

PRESIDENTIAL ADDRESS

Reflections On: Our Planet and Its Life, Origins, and Futures

James J. McCarthy

THE THEME OF THE 175TH ANNUAL MEETING of the American Association for the Advancement of Science (AAAS), “Our Planet and Its Life, Origins, and Futures,” celebrated an enormous breadth of scientific accomplishments that transcends many subdisciplines of the natural and social sciences. It was intended to be both a reflection on what has been learned and a look forward to what must yet be better known if we are to make wise choices as stewards of our planet. The program committee saw this as an opportunity to examine how we have come to know and understand the coevolution of life with its interacting biological, biogeochemical, and physical environments. Further advances in this area are essential to develop scenarios that can be useful in guiding decisions to address some of society’s most pressing problems. We must work toward a future that embraces the wise application of science to improve human health and well-being and to sustain the great diversity of life on our planet.

The occasion of this annual meeting, which opened on the very day of the 200th anniversary of the birth of both Charles Darwin and President Abraham Lincoln, prompted special reflection on the significance of Darwin’s contributions to our knowledge of the coevolution of organisms and their environment and the role that President Lincoln played in the advancement of science and, in particular, its application for the benefit of societal well-being. The meeting program was rich with papers and symposia that celebrated the 150th anniversary of Darwin’s publication *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life*. Darwin’s thesis was the product of decades of careful observations of the natural world, which he argued could be explained by natural selection. This year he is being properly heralded for his unequalled influence on our understanding of how life on Earth is sustained and how it changes to

James J. McCarthy is the Alexander Agassiz Professor of Biological Oceanography at Harvard University. He has served as president of the AAAS from February 2009 to February 2010. This essay is adapted from the Presidential Address he delivered at the AAAS Annual Meeting in Chicago on 12 February 2009.



accommodate differing conditions over time. Today, even with our far more sophisticated understanding of the processes by which evolution occurs, Darwin’s thesis remains robust. We now also know much more about how physical and chemical aspects of the environment for life have changed, and how inextricably life and its environment continue to coevolve. Regulatory aspects of feedbacks in the collective Earth system, between life and the physics and chemistry of the atmosphere, soils, and oceans, have provided a persistent habitable condition for a vast diversity of life over the past three billion-plus years.

A profound lesson from the past few decades of scientific discovery across the Earth and life sciences is that the weight of the human footprint on essential life-supporting services of the Earth system has grown dramatically since the time of Darwin. Over the past 150 years, our population has grown five-fold. Our consumption of resources has grown even more. Some of this consumption has resulted in degraded conditions in terrestrial and coastal marine ecosystems that will, under the best of circumstances, persist for generations to come. Greenhouse gases released today by anthropogenic activities will affect the heat budget of Earth’s atmosphere for tens of human generations. Some depleted aquifers will take even longer to recharge. For all intents and purposes, resources such as fossil oil have no prospect for regeneration on meaningful societal time scales. Species extinctions are irreversible.

Could Darwin have imagined that so soon in Earth history a single species would be altering the prospects for the survival of other species across all continents and to the greatest depths of the sea? Crutzen and colleagues suggest that this effect is sufficiently profound to declare that we have transitioned from the Holocene era of Earth history to the Anthropocene. Human population increased only 40% during Darwin’s 73 years of life (from 1.0 billion to 1.4 billion). Someone today in her 73rd year would have witnessed a 300% increase in population over her lifetime. Demographic studies suggest that because of declining birth-rates across much of the developing world, a future doubling of today’s population of 6.8 billion is unlikely. Most projections point to a leveling off of human population at 9 to 11 billion within the next two to three generations. The aggregate impact of our species on all others and on the systems that support us all in the future will, of course, depend not only on our population size but also on how we use Earth’s resources.

A 19th-Century Foundation for Climate Science

By remarkable coincidence, there were other notable findings and developments in 1859 that contribute to our knowledge of the Earth system and our capacity to alter it. In that year, the Irish chemist Sir John Tyndall discovered that CO_2 absorbs infrared energy as a radiatively active constituent in Earth's atmosphere. The quantitative relationship between CO_2 concentration and infrared absorption is very well established. In fact, a common way to measure the carbon content of plant and animal material is to combust a sample at high temperature. That process converts the carbon to CO_2 , which is then quantified by its attenuation of an infrared beam passing through the chamber. Tyndall's work built on that of Joseph Fourier, who postulated that Earth's surface temperature is a balance between energy from the Sun ("light rays") and that emitted by Earth ("dark rays"). It was, however, Tyndall who discovered that this balance is determined by the composition of the atmosphere, notably the concentration of CO_2 and aqueous vapor (1).

Our capacity to extract subsurface oil for fuel received a boost in 1859 from Edwin L. Drake's success with the first shallow commercial oil well in Titusville, Pennsylvania. Within a few years, portions of the Pennsylvania landscape were dramatically transformed by the proliferation of wells. Although the advent of assembly-line automobile production would not come for another four decades, the spark-ignited internal combustion engine was invented by Lenoir, also in 1859. The combustion of coal, oil, and natural gas worldwide fueled the industrial era, and today global use of these fossil fuels provides about 80% of the energy that we consume to heat buildings, power industries, propel vehicles, and generate electricity. Physical and biological systems in the ocean and on land that remove CO_2 from the atmosphere are unable to absorb or assimilate additional CO_2 at the rate at which it is being produced by the combustion of fossil fuels. More than half of the fossil fuel carbon released by human activities today will remain in the atmosphere for up to a century.

When it comes to the effect of human activities on climate, Svante Arrhenius, a Swedish chemist born in 1859, certainly qualifies as a visionary. He received the Nobel Prize in Chemistry for his theory of electrolytic dissociation, and the mathematical relation that describes the dependence of chemical reactions on temperature—the Arrhenius equa-

tion—is named for him. In the 1890s, Arrhenius became interested in the possible effects of the CO_2 released from fossil fuel combustion on Earth's surface temperature. But his interest in this topic arose as he was attempting to calculate how large a change in atmospheric CO_2 concentration would have been required to explain a past cool period of glacial advance during the Pleistocene (1). He was aware that many natural processes had influenced Earth's climate on longer time scales. The theory of cyclic glacial episodes had been advanced by Louis Agassiz in the 1840s, and there was a great deal of speculation as to whether a period of intense volcanic activity could, by means of dust clouds, initiate a cool period and give rise to an expansion of glaciers. Another mechanism that could drive the pacing of glacial cycles—variations in the Sun-Earth orbital properties—had been promoted by James Croll and others. Arrhenius began his calculations to examine the plausibility of atmospheric CO_2 concentrations having had a role in these glacial cycles.

Of course, Arrhenius realized that his calculations could work forward as well. In his now-famous work on this topic, he published his estimate that, if releases of fossil fuel emissions were to double the content of CO_2 in the atmosphere, they would cause a globally averaged temperature increase of 5° to 6°C (2). For comparison, this is about twice the temperature rise estimated by the Intergovernmental Panel on Climate Change (IPCC) for a doubling of CO_2 . Arrhenius, however, could not envision how rapidly an intensely fossil fuel-dependent industrialized society would arise. He estimated that it would take about 3000 years for the atmospheric CO_2 concentration to double (3), whereas current IPCC scenarios for the rate of the combustion of fossil fuel and proportion of the CO_2 absorbed by the ocean project a doubling of atmospheric CO_2 concentrations to occur between 2050 and 2080. Although Arrhenius' calculations are occasionally referred to as having been fortuitous "back-of-the-envelope" values, he complained to a friend that it was "unbelievable that so trifling a matter has cost me a full year" (1). Critiques of Arrhenius' work by other scientists at the time have been discussed by Weart (4).

Further efforts to refine the relationship between anthropogenic release of CO_2 and

climate lay largely dormant until the 1930s, when Guy Callendar, a British engineer, took up the problem. Callendar was confident that the warming that had been observed from the late 1800s to the 1930s was attributable to an atmospheric accumulation of fossil fuel emissions, and he predicted an even warmer future if this trend continued (5). He may well have been puzzled about the apparent leveling off or downward trend in the Earth's average surface temperature during the 1940s and 1950s. It would be decades later before it could be shown that the anthropogenic release of reflective aero-

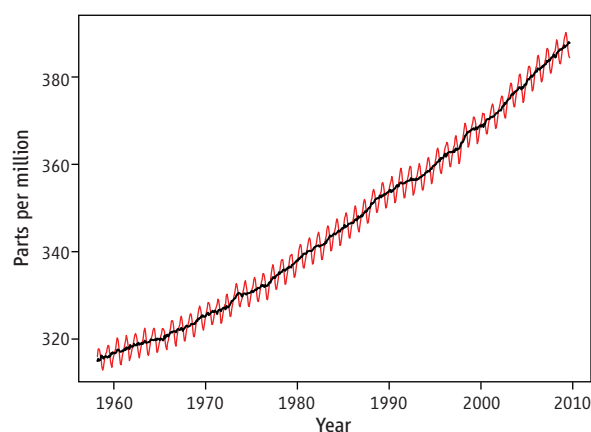


Fig. 1. Keeling curve for atmospheric CO_2 . Monthly mean atmospheric CO_2 at Mauna Loa Observatory, Hawaii.

sols, in addition to natural processes, contributed to a slight cooling during this period even though the CO_2 content of the atmosphere was continuing to increase.

The Past Half-Century: New Observations and Ideas

In 1957, the oceanographer Roger Revelle, expressing concern about the consequences of CO_2 release from fossil fuel combustion, wrote: "[H]uman beings are now carrying out a large scale experiment of a kind that could not have happened in the past nor be reproduced in the future. Within a few centuries we are returning to the atmosphere and oceans the concentrated organic carbon stored in sedimentary rocks over hundreds of millions of years" (6). A problem, which any experimental scientist would recognize immediately, is that there is no control against which to compare this experiment—we have only one planet Earth. It would be another couple of decades before we would know how different the atmosphere is on Venus and Mars and come to fully appreciate the role that life processes have played in the evolution of Earth's atmosphere.

Revelle knew that observing this experiment in the fullest possible way was essential: “This experiment, if adequately documented, may yield a far-reaching insight into the processes determining weather and climate” (6). First and foremost, he knew that it was essential to establish precise measurements of the CO₂ content of the atmosphere, and so he recruited a bright young chemist, Charles David Keeling, to develop the analysis and begin these measurements on island locations distant from intense local anthropogenic sources of CO₂. A graph of the continuous record of measurements for CO₂ from 1958 to the present is now widely known as the “Keeling curve.” It shows the rhythm of seasonal cycles in terrestrial photosynthesis and respiration, with an average upward slope that has more than doubled, from <1 part per million by volume (ppmv)/year to >2 ppmv/year over the five decades of observation (Fig. 1). Because of rapid inter-hemispheric exchange, the annual average atmospheric CO₂ concentration at locations away from intense local sources of CO₂ is nearly constant, regardless of latitude.

Agassiz’s conclusion that cyclical glacial events had occurred across North America and northern Eurasia needed a mechanism to explain it. Although past episodes of volcanism had been suggested, Croll’s orbital theory had the potential to explain the past and project the future as well. This idea received substantial reinforcement with Milankovitch’s calculations early in the 1900s on the frequency and amplitude of three components of Earth-Sun orbital relations (7). There was, however, little consensus within the Earth science community regarding the significance of orbital cycles in the pacing of glacial events until the 1970s. In part this is because orbital forcing would yield asymmetric cycles, with long glacial periods interspersed with short interglacial periods, which was counter to the prevailing view within geological sciences of four short ice ages over the Quaternary, with long warm periods between them (8). The pioneering work of Emiliani and Broecker interpreting oxygen isotope data in corals and in fossil foraminifera from marine sediments supported the idea of orbital-induced Quater-

nary climate cycles (8). Stronger support then emerged with the publication, by paleoclimatologists Hayes, Shackleton, and Imbrie, of data on oxygen isotopes and abundances of foraminifera fossils in cores of Indian Ocean sediments (9). For many Earth and climate scientists, this work demonstrated a convincing consistency between cycles in the sediment record and Milankovitch calculations of the climatological effects of cycles in Sun-Earth orbital relationships.

At about the same time, public and scientific conceptualizations of “our” Earth were profoundly altered by the first views of Earth from space. Three images of Earth from space remain particularly powerful decades after they were first released: the photograph known as “Earthrise,” photographed by Apollo 8 astronaut William Anders on 24 December 1968; the photograph referred to as “The Blue Marble,” taken by the crew of Apollo 17 on 7 December 1972; and variations of “Earth at Night.”

The Earthrise photograph was taken with a handheld camera as astronauts for the first

Fig. 2. (A) Earthrise (24 December 1968). Image of the rising Earth taken from the Apollo 8 spacecraft. (B) Earth taken on 7 December 1972 by the crew of the Apollo 17 spacecraft at a distance of about 29,000 km. This is the first time that the Apollo trajectory made it possible to photograph the south polar ice cap. (C) Earth’s cities at night. This image of Earth’s city lights at night shows the spatial distribution or arrangement of settlements. White areas of light show organized areas where population is typically large.



time orbited the Moon and photographed Earth from space. As the path of the spacecraft rounded the Moon and pointed back toward Earth, the planet appeared to rise above the lunar surface and hence the name given to this photograph. Anders' profound reflection on this experience is widely quoted: "We came all this way to explore the Moon, and the most important thing is that we discovered the Earth" (10) (Fig. 2A).

The Blue Marble photograph, sometimes referred to as the most widely reproduced image of Earth, was taken on the last lunar mission. It was, though, the first time that astronauts, who were at the time orbiting Earth to position for their lunar trajectory, saw Earth fully illuminated by the Sun from behind them. Because this launch occurred close to the summer solstice, most of the Antarctic ice cap is visible (Fig. 2B).

Jasonoff (11) has written about the power of the Earthrise and Blue Marble images to alter perceptions of our planet's vulnerability. For the most part, national boundaries are invisible in these images, and consciousness of collective human responsibility for the future of our planet is aroused by them. She compares the contrasting perspectives evoked by the image of a well-engineered "Spaceship Earth," a phrase coined by Buck-

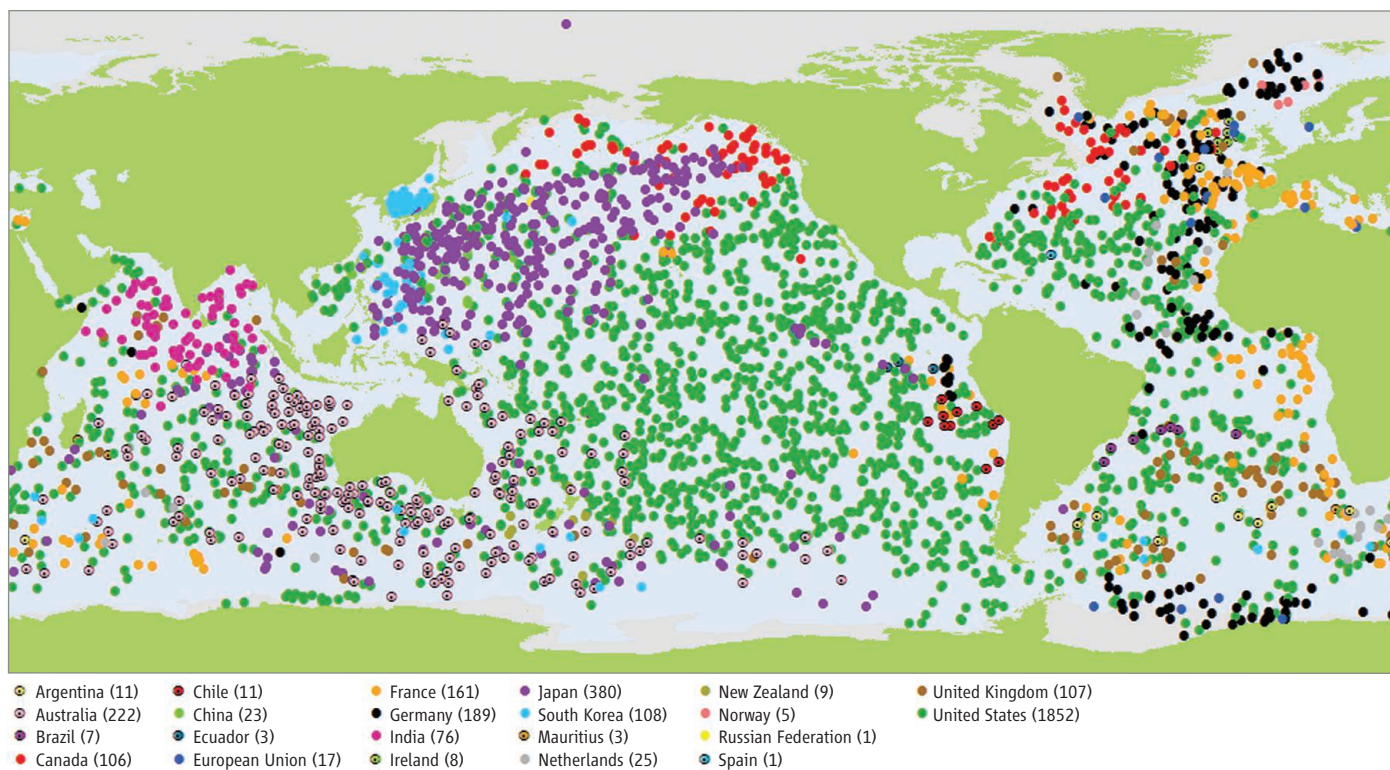
minster Fuller, and that of a fragile craft at risk, as envisioned by Rene Dubos. In analyzing the iconic power of these images, Jasonoff also remarks that they "set up an unresolved dialectic between those who wish to approach environmental problems on a global scale, with gaze averted from the particularities of culture and place, and those who believe that the work of saving the planet must begin with more down-to-Earth considerations, in the realities of lived experience, with questions about the kinds of lives people want to forge for themselves, their communities, and their descendants" [(11), p. 49].

The Earth-at-Night images have been produced in a variety of forms to convey different information. Currently they are a product of data collected by a Defense Meteorological Satellite Program—Operational Linescan System (DMSP-OLS) satellite in a near-polar Sun-synchronous orbit. This system was designed to observe clouds by moonlight, but when integrated over an annual cycle, the data can be used to document globally the distributions of various sources of illumination across land and sea. Natural light such as the aurora borealis and aurora australis, lightning and fires started by lightning, reflected moonlight, and clouds are all regularly documented. Images showing oil field gas flares,

illuminated squid fishing fleets, and tropical forest burns, though, are dramatic evidence of local human activities. Transient components of these light sources can be filtered to leave geographically fixed sources such as cities, industries, highways, etc. The near-continuum of the illuminated metropolitan areas of Boston, New York, and Washington creates an image of intense human presence, not simply in population numbers but in affluent life-style, particularly when contrasted with comparably populated areas in many other regions (Fig. 2C).

Several astronauts were accomplished Earth scientists before their spaceflights. One of great distinction, Piers Sellers, has remarked, "Apart from letting humanity see Earth differently than ever before, the view from space has also expanded our understanding of how the planet works, and just in time to grasp the impact humanity is having on the planet and its climate system. For the first time, we see our planet as a whole, a system of intricately connected parts that interact—and can be perturbed—in ways humans had not previously glimpsed" (12).

Jasonoff (11) has also suggested that these images stimulate systematic thinking about Earth's features. Certain features of Earth have now become observable in totality and,



CREDIT: ARGONAUT INFORMATION CENTRE

Fig. 3. Argo floats. The 3325 Argo drifting buoys shown by country of origin for measuring ocean properties deployed across the oceans in February 2009.

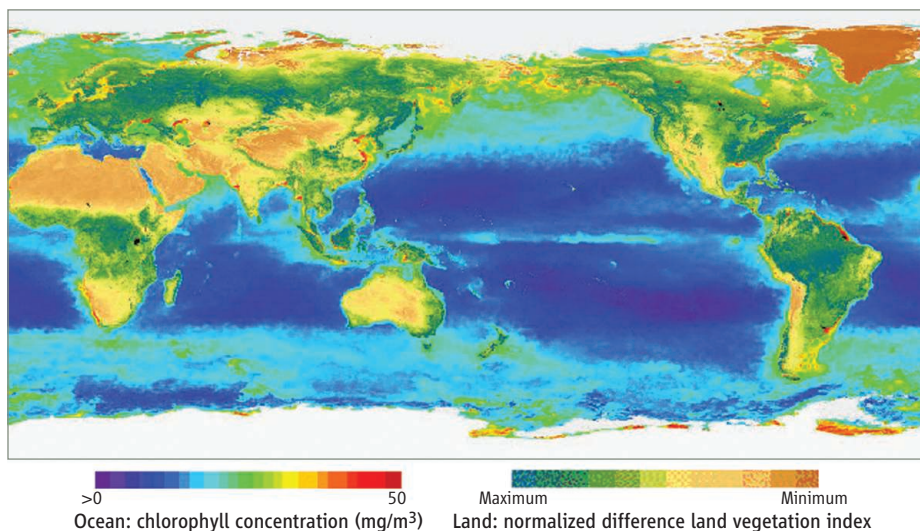


Fig. 4. Global biosphere. Derived weekly maps of surface-ocean chlorophyll distributions from September 1997 to June 1998 reveal dynamic seasonal patterns in primary production during the 1997–1998 El Niño.

more important, interacting scales of the Earth system can now be comprehended that previously were the subject of speculation or at best approximated crudely. The first two images invoke a sense of beauty and perhaps fragility, but they offer little potential for substantive quantitative scientific inquiry. The third image, which can be as awe-inspiring, can clearly be used to document the spatial extent and intensity of certain human activities and to chronicle their changes over time.

Over the past three decades, a broad array of Earth-orbiting satellite sensors and systems have evolved from proof of concept to operational missions and have totally transformed research approaches in many branches of the atmospheric, oceanic, and ecological sciences. An early taste of this new capability came with the launch of SEASAT in 1978. Although a premature circuit failure allowed only a few months of operation, the potential realized with this mission for measuring variation in ocean surface height, wind speed and direction, sea surface temperature, cloud distributions, and polar ice conditions was in many regards as breathtaking for scientists as any prior image of Earth from space. Satellite sensors and systems now provide observational capabilities across the Earth sciences with entirely new dimensions. Today we have geographic continuity in data that was unimaginable a generation ago. Satellite systems are also in many cases both effective complements to and enhanced by in situ land and ocean observations. Observing physical, chemical, and biological ocean properties,

for example, involves vast arrays of surface and subsurface drifting buoys. Argo drifting buoys, for example, profile the upper 2000 m of the ocean every 10 days. At the time of the annual meeting (February 2009), 3325 of these were deployed across the global ocean. More than half of the buoys were supported by the United States, but 22 nations participate in this program (Fig. 3).

Many patterns and features in the ocean's physical and biological characteristics have been revealed with these new technologies. Manifestations of interannual climate cycles, such as the El Niño–Southern Oscillation, can now be documented across marine and terrestrial realms as synchronous changes

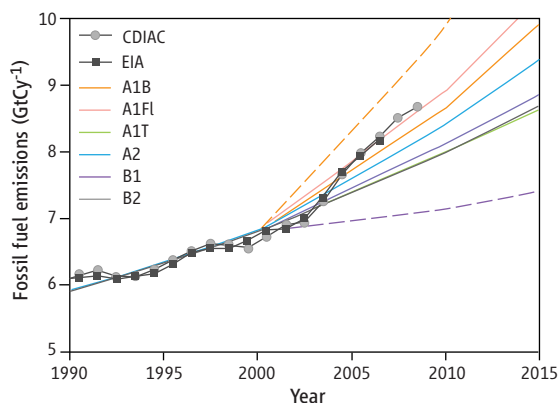


Fig. 5. Actual CO₂ emissions versus IPCC scenarios. Observed global CO₂ emissions from both the Energy Information Administration and global Carbon Dioxide Information Analysis Center data, compared with emissions scenarios and stabilization trajectories.

in the intensity of equatorial ocean upwelling, the locations of atmospheric convection, sea level, and the occurrence of precipitation across continents. Images that show the distribution and intensity of ocean and land biomass are compelling examples of such capabilities (Fig. 4).

Continuity in these data sets for land and ocean properties and processes has now become essential in weather forecasting, hurricane warning, management of agriculture, and forestry. These data sets are, in addition, absolutely essential for documenting global climate change such as land surface and ocean surface temperatures, deforestation and other land-use changes, Arctic ice extent, sea-level rise, etc., and for anticipating the impacts of these changes on natural and socioeconomic systems. The precision with which sea-level rise has been measured since the early 1990s with satellite altimeters is vastly superior to earlier data from tide gauges. A downward trend in summer sea ice for the entire Arctic can be documented from the 1950s, but over the past three decades these observations have become far more precise with satellite data. Furthermore, the precision with which cloud cover and winds over the Arctic Ocean and the thickness of sea ice can now be determined with satellite data makes it possible to interpret causes of interannual variation in sea ice extent and volume.

Ironically, as assessments of climate change science and climate impacts have increasingly called attention to changes in climate and documented impacts that were not evident even a half decade earlier (13–15), the Earth-observing systems on which advances in this science depend are woefully underfunded. Budgets to develop, deploy, and operate these systems and to support the scientific use of the data have not grown in proportion to the widely recognized need for these capabilities. Worse, domestic funding to sustain them has actually declined over the past decade, even though the United States pioneered many of these systems. Some of the systems now at risk are international partnerships with U.S. funding requirements.

Several organizations have been rising to the challenge of prioritization and support for the deployment of new satellite sensors and renewal of those essential time-series observations of

atmospheric, oceanic, and terrestrial properties and processes. For example, in 2007 a committee of the National Research Council (NRC) prioritized 17 new Earth-observation missions for the 2010–2020 time period out of more than 100 that were proposed. A few months later, the AAAS Board issued a Board Statement on the “Crisis in Earth Observation from Space.” It stated that the NRC had provided the “blueprint for a program that will bring immense returns for modest costs” and urged the Congress and the Administration to implement this plan.

The decline in funding for Earth observations has in part been a consequence of NASA’s refocusing of priorities with a new emphasis on a return mission to the Moon and on to Mars. The outcome of the Obama Administration’s review of NASA’s mission for the next decade will signal the degree to which the United States is committed to sustaining and enhancing critical Earth observations.

Capacity to leap beyond the rudimentary calculations of Arrhenius and to use the vast outpouring of data from satellites and other monitoring technologies originated with the development of code to run computer-based climate models. Manabe, Bryan, and Wetherald were pioneers in the application of this approach to climate scenarios with three-

dimensional coupled atmosphere-ocean models. Manabe and Wetherald (16) provided the first model results run with twice the preindustrial concentration of atmospheric CO₂, which yielded an increased average global temperature of 2°C. Though primitive by today’s standards, with, for example, a non-interactive ocean, even early models pointed to enhanced high-latitude warming and an intensified hydrological cycle in a warmer world (8). Concerted efforts at many climate modeling centers during the 1980s and 1990s led to improved realism and increased spatial resolution of climate models with the inclusion of cloud physics, interactive oceans, atmospheric aerosols, and interactive vegetation. Over the period of IPCC reports, the geographic and vertical resolution of models have increased about fivefold (17).

Many widely used assessments of future climate change and climate impacts have been based on the IPCC Special Report on Emission Scenarios (SRES) (18) to generate plausible future climate conditions using several climate models. They portray collective choices that societies make with respect to economic growth, population growth, and options for energy-generating technologies, in addition to their relative emphases on global versus local solutions to economic, social,

and environmental sustainability. Thirty-five of these were developed, representing a wide range of demographic, economic, and technological forces that can influence future greenhouse gas and sulfur emissions, and each clustered around one of four storylines for societal development. They explicitly did not include any assumptions regarding implementation of the United Nations Framework Convention on Climate Change or acceptance of the Kyoto Protocol emissions targets and timetables.

The Northeast Climate Impacts Assessment (19) used high and low SRES emission scenarios, as did the recently released State of Knowledge Report of the U.S. Global Change Research Program (15). In these instances, it is clear that projected impacts across a wide swath of natural and socioeconomic sectors unfold very differently under low- and high-emission scenarios. Because of the relatively long average atmospheric residence time of these incremental greenhouse gases, the outcomes for high- and low-emission scenarios are similar for the first few decades, but beyond that they diverge distinctly. Although this might seem like an obvious outcome, it stands as a powerful statement that in order to diminish the probability of costly impacts decades from now, action must be taken today.

Arrhenius envisioned the prospect of globally warmer conditions having positive local benefits, such as longer growing seasons at high latitudes. As of the 2001 IPCC report, however, it has been evident that negative climate impacts are already in play across the globe. Moreover, it is now well established that the preponderance of projections for impacts above 450 to 550 ppmv of CO₂ are largely negative.

In the 1983 National Academy of Sciences Carbon Dioxide Assessment Committee report, the authors considered the potential for wide-ranging impacts of human-induced climate change, including water availability, agricultural productivity, coastal conditions with sea-level rise, etc., and offered this sobering precaution: “There may yet be surprises ... In our calm assessments we may be overlooking things that should alarm us.” Indeed, as the past decade of new findings has shown, a warming climate does reveal surprises. To date, most, however, have been unpleasant.

The record of past climate tells us that the transition from one climate state to another is rarely a smooth process. An NRC study (20) on abrupt climate change has the ominous subtitle “inevitable surprises.” A change in climate can cross a threshold and precipi-

CREDIT: MET OFFICE HADLEY CENTRE, UK, AND CLIMATIC RESEARCH UNIT, UNIVERSITY OF EAST ANGLIA, UK, WORLD METEOROLOGICAL ORGANIZATION

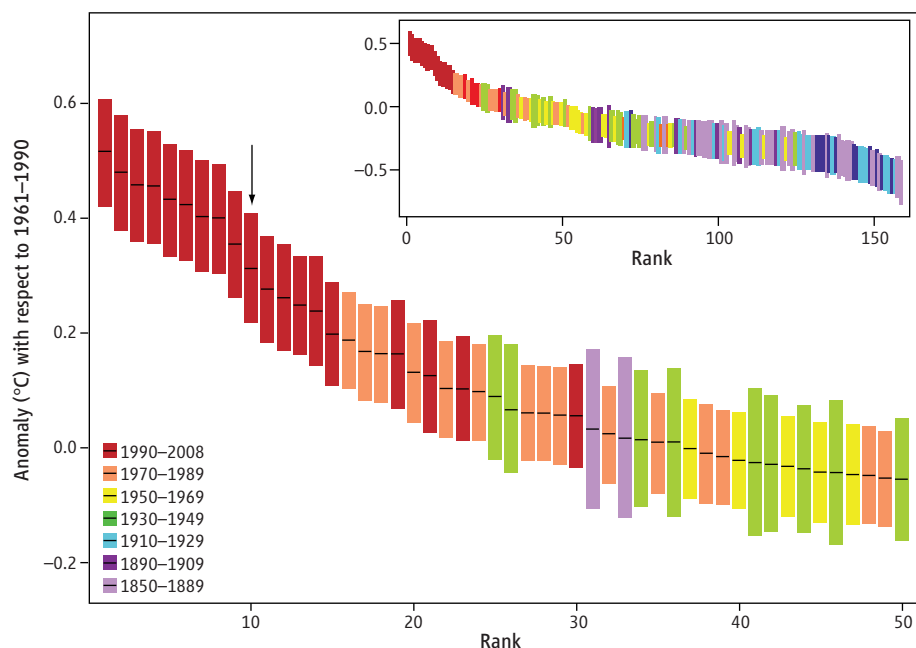


Fig. 6. Global surface temperature. Global ranked surface temperatures for the warmest 50 years. The inset shows global ranked surface temperatures from 1850. The size of the bars indicates the 95% confidence limits associated with each year. The source data are blended land-surface air temperature and sea surface temperature from the HadCRUT3 series. Values are simple area-weighted averages for the whole year (28).

tate a change in some other aspect of the system that unfolds more rapidly than the rate of change in the causative agent. An example is the unanticipated collapse of Larsen Ice Shelf B on the Antarctic Peninsula in 2002. In a period of about 1 month, an ice shelf 200 m thick disintegrated, releasing a 700 km³ volume of icebergs to the sea. It is thought from sediment records that this ice shelf had been stable since the Last Glacial Maximum. Another involving biological systems is the enhanced success of bark beetles with warmer winter temperatures and dry summer conditions that favor the beetle's survival and diminish trees' defense systems. The result may be the massive death of trees across millions of hectares of forest within only a few years, as with the 1990s spruce bark beetle infestation on the Kenai Peninsula.

Several recent scientific papers and reports have addressed tipping points. Lenton *et al.* (21) broaden this concept by defining tipping elements as subsystems of the Earth system that are at least subcontinental in scale and can be switched, under certain circumstances, into a qualitatively different state by small perturbations. The authors take into consideration equilibrium properties, threshold behavior, and critical rates of forcing, and suggest how this analysis can be of policy relevance in decision-making. A range of adverse impacts of abrupt climate change can be compared to develop cautionary strategies via a forewarning system.

A recent National Science Foundation (NSF) report, *Transitions and Tipping Points in Complex Environmental Systems*, addresses these issues across the domains of research, education, and decision-making processes. It argues that NSF should give high priority to interdisciplinary research that focuses on complex environmental systems in order to provide a stronger foundation for informing policy decisions relating to global environmental issues (22).

Over the past two decades, many of the future climate projections from the IPCC and other groups have been proven to be conservative. This is in part because an IPCC assessment is by its very nature highly conservative. The content of an IPCC assessment is based on peer-reviewed publications in scientific journals. Thus, the most recent findings, perhaps already widely known among experts, may not be included in an assessment report if the work has not been published. Furthermore, recently published findings that have yet to be corroborated by other investigators may receive less emphasis than well-established

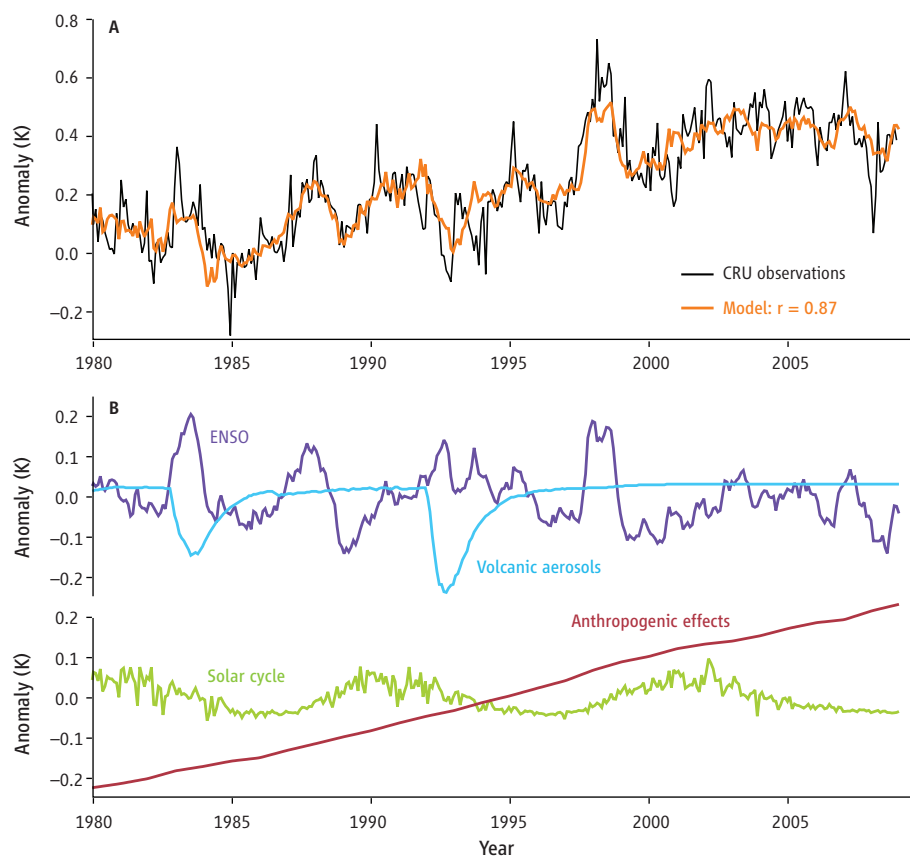


Fig. 7. Reconstructing Earth's recent climate. (A) Observed monthly mean global temperatures (black) and an empirical model (orange) that combines four different influences. (B) Individual contributions of these influences, namely El Niño–Southern Oscillation (purple), volcanic aerosols (blue), solar irradiance (green), and anthropogenic effects (red). Together the four influences explain 76% (r^2) of the variance in the global temperature observations.

work from an earlier period. At times the IPCC assessments have been mischaracterized as extreme exaggerations. A U.S. senator, for example, in a 2001 U.S. Senate hearing, stated that the IPCC summaries for policy-maker documents “tend to take very alarmist viewpoints ... they aren't science, they're UN politics.” Responses to such mischaracterizations of IPCC reports describe how the IPCC procedures are faithful to the science and how consistency among the summary statements and the thoroughly documented underlying reports of the working groups is ensured (23–25).

Unfortunately, when data confirm that projections for future climate have been overly conservative, this implies more serious negative impacts. Some aspect of the projected rates for greenhouse gas emissions or for the modeled climate response to these emissions has been underestimated. Greenhouse gas emission data summarized (26) and recently updated (Fig. 5) indicate that since 2005, the global annual CO₂

emission rate has been at or above the highest rates projected only 5 years earlier with the set of IPCC SRES marker scenarios. The annual rate of increase in 2007 was 20% higher than the rate of increase one decade earlier. This growth in emissions has largely been due to the fact that rapid economic development in China has been highly dependent on coal. China has now passed the United States as the nation with the highest CO₂ emissions. Fossil fuel emission rates are also growing in India but are currently only about one-fifth those of China. Land-use changes, especially deforestation in tropical nations, now account for about 15% of the global CO₂ emission total of >10 Pg of carbon per year (27). This change in land use is consistent with a carbon cycle that is generating stronger climate forcing sooner than expected. Preliminary data for 2009 indicate, however, that the global economic downturn is being reflected in lower CO₂ emissions.

Although 1998 still stands as the warmest year in recent climate history, the 11 warm-

est years in the instrumental record have occurred in the past 12 years. According to the UK Met Office Hadley Centre, 2008 was the 10th warmest year (Fig. 6) [the 8th warmest according to the National Oceanic and Atmospheric Administration (NOAA)]. Late in 2007 and early in 2008, many regions were anomalously cool relative to the past decade, which was consistent with the development of a moderate-to-strong La Niña, and this helps to explain the ranking of 2008 (28). Small wobbles in the otherwise steady increase in global temperature over the past two decades are highly consistent with the global climate signal associated with El Niño and La Niña events, volcanoes, and solar variability, superimposed on the warming due to the secular increase in atmospheric greenhouse gas concentrations (29) (Fig. 7).

In 2001, the IPCC could not identify any body of science that pointed to a likelihood of a large reduction in Greenland ice during the present century (30). Since then, several major outlet glaciers for the Greenland ice cap have shown changes. The termini of many are retreating and thinning at unusual rates, and the increasing frequency of “icequake” seismic events that are spatially coincident with exit glaciers indicates that an acceleration of ice loss is now under way (31). Laser altimetry studies demonstrate that extensive dynamic thinning is occurring for glaciers at all latitudes on Greenland, with the most profound changes at the ocean margins (32). An abnormally cold 2007–2008 winter across the southern half of Greenland was more than offset by a record-setting summer with an intense melt season, and thus the mass of Greenland ice proceeds along its recent downward trajectory (33). Records of numbers of summer melting days continue to be broken (34). The trend in the total area of melt during 1979–2008 is approximately $+15,900 \text{ km}^2 \text{ year}^{-1}$ and is significant at the 95% confidence interval ($P < 0.01$) (33).

Changes are also evident in the rate of sea-level rise. In 2001, the IPCC reported that “[w]ithin present uncertainties, observations and models are both consistent with a lack of significant acceleration of sea level rise during the 20th century” (35). But Rahmstorf *et al.* (36) have now demonstrated that sea-level rise has accelerated since 1990. The linear IPCC model projections in 1990 gave a best esti-

mate of rise at 2 mm/year. Satellite altimeter data, however, yield an increase of $3.3 \pm 0.4 \text{ mm/year}$ over the 1993–2006 period. This observed rate of increase is at the upper end of what was projected from the early IPCC scenarios (Fig. 8).

The 2007 IPCC report projected 0.28 to 0.59 m of sea-level rise by 2100. These estimates do not preclude higher rates of rise due to increased rates of ice loss on Greenland and Antarctica. Although the IPCC authors were aware of publications relating to recent changes in Greenland and Antarctic ice balance, they lacked confidence that they could extrapolate meaningfully from these data to future sea-level rise. Rahmstorf (37) used a semi-empirical relationship from 20th-century temperature and sea-level changes to project future sea-level rise from the IPCC scenarios for warming and derived an estimate of sea-level rise of 0.5 to 1.4 m for 2100 relative to the 1990 level. When current outlet glacier discharge rates for Greenland are included to improve on the IPCC 2007 projections, Pfeffer *et al.* (38) estimated a sea-level rise between 0.8 and 2 m, with a “most likely” estimate being 0.8 m.

A sea-level rise of 0.8 to 2 m over the next nine decades would be of enormous consequence for lives, livelihoods, and property in coastal regions across the globe. Major cities, large portions of nations, indeed entire island nations will become uninhabitable. Add additional tropical storm intensity (39, 40), and damage from any rise in sea level becomes intensified. Recently, the presidents of the island nations of Kiribati and the Maldives have stated that their people must prepare to evacuate (www.sciencenews.org/view/feature/id/40789/title/First_wave). President Anote Tong of Kiribati has promoted training pro-

grams to facilitate acceptance of his citizens by other nations.

In 1995, the IPCC was unable to find conclusive evidence that the frequency, intensity, or persistence of extreme weather events had changed. By 2001, however, new data indicated that hot weather had become more extreme and precipitation events more intense in many regions, and that wind and precipitation intensities associated with tropical storms had increased during the latter half of the 20th century. Evidence for these increases is now substantial. Record heat waves across several regions have taken lives and affected agriculture (41). The 2007 IPCC projections for weather-related stresses with a warmer climate during the balance of this century include increased incidence of extreme high sea level, increased intensity of tropical cyclone activity, and increased area affected by droughts (likely; $>66\%$ probability); increased heavy precipitation events over most areas and increased frequency of warm spells/heat waves over most land areas (very likely; $>90\%$ probability); and warmer and more frequent hot days and nights over most land areas (virtually certain; $>99\%$ probability) (42). In every category of change, adaptive measures will be needed, in some cases urgently and with little advance notice, to minimize loss of life, livelihood, and property as future weather extremes take their toll.

One perplexing aspect of the behavior of the climate system is the degree to which associated changes in biogeochemical cycles and physical aspects of climate tend to amplify rather than mitigate or buffer a change. Albedo feedback in the Arctic is a good example of this. The melting of snow and ice reduces the reflectivity of the surface, and as a result the bare or vegetated land and open water absorb more incident solar energy and warm even more. Rising CO_2 concentrations associated with rising temperatures trigger changes in complex terrestrial ecosystem community dynamics, such as physiological regulation and ecological aspects of water availability.

For example, ecosystems that accumulate carbon under one temperature and CO_2 regime can become a source of CO_2 or methane under another. Boreal terrestrial ecosystems are of central interest in scenarios for a warmer world. Ice core data provide evidence of strong methane feedback responses during periods of warming over the past

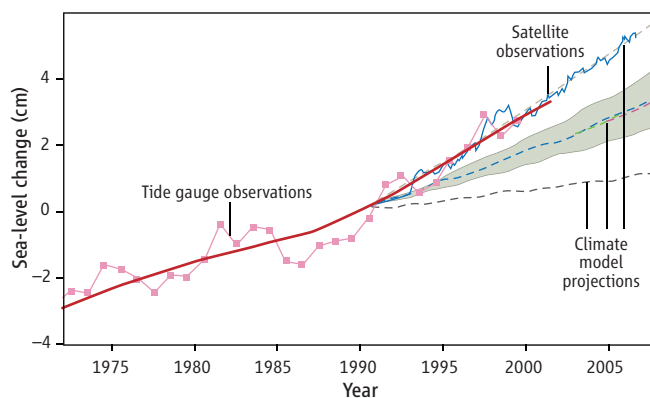


Fig. 8. Sea-level rise. Sea-level data are based primarily on tide gauges (annual, red) and satellite altimeter measurements (3-month data spacing, blue; up to mid-2006) and their trends.

several glacial cycles, and frozen soils in the Arctic are known to hold substantial reservoirs of methane.

Field studies of lakes formed over melting permafrost suggest that these systems were a major source of methane during past warming periods (43). Data from Greenland ice similarly imply that most of the increase in atmospheric methane concentration during the warming immediately after the Younger Dryas (~11,600 years before the present) arose from wetland sources (44). Release from seabed methane clathrates has been suggested as another potentially strong positive feedback associated with Arctic warming. The size of this reservoir is estimated at 10^{19} g of carbon, or roughly comparable to the total inventory of coal, oil, and natural gas (45). Recent reports of seabed methane releases west of Spitsbergen are hypothesized to be related to warming in this region over the past three decades (46). Future releases associated with the warmer climate projected for this century are estimated to be similar in magnitude to the terrestrial biosphere's temperature-amplifying feedback (47).

When authors of the 2001 IPCC Working Group II Report looked broadly at the potential for climate change impacts, they found five categories of impacts, which they labeled as "reasons for concern" (RFCs). These included (i) risks to unique and threatened systems (and species); (ii) risks of extreme weather events; (iii) changes that could have positive impacts in some regions and negative ones in others; (iv) changes by which the preponderance of people would be negatively affected; and (v) risks of large-scale discontinuities such as the substantial loss of ice from Greenland or Antarctica, a dramatic increase in the release of methane from frozen ground or seabed sediments, dramatic changes in ocean currents, etc. These RFCs were presented diagrammatically, in what has come to be known as the "burning embers diagram." Some of the same authors and others from the IPCC 2001 assessment recently repeated this analysis and found that compared with the results reported in 2001, smaller increases in global temperature are now estimated to lead to more significant or more substantial consequences in each of the five RFCs. Most dramatic were the changes in the final category (Fig. 9), where surprises with respect to effects of Greenland and Ant-

arctic ice loss on sea-level rise and changes in high-latitude soil carbon dynamics now loom larger than thought likely only a few years ago. Shifts to stronger color intensity in the burning embers diagram suggest, compared to 2001, that we are now drifting even more rapidly toward dangerous interference with the climate system (48).

Decisions Today Will Determine Which Possible Future Climate Is Realized

In 2007, the IPCC used SRES scenarios to project average global temperature increases for 2001. Mean values for these ranged from 1.8° to 4°C. Each includes assumptions about population, economic development, and dependence on fossil fuels for energy. One of the four SRES marker scenarios has three variants. Each of these assumes the

same projections for population, economic development, and societal characteristics, while the fraction of energy needs met with fossil fuels unfolds on three different paths. One is intensively dependent on fossil

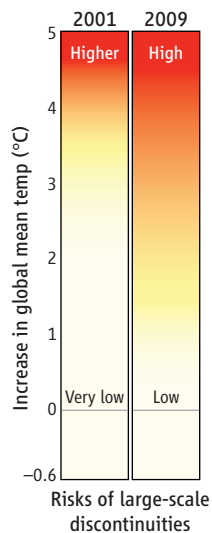


Fig. 9. IPCC RFCs. Increased prospects for low-probability, high-consequence climate impact as assessed in the IPCC Third Assessment (2001) and subsequently (2009) by the same authors. Red (high risk) has moved down to smaller temperature increases since 2001.

fuels, rather similar to the current world energy mix; the second represents a strong shift to alternative energy technologies over this century; and the third is an intermediate path. The range for end-of-century warming for these three scenarios, 2.4° to 4°C, indicates the high sensitivity of climate change to the fossil fuel intensity of society's energy systems.

A clear breakthrough in conceptualizing the practicality of dramatic greenhouse gas emission reductions came with the proposal of a stabilization triangle that characterizes the shape of the area of emissions avoided that will be required to stabilize emissions by some future date (49) (Fig. 10). Subdividing this triangle into component triangles (wedges) allows one to examine the efficacy and cost-effectiveness of individual efficiencies and technologies against one another. With existing technologies and the commercial-scale adoption of others that can provide energy needed for transportation, industry, domestic needs, etc., with little or no carbon emission, the authors

demonstrated that ample resources exist today to begin serious emission reduction.

Beyond the exploration of such a concept in a scientific journal, just how realistic is a proposed transition to a dramatically enhanced future with a decarbonized global energy system? The 2007 IPCC report (13) has considered various strategies for this and their associated costs. They reviewed the history of greenhouse gas emission growth since 1970 and explored prospects for emission reductions with existing and likely future technologies, looking at energy supply, transport, buildings, industry, agriculture, forestry, and waste management. They considered the full range of technologies and practices currently available and the potential of those that are projected to be available before 2030. These analyses demonstrate that there is substantial economic potential for the mitigation of global emissions that could reduce the projected growth of emissions. They further found that mitigation opportunities with net negative costs have the potential to reduce emissions by around 6 gigatons (Gt) of CO₂ equivalent year⁻¹ in 2030.

The global economic downturn that began in 2008 has slowed the rate of energy use. It is expected that 2009 will be the first year since 1981 to have significantly lower energy use than the prior year, by perhaps as much as 3% (50). Projected economic recovery, however, points to the resumption of an upward trajectory in energy use by 2010, with an overall growth of 40% in 2030 relative to 2007, with non-Organisation for Economic Co-operation and Development countries accounting for 90% of this. Projected business-as-usual growth in coal combustion exceeds that for oil and gas.

The International Energy Agency (IEA) also projects the mix of fuels and associated investments that would be required to attain atmospheric stabilization at 450 ppmv of CO₂. This scenario requires that peak emissions be reached before 2020, with end-use efficiency accounting for two-thirds of the early reductions in CO₂ emissions. By 2030, it is projected that emissions can be reduced relative to 2009 by phasing in more efficient coal- and gas-fired power plants (5%), increased dependence on renewables (20%), the use of biofuels for transportation (35%), augmented nuclear power (10%), and carbon capture and storage (10%).

In stating that "[c]ontinuing on today's energy path, without any change in govern-

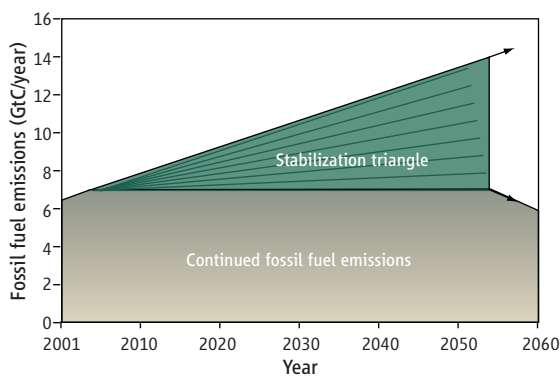


Fig. 10. A path toward stabilization of CO₂ emissions. A stabilization triangle of avoided emissions (green) and allowed emissions (blue) is shown. The allowed emissions are fixed at 7 Gt of carbon year⁻¹, beginning in 2004. The stabilization triangle is divided into seven wedges, each of which reaches 1 Gt of carbon year⁻¹ in 2054. With linear growth, the total avoided emissions per wedge is 25 Gt of carbon, and the total area of the stabilization triangle is 175 Gt of carbon. The arrow at the bottom right of the stabilization triangle points downward to emphasize that fossil fuel emissions must decline substantially below 7 Gt of carbon year⁻¹ after 2054 to achieve stabilization at 500 ppm.

ment policy, would mean rapidly increasing dependence on fossil fuels, with alarming consequences for climate change and energy security,” and “[w]ith a new international climate policy agreement, a comprehensive and rapid transformation in the way we produce, transport and use energy—a veritable low-carbon revolution—could put the world onto this 450-ppm trajectory,” the IEA is effectively endorsing the practicality of a dramatic decarbonization of our global energy system. Aggressive research and development to enhance efficiencies, to improve and implement renewable energy technologies, and to avoid releases of greenhouse gases will be required. Within the United States, the Obama Administration’s American Recovery and Reinvestment Act is an excellent start. It provides the largest boost in history in federal support for research, development, demonstration, and deployment of clean and efficient energy technologies.

As national governments work toward a stable future climate, the scientific community that has revealed the causes of current and probable future shifts in climate and projected plausible consequences of this trajectory still has serious work to do. Cooperative efforts begun in the 1980s to bridge gaps among the Earth and life sciences in order to address interrelated components of the Earth system have led to much of the understanding that is represented in the IPCC assessments. Further advances in these areas need to be encouraged, and enhanced with closer partnerships

with engineering and social science communities. The charter of the Earth System Science Partnership reflects a substantial step in this direction (51). Its initiatives relating to the carbon cycle, food security, water, and human health in the context of global environmental change will provide essential new understanding as society steers to a future that diminishes risk for future human well-being and life all across our planet.

In the past year, we have seen the new U.S. administration place scientists of the highest caliber in key positions as advisors and heads of departments and agencies that oversee the pursuit and application of science and technology in this country. We see encouraging indications that much of what is needed in the way of a new spirit of global cooperation in address-

ing societal problems is being pursued. Never before have scientists been so influential in their active support of sound government policies, nor as selfless in accepting positions of great responsibility in the governance of our nation. It is a moment of pride for the AAAS as we see how many of these scientists have been engaged with our organization throughout their careers. Our most important work, to “advance science, engineering, and innovation throughout the world for the benefit of all people” continues with a new spirit of confident optimism.

References

- E. Crawford, *Ambio* **26**, 6 (1997).
- S. Arrhenius, *Phil. Mag.* **41**, 237 (1896).
- H. Rodhe, *Nature* **401**, 223 (1999).
- S. R. Weart, *The Discovery of Global Warming* (Harvard Univ. Press, Cambridge, MA, 2003).
- J. R. Fleming, *The Callendar Effect: The Life and Work of Guy Stewart Callendar (1989-1964)*, the Scientist Who Established the Carbon Dioxide Theory of Climate Change (American Meteorological Society, Boston, 2007).
- R. Revelle, H. E. Suess, *Tellus* **9**, 18 (1957).
- J. Imbrie, K. P. Imbrie, *Ice Ages, Solving the Mystery* (Harvard Univ. Press, Cambridge, MA, 1979).
- T. C. Peterson, W. M. Connolly, J. Fleck, *Bull. Am. Meteorol. Soc.* **89**, 1325 (2008).
- J. D. Hays, J. Imbrie, N. J. Shackleton, *Science* **194**, 1121 (1976).
- www.nmspaceuseum.org/halloffame/detail.php?id=71
- S. Jasanoff, in *Earthly Politics: Local and Global in Environmental Governance (Politics, Science, and the Environment)*, M. L. Martello, S. Jasanoff, Eds. (Massachusetts Institute of Technology Press, Cambridge, MA, 2004).
- http://earthobservatory.nasa.gov/Features/EarthPerspectives/
- www.ipcc.ch/
- Impacts of a Warming Arctic, 2004 (http://amap.no/acia/).
- T. R. Karl, J. M. Melillo, T. C. Peterson, *Global Climate Change Impacts in the United States*, T. R. Karl, J. M. Melillo, T. C. Peterson, Eds. (Cambridge Univ. Press, Cambridge, 2009).
- S. Manabe, R. T. Wetherald, *J. Atmos. Sci.* **32**, 3 (1975).
- H. Le Treut et al., “Chapter 1: Historical overview of climate change science,” IPCC, 2007 (www.ipcc.ch/).
- N. Nakicenovic et al., *IPCC Special Report on Emissions Scenarios*, IPCC, 2000 (www.ipcc.ch/).
- P. C. Frumhoff, J. J. McCarthy, J. M. Melillo, S. C. Moser, D. J. Wuebbles, *Confronting Climate Change in the U.S. Northeast: Science, Impacts, and Solutions*, synthesis report of the Northeast Climate Impacts Assessment (2007).
- Abrupt Climate Change: Inevitable Surprises* (National Academy Press, Washington, DC, 2002).
- T. M. Lenton et al., *Proc. Natl. Acad. Sci. U.S.A.* **105**, 1786 (2008).
- Transitions and Tipping Points in Complex Environmental Systems* (NSF Advisory Committee for Environmental Research and Education, 2009).
- J. T. Houghton et al., Eds., *Climate Change 1995: The Science of Climate Change* (IPCC, 1996) (www.ipcc.ch/).
- In *Hearing on Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report*, U.S. Senate, Committee on Commerce, Science, and Transportation (U.S. Government Printing Office, Washington, DC, 2001).
- B. Bolin, *A History of the Science and Politics of Climate Change: The Role of the Intergovernmental Panel on Climate Change* (Cambridge Univ. Press, Cambridge, 2008).
- M. R. Raupach et al., *Proc. Natl. Acad. Sci. U.S.A.* **104**, 10285 (2007).
- Global Carbon Project (2009) (www.globalcarbonproject.org/carbonbudget/).
- World Meteorological Organization (WMO), “WMO statement on the status of the global climate in 2008” (WMO, 2009).
- J. L. Lean, D. H. Rind, *Geophys. Res. Lett.* **36**, L15708 (2009).
- O. Anisimov, B. Fitzharris, in *Climate Change 2001: Impacts, Adaptation, and Vulnerability*, J. J. McCarthy, O. F. Canziani, N. A. Leary, D. J. Dokken, K. S. White, Eds. (Cambridge Univ. Press, Cambridge, 2001).
- G. Ekström, M. Nettles, V. C. Tsai, *Science* **311**, 1756 (2006).
- H. D. Pritchard, R. J. Arthern, D. G. Vaughan, L. A. Edwards, *Nature* **461**, 971 (2009).
- J. E. Box et al., in *Arctic Report Card 2009*, p. 39; www.arctic.noaa.gov/repportcard.
- M. Tedesco, X. Fettweis, M. van den Broeke, R. van de Wal, P. Smeets, *Eos* **89**, 391 (2008).
- IPCC Working Group I, Summary for Policy Makers (IPCC, 2001) (www.ipcc.ch/).
- S. Rahmstorf et al., *Science* **316**, 709 (2007).
- S. Rahmstorf, *Science* **315**, 368 (2007).
- W. T. Pfeffer, J. T. Harper, S. O’Neel, *Science* **321**, 1340 (2008).
- P. J. Webster, G. J. Holland, J. A. Curry, H.-R. Chang, *Science* **309**, 1844 (2005).
- K. A. Emanuel, *Nature*, 10.1038/nature03906 (2005).
- World Disasters Report, International Federation of Red Cross and Red Crescent Societies* (2005).
- IPCC Working Group I, Summary for Policy Makers (IPCC, 2007) (www.ipcc.ch/).
- K. M. Walter, M. E. Edwards, G. Grosse, S. A. Zimov, F. S. I. Chapin, *Science* **318**, 633 (2007).
- V. Petrenko et al., *Science* **324**, 506 (2009).
- B. Buffett, D. Archer, *Earth Planet. Sci. Lett.* **227**, 185 (2004).
- G. K. Westbrook et al., *Geophys. Res. Lett.* **36**, L15608 (2009).
- D. Archer, *Biogeosci. Discuss.* **4**, 993 (2007).
- United Nations Framework Convention on Climate Change, http://unfccc.int/2860.php.
- S. Pacala, R. Socolow, *Science* **305**, 968 (2004).
- IEA, *World Energy Outlook 2009: Executive Summary* (www.iea.org).
- R. Leemans et al., *Curr. Opin. Environ. Sustain.* **1**, 1 (2009).
- M. R. Raupach et al., *Proc. Natl. Acad. Sci. U.S.A.* **104**, 10288 (2007).
- J. B. Smith et al., *Proc. Natl. Acad. Sci. U.S.A.* **106**, 4133 (2009).

10.1126/science.1184937