

REPORTING ON CLIMATE CHANGE: UNDERSTANDING THE SCIENCE

FOURTH EDITION

Bud Ward & L. Jeremy Richardson

THANKS TO TECHNICAL REVIEWERS & CONTRIBUTORS

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Reporting on Climate Change: Understanding the Science, Fourth Edition

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EDITOR'S NOTE

Considering the sheer number of advances in our understanding of climate science over the last decade, the release of this fourth edition of *Reporting on Climate Change: Understanding the Science* is long overdue. Although written primarily for journalists, this volume aims to assist educators, communicators, and the public at large.

The volume is particularly important at the present moment for at least three reasons. First, the changes in the reporting industry over the past decade are having a profound impact on science journalism. As the public moves away from print media toward online sources, the business model for news outlets has changed dramatically. In many cases, the first victims of budget cuts are—you guessed it—the science and environmental reporters. That has only exacerbated the fact that most journalists—even those assigned to covering science news—have no scientific or technical background. The need for a volume such as this has therefore only grown.

Second, the misinformation propagated by opponents of climate change action has grown more voluminous over the past year, following criticism of the Intergovernmental Panel on Climate Change (IPCC), a bunch of stolen e-mails, and an unusually snowy winter in much of the United States in 2010. As we shall see, the mistakes of the IPCC have been largely overblown, several independent reviews have cleared scientists of any scientific wrongdoing in the e-mail controversy, and the heavy snow (although allowing for easy jokes about Al Gore) is actually consistent with our understanding of climate change impacts. In short, none of these events has altered our fundamental understanding of the science of climate change. In reality, the science of human-induced climate change has become even more solid over the past decade. The third edition of this volume was based primarily on the IPCC's Third Assessment Report (TAR), released in 2001. In 2007, the IPCC released its Fourth Assessment Report (AR4), which established a stronger scientific consensus and a greater level of confidence in the conclusions.

Third, although the U.S. House of Representatives passed legislation in June 2009 to set up a cap-and-

trade system to limit greenhouse gases, the 2010 elections have ushered in a new class of representatives who openly question the science of climate change, and many more aren't convinced that solving the problem is worth the cost. The political appetite on Capitol Hill for addressing climate change remains as low as ever. Even President Obama has acknowledged the reality that climate legislation will have to be tackled in "bite-size" pieces in the 112th Congress. It is critical that policy makers be armed with accurate information on the science of climate change—and the risks associated with failing to address the problem.

Finally, the editor would like to specifically recognize and thank the editor of the third edition, Bud Ward, whose talent in communicating the science of climate change was evident in that edition. The new edition relies heavily on his work, and many parts were so clear and accessible that they remain unchanged in this edition. Chapter 10 on the ozone hole was very ably updated by Stephen O. Andersen, David W. Fahey, Marco Gonzalez, K. Madhava Sarma, Stephen Seidel, and Durwood Zaelke, for whose insight and expertise we are very grateful. Special thanks to Jay Gulledge of the Pew Center on Global Climate Change, whose insightful comments and suggestions significantly improved this volume. The editors would like to offer sincere thanks to the sponsoring organization, the Environmental Law Institute, for its ongoing leadership in creating and updating this volume. Scott Schang at ELI led the effort to create the fourth edition. We would also like to thank the Department of Energy and many reviewers who made earlier editions of this guide possible.

We hope that the fourth edition of *Reporting on Climate Change: Understanding the Science* will find its way into the hands of reporters and editors alike, as they sort through the myriad dissonant voices in the public discussion on the science of climate change and what to do about it.

L. Jeremy Richardson, Ph.D.

Editor

June 2011

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EXECUTIVE SUMMARY

The fourth edition of *Reporting on Climate Change: Understanding the Science* is intended to serve as a resource for journalists who are covering the scientific and political developments on this important issue. Ultimately, the aim is to reach the general public—once armed with accurate information, journalists and editors can help foster an informed and honest policy debate.

This volume delves into the details of the important scientific concepts that underpin our understanding of climate change. These concepts are presented here in accessible language, so that those without training in science can gain insight into our knowledge of the climate system and how it works. The volume as a whole presents a complete picture of the science and serves as a reference for nontechnical readers; the main concepts and important take-home messages contained in it are summarized below.

RECENT CONTROVERSIES HAVE NOT CHANGED OUR SCIENTIFIC UNDERSTANDING

Most of the information here is based on the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), released in 2007. The IPCC assessment process represents an ambitious scientific undertaking: the assessments are comprehensive, detailed, and consensus-based. The IPCC has an unparalleled peer-review process and is formally approved by about 120 governments as a guide for decisionmakers. It remains the gold standard in assessing and summarizing the current state of the science of climate change, despite some bad press in the past year over a small number of mistakes and some highly publicized e-mails. The AR4 (three volumes totaling almost 3,000 pages) has been scrutinized more intensely than perhaps any other scientific document in history—some 2,000 experts volunteered their time to write, edit, and review the material contained in these volumes. The AR4 is a consensus document, in that all authors of a given section had to agree to all text in that section, and all lead authors and governments had to agree to all text in the Summary for Policymakers. Consequently, the report presents a conservative or “lowest-common-denominator” interpreta-

tion of scientific confidence and certainty. (See Appendix A for an overview of the IPCC process.)

Two errors in the AR4 received considerable press attention. Both appeared in the second volume, “Impacts, Adaptation, and Vulnerability” (Working Group II). *But the fundamental scientific understanding of climate change is described in the first volume, “The Physical Science Basis,” and no errors in this volume have yet surfaced.* Following is a very brief description of the controversies.

Himalayan Glaciers. The chapter on projected climate change impacts in Asia in the AR4 Working Group II volume contains an unsubstantiated and apparently implausible claim that the Himalayan glaciers could disappear by 2035. This statement was apparently based on a non-peer-reviewed paper, and its inclusion is counter to IPCC guidelines. However, this single incorrect sentence and subsequent correction do not take away from the robust and consistent statement appearing in the first volume:

Climate change is expected to exacerbate current stresses on water resources from population growth and economic and land-use change, including urbanisation. On a regional scale, mountain snow pack, glaciers and small ice caps play a crucial role in freshwater availability. Widespread mass losses from glaciers and reductions in snow cover over recent decades are projected to accelerate throughout the 21st century, reducing water availability, hydropower potential, and changing seasonality of flows in regions supplied by meltwater from major mountain ranges (e.g. Hindu-Kush, Himalaya, Andes), where more than one-sixth of the world population currently lives.

Sea-Level Rise in the Netherlands. The IPCC was also criticized for allegedly overstating the threat of sea-level rise to the Netherlands. The second volume included the following incorrect sentence: “The Netherlands is an example of a country highly susceptible to both sea level rise and river flooding because 55 percent of its territory is below sea level.” It turns out that the figure includes land that is above sea level but susceptible to river flooding. The figure was originally obtained directly

from the Dutch government, and the agency responsible, the Netherlands Environmental Assessment Agency, recently clarified that 26% of the land area is below sea level, and another 29% is susceptible to river flooding. Although the original statement, obtained directly from the Dutch government, was incorrect, it does not undermine the IPCC's conclusions on future sea-level rise due to climate change.

In response to these errors, the IPCC and the U.N. together commissioned an independent review (<http://reviewipcc.interacademycouncil.net/>) of IPCC policies and procedures. The review, conducted by the InterAcademy Council, found that the IPCC's process "has been successful overall, but IPCC needs to fundamentally reform its management structure and strengthen its procedures to handle ever larger and increasingly complex climate assessments as well as the more intense public scrutiny coming from a world grappling with how best to respond to climate change." The IAC offers a number of recommendations for improving the IPCC's procedures to ensure impartiality and transparency.

Hacked E-mails. In November 2007 unknown persons hacked into the e-mail servers of the Climate Research Unit (CRU) at the University of East Anglia in England. The CRU is one of four organizations worldwide that independently gather worldwide thermometer data to construct records of global temperature. The hackers sorted through and selected more than 1,000 e-mails and posted them on the web. This action was not authorized by the owner of the e-mails (the university) and is being investigated as a possible crime.

The vast majority of the e-mails were routine and unsuspecting, if impolite, but a dozen or two created the appearance of controversy. To date, several independent investigations have concluded that the scientists involved in the e-mail exchanges acted ethically and properly. Unfortunately, the "controversies" reported by the press were largely phrases that had been taken out of context. For example, one researcher wrote about using a "trick" to "hide the decline." As used here, a "trick" is a clever or novel way of solving a problem—not an attempt to trick or deceive the public about climate data, as was commonly reported or implied in the press. A more in-depth description of the hacked e-mails was prepared by the Pew Center on Global Climate

Change (<http://www.pewclimate.org/docUploads/east-anglia-cru-hacked-emails-12-07-09.pdf>). Five separate investigations (three in the United Kingdom and two in the United States) have cleared the scientists of any scientific misconduct, but several of them called for greater transparency in the handling of scientific data.

WARMING IS UNEQUIVOCAL

The AR4 concluded that the warming of the climate system is unequivocal. The scientific community chose this word (with the blessing of world governments that scrutinized the summary line by line) because the increase in global average temperature is no longer in doubt. Scientists rarely use such conclusive language, preferring instead to provide probabilities and uncertainties to bound their results.

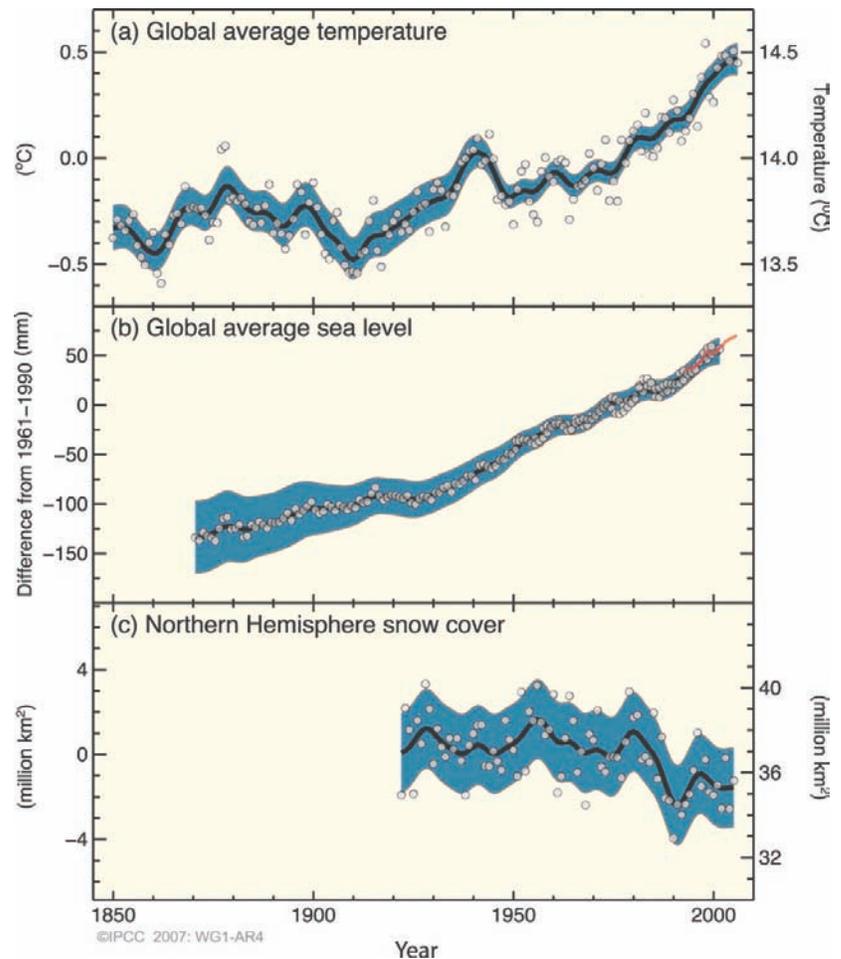


Figure 1. Actual data showing observed changes in (a) global average surface temperature; (b) global average sea level from tide gauge measurements (blue) and satellite data (in red); and (c) Northern Hemisphere snow cover for March–April. All are differences relative to the averages for the period 1961–1990. Source: IPCC AR4, Summary for Policymakers, Figure SPM.1.

The AR4 states in its Summary for Policymakers (WGI), “Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.”

Quite simply, anyone who argues that the Earth has not warmed over the past century is either misinformed or disingenuous. This question is no longer debated in the scientific community.

OBSERVATIONS ARE CONSISTENT

The conclusion that the world has warmed is based on multiple, independent lines of evidence, which is why scientists are so convinced. Multiple data sets, observations of different physical quantities, and measurements from around the world, all point to the same conclusion—a warming world. The AR4 highlights a few of the main observational lines of evidence:

- Both land surface air temperatures and SSTs [sea surface temperatures] show warming. In both hemispheres, land regions have warmed at a faster rate than the oceans in the past few decades, consistent with the much greater thermal inertia of the oceans.
- The warming of the climate is consistent with observed increases in the number of daily warm extremes, reductions in the number of daily cold extremes and reductions in the number of frost days at mid-latitudes.
- Changes in temperature are broadly consistent with the observed nearly worldwide shrinkage of the cryosphere.
- Observations of sea-level rise since 1993 are consistent with observed changes in ocean heat content and the cryosphere.
- Observations are consistent with physical understanding regarding the expected linkage between water vapor and temperature, and with intensification of precipitation events in a warmer world.

That these different lines of observational evidence support one another and lead to the same conclusion strengthens scientists’ confidence in the result.

HUMANS ARE PRIMARILY RESPONSIBLE FOR CHANGES IN CLIMATE

Having established that there has been a warming trend, the next obvious question is, why? Here the AR4 is much more certain than in previous assessments:

Most of the observed increase in global average temperatures since the mid-20th century is very likely [$>90\%$ probability] due to the observed increase in anthropogenic greenhouse gas concentrations. Discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes, and wind patterns.

Scientists have considered all potential causes of the warming trend—not only human effects like greenhouse gas emissions but also natural effects like solar variability. The warming trend, particularly in the last 50 years, is simply not consistent with changes in the Sun over that time. The science of detection and attribution is discussed in more detail in Chapter 9, and a complete discussion of natural changes in climate appears in Chapter 2.

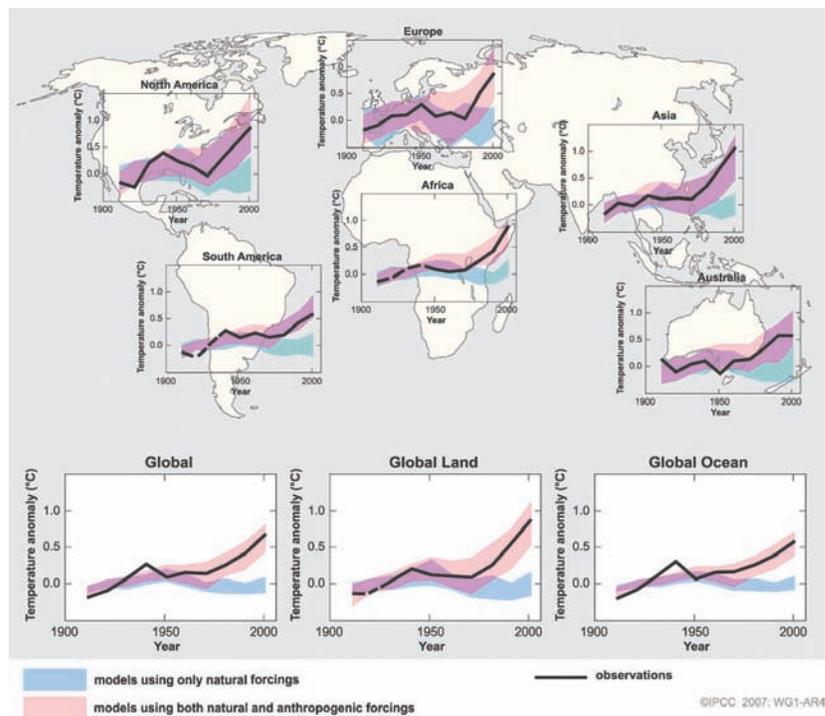


Figure 2. Comparison of observed changes in surface temperature with climate model predictions for each continent and the globe as a whole. Data are in black, and models are shown by the shaded areas (blue for natural effects only, and red for both natural and human impacts). Source: IPCC AR4, Summary for Policymakers, Figure SPM.4.

WE ARE FEELING THE EFFECTS NOW

The effects of human-induced climate change are being felt around the world—including in the United States. The U.S. Global Change Research Program (USGCRP) coordinates and integrates federal research on climate change and its implications for society. Since 1989, its assessment reports have helped summarize the science of climate change (see www.globalchange.gov for helpful resources). The USGCRP released an assessment report in June 2009 called *Global Climate Change Impacts in the United States*, which assessed the current impacts and future projections for climate change in the United States. Among the key findings of the report are:

- **Climate changes are underway in the United States and are projected to grow.** *Climate-related changes are already observed in the United States and its coastal waters. These include increases in heavy downpours, rising temperature and sea level, rapidly retreating glaciers, thawing permafrost, lengthening growing seasons, lengthening ice-free seasons in the ocean and on lakes and rivers, earlier snowmelt, and alterations in river flows. These changes are projected to grow.*
- **Widespread climate-related impacts are occurring now and are expected to increase.** *Climate changes are already affecting water, energy, transportation, agriculture, ecosystems, and health. These impacts are different from region to region and will grow under projected climate change.*

The report can be found at <http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts/key-findings>.

WHAT KINDS OF CHANGES ARE PROJECTED?

In addition to the climate system's response to increased greenhouse gas (GHG) concentrations, many other factors will have an influence on the Earth's climate in the next century. These include variables like population growth, demographics, technological change, the extent of future GHG emissions, and policy decisions made today and beyond. For this reason, the IPCC has constructed a number of standardized socioeconomic scenarios to represent a range of plausible futures, which are contained in a separate IPCC report, the *Special Report on Emission Scenarios (SRES)* published in 2000. The climate models in the AR4 (and the IPCC's 2001 Third Assessment Report) were driven by the GHG emissions and land surface changes prescribed in these scenarios. Over the past decade the climate assessment research

community has developed new understanding of socioeconomic drivers, and the Fifth Assessment Report, due in 2013–2014, will employ a new set of greenhouse gas emissions scenarios that are currently in development.

Even so, over the last decade our collective scientific understanding of the climate system has improved dramatically, both observationally (through longer, more numerous, and higher-quality data sets of climate variables) and theoretically (more detailed and more numerous model results suitable for comparison to observations). The AR4 was therefore able to make more highly quantitative estimates of future climate change than previous assessments. Specifically, the AR4 was able to refine ranges of expected temperature increase and sea-level rise (depending on the emissions scenario):

- As shown in the table, the global average temperature increase (above the level in 2000) projected for the year 2100 ranges from 0.6°C to 4.0°C depending on the emission scenario. Although some areas will warm more than others, an increase in temperature is expected everywhere on the globe. (See Chapter 7 for details.)
- Also shown in the table is the range of global average sea-level rise for 2100. Again, the projection is scenario-dependent, and the AR4 gives a range of 0.18 m to 0.59 m for the average increase in sea level worldwide. However, this projection is probably an underestimate, because the IPCC determined it was not possible to make an accurate prediction of future changes in the rate of ice flow from the Greenland and Antarctica ice sheets. Clearly, ice loss from the large, land-based ice sheets will be a major contributor to sea-level rise throughout this century and beyond. (See Chapter 8 for details.)
- Worldwide, snow cover is expected to decrease, along with widespread deepening of thaw depth in permafrost regions.
- Arctic sea ice is particularly sensitive to warming, and some models predict that the Arctic could be practically ice-free in the summer by the end of the century. Models for Arctic sea ice extent have underestimated the observed rate of shrinkage, and refined projections now suggest an ice-free Arctic in the summer by as early as 2035, or as late as 2080.
- Projections of changes in extreme weather events are better quantified than in previous assessments. Heat waves, for example, are expected to be more intense, longer-lasting, and more frequent in a future climate, both globally and in most regions.

Case	Temperature change (°C at 2090–2099 relative to 1980–1999) ^{a, d}	(m at 2090–2099 relative to 1980–1999)	Sea-level rise
	Best estimate	Likely range	Model-based range excluding future rapid dynamical changes in ice flow
Constant year 2000 concentrations ^b	0.6	0.3 – 0.9	Not available
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

Notes:

- a) Temperatures are assessed best estimates and likely uncertainty ranges from a hierarchy of models of varying complexity as well as observational constraints.
- b) Year 2000 constant composition is derived from Atmosphere–Ocean General Circulation Models (AOGCMs) only.
- c) All scenarios above are six SRES marker scenarios. Approximate CO₂-eq concentrations corresponding to the computed radiative forcing due to anthropogenic GHGs and aerosols in 2100 (see p. 823 of the Working Group I TAR) for the SRES B1, AIT, B2, A1B, A2, and A1FI illustrative marker scenarios are about 600, 700, 800, 850, 1250, and 1550ppm, respectively.
- d) Temperature changes are expressed as the difference from the period 1980–1999. To express the change relative to the period 1850–1899 add 0.5°C.

Table 1. Projected global average surface warming and sea-level rise at the end of the 21st century.

POTENTIAL CONSEQUENCES ARE HIGH

While it's impossible to predict with certainty the exact state of the climate a century from now, the broad projections highlighted above, and the severity of the changes, represent a few of the challenges that society will face if it fails to curb GHG emissions.

The concept of uncertainty often fuels the debate over how, or even whether, to respond to the threat of climate change. Opponents of action often argue that because we can't be sure humans are to blame, we shouldn't take economically costly actions to reduce emissions. However, policymakers are often forced to act in the face of uncertainty. Many policy decisions are probably taken in the face of less certainty than the 90% probability the IPCC has assigned to the prospect that humans are changing the climate.

Although inherent uncertainties remain (particularly with respect to human development, socioeconomics, demographics, population growth, and how sensitive the climate system is to increased GHG concentrations), it is nevertheless clear that there is significant potential for negative consequences. Evidence suggests in some cases that actual observations of climate change are outpacing model projections—meaning that we may actually be *underestimating* the potential impacts.

In reality, uncertainty cuts both ways. The average temperature of the Earth could ultimately be lower than we think, but it could also be higher. Actually, it is more likely to be higher than our best estimate at the present time. This is because the uncertainty is asymmetric—there is a *greater* chance of more serious impacts, than there is of lesser impacts. (See Figure 3.)

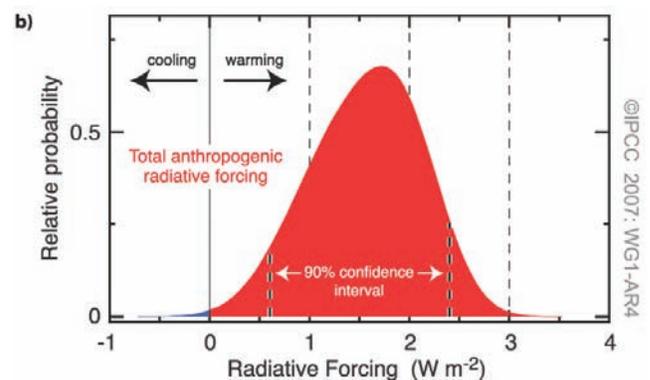


Figure 3. This plot shows the probability of the size of the human impact on climate, in Watts per square meter (W/m^2). It indicates that a range of values is possible but that the most probable value is just below $2 W/m^2$. Importantly, negative values (meaning a cooling effect) are extremely unlikely. Source: IPCC, AR4 WGI, Technical Summary, Figure TS.5b.

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In policy circles, much discussion centers on the “safe” level of greenhouse gas concentrations in the atmosphere. 550 parts per million (ppm)? 450 ppm? 350? Or limiting the post-industrial temperature increase to 2°C? Even 1.5°C? The problem is that science can’t tell us what the “safe” level is—it can only offer insights into the consequences of those physical states. In terms of making policy decisions, climate change should be considered in a risk framework, and the risks of catastrophic impacts clearly rise with the continued emissions of greenhouse gases.

CONCLUSION

In short, this volume provides details of the scientific principles that govern the climate system, and

an in-depth look at what we do know and still don’t know about climate change, all in non-technical terms. We hope this will provide editors, journalists, and the general public with critical insights into the current scientific understanding of climate change. The nature of science is such that there will always be more to learn and study, and more questions to ask. However, at the end of the day, the decision on whether to respond to the threat of climate change, and how to do so, belongs to society’s decisionmakers. Ultimately, society must decide whether the benefits of responding to the threat of climate change—clean energy, new jobs, improved national security, energy savings, fewer damages due to the impacts of climate change, and reduced risks of catastrophic climatic events—are worth the costs.

CHAPTER 1: THE CLIMATE SYSTEM AND THE FORCES THAT DRIVE IT

Climate—the prevailing regime of temperature, precipitation, humidity, wind, sunshine, snow, ice, sea conditions, etc.—is a particular characteristic of individual regions of planet Earth. The climate of the Earth as a whole is also unique—making vast areas of the Earth a hospitable refuge for life as we know it in a vast, harsh, hostile, and largely sterile universe. Carl Sagan, the famous astronomer who led NASA’s Voyager missions in the 1970s and 1980s, coined the phrase “Pale Blue Dot” to describe the Earth, after the Voyager 2 spacecraft snapped a picture of the Earth from beyond Neptune.

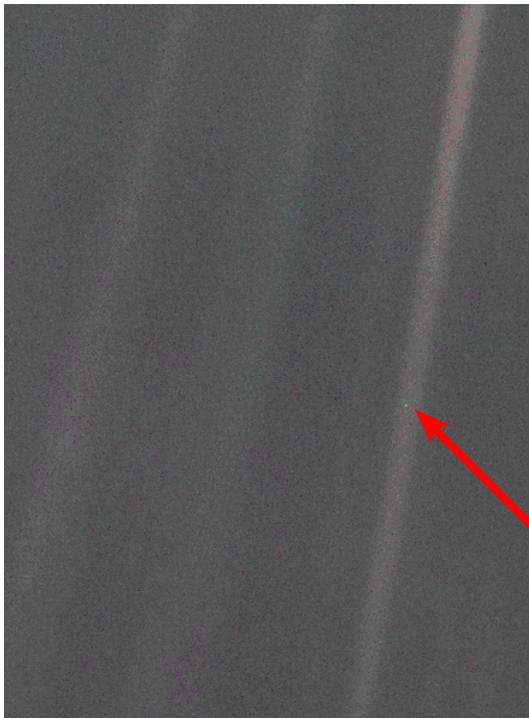


Figure 4. Seen from 6.1 billion kilometers (3.7 billion miles), Earth appears as a tiny dot (the blueish-white speck approximately halfway down the brown band to the right) within the darkness of deep space. Source: http://en.wikipedia.org/wiki/Pale_Blue_Dot.

Climate on Earth has changed repeatedly as the planet has evolved geologically over its 4.6 billion-year existence. During most of the Earth’s history, climate—

and even the atmosphere itself—has been dramatically different from what it is today. On Earth, species have evolved and have become extinct as a result of climate change. Even during the eye blink of humans’ existence on Earth, settlements, cities, and states have emerged and vanished as a result of climate change.

Understanding climate presents an enormous intellectual challenge. It involves all the “earth sciences”—physical sciences, life sciences, and some would say even social sciences. It goes way beyond meteorology (the science of weather) and beyond the atmosphere itself. Climate results from the interaction of the Sun’s radiation, the Earth’s orbital mechanics, the circulation and chemistry of the Earth’s atmosphere, the changing polar ice and glaciers, the deep ocean currents, the weathering and shifting of the Earth’s crust, and even the plants and animals that populate the Earth’s surface. And now, even humans. Some geologists have begun referring to the present period in Earth’s history as the “Anthropocene” to indicate that human activities are now being observed in the Earth’s ecosystems.

THE SUN

The energy source that drives much of what happens on Earth—not only the climate but also life itself—is the Sun. The Sun, which comprises about 99.8 percent of the mass in the solar system, consists mostly of hydrogen. At the Sun’s core, hydrogen atoms are constantly being combined to form atoms of helium in the reaction known as thermonuclear fusion. In essence, the Sun is like a hydrogen bomb that has been going off continually for billions of years. Although the amount of energy released by the Sun is enormous, the intensity of solar radiation (**solar irradiance**) declines as it moves away, which is one reason why the more distant planets are colder than planets closer to the Sun, like Earth.

The Sun produces energy in the form of **electromagnetic radiation**. What is electromagnetic radiation? Technically speaking, it is a wave of fluctuating electric and magnetic fields in space. It comes in many forms, most of which people recognize. Visible light, the warmth of a glowing fire, the X-rays used by the dentist,

even the radio waves we listen to—all are electromagnetic radiation.

Electromagnetic radiation travels in waves, and it is the length of these waves that distinguishes the various kinds of electromagnetic radiation. Energy coming from the Sun runs the gamut from very short-wavelength (high energy) X-rays and gamma rays, to ultraviolet and visible light, to the longer-wavelength infrared radiation (heat). But most of the energy affecting the Earth and its climate arrives at wavelengths within and near the spectrum of visible light, known to most people simply as sunlight (it is the invisible ultraviolet portion of sunlight that causes sunburn).

As solar radiation in these various wavelengths hits the Earth's atmosphere, land surface, and ocean surface, it heats them. This heat is the main energy input to our climate system. For this reason, climate scientists must—and do—study changes in the Sun's output. Of course, incoming solar energy has other effects as well. It breaks apart molecules in the atmosphere and thus drives various changes in atmospheric chemistry. Plants use solar energy to convert water and carbon dioxide into sugars and oxygen—the biological process known as **photosynthesis**. Photosynthesis is one of the foundations of the entire web of life and has shaped the Earth's atmosphere into what it is today.

For a long time, scientists believed that the amount of solar energy leaving the Sun and arriving at the Earth changed very little over time. They coined the term “solar constant” to describe something that they later realized wasn't constant—research in recent decades indicates that solar output does indeed change, over time scales ranging from minutes to decades and even longer. The solar output varies by less than 0.1 percent from decade to decade (more over longer time frames), and the value of the total, unaveraged solar irradiance hovers around 1370 Watts per square meter (W/m^2). Averaged over the surface area of the globe, the top of the Earth's atmosphere receives about $342 W/m^2$ of incoming solar radiation, measured in terms of its climate-forcing effect averaged

over the whole globe for an entire year. (See Forcing vs. Feedback, page 11). Small changes in this critical part of the planet's **energy budget** can have a big impact on the climate—which is why scientists are keen to understand this number and how it changes over time.

The 11-year solar cycle of sunspot activity correlates with slight changes in solar output. Other changes over longer periods have been observed or speculated upon, but high-quality, consistent modern instrumental observations have been made only since the dawn of the satellite era in the late 1970s. Historical records suggesting an absence of observed sunspots between 1645 and 1710 (the **Maunder Minimum**) have been linked with what was believed to be a cooler period of climate during the 17th to 19th centuries, known as the **Little Ice Age**. But pre-instrumental climate records are as dubious as pre-instrumental records of solar activity: recently, for example, the Little Ice Age has been pictured as a phenomenon limited to the northern hemisphere and most intense in the region surrounding the North Atlantic Ocean. (See Chapter 2 for more discussion on climate variability.)

Of the $342 W/m^2$ of incoming solar radiation, some 29% is reflected back to space by clouds, the atmosphere itself, and the Earth's surface. The atmosphere

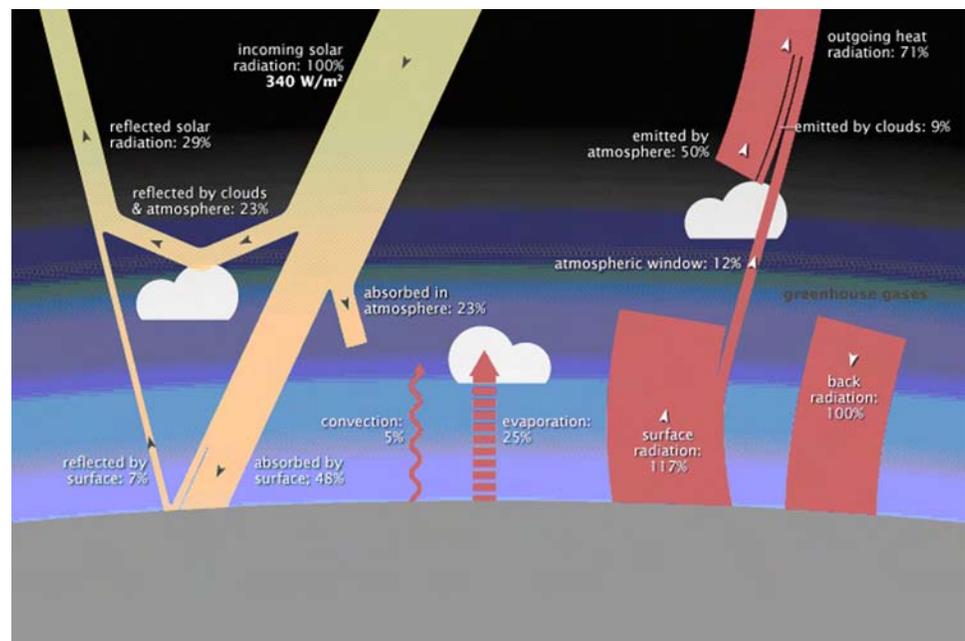


Figure 5. *The Energy Balance of the Earth's Atmosphere. The atmosphere releases heat radiation equivalent to about 59% of the incoming solar radiation, as is known from satellite measurements. This energy must be balanced by radiation absorbed by the atmosphere—but where does it come from? A large fraction comes from the incoming radiation from the Sun (about 25% of the incoming solar radiation is absorbed in the atmosphere), another large amount comes from evaporation from the Earth's surface, and the rest comes from convection and heat from the Earth's surface. Source: <http://earthobservatory.nasa.gov/Features/Energy-Balance/page6.php>.*

itself absorbs about 23% of the incoming radiation, and nearly half (about 48%) is absorbed by the land and ocean surface.

When incoming solar radiation, mostly in the wavelengths of visible light, is absorbed by the Earth's surface, it is converted to heat. This heat eventually warms the atmosphere in a number of ways. Some heat energy is radiated into the atmosphere as infrared radiation, the longer wavelengths we can feel when we hold our hands up to a warm bed of coals. Some of it heats the atmosphere directly via molecular motion (**convection**). Some of the heat evaporates water from the surface, causing water vapor to enter the atmosphere. The water vapor then emits heat back to the atmosphere when it rises and condenses into liquid again.

THE GREENHOUSE EFFECT

Ultimately, the Earth releases back into space as much radiation energy as it receives from the Sun. Although the dominant wavelengths of incoming and outgoing radiation are different, the total amount of incoming and outgoing energy ultimately must balance as dictated by the laws of physics. In scientist-speak, the system is in **equilibrium** when this balance exists. The heated surface and atmosphere radiate their energy at infrared wavelengths. Some of it is re-radiated back down to the Earth and atmosphere, but after working its way through the system, all of this heat is eventually radiated as infrared back to outer space. The higher a body's temperature, the more heat energy it will radiate as infrared (other things being equal). If the amount of incoming energy increases, the Earth system must adjust to restore equilibrium; its surface and atmosphere will therefore warm until they reach temperatures sufficient to give off enough infrared radiation to balance the increased amount of energy the planet is taking in.

The atmosphere is transparent to most of the incoming solar radiation at the visible wavelengths in which it arrives from the Sun—it lets visible light through without absorbing much of it. However, it is less transparent to infrared and thus readily absorbs some of the infrared radiation released from the Earth's warm surfaces.

The nitrogen and oxygen that make up about 99% of the atmosphere do not absorb infrared radiation. What absorbs it are certain **trace gases**, which each constitute only a small fraction of 1% of the entire atmosphere. The trace gases that absorb infrared radiation include water vapor, carbon dioxide, methane, nitrous oxide, ozone, and various chlorine-, fluorine-, and bromine-containing molecules.

These gases cause the atmosphere to absorb outgoing infrared energy, and to retain it longer before eventually radiating it back to space. In order to achieve the energy equilibrium that the laws of physics dictate, the Earth must warm so that the amount of infrared energy emitted back to space balances the incoming solar radiation. As a result, the temperature of the lower atmosphere overall is quite a bit warmer (about 33°C [59°F] warmer) than it would be if the atmosphere did not contain these gases. This effect is called the **greenhouse effect**—by imperfect analogy with the way the greenhouse glass generally lets in visible sunlight while trapping outgoing infrared radiation, thereby keeping the greenhouse warm. (Greenhouses also have other mechanisms in effect.) The atmosphere's greenhouse effect is entirely natural, has been well measured and documented, and is widely accepted and uncontroversial among Earth scientists.

The laws of physics govern how heat-trapping trace gases (called **greenhouse gases**, or GHGs) absorb infrared radiation. *The physical mechanism described above, by which GHGs absorb infrared radiation and heat the atmosphere, remains undisputed and has been understood for well over a century.*

In fact, the natural greenhouse effect is a big reason why the Earth is hospitable. Venus, which has large concentrations of GHGs, has an unbearable average surface temperature of 464°C, while Mercury, which is much closer to the Sun but has virtually no atmosphere to trap heat, is a cooler 167°C on average at the surface. If Earth had no atmosphere at all, it would be a frigid -18°C (0°F) on average at the Earth's surface—but the real Earth has an average surface temperature of about 15°C (59°F). Thus, the natural greenhouse effect is crucial for maintaining the average temperature at a relatively comfortable level.

However, various human activities such as fossil fuel combustion and deforestation have, since the start of the Industrial Era, been increasing atmospheric concentrations of key greenhouse gases on a global scale. On the basis of decades of scientific research, the vast majority of earth scientists now agree that the increased atmospheric concentrations of greenhouse gases are absorbing more infrared energy and causing a progressive warming of the Earth's lower atmosphere. Recent polls of scientists actively researching the climate system and Earth scientists in general support this conclusion—see Chapter 13. The portion of the warming caused by human activities is often called the **anthropogenic** greenhouse effect. (See Chapter 3, Greenhouse Gases, and Chapter 4, The Human Effect, for additional details on this discussion.) There has been considerably more controversy about the anthropogenic greenhouse effect than about the natu-

ral greenhouse effect, although the controversy is more often driven by political and economic motivations.

The following discussion will focus on some of the mechanisms that drive the climate system in addition to the Sun: atmospheric circulation, oceans, the cryosphere, and living things and changes in atmospheric composition.

ATMOSPHERIC CIRCULATION

Incoming solar radiation warms the equator more than it does the poles. The reason is that the Sun's rays fall nearly perpendicular to the Earth's surface at the equator, but strike it obliquely (at an angle) at the poles. Not only does a given amount of solar radiation spread out over a larger land area at the poles, but it also passes through a thicker slice of the atmosphere, causing more light to be reflected back to space before reaching the surface. Moreover, the ice-covered polar surface reflects more light back to space than the ocean and land of the tropics, because ice and snow are more reflective than land, trees, and open water. (Anyone who has walked outside and squinted at snow-covered ground on a sunny day understands this intuitively.)

The natural tendency of Earth's atmosphere and oceans is to even out this heat by redistributing it from the warm equator to the frigid poles. A number of mechanisms, primarily convection, are responsible for this redistribution of heat. Convection is the tendency of warm air to rise because it is less dense, lighter, and more buoyant. This is the principle that makes chimneys draw heat and smoke upward and hot-air balloons stay aloft. A small-scale illustration of atmospheric convection is the offshore breeze many beachgoers observe each evening as the land cools more rapidly than the sea, and as rising (warm) offshore air masses pull cooler air in to replace them.

The idealized picture of a convective conveyor belt moving cool air toward the equator and warm air toward the poles is complicated by several factors. As Earth spins on its axis, the moving air is deflected by the **Coriolis effect**. This is the force that causes wind

to rotate clockwise around low-pressure centers in the Northern Hemisphere and counter-clockwise in the Southern Hemisphere. Still other influences on the movement of air are exerted by the placement of landmasses and mountains. The end result is a more complex pattern of swirls and eddies.

Higher up in the atmosphere, air circulates around the planet in fairly consistent large-scale streams—such as the westerlies, the trade winds, and the jet streams. These circulation patterns determine climate at the regional scale in many places. Variations in the large-scale circulation patterns can and do occur, and these variations can often bring a major weather shift to a given region.

OCEANS

Oceans, too, are a major heat-transfer engine in the Earth's climate system. Tropical oceans, especially, are big absorbers of solar energy. Oceans absorb more than half of the solar energy reaching the Earth's surface. Once the ocean surface is heated by the Sun, that heat is redistributed by a complex global system of ocean currents. The movement of ocean currents, however, is much slower than the movement of atmospheric circulation currents.

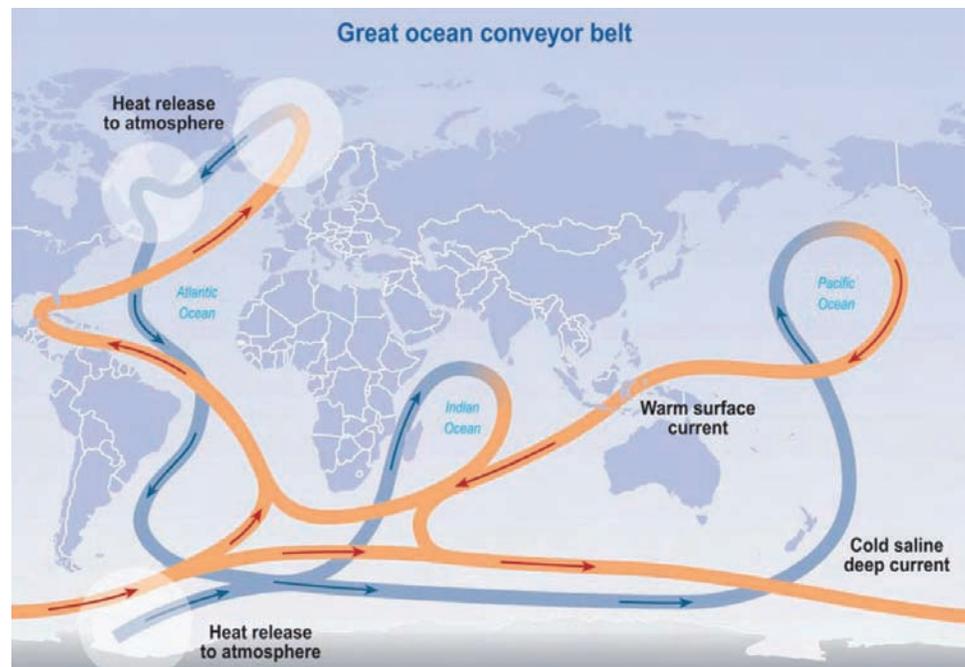


Figure 6. Schematic illustration of the global circulation system in the world ocean consisting of major north-south thermohaline circulation routes in each ocean basin. Warm surface currents and cold deep currents are connected in the few areas of deepwater formation in the high latitudes of the Atlantic and around Antarctica (blue), where the major ocean-to-atmosphere heat transfer occurs. This current system contributes substantially to the transport and redistribution of heat. Source: IPCC, *Climate Change 2001: The Scientific Basis*.

The water in the oceans is structured in layers, and these layers are important to circulation patterns. The uppermost layer, where heat is first absorbed, is well mixed by wind and waves and exchanges heat and gases with the atmosphere on the shortest timescales. Much of the energy absorbed by the ocean's upper layer evaporates water. That heat transfers to warm, humid air that produces convective updrafts that can drive weather systems. Warm late-summer surface water from the tropical Atlantic, for example, fuels hurricanes.

Currents and seasonal changes drive the mixing of water from the surface layer of the ocean with water from deeper layers. As the water mixes, there is also a transport of heat, dissolved gases, dissolved minerals, and even microscopic sea creatures. Heat convection is one of the forces that drives ocean currents, just as in the atmosphere, but there are different forces also at work. Prevailing winds, for example, can add momentum to ocean surface currents. Moreover, convection works differently in the oceans. The density differences between water masses are caused not just by temperature but also by salinity. The saltier the water is, the denser it is. Thus, cold, salty water tends to sink below warmer, fresher water. The large currents set up by this force are called **thermohaline circulation**. (Figure 6.)

Thermohaline circulation offers an example of the complexities and feedbacks involved in ocean currents, and the many ways in which they interact with surface weather and climate. When water evaporates from the surface layer, for example, the surface water becomes cooler and saltier. Precipitation and the melting of ice can make surface water fresher. In other words, activity in the atmosphere affects activity in the ocean, even as activity in the ocean affects activity in the atmosphere. The complexity of such feedbacks is one thing that makes predicting climate change difficult.

One of the best-known examples of thermohaline circulation is the Gulf Stream, a "river" of relatively warm, fresh surface water that flows from the tropics to the northern North Atlantic Ocean, where it gives off its heat to the atmosphere. As the water becomes colder and saltier, it sinks. This process is a major driver of the global thermohaline circulation of the ocean. The heat trans-

ported from the tropics northward also makes much of Western Europe considerably warmer than it otherwise would be. The notion that this North Atlantic "conveyor belt" might stop transporting heat to northern latitudes was the inspiration for the science fiction thriller, *The Day After Tomorrow*. Although the movie greatly exaggerated the potential effects of altered ocean currents, it reflected the fact that ocean heat transport is a major determinant of regional climate patterns.

The ocean surface layer both absorbs and releases carbon dioxide (CO_2), a major greenhouse gas, and oxygen, a gas essential to many forms of life. In fact, the ocean acts as a pump that removes a significant portion of the added anthropogenic CO_2 from the atmosphere. This dissolved CO_2 is taken up by microscopic plant life, phytoplankton, to make shells, and works its way through the food web as the phytoplankton are consumed by other forms of marine life. When these plankton die, their shells sift down as sediment to the ocean floor, where the CO_2 is deposited into long-term storage as calcium carbonate—fated, over geological timescales, to become limestone. The rate at which this biological carbon pump removes CO_2 from the atmosphere depends partly on how ocean currents mix surface layers and deeper layers. Of growing concern is that the increase in atmospheric concentration of CO_2 is changing the chemistry of the oceans, threatening various shell-forming organisms and the predators that feed on them.

One of the most important connections of the ocean with climate is its vast **heat capacity**. The ocean has the capacity to absorb and store far more heat than does the

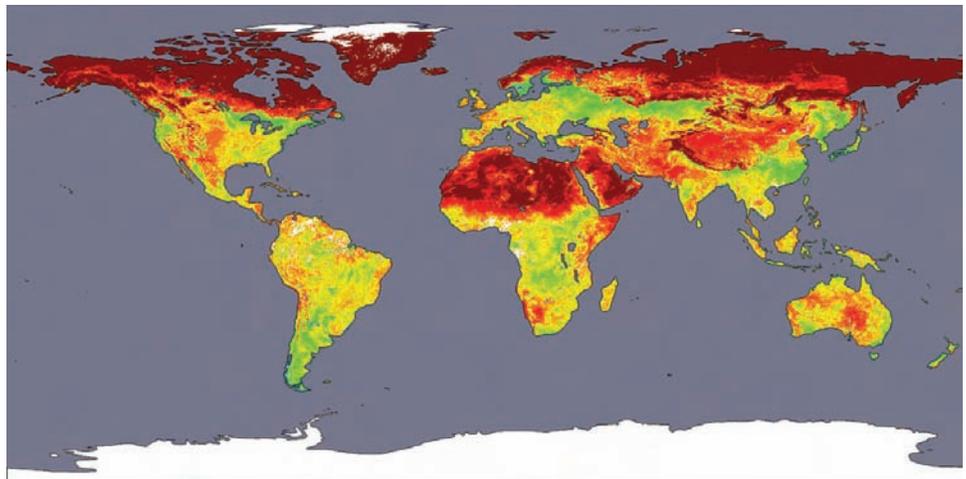


Figure 7. How much sunlight does Earth's surface reflect? A NASA "Terra" satellite collects detailed measurements of the planet's reflectivity, its "albedo." Areas shown here in red are the brightest and most reflective regions; in yellows and greens of intermediate values; blues and violets indicate relatively dark surfaces; white indicates no data, and no data for oceans. Image drawn from data between April 7 and April 22, 2002. Source: Image courtesy Crystal Schaaf, Boston University, based upon data processed by the MODIS Land Science Team.

atmosphere. Since it may take the oceans a long time—decades or centuries—to warm up in response to anthropogenic global warming, they are expected to cause a time lag in the response of the climate system to the forcing of an enhanced greenhouse effect.

That time lag can be viewed as both good news and bad news from a policy perspective. The good news is that it may give humans some extra time to prepare for, adapt to, or head off global warming. But the bad news is that, by delaying the appearance of observable climate change, it may lull people into a false sense of security that keeps them from recognizing the need to take necessary preventive actions. In addition, the effects of warmer surface temperatures and of rising sea levels will persist long after greenhouse gas emissions have leveled off.

ICE: THE CRYOSPHERE

Polar sea ice, continental ice sheets, seasonal and permanent sea ice, alpine glaciers, seasonal snow cover, permafrost, and other frozen aspects of the planet collectively known as the **cryosphere** also interact with climate in important ways. The most obvious and important, perhaps, is the extent to which ice and snow reflect sunlight. Scientists use the term **albedo** to refer to reflectivity—with an albedo of one being the high end of the scale (reflecting all incoming light) and zero being the low end (absorbing all light). (Figure 6.) Because of its whiteness, normal snow has an albedo close to one; dull black substances like charcoal have an albedo close to zero.

Polar ice holds a vast amount of water—at least 80% of the planet’s fresh water is locked up in polar ice. The biggest share is in the Antarctic, whose ice sheets constitute more than seven million cubic miles of ice. As vast as the current polar ice masses are, they are dwarfed by the ice present on Earth during its regular glacial periods, or ice ages, which typically occur every 100,000 years or so (although the frequency of occurrence has changed over geologic time). The glacial cycles are triggered by cycles in the Earth’s orbital mechanics—regular changes in its tilt, wobble, and orbit, much as you could observe in a spinning top.

However, the amplitude of glacial cycles (i.e., the amount of warming and cooling between cold ice ages and warm interglacials) is very likely amplified by the climate feedback effects produced by ice and snow. In other words, less snow and ice means a lower overall albedo for the Earth—which means that less incoming solar radiation is reflected back to space, causing the Earth to warm.

Higher temperatures in turn lead to even less ice and snow, further lowering the planet’s albedo. This feedback mechanism serves to amplify the effect of human-induced warming.

This is an important, but not the only, interaction between the cryosphere and the climate system.

Much of the polar ocean surface is covered with sea ice during the winter, and the extent of sea-ice cover affects other climate variables like evaporation and heat transfer between ocean and atmosphere, which in turn can affect thermohaline circulation.

In fact, fairly good measurements using satellites, submarines, and other methods indicate that Arctic sea-ice extent and thickness have markedly decreased over the last three decades. The declines have actually outpaced model projections for ice loss. Since the release of the AR4, more recent studies have linked the decline in polar ice to human-induced global warming.

The cryosphere also adds to the potential impact of climate change on sea-level rise. As water warms, it expands—and as the oceans are heated by global warming, such **thermal expansion** alone is expected to cause significant sea-level rise (see Chapter 6). But the melting of mountain glaciers and land-based polar ice causes additional sea-level rise. However, scientists do not yet know how to predict how quickly large ice sheets will contribute to future sea-level rise. One speculative scenario involves the collapse of the West Antarctic Ice Sheet; such an event would cause sea level to rise much more and more suddenly than thermal expansion alone could. Even so, it’s clear that the West Antarctic Ice Sheet, along with the Greenland Ice Sheet, have been contributing to sea-level rise over the last decade.

Two parts of the cryosphere that get much less media attention—and therefore much less public awareness—than the ice sheets are the vast expanses of permafrost in northern latitudes and the huge deposits of methane locked up in an icy, slushy form called hydrates or **clathrates**, usually out of sight on the sea floor. Global warming could cause thawing permafrost to release important amounts of methane and carbon dioxide—a feedback that could amplify the anthropogenic greenhouse effect. A slight warming of the ocean in certain places could potentially cause a rather sudden release of large amounts of gaseous methane from hydrates into the atmosphere. Either of these could cause sudden, dramatic changes in the Earth’s climate.

Although scientists do not yet know how to predict whether or when potentially catastrophic ice sheet collapse or greenhouse gas release from permafrost or clathrates might happen, geologists have found evidence of similar events occurring during past warm climates. Hence, the risk of such events appears to be real.

LIVING THINGS, ATMOSPHERIC CHANGE, AND CLIMATE CHANGE

Not all the forces driving the climate system are purely physical. Living things play a role too. Life on Earth is a vast and complex interacting web of microbes, plants, and animals—in the sea and on land—and many of them influence the climate. In fact, marine organisms remove some 40% of anthropogenic CO₂ emissions from the atmosphere each year.

For example, plankton in the ocean pump the greenhouse gas carbon dioxide out of the atmosphere. Terrestrial plants, forests, and soils play important roles in removing carbon dioxide, storing it in carbon compounds. The world's soils are an important carbon sink; only a fraction of the carbon absorbed is later released to the atmosphere, although this may change in a warming world.

In fact, hundreds of millions of years ago, before life emerged from the ocean onto land, blue-green algae were largely responsible for turning the Earth's atmosphere from one with little oxygen and lots of carbon dioxide into one with lots of oxygen and only a trace of carbon dioxide, by “breathing in” CO₂ and “breathing out” O₂.

The biosphere (i.e., all life on Earth) also plays important roles in regulating the atmospheric concentration of another greenhouse gas—methane. (See Chapter 3, Greenhouse Gases.) Land cover—the type and extent of plants on various land areas—affects climate in a number of other ways. Vegetation directly affects albedo

and also affects and is affected by soil moisture, surface water and ground water abundance, precipitation, and other aspects of climate.

Humans are also involved in many significant interactions with the climate system. While humans or their close ancestors and relatives have inhabited the planet for roughly one million years, life was harsh and human population stayed consistently much lower than today until the most recent ice age ended. It was then that the nomadic hunter-gatherer lifestyle was replaced by the development of agriculture, and climate change may have contributed to this shift.

Agriculture, in turn, caused two important developments. First, it brought about the beginning of an exponential explosion in human population. And second, it changed the vegetative cover of significant swaths of the planet's landmass—sometimes turning desert into paradise, and sometimes the reverse.

Industrialization and the scientific revolution, two uniquely human developments, also had profound effects on the planet, its atmosphere, and its climate. The concentration of humans in cities has actually created unique microclimates—urban “islands” that are hotter and rainier than surrounding areas. Industrial technology also led to explosive growth in the extraction and burning of fossil fuels: coal, oil, and natural gas. Fossil fuel combustion on a vast scale, combined with deforestation and agricultural land use, has raised atmospheric concentrations of the greenhouse gas carbon dioxide, contributing significantly to global warming.