the widespread use of HURDAT for meteorological, engineering, and financial decision making, it is surprising that very little has been published regarding the uncertainties inherent in the database.”

Readers may note the similarity between this comment and one made by McLean (2018) reported in Section 2.2.1. McLean examined the HadCRUT4 surface station temperature record and wrote, “It seems very strange that man-made warming has been a major international issue for more than 30 years and yet the fundamental data has never been closely examined.” McLean uncovered so many errors and methodological problems with the HadCRUT4 database that it is plainly not suited for scientific research. Landsea and Franklin are only slightly less critical of the HURDAT2 database.

Landsea and Franklin explain “a best track is defined as a subjectively smoothed representation of a tropical cyclone’s history over its lifetime, based on a poststorm assessment of all available data.” While based on observational data, a best track is a stylized fact, a subjective interpretation of several different and “often contradictory” datasets by a small group of specialists tasked with assigning numbers to an extremely complex and ultimately unknowable set of natural processes. “Because the best tracks are subjectively smoothed,” the authors write, “they will not precisely recreate a storm’s history, even when that history is known to great accuracy.” So how accurate are best tracks?

Landsea and Franklin compared two surveys completed by the specialists employed by the National Hurricane Center, six in 1999 and 10 in 2010, asking them to assign uncertainty values to each of six quantities used to produce a best track. The results of the comparison did show progress in reducing uncertainty in the ten years that passed between surveys, but the amount of uncertainty remaining was surprising. The quantity with the least uncertainty is position, ranging from 7.5% for U.S. landfalling cyclones to 12.5% for satellite-only monitoring. Intensity and central pressure have uncertainties ranging from 17.5% to 20% for satellite-only and 10% to 12.5% for both satellite-aircraft monitoring and at landfall in the United States. For wind radii, the relative uncertainty for cyclones making a U.S. landfall is around 25% to 30%, and for those being observed by satellite only, 35% to 52.5%.

Finally, Landsea and Franklin note the best tracks database “goes back to 1851, but it is far from being complete and accurate for the entire century and a half.” As one looks further back in time, “in addition to larger uncertainties, biases become more pronounced as well with tropical cyclone frequencies being underreported and the tropical cyclone instensities being underanalyzed. That is, some storms were missed and many intensities are too low in the preaircraft reconnaissance era (before 1944 for the western half of the basin) and in the presatellite era (before 1972 for the entire basin).”

* * *

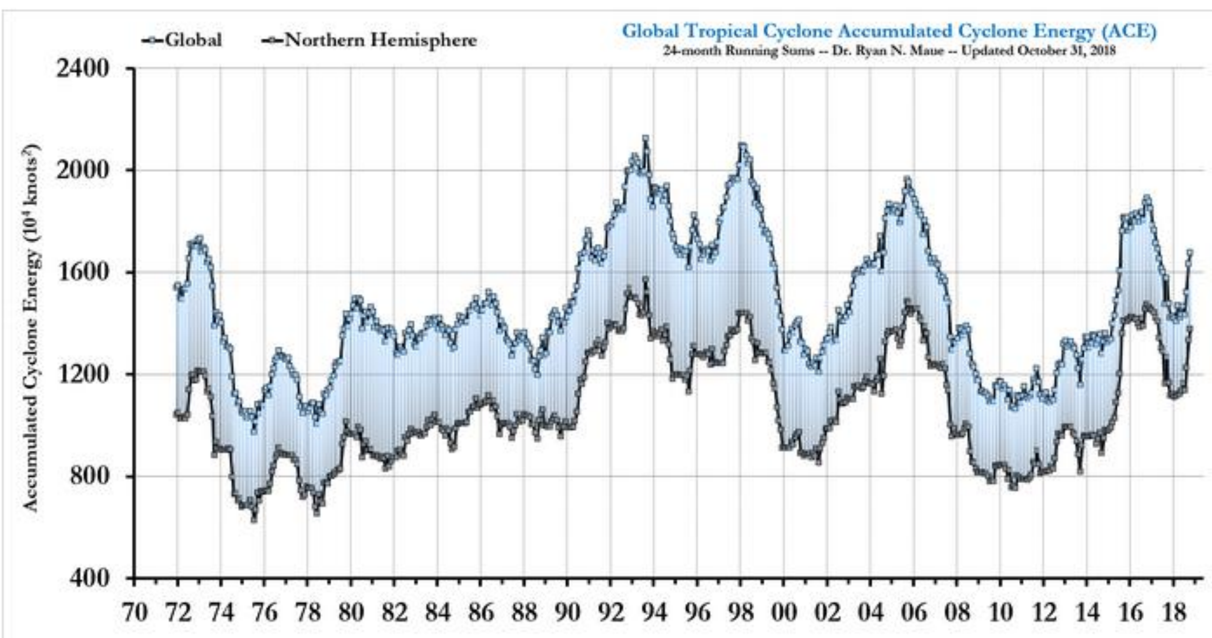
Source: Landsea, C.W. and Franklin, J.L. 2013. Atlantic hurricane database uncertainty and presentation of a new database format. *Monthly Weather Review* **141:** 3576–92.

Searching for a Trend

Maue (2011) obtained global TC life cycle data from the IBTrACS database of Knapp *et al*. (2010), which contains six-hourly best-track positions and intensity estimates for the period 1970–2010, from which he calculated the accumulated cyclone energy (ACE) metric (Bell *et al*., 2000), analogous to the power dissipation index (PDI) used by Emanuel (2005) in his attempt to link hurricanes with global warming. Maue found "in the pentad since 2006, Northern Hemisphere and global tropical cyclone ACE has decreased dramatically to the lowest levels since the late 1970s." He also found "the global frequency of tropical cyclones has reached a historical low." Maue noted "there is no significant linear trend in the frequency of global TCs," in agreement with the analysis of Wang *et al*. (2010). "[T]his current period of record inactivity," as Maue describes it, suggests the long-held contention that global warming increases the frequency and intensity of tropical storms is simply not true. Maue has continuously updated his analysis, with the latest results shown in Figure 2.3.1.6.2.

Villarini *et al*. (2011) used a statistical model developed by Villarini *et al*. (2010), in which "the frequency of North Atlantic tropical storms is modeled by a conditional Poisson distribution with a rate of occurrence parameter that is a function of tropical Atlantic and mean tropical sea surface temperatures (SSTs)," to examine "the impact of different climate models and climate change scenarios on North Atlantic and U.S. landfalling tropical storm activity." The five researchers report their results "do not support the notion of large increases in tropical storm frequency in the North Atlantic basin over the twenty-first century in response to increasing greenhouse gases." They also note "the disagreement among published results concerning increasing or decreasing North Atlantic tropical storm trends in a warmer climate can be largely explained (close to half of the variance) in terms of the different SST projections (Atlantic minus tropical mean) of the different climate model projections."

Figure 2.3.1.6.2
Cyclonic energy, globally and Northern Hemisphere, from 1970 through October 2018



Last four decades of global and Northern Hemisphere Accumulated Cyclone Energy (ACE): 24-month running sums. Note that the year indicated represents the value of ACE through the previous 24 months for the Northern Hemisphere (bottom line/gray boxes) and the entire globe (top line/blue boxes). The area in between represents the Southern Hemisphere total ACE. *Source:* Maue, 2018.

Vecchi and Knutson (2011) conducted an analysis of the characteristics of Atlantic hurricanes whose peak winds exceeded 33 meters/second for the period 1878–2008 based on the HURDAT database, developing a new estimate of the number of hurricanes that occurred in the pre-satellite era (1878–1965) based on analyses of TC storm tracks and the geographical distribution of the tracks of the ships that reported TC encounters. The two researchers report "both the adjusted and unadjusted basin-wide hurricane data indicate the existence of strong interannual and decadal swings." Although "existing records of Atlantic hurricanes show a substantial increase since the late 1800s," their analysis suggests "this increase could have been due to increased observational capability." They write, "after adjusting for an estimated number of 'missed' hurricanes (including hurricanes that likely would have been mis-classified as tropical storms), the secular change since the late-nineteenth century in Atlantic hurricane frequency is nominally negative – though not statistically significant." The two researchers from NOAA's Geophysical Fluid Dynamics Laboratory contend their results "do not support the hypothesis that the warming of the tropical North Atlantic due to anthropogenic greenhouse gas emissions has caused Atlantic hurricane frequency to increase."

Ying *et al.* (2011), working with tropical cyclone best track and related observational severe wind and precipitation datasets created by the Shanghai Typhoon Institute of the China Meteorological Administration, identified trends in observed TC characteristics over the period 1955 to 2006 for the whole of China and four sub-regions. They found over the past half-century there have been changes in the frequency of TC occurrence in only one sub-region, where they determined "years with a high frequency of TC influence have significantly become less common." They also note, "during the past 50 years, there have been no significant trends in the days of TC influence on China" and "the seasonal rhythm of the TC influence on China also has not changed." They found "the maximum sustained winds of TCs affecting the whole of China and all sub-regions have decreasing trends" and "the trends of extreme storm precipitation and 1-hour precipitation were all insignificant." Thus, for the whole of China and essentially all of its component parts, major measures of TC impact have remained constant or slightly decreased.

Sun *et al*. (2011) analyzed data pertaining to TCs for the period 1951–2005 over the northwestern Pacific and South China Sea, obtained from China's Shanghai Typhoon Institute and the National Climate Center of the China Meteorological Administration. They determined the frequency of all TCs affecting China "tended to decrease from 1951 to 2005, with the lowest frequency [occurring] in the past ten years." In addition, the average yearly number of super typhoons was "three in the 1950s and 1960s" but "less than one in the past ten years." They write "the decrease in the frequency of super typhoons, at a rate of 0.4 every ten years, is particularly significant (surpassing the significance test at the 0.01 level)," adding "there is a decreasing trend with the extreme intensity of these TCs during the period of influence in the past 55 years." The authors' findings are shown in Figure 2.3.1.6.3.

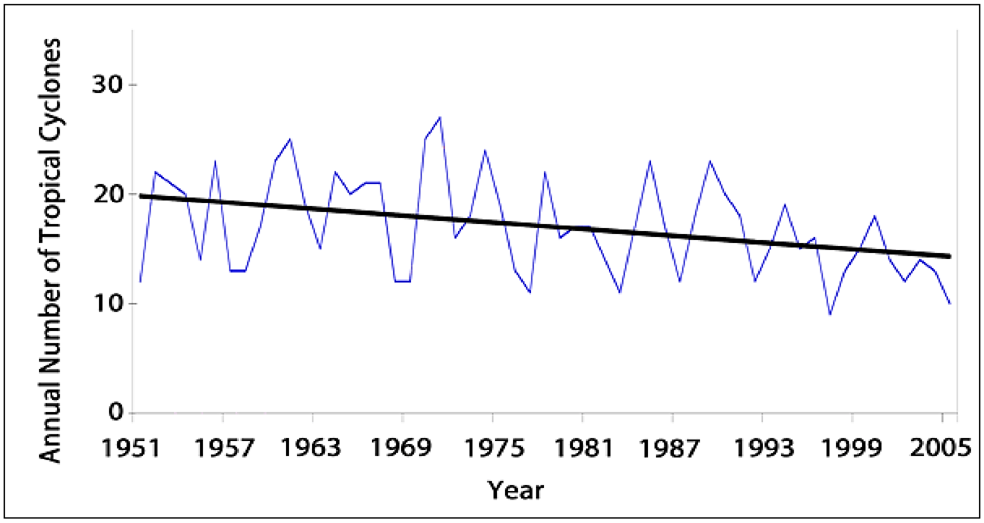
Xiao *et al*. (2011) "developed a Tropical Cyclone Potential Impact Index (TCPI) based on the air mass trajectories, disaster information, intensity, duration and frequency of tropical cyclones," using observational data obtained from the China Meteorological Administration's *Yearbook of Tropical (Typhoon) Cyclones in China* for the years 1951–2009 plus the *Annual Climate Impact Assessment* and *Yearbook of Meteorological Disasters* in China, also compiled by the China Meteorological Administration, but for the years 2005–2009. The five researchers report "China's TCPI appears to be a weak decreasing trend over the period [1949–2009], which is not significant overall, but significant in some periods."

Hoarau *et al*. (2012) analyzed intense cyclone activity in the northern Indian Ocean from 1980 to 2009 based on a homogenous reanalysis of satellite imagery. The three French researchers conclude "there has been no trend towards an increase in the number of categories 3–5 cyclones over the last 30 years," noting "the decade from 1990 to 1999 was by far the most active with 11 intense cyclones while 5 intense cyclones formed in each of the other two decades"; i.e., those that preceded and followed the 1990s. They state there has "not been a regular increase in the number of cyclone 'landfalls' over the last three decades (1980–2009)."

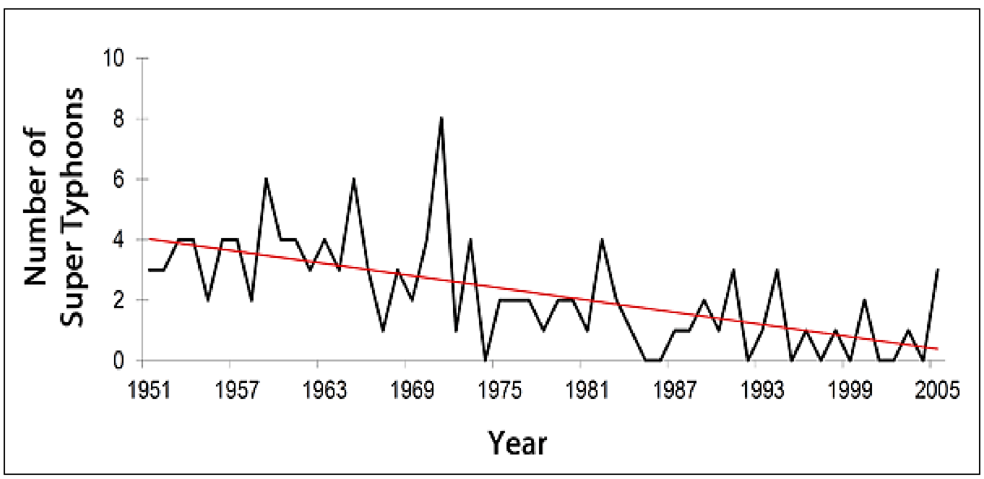
Zhao *et al.* (2018) studied TC frequency in the western North Pacific, "the most active basin over the global oceans, experienc[ing] on average about 26 TCs each year, accounting for nearly 1/3 of the global annual total TC counts," during 1979–2014. They note an "abrupt shift" occurred in 1998, after which TC frequency dropped precipitously. The mean annual TC frequency fell from 20 during 1979–1997 to only 15.5 from 1998–2014. "A similar reduc-

Figure 2.3.1.6.3
Declining number of typhoons and frequency of super typhoons affecting China (1951–2005)

A. Annual number of typhoons



B. Annual number of super typhoons



Source: Sun *et al.*, 2011.

tion of TC frequency was observed in the WNP basin and of global TC activity was observed by Liu and Chan (2013) and Maue (2011)."

Before the active 2017 season, the United States had not experienced landfall of a Category 3 or greater hurricane in nearly 12 years, the longest such "hurricane drought" in the United States since the 1860s (Truchelut and Staeling, 2017; Landsea, 2018). Landsea (2015) explained why hurricanes making landfall on the U.S. coast is representative of global hurricane activity:

> Hurricanes striking the continental United States compose a sizable percentage (23%) of all Atlantic basin hurricanes since 1972, the first year for reliable all Atlantic basin hurricane frequency owing to the invention of Dvorak satellite intensity technique

(Dvorak 1975) coupled with available satellite imagery for the basin. The rather lengthy coastline of the United States tends to experience more hurricane strikes in busy seasons, but not every active year causes more U.S. landfalls because of variability in genesis locations and steering flow. The linear correlation coefficient of U.S. hurricanes with all Atlantic basin hurricanes is 0.49 for the years 1972–2014 (statistically significant beyond the 99.8% level after accounting for serial correlation). Thus, while the sample size per season of U.S. hurricanes is substantially smaller than for all Atlantic basin hurricanes, the U.S. hurricane time series reflects some of the same variability as seen in the whole basin.

Commenting on claims by Kunkel *et al.* (2013) that Atlantic basinwide activity had risen in recent years, Landsea (2015) writes, "The long U.S. landfall record is an indication that this recent upward phase of activity in the Atlantic basin was preceded by quiet and active periods of similar magnitude. Furthermore, because of the use of over 100 years of reliable U.S. hurricane records, one can conclude that there has been no long-term century-scale increase in U.S. hurricane frequencies."

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2.3.2 Melting Ice

> *The Antarctic ice sheet is likely to be unchanged or is gaining ice mass. Antarctic sea ice is gaining in extent, not retreating. Recent trends in the Greenland ice sheet mass and Artic sea ice are not outside natural variability.*

According to the Working Group I contribution to the IPCC's Fifth Assessment Report, "over the last two decades, the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent (*high confidence*)" (IPCC, 2013, p. 9). The IPCC gives estimates of the average rate of net ice loss during the late twentieth and early twenty-first centuries for glaciers around the world, the Greenland and Antarctic ice sheets, and mean Arctic sea ice extent, noting "mean Antarctic sea ice extent *increased* at a rate in the range of 1.2 to 1.8% per decade between 1979 and 2012" (italics added).

A tutorial on the cryosphere – those places on or near Earth's surface so cold that water is present around the year as snow or ice in glaciers, ice sheets, and sea ice – appears in Chapter 5 of *Climate Change Reconsidered II: Physical Science* (NIPCC, 2013) and will not be repeated here. This section focuses narrowly on the IPCC's claim to know with "high confidence" that Antarctica is in fact losing mass and that melting in the Arctic is due to anthropogenic rather than natural forcing. The possible effects of ice melting on sea-level rise are the subject of Section 2.3.3.

Any discussion of the issue must begin by observing that glaciers, ice sheets, and sea ice around the world continuously advance and retreat due to the net difference between accumulation and ablation. Both the acquisition and loss of ice and snow are determined by physical processes that include regional temperature fluctuations, precipitation variability, solar cycles, ocean current cycles, wind, and local geological conditions. Globally, a general pattern exists of ice retreating since the end of the Little Ice Age, a period when many glaciers reached or approached their maximum extents of the Holocene. The melting observed during the modern era precedes any possible anthropogenic forcing and observed melting today is not proof of a human impact on climate.

Complicating this discussion is the fact, well-known among experts in the field but not widely communicated to other researchers or the public, that measurements of mass balance (the net balance between the mass gained by snow deposition – accumulation – and the loss of mass by melting, calving, or other processes – ablation) vary depending on the techniques used. Inference, not direct observation, is required to produce such estimates. Computer models have a particularly poor record of hindcasting ice sheets and sea ice (Rosenblum and Eisenman, 2017). Even if recent trends represent a change from historical patterns, this would not be *prima facie* evidence of an anthropogenic problem. Melting ice produces human and ecological benefits as well as incurring costs, a fact well understood by many millions of people whose supplies of fresh water rely on melting glaciers. No effort has yet been made to weigh those real benefits against the imagined costs.

2.3.2.1 Antarctic Ice Sheet and Sea Ice

We start in Antarctica because it is massively large compared to the Arctic ice sheet, accounting for 90% of the world's ice. Even very small increases in the Antarctic ice sheet mass balance are enough to offset or compensate for melting at the opposite pole.

There are conflicting estimates and no single authoritative measure of Antarctica's mass balance or its changes over geological time or human history. Until recently, most researchers believed Antarctica's ice sheet experienced little net gain or loss since satellite data first became available in 1992 (Tedesco and Monaghan, 2010; Quinn and Ponte, 2010; Zwally and Giovinetto, 2011). More recently, modelers using the IPCC's dubious forecasts of temperature and precipitation and perhaps looking for a human signal find a small net loss by the ice sheet (IMBIE Team, 2018).

Climate models generally predict that a warmer climate would result in more snowfall over Antarctica. This is due to the ability of warmer air (but still below freezing) to transport more moisture across the Antarctic continent. By itself, increased snowfall would increase the Antarctic ice sheet so much it would cause a drop in global sea level of 20 to 43 millimeters (0.8 – 1.7 inches) in 2100 and 73 to 163 mm (2.9 – 6.4 inches) in 2200, compared with today (Ligtenberg *et al.*, 2013). However, models also predict this increase would be more than offset by increases in surface melt, ice discharge, ice-shelf collapses, and ocean-driven melting. One key complication that current climate models failed to account for is the significant geothermal heating beneath the ice sheet (Schroeder *et al.*, 2014) as well as some 138 volcanoes, 91 of which have not been previously identified, recently discovered beneath the West Antarctic (van Wyk de Vries *et al.*, 2018). Due to the complexity of the processes involved, the future and even current ice sheet mass balances of Antarctica are unknown.

While the Antarctic ice sheets were once thought to have been stable over long periods of geological time, this thinking is now known to be incorrect. The editors of *Nature Geoscience* (2018) write, "first came sediment and model evidence that the West Antarctic ice sheet collapsed during previous interglacial periods and under Pliocene warmth. Then came erosional data showing that several regions of the East Antarctic ice sheet also retreated and advanced throughout the Pliocene. An extended record of ice-sheet extent from elsewhere on the East Antarctic coast now paints a more complicated picture of the sensitivity of this ice sheet to warming."

According to the editors of *Nature Geoscience*, Antarctic ice sheet changes occur very slowly. "In terms of immediate sea-level rise, it is reassuring that it seems to require prolonged periods of time lasting hundreds of thousands to millions of years to induce even partial retreat [of the East Antarctic ice sheet]. Nevertheless, we must not take its stability completely for granted – we cannot be sure how the East Antarctic ice sheet will respond to rates of warming that might exceed one to two degrees in a few thousand years."

Antarctic melting is not to be feared even "in a few thousand years" if temperatures in the Antarctic do not rise substantially. Stenni *et al*. (2017) report that their new reconstruction of Antarctic temperature "confirm[s] a significant cooling trend from 0 to 1900 CE (current era) across all Antarctic regions where records extend back into the 1st millennium, with the exception of the Wilkes Land coast and Weddell Sea coast regions. Within this long-term cooling trend from 0–1900 CE we find that the warmest period occurs between 300 and 1000 CE, and the coldest interval from 1200 to 1900 CE. Since 1900 CE, significant warming trends are identified for the West Antarctic Ice Sheet, the Dronning Maud Land coast and the Antarctic Peninsula regions, and these trends are robust across the distribution of records that contribute to the unweighted isotopic composites and also significant in the weighted temperature reconstructions. Only for the Antarctic Peninsula is this most recent century-scale trend unusual in the context of natural variability over the last 2000-years."

Growing evidence suggests temperatures in the region rose in the modern era prior to about 1998 but have since stopped and may now be cooling once more. Carrasco (2013) reported finding a decrease in the warming rate from stations on the western side of the Antarctic Peninsula between 2001 and 2010, as well as a slight cooling trend for King George Island (in the South Shetland Islands just off the peninsula). Similarly, in an analysis of the regional stacked temperature record over the period 1979–2014, Turner *et al.* (2016) reported a switch from warming (1979–1997) to cooling (1999–2014). While warming on the Antarctic Peninsula (typically measured at the Faraday/Vernadsky station) is often cited as proof that Antarctica is warming, temperatures elsewhere on the enormous continent suggest a different story.

More recently, Oliva *et al.* (2017) updated the study by Turner *et al.* (2016) "by presenting an updated assessment of the spatially-distributed temperature trends and interdecadal variability of mean annual air temperature and mean seasonal air temperature from 1950 to 2015, using data from ten stations distributed across the Antarctic Peninsula region." They found the "Faraday/Vernadsky warming trend is an extreme case, circa twice those of the long-term records from other parts of the northern Antarctic Peninsula." They also note the presence of significant decadal-scale variability among the 10 temperature records, which they linked to large-scale atmospheric phenomena such as ENSO, the Pacific Decadal Oscillation, and the Southern Annular Mode. Perhaps most important is their confirmation that "from 1998 onward, a turning point has been observed in the evolution of mean annual air temperatures across the Antarctic Peninsula region, changing from a warming to a cooling trend." This cooling has amounted to a 0.5° to 0.9°C decrease in temperatures in most of the Antarctic Peninsula region, the only exception being three stations located in the southwest sector of the peninsula that experienced a slight delay in their thermal turning point, declining only over the shorter period of the past decade. Oliva *et al.* (2017) cite independent evidence from multiple other sources in support of the recent cooling detected in their analysis, including an "increase in the extent of sea ice, positive mass-balance of peripheral glaciers and thinning of the active layer of permafrost."

Colder temperatures in Antarctica appear to have halted net melting on the continent. Lovell *et al*. (2017) set out to determine the temporal changes in the glacial terminus positions of 135 outlet glaciers (91 marine- and 44 land-terminating) spanning approximately 1,000 kilometers across three major drainage basins along the coastline of East Antarctica (Victoria Land, Oates Land, and George V Land). This was accomplished by comparing terminus position changes in seven satellite images over the period 1972–2013. In describing their findings, Lovell *et al*. write, "between 1972 and 2013, 36% of glacier termini in the entire study area advanced and 25% of glacier termini retreated, with the remainder showing no discernible change outside of the measurement error (± 66 m or ± 1.6 m yr^{-1}) and classified as 'no change.'" Although there were some regional differences in glacier termini changes, the authors found no correlation with those changes and changes in air temperature or sea ice trends. Instead, they write, "sub-decadal glacier terminus variations in these regions over the last four decades were more closely linked to non-climatic drivers, such as terminus type and geometry, than any obvious climatic or oceanic forcing."

Similarly, Fountain *et al*. (2017) analyzed changes in glacier extent along the western Ross Sea in Antarctica over the past 60 years. The authors used digital scans of paper maps based on aerial imagery acquired by the U.S. Geological Survey, along with modern-day satellite imagery from a variety of platforms, to calculate changes in the terminus positions, ice speed, calving rates, and ice front advance and retreat rates from 34 glaciers in this region over the period 1955–2015. The authors report "no significant spatial or temporal patterns of terminus position, flow speed, or calving emerged, implying that the conditions associated with ice tongue stability are unchanged," at least over the past six decades. However, they also report "the net change for all the glaciers, weighted by glacier width at the grounding line, has been [one of] *advance"* (italics added) with an average rate of increase of +12 ± 88 m yr^{-1}. Over a period during which the bulk of the modern rise in atmospheric CO_2 has occurred, not only have the majority of glaciers from this large region of Antarctica not retreated, they have collectively grown.

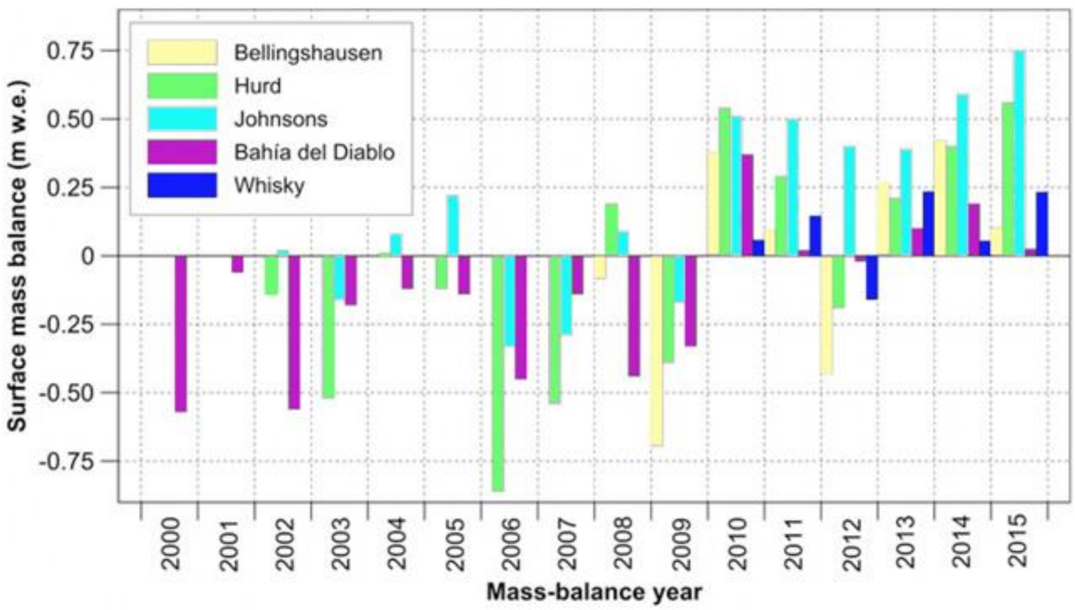
Engel *et al.* (2018) analyzed surface mass-balance records from two glaciers on James Ross Island, located off the northeastern edge of the Antarctic Peninsula. The first glacier, Whisky Glacier, is a land-terminating valley glacier, while the second, Davies Dome, is an ice dome. According to the authors, "because of their small volume, these glaciers are expected to have a relatively fast dynamic response to climatic oscillations and their mass balance is also considered to be a sensitive climate indicator," citing the work of Allen *et al*. (2008). The researchers found that over the period of study (2009–2015), Davis Dome and Whisky Glacier experienced cumulative mass *gains* of 0.11 ± 0.37 and 0.57 ± 0.67 meters of water equivalent, respectively; their annual surface mass balances were *positive* in every year except 2011/2012.

Engel *et al*. (2018) write their findings "indicate a change from surface mass loss that prevailed in the region during the first decade of the 21st century to predominantly positive surface mass balance after 2009/2010." They also note the positive mass balances observed on Davis Dome and Whisky Glacier "coincide with the surface mass-balance records from Bahía del Diablo Glacier on nearby Vega Island, Bellingshausen Ice Dome on King George Island and Hurd and Johnsons glaciers on Livingston Island," which records reveal "a regional change from a predominantly negative surface mass balance in the first decade of the 21st century to a positive balance over the 2009–2015 period." Their findings appear in Figure 2.3.2.1.1. The authors also noted "a significant decrease in the warming rates reported from the northern Antarctic Peninsula since the end of the 20th century" which "is also consistent with the regional trend of climate cooling on the eastern side of the Antarctic Peninsula."

Moving from the Antarctic ice sheet to the *sea ice* surrounding the continent, Comiso *et al*. (2017) report "the Antarctic sea ice extent has been slowly increasing contrary to expected trends due to global warming and results from coupled climate models." They note record high levels of sea ice extent were reported in 2012 and 2014, and "the positive trend is confirmed with newly reprocessed sea ice data that addressed inconsistency issues in the time series." The authors produce a new sea ice record "to show that the positive trend in sea ice extent is real using an updated and enhanced version of the sea ice data" in response to concerns expressed by Eisenman *et al.* (2014) that the trend might be an artifact of inconsistency in the processing of data before and after January 1992. That problem was fixed when the entire dataset was reprocessed, as reported by Comiso and Nishio (2008). To further improve the dataset, Comiso *et al.* (2017) correct inconsistencies among sensors, "the tie point for open water was made dynamic; and the threshold for the lower limit for ice was relaxed to allow retrieval of ice at 10% ice concentration. Further adjustments in brightness temperature T_B were made to improve consistency in the retrieval of ice concentration, ice extent, and ice area from the different sensors." After making these improvements, the authors report a positive trend of +19.9 ± 2.0 10^3 km^2/year, or +1.7 ± 0.2% / decade. The results of their new analysis are shown in Figure 2.3.2.1.2.

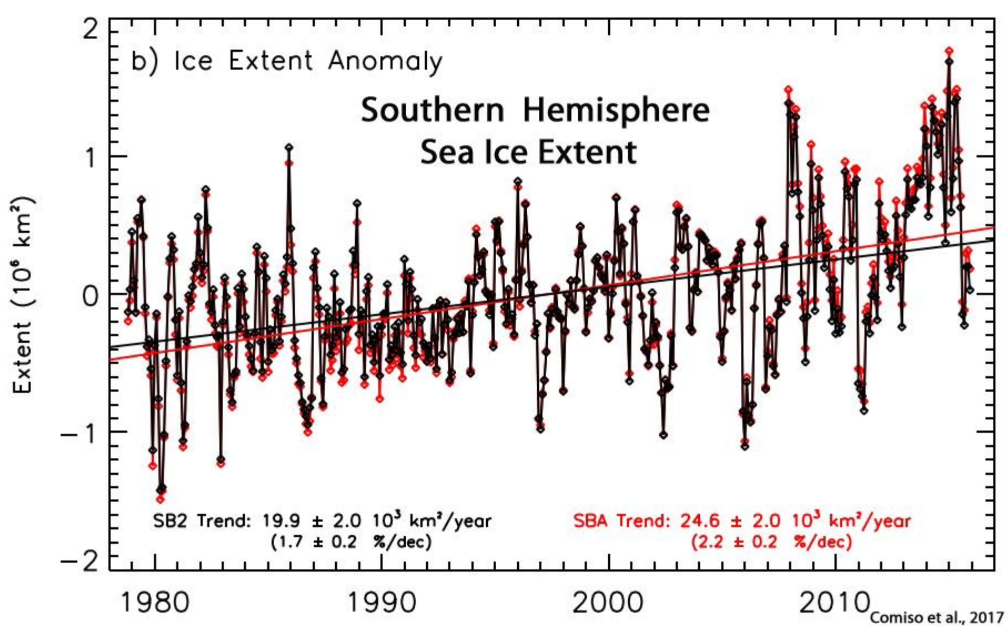
Comiso *et al.* (2017) write, "The positive trend, however, should not be regarded as unexpected despite global warming and the strong negative trend in the Arctic ice cover because the distribution of global surface temperature trend is not uniform. In the Antarctic region the trend in surface temperature is about 0.1°C $decade^{-1}$ while the trend is 0.6°C $decade^{-1}$ in the Arctic and 0.2°C $decade^{-1}$ globally since 1981." Actually, the satellite record shows a global temperature trend from 1979 to 2016 of only 0.1°C $decade^{-1}$, just half of their estimate (Christy *et al.,* 2018), which makes the increasing extent of Southern Hemispheric sea ice even more expected.

Figure 2.3.2.1.1
Surface mass-balance records for glaciers around the northern Antarctic Peninsula



Source: Engel *et al.,* 2018.

Figure 2.3.2.1.2
Monthly averages of the Antarctic sea ice extent, November 1978 to December 2015



Time series of monthly anomalies of sea ice extents derived using the newly enhanced SB2 data (black) and the older SBA data (red) from November 1978 to December 2015. The trend lines using SB2 and SBA data are also shown and the trend values with statistical errors are provided. Adapted from Comiso *et al*., 2017, Figure 3b.

Purich *et al*. (2018) believe the expansion of Antarctic sea ice can be explained by the addition of fresh water to the Southern Ocean surface, a process called "surface freshening." "The majority of CMIP5 models underestimate or fail to capture this historical surface freshening," they write, "yet little is known about the impact of this model bias on regional ocean circulation and hydrography." The authors use GCMs to model the addition of freshwater to the Southern Ocean and find it "causes a surface cooling and sea ice increase under preindustrial conditions, because of a reduction in ocean convection and weakened entrainment of warm subsurface waters into the surface ocean."

* * *

Despite climate model predictions, the Antarctic ice sheet is likely to be unchanged or is gaining ice mass while Antarctic sea ice is gaining in extent, not retreating. A long regional cooling trend in surface temperatures appears to have ended around the beginning of the twentieth century, probably due to internal variability unrelated to the human presence. The subsequent warming trend may have ended in the past decade.

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2.3.2.2 Arctic Ice Sheet and Sea Ice

According to Kryk *et al*. (2017), "Greenland is the world's largest, non-continental island located between latitudes 59 ° and 83 ° N, and longitudes 11 ° and 74 ° W. Greenland borders with Atlantic Ocean to the East, with the Arctic Ocean to the North and Baffin Bay to the West. Three-quarters of Greenland is solely covered by the permanent ice sheet." Models cited by the IPCC find "the average rate of ice loss from the Greenland ice sheet has *very likely* substantially increased from 34 [-6 to 74] Gt yr^{-1} over the period 1992 to 2001 to 215 [157 to 274] Gt yr^{-1} over the period 2002 to 2011" (IPCC, 2013, p. 9). Also according to the IPCC, "the annual mean Arctic sea ice extent decreased over the period 1979 to 2012 with a rate that was *very likely* in the range of 3.5 to 4.1% per decade. …"

While it is easy to find alarming accounts of rising temperatures and melting ice in the Arctic region even in respected science journals (e.g., Lang *et al.*, 2017), such accounts neglect to report natural variability in the historical and geological record against which recent trends must be compared. MacDonald *et al.* (2000) used radiocarbon-dated macrofossils to document how "Over most of Russia, forest advanced to or near the current arctic coastline between 9000 and 7000 yr B.P. (before present) and retreated to its present position by between 4000 and 3000 yr B.P. … During the period of maximum forest extension, the mean July temperatures along the northern coastline of Russia may have been 2.5° to 7.0°C warmer than modern. The development of forest and expansion of treeline likely reflects a number of complimentary environmental conditions, including heightened summer insolation, the demise of Eurasian ice sheets, reduced sea-ice cover, greater continentality with eustatically lower sea level, and extreme Arctic penetration of warm North Atlantic waters."

Miller *et al*. (2005) summarized the main characteristics of the glacial and climatic history of the Canadian Arctic's Baffin Island since the Last Glacial Maximum by presenting biotic and physical proxy climate data derived from six lacustrine sediment cores recovered from four sites on Baffin Island. This work revealed that "glaciers throughout the Canadian Arctic show clear evidence of Little Ice Age expansion, persisting until the late 1800s, followed by variable recession over the past century." They also report that wherever the Little Ice Age advance can be compared to earlier advances, "the Little Ice Age is the most extensive Late Holocene advance," and "some glaciers remain at their Little Ice Age maximum." Since the Little Ice Age in the Canadian Arctic spawned the region's most extensive glacial advances of the entire Holocene, it is only to be *expected* that the region should be experiencing significant melting as the planet recovers from that historic cold era.

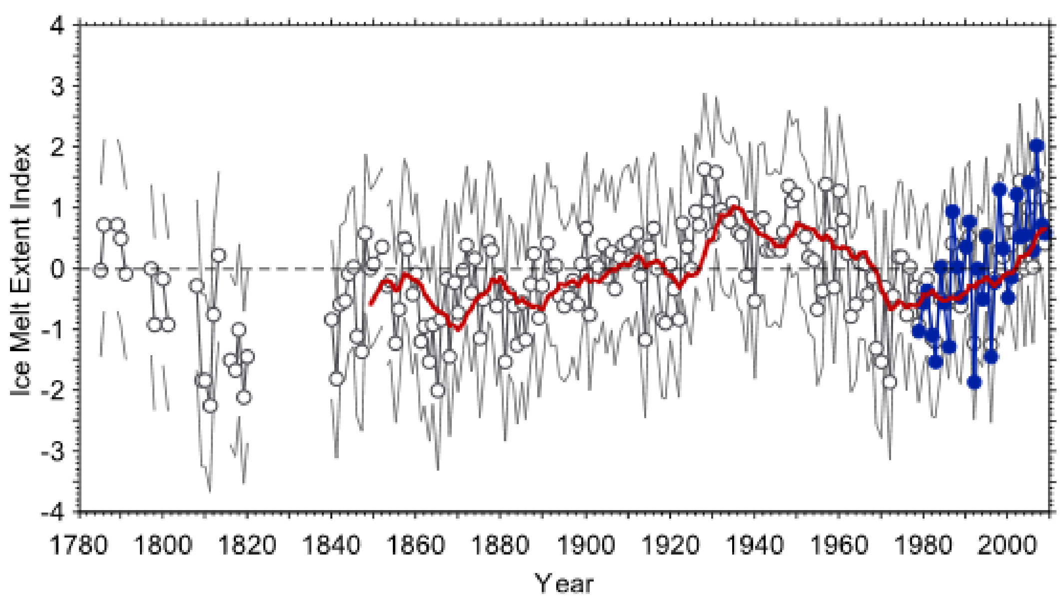
Also working with sediment cores recovered from three mid-Arctic lakes on the Cumberland Peninsula of eastern Baffin Island, Frechette *et al*. (2006) employed radiocarbon dating of macrofossils contained in the sediment, together with luminescence dating, to isolate and study the portions of the cores pertaining to the interglacial that preceded the Holocene, which occurred approximately 117,000 to 130,000 years ago, reconstructing the past vegetation and climate of the region during this period based on pollen spectra derived from the cores. This work revealed that "in each core," as they describe it, "last interglacial sediments yielded remarkably high pollen concentrations, and included far greater percentages of shrub (*Betula* and *Alnus*) pollen grains than did overlying Holocene sediments." They then infer "July air temperatures of the last interglacial to have been 4 to 5°C warmer than present on eastern Baffin Island." This clearly reveals that Arctic region temperatures today are not unprecedented. In a companion study, Francis *et al*. (2006) estimated "summer temperatures during the last interglacial were higher than at any time in the Holocene, and 5 to 10°C higher than present."

A major review of the literature conducted in 2006 (CAPE-Last Interglacial Project Members, 2006) reported "quantitative reconstructions of LIG [Last Interglaciation] summer temperatures suggest that much of the Arctic was 5°C warmer during the LIG than at present." With respect to the impacts of this warmth, they note Arctic summers of the LIG "were warm enough to melt all glaciers below 5 km elevation except the Greenland Ice Sheet, which was reduced by ca 20–50% (Cuffey and Marshall, 2000; Otto-Bliesner *et al*., 2006)." In addition, they write "the margins of permanent Arctic Ocean sea ice retracted well into the Arctic Ocean basin and boreal forests advanced to the Arctic Ocean coast across vast regions of the Arctic currently occupied by tundra."

Frauenfeld *et al*. (2011) used the known close correlations of total annual observed melt extent across the Greenland ice sheet, summer temperature measurements from stations located along Greenland's coast, and variations in atmospheric circulation across the North Atlantic to create a "near-continuous 226-year reconstructed history of annual Greenland melt extent dating from 2009 back into the late eighteenth century." Their graph of the record appears as Figure 2.3.2.2.1. The researchers found "the recent period of high-melt extent is similar in magnitude but, thus far, shorter in duration, than a period of high melt lasting from the early 1920s through the early 1960s. The greatest melt extent over the last 2-1/4 centuries occurred in 2007; however, this value is not statistically significantly different from the reconstructed melt extent during 20 other melt seasons, primarily during 1923–1961." Similarly, Bjørk *et al*. (2018) found the rates at which Greenland's peripheral glaciers are currently retreating were exceeded during the "early twentieth century post-Little-Ice-Age retreat."

Vasskog *et al*. (2015) provides a summary of what is (and is not) presently known about the history of the Greenland ice sheet (GrIS) over the previous glacial-interglacial cycle. The authors find that during the last interglacial period (130–116 ka BP), global temperatures were 1.5°–2.0°C warmer than the peak warmth of the present interglacial, or Holocene, in which we are now living. They estimate the GrIS was "probably between ~7[%] and 60% smaller than at present," and that melting contributed to a rise in global sea level of "between 0.5 and 4.2 m." Comparing the present interglacial to the past interglacial, atmospheric CO_2 concentrations are currently 30% higher yet global temperatures are 1.5°–2°C cooler, GrIS volume is from 7% to 60% larger, and global sea level is at least 0.5-4.2 m lower, none of which observations signal catastrophe for the present.

Figure 2.3.2.2.1
Reconstructed history of the total ice melt extent index over Greenland, 1784–2009



Observed values of the ice melt index (blue solid circles), reconstructed values of the ice melt index (gray open circles), the 10-year trailing moving average through the reconstructed and fitted values (thick red line), and the 95% upper and lower confidence bounds (thin gray lines). Source: Frauenfeld *et al.,* 2011, Figure 2.

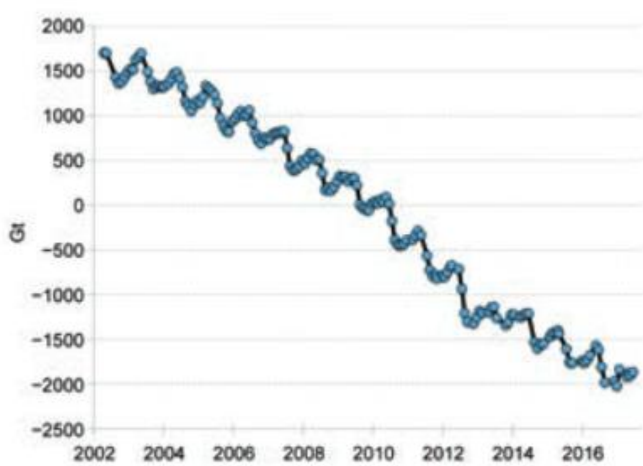
Lusas *et al*. (2017) observe, "Prediction of future Arctic climate and environmental changes, as well as associated ice-sheet behavior, requires placing present-day warming and reduced ice extent into a long-term context." Using calibrated radiocarbon dating of organic remains in small lakes near the Istorvet ice cap in East Greenland, they discover "deglaciation of the region before ~10,500 years BP, after which time the ice cap receded rapidly to a position similar to or less extensive than present." The record "suggests that the ice cap was similar to or smaller than present throughout most of the Holocene. This restricted ice extent suggests that climate was similar to or warmer than present, in keeping with other records from Greenland that indicate a warm early and middle Holocene."

Mangerud and Svendsen (2017) observe that remains of shallow marine mollusks that are today extinct close to Svalbard, a Norwegian group of islands located in the Arctic Ocean north of continental Norway, are found in deposits there dating to the early Holocene. The presence of "the most warmth-demanding species found, *Zirfaea crispata*," indicates August temperatures on Svalbard were 6°C warmer at around 10,200 – 9,200 YBP, when this species lived there. Another mussel, *Mytilus edulis*, returned to Svalbard in 2004 "following recent warming, and after almost 4000 years of absence, excluding a short re-appearance during the Medieval Warm Period 900 years ago." Based on their study of these mollusk remains, the authors conclude "a gradual cooling brought temperatures to the present level at about 4.5 cal. ka BP. The warm early-Holocene climate around Svalbard was driven primarily by higher insolation and greater influx of warm Atlantic water, but feedback processes further influenced the regional climate." These findings, like those of Kryk *et al*. (2017), make it clear that today's temperatures in this part of the Arctic are not unprecedented and indeed are cool compared to past periods.

Hofer *et al*. (2017) observe that the loss of mass by the GrIS has generally been attributed to rising temperatures and a decrease in surface albedo, but "we show, using satellite data and climate model output, that the abrupt reduction in surface mass balance since about 1995 can be attributed largely to a coincident trend of decreasing summer cloud cover enhancing the melt-albedo feedback. Satellite observations show that, from 1995 to 2009, summer cloud cover decreased by 0.9 ± 0.3% per year. Model output indicates that the GrIS summer melt increases by 27 ± 13 gigatons (Gt) per percent reduction in summer cloud cover, principally because of the impact of increased shortwave radiation over the low albedo ablation zone." The authors attribute the reduction in cloud cover to "a state shift in the North Atlantic Oscillation promoting anticyclonic conditions in summer [which] suggests that the enhanced surface mass loss from the GrIS is driven by synoptic-scale changes in Arctic-wide atmospheric circulation," not anthropogenic forcing.

As with changing views about the Antarctic ice sheet, past estimates of Greenland's mass balance and changes to the same showed little net loss and possibly small gains (Johannessen *et al.,* 2005; Zwally *et al.,* 2011; Jezek, 2012). More recently, computer models as well as satellite data appear to show a steady loss of mass from the Greenland ice sheet between 2002 and 2017, as shown in Figure 2.3.2.2.2. However, "Glacier area measurements from LANDSAT and ASTER, available since 1999 for 45 of the widest and fastest-flowing marine-terminating glaciers, reveal a pattern of continued relative stability since 2012–13" (Box *et al.,* 2018).

Figure 2.3.2.2.2
Change in total mass (Gt) of the Greenland ice sheet from GRACE satellite measurements, 2002–2017



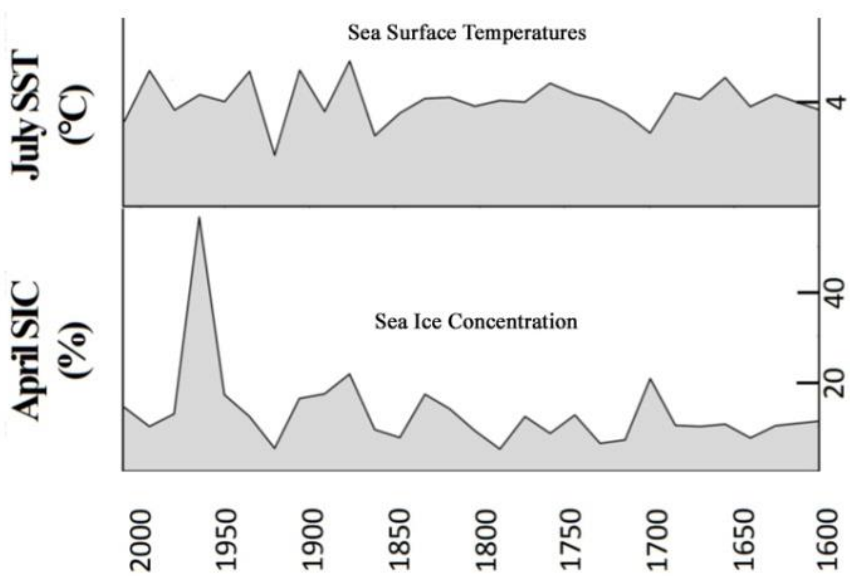
Data are based on an unweighted average of JPL RL05, GFZ RL05, and the CSR RL05 solutions, which reduce noise in the GRACE data for 2017. *Source:* Box *et al.,* 2018, Figure 5.12, p. S154, citing Sasgen *et al.,* 2012.

Turning from the GrIS to Arctic *sea ice*, Darby *et al*. (2001) developed a 10,000-year multi-parameter environmental record from a thick sequence of post-glacial sediments obtained from cores extracted from the upper continental slope off the Chukchi Sea Shelf in the Arctic Ocean. They uncovered "previously unrecognized millennial-scale variability in Arctic Ocean circulation and climate" along with evidence suggesting "in the recent past, the western Arctic Ocean was much warmer than it is today." More specifically, they write, "during the middle Holocene the August sea surface temperature fluctuated by 5°C and was 3–7°C warmer than it is today," and they report their data reveal "rapid and large (1–2°C) shifts in bottom water temperature," concluding that "Holocene variability in the western Arctic is larger than any change observed in this area over the last century."

Van Kooten (2013, pp. 232–3) observes, "Historically, the Arctic is characterized by warm periods when there were open seas and the Arctic sea ice did not extend very far to the south. Ships' logs identify ice-free passages during the warm periods of 1690–1710, 1750–1780 and 1918–1940, although each of these warm periods was generally preceded and followed by colder temperatures, severe ice conditions and maximum southward extent of the ice (e.g., during 1630–1660 and 1790–1830)." Van Kooten continues, "there must have been little ice in the Davis Strait west of Greenland as the Vikings

Kryk *et al*. (2017) note "Arctic temperatures are very variable, making it difficult to identify long-term trends, particularly on a regional scale," and "only until recently, the area of the North Atlantic, including SW Greenland region, was one of the few areas in the world where cooling was observed, however in the period 1979–2005 the trend reversed and strong warming was observed." The authors use changes in diatom species composition in Godthåbsfjord region, SW Greenland, to create a reconstruction of sea surface temperature and sea ice concentration (SIC) from 1600–2010 showing, among other things, that current temperatures and SIC are not at all unprecedented. Their findings are reproduced as Figure 2.3.2.2.3. See also Werner *et al.* (2017) for a review of four Arctic summer temperature reconstructions and the authors' original reconstruction, all showing temperature peaks higher than those observed in recent years.

Figure 2.3.2.2.3
Southwest Greenland sea surface temperatures and sea ice concentration, 1600–2010



SST = sea surface temperature, SIC = sea ice concentration. *Source:* Adapted from Kryk *et al.,* 2017, Figure 3.

The melting trend recorded by satellites since 1979 was preceded by a period of expanding ice extent from 1943 to about 1970 (e.g., Suo *et al.*, 2013), so looking only at the record since 1979 exaggerates the appearance of unusual melting. Not until ~2005 did the recent melting period reach the low point previously reached in 1943. Given uncertainties in measurement and changes in technology, it is possible today's sea ice extent is still not the lowest since 1900. See, for example, the Arctic sea ice dataset created by Connolly *et al.* (2017) reproduced as Figure 2.3.2.2.4.

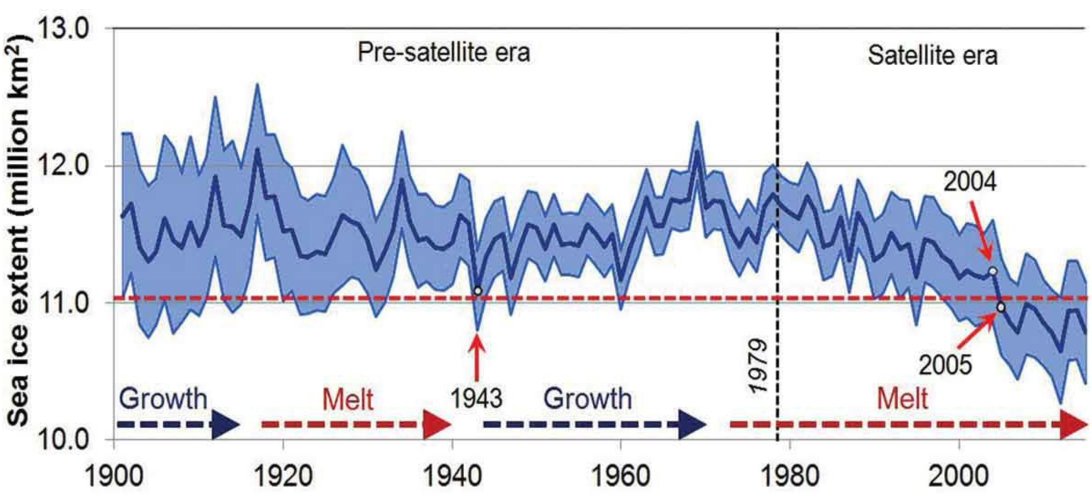
Commenting on their findings, Connolly *et al.* (2017) write, "if we also consider the full envelope of the associated confidence intervals, we cannot rule out the possibility that similarly low sea ice extents occurred during the 20th century. That is, the upper bounds of the estimates for all years since 2004 are still greater than the lower bounds for several years in the early 20th century." They also note "this late-1970s reversal in sea ice trends was *not* captured by the hindcasts of the recent CMIP5 climate models used for the latest IPCC reports, which suggests that current climate models are still quite poor at modelling past sea ice trends."

Slawinska and Robock (2018) used the Community Earth System Model to study the impacts of volcanic perturbations and the phase of the Atlantic Multidecadal Oscillation on the extent of sea ice and other climate indices. The authors show "at least in the Last Millennium Ensemble, volcanic eruptions are followed by a decadal-scale positive response of the Atlantic multidecadal overturning circulation, followed by a centennial-scale enhancement of the Northern Hemispheric sea ice extent. It is hypothesized that a few mechanisms, not just one, may have to play a role in consistently explaining such a simulated climate response at both decadal and centennial time scales." Of particular relevance to the topic being addressed here, the authors contend "prolonged fluctuations in solar irradiance associated with solar minima potentially amplify the enhancement of the magnitude of volcanically triggered anomalies of Arctic sea ice extent." As such natural sources of variability are better understood, the possible role of anthropogenic greenhouse gases in sea ice extent necessarily becomes smaller.

* * *

The Greenland ice sheet and neighboring glaciers and sea ice vary in mass and extent over time due to natural forces unrelated to the human presence. Recent temperatures and melting are not outside the range of natural variability found even in the past century. If there is anything strange or unusual about

Figure 2.3.2.2.4
Annual Arctic sea ice extent trends from 1900 to 2017



Periods of net sea ice growth and melt are indicated at the bottom of the figure. Satellite data became available in 1979. *Source:* Connolly *et al.,* 2017.

current Arctic temperatures it is that they are *lower* than what they were during the maximum warmth of the current interglacial and, even more so, the prior interglacial. If the Arctic behaves anything like the Antarctic in this regard, one can extend this comparison back in time through *three more* interglacials, all of which were also warmer than the current one (Petit *et al*., 1999; Augustin *et al*., 2004). Furthermore, it should be evident that the region's current life forms, including most notably polar bears, fared just fine during these much warmer interglacials, or else they would not be here today.

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2.3.2.3 Non-polar Glaciers

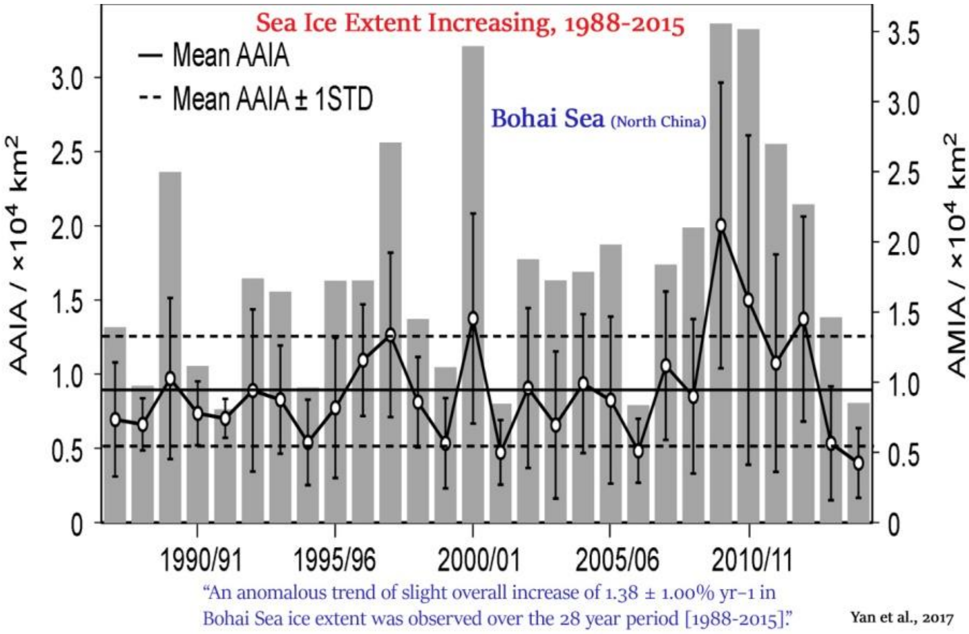
During the past 25,000 years (late Pleistocene and Holocene) glaciers around the world have fluctuated broadly in concert with changing climate, at times shrinking to positions and volumes smaller than today. Many non-polar glaciers have been retreating since the Little Ice Age, a natural occurrence unrelated to the human presence. This fact notwithstanding, mountain glaciers around the world show a wide variety of responses to local climate variation and do not respond to global temperature change in a simple, uniform way.

Tropical mountain glaciers in both South America and Africa have retreated in the past 100 years because of reduced precipitation and increased solar radiation; retreat of some glaciers elsewhere began at the end of the Little Ice Age in 1850, when no impact from anthropogenic CO_2 was possible. The data on global glacial history and ice mass balance do not support the claims made by the IPCC that CO_2 emissions are causing most glaciers today to retreat and melt. Chapter 5 of *Climate Change Reconsidered II: Physical Science* (NIPCC, 2013) reported many examples of glaciers that were either stable or advancing in the modern era. Rather than attempt a similarly comprehensive literature review again, we mention only a few examples reported most recently in the literature.

Yan *et al.* (2017) studied sea ice on the Bohai Sea, a gulf of the Yellow Sea on the northeastern coast of China. Despite being one of the busiest seaways in the world, the sea is becoming ice-covered during winter months with growing frequency. The recent global winter cooling trend reported in Section 2.3.1 has affected the Bohai Sea, producing media reports of record-setting cold and ice (*Beijing Review*, 2010, 2014; *China Daily*, 2012; *China Travel Guide*, 2013; *Daily Mail*, 2016). Yan *et al.* observe, "Despite the backdrop of continuous global warming, sea ice extent has been found not to consistently decrease across the globe, and instead exhibit heterogeneous variability at middle to high latitudes." Using satellite imagery, Yan *et al.* reveal an upward trend of 1.38 ± 1.00% yr^{-1} (R = 1.38, i.e. at a statistical significance of 80%) in Bohai Sea ice extent over the 28-year period. The researchers also report a decreasing mean ice-period average temperature based on data from 11 meteorological stations around the Bohai Sea. Their results are shown in Figure 2.3.2.3.1.

Sigl *et al.* (2018) note "Starting around AD 1860, many glaciers in the European Alps began to retreat from their maximum mid-19th century terminus positions, thereby visualizing the end of the Little Ice Age in Europe," confirming this retreat began before human greenhouse gas emissions could have been a principal driving factor. The authors note some researchers nevertheless contend radiative forcing by increasing deposition of industrial black carbon to snow might account for "the abrupt glacier retreats in the Alps." To test this hypothesis, they used "sub-annually resolved concentration records of refractory black carbon (rBC; using soot photometry) as well as distinctive tracers for mineral dust, biomass burning and industrial pollution from the Colle Gnifetti ice core in the Alps from AD 1741 to 2015. These records allow precise assessment of a potential relation between the timing of observed acceleration of glacier melt in the mid-19th century with an increase of rBC deposition on the glacier caused by the industrialization of Western Europe."

Figure 2.3.2.3.1
Increasing sea ice extent on Bohai Sea in northeastern China, 1988–2015



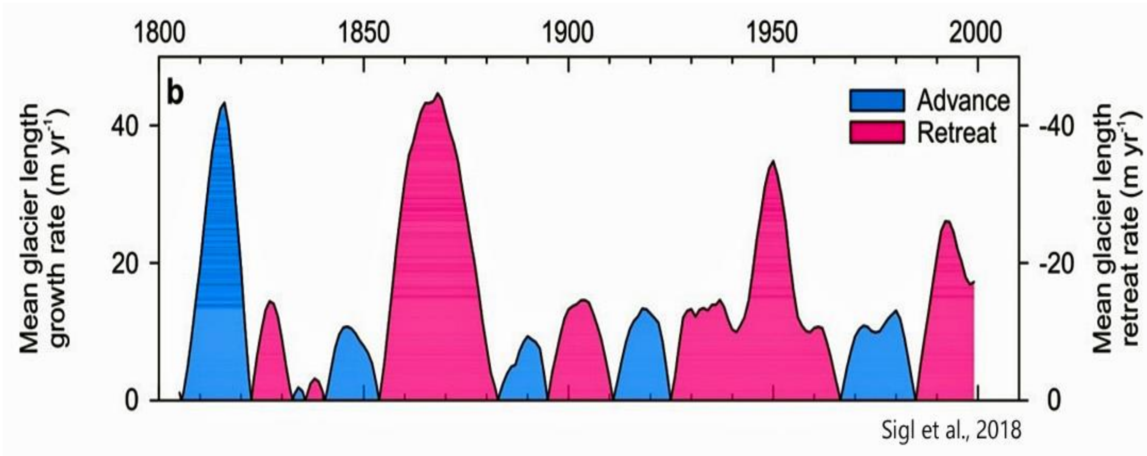
Left axis and solid lines are annual average ice area (AAIA). Right axis and shaded columns are annual maximum ice area (AMIA). Source: Adapted from Yan *et al.,* 2017.

Sigl *et al*. (2018) establish that industrial black carbon (BC) deposition began in 1868–1884 (5%–95% range) with the highest change point probability in 1876. "The median timing of industrial BC deposition at the four Greenland ice-core sites is AD 1872 (ToE analysis) or AD 1891 (Bayesian change-point), respectively, in good agreement with the Alpine ice cores," they report. By that time, they report, "the majority of Alpine glaciers had already experienced more than 80 % of their total 19th century length reduction, casting doubt on a leading role for soot in terminating of the Little Ice Age." Their plot of mean glacier length retreat and advance rates, shown in Figure 2.3.2.3.2, shows significant natural variability correlated with ambient temperature (not shown in the graph) but unrelated to soot emissions or human greenhouse gas emissions.

More evidence that natural variability in glacier advances and retreats exceeds that witnessed in the modern era comes from Oppedal *et al*. (2018). The authors produce a 7,200-year-long reconstruction of advances and retreats of the Diamond glacier, a "cirque glacier" (a glacier formed in a bowl-shaped depression on the side of or near mountains) on north-central South Georgia, an island south of the Antarctic Convergence. The authors infer glacier activity "from various sedimentary properties including magnetic susceptibility (MS), dry bulk density (DBD), loss-on-ignition (LOI) and geochemical elements (XRF), and tallied to a set of terminal moraines." They plot their findings in the figure reproduced here as Figure 2.3.2.3.3.

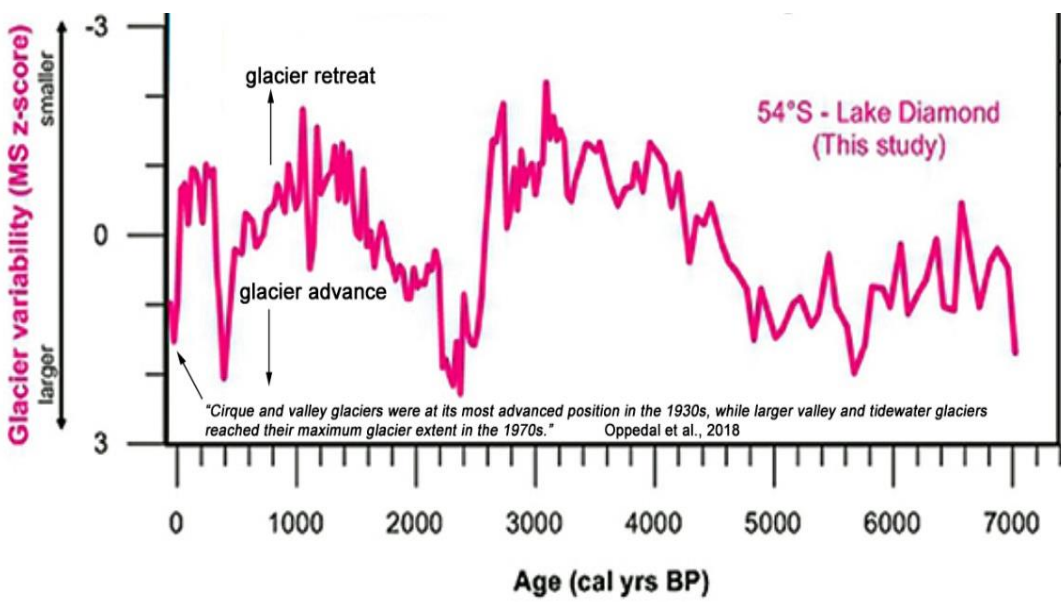
Oppedal *et al*. (2018) also found the study site was "deglaciated prior to 9900 ± 250 years ago when Neumayer tidewater glacier retreated up-fjord." Significantly, one of the periods when the glacier "was close to its Maximum Holocene extent" was "in the Twentieth century (likely 1930s)." Clearly, the extent of this glacier has varied considerably over the past 7,000 years and the retreat since 1930 is well within the bounds of natural variation. As for a mechanism explaining the waxing and waning of this glacier, Oppedal *et al.* write, "glacier fluctuations are largely in-phase with reconstructed Patagonian glaciers, implying that they respond to centennial climate variability possibly connected to corresponding modulations of the Southern Westerly Winds."

Figure 2.3.2.3.2
Nineteenth century glacier retreat in the Alps preceded the emergence of industrial black carbon deposition on high-alpine glaciers



Mean glacier length change rate (smoothed with an 11-year filter) of the glacier stack length record indicating phases of average glacier advances (blue) and of glacier retreat (red). *Source:* Adapted from Sigl *et al.,* 2018, Figure 8b.

Figure 2.3.2.3.3
Glacier reconstruction for Diamond glacier on South Georgia island



Source: Adapted from Oppedal *et al*., 2018.

* * *

On the matter of whether trends in melting ice in recent decades can be attributed to the human presence, the IPCC writes, "anthropogenic forcings are *very likely* to have contributed to Arctic sea ice loss since 1979" and "ice sheets and glaciers are melting, and anthropogenic influences are likely to have contributed to the surface melting of Greenland since 1993 and to the retreat of glaciers since the 1960s" (IPCC, 2013, p. 870). But such melting is not occurring at the rates reported by the IPCC, and melting is not unusual by historical or geological time standards. Computer models *assume* attribution to the human presence and then, in a circular fashion, are cited as proof of such attribution.

In conclusion, the Antarctic ice sheet is likely to be unchanged or is gaining ice mass. Antarctic sea ice is gaining in extent, not retreating. The Greenland ice sheet and Artic sea ice are losing mass but historically show variability exceeding the changes seen in the late twentieth and early twenty-first centuries. Any significant warming, whether anthropogenic or natural, will melt ice. To claim anthropogenic global warming is occurring based on such information is to confuse the consequences of warming with its cause.

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2.3.3 Sea-level Rise

> *Long-running coastal tide gauges show the rate of sea-level rise is not accelerating. Local and regional sea levels exhibit typical natural variability.*

According to the Working Group I contribution to the IPCC's Fifth Assessment Report (IPCC, 2013), "it is very likely that the global mean rate [of sea level rise] was 1.7 [1.5 to 1.9] mm yr^{-1} between 1901 and 2010 for a total sea level rise of 0.19 [0.17 to 0.21] m" (p. 1139) and "it is very likely that the rate of global mean sea level rise during the 21st century will exceed the rate observed during 1971–2010 for all Representative Concentration Pathway (RCP) scenarios due to increases in ocean warming and loss of mass from glaciers and ice sheets" (p. 1140).

Also according to the IPCC (2013), mass loss from the Greenland and Antarctic ice sheets over the period 1993–2010 expressed as sea-level equivalent was "about 5.9 mm (including 1.7 mm from glaciers around Greenland) and 4.8 mm, respectively," and ice loss from glaciers between 1993 and 2009 (excluding those peripheral to the ice sheets) was 13 mm (p. 368). The total is 23.7 mm (5.9 + 4.8 + 13), which is slightly less than 1 inch.

Like ice melting, sea-level rise is a research area that has recently come to be dominated by computer models. Whereas researchers working with datasets built from long-term coastal tide gauges typically report a slow linear rate of sea-level rise, computer modelers assume a significant anthropogenic forcing and tune their models to find or predict an acceleration of the rate of rise. This section reviews recent research to determine if there is any evidence of such an acceleration and then examines claims that islands and coral atolls are being inundated by rising seas.

2.3.3.1 Recent Sea-level Trends

The recent Pleistocene Ice Age slowly ended 20,000 years ago with an initially slow warming and a concomitant melting of ice sheets. As a result, sea level rose nearly 400 feet to approximately the present level. For the past thousand years it is generally believed that globally averaged sea-level change has been less than seven inches per century, a rate that is functionally negligible because it is frequently exceeded by coastal processes such as erosion and sedimentation. Local and regional sea levels continue to exhibit typical natural variability – in some places rising and in others falling – unrelated to changes in the global average sea level.

Measuring changes in sea level is difficult due to the roles and impacts of gravity variations, density of the water due to salinity differences, temperature of the water, wind, atmospheric pressure differences, changes in land level and land uses, and uncertainty regarding new meltwater from glaciers. The change in technologies used to measure sea level with the arrival of satellite altimetry created discontinuities in datasets resulting in conflicting estimates of sea levels and their rates of change (e.g., Chen *et al.*, 2013; Cazenave *et al.*, 2014). While some researchers infer from satellite data rates of sea-level rise of 3 mm yr^{-1} or even higher (Nerem *et al*., 2018), the accuracy of those claims have been severely criticized (Church *et al.,* 2010; Zhang and Church, 2012; Parker, 2015; Parker and Ollier, 2016; Mörner, 2017; Roach *et al.,* 2018). Others have spliced together measurements from different locations at different times (Church and White, 2006). In fact, all the (very slight) acceleration reported by Church and White (2006) occurred prior to 1930 – when CO_2 levels were under 310 ppm (Burton, 2012).

Many researchers place the current rate of global sea-level rise at or below the IPCC's historic estimate for 1901–2020 of 1.7 mm/year. Parker and Ollier (2016) averaged all the tide gauges included in the Permanent Service for Mean Sea Level (PSMSL), a repository for tide gauge data used in the measurement of long-term sea-level change based at the National Oceanography Centre in Liverpool, England, and found a trend of about + 1.04 mm/year for 570 tide gauges of any length. When they selected tide gauges with more than 80 years of recording, they found the average trend was only + 0.25 mm/year. They also found no evidence of acceleration in either dataset.

Parker and Ollier (2017) described six datasets they characterized as especially high quality:

- The 301 stations of the PSMSL database having a range of years greater than or equal to 60 years, "PSMSL-301."
- Mitrovica's 23 gold standard tide stations with minimal vertical land motion suggested by Douglas, "Mitrovica-23."
- Holgate's nine excellent tide gauge records of sea-level measurements, "Holgate-9."
- The 199 stations of the NOAA database (global and the USA) having a range of years greater than or equal to 60 years, "NOAA-199."
- The 71 stations of the NOAA database (USA only), having a range of years greater than or equal to 60 years, "US 71."
- The eight tide gauges of California, USA of years range larger than 60 years, "California-8."

According to Parker and Ollier (2017), "all consistently show a small sea-level rate of rise and a negligible acceleration." The average trends and accelerations for these data sets are:

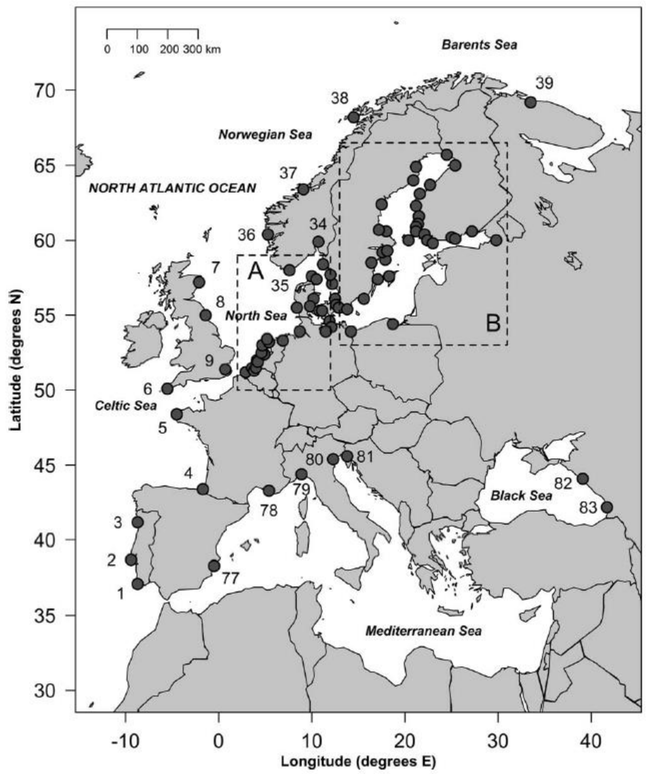
- $+ 0.86 \pm 0.49$ mm/year and $+ 0.0120 \pm 0.0460$ mm/year^2 for the PSMSL-301 dataset.
- $+ 1.61 \pm 0.21$ mm/year and $+ 0.0020 \pm 0.0173$ mm/year^2 for the Mitrovica-23 dataset.
- $+ 1.77 \pm 0.17$ mm/year and $+ 0.0029 \pm 0.0118$ mm/year^2 for the Holgate-9 dataset.
- $+ 1.00 \pm 0.46$ mm/year and $+ 0.0052 \pm 0.0414$ mm/year^2 for the NOAA-199 dataset.
- $+ 2.12 \pm 0.55$ mm/year and $- 0.0077 \pm 0.0488$ mm/year^2 for the US 71 dataset.
- $+ 1.19 \pm 0.29$ mm/year and $+ 0.0014 \pm 0.0266$ mm/year^2 for the California-8 dataset.

Bezdek (2017) notes "one region in the USA identified as being particularly susceptible to sea-level rise is the Chesapeake Bay region, and it has been estimated that by the end of the century Norfolk, Virginia could experience sea-level rise of 0.75 meters to more than 2.1 meters." The author's research revealed that water intrusion was in fact a "serious problem in much of the Chesapeake Bay region" but "due not to 'sea level rise' but primarily to land subsidence due to groundwater depletion and, to a lesser extent, subsidence from glacial isostatic adjustment. We conclude that water intrusion will thus continue even if sea levels decline." The author goes on to recommend water management policies that have been "used successfully elsewhere in the USA and other nations to solve water intrusion problems."

Wang and Zhou (2017) studied two tide gauge stations in the Pearl River Estuary on the coast of China (Macau and Hong Kong), applying a "peaks-over-threshold model of extreme value theory to statistically model and estimate secular parametric trends of extreme sea level records." Tide gauge data for Macau and Hong Kong spanned the period 1925–2010 and 1954–2014, respectively. In describing their findings, the two Chinese researchers note there are "evident decadal variations in the intensity and frequency of extremes in [the] sea level records," but "none of the parameters (intensity and frequency) of daily higher high-water height extremes in either Macau or Hong Kong has a significant increasing or decreasing trend." Similar results were obtained upon examination of trends of extremes in tidal residuals, where Wang and Zhou again report "none of the parameters presents a significant trend in recent decades."

Watson (2017) notes "some 28 of the 30 longest records in the Permanent Service for Mean Sea Level (PSMSL) global data holdings are European, extending as far back as 1807 (Brest, France). Such records provide the world's best time series data with which to examine how kinematic properties of the trend might be changing over time." He chose 83 tide gauge records with a minimum of 80 years reporting, at the locations shown in Figure 2.3.3.1.1, and used "a recently developed analytical package titled 'msltrend' specifically designed to enhance estimates of trend, real-time velocity, and acceleration in the relative mean sea-level signal derived from long annual average ocean water level time series."

Figure 2.3.3.1.1
Location of tide gauge records in Europe with at least 80 years of reporting



Source: Watson, 2017, Figure 1, p. 24.

Even though "the msltrend package has been specifically designed to enhance substantially estimates of trend, real-time velocity, and acceleration in relative mean sea level derived from contemporary ocean water level data sets," Watson (2017) reports (with apparent surprise), "Key findings are that at the 95% confidence level, no consistent or compelling evidence (yet) exists that recent rates of rise are higher or abnormal in the context of the historical records available across Europe, nor is there any evidence that geocentric rates of rise are above the global average. It is likely a further 20 years of data will distinguish whether recent increases are evidence of the onset of climate change–induced acceleration." Watson (2017), like many other researchers, observed "the quasi 60-year oscillation identified in all oceanic basins of the world (Chambers, Merrifield, and Nerem, 2012)."

Frederikse *et al*. (2018) comment on how "different sea level reconstructions show a spread in sea level rise over the last six decades," citing among the reasons for disagreement "vertical land motion at tide-gauge locations and the sparse sampling of the spatially variable ocean." The authors create a new reconstruction of sea level from 1958 to 2014 using tide-gauge records, observations of vertical land motion, and estimates of ice-mass loss, terrestrial water storage, and barotropic atmospheric forcing and find "a trend of 1.5 ± 0.2 mm yr^{-1} over 1958–2014 (1σ), compared to 1.3 ± 0.1 mm yr^{-1} for the sum of contributors," an acceleration of 0.07 ± 0.02 mm yr^{-2}.

Ahmed *et al*. (2018) used a geographic information system (GIS) and remote sensing techniques to study land erosion (losses) and accretion (gains) for the entire coastal area of Bangladesh for the period 1985–2015. Because it is a low-lying river delta especially vulnerable to sea-level rise, concerns are often expressed that it could be a victim of global warming-induced sea-level rise (e.g., Cornwall, 2018). Ahmed *et al.* find "the rate of accretion in the study area is slightly higher than the rate of erosion. Overall land dynamics indicate a net gain of 237 km^2 (7.9 km^2 annual average) of land in the area for the whole period from 1985 to 2015." Rather than sinking beneath rising seas, Bangladesh is actually *growing into the sea.*

Contrary to the IPCC's statement that it is "very likely" sea-level rise is accelerating, Burton (2018) reports the highest quality coastal tide gauges from around the world show no evidence of acceleration since the 1920s or before, and therefore no evidence of being affected by rising atmospheric CO_2 levels. Figure 2.3.3.1.2 shows three coastal sea-level measurement records (in blue), all more than a century long, in each case juxtaposed with atmospheric CO_2 levels (in green).

The mean sea-level (MSL) trend at Honolulu, Hawaii, USA is +1.48 mm/year; at Wismar, Germany is +1.42 mm/year; and at Stockholm, Sweden is -3.75 mm/year. The first two graphs are typical sea-level trends from especially high-quality measurement records located on opposite sides of the Earth at sites that are little affected by distortions like tectonic instability, vertical land motion, and ENSO. The trends are nearly identical, and perfectly typical: only about 6 inches per century, a rate that has not increased in more than nine decades. At Stockholm, sea-level rise is negative due to regional vertical land motion. To see how typical these trends are, as well as to observe natural variability for reasons already presented, see the entire 375 tide stations for which NOAA did long-term trend analysis at http://sealevel.info/MSL_global_thumbnails5.html.

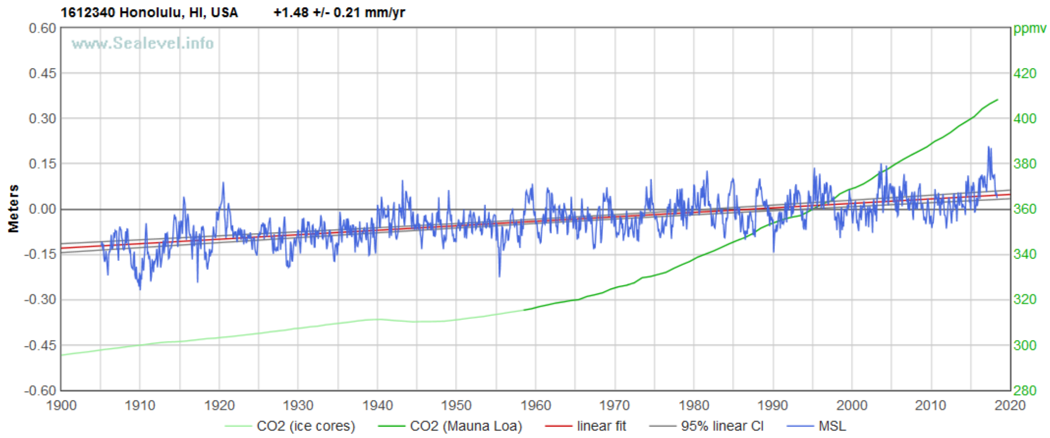
Local sea-level trends vary considerably because they depend not only on the average global trend, but also on tectonic movements of adjacent land. In many places vertical land motion, either up or down, exceeds the very slow global sea-level trend. Consequently, at some locations sea level is rising much faster than the global rate, and at other locations sea level is falling. Figure 2.3.3.1.3 shows sea level since 1930 at Grand Isle, Louisiana, USA and Skagway, Alaska, USA.

* * *

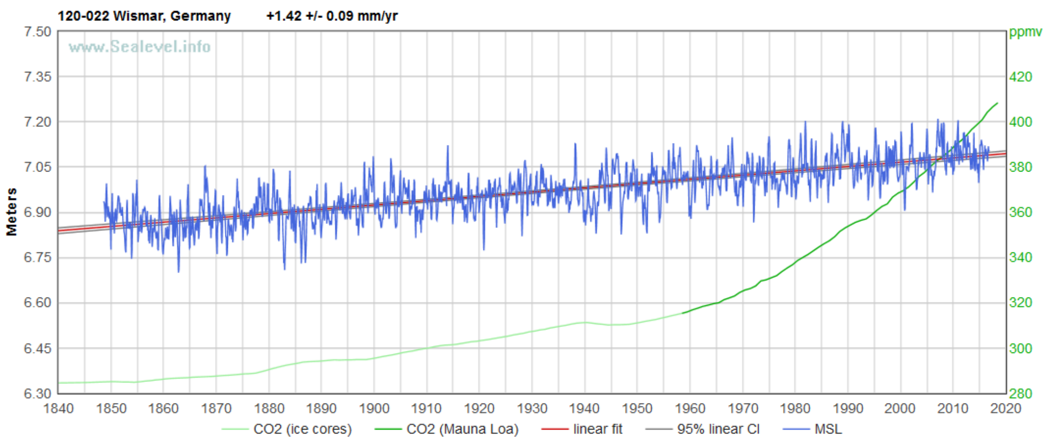
The best available data show dynamic variations in Pacific sea level in accord with El Niño-La Niña cycles, superimposed on a natural long-term rise in the volume of water in Earth's oceans (called the eustatic rise) (Australian Bureau of Meteorology, 2011; Scafetta, 2013). Though the range of natural variation has yet to be fully described, evidence is lacking for any recent changes in global sea level that lie outside natural variation.

Figure 2.3.3.1.2
Coastal measurement of sea-level rise (blue) in three cities vs. aerial CO_2 concentration (green)

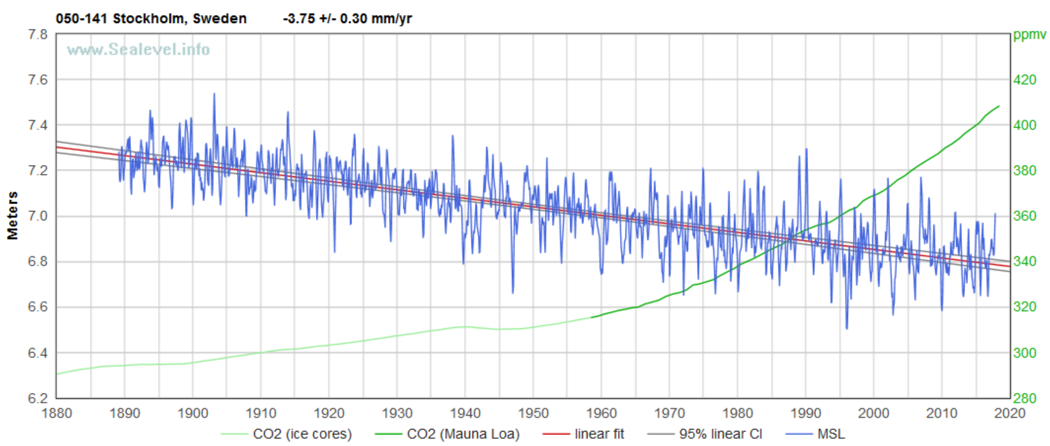
A. Honolulu, Hawaii, USA



B. Wismar, Germany



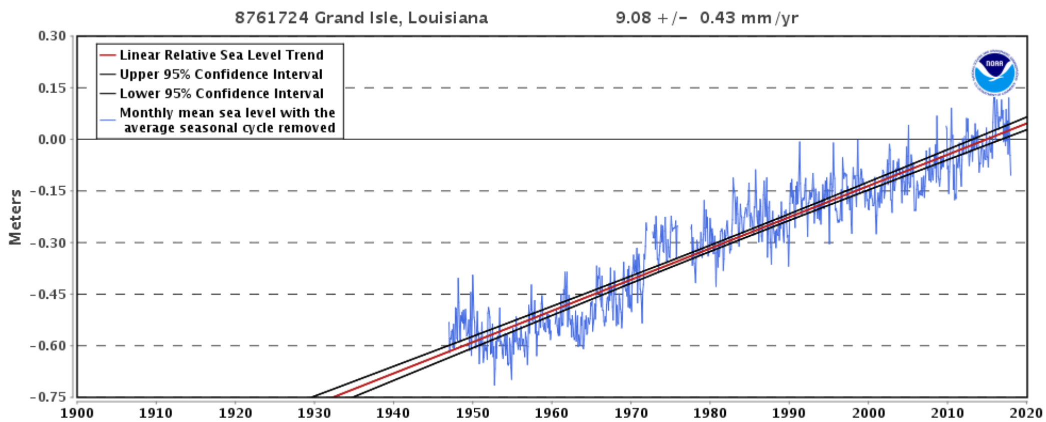
C. Stockholm, Sweden



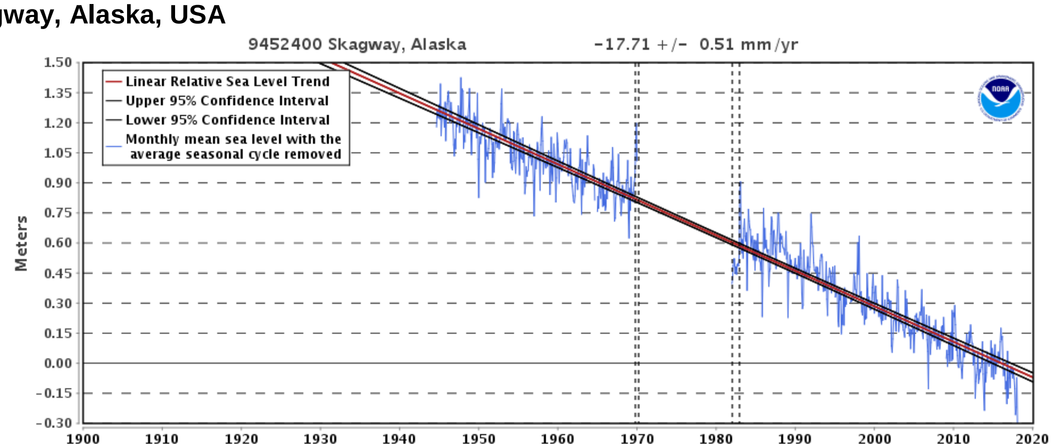
Mean sea level at Honolulu, HI, USA (NOAA 1612340, 760-031, PSMSL 155), Wismar, Germany (NOAA 120-022, PSMSL 8), and Stockholm, Sweden (NOAA 050-141, PSMSL 78). Monthly mean sea level in meters (blue, left axis) without the regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. CO_2 concentrations in ppmv (green, right axis). The long-term linear trend (red) and its 95% confidence interval (grey). The plotted values are relative to the most recent mean sea-level data established by NOAA CO-OPS. *Source:* Burton, 2018.

Figure 2.3.3.1.3
Sea level from 1930, for Grand Isle, Louisiana, USA and Skagway, Alaska, USA

A. Grand Isle, Louisiana, USA



B. Skagway, Alaska, USA



See previous figure for notes. *Source*: Burton, 2018, using NOAA data.

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2.3.3.2 Islands and Coral Atolls

Small islands and Pacific coral atolls (an island made of coral that encircles a lagoon partially or completely) are thought to be particularly at risk of harm from sea-level rise due to their low elevation and fragile shorelines. Since global sea levels have risen slowly but steadily since 1900, and that rise is alleged to have accelerated since 1990, its negative effects should be visible as a loss of surface area, but repeated studies have found this is not the case.

Island researchers generally have found that atoll shorelines are most affected by direct weather and infrequent high tide events due to El Niño-Southern Oscillation events and the impacts of increasing human populations. Pacific island ecologies are very resilient to hurricanes and floods since they happen so frequently, and plants and animals have learned to adapt and recover (Smithers and Hoeke, 2014; Mann and Westphal, 2016). Most flooding results not from sea-level rise, but from spring tides or storm surges in combination with development pressures such as borrow pit digging (a hole where soil, gravel, or sand has been dug for use at another location) or groundwater withdrawal. Persons emigrating from the islands generally do so for social and economic reasons rather than in response to environmental threats.

Biribo and Woodroffe (2013) write, "low-lying reef islands on atolls appear to be threatened by impacts of observed and anticipated sea-level rise," noting that "widespread flooding in the interior of Fongafale on Funafuti Atoll, in Tuvalu, is often cited as confirmation that 'islands are sinking' (Patel, 2006)." To see if this was true, the two scientists examined changes in shoreline position on most of the reef islands on Tarawa Atoll, the capital of the Republic of Kiribati, by analyzing "reef-island area and shoreline change over 30 years determined by comparing 1968 and 1998 aerial photography using geographical information systems."

Biribo and Woodroffe (2013) determined that the reef islands of Tarawa Atoll "substantially increased in size, gaining about 450 ha, driven largely by reclamations on urban South Tarawa, accounting for 360 ha (~80% of the net change)." Of the 40 islands of North Tarawa, where population is absent or sparse, they report that "25 of the reef islands in this area showed no change at the level of detection, 13 showed net accretion and only two displayed net erosion." In addition, they indicate that "similar reports of reef island area increase have been observed on urban Majuro, in the Marshall Islands, again mainly related to human activity," citing Ford (2012). And they say "a recent analysis of changes in area of 27 reef islands from several Pacific atolls for periods of 35 or 61 years concluded that they were growing (Webb and Kench, 2010)," likely "as a result of more prolific coral growth and enhanced sediment transport on reef flats when the sea is higher," under which conditions they note that "shorelines will actually experience accretion, thus increasing reef island size (Kinsey and Hopley, 1991)."

Introducing their study, Kench *et al.* (2015) write, "low-lying coral reef islands are coherent accumulations of sand and gravel deposited on coral reef surfaces that provide the only habitable land in atoll nations such as Kiribati, Tuvalu, and the Marshall Islands in the Pacific Ocean, and the Maldives in the Indian Ocean." And they write that in extreme cases, "rising sea level is expected to erode island coastlines," forcing "remobilization of sediment reservoirs and promoting island destabilization," thereby making them "unable to support human habitation and rendering their populations among the first environmental refugees," citing Khan *et al.* (2002) and Dickinson (2009). But will this ever really happen?

One phenomenon that suggests it could occur is the high rate of sea-level rise ($5.1 \pm 0.7 mm/yr^{-1}$) and the consequent changes in shoreline position that have occurred over the past 118 years at 29 islands of Funafuti Atoll in the tropical Pacific Ocean. However, Kench *et al.* (2015) write, "despite the magnitude of this rise, no islands have been lost," noting, in fact, that "the majority have enlarged, and there has been a 7.3% increase in net island area over the past century (AD 1897–2013)." They add "there is no evidence of heightened erosion over the past half-century as sea-level rise accelerated," noting that "reef islands in Funafuti continually adjust their size, shape, and position in response to variations in boundary conditions, including storms, sediment supply, as well as sea level." The scientists conclude that "islands can persist on reefs under rates of sea-level rise on the order of 5 mm/year," which is a far greater rate-of-rise than what has been observed over the past half-century of significant atmospheric CO_2 enrichment.

Ford and Kench (2015) used historic aerial photographs and recent high-resolution satellite imagery to determine "shoreline changes on six atolls and two mid-ocean reef islands in the Republic of the Marshall Islands." This work revealed, "since the middle of the 20th century more shoreline has accreted than eroded, with 17.23% showing erosion, compared to 39.74% accretion and 43.03% showing no change." Consequently, they determine "the net result of these changes was the growth of the islands examined from 9.09 km^2 to 9.46 km^2 between World War Two (WWII) and 2010." In light of these findings, Ford and Kench conclude that "governments of small island nations need to acknowledge that island shorelines are highly dynamic and islands have persisted and in many cases grown in tandem with sea level rise."

Purkis *et al.* (2016) observed that "being low and flat, atoll islands are often used as case studies against which to gauge the likely impacts of future sea-level rise on coastline stability." The authors examined remotely sensed images from Diego Garcia, an atoll island situated in the remote equatorial Indian Ocean, to determine how its shoreline has changed over the past five decades (1963–2013), during which time sea level in the region has been rising more than 5 mm per year, over at least the last 30 years, based on data they obtained from the National Oceanographic Data Center. According to the four scientists, "the amount of erosion on Diego Garcia over the last 50 years is almost exactly balanced by the amount of accretion, suggesting the island to be in a state of equilibrium." Commenting on the significance of this finding, Purkis *et al.* write their study "constitutes one of the few that have documented island shoreline dynamics at timescales relevant to inform projections of future change."

Testut *et al*. (2016) acquired baseline data on both absolute and relative sea-level variations and shoreline changes in the Scattered Islands region of the Indian Ocean, based on aerial image analysis, satellite altimetry, field observations, and *in situ* measurements derived from the 2009 and 2011 Terres Australes et Antarctiques Francaises scientific expeditions. They discovered "Grande Glorieuse Island has increased in area by 7.5 ha between 1989 and 2003, predominantly as a result of shoreline accretion," which "occurred over 47% of shoreline length." They also note "topographic transects and field observations show that the accretion is due to sediment transfer from the reef outer slopes to the reef flat and then to the beach."

Duvat *et al.* (2017) studied shoreline change in atoll reef islands of the Tuamotu Archipelago in French Polynesia by examining aerial photographs and satellite images of 111 atoll reef islands from the area taken over the past 50 years. According to the researchers, their findings bring "new irrefutable evidences on the persistence of reef islands over the last decades." Over the past three to five decades, the total net land area of the studied atolls "was found to be stable, with 77% of the sample islands maintaining their area, while 15% expanded and 8% contracted." Furthermore, they note that seven out of the eight islands that decreased in area were very small in area (less than 3 hectares), whereas "all of the 16 islands larger than 50 hectares were stable in area."

McAneney *et al*. (2017) created a 122-year record of major flooding depths at the Rarawai Sugar Mill on the Ba River in the northwest of the Fijian Island of Viti Levu. "Reconstructed largely from archived correspondence of the Colonial Sugar Refining Company, the time series comprises simple measurements of height above the Mill floor." The authors report their findings as follows: "It exhibits no statistically significant trends in either frequency or flood heights, once the latter have been adjusted for average relative sea-level rise. This is despite persistent warming of air temperatures as characterized in other studies. There is a strong dependence of frequency (but not magnitude) upon El Niño-Southern Oscillation (ENSO) phase, with many more floods in La Niña phases. The analysis of this long-term data series illustrates the difficulty of detecting a global climate change signal from hazard data…."

Summarizing her own review of the scientific literature on sea-level rise, Curry (2018) writes, "Tide gauges show that sea levels began to rise during the 19th century, after several centuries associated with cooling and sea level decline. Tide gauges also show that rates of global mean sea level rise between 1920 and 1950 were comparable to recent rates. Recent research has concluded that there is no consistent or compelling evidence that recent rates of sea level rise are abnormal in the context of the historical records back to the 19th century that are available across Europe."

Kench *et al*. (2018) recount the "dispiriting and forlorn consensus" that rising sea levels will inundate atoll islands and argue there is "a more nuanced set of options to be explored to support adaptation in atoll states. Existing paradigms are based on flawed assumptions that islands are static landforms, which will simply drown as the sea level rises. There is growing evidence that islands are geologically dynamic features that will adjust to changing sea level and climatic conditions," citing Webb and Kench (2010), Ford (2013), McLean and Kench (2015), and Duvat and Pillet (2017). The authors test the theory that rising sea levels were inundating atoll islands by analyzing "shoreline change in all 101 islands in the Pacific atoll nation of Tuvalu." "Surprisingly," they write, "we show that all islands have changed and that the dominant mode of change has been island expansion, which has increased the land area of the nation." The nation saw a net increase in land area of 73.5 ha (2.9%) despite sea-level rise. While 74% of the islands gained land area, 27% decreased in size. "Expansion of islands on reef surfaces indicates a net addition of sediment," the researchers write. "Implications of increased sediment volumes are profound as they suggest positive sediment generation balances for these islands and maintenance of an active linkage between the reef sediment production regime and transfer to islands, which is critical for ongoing physical resilience of islands."

Finally, Kench *et al.* (2018) report "direct anthropogenic transformation of islands through reclamation or associated coastal protection works/development has been shown to be a dominant control on island change in other atoll nations. However, in Tuvalu direct physical interventions that modify coastal processes are small in scale because of much lower population densities. Only 11 of the study islands have permanent habitation and, of these, only two islands sustain populations greater than 600. Notably, there have been no large-scale reclamations on Tuvaluan islands within the analysis window of this study (the past four decades)." These results, Kench *et al.* write, "challenge perceptions of island loss, showing islands are dynamic features that will persist as sites for habitation over the next century, presenting alternate opportunities for adaptation that embrace the heterogeneity of island types and their dynamics."

* * *

Small islands and Pacific coral atolls are not being inundated by rising seas due to anthropogenic climate change. Direct evidence reveals many islands and atolls are increasing, not decreasing, in area as natural process lead to more prolific coral growth and enhanced sediment transport on reef flats. Combined with evidence that sea levels are not rising at unusual or unprecedented rates around the world, this means the IPCC's concern over rising sea levels is without merit.

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2.3.4 Harm to Plant Life

The effects of elevated CO_2 on plant characteristics are net positive, including increasing rates of photosynthesis and biomass production.

According to the Working Group II contribution to the IPCC's Fifth Assessment Report, a "large fraction of both terrestrial and freshwater species faces increased extinction risk under projected climate change during and beyond the 21st century, especially as climate change interacts with other stressors, such as habitat modification, over-exploitation, pollution, and invasive species (*high confidence*)" (IPCC 2014, pp. 14–15). Like so many of the IPCC's other predictions, this one ignores natural variability and extensive data on plant and animal life that contradict it.

Chapter 5 addresses the impact of climate change and fossil fuels on the environment in great detail. In this section we focus narrowly on the science concerning the effects of rising levels of carbon dioxide (CO_2) on plant life. This section updates the literature review in Chapter 2 of *Climate Change Reconsidered II: Biological Impacts* (NIPCC, 2014) examining the effect of elevated CO_2 on plant characteristics. The key findings of that report are presented in Figure 2.3.4.1. There is a host of other effects of significance, including the efficiency with which plants and trees utilize water, which are addressed in Chapter 5.

Figure 2.3.4.1
Key Findings: Impacts on plant characteristics

- Atmospheric CO_2 enrichment (henceforth referred to as "rising CO_2") enhances plant growth, development, and ultimate yield (in the case of agricultural crops) by increasing the concentrations of plant hormones that stimulate cell division, cell elongation, and protein synthesis.
- Rising CO_2 enables plants to produce more and larger flowers, as well as other flower-related changes having significant implications for plant productivity and survival, almost all of which are positive.
- Rising CO_2 increases the production of glomalin, a protein created by fungi living in symbiotic association with the roots of 80% of the planet's vascular plants, where it is having a substantial positive impact on the biosphere.
- Rising CO_2 likely will affect many leaf characteristics of agricultural plants, with the majority of the changes leading to higher rates and efficiencies of photosynthesis and growth as well as increased resistance to herbivory and pathogen attack.
- Rising CO_2 stimulates photosynthesis in nearly all plants, enabling them to produce more nonstructural carbohydrates that can be used to create important carbon-based secondary compounds, one of which is lignin.

- Rising CO_2 leads to enhanced plant fitness, flower pollination, and nectar production, leading to increases in fruit, grain, and vegetable yields of agricultural crops as well as productivity increases in natural vegetation.

- As rising CO_2 causes many plants to increase biomass, the larger plants likely will develop more extensive root systems enabling them to extract greater amounts of mineral nutrients from the soil.

- Rising CO_2 causes plants to sequentially reduce the openness of their stomata, thus restricting unnecessary water loss via excessive transpiration, while some plants also reduce the density (number per area) of stomates on their leaves.

- Rising CO_2 significantly enhances the condensed tannin concentrations of most trees and grasses, providing them with stronger defenses against various herbivores both above and below ground. This in turn reduces the amount of methane, a potent greenhouse gas, released to the atmosphere by ruminants browsing on tree leaves and grass.

- As the atmosphere's CO_2 content rises, many plant species may not experience photosynthetic acclimation even under conditions of low soil nitrogen. In the event that a plant cannot balance its carbohydrate sources and sinks, CO_2-induced acclimation provides a way of achieving that balance by shifting resources away from the site of photosynthesis to enhance sink development or other important plant processes.

Source: Chapter 2. "Plant Characteristics," *Climate Change Reconsidered II: Biological Impacts.* Nongovernmental International Panel on Climate Change. Chicago, IL: The Heartland Institute, 2014.

Introduction

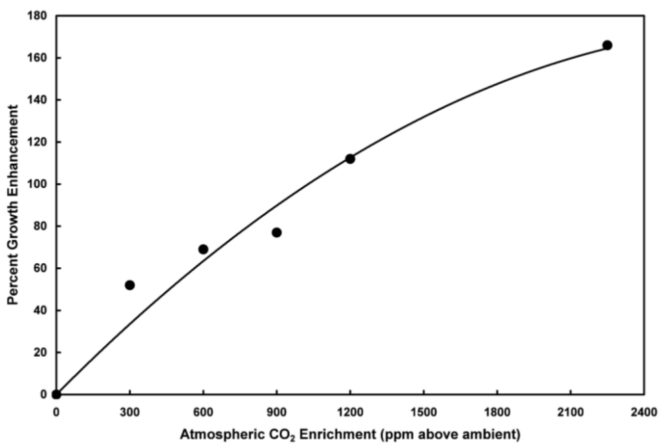
"It should be considered good fortune that we are living in a world of gradually increasing levels of atmospheric carbon dioxide" writes Wittwer (1995). He adds, "the rising level of atmospheric CO_2 is a universally free premium, gaining in magnitude with time, on which we can all reckon for the foreseeable future." Similarly, Benyus (2002) writes, "Organisms don't think of CO_2 as a poison. Plants and organisms that make shells, coral, think of it as a building block."

The geological history briefly recounted in Section 2.1.2.3 shows life flourished when atmospheric CO_2 concentrations were at double and triple their current levels. Section 2.3.1.3 showed how the frequency and intensity of drought has not increased in the modern era. Instead, the Earth has experienced a significant "greening" observed by satellites during the past 30 years, with approximately 20% of Earth's surface becoming greener, including 36% of Africa, while only 3% of Earth has browned (Myneni, 2015; see also Bastos *et al.*, 2017; Brandt, 2017; Zeng *et al.*, 2018). As atmospheric CO_2 concentrations increase, so does plant growth.

The positive relationship between atmospheric CO_2 concentrations and plant growth is well known by botanists, biologists, and agronomists. Kimball (1983a, 1983b), for example, conducted two of the earliest analyses of the peer-reviewed scientific literature dealing with plant responses to atmospheric CO_2 enrichment. From 770 individual plant responses, he determined that a 300 parts per million (ppm) rise in the air's CO_2 content boosted the productivity of most herbaceous plants by approximately 33%. Other reviews conducted soon afterwards by Cure and Acock (1986), Mortensen (1987), and Lawlor and Mitchell (1991) produced similar results. On the basis of research such as this, commercial greenhouses use CO_2 generators to elevate the level of CO_2 in their facilities to 800 to 1,200 ppm (e.g., Ontario.ca, 2009). Recall that the ambient concentration of CO_2 in 2018 was about 405 ppm and the pre-industrial level is thought to have been about 280 ppm. An increase of 300 ppm is therefore an approximate doubling of the pre-industrial level.

Perhaps the largest such review was that of Idso (1992), who analyzed papers published over the decade subsequent to the reviews of Kimball. This comprehensive assessment of the pertinent literature incorporated a total of 1,087 observations of plant responses to atmospheric CO_2 enrichment obtained from 342 peer-reviewed scientific journal articles. Idso determined that 93% of the plant responses to atmospheric CO_2 enrichment were positive, 5% were negligible, and only 2% were negative. The mean growth response curve of the plants investigated in these studies is depicted in Figure 2.3.4.2. The database of experiments was published in a peer-reviewed journal in 1994 (Idso and Idso, 1994) and has been maintained and continuously updated by the Center for the Study of Carbon Dioxide and Global Change (Idso, 2018). See Idso (2012, 2013) for more recent surveys of the literature, and appendices to *Climate Change Reconsidered II: Biological Impacts* (NIPCC, 2014, pp. 1,045–62).

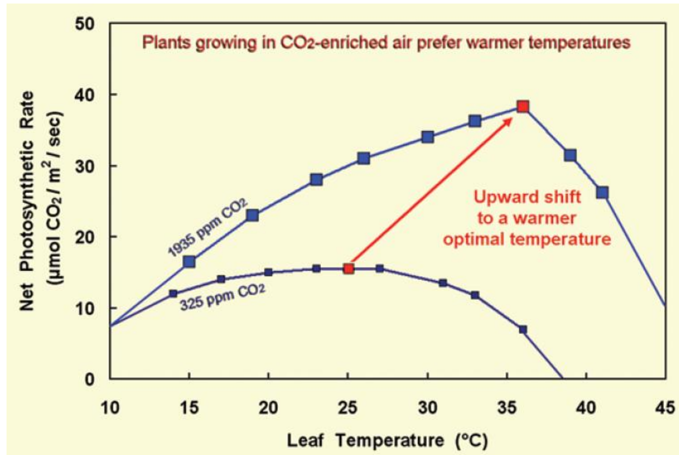
Figure 2.3.4.2
Positive impact of CO_2 on plants and trees



Source: NIPCC, 2014, p. 1, Figure 1, citing Idso, 1992.

Additional research shows the positive effects of this "aerial fertilization" are even greater when combined with rising temperatures, the mechanisms by which are explained later in this section. Figure 2.3.4.3 shows how the net photosynthetic rate for one type of tree (bigtooth aspen) exposed to elevated CO_2 increases as temperature rises, and how higher CO_2 levels enable the tree to produce glucose at temperatures considerably higher than it would otherwise tolerate. Many other plants show a similar response.

Figure 2.3.4.3
Positive impact of CO_2 is enhanced by warmer temperatures



Relationship of leaf temperature and CO_2 exchange rate, a proxy for net photosynthetic rate, for two levels of exposure to CO_2, 1,935 ppm (large boxes) and 325 ppm (small boxes), for bigtooth aspen (*Populus grandidentata*). *Source:* Adapted from Jurik *et al.,* 1984, Figure 1, p. 1023.

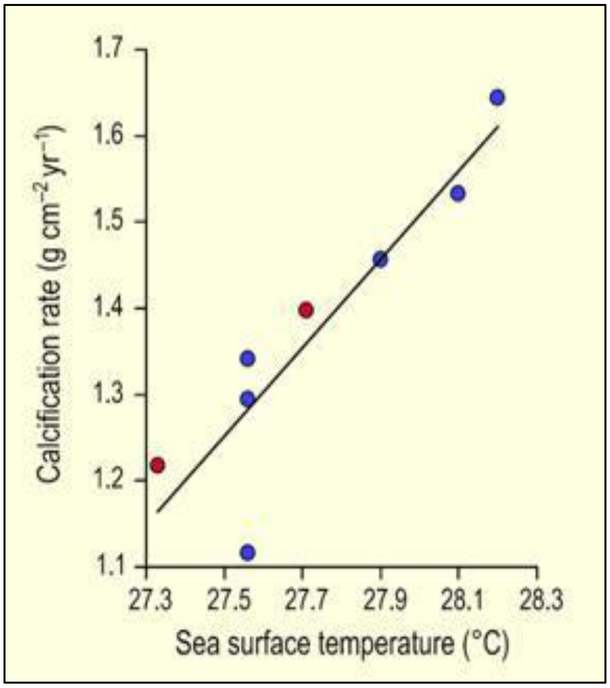
Warmer water temperatures similarly benefit some (but not all) kinds of sea life. Figure 2.3.4.4 shows how calcification rates for *Montastraea annularis*, a species of coral, rise with seawater temperatures. This species is the most abundant species of reef-building coral in the Caribbean.

Literature Review

Chapter 5 surveys literature on the impacts of rising temperatures and atmospheric CO_2 levels on ecosystems, plants under stress, water use efficiency, and the future impacts of climate change on plants. Here we focus on the more narrow topic of plant responses to atmospheric CO_2 enrichment.

Weiss *et al*. (2010) grew rooted shoot cuttings of the cacti *Hylocereus undatus* (red pitaya) and *Selenicereus megalanthus* (yellow pitaya) for one full year (August 2006 to August 2007) in vented chambers maintained at either ambient or elevated atmospheric CO_2 concentrations (380 or 1,000 ppm, respectively) in a cooled greenhouse, where the plants were fertilized twice weekly. The researchers

Figure 2.3.4.4
Positive impact of warmer temperatures on reef-building coral in the Caribbean



Yearly mean calcification rate of *Montastraea annularis* vs. mean annual sea surface temperature for the several sites studied by Carricart-Ganivet (2004) (blue circles) and two sites studied by Carricart-Ganivet and Gonzalez-Diaz (2009) (red circles). The line that has been fit to the data is described by: Calcification Rate = 0.51 SST - 12.85 ($r^2 = 0.82$, $p < 0.002$). Adapted from Carricart-Ganivet and Gonzalez-Diaz, 2009.

measured net photosynthesis on four days in mid-April and made final biomass determinations at the conclusion of the study. In addition, they conducted a second one-year study of eight-year-old plants to investigate the fruit development responses of mature plants to atmospheric CO_2 enrichment; this work was done in open-top chambers maintained in the same greenhouse.

Weiss *et al*. (2010) report, "*H. undatus* plants enriched with CO_2 demonstrated 52%, 22%, 18% and 175% increases, relative to plants measured in ambient CO_2, in total daily net CO_2 uptake, shoot elongation, shoot dry mass, and number of reproductive buds, respectively," while corresponding responses for *S. megalanthus* were 129%, 73%, 68%, and 233%. They also found a slight (7%) increase in the fruit fresh mass of *H. undatus* and a much greater 63% increase in the fruit fresh mass of *S. megalanthus* due to the CO_2 enrichment. They conclude their experiments demonstrate "the vast potential of possible increases in the yields of CAM [crassulacean acid metabolism] crops under CO_2 enrichment."

Jiang *et al*. (2012) studied the relationship between CO_2 enrichment and brassinosteroids (BRs), "naturally occurring plant steroid hormones that are ubiquitously distributed in the plant kingdom." They report "BRs play prominent roles in various physiological processes including the induction of a broad spectrum of cellular responses, such as stem elongation, pollen tube growth, xylem differentiation, leaf epinasty, root inhibition, induction of ethylene biosynthesis, proton pump activation, regulation of gene expression and photosynthesis, and adaptive responses to environmental stress." They also note, "as potent plant growth regulators, BRs are now widely used to enhance plant growth and yield of important agricultural crops."

Working with well-watered and fertilized cucumber plants that had reached the three-leaf growth stage in pots within controlled environment growth chambers maintained at either ambient (380 ppm) or enriched (760 ppm) atmospheric CO_2 concentrations and with or without being sprayed with a solution of brassinosteroids (0.1 µM 24-epibrassinolide), Jiang *et al*. (2012) measured rates of net photosynthesis, leaf area development, and shoot biomass production over a period of one additional week. They determined that their doubling of the air's CO_2 concentration resulted in a 44.1% increase in CO_2 assimilation rate and the BR treatment "also significantly increased CO_2 assimilation under ambient atmospheric CO_2 conditions and the increase was close to that by CO_2 enrichment."

Jiang *et al*. (2012) report the combined treatment of "plants with BR application under CO_2-enriched conditions showed the highest CO_2 assimilation rate, which was increased by 77.2% relative to the control." Likewise, "an elevation in the atmospheric CO_2 level from 380 to 760 ppm resulted in a 20.5% and 16.0% increase in leaf area and shoot biomass accumulation, respectively," while the plants that received the BR application "exhibited 22.6% and 20.6% increases in leaf area and shoot biomass accumulation, respectively." The combined treatment of "CO_2 enrichment and BR application further improved the plant growth, resulting in 49.0% and 40.2% increases in leaf area and shoot biomass, relative to that of the control, respectively."

Goufo *et al*. (2014) note crop plants need *phenolic compounds* "for structural support, constitutive and induced protection and defense against weeds, pathogens and insects." They point out carbon dioxide is one of the four major raw materials plants need to produce phenolic compounds, the other three being water, nutrients, and light. They conducted a two-year field study of a japonica rice variety (*Oryza sativa* L. cv. Ariete), employing open-top chambers maintained at either 375 or 550 ppm CO_2 over two entire life cycles of the crop, during which time numerous plant samples were collected at five growth stages and assessed for many plant-produced substances, including phenolics. They found all plant organs had higher levels of phenolic acids and flavonoids in response to "CO_2 enrichment during the maturity stages."

Goufo *et al*. (2014) explain "phenolic compounds are emerging as important defense compounds in rice," particularly noting the phenolic compound tricin "inhibits the growth of *Echinochloa colonum*, *Echinochloa crusgalli*, *Cyperus iris* and *Cyperus difformis*," which they say "are the most noxious weeds in rice fields." They add that several flavonoids "have also been found to exhibit antibiotic activities against the soil-borne pathogenic fungi *Rhizoctonia solani* and *Fusarium oxysporum*," which they say are "the causal agents of rice seedling rot disease." They suggest the ongoing rise in the atmosphere's CO_2 concentration may "increase plant resistance to specific weeds, pests and pathogens."

Zhang *et al*. (2017) grew cotton in climate-controlled growth chambers under two temperature (27/20°C (80.6/68°F) or 34/27°C (93.2/80.6°F) day/night) and CO_2 (400 or 800 ppm) regimes. The plants were sampled and various parameters measured to observe the impact of elevated CO_2 and elevated temperature. At the end of the experiment (105 days after sowing), they report, elevated temperature enhanced dry matter by 43% under ambient CO_2 conditions and by 60% under elevated CO_2 conditions (Figure 2.3.4.5, left panel). Elevated CO_2 also enhanced dry matter, by 17% under ambient temperature conditions and 31% under elevated temperatures. The highest increase in dry matter content was noted in the elevated temperature and elevated CO_2 treatment, suggesting to the authors that "[CO_2] enrichment could enhance the effect of rising temperature on dry matter content."

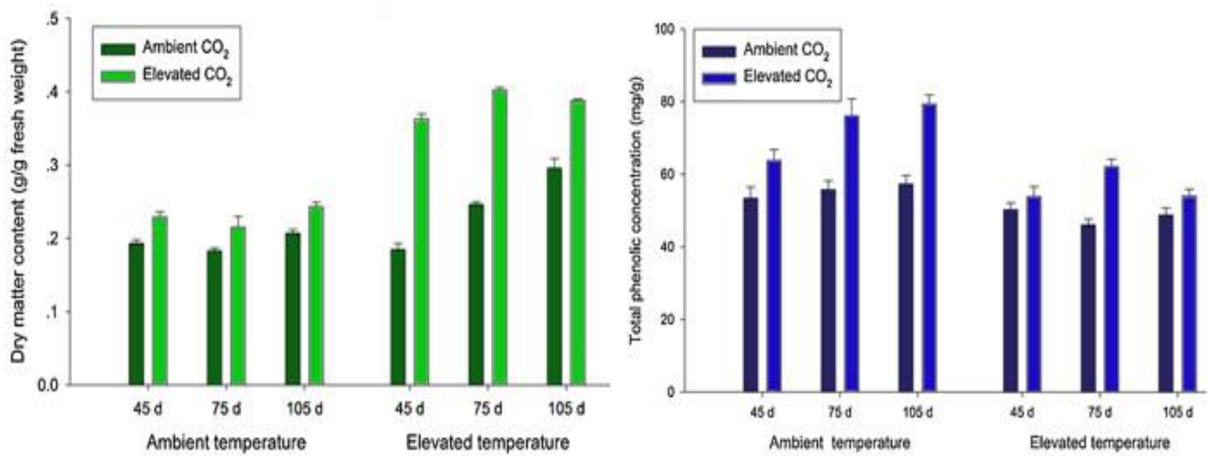
Reporting on other parameters, Zhang *et al*. (2017) note that although early measurements made at 45 days after sowing revealed calculable differences, by 75 days after sowing and on through the end of their experiment they found no significant effect of elevated CO_2 on leaf nitrogen or carbon/nitrogen (C:N) ratio at either ambient or elevated temperature. Leaf soluble sugars, total starch, and total foliar nonstructural carbohydrates, by contrast, all experienced marked increases from elevated CO_2 under ambient and elevated temperatures. Elevated CO_2 also tended to enhance total leaf phenolic concentrations, while elevated temperature tended to reduce them (Figure 2.3.4.5, right panel).

Sgherri *et al*. (2017) write, lettuce is "an important source of phytochemicals such as phenolic compounds," which compounds (including antioxidants), "have been recognized as phytonutrients able to lower the incidence of some types of cancer and cardiovascular diseases (Hooper and Cassidy, 2006)." Noting plant phytochemical composition and antioxidant activity can be altered by environmental factors, such as rising atmospheric CO_2 and salinity stress, they investigated the effects of elevated CO_2 and salinity stress on the phytochemical composition of two lettuce cultivars, Blonde of Paris Batavia (a green leaf cultivar) and Oak Leaf (a red leaf cultivar).

Sgherri *et al*. (2017) grew the two lettuce cultivars under both ambient (400 ppm) and elevated (700 ppm) CO_2 for 35 days after sowing. They then subjected a portion of plants in each CO_2 treatment to salt stress by adding Hoagland solution supplemented with 200 millimeters sodium chloride (NaCl) each day until harvest. Upon harvest, they took measurements to ascertain plant growth and phytonutrient differences. Under ambient CO_2 growth conditions, Sgherri *et al*. report salinity stress caused yield reductions of 5% and 10% in the green and red lettuce cultivars, respectively. Under normal salt conditions, elevated CO_2 stimulated yields, inducing gains of 29% and 38% in the green and red cultivars, respectively. In the combined treatment of elevated CO_2 and salinity stress, the positive impacts of elevated CO_2 ameliorated the negative impacts of salt stress. With respect to phytochemicals, as shown in Figure 2.3.4.6, both salt stress and elevated CO_2 increased plant antioxidant capacity, total phenols, and total flavonoids. Sgherri *et al*. conclude, "the application of moderate salinity or elevated CO_2, alone or in combination, can induce the production of some phenolics that increase the health benefits of lettuce."

Figure 2.3.4.5
Impact of elevated CO_2 and temperature on cotton plants

A. Dry matter content (g/g of fresh weight) **B. Total phenolic concentration (mg/g)**

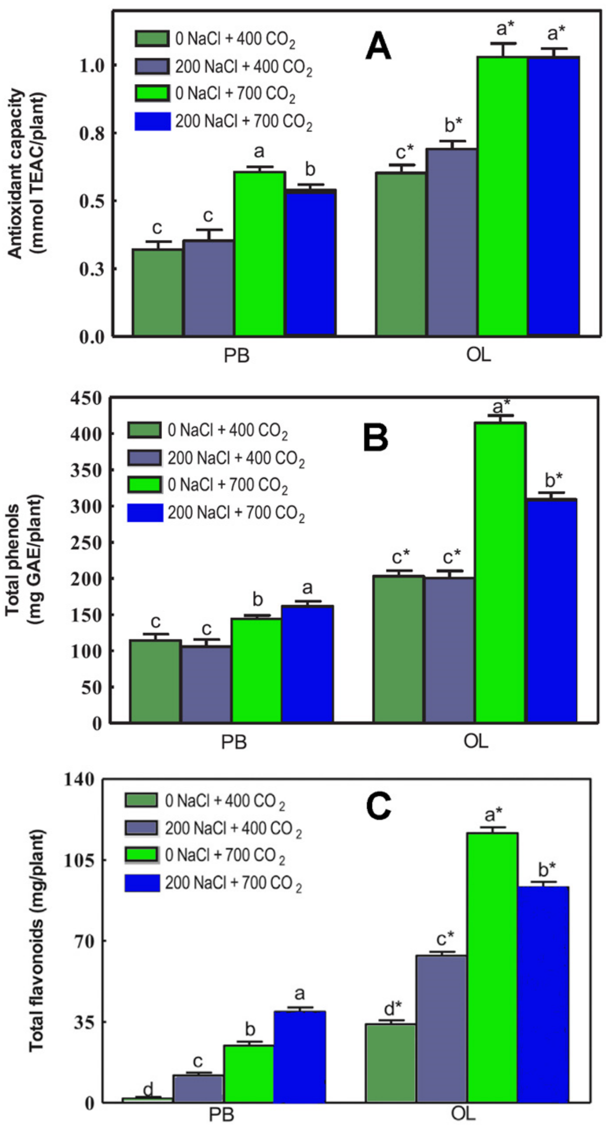


Ambient temperature is 27/20°C (80.6/68°F) day/night and elevated temperature is 34/27°C (93.2/80.6°F) day/night. Ambient CO_2 concentration is 400 ppm and elevated is 800 ppm. *Source*: Zhang *et al*., 2017.

Li *et al.* (2017) observe that more frequent droughts are among the predicted effects of future climate change. While the beneficial effects of elevated levels of CO_2 on winter wheat (*Triticum aestivum L.*) plants exposed to drought conditions for a single generation are well documented, "the transgenerational effect of e[CO_2] [elevated CO_2] in combination of drought on stomatal behavior, plant water consumption and water use efficiency (WUE) have not been investigated." The researchers harvested seeds from plants after two generations (2014–2015) continuously grown in ambient CO_2 (a[CO_2], 400 μmol l^{-1}) and e[CO_2] (800 μmol l^{-1}) and sowed them in four- liter pots, and the plants were grown separately in greenhouse cells with either a[CO_2] or e[CO_2]. At stem elongation stage, in each of the cells half of the plants were subjected to progressive drought stress until all the plant available soil water was depleted, and the other half were well-watered and served as controls. "The results," the researchers report, "showed that transgenerational exposure of the winter wheat plants to e[CO_2] could attenuate the negative impact of drought stress on dry biomass (DM) and WUE. The modulations of multi-generational e[CO2] on leaf abscisic acid concentration, stomatal conductance, and leaf water status could have contributed to the enhanced DM and WUE. These findings provide new insights into the response of wheat plants to a future drier and CO_2-enriched environment."

Nakano *et al.* (2017) studied the possible impact of future higher levels of CO_2 in the atmosphere on rice (*Oryza sativa* L.) grain yield. They grew "a chromosome segment substitution line (CSSL) and a near-isogenic line (NIL) producing high spikelet numbers per panicle (CSSL-*GN1* and NIL-*APO1*, respectively) under free-air CO_2 enrichment (FACE) conditions and examined the effects of a large sink capacity on grain yield, its components, and growth-related traits under increased atmospheric CO_2 concentrations." They found that under ambient conditions, CSSL-*GN1* and NIL-*APO1* exhibited a similar grain yield to Koshihikari rice, but under FACE conditions, CSSL-*GN1* and NIL-*APO1* had an equal or higher grain yield than Koshihikari because of the higher number of spikelets and lower reduction in grain filling. "Thus," they conclude, "the improvement of source activity by increased atmospheric CO_2 concentrations can lead to enhanced grain yield in rice lines that have a large sink capacity. Therefore, introducing alleles that increase sink capacity into conventional varieties represents a strategy that can be used to develop high-yielding varieties under increased atmospheric CO_2 concentra-

Figure 2.3.4.6
Two lettuce cultivars subjected to salt treatment under ambient or elevated CO_2



Panel (A) reports change in antioxidant capacity, (B) change in total phenols, and (C) change in total flavonides in Blonde of Paris green-leaf (PB) and Oak Leaf red-leaf (OL). TEAC is trolox equivalent antioxidant capacity; GAE is gallic acid equivalent. Dark green is control plot (no additional sodium chloride (NaCl) and ambient CO_2 (400 ppm)), purple is 200 mm of NaCl added every day at ambient CO_2, bright green is no NaCl and 700 ppm CO_2 and blue is 200 NaCl and 700 CO_2. *Source:* Adapted from Sgherri *et al.*, 2017.

tions, such as those predicted in the near future."

Pau *et al.* (2018) analyzed "a 28-year record of tropical flower phenology in response to anthropogenic climate and atmospheric change." They found "compared to significant climatic factors, CO_2 had on average an approximately three-, four-, or fivefold stronger effect than rainfall, solar radiation, and the Multivariate ENSO Index, respectively." That effect is invariably positive, resulting in increased flowering of mid-story trees and shrub species and a lengthening of flowering duration for canopy and mid-story trees. The authors conclude, "Given that atmospheric CO_2 will likely continue to climb over the next century, a long-term increase in flowering activity may persist in some growth forms until checked by nutrient limitation or by climate change through rising temperatures, increasing drought frequency and/or increasing cloudiness and reduced insolation."

* * *

In conclusion, the effects of elevated CO_2 on plant characteristics are net positive, including increasing rates of photosynthesis and production of biomass and phenolics. Thousands of laboratory and field experiments reveal why plants benefit from higher CO_2 levels and higher temperatures. By focusing narrowly on the effects of elevated CO_2 on plants, this section provides the scientific basis for discussions in Chapters 5, 7, and 8 on the impacts on ecosystems, agriculture, and human well-being.

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2.4 Why Scientists Disagree

Previous sections in this chapter revealed considerable disagreement among scientists on basic matters of climatology, including how to reduce and report uncertainty, natural versus anthropogenic impacts on the planet's energy budget and carbon cycle, and whether temperature reconstructions and computer models are reliable tools for scientific research. *Why do scientists disagree on so many matters?*

It should be said at the outset that disagreement is not uncommon in science. Today's "truth" is not the same as yesterday's "truth" or tomorrow's "truth," because truth, like science, is never settled. The Scientific Method assures that every theory can be challenged by experiment and a better understanding of complex physical processes that are currently poorly understood or unknown. Still, disagreements over matters of science regarding climate seem particularly stubborn and involve matters fundamental to our understanding of climate, not only on the "frontiers" or periphery of scientific research. This section offers four explanations for why this is the case:

- Fundamental uncertainties arise from insufficient observational evidence and disagreements over how to interpret data and set the parameters of models.

- Climate is an interdisciplinary subject requiring insights from many fields. Very few scholars have mastery of more than one or two of these disciplines.

- Many scientists trust the United Nations' Intergovernmental Panel on Climate Change (IPCC) to objectively report the latest scientific findings on climate change, but it has failed to produce balanced reports and has allowed its findings to be misreported to the public.

- Climate scientists, like all humans, can have tunnel vision. Bias, even or especially if subconscious, can be especially pernicious when data are equivocal and allow multiple interpretations, as in climatology.

2.4.1 Scientific Uncertainties

Fundamental uncertainties and disagreements prevent science from determining whether human greenhouse gas emissions are having effects on Earth's atmosphere that could endanger life on the planet.

The first and most obvious reason why scientists disagree is because the human impact on climate remains a puzzle. Essex and McKitrick (2007) write, "Climate is one of the most challenging open problems in modern science. Some knowledgeable scientists believe that the climate problem can never be solved." Bony *et al.* (2015) write, "Fundamental puzzles of climate science remain unsolved because of our limited understanding of how clouds, circulation and climate interact." Reporting in *Nature* on Bony's 2015 study, Schiermeier (2015) wrote, "There is a misconception that the major challenges in physical climate science are settled. 'That's absolutely not true,' says Sandrine Bony, a climate researcher at the Laboratory of Dynamic Meteorology in Paris. 'In fact, essential physical aspects of climate change are poorly understood'" (p. 140). See also Stevens and Bony (2013); Stouffer *et al*. (2017), and Collins *et al*. (2018).

Uncertainty was the topic of an earlier section of this chapter (Section 2.1.1.3) and examples of uncertainty appear in other sections. Here is a brief summary of areas where uncertainty prevents climate scientists from attaining what the IPCC refers to as "high agreement" or even "medium agreement."

Methodological Uncertainty

Efforts to predict future climate conditions rely on complex general circulation models (GCMs) and even more complex integrated assessment models (IAMs). Such models introduce uncertainty into climate science and therefore are a source of disagreement for four reasons:

- *Parametric uncertainty* involves the proper setting of parameters and their variability in a simulation. So little is known about climate processes that parameterization for climate models is a subjective process only weakly constrained by observational data and best practices, causing wide variation in model outputs (Lupo *et al.*, 2013; Hourdin, 2017).

- *Stochastic uncertainties* arise from random events that cannot be predicted (Kelly and Kolstad, 1998). In climatology, they include abrupt economic downturns, changes in the Sun, volcanic eruptions, and wars. Any of these events could have a greater effect on climate than decades of forcing by CO_2.

- *Epistemic uncertainty* is due to what modelers do not know: the behavior of atmospheric and ocean processes; missing, erroneous, or unknowingly adjusted data; unacknowledged variabilities and uncertainties in data; and more (Roy and Oberkampf, 2011; Loehle, 2018).

- *Propagation of error* means errors or uncertainty in one variable, due perhaps to measurement limitations or confounding factors, are compounded (propagated) when that variable becomes part of a function involving other variables that are also uncertain, leading to "cascading uncertainties" or "uncertainty explosions" (Curry and Webster, 2011; Frank, 2015; Curry, 2018).

Temperature Record

Fundamental to the theory of anthropogenic climate change is an accurate reconstruction of a record of Earth's surface temperature. Yet this is probably the source of greatest uncertainty in climate science. The IPCC itself admits its temperature reconstructions are highly uncertain:

> The uncertainty in observational records encompasses instrumental/recording errors, effects of representation (e.g., exposure, observing frequency or timing), as well as effects due to physical changes in the instrumentation (such as station relocations or new satellites). All further processing steps (transmission, storage, gridding, interpolating, averaging) also have their own particular uncertainties. Because there is no unique, unambiguous, way to identify and account for non-climatic artefacts in the vast majority of records, there must be a degree of uncertainty as to how the climate system has changed (IPCC, 2013, p. 165).

McLean (2018) conducted an audit of the HadCRUT4 dataset and found "more than 70 issues of concern," including failure to check source data for errors, resulting in "obvious errors in observation station metadata and temperature data" (p. 88). He found the dataset "has been incorrectly adjusted in a way that exaggerates warming." Emails from a programmer responsible for maintaining and correcting errors in the HadCRUT climate data between 2006 and 2009 reveal inaccuracies, data manipulation, and incompetence that render the dataset unreliable (Goldstein, 2009; Montford, 2010). In 2009, in response to an academic's request for the HadCRUT dataset, Phil Jones, director of the Climatic Research Unit at the University of East Anglia, admitted, "We, therefore, do not hold the original raw data but only the value-added (i.e., quality controlled and homogenized) data" (Michaels, 2009).

Studies of the positioning of weather stations in the United States – thought to have the best network of such stations in the world – found extensive violations of siting rules leading to contamination by urban heat islands (Pielke, 2007a, 2007b). The IPCC claims to control for heat island effects but researchers have found its adjustments are too small (e.g. McKitrick and Michaels, 2007; Soon *et al.* 2015; Quereda Sala *et al.*, 2017).

The warming since 1850 is meaningful information only if it exceeds natural variability. Proxy temperature records from the Greenland ice cores for the past 10,000 years demonstrate a natural range of warming and cooling rates between +2.5°C and -2.5°C/century, significantly greater than rates measured for Greenland or the globe during the twentieth century (Alley, 2000; Carter, 2010; Lamb, 2011, 2012). The ice cores also show repeated "Dansgaard–Oeschger" events when air temperatures rose at rates of about 10°C per century. There have been about 20 such warming events in the past 80,000 years.

In its Fifth Assessment Report (AR5), the IPCC admits the global mean surface temperature stopped rising from 1997 to 2010, reporting the temperature increase for that period was 0.07°C [-0.02 to 0.18] (IPCC, 2013, p. 37). This "pause" was interrupted by the major El Niño events of 2010–2012 and 2015–2016. During "the pause" humans released approximately one-third of all the greenhouse gases emitted since the beginning of the Industrial Revolution. If atmospheric CO_2 concentrations drive global temperatures, their impact surely would have been visible during this period. Either CO_2 is a weaker driver of climate than the IPCC assumes, or natural drivers and variation play a bigger role than it realizes (Davis *et al*., 2018).

Energy Budget

Climate models wrongly assume that global temperatures, solar influences, and exchanges among global carbon reservoirs would remain unchanged decade after decade and century after century, *but for* the human presence. But the ACRIM total solar irradiance (TSI) composite shows a small upward pattern from around 1980 to 2000, an increase not acknowledged by the IPCC or incorporated into the models on which it relies (Scafetta and Willson, 2014). The absolute forcing of incoming solar radiation is approximately 340 Wm^{-2} at the top of the atmosphere, more than 10 times the forcing of all atmospheric CO_2, so even small changes in the absolute forcing of the Sun could result in values larger than the much smaller predicted changes in radiative forcing caused by human greenhouse gas emissions.

Two TSI reconstructions for the period 1900–2000 by Scafetta and West (2006) suggest the Sun contributed 46% to 49% of the 1900–2000 warming of Earth, but with uncertainties of 20% to 30% in their sensitivity parameters. Close correlations exist between TSI proxy models and many twentieth-century climate records including temperature records of the Arctic and of China, the sunshine duration record of Japan, and the Equator-to-Pole (Arctic) temperature gradient record (Soon, 2005, 2009; Ziskin and Shaviv, 2012). The solar models used by the IPCC report less variability than other reconstructions published in the scientific literature (Soon *et al.*, 2015), leading the IPCC to understate the importance of solar influences. Some solar scientists are investigating the possibility of the Sun entering a grand solar minimum (GSM), which could manifest itself within two decades (Lockwood *et al*., 2011).

Small changes in cloud cover, cloud brightness, and cloud height – all of which are known to vary spatially and over time and none of which is well modeled – could alter the planet's energy budget enough to explain the slight warming of the twentieth century (Lindzen, 2015). The role of water vapor and clouds on reflectivity and the planet's energy budget is not accurately modeled (Chou and Lindzen, 2004; Spencer *et al.*, 2007; Lindzen and Choi, 2011).

Research conducted by CERN (the European Institute for Nuclear Research) in 2016 provided experimental results supporting the theory that variations in the number of cosmic rays hitting Earth's atmosphere create more or fewer (depending on the strength of the solar magnetic wind) of the low, wet clouds that reflect solar heat back into space (Kirkby *et al*., 2016). This could be the mechanism for converting small changes in TSI into larger changes in surface temperature, a mechanism the IPCC contends is missing (Svensmark, 2007; Svensmark *et al.*, 2017). The CLOUD experiment also found pure biogenic nucleation can produce aerosols in the pristine pre-industrial atmosphere, creating clouds (Gordon *et al.*, 2016). "The results from CLOUD suggest that estimates of high climate sensitivity may have to be revised downwards" (CERN, 2016).

The role of ocean currents in determining temperature and precipitation is probably understated by climate models (D'Aleo and Easterbrook, 2016). El Niño and La Niña cycles dominate the flux of water and energy in the tropical Pacific over periods of two to seven years. These cyclical episodes have large impacts on global temperatures, rainfall, and storm patterns relative to the forcing of CO_2. Partly due to the failure to accurately model these processes, climate sensitivity to a doubling of CO_2 is probably overstated by climate models (Lewis and Curry, 2014; Bates, 2016; Christy and McNider, 2017).

Carbon Cycle

The carbon cycle is not sufficiently understood or measured with sufficient accuracy to make declarative statements about the human contribution of CO_2 to the atmosphere, how long it resides there, and how it affects exchange rates among the planet's four carbon reservoirs (lithosphere, oceans, biosphere, and atmosphere) (Falkowski *et al.* 2000; Harde, 2017a, 2017b). Empirical measurements are available for only ~20% of major volcanic gas emission sources (Burton *et al.*, 2013). CO_2 emissions from volcanoes could be "a significant previously unrecognized contribution to global CO_2 emissions from natural sources" (Ilyinskaya *et al.*, 2018; see also Viterito, 2017 and Smirnov *et al.*, 2017). More than 80% of our ocean is unmapped, unobserved, and unexplored (NOAA, 2018). Seagrass meadows in Greenland could be emerging as a major carbon sink (Marbà *et al.*, 2018). New satellite images have increased estimates of global forest cover by at least 9%, "requiring revision to the biospheric carbon sink" (Bastin *et al.*, 2017).

Anthropogenic greenhouse gas emissions are minuscule compared to the exchanges among these carbon reservoirs, meaning even small mismeasurements or uncertainty regarding natural processes could account for all the forcing attributed to anthropogenic CO_2. Human greenhouse gas emissions thought to remain in the atmosphere each year constitute just two-tenths of 1% (0.195%) of the total amount of carbon thought to be in the atmosphere (IPCC, 2014; Ruddiman, 2008). Even human greenhouse gas emissions are not measured with precision. Nearly half of global economic activity takes place in the informal market and is unlikely to be accurately accounted for (Jutting and de Laiglesia, 2009). Authoritarian regimes inflate yearly GDP growth rates by a factor between 1.15 and 1.3, meaning GCMs are relying on false data (Martinez, 2018).

Computer Model Problems

Climate models fail to accurately hindcast past temperatures and consistently "run hot," predicting warmer temperatures than are likely to occur (Monckton *et al.*, 2015; Idso and Idso, 2015; Hope *et al.*, 2017; McKitrick and Christy, 2018). Computer modelers "tune" their models until they reach a result that matches observations or the expectations of the modelers, their peers, or funders (Hourdin *et al.*, 2017). Modeling turbulence is "one of the most basic and intractable research problems facing humanity. You can't compute it. You can't measure it. But rain falls because of it" (Essex and McKitrick, 2007, p. 20). The hydrology of the atmosphere and dynamics of the ocean-atmosphere interface are poorly understood and modeled, yet even small errors in this area have major effects on models (Legates, 2014; Christy and McNider, 2017).

Lupo *et al.* (2013) cite extensive scholarly research finding climate models underestimate surface evaporation caused by increased temperature by a factor of 3; inadequately represent aerosol-induced changes in infrared radiation; are unable to capture many important regional and lesser-scale phenomena such as clouds; assume all temperature rise since the start of the Industrial Revolution has resulted from human activities when in reality, major anthropogenic emissions commenced only in the mid-twentieth century; poorly simulate internal climate oscillations such as the AMO and PDO; and fail to incorporate the effects of variations in solar magnetic field or in the flux of cosmic rays, both of which are known to significantly affect climate. Forecasts of future warming fail to consider the cooling effects of the Greening of the Earth phenomenon (Jeong *et al*., 2010).

Modelers assume a CO_2 increase causes a temperature increase and so they program that into their models. When asked how they know this happens they say the model shows it, or other models (similarly programmed) show it, or their model doesn't work *unless* CO_2 is assumed to increase temperatures. Modelers may get the benefit of the doubt from their colleagues and policymakers owing to the complexity of models and the expense of the supercomputers needed to run them. That does not make them accurate maps of a highly complex territory.

Climate Impacts

Measurement of climate impacts is severely handicapped by missing and unreliable data, smoothed and "homogenized" databases, overlooked variability, and the substitution of global and stylized facts for regional and local observational data. Uncertainty leads to widely varying claims about whether "climate change" is already happening and can be attributed to the human presence. Some examples of still unresolved issues in this area include:

- Are the number and intensity of heat waves rising and cold days falling globally as forecast by the IPCC? (Li *et al.*, 2015; Sardeshmukh *et al.*, 2015; EPA, 2016; Sun *et al.*, 2016)

- Have there been increasing trends in storms, floods, droughts, or hurricanes in the modern era? (IPCC, 2013, p. 112; Hao *et al.*, 2014, 2016; Sutton *et al.*, 2018)

- How much of rising property damage caused by extreme weather events is due to population growth and the increasing value and vulnerability of property located near river and lake shorelines, and not to anthropogenic climate change? (Pielke and Landsea, 1998; Crompton and McAneney, 2008; Pielke *et al*., 2008; Barredo, 2009, 2010; Neumayer and Barthel, 2011).

- Do the well-known benefits of aerial CO_2 fertilization and warmer temperatures more than offset the hypothetical negative effects of climate change on plant life? (Idso, 2012, 2013; Myneni, 2015; Bastos *et al*., 2017; Brandt, 2017; Zeng *et al.*, 2018)

- What impact will physical limits on the supply of fossil fuels and market forces, such as rising prices, have on future greenhouse gas emissions? (Tans, 2009; Doiron, 2016; Wang *et al*., 2017)

* * *

In short, scientists disagree because so much about the climate is still unknown. This simple truth is not publicized because uncertainty discourages action (Samieson, 1996; Shackley and Wynne, 1996), and so climate activists coach scientists to conceal it (Moser and Dilling, 2007). Kreutzer *et al.* (2016) write, “The idea that the science of climate change is ‘settled’ is an absurdity, contrary to the very spirit of scientific enquiry. Climate science is in its infancy, and if its development follows anything resembling the normal path of scientific advancement, we will see in the years ahead significant increases in our knowledge, data availability, and our theoretical understanding of the causes of various climate phenomena.”

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2.4.2 An Interdisciplinary Topic

> *Climate is an interdisciplinary subject requiring insights from many fields of study. Very few scholars have mastery of more than one or two of these disciplines.*

"Global warming is a topic that sprawls in a thousand technical directions," write Essex and McKitrick (2007, p. 17). They continue, "There is no such thing as an 'expert' on global warming, because no one can master all the relevant subjects. On the subject of climate change everyone is an amateur on many if not most topics, including ourselves."

The collaboration of experts from such fields as agronomy, astronomy, astrophysics, biology, botany, cosmology, economics, geochemistry, geology, history, oceanography, paleontology, physics, scientific forecasting, and statistics, among other disciplines, explains at least some of the confusion and disagreement on basic issues of climatology. Geologists, for example, view time in millennia and eons and are aware of past fluctuations in both global temperatures and carbon dioxide concentrations in the atmosphere, with the two often moving in opposite directions. Solar physicists think of time in terms of seconds and even nanoseconds and study action at an atomic level. Few geologists understand solar physics while few physicists understand geology.

In their attempts to summarize and simplify their research findings for researchers in other fields, scientists and others resort to "stylized facts," generalizations that may accurately convey the gist of their scientific research but are necessarily inaccurate, overly simplified, and often unsuited for use as inputs to the work of other researchers. The "mean global surface temperature" is one such stylized fact, the use of which in climate science has caused extensive controversy and disagreement. Historical records of total solar irradiance (TSI), greenhouse gas "inventories" and emission scenarios, global sea-level rise, and hurricane "best tracks" are just a few more of the many examples discussed earlier in this chapter and in other chapters of this book.

Related to this is the fact that scientists are often optimistic about the resilience or safety of the environment in their own area of research and expertise, but are pessimistic about risks with which they are less familiar. Simon (1999) wrote,

> This phenomenon is apparent everywhere. Physicians know about the extraordinary progress in medicine that they fully expect to continue, but they can't believe in the same sort of progress in natural resources. Geologists know about the progress in natural resources that pushes down their prices, but they worry about food. Even worse, some of those who are most optimistic about their own areas point with alarm to other issues to promote their own initiatives. The motive is sometimes self-interest (pp. 47–8).

Physical scientists who think they can discern a human impact on climate are apt to call for actions to diminish or end such an impact, the logical solution to the "problem" they have found. But when doing so they step outside their area of expertise and express only informed opinions. First, can they actually predict future human carbon dioxide emissions, and then future CO_2 levels in the atmosphere, and then the impact of that concentration on the global mean surface temperature, and then the impact of that change on weather, sea level, plants, and human well-being? And on each of these impacts, where? when? And how do we know? How many physicists, geologists, or chemists know enough to endorse the science behind each step in this chain argument? The answer is "none."

Second and equally important, climate change is not a "problem" simply because physicists or climatologists say it is. What to do about climate change is a question whose answer lies in the domain of social science, not physical science. Who benefits and who is hurt if climate change is allowed to proceed unabated? Whose rights are violated and whose should be protected? What institutions, laws, and precedents exist that govern situations like this? Who has the right to decide, to intervene, and to enforce action? What are the probabilities of success of such interventions based on past experience? Physicists, climatologists, and other physical scientists may have opinions on all these matters, but they have no expertise.

Economists, of course, do not have all the answers, either. They typically enter the debate late in the chained argument and are asked to "monetize" climate impacts, recommend a discount rate used to value benefits that occur beyond 50 or 60 years in the future, and give advice on the best way to reduce "carbon pollution." These matters were addressed in Chapter 1 and will be again in Chapter 8, but it is worth noting here that economists give conflicting advice on every point. Some call for immediate action (e.g., Stiglitz, 2018), while others say the benefits exeed the costs in the short and medium run, so "climate change would appear to be an important issue primarily for those who are concerned about the distant future, faraway lands, and remote probabilities" (Tol, 2018).

Monetizing climate impacts requires evaluating risks, which in turn requires choosing one of hundreds or thousands of competing climate impact scenarios. Economists must then estimate or assume how quickly and successfully humans can substitute renewable energies for fossil fuels or adapt to climate changes or (more likely) some combination of both. There is no agreement among economists on this matter, or on the right discount rate to use; some recommend 7% while others recommend rates as low as 0%. The choice of discount rates means the difference between action today and no action until 2050 or even beyond. Rather than recommend a carbon tax or some other government "solution" to climate change, some economists recommend ways to tap local knowledge to turn climate change into a win-win opportunity (Goklany, 2007; Lomberg, 2010; van Kooten, 2013; Morris, 2015; Kahn, 2010, 2016–17; Olmstead and Rhode, 2016–17; Zycher, 2017; Anderson *et al.*, 2018; Tol, 2018).

The Rise of Computer Models

"*Climatology*," writes Ball (2015), "is the study of weather patterns of a place or region, or the change of weather patterns over time. *Climate science* is the study of one component piece of climatology." Many of the practitioners of climate science are not climatologists or even very familiar with the subject. They come from other disciplines – physics, geology, biology, or even engineering, economics, and law – and lend their expertise to the effort to solve the puzzle that is Earth's climate. "The analogy I've used for decades," Ball writes,

> is that climatology is a puzzle of thousands of pieces; climate science is one piece of the puzzle. A practical approach to assembling the puzzle is to classify pieces into groups. The most basic sorting identifies the corner pieces, the edge pieces and then color. Climatologists say the four corner pieces, which are oceans, atmosphere, lithosphere, and the cosmos are not even fully identified or understood. Climate scientists tend to hold one piece of the puzzle and claim it is the key to everything.

Because it is a young discipline – many of its pioneers are still writing or only recently deceased – climatology very quickly fell victim to the growth of specialization in the academy. To bridge the distances between specialties, academics have turned to systems analysis, sometimes defined as "the analysis of the requirements of a task and the expression of those requirements in a form that permits the assembly of computer hardware and software to perform the task." In climate science, general circulation models (GCMs) and integrated assessment models (IAMs) are used to "perform the task" as well as handle the immense amounts of data being generated by new satellites and spectrometer analysis of various temperature and weather proxies.

Computer models are useful, but they cannot solve disagreements when there is no agreement on a general theory of climate (Essex and McKitrick, 2007). When an expert in one field, say physics, presents an estimate of the sensitivity of the climate to rising carbon dioxide levels, an expert in another field, say geology, can quickly challenge her understanding of the carbon cycle, and rightly so. The physicist probably accepts uncritically estimates of the size of carbon reservoirs and exchange rates offered by, say, the IPCC, and is unaware of the significant uncertainty and error bars surrounding those estimates. If she knew, her calculation of climate sensitivity would likely be much different. Many geologists are unfamiliar with the extensive literature on the impact of rising levels of atmospheric CO_2 on photosynthesis and plant growth, so they stand to be corrected by biologists, botanists, and agronomists. And then it might take an economist to estimate how the application of technology will change agriculture and forestry in the future, affecting the rate of exchange between the biosphere and atmosphere and once again affecting the estimate of climate sensitivity. As reported in Section 2.1.1.3, uncertainties propagate and confusion and disagreement rise exponentially.

GCMs and IAMs can be tuned according to the knowledge, opinions, and biases of their modelers, and then run with an infinite combination of databases reflecting underlying uncertainties in observational data (Hourdin *et al.*, 2017). No wonder 102 GCMs produce the wide array of hindcasts and forecasts of temperature, shown in the graph from McKitrick and Christy (2018) reproduced as Figure 2.2.2.1 earlier in this chapter. It brings to mind the famous tale of a group of blind men touching various parts of an elephant, each arriving at a very different idea of what it is like: to one it is like a tree, to another, a snake, and to a third, a wall. A wise man tells the group, "You are all right. An elephant has all the features you mentioned."

The role of "wise man" in climate science falls to computer modelers, but as Ball (2015) remarks, they are seldom climatologists. He writes,

> After a discussion with a computer modeler in 1998, I realized the limitations of his weather and climate knowledge. Despite this,

> I watched modelers take over as climate scientists and become keynote speakers at most climate conferences. It became so technologically centered that whoever had the biggest fastest computers were the 'state of the art' climate experts. I recall the impact of the Cray computer on climate science. The idiocy continues today with the belief that the only limitation to the models is computer capacity and speed.

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2.4.3 Failure of the IPCC

Many scientists trust the United Nations' Intergovernmental Panel on Climate Change (IPCC) to objectively report the latest scientific findings on climate change, but it has failed to produce balanced reports and has allowed its findings to be misreported to the public.

The Intergovernmental Panel on Climate Change (IPCC) was created in 1988 by the United Nations as a joint project of two of its agencies, the Environmental Programme (UNEP) and the World Meteorological Organization (WMO). Its initial Statement of Principles reads, "The role of the IPCC is to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts, and options for adaptation and mitigation" (IPCC, 1988).

The IPCC provides research support to the UN's Framework Convention on Climate Change (UNFCCC), an entity that arose from the 1992 United Nations Conference on Environment and Development (UNCED), also known as the Rio Earth Summit. The IPCC supports the Conference of the Parties (COP), which meets annually to oversee implementation of the 1997 Kyoto Protocol and 2015 Paris Accord.

The regular and special reports of the IPCC dominate the climate change debate, and rightly so. The five multi-volume "assessments" produced to date total more than 10,000 pages, much of it consisting of dense literature reviews in which hundreds and possibly thousands of climate scientists and policy advocates take part. The hefty tomes identify hundreds of scientists as lead authors, contributors, or reviewers and are presented by the IPCC as representing the "consensus" of the scientific community on the climate change issue. Many of the world's science academies, membership organizations, and leading journals have endorsed the IPCC's findings and give its spokespersons extensive attention. In 2007, the IPCC was a co-recipient (with former U.S. Vice President Al Gore) of the Nobel Peace Prize.

While there is no disputing the fact that the IPCC has summarized immense amounts of high-quality and consequential research, researchers and policymakers should understand that the organization labors under political and institutional constraints that undermine the credibility of its work, and that an audit of its procedures found disturbing violations of proper scientific procedures.

Political and Institutional Restraints

The IPCC was created by the United Nations to build a scientific case for giving it authority to regulate the planet's atmosphere as a collective good or resource commons, a kind of resource defined and described in Chapter 1, Section 1.3. Much of what the IPCC does and does not do can be explained by the "seeing like a state" phenomenon described by James C. Scott (1998) and explained in Chapter 1, Section 1.3.4.

The story of the creation of the IPCC is told well in such books as *The Age of Global Warming: A History* (Darwall, 2013) and *Searching for the Catastrophe Signal: The Origins of the Intergovernmental Panel on Climate Change* (Lewin, 2017) and will not be repeated here. Article 1.2 of the Framework Convention on Climate Change (UNFCCC, 1992), which provides the IPCC's mandate, defines climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." Working Group I of the IPCC has interpreted this as a mandate to not study climate change "in the round" or to look at natural as well as man-made influences on climate. Instead, it seeks to find and report only a possible human impact on climate, and thereby make a scientific case for adopting national and international policies that could reduce that impact. Missing from the 1,535-page Working Group I contribution to IPCC's Fifth Assessment Report (IPCC, 2013) is a serious analysis of natural causes of climate variability. The section titled "Natural Radiative Forcing Changes: Solar and Volcanic" runs only six pages, and "The Carbon Dioxide Fertilization Effect" merits only a single page. A balanced report would have devoted hundreds of pages to each topic.

Similarly, Working Group II of the IPCC views its assignment as being to catalogue all possible *harms* of "climate change," including those arising from natural as well as anthropogenic causes, and it hardly mentions the benefits of a warmer climate, increasing atmospheric CO_2, or the fossil fuels it argues should be banned by the end of the twenty-first century (IPCC, 2014). Yet it is apparent, even obvious, that the moderate warming experienced in the late-twentieth and early twenty-first centuries has been beneficial to many parts of the world. Increasing crop yields, the retreat of deserts, and the reduced toll of cold days and nights are well documented in the peer-reviewed literature but almost entirely absent from the IPCC's work.

A second institutional constraint on the IPCC is the inevitable consequence of asking a committee to deal with a complex and controversial issue. The incentive structure of committees leads them to allow the inclusion of declaratory statements and confident predictions so long as they are accompanied by caveats and admissions of uncertainty and dissenting views. The result is a schizophrenic style that veers from declarations of "extreme confidence" to admissions of complete doubt and uncertainty, often before a paragraph ends but sometimes in a different chapter or volume of the assessment report. An example, provided by Gleditsch and Nordås (2014), is in Chapter 22 of the Working Group II contribution to AR5 (on Africa), which "states explicitly that 'causality between climate change and violent conflict is difficult to establish' (p. 5), yet goes on to say on the same page that 'the degradation of natural resources as a result of both overexploitation and climate change will contribute to increased conflicts over the distribution of these resources.'" Once the pattern is noticed, it becomes apparent on many pages of every working group report.

The IPCC is able to present conflicting opinions side-by-side and yet avoid nonsense by making ample use of what Gleditsch and Nordås call "expressions of uncertainty." Such words as may, might, can, and could, and such phrases as "has a potential to," "is a potential cause of," and "is sensitive to" appear on average 1.2 times per page in the Working Group I Summary for Policymakers (SPM) and 1.3 times per page in the Working Group II SPM. They write, "The frequent use of 'may' terms might have been justified as a way of indicating that 'under certain circumstances, a relationship is likely.' But this does not work well if those circumstances are not specified. On the whole, it would probably be best to avoid the use of terms like 'may' in academic writing except to state conjectures. Misrepresentation of the scientific basis is a real hazard when using such terminology" (p. 88).

A third institutional constraint is that the IPCC's "members" are not scientists but national governments that are members of the United Nations. The WMO, for example, has "191 member States and Territories" (WMO, n.d.). The national governments that created the IPCC also fund it, staff it, select the scientists who participate in its work, and importantly, revise and rewrite the reports after the scientists have concluded their work. In 2014, a reporter for *Science* described the political interference on display in events leading up to the release of the Working Group III contribution to AR5: "Although the underlying technical report from WG III was accepted by the IPCC, final, heated negotiations among scientific authors and diplomats led to a substantial deletion of figures and text from the influential 'Summary for Policymakers' (SPM). … [S]ome fear that this redaction of content marks an overstepping of political interests, raising questions about division of labor between scientists and policy-makers and the need for new strategies in assessing complex science. Others argue that SPM should explicitly be coproduced with governments" (Wible, 2014). The subtitle of the article is "Did the 'Summary for Policymakers' become a summary *by* policy-makers?"

Serving the State

The IPCC's first report (IPCC, 1990) found "increases in atmospheric concentrations of greenhouse gases may lead to irreversible change in the climate which could be detectable by the end of this century" (p. 53). Every assessment report since then has claimed with rising certainty that there is a "discernable human impact" on the climate and that steps must be taken to avoid a global climate crisis, even though the IPCC's estimates of climate sensitivity to CO_2 have stayed largely unchanged since 1990 and declined in the peer-reviewed literature, temperatures have risen only half as much as the IPCC predicted, and few if any of the negative climate impacts predicted by the IPCC have been observed. *Why, as direct evidence increasingly pointed away from a climate change crisis, has the IPCC's rhetoric become more extreme?* The problems of "tunnel vision" and "moral hazard" afflicting government bureaucracies, described in Chapter 1, Section 1.4.3, provide an explanation for this trend. So too does the phenomenon of "seeing like a state," whereby government agencies produce data and stylized facts they believe will satisfy their political overseers.

Many admissions of uncertainty appear in the IPCC's hefty assessment reports, including AR5, a fact established earlier in this chapter and repeated in other chapters, but the IPCC's purpose and agenda work to ensure that uncertainty is not broadly advertised. The opening words of the foreword to the Working Group I contribution to AR5, for example, read: "'Climate Change 2013: the Physical Science Basis' presents clear and robust conclusions in the global assessment of climate change science – not the least of which is that the science now shows with 95 percent certainty that human action is the dominant cause of observed warming since the mid-20th century" (p. v). The authors – the Secretary General of the WMO and Executive Director of the UNEP – continue in this same declarative tone, "warming in the climate system is unequivocal, with many of the observed changes unprecedented over decades to millennia."

Only people deeply familiar with AR5 realize what the Secretary General and Executive Director chose *not* to say. The "95 percent certainty" is not an expression of statistical significance but only a rhetorical expression of the strength of opinions, a number quite literally arrived at by a show of hands around a table. It is not derived from a poll of the scientists who contributed to the volume but only the opinion of a few individuals, including nonscientists, who were involved in the writing and rewriting of the Summary for Policymakers. The only survey done of contributors to AR5 found a majority do not endorse this statement (Fabius Maximus, 2015).

Similarly, the IPCC found the warming is "unequivocal" except when it is not, such as during the "pause" from 1997 to 2010 when the real scientists who helped write AR5 acknowledge there was no warming at all ("0.07°C [-0.02 to 0.18])" (IPCC, 2013, p. 37). Similarly, "observed changes [are] unprecedented" except, as this chapter documents, for temperatures, extreme weather events, polar ice melting, and sea-level rise. What is left?

The doubts and uncertainty that the Scientific Method requires be revealed so other researchers know what is scientific fact and what is conjecture or speculation do appear in AR5, and in other IPCC assessment reports, but they are scrubbed from the Summaries for Policymakers (SPMs). This scientific malpractice has been protested by many distinguished scientists (Seitz, 1996; Landsea, 2005; Lindzen, 2012; Tol, 2014; Stavins, 2014). Unfortunately, many scientists look no further than the SPMs and trust them to accurately depict the current state of climate science.

Tol (2014) commented on how the AR5 Summary for Policymakers, "drafted by the scholars of the IPCC, is rewritten by delegates of the governments of the world," each with political agendas that lead to interference with the report's scientific content. Even the scientists who participate are biased: "The IPCC does not guard itself against selection bias and groupthink. Academics who worry about climate change are more likely to publish about it, and more likely to get into the IPCC. Groups of like-minded people reinforce their beliefs. The environment agencies that comment on the draft IPCC report will not argue that their department is obsolete. The IPCC should therefore be taken out of the hands of the climate bureaucracy and transferred to the academic authorities" (Tol, 2014).

The IAC Audit

It is often remarked that nearly all of the world's national science academies have "endorsed" the IPCC's findings. Such a claim is superficially true but scientifically meaningless: none of these academies surveyed its members to see if they agree with everything contained in the IPCC's massive reports. Even if *most* of the members say they approve of *most* of what the IPCC writes in its latest report, what does this say about the views of the much smaller community of climate scientists, engineers, economists, and others who specialize in climatology and have informed opinions on it? Voting is not an effective way of separating sound science from pseudoscience.

Also very telling is that when the presidents of those same institutions conducted an audit of the IPCC's practices, they found ample grounds to doubt the organization's credibility. The InterAcademy Council (IAC), made up of the presidents of the world's leading national science academies, audited the IPCC in 2010 (IAC, 2010). Among its findings:

- *Fake confidence intervals*: The IAC was highly critical of the IPCC's method of assigning "confidence" levels to its forecasts, singling out "… the many statements in the Working Group II Summary for Policymakers that are assigned high confidence but are based on little evidence. Moreover, the apparent need to include statements of 'high confidence' (i.e., an 8 out of 10 chance of being correct) in the Summary for Policymakers led authors to make many vaguely defined statements that are difficult to refute, therefore making them of 'high confidence.' Such statements have little value" (p. 61).

- *Use of gray sources*: Too much reliance on unpublished and non-peer-reviewed sources. Three sections of the IPCC's 2001 climate assessment cited peer-reviewed material only 36%, 59%, and 84% of the time (p. 63).

- *Political interference*: Line-by-line editing of the summaries for policymakers during "grueling Plenary session that lasts several days, usually culminating in an all-night meeting. Scientists and government representatives who responded to the Committee's questionnaire suggested changes to reduce opportunities for political interference with the scientific results …" (p. 64).

- *The use of secret data*: "An unwillingness to share data with critics and enquirers and poor procedures to respond to freedom-of-information requests were the main problems uncovered in some of the controversies surrounding the IPCC (Russell *et al.*, 2010; PBL, 2010). Poor access to data inhibits users' ability to check the quality of the data used and to verify the conclusions drawn …" (p. 68).

- *Selection of contributors is politicized*: Politicians decide which scientists are allowed to participate in the writing and review process: "political considerations are given more weight than scientific qualifications" (p. 14).

- *Chapter authors exclude opposing views*: "Equally important is combating confirmation bias – the tendency of authors to place too much weight on their own views relative to other views (Jonas *et al.*, 2001). As pointed out to the Committee by a presenter and some questionnaire respondents, alternative views are not always cited in a chapter if the Lead Authors do not agree with them ...” (p. 18).

- *Need for independent review*: “Although implementing the above recommendations would greatly strengthen the review process, it would not make the review process truly independent because the Working Group Co-chairs, who have overall responsibility for the preparation of the reports, are also responsible for selecting Review Editors. To be independent, the selection of Review Editors would have to be made by an individual or group not engaged in writing the report, and Review Editors would report directly to that individual or group (NRC, 1998, 2002)” (p. 21).

The quotations above are from a publicly circulated draft of the IAC’s final report, still available online (see reference). The final report was heavily edited to water down and perhaps hide the extent of problems uncovered by the investigators, itself evidence of misconduct. The IPCC accepted the IAC’s findings and promised to make changes … too late to affect AR5.

Some climate scientists spoke out early and forcefully against the problems they saw as compromising the integrity of the IPCC, but their voices were difficult to hear amid a steady drumbeat of alarmism from media outlets. As a result, many scientists, economists, and policymakers have been misled into thinking the IPCC is the final or even only authority on climate change. German meteorologist and physicist Klaus-Ekhart Pul said in an interview in 2012, “Ten years ago I simply parroted what the IPCC told us. One day I started checking the facts and data – first I started with a sense of doubt but then I became outraged when I discovered that much of what the IPCC and the media were telling us was sheer nonsense and was not even supported by any scientific facts and measurements. To this day I still feel shame that as a scientist I made presentations of their science without first checking it” (translated by Gosselin, 2012).

* * *

This is a harsh criticism of an organization that, as noted at the beginning of this section, has summarized large amounts of high-quality and consequential research. It is not our purpose to disparage the individuals involved, and a careful reading of this section will show that we did not do so. The IPCC’s failures arise from its mission, its oversight by two government agencies, and the inevitable dynamics of assigning a committee to address a complex problem. Our point is a simple one: The IPCC is not the final word on climate science.

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2.4.4 Tunnel Vision

Climate scientists, like all humans, can have tunnel vision. Bias, even or especially if subconscious, can be especially pernicious when data are equivocal and allow multiple interpretations, as in climatology.

Bias, or what might better be called "tunnel vision" (Breyer, 1993), is another reason for disagreement among scientists and other writers on climate change. Scientists, no less than other human beings, bring their personal beliefs and interests to their work and sometimes make decisions based on them that direct their attention away from research findings that would contradict their opinions. Bias is often subconscious but, if recognized, can be overcome by careful adherence to procedures or by being guided by professional ethics, but sometimes it leads to outright corruption.

Essex and McKitrick (2007) write, "Journalists have taken to writing 'exposé' articles that never seem to expose the substance of the scientific arguments at issue, but instead grub around for connections, however tenuous, between scientists and the petroleum industry … but always leaving just-barely unstated the libelous premise that such people would falsify their research or misrepresent their real views for some filthy lucre" (p. 52). "Charges of 'sowing doubt' mean nothing," they add. "They can be hurled at any opponent: my idea is the right one and yours is just sowing doubt. But the lessons of half a millennium have taught us over and over that doubt is part of the lifeblood of scientific advance. We need it. It's worth fighting for" (p. 55).

To obtain funding (and more funding), it helps scientists immensely to have the public – and thus Congress and potentially private funders – worried about the critical nature of the problems they study. This incentive makes it less likely researchers will interpret existing knowledge or present their findings in a way that reduces public concern (Lichter and Rothman, 1999; Kellow, 2007; Kabat, 2008). As a result, scientists often gravitate toward emphasizing worst-case scenarios, though there may be ample evidence to the contrary. This bias of alarmism knows no political bounds, affecting scientists of all political stripes (Berezow and Campbell, 2012; Lindzen, 2012).

Freedman (2010) identifies a long list of reasons why experts are often wrong, including pandering to audiences or clients, lack of oversight, reliance on flawed evidence provided by others, and failure to take into account important confounding variables. Scientists, especially those in charge of large research projects and laboratories, may have a financial incentive to seek more funding for their programs. They are not immune to having tunnel vision regarding the importance of their work and employment. Each believes his or her mission is more significant and essential relative to other budget priorities.

Park *et al.* (2014), in a paper published in *Nature*, summarized research on publication bias, careerism, data fabrication, and fraud to explain how scientists converge on false conclusions. They write, "Here we show that even when scientists are motivated to promote the truth, their behaviour may be influenced, and even dominated, by information gleaned from their peers' behaviour, rather than by their personal dispositions. This phenomenon, known as herding, subjects the scientific community to an inherent risk of converging on an incorrect answer and raises the possibility that, under certain conditions, science may not be self-correcting."

Some journalists seem to recognize only one possible source of bias, and that is funding from "the fossil fuel industry." The accusation often permeates conversations of the subject, perhaps second only to the "consensus" claim, and the two are often paired, as in "only scientists paid by the fossil fuel industry dispute the overwhelming scientific consensus." The accusation doesn't carry any weight for many reasons:

- There has never been any evidence of a climate scientist accepting money from industry to take a position or change his or her position in the climate debate (Singer, 2010; Cook, 2014).

- Vanishingly few global warming skeptics have ever been paid by the fossil fuel industry, certainly not more than a tiny fraction of the 31,478 American scientists who signed the Global Warming Petition or the hundreds of meteorologists and climate scientists reported in Section 2.1 who tell survey-takers they do not agree with the IPCC.

- Funding of alarmists by government agencies, liberal foundations, environmental advocacy groups, and the alternative energy industry exceeds funding from the fossil fuel industry by as much as four orders of magnitude (Nova, 2009; Butos and McQuade, 2015). Does government and interest-group funding of alarmists not also have a "corrupting" influence on its recipients?

- The most prominent organizations supporting global warming skepticism get little if any money from the fossil fuel industry. Their support comes overwhelmingly from individuals (and their foundations) motivated by concern over the corruption of science and the enormous costs it is imposing on the public.

Curry (2015) worries more about the influence of government grants than private funding on scientists: "I am very concerned that climate science is becoming biased owing to biases in federal funding priorities and the institutionalization by professional societies of a particular ideology related to climate change. Many scientists, and institutions that support science, are becoming advocates for UN climate policies, which is leading scientists into overconfidence in their assessments and public statements and into failures to respond to genuine criticisms of the scientific consensus. In short, the climate science establishment has become intolerant to disagreement and debate, and is attempting to marginalize and de-legitimize dissent as corrupt or ignorant."

The extensive funding of global warming alarmism by government agencies, corporations, and liberal foundations and the negative effect it has on the public's understanding of the issue were described in Chapter 1, Sections 1.4.4 and 1.4.5. Darwall (2018) describes how political, business, and advocacy group interests converge to form a "Climate Industrial Complex" with immense resources at its disposal. He writes, "there is another Moore's law. The second one says the richer you are, the more likely you are to support green causes. … Climate change is ethics for the wealthy: It legitimizes great accumulations of wealth. Pledging to combat it immunizes climate-friendly corporate leaders and billionaires from being targeted as memmbers of the top one-tenth of the top one percent" (pp. 211-12). If supporting renewable energy harmed their interests, Darwall writes, these major donors to the global warming movement would "drop it in a nanosecond."

* * *

Scientists disagree about climate change for many reasons, and often different reasons. Skepticism, the heart of science, means questioning orthodoxy and always asking, *how do we know?* Disagreement over climate science is to be expected and even encouraged for reasons presented in this section. As Essex and McKitrick (2007) write, "We need it. It's worth fighting for."

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2.5 Appeals to Consensus

As explained in Section 2.1.1.2, scientific disagreements are not resolved by a show of hands. While consensus is a method used in politics to achieve change, the Scientific Method is used by scientists to reduce uncertainty and errors with the goal of understanding "why things are the way they are and act the way they do." This chapter makes clear the presence of disagreement on a wide range of important scientific topics in climate science, including most notably reconstructions of temperature trends in the past, the reliability of climate models, the sensitivity of climate to a doubling of CO_2, and the role of solar influences. Along the way we discovered uncertainty and disagreement over scores of other important matters.

Regrettably, claims of a "scientific consensus" on the causes and consequences of climate change have been used to shut down debate and provide cover to those who want political action. This section rebuts such claims by disclosing flaws in surveys allegedly finding a consensus and describing evidence of a distinct *absence* of consensus on many of the most important topics in climate science.

2.5.1 Flawed Surveys

Surveys and abstract-counting exercises that are said to show a "scientific consensus" on the causes and consequences of climate change invariably ask the wrong questions or the wrong people. No survey data exist that support claims of consensus on important scientific questions.

Claims of a "scientific consensus" on the causes and consequences of climate change rely on a handful of essays reporting the results of surveys or efforts to count the number of articles published in peer-reviewed journals that appear to endorse or reject the positions of the IPCC. The U.S. National

Aeronautics and Space Administration (NASA) on its website cites four sources supporting its claim that "Multiple studies published in peer-reviewed scientific journals show that 97% or more of actively publishing climate scientists agree: Climate-warming trends over the past century are extremely likely due to human activities" (NASA, 2018). As this section reveals, those surveys and abstract-counting exercises do not support that claim.

2.5.1.1 Oreskes, 2004

The most frequently cited source for a "consensus of scientists" is a 2004 essay for the journal *Science* written by historian Naomi Oreskes (Oreskes, 2004). Oreskes reported examining abstracts from 928 papers reported by the Institute for Scientific Information database published in scientific journals from 1993 and 2003, using the keywords "global climate change." Although not a scientist, she concluded 75% of the abstracts either implicitly or explicitly supported the IPCC's view that human activities were responsible for most of the observed warming over the previous 50 years while none directly dissented.

Oreskes' essay appeared in a "peer-reviewed scientific journal," as NASA reports on its website, but the essay itself was not peer-reviewed. It was an opinion essay and the editors had not asked to see her database. This opinion essay became the basis of a book, *Merchants of Doubt* (Oreskes and Conway, 2010), and then an academic career built on claiming that global warming "deniers" are a tiny minority within the scientific community, and then a movie based on her book released in 2015. Her 2004 claims were repeated in former Vice President Al Gore's movie, *An Inconvenient Truth*, and in his book with the same title (Gore, 2006).

Oreskes did not distinguish between articles that acknowledged or assumed some human impact on climate, however small, and articles that supported the IPCC's more specific claim that human emissions are responsible for more than 50% of the global warming observed during the past 50 years. The abstracts often are silent on the matter, and Oreskes apparently made no effort to go beyond those abstracts. Her definition of consensus also is silent on whether man-made climate change is dangerous or benign, a rather important question.

Oreskes' literature review overlooked hundreds of articles in peer-reviewed journals written by prominent global warming skeptics including John Christy, Sherwood Idso, Richard Lindzen, and Patrick Michaels. More than 1,350 such articles (including articles published after Oreskes' study was completed) are identified in an online bibliography (Popular Technology.net, 2014).

Oreskes' methodology was flawed by assuming a nonscientist could decern the findings of scientific research by reading only the abstracts of published papers. Even trained climate scientists are unable to do so because abstracts do not accurately reflect their articles' findings. According to Park *et al.* (2014), abstracts routinely overstate or exaggerate research findings and contain claims that are irrelevant to the underlying research. Park *et al*. find "a mismatch between the claims made in the abstracts, and the strength of evidence for those claims based on a neutral analysis of the data, consistent with the occurrence of herding." They note abstracts often are loaded with "keywords" to ensure they are picked up by search engines and thus cited by other researchers.

Oreskes' methodology is further flawed, as are the other surveys and abstract-counting exercises discussed in this section, by surveying the opinions and writings of scientists and often nonscientists who may write about climate but are by no means experts on or even casually familiar with the science dealing with attribution – that is, attributing a specific climate effect (such as a temperature increase) to a specific cause (such as rising atmospheric CO_2 levels). Most articles simply reference or assume to be true the claims of the IPCC and then go on to address a different topic, such as the effect of ambient temperature on the life-cycle of frogs or correlations between temperature and outbreaks of influenza. Attribution is the issue the surveys ask about, but they ask people who have never studied the issue. The number of scientists actually knowledgeable about this aspect of the debate may be fewer than 100 in the world. Several are prominent skeptics (John Christy, Richard Lindzen, Patrick Michaels, and Roy Spencer, to name only four) and many others may be.

Monckton (2007) finds numerous other errors in Oreskes' essay, including her use of the search term "global climate change" instead of "climate change," which resulted in her finding fewer than one-thirteenth of the estimated corpus of scientific papers on climate change published over the stated period. Monckton also points out Oreskes never stated how many of the 928 abstracts she reviewed actually endorsed her limited definition of "consensus." Medical researcher Klaus-Martin Schulte used the same database and search terms as Oreskes to examine papers published from 2004 to

February 2007 and found fewer than half endorsed the "consensus" and only 7% did so explicitly (Schulte, 2008). His study is described in more detail in Section 2.5.2.1.

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2.5.1.2 Doran and Zimmerman, 2009

Doran and Zimmerman (2009) reported conducting a survey that found "97% of climate scientists agree" that mean global temperatures have risen since before the 1800s and that humans are a significant contributing factor. The researchers had sent an online survey to 10,257 Earth scientists working for universities and government research agencies, generating responses from 3,146 people. The survey asked only two questions:

> Q1. When compared with pre-1800s levels, do you think that mean global temperatures have generally risen, fallen, or remained relatively constant?
>
> Q2. Do you think human activity is a significant contributing factor in changing mean global temperatures?

Overall, 90% of respondents answered "risen" to question 1 and 82% answered "yes" to question 2. The authors achieved their 97% figure by reporting the "yes" answers from only 79 of their respondents who "listed climate science as their area of expertise and who also have published more than 50% of their recent peer-reviewed papers on the subject of climate change." That is, Doran and Zimmerman applied *ex post facto* criteria to exclude 10,178 of their 10,257 sample population. Commenting on the survey, Solomon (2010) wrote:

> The two researchers started by altogether excluding from their survey the thousands of scientists most likely to think that the Sun, or planetary movements, might have something to do with climate on Earth – out were the solar scientists, space scientists, cosmologists, physicists, meteorologists and astronomers. That left the 10,257 scientists in disciplines like geology, oceanography, paleontology, and geochemistry. … The two researchers also decided that scientific accomplishment should not be a factor in who could answer – those surveyed were determined by their place of employment (an academic or a governmental institution). Neither was academic qualification a factor – about 1,000 of those surveyed did not have a Ph.D., some didn't even have a master's diploma.

Most "skeptics" of man-made global warming would answer those two questions the same way as alarmists would. The controversy in the science community is not over whether the climate warmed since the Little Ice Age or whether there is a human impact on climate, but "whether the warming since 1950 has been dominated by human causes, how much the planet will warm in the 21st century, whether warming is 'dangerous,' whether we can afford to radically reduce CO_2 emissions, and whether reduction will improve the climate" (Curry, 2015). The IPCC has expressed informed opinions on all these subjects, but those opinions often are at odds with extensive scientific research.

The survey by Doran and Zimmerman fails to produce evidence that would back up claims of a "scientific consensus" about the causes or consequences of climate change. They simply asked the wrong people the wrong questions. The "97%" figure so often attributed to their survey refers to the opinions of only 79 scientists, hardly a representative sample of scientific opinion.

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2.5.1.3 Anderegg et al., 2010

The third source cited by NASA as proof of a "scientific consensus" is Anderegg *et al.* (2010), who report using Google Scholar to identify the views of the most prolific writers on climate change. The authors found "(i) 97–98% of the climate researchers most actively publishing in the field support the tenets of ACC [anthropogenic climate change] outlined by the Intergovernmental Panel on Climate Change, and (ii) the relative climate expertise and scientific prominence of the researchers unconvinced of ACC are substantially below that of the convinced researchers." Like Oreskes (2014), Anderegg *et al.* was not peer reviewed. It was an "invited paper," which allowed its authors to bypass peer review.

This is not a survey of scientists, whether "all scientists" or specifically climate scientists. Instead, Anderegg *et al.* simply counted the number of articles found on the internet written by 908 scientists. This counting exercise is the same flawed methodology utilized by Oreskes, falsely assuming abstracts of papers accurately reflect their findings. Further, Anderegg *et al.* did not determine how many of the 908 authors believe global warming is harmful or that the science is sufficiently established to be the basis for public policy. Anyone who cites this study in defense of these views is mistaken.

Anderegg *et al.* also didn't count as "skeptics" the scientists whose work exposes gaps in the man-made global warming theory or contradicts claims that climate change will be catastrophic. Avery (2007) identified several hundred scientists who fall into this category, even though some profess to "believe" in global warming.

Looking past the "97–98%" claim, Anderegg *et al.* found the average skeptic has been published about half as frequently as the average alarmist (60 versus 119 articles). Most of this difference was driven by the hyper-productivity of a handful of alarmist climate scientists: The 50 most prolific alarmists were published an average of 408 times, versus only 89 times for the skeptics. The extraordinary publication rate of alarmists should raise a red flag. It is unlikely these scientists actually participated in most of the experiments or research contained in articles bearing their names. The difference in productivity between alarmists and skeptics can be explained by several factors other than merit:

- Publication bias: Articles reporting statistically significant correlations are much more likely to get published than those that do not (Fanelli, 2012);

- Heavy government funding of the search for one result but little or no funding for other results: The U.S. government alone paid $64 billion to climate researchers during the four years from 2010 to 2013, virtually all of it explicitly assuming or intended to find a human impact on climate and virtually nothing on the possibility of natural causes of climate change (Butos and McQuade, 2015, Table 2, p. 178);

- Resumé padding: It is increasingly common for academic articles on climate change to have multiple and even a dozen or more authors, inflating the number of times a researcher can claim to have been published (Hotz, 2015). Adding a previously published researcher's name to the work of more junior researchers helps ensure publication (as was the case with Anderegg *et al.* (2010) and Doran and Zimmerman (2009), in both cases the primary authors were college students);

- Differences in the age and academic status of global warming alarmists versus skeptics: Climate scientists who are skeptics tend to be older and more are emeritus than their counterparts on the alarmist side; skeptics are thus under less pressure and often are simply less eager to publish.

So what, exactly, did Anderegg *et al.* discover? That a small clique of climate alarmists had their names added to hundreds of articles published in academic journals, something that probably would have been impossible or judged unethical just a decade or two ago. Anderegg *et al.* simply assert those "top 50" are more credible than scientists who publish less, but they make no effort to prove this and there is ample evidence they are not (Solomon, 2008). Once again, Anderegg *et al.* did not ask if authors believe global warming is a serious problem or if science is sufficiently established to be the basis for public policy. Anyone who cites this study as evidence of scientific support for such views is misrepresenting the paper.

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2.5.1.4 Cook et al., 2013

NASA's fourth source proving a "scientific consensus" is an abstract-counting exercise by Cook *et al.* (2013). The authors reviewed abstracts of peer-reviewed papers from 1991 to 2011 and found 97% of those that stated a position either explicitly or implicitly affirmed that human activity is responsible for some warming. The study was quickly critiqued by Legates *et al.* (2015), who found "just 0.3% endorsement of the standard definition of consensus: that most warming since 1950 is anthropogenic." They note "only 41 papers – 0.3% of all 11,944 abstracts or 1.0% of the 4,014 expressing an opinion, and not 97.1% – had been found to endorse the standard or quantitative hypothesis."

Scientists whose work questions the consensus, including Craig Idso, Nils-Axel Mörner, Nicola Scafetta, and Nir J. Shaviv, protested that Cook misrepresented their work (Popular Technology.net, 2012, 2013). Richard Tol, a lead author of the IPCC reports, said of the Cook report, "the sample of papers does not represent the literature. That is, the main finding of the paper is incorrect, invalid and unrepresentative" (Tol, 2013). On a blog of *The Guardian*, a British newspaper that had reported on the Cook report, Tol (2014) explained:

> Any conclusion they draw is not about 'the literature' but rather about the papers they happened to find. Most of the papers they studied are not about climate change and its causes, but many were taken as evidence nonetheless. Papers on carbon taxes naturally assume that carbon dioxide emissions cause global warming – but assumptions are not conclusions. Cook's claim of an increasing consensus over time is entirely due to an increase of the number of irrelevant papers that Cook and Co. mistook for evidence.

Montford (2013) revealed the authors of Cook *et al.* were marketing the expected results of the paper before the research itself was conducted; changed the definition of an endorsement of the global warming hypothesis mid-stream when it became apparent the abstracts they were reviewing did not support their original (IPCC-based) definition; and gave incorrect guidance to the volunteers recruited to read and score abstracts. Montford concludes "the consensus referred to is trivial" since the paper "said nothing about global warming being dangerous" and "the project was not a scientific investigation to determine the extent of agreement on global warming, but a public relations exercise."

* * *

Friends of Science, a group of Canadian retired Earth and atmospheric scientists, reviewed the four surveys and abstract-counting exercises summarized above (Friends of Science, 2014). They conclude, "these surveys show there is no 97% consensus on human-caused global warming as claimed in these studies. None of these studies indicate any agreement with a catastrophic view of human-caused global warming" (p. 4). We concur.

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2.5.2 Evidence of Lack of Consensus

Some survey data, petitions, and the peer-reviewed literature show deep disagreement among scientists on scientific issues that must be resolved before the man-made global warming hypothesis can be accepted.

In contrast to the surveys and abstract-counting exercises described above, which try but fail to find a consensus in support of the claim that global warming is man-made and dangerous, many authors and surveys have found widespread disagreement or even that a majority of scientists oppose the alleged consensus. These surveys and studies generally suffer the same methodological errors as afflict the ones described above, but they suggest that even playing by the alarmists' rules, the results demonstrate disagreement rather than consensus on key issues.

2.5.2.1 Klaus-Martin Schulte, 2008

Schulte (2008), a practicing physician, observed, "Recently, patients alarmed by the tone of media reports and political speeches on climate change have been voicing distress, for fear of the imagined consequences of anthropogenic 'global warming.'" Concern that his patients were experiencing unnecessary stress "prompted me to review the literature available on 'climate change and health' via PubMed" and then to attempt to replicate Oreskes' 2004 report.

"In the present study," Schulte writes, "Oreskes' research was brought up to date by using the same search term on the same database to identify abstracts of 539 scientific papers published between 2004 and mid-February 2007." According to Schulte, "The results show a tripling of the mean annual publication rate for papers using the search term 'global climate change', and, at the same time, a significant movement of scientific opinion away from the apparently unanimous consensus which Oreskes had found in the learned journals from 1993 to 2003. Remarkably, the proportion of papers explicitly or implicitly rejecting the consensus has risen from zero in the period 1993–2003 to almost 6% since 2004. Six papers reject the consensus outright."

Schulte also found "Though Oreskes did not state how many of the papers she reviewed explicitly endorsed the consensus that human greenhouse-gas emissions are responsible for more than half of the past 50 years' warming, only 7% of the more recent papers reviewed here were explicit in endorsing the consensus even in the strictly limited sense she had defined. The proportion of papers that now explicitly or implicitly endorse the consensus has fallen from 75% to 45%."

Schulte's findings demonstrate that if Oreskes' methodology were correct and her findings for the period 1993 to 2003 accurate, then scientific publications in the more recent period 2004–2007 show a strong tendency away from the consensus Oreskes claimed to have found. We doubt the utility of the methodology used by both Oreskes and Schulte. Nevertheless, it is useful to note the same methodology applied during two time periods seems to reveal a significant shift from consensus to open debate on the causes of climate change.

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2.5.2.2 Bray and von Storch, 2015–2016

Surveys by German scientists Dennis Bray and Hans von Storch conducted in 1996, 2003, 2008, 2010, and 2015-16 have consistently found climate scientists have deep doubts about the reliability of the science underlying claims of man-made climate change. Questions about climate science in the surveys, which have stayed largely the same over the years in order to discern trends, ask respondents to rank their agreement with a statement on a scale from 1 to 7, with 1 = "very inadequate," "poor," or "none" (depending on the wording of the question) and 7 = "very adequate," "very good," or "a very high level." Histograms then show the probability distribution of answers for each question.

Bast and Taylor (2007) analyzed the results of the 2003 survey and found only 55.8% of respondents agreed with the statement that "climate change is mostly the result of anthropogenic (manmade) causes" and more scientists "strongly disagree" than "strongly agree." When climate scientists were asked if "climate models can accurately predict climate conditions in the future," only a third (35.1%) agreed, while 18.3% were uncertain and nearly half (46.6%) disagreed. Most histograms showed bell-shaped distributions suggesting disagreement and uncertainty rather than agreement and confidence. Bast (2010) analyzed the Bray and von Storch 2010 survey and once again found bell-shaped distributions for about a third of the questions addressing scientific issues. Bast writes, "The remaining two-thirds are divided almost equally between distributions that lean toward skepticism and those that lean toward alarmism." He concludes, "There is certainly no consensus on the science behind the global warming scare."

The latest survey by Bray and von Storch (2016) was conducted in 2015 and released in 2016. The survey was sent by email to 3,879 individuals who were mostly contributors to past IPCC reports and writers appearing in 10 top-ranked peer-reviewed climate journals. Complete and partial responses were received from 651 respondents, a 17% response rate. All but 55 of the respondents (8.5%) reported working for universities or government agencies, suggesting as could be expected by the sampling procedure that proponents of the IPCC's views were over-represented in the sample. Given that the number of scientists active in fields related to climate number in the thousands, this small number of responses cannot be a representative sample of scientific opinion.

Surprisingly, given the skewed sample that was surveyed, only 48% of respondents said they agree "very much" with the statement that "most of recent or near future climate change is, or will be, the result of anthropogenic causes." Recall that the IPCC (2013) wrote in its Fifth Assessment Report that "It is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together" (p. 17). The IPCC defines "extremely likely" as "95–100% probability" (p. 36). It appears a majority of even the career climate scientists surveyed by Bray and von Storch disagree with the IPCC.

On whether "climate models accurately simulate the climatic conditions for which they are calibrated," a plurality (41.53%) ranked this a 5 and equal numbers (20%) ranked it a 4 or a 6, a bell-shaped distribution that skews toward the alarmist direction but still shows deep disagreement. Only 4% said they agree "very much" with the statement. The IPCC (2013) expressed *very high confidence* that its computer model simulations agree with the observed trend from 1951 to 2012 (p. 15).

On other questions there are once again bell-shaped distributions showing *most* scientists are unsure about basic questions of climate science. For example, 80% of respondents gave a 4 or less when asked how well atmospheric models can deal with the influence of clouds and precipitation and 76% give a 4 or less to the ability of climate models to simulate a global mean value of precipitation values for the next

50 years. Only 9% ranked the ability of climate models to simulate a global mean value for temperature for the next 50 years as "very good." The IPCC (2013) contends it can forecast temperatures to 2100 and beyond with "*high confidence*" (p. 21). Interestingly, 42% of respondents agreed with the statement that "the collective authority of a consensus culture of science paralyzes new thought," with 9% saying they "strongly agree."

Setting aside its small and skewed sample, Bray and von Storch's results should be easy to interpret. On most questions, most scientists are somewhere in the middle, somewhat convinced that man-made climate change is occurring but concerned about the lack of reliable data and other fundamental uncertainties. Very few scientists share the "95–100% probability" claimed by the IPCC.

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2.5.2.3 Verheggen et al., 2014, 2015

Verheggen *et al.* (2014) and Strengers, Verheggen, and Vringer (2015) reported the results of a survey they conducted in 2012 of contributors to the IPCC reports, authors of articles appearing in scientific literature, and signers of petitions on global warming (but not the Global Warming Petition Project, described below). By the authors' own admission, "signatories of public statements disapproving of mainstream climate science … amounts to less than 5% of the total number of respondents," suggesting the sample is heavily biased toward pro-"consensus" views. Nevertheless, this survey found fewer than half of respondents agreed with the IPCC's most recent claims.

A total of 7,555 people were contacted and 1,868 questionnaires were returned, for a response rate of 29%. Verheggen *et al.* asked specifically about agreement or disagreement with the IPCC's claim in its Fifth Assessment Report (AR5) that it is "virtually certain" or "extremely likely" that net anthropogenic activities are responsible for more than half of the observed increase in global average temperatures in the past 50 years.

When asked "What fraction of global warming since the mid-20th century can be attributed to human induced increases in atmospheric greenhouse gas (GHG) concentrations?," 64% chose fractions of 51% or more, indicating agreement with the IPCC AR5. (Strengers, Verheggen, and Vringer, 2015, Figure 1a.1) When those who chose fractions of 51% or more were asked, "What confidence level would you ascribe to your estimate that the anthropogenic GHG warming is more than 50%?," 65% said it was "virtually certain" or "extremely likely," the language used by the IPCC to characterize its level of confidence (Strengers, Verheggen, and Vringer, 2015, Figure 1b).

The math is pretty simple: Two-thirds of the respondents to this survey – a sample heavily biased toward the IPCC's point of view by including virtually all its editors and contributors – agreed with the IPCC on the impact of human emissions on the climate, and two-thirds of those who agreed were as confident as the IPCC in that finding. Sixty-five percent of 64% is 41.6%, so fewer than half of the survey's respondents support the IPCC. More precisely – since some responses were difficult to interpret – 42.6% (797 of 1,868) of respondents were highly confident that more than 50% of the warming is human-caused.

This survey, like the Bray and von Storch surveys previously described, shows the IPCC's position on global warming is the minority view of the science community. Since the sample was heavily biased toward contributors to the IPCC reports and academics most likely to publish, one can assume a survey of a larger universe of scientists would reveal even less support for the IPCC's position. Verheggen *et al.* reported their findings only in tables in a report issued a year after their original publication rather than explain them in the text of their peer-reviewed article. It took the efforts of a blogger to call attention to the real data (Fabius Maximus, 2015). Once again, the data reveal no scientific consensus.

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2.5.2.4 Survey of Meteorologists

One way to test with a poll or survey whether a purported consensus position on a particular topic of science is correct is to ask experts in neighboring fields for their opinions. For example, if the objective is to determine whether acupuncture is a legitimate health therapy, it would not make sense to poll acupuncturists, who have an obvious emotional as well as financial stake in the matter. A survey that found 97% consensus on this issue among them would be meaningless. On the other hand, a survey of experts in neighboring disciplines such as doctors, physical therapists, and nurses would make sense. Many of them know enough about the subject to make an informed judgement and they are less likely to be biased by professional interests.

In the case of climatology, the alleged consensus position is that computer models can accurately predict a human impact on the climate decades and even centuries in the future. Climate scientists, in particular climate modelers, may be too wed to this postulate to view it objectively, leaving it up to experts of neighboring fields to decide its validity. One such "neighboring discipline" is meteorology.

The leadership of the American Meteorological Society (AMS) has long supported the IPCC and the anthropogenic global warming theory, but its members have been much more skeptical. According to its website, "It is clear from extensive scientific evidence that the dominant cause of the rapid change in climate of the past half century is human-induced increases in the amount of atmospheric greenhouse gases" (AMS, 2012). As part of its campaign to "educate" its members on the issue, the AMS contracts with an advocacy organization called the Center for Climate Change Communication to conduct an annual survey of its members' views.

The latest AMS survey, Maibach *et al.* (2017), generated 465 complete and partial responses from AMS members. The survey asked respondents to complete the following sentence, "Do you think that the climate change that has occurred over the past 50 years has been caused by…," by choosing among seven options ranging from "largely or entirely due to human activity (81–100%)" to "there has been no climate change over the past 50 years." As could be expected, only 1% of respondents chose the "no climate change" option. Much more interesting is that only 15% chose the "largely or entirely by human activity (81–100%)," while 34% said "mostly by human activity (60–80%)" and the rest, 51%, said "more or less equally by human activity and natural events," "mostly by natural events," or "largely or entirely by natural events."

The AMS survey also asked "over the next 50 years, to what extent can additional climate change be averted if mitigation measures are taken worldwide (i.e., substantially reducing emissions of carbon dioxide and other greenhouse gases)?" Only 1% said "almost all additional climate change can be averted," the same percentage as "don't think there will be additional climate change over the next 50 years." Sixty-nine percent said either "a moderate amount" or "a small amount" of climate change could be averted, and 13% said "almost no additional climate change can be averted." This is consistent with the view that most climate change is due to natural causes and not human activity.

The AMS survey also asked, "which of the following best describes the impact(s) of local climate change in your media market over the past 50 years?" If climate change is already happening and causing harms, as the IPCC and its many allies have been saying for three decades, meteorologists would be in a good position to know since many of them are paid to report on it every day. But 49% said "the impacts have been approximately equally mixed between beneficial and harmful," and another 12% said the impacts have been "primarily beneficial" or "exclusively beneficial." Only 3% said "the impacts have been exclusively harmful." Compare this to the long lists of alleged "damages" caused by climate change and near absence of benefits reported in the IPCC's latest reports.

It is disappointing that even 15% of meteorologists apparently believe climate change is mostly caused by human activity and that 36% think the impacts of climate change have been primarily harmful. The evidence reported earlier in this chapter makes it clear that both views are probably wrong.

But the fact that a majority of meteorologists do not subscribe to the IPCC's claims of *very high confidence* is independent confirmation that the alleged consensus is not generally supported by the science community.

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2.5.3 Global Warming Petition Project

> *Some 31,000 scientists have signed a petition saying "there is no convincing scientific evidence that human release of carbon dioxide, methane, or other greenhouse gases is causing or will, in the foreseeable future, cause catastrophic heating of the Earth's atmosphere and disruption of the Earth's climate."*

The Global Warming Petition Project (2015) is a statement about the causes and consequences of climate change signed by 31,478 American scientists, including 9,021 with Ph.D.s. The full statement reads:

> We urge the United States government to reject the global warming agreement that was written in Kyoto, Japan in December, 1997, and any other similar proposals. The proposed limits on greenhouse gases would harm the environment, hinder the advance of science and technology, and damage the health and welfare of mankind.
>
> There is no convincing scientific evidence that human release of carbon dioxide, methane, or other greenhouse gases is causing or will, in the foreseeable future, cause catastrophic heating of the Earth's atmosphere and disruption of the Earth's climate. Moreover, there is substantial scientific evidence that increases in atmospheric carbon dioxide produce many beneficial effects upon the natural plant and animal environments of the Earth.

This is a strong statement of dissent from the perspective advanced by the IPCC. The fact that more than 15 times as many scientists have signed it as are alleged to have "participated" in some way or another in the research, writing, and review of the IPCC's assessments (IPCC, n.d.) is significant. These scientists actually endorse the statement that appears above. By contrast, fewer than 100 of the scientists (and nonscientists) who are listed in the appendices to the IPCC reports actually participate in the writing of the all-important Summary for Policymakers or the editing of the final report to comply with the summary, and therefore could be said to endorse the main findings of that report. The survey by Verheggen *et al.* (2014) reported above shows many or even most of the scientists who participate in the IPCC do not endorse its declarative statements and unqualified predictions.

The Global Warming Petition Project has been criticized for including names of suspected nonscientists, including names submitted by environmental activists for the purpose of discrediting the petition. But the organizers of the project painstakingly reconfirmed the authenticity of the names in 2007, and a complete directory of those names appeared as an appendix to *Climate Change Reconsidered: Report of the Nongovernmental International Panel on Climate Change (NIPCC)*, published in 2009 (NIPCC, 2009). For more information about The Petition Project, including the text of the letter endorsing it written by the late Dr. Frederick Seitz, past president of the National Academy of Sciences and president emeritus of Rockefeller University, visit the project's website at www.petitionproject.org.

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2.5.4 Conclusion

> *The most important fact about climate science, often overlooked, is that scientists disagree about the environmental impacts of the combustion of fossil fuels.*

As this section makes apparent, the surveys and abstract-counting exercises that are said to show a "scientific consensus" on the causes and consequences of climate change invariably ask the wrong questions or the wrong people. No survey data exist that support claims of consensus on important scientific questions. At best, there is broad agreement that the planet may have warmed in the late twentieth century and that a human impact could be discernible, but even these statements are no more than expressions of opinion unless the terms are carefully qualified and defined. There is no consensus on the following matters:

- anthropogenic greenhouse gas emissions are responsible for most or all of the warming of the twentieth and early twenty-first centuries;
- climate models can accurately forecast temperatures and precipitation 50 or more years into the future;
- mean surface temperatures or their rate of change in the twentieth and twenty-first centuries exceed those observed in the historical and geological record;
- climate impacts such as storms, floods, the melting of ice, and sea-level rise are unprecedented since before the beginning of the industrial age; and
- rising CO_2 levels and temperatures would have a negative impact on plant life.

In each of these areas, at issue here is not whether some scientists are right and others wrong, but that considerable and valid evidence exists *on all sides.* As befits a young academic discipline, scientists are still learning how much they do not know. Consensus may have a place in science, and it may someday arrive on key issues in climate science, but that day has not yet arrived.

Phil Jones, director of the Climatic Research Unit at the University of East Anglia, when asked if the debate on climate change is over, told the BBC, "I don't believe the vast majority of climate scientists think this. This is not my view" (BBC News, 2010). When asked, "Do you agree that according to the global temperature record used by the IPCC, the rates of global warming from 1860–1880, 1910–1940 and 1975–1998 were identical?" Jones replied,

> Temperature data for the period 1860–1880 are more uncertain, because of sparser coverage, than for later periods in the 20th Century. The 1860–1880 period is also only 21 years in length. As for the two periods 1910–40 and 1975–1998 the warming rates are not statistically significantly different … I have also included the trend over the period 1975 to 2009, which has a very similar trend to the period 1975–1998. So, in answer to the question, the warming rates for all four periods are similar and not statistically significantly different from each other.

Finally, when asked "Do you agree that from 1995 to the present there has been no statistically significant global warming" Jones answered "yes." Each of his statements contradicts claims made by the IPCC at the time, claims that are still being repeated today. It was an honest admission by Jones of the lack of scientific consensus on one of the most complex and controversial scientific issues of the day.

Sarewitz (2016) observes that "the vaunted scientific consensus around climate change – which largely rests on fundamental physics that has been well understood for more than a century – applies only to a narrow claim about the discernible human impact on global warming. The minute you get into questions about the rate and severity of future impacts, or the costs of and best pathways for addressing them, no semblance of consensus among experts remains" (p. 30).

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2.6 Conclusion

> *Because scientists disagree, policymakers must exercise special care in choosing where they turn for advice.*

Climate is an exciting field of study for scientists from many fields and types of training. While much has been learned, there is still more that is unknown than known about climate processes.

The "science tutorial" at the beginning of this chapter attempted to explain the main methodological issues and most important types of observations that together account for much of the controversy within climate science. One recurring theme has been the presence of uncertainty – in temperature records, the carbon cycle, the energy budget, human greenhouse gas emissions, and many more key areas – but also the promise that uncertainty can be reduced through rigorous adherence to the Scientific Method. Regrettably, the disciplines of the Scientific Method have not been consistently applied in all areas of climate science, resulting in polarization, intolerance, and expressions of false certainty.

The good news in this chapter is that the feared negative impacts of climate change – more frequent and intense extreme weather events, more melting ice at the poles, rapidly rising sea levels, and harm to plant life – are unlikely to emerge. There is no compelling scientific evidence of long-term trends in any of these areas that exceed the bounds of natural variability. Climate science suggests a warmer world with higher levels of atmospheric CO_2 is likely to see fewer extreme weather events and a continuation of the Greening of the Earth witnessed in the past four decades. Drawing from an extensive review of the scientific evidence, our conclusion is that the human effect on the global climate is very small and the impacts of that effect are likely to be benign.

We understand why scientists disagree on this matter. Fundamental uncertainties arise from the lack of a comprehensive physical theory of climate, from the large errors and low resolution of climate models, from insufficient or inaccurate observational evidence, and from disagreements over how to interpret data and how to set the parameters of models. Climate is an interdisciplinary subject requiring insights from many fields. Very few scholars have mastery of more than one or two of these disciplines. The Intergovernmental Panel on Climate Change (IPCC) is widely viewed as an independent source of science on all causes of climate change, but it is not. It is agenda-driven, and many people, scientists included, have been misled by its work. Finally, climate scientists, like all humans, can have tunnel vision. Sources of bias include careerism, grant-seeking, political views, and confirmation bias.

Fundamental uncertainties and disagreements prevent science from determining whether human greenhouse gas emissions are having effects on Earth's atmosphere that could endanger life on the planet. Because scientists disagree, policymakers must exercise special care in choosing where they turn for advice. Rather than rely exclusively on the IPCC, policymakers should seek out advice from independent, nongovernment organizations and scientists whose views are less likely to be affected by political and financial conflicts of interest. Policymakers should resist pressure from lobby groups to silence scientists who question the authority of the IPCC to speak for "climate science."

The distinguished British biologist Conrad Waddington (1941) wrote, "It is … important that scientists must be ready for their pet theories to turn out to be wrong. Science as a whole certainly cannot allow its judgment about facts to be distorted by ideas of what ought to be true, or what one may hope to be true." That statement merits reflection by those who continue to assert the fashionable belief, in the face of direct evidence to the contrary, that anthropogenic greenhouse gas emissions are causing or will cause dangerous global warming.

Reference

Waddington, C.H. 1941. *The Scientific Attitude*. London, UK: Penguin Books.