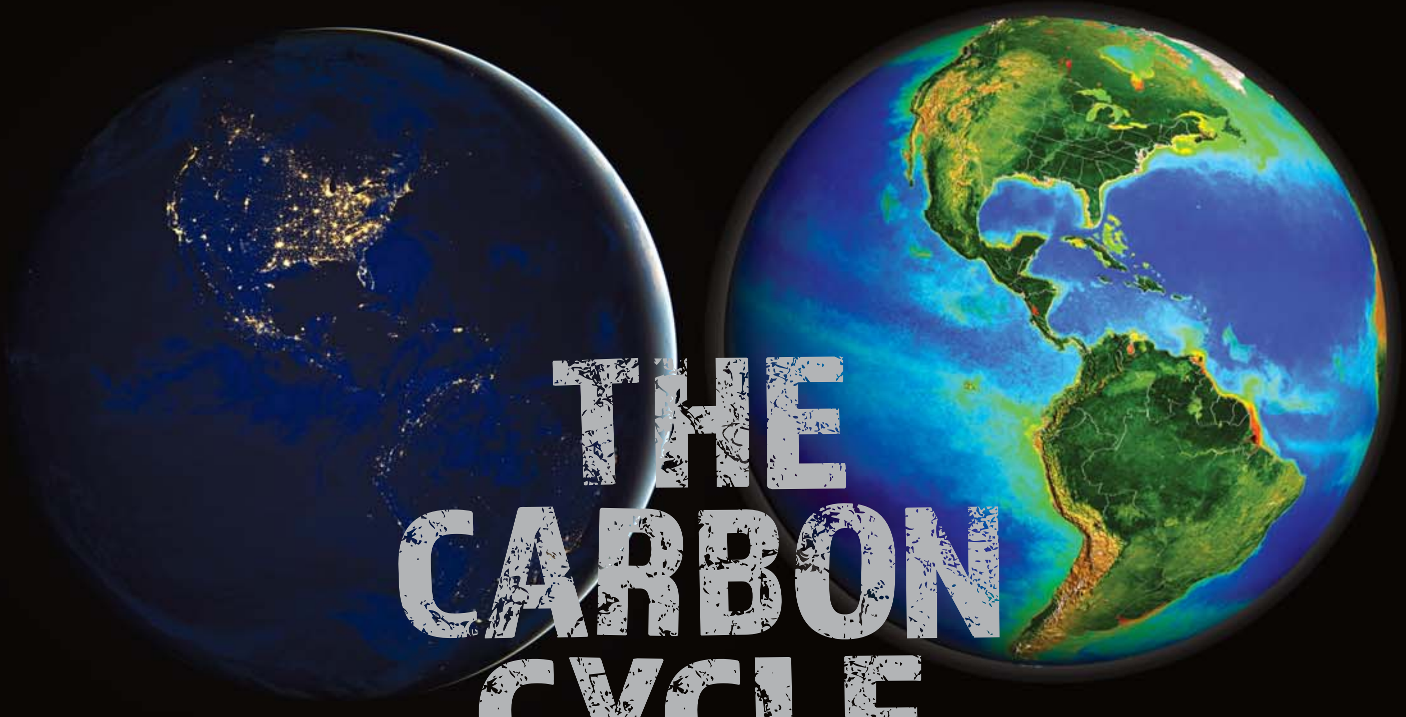

THE CARBON CYCLE in a changing climate

Heather D. Graven

As temperatures rise, precipitation patterns change, and land- and sea-ice extents shrink, scientists are learning how the exchanges of carbon between Earth's atmosphere, ocean, and land ecosystems respond to and feed back on climate change.

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Heather Graven is a lecturer in climate physics and Earth observation at Imperial College London.

The term "carbon cycle" refers to the natural two-way flows of carbon that are driven by physical, chemical, and biological processes on Earth. Each year plant photosynthesis and ocean dissolution remove 25% of the carbon dioxide from the atmosphere, an amount equivalent to 200 billion tons of carbon. But an almost equal amount—195 billion tons of carbon—is released back to the atmosphere by respiration and ocean outgassing. That near balance is akin to an individual person maintaining a relatively constant body weight despite annually consuming, according to the US Department of Agriculture, nearly a ton of food. The difference between the natural removals and releases reflects the carbon cycle's response to human activities, including fossil-fuel combustion, cement production, and land-use changes, such as the conversion of forests to agricultural lands.

The excess CO_2 that's accumulating in the atmosphere comes primarily from fossil-fuel combustion. Because carbon-14 has a half-life of 5700 years, fossil fuels, which are millions of years old, have lost all their ^{14}C to radioactive decay. Fossil-fuel combustion therefore decreases the ratio of radiocarbon to total carbon ($^{14}C/C$) in the atmosphere. That isotopic change is passed on to plants through photosynthesis and is recorded in tree rings. In 1955 Hans Suess showed that the $^{14}C/C$ ratio in tree rings had decreased over the early 20th century. That decrease could have resulted only from the burning of fossil fuels.[1] Soon after Suess's discovery, Charles David Keeling began making high-precision measurements of atmospheric CO_2 concentration.[2] As shown in figure 1, the long-term measurements that Keeling initiated unequivocally demonstrate the increasing CO_2 concentration.

In 2015 Earth's atmospheric CO_2 concentration was 401 ppm, approximately 40% higher than it was before the start of the Industrial Revolution circa 1870. Atmospheric CO_2 concentration is now higher than at any time in at least the past several million years.[3] And recent increases in atmospheric CO_2—the 2015 increase was 3.1 ppm—are much more rapid than at any time in the past 66 million years.[4]

Earth's climate and carbon cycle have varied in the past. Imbalances in the carbon cycle have occurred as a result of external factors such as variations in Earth's orbit around the Sun and complex interactions within the Earth system. (See the article by Judith Lean, Physics Today, June 2005, page 32.) In the past million years, Earth has cycled between cold glacial periods with low atmospheric CO_2 concentrations (190 ppm) and warmer interglacial periods with higher atmospheric CO_2 concentrations (280 ppm).[3] The temperature changes associated with glacial cycles have been much larger than one would expect from changes in incident radiation from the Sun. Thus Earth's climate system must have strong feedback processes that amplify or dampen an external force. The transfer of carbon between the atmosphere, the ocean, and plants and soils on land is a particularly important feedback for the climate.

Some interactions between Earth's climate and the carbon cycle occur on yearly time scales. Plants take in CO_2 during the summer to produce leaves, wood, and other organic material. Carbon is released back to the atmosphere when the growing season ends and plant and soil respiration exceeds CO_2 uptake by photosynthesis, as clearly seen in seasonal variations of atmospheric CO_2. Soil respiration is the release of CO_2 by microbial decomposition of organic matter. In addition to an overall increase in atmospheric CO_2 concentration, observations have shown a steady increase in the amplitude of the seasonal cycle of CO_2 in the Northern Hemisphere.[5] Since 1960 the amplitude has increased by as much as 50% for latitudes north of 45° N. The increasing amplitude indicates that plants and soils in the Northern Hemisphere are now exchanging 35–60% more CO_2 on a seasonal basis than they did 50 years ago.

Natural climate oscillations with periods of several years called El Niño–Southern Oscillations (ENSOs) alter temperature, precipitation, and CO_2 exchanges in the tropics and many other parts of the world. (For more on El Niño dynamics, read the article by David Neelin and Mojib Latif, Physics Today, December 1998, page 32.) Robert Bacastow, a researcher working with Keeling in the 1970s, first discovered irregular variations in the growth rate of atmospheric CO_2 and, somewhat serendipitously, connected them to El Niño variations. One day while he was browsing the display of new books at the Scripps

Institution of Oceanography's library, Bacastow found a book on climate[6] that contained a chapter called "Cyclic and quasi-periodic phenomena." Inside was a plot of variations in the surface pressure gradient over the tropical Pacific Ocean (a measure of ENSO) that was remarkably similar to the variations he observed in the CO_2 growth rate.[7,8] Following that discovery, Bacastow, Keeling, and other researchers established that atmospheric CO_2 increases more rapidly during strong El Niño periods because warm and dry conditions in the tropics reduce plant photosynthesis and promote both wildfires and intentional land-clearing fires. According to the Global Fire Emissions Database, on some individual days in September and October 2015, during the most recent El Niño event, strong fires in Indonesia emitted more CO_2 than the average daily fossil-fuel emissions in the US.

Because the carbon cycle is strongly linked with Earth's climate, changes in climate that are driven by increasing atmospheric CO_2 and other climate pollutants disturb the carbon cycle. Carbon cycle–climate feedbacks are important controls on the buildup of atmospheric CO_2 and thus climate change. The effects of climate change on the carbon cycle are also important to the functioning of natural ecosystems and to industries such as agriculture, logging, and fishing. Researchers are investigating the mechanisms and magnitude of carbon cycle–climate interactions and feedbacks with a view to understanding climate effects on natural and managed ecosystems. Information from that research will help governments and other organizations design policies for mitigating climate change and adapting to a changing climate.

Carbon cycle–climate interactions

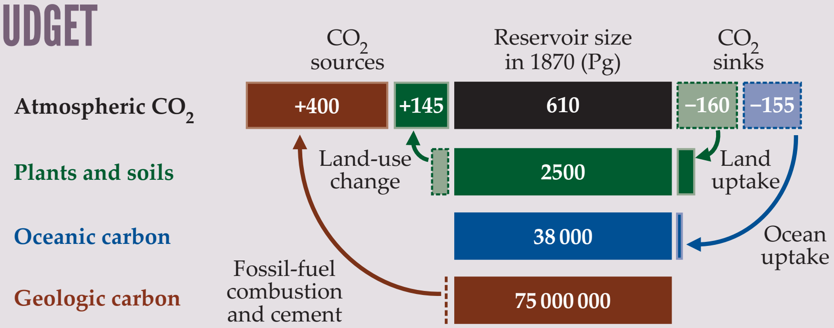
Presently, some of the CO_2 added to the atmosphere by human activities is being removed by the ocean and by plants and soils on land (see box 1). That natural removal is occurring because CO_2 is soluble in ocean water and because plants currently take up more carbon through photosynthesis than the amount released from plants and soils through respiration and other processes. The positive net uptake of CO_2 into plants and soils is happening in part because plants are being "fertilized" by the extra CO_2 in the atmosphere.

Understanding past changes in the carbon cycle and predicting future behavior is challenging because changes in climate and CO_2 concentration can have large, sometimes competing effects. Rising CO_2 concentration tends to increase the carbon uptake to land and ocean reservoirs, whereas climate change can increase or decrease the uptake. The balance between positive and negative influences on carbon uptake is currently not well constrained in climate models, and future projections of atmospheric CO_2 concentration have large uncertainties.[9] Box 2 describes three questions that are subjects of current research.

Carbon cycle–climate interactions can involve a broad range of environmental processes. Studies of those interactions employ many techniques and involve many different fields. Some concentrate on physical ocean, atmosphere, soil, and ice dynamics, whereas others are concerned with biological aspects such as ecology and physiology.

Some key climate sensitivities in the terrestrial carbon cycle involve the impact of temperature and drought on photosynthesis and respiration, species composition, and disturbances such as fires and insects. Photosynthesis can be stimulated by warmer temperatures, especially at high latitudes where temperature is a limiting factor. Temperature also influences the onset of photosynthesis in spring months. Observations of spring bud burst, satellite-derived leaf area cover, and atmospheric CO_2 concentrations clearly indicate that spring has been

BOX 1. THE GLOBAL CARBON BUDGET



The global carbon budget accounts for the amount of carbon released to the atmosphere as CO_2 by human activities (sources) and the portion of that CO_2 transferred to and stored in the ocean and in terrestrial plants and soils (sinks). The accumulation of CO_2 in the atmosphere is the difference between the sources and sinks.

Each row of the diagram represents a carbon reservoir, with the amount of carbon in each reservoir in 1870 shown in the middle column in petagrams (1 Pg = 10^{15} g).[3] The boxes and arrows to the left and right depict the carbon budget[16] in petagrams for the period 1870–2014. Those to the left represent CO_2 sources, and those to the right CO_2 sinks. On each row, the sizes of the boxes that represent sources and sinks are scaled by the amount of carbon in the reservoir in that row. Boxes with dashed lines indicate a removal; boxes with solid lines indicate an addition. Geologic carbon is carbon contained in rocks and fossil fuels.

Since 1870 the amount of carbon in the atmosphere as CO_2 has increased[16] by 230 Pg, or roughly 40%. Terrestrial plants and soils have taken up CO_2 through natural processes, but agricultural expansion and other land-use activities have released CO_2. (For more on land use and its role in climate change, read the article by Roger Pielke, Rezaul Mahmood, and Clive McAlpine on page 40.) The total amount of carbon in plants and soils today is therefore similar to that in 1870. Ocean uptake of CO_2 has removed roughly 155 Pg of the 545 Pg of carbon that fossil-fuel emissions and land-use change have added to the atmosphere. The large reservoir of carbon in the ocean has thus grown, but by less than 0.5%. Ocean uptake of CO_2 reduces the atmospheric CO_2 concentration, thereby mitigating climate change, but it causes ocean acidification because the dissolved CO_2 reacts with ocean water and decreases ocean pH.

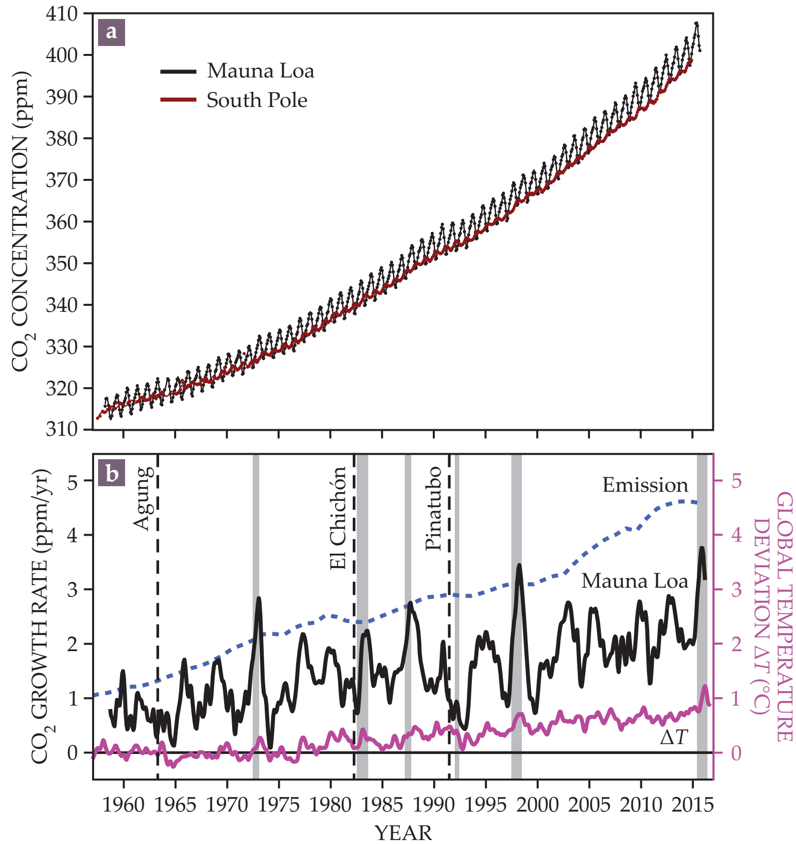


FIGURE 1. THE RELENTLESS CLIMB of atmospheric carbon dioxide. **(a)** Since the late 1950s, atmospheric CO_2 concentrations have been measured at the Mauna Loa Observatory in Hawaii and the South Pole Observatory in Antarctica. The prominent annual cycles in the Mauna Loa record reflect the seasonal uptake and release of CO_2 by plants and soils in the Northern Hemisphere. The difference in CO_2 between Mauna Loa and the South Pole has grown larger as fossil-fuel emissions have increased because emissions are concentrated in the Northern Hemisphere. **(b)** The annual growth rate of CO_2 at Mauna Loa and the CO_2 growth rate expected from fossil-fuel emissions are plotted with the deviation in global temperature ΔT relative to the 1950–80 average. Except during strong El Niño conditions in 1972–73 and 1997–98, the observed CO_2 growth rate is lower than expected from fossil-fuel emissions because of CO_2 uptake by the ocean and by plants and soils on land (see box 1). When temperatures are warm, as commonly found during El Niño periods (gray shading), CO_2 increases more rapidly. Strong volcanic eruptions (dashed vertical lines) generally result in cooler temperatures and slower rates of change in CO_2. (Atmospheric CO_2 concentration data courtesy of Scripps Institution of Oceanography, global temperature data courtesy of NASA, and fossil-fuel emissions data courtesy of Oak Ridge National Laboratory. Emissions estimates for 2014–15 from ref. 16.)

arriving earlier in mid to high latitudes for several decades.[3] Warmer temperatures can also cause heat stress in plants, contribute to drought, and thereby reduce photosynthesis. Drought and heat stress can additionally lead to tree death, which has long-term impacts on ecosystems and the carbon cycle. For example, after strong droughts in the Amazon region in 2005 and 2010, tree mortality doubled.[10]

Warming temperatures increase respiration in soils. Soils presently hold at least 2000 petagrams (1 Pg = 10^{15} g) of carbon,[3] more than twice as much as is held in atmospheric CO_2. Soil-incubation studies have indicated that the rate of CO_2 release by respiration increases by 4–7% for each 1 °C increase in temperature, but that sensitivity is rather uncertain. Respiration rates also depend on the amount of organic material in the soil. Increases in temperature and in photosynthesis are therefore expected to increase respiration. An increase in the release of nutrients to the soil, driven by amplified soil respiration, could also act as a feedback to increase photosynthesis. Changes in climate or availability of nutrients could, furthermore, alter the complex and symbiotic relationships between plants and the fungal and microbial communities in the soil. All those considerations reveal a complex pattern of coincident negative and positive climate feedbacks. Differences between the response of photosynthesis and respiration to future CO_2 emissions and climate change will determine how the terrestrial CO_2 sink will evolve—and potentially even become a net source of CO_2 to the atmosphere.

Climate change can alter the species present in terrestrial ecosystems. In particular, warming Arctic regions are seeing an increase in the abundance of shrubs and other vegetation.[11] Changes in species composition can affect the carbon balance in ecosystems because, for example, an increase in biomass reflects more storage of carbon. Warming and drought stress can make ecosystems more susceptible to wildfires, insect damage, and other disturbances, as evidenced by the recent and widespread bark beetle infestation in the western US. The powerful wildfire in Alberta, Canada, in May 2016 was influenced by warm, dry spring conditions that resulted from the strong El Niño in 2015–16. Species changes interplay with disturbance and land-use change, such that regrowth after fire or abandonment of agricultural lands can create a different composition of species than existed before.

In the ocean carbon cycle, three of the key climate sensitivities are (1) the dependence of CO_2 solubility on ocean temperature and pH, (2) the effect of changes in ocean circulation on carbon dynamics, and (3) the response of marine ecosystems to changes in temperature, ocean pH, and nutrient concentrations. Warming temperatures decrease the solubility of CO_2 in ocean water, while dissolution of CO_2 produces hydrogen ions and makes ocean water more acidic. Both those effects reduce the efficiency of CO_2 uptake by the ocean over time.

As the upper ocean warms and receives fresh water inputs from melting ice and continental runoff, surface water is becoming less dense and more buoyant. That process, called stratification, has increased the vertical gradient in seawater density over much of the ocean.[3] Stratification inhibits vertical mixing

BOX 2. THE BIG QUESTIONS

COURTESY OF THE NATIONAL PARK SERVICE

Below are some of the most critical questions about carbon cycle and climate interactions that are driving current research. Answers to those questions are relevant not only for predicting future atmospheric carbon dioxide concentration and its impact on climate and ecosystems but also for understanding historical changes over past decades and millennia.

▶ **Permafrost:** How much carbon will be released from permafrost? How quickly will the carbon-rich soil release its contents and in what form—carbon dioxide or methane? The photograph shows a collapsed section of permafrost called a thaw slump that slid away from a steep slope 295 m above the Noatak River in Alaska. Current estimates indicate that thawing permafrost might release upwards of 150 Pg (1 Pg = 10^{15} g) of carbon,[17] equivalent to roughly 15 years of current CO_2 emissions from fossil-fuel combustion. Furthermore, depending on how much microbial respiration occurs underwater in lakes and ponds, a significant fraction of permafrost carbon could be released as methane, a stronger greenhouse gas than CO_2. To better assess the threat from permafrost thaw, we need more data on the current amount and distribution of carbon in permafrost soils, accurate simulation of land-surface processes such as thawing and pond formation, and knowledge of how well organic matter in the permafrost resists respiration. Permafrost dynamics and resulting carbon release are currently being implemented in coordinated Earth-system model experiments.

▶ **Ocean circulation:** How will ocean circulation be altered by climate change, and what are the implications for ocean ecosystems and ocean CO_2 absorption? Whereas most of the ocean has been warming, the northwest Atlantic has been cooling. The cooling there could reflect a weakening in the northward transport of heat, possibly related to Arctic warming, loss of sea ice, and melting of the Greenland ice sheet. Over the Southern Ocean, winds have been strengthening because of climate change and because of the ozone hole in the stratosphere. (See the article by Adele Morrison, Thomas Frölicher, and Jorge Sarmiento, PHYSICS TODAY, January 2015, page 27.) Those high-latitude regions strongly influence ocean carbon and ecosystems, so understanding the changes occurring there and how they affect ocean circulation is a key part of investigating carbon cycle–climate interactions.[18] These regions also have an abundance of eddies—swirls of water a few kilometers to a hundred kilometers wide—that influence not only the local ocean area but also large-scale ocean currents. High-resolution ocean models are now starting to resolve eddies, and new ocean observations, in particular from the more than 3000 autonomous floats in the Argo program, are revealing finer three-dimensional structures in ocean properties than were previously possible. (See PHYSICS TODAY, July 2000, page 50, and the article by Karim Sabra, Bruce Cornuelle, and Bill Kuperman, PHYSICS TODAY, February 2016, page 32.)

▶ **Nutrient cycling:** How will nutrient demand and availability affect ecosystem function and CO_2 uptake? Photosynthesis by plants on land and by phytoplankton in the ocean is often limited by nutrient availability. Ocean-circulation changes associated with climate change are expected to reduce nutrient supply to low- and mid-latitude surface waters, with potential impacts on ecosystems and fisheries. Recent studies have suggested that availability of nitrogen, and perhaps also phosphorus, may limit CO_2 absorption by terrestrial plants and soils. That limitation would result in a higher concentration of atmospheric CO_2 and stronger climate change in the future.[9] The interplay between climate, CO_2, and nutrient cycling is a key uncertainty in model predictions of climate change.

and so reduces the downward transport of dissolved anthropogenic CO_2 and the upward supply of nutrients to surface-dwelling organisms.

Marine ecosystems are sensitive to temperature and ocean water acidity. Higher temperature can enhance photosynthesis by phytoplankton. Yet other marine organisms, like their terrestrial counterparts, experience heat stress. For instance, during coral bleaching events, corals eject their colorful algal symbionts. The ejection reveals the white carbonate shells of the corals but also starves the corals of their food source. Large-scale coral bleaching was reported during strong El Niño conditions in 1997–98 and 2015–16. Corals and other organisms that produce carbonate structures are also sensitive to ocean acidification resulting from ocean CO_2 uptake.

Ocean-circulation changes are expected to reduce photosynthesis in most parts of the ocean because the supply of nutrients to phytoplankton will decrease as a result of stratification. In the high latitudes, however, nutrients are more readily available, and changes in ocean circulation may actually enhance photosynthesis. That's because stratification will help phytoplankton stay in the upper ocean where they can harvest light most efficiently. Disruptions in ocean carbon cycling

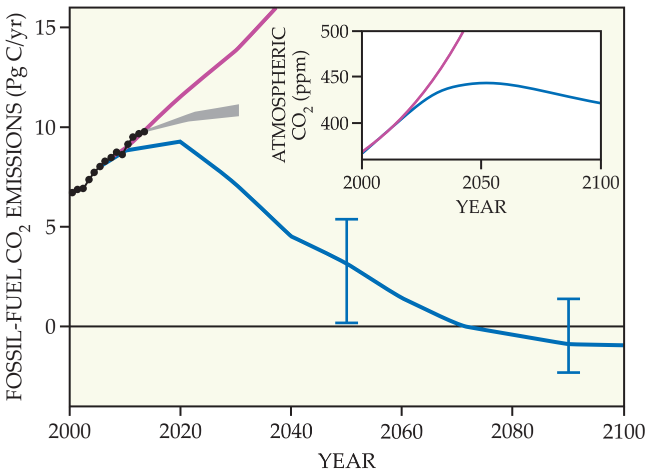


FIGURE 2. FOSSIL-FUEL CARBON DIOXIDE emissions for 2000–2100. The plot shows historical data through 2013 (black) and projected pathways[13] based on high-CO_2 (purple) and low-CO_2 (blue) scenarios published in 2011. The inset shows the corresponding atmospheric CO_2 concentrations. In the low-CO_2 scenario, CO_2 concentration peaks in 2050 and then begins to decrease slightly; the projected maximum rise in temperature is 1.4–2.5 °C (see the table on page 54). In the high-CO_2 scenario, CO_2 concentration continues to increase rapidly and leads to a projected temperature rise of 2.6–4.8 °C at the end of the century.[3] Fossil-fuel emissions compatible with the scenarios were calculated from multiple Earth-system models; the error bars indicate the range in the models' results.[14] Estimated fossil-fuel emissions associated with the nationally determined contributions (NDCs) from the 2015 Paris Agreement (gray) are higher than what's needed to maintain a good chance of meeting a target of 2 °C maximum temperature rise. The estimate includes all NDCs submitted by 7 December 2015 as compiled by Climate Action Tracker and assumes that fossil-fuel CO_2 emissions over 2015–30 comprise the same fraction of total greenhouse gas emissions as in 2013.

could affect marine fisheries via a cascade of effects through the food chain.

Modeling the past and the future

Synthesizing current knowledge to understand and predict the effects of climate change on the global carbon cycle and vice versa requires the use of complex numerical models. Models can focus on specific components of the carbon cycle, such as soil dynamics, or incorporate the entire Earth system with wide-ranging coupled submodels. Research groups across the world regularly organize coordinated Earth-system model simulations to investigate historical changes and future scenarios.[3,9]

Climate change projections derived from Earth-system models depend not only on the total amount of CO_2 emitted but also on the modeled sensitivity of climate to CO_2 and the efficiency of natural CO_2 sinks. The projections are also sensitive to emissions of other climate pollutants, changes in surface albedo, and climate feedbacks in the atmosphere and ocean. Uncertainties in carbon cycle–climate interactions are a major contributor to the overall uncertainty of future climate change. A top priority for climate scientists is to improve how models incorporate those interactions.

Developing simulations of the carbon cycle in Earth-system models requires that a multitude of physical and biological processes be represented within the computational limits of the models. Currently, Earth-system models have spatial resolutions of about 1° in latitude and longitude and temporal resolutions of about an hour; they simulate time ranges of a decade to thousands of years. The models often use parameterizations that simplify the representation of complex processes. One example is the rate of CO_2 exchange across the ocean surface, which is sensitive to wind-driven turbulence, convection, waves, and bubbles in the upper part of the ocean. The involved processes span spatial scales from the thickness of the surface microlayer (less than 1 mm) to the depth of the actively mixed surface layer (up to several hundred meters), so an Earth-system model can't explicitly include all of them. The rate of CO_2 exchange is therefore often parameterized using a quadratic dependence on wind speed that has been determined empirically.[12] As computational capabilities grow, higher-resolution models that include more processes and complexity continue to be developed.

To evaluate how well a model represents climate and carbon-cycle dynamics, the model output is compared with various types of observations. Laboratory and field-based experiments have been undertaken to observe and manipulate carbon cycling. For example, some researchers study the effects of temperature by artificially warming individual leaves, forest plots, or volumes of ocean water in containers called "mesocosms."

Simulation of recent carbon fluxes associated with seasonal and interannual variations such as El Niño can be compared with atmospheric CO_2 data and with observations of CO_2 fluxes from ocean cruises or field sites on land. Simulations over the industrial period since 1870, or even longer periods, are used to examine longer-term processes. One useful technique uses the ^{14}C that was produced by nuclear weapons testing in the 1950s and 1960s. For example, by measuring the increase in ^{14}C in the ocean from the infiltration of bomb-produced ^{14}C, scientists have been able to evaluate the model parameterization for the rate of air–sea CO_2 exchange.

Policy implications

In December 2015, representatives from more than 190 countries met in Paris for the 21st Conference of Parties to the United Nations Framework Convention on Climate Change. There they agreed to cooperate to reduce global greenhouse gas emissions and limit the rise in global average temperature to less than 2 °C. The Paris Agreement, which enters into force on 4 November 2016, brings together individual countries' nationally determined contributions (NDCs). For example, the US's NDC is an economy-wide reduction in greenhouse gas emissions to 26–28% below 2005 levels by 2025. And India's NDC is a reduction in emissions intensity (in kilograms of CO_2 emitted per unit GDP) to 33–35% below 2005 levels by 2030.

Understanding interactions between the climate and the carbon cycle is crucial for the success of the Paris Agreement and other policies aiming to mitigate climate change. That's because the interactions influence how much CO_2 and other greenhouse gases humans can emit and still maintain a good chance of keeping warming below 2 °C from pre-industrial levels.

Figure 2 illustrates one hypothetical scenario[13] that might

ONE SCENARIO, SEVEN MODELS			
Model	Fossil fuel CO_2 emissions (Pg C/yr)		Maximum *T* rise (°C)
	2045–55	2080–2100	
MIROC-ESM	0.2	−2.3	2.5
CanESM2	1.7	−1.1	2.4
GFDL-ESM2M	3.7	−1.1	1.4
NorESM1-ME	2.3	−0.2	1.5
IPSL-CM5A-MR	4.6	0.1	2.2
HadGEM2-ES	3.1	0.4	2.0
MPI-ESM-LR	5.4	1.4	1.8

PROJECTIONS FROM SEVEN MODELS for the low-CO_2 scenario[14] described in figure 2. The model with the largest temperature rise is highlighted in purple and the one with the smallest temperature rise in green. The temperature rise is influenced by the modeled sensitivity of climate to CO_2, whereas the emissions are determined by the modeled CO_2 sinks. A model with a relatively strong climate sensitivity to CO_2 and relatively weak CO_2 sinks could therefore simulate both the strongest increase in temperature and the strongest required reduction in CO_2 emissions, as in the MIROC-ESM model.

limit warming to roughly 2 °C: CO_2 concentration rises from 2010 to 2050, peaks at 443 ppm, and then slowly decreases thereafter. Multiple Earth-system models were used to simulate the climate and carbon-cycle changes under that scenario. The simulated temperature rise varied between models—from 1.4 °C to 2.5 °C—depending on the climate's sensitivity to CO_2 and other influences in a given model.

The level of fossil-fuel emissions consistent with the scenario depend on the natural CO_2 sinks simulated by the models. For example, imagine that the change in atmospheric CO_2 concentration over the years 2045–55 is to be roughly zero but the modeled CO_2 uptake by the land—including the effect of land-use change—and ocean is 2 Pg C/yr. That implies that fossil-fuel emissions for the period could be 2 Pg C/yr. The implied fossil-fuel emissions have a large range across the models[14] (see figure 2 and the table above), but they all require that emissions in 2050 are at least 40% lower than they were in 2010, and nearly zero by the end of the century. Some models imply that negative emissions, or the net removal of CO_2 from the atmosphere, will be necessary.

Achieving near-zero emissions levels may require not only a decrease in fossil-fuel combustion but also the large-scale implementation of technologies to remove CO_2 from the atmosphere.[13] One potential approach would combine the combustion of biofuels, made from wood or other plant material, with carbon capture. The captured carbon would then be pumped to underground saline aquifers or geological reservoirs for long-term storage. However, those technologies are only in the early stages of demonstration and development, and their large-scale deployment could require large amounts of land, water, and energy that limit their practical use or desirability.[15]

In contrast to the low-CO_2 scenario mentioned above, the pledges made in the Paris Agreement indicate that global fossil-fuel emissions will likely continue to increase until at least 2030. That difference in the projected and required near-term emissions has been dubbed the emissions gap. A rise in emissions over 2015–30 means that emissions have to be reduced much more rapidly after 2030 to maintain a good chance of keeping maximum warming to 2 °C. Recognizing the gap, the Paris Agreement includes an ambition to ramp up NDCs over time and to review progress toward reducing greenhouse gas emissions. The reviews, called global stocktakes, will be conducted over five-year periods starting in 2023. Scientific input will be critical to the implementation of the Paris Agreement and to its assessment through the global stocktakes.

New insights and better constraints on carbon cycle–climate feedbacks will help to quantify necessary reductions in CO_2 emissions and clarify the policies needed to meet climate change targets under different scenarios. Carbon cycle–climate feedbacks become even more important[14] for pathways in which the global average temperature rises more than 2 °C because then the carbon cycle is exposed to conditions that are more extreme.

Understanding the interactions between the climate and the carbon cycle is also important in designing policies for adaptation to climate change. In addition to expected climate extremes and sea-level rise, governments want to know what level of ocean acidification, species shifts, and other ecosystem changes to expect. (For more on climate policy options, read the article by Paul Higgins, PHYSICS TODAY, October 2014, page 32.)

To give policymakers the best possible information, scientists must continue to investigate the vast network of interconnected biological, chemical, and physical processes that govern global climate. And a major focus has to be the interactions between the climate and the carbon cycle. Continued measurement of atmospheric CO_2 and other aspects of the global carbon cycle will be essential if we are to improve estimates of carbon sinks and their response to global change.

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