



1 Overview of the Global Carbon Cycle

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KEY FINDINGS

1. Atmospheric carbon dioxide (CO₂) has increased from a preindustrial abundance of 280 parts per million (ppm) of dry air to over 400 ppm in recent years—an increase of over 40%. As of July 2017, global average CO₂ was 406 ppm. Methane (CH₄) has increased from a preindustrial abundance of about 700 parts per billion (ppb) of dry air to more than 1,850 ppb as of 2017—an increase of over 160%. The current understanding of the sources and sinks of atmospheric carbon supports the dominant role of human activities, especially fossil fuel combustion, in the rapid rise of atmospheric carbon (*very high confidence*).
2. In 2011, the total global anthropogenic radiative forcing resulting from major anthropogenic greenhouse gases (GHGs, not including anthropogenic aerosols) relative to the year 1750 was higher by 2.8 watts per meter squared (W/m²). As of 2017, the National Oceanic and Atmospheric Administration's Annual Greenhouse Gas Index estimates anthropogenic radiative forcing at 3.1 W/m², an increase of about 11% since 2011. In 2017, CO₂ accounted for 2.0 W/m² and CH₄ accounted for 0.5 W/m² of the rise since 1750. The global temperature increase in 2016 relative to the 1880 to 1920 average was over +1.25°C, although this warming was partially boosted by the 2015–2016 El Niño. Global temperature, excluding short-term variability, now exceeds +1°C relative to the 1880–1920 mean in response to this increased radiative forcing (Hansen et al., 2017; *very high confidence*).
3. Global fossil fuel emissions of CO₂ increased at a rate of about 4% per year from 2000 to 2013, when the rate of increase declined to about 2% per year. In 2014, the growth in global fossil fuel emissions further declined to only 1% per year (Olivier et al., 2016). During 2014, the global economy grew by 3%, implying that global emissions became slightly more uncoupled from economic growth, likely a result of greater efficiency and more reliance on less carbon intensive natural gas and renewable energy sources. Emissions were flat in 2015 and 2016 but increased again in 2017 by an estimated 2.0% (*high confidence*).
4. Net CO₂ uptake by land and ocean removes about half of annually emitted CO₂ from the atmosphere, helping to keep concentrations much lower than would be expected if all emitted CO₂ remained in the atmosphere. The most recent estimates of net removal by the land, which accounts for inland water emissions of about 1 petagram of carbon (Pg C) per year, indicate that an average of 3.0 ± 0.8 Pg C per year were removed from the atmosphere between 2007 and 2016. Removal by the ocean for the same period was 2.4 ± 0.5 Pg C per year. Unlike CO₂, CH₄ has an atmospheric chemical sink that nearly balances total global emissions and gives it an atmospheric lifetime of about 9 to 10 years. The magnitude of future land and ocean carbon sinks is uncertain because the responses of the carbon cycle to future changes in climate are uncertain. The sinks may be increased by mitigation activities such as afforestation or improved cropping practices, or they may be decreased by natural and anthropogenic disturbances (*high confidence*).
5. Estimates of the global average temperature response to emissions range from +0.7 to +2.4°C per 1,000 Pg C using an ensemble of climate models, temperature observations, and cumulative emissions (Gillett et al., 2013). The Intergovernmental Panel on Climate Change (IPCC 2013) estimated that to have a 67% chance of limiting the warming to less than 2°C since 1861 to 1880 will require cumulative emissions from all anthropogenic sources to stay below about 1,000 Pg C since that period, meaning that only 221 Pg C equivalent can be emitted from 2017 forward. Current annual global CO₂ emissions from fossil fuel combustion and cement production are 10.7 Pg C per year, so this limit could be reached in less than 20 years. This simple estimate, however, has many uncertainties and does not include carbon cycle–climate feedbacks (*medium confidence*). These conclusions are consistent with the findings of the recent *Climate Science Special Report* (USGCRP 2017).

Note: Confidence levels are provided as appropriate for quantitative, but not qualitative, Key Findings and statements.



1.1 The Role of Carbon in the Earth System

Carbon is an essential component of the Earth system. It is fundamental for the existence of life on Earth because of its ability to combine with other important elements, such as oxygen, nitrogen, and phosphorus, and with hydrogen to form the organic molecules that are essential for cellular metabolism and reproduction. Atmospheric carbon in the forms of carbon dioxide (CO₂) and methane (CH₄) helps regulate the Earth's climate by “trapping” heat in the atmosphere. This trapping of energy is known as the greenhouse effect, and CO₂ and CH₄, along with other greenhouse gases (GHGs) such as water vapor and nitrous oxide (N₂O), keep the Earth's climate in a habitable range. Carbon also is of significant socioeconomic importance because the burning of carbon-based fossil fuels is currently the dominant global means of energy production. Production and consumption of coal, oil, and natural gas release CO₂, CH₄, and other gases to the atmosphere. Considered in this chapter are the global carbon cycle and perturbations to it by human activities, as well as global climate–carbon cycle feedbacks and strategies to control or sequester emissions (see Box 1.1, Why a Global Carbon Cycle Context, this page).

In 2011, the total global radiative anthropogenic forcing (i.e., caused by humans) relative to the year 1750 was 2.8 watts per meter squared (W/m²; Myhre et al., 2013). As of 2017, atmospheric observations of important radiatively active trace species (CO₂, CH₄, N₂O, CFC-11, CFC-12, and 15 minor halogenated gases) suggest that anthropogenic radiative forcing has risen to 3.1 W/m², an additional 11% (see Figure 1.1, p. 45).¹ The largest portion of this forcing, 2.0 W/m², is due to CO₂, with CH₄ accounting for 0.5 W/m². The global temperature in 2016 relative to the 1880 to 1920 average is greater by 1.25°C in response to this increased radiative forcing (Hansen et al., 2017). Other aspects of the climate system also are changing in response to the increased radiative forcing—the amount,

¹ National Oceanic and Atmospheric Administration Annual Greenhouse Gas Index. www.esrl.noaa.gov/gmd/ccgg/aggi.html.

Box 1.1 Why a Global Carbon Cycle Context

Although the focus of this report is on the state of the North American carbon cycle, this chapter provides a brief overview of the global carbon cycle. The North American budgets of carbon dioxide and methane must be put into the context of the global budgets. Carbon emissions from one region of the world are dispersed throughout the global atmosphere so that the radiative effects of regional emissions are global. Furthermore, influx of greenhouse gases from other parts of the world is a major contribution to the atmospheric greenhouse gas budgets of North America. Accurate estimates of the North American carbon budget depend on knowledge of contributions from the rest of the world, and hence globally distributed observations and knowledge of the global carbon budget is necessary.

distribution, and timing of rainfall, with extreme hydrological events becoming increasingly frequent, intense, and widespread (Hartmann et al., 2013). These changes may have significant effects on global food production. For example, currently productive regions may not be able to sustain agriculture in the future, especially if water availability becomes limited. Heat stress also can significantly affect agriculture, especially at tropical and subtropical latitudes but also at midlatitudes (Battisti and Naylor 2009). Even though CO₂ can result in increased terrestrial plant productivity (i.e., “CO₂ fertilization”), the negative impacts of climate change on agriculture are expected to dominate. In the ocean, the decrease in pH of ocean surface water is already about 0.1 pH unit (a decrease in pH of 7.5 to 7.4) since the start of the Industrial Revolution (Bates 2007). This increasing acidification of the ocean, along with water warming and pollution, endangers many marine organisms, including corals, shellfish, and

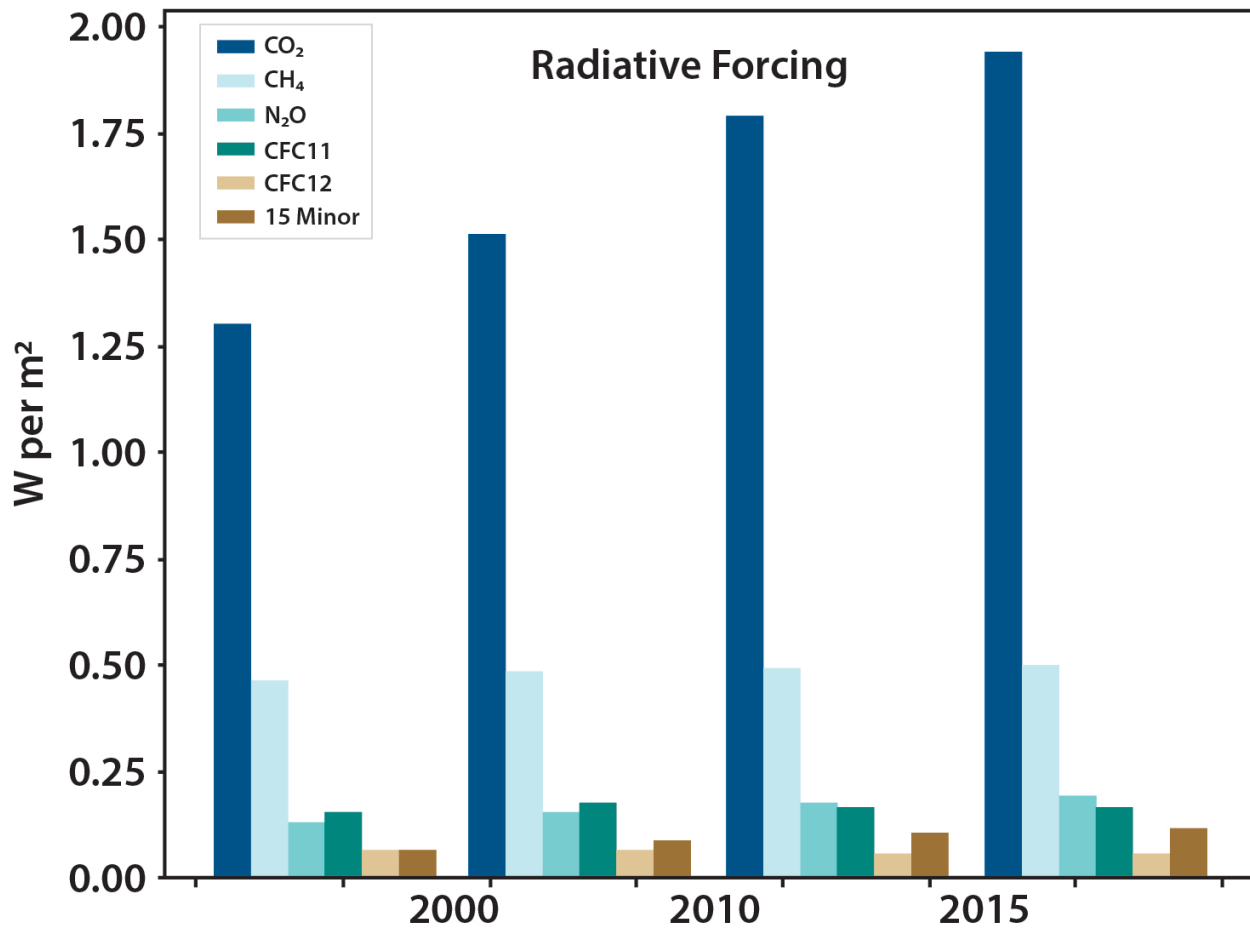


Figure 1.1. Radiative Forcing (Relative to 1750) Due to Major Greenhouse Gases (GHGs). Major GHGs include carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), trichlorofluoromethane (CFC11), and dichlorodifluoromethane (CFC12). The 15 minor GHGs include CFC-113; CCl₄; CH₃CCl₃; HCFCs 22, 141b, and 142b; HFCs 134a, 152a, 23, 143a, and 125; SF₆; and halons 1211, 1301, and 2402. Radiative forcing calculations, in watts (W) per m², are based on measurements of GHGs in air trapped in snow and ice in Antarctica and Greenland prior to about 1980 and atmospheric measurements taken since then. [Figure source: Redrawn from National Academies of Sciences, Engineering, and Medicine 2018.]

marine plankton. Increasing CH₄ emissions can lead to tropospheric ozone formation, with implications for air quality (Fiore et al., 2002). Understanding and predicting future evolution of the global carbon cycle are critical for confronting these issues and, therefore, represent a challenging societal and scientific problem.

1.2 The Natural Carbon Cycle

In the Earth System, carbon is stored in rocks (as carbonates), sediments, ocean and freshwaters, soils

and terrestrial biomass, and the atmosphere. By far the larger reservoir of carbon is the deep water of the ocean, which is thought to contain about 80% of the Earth System's carbon (excluding rock; see Figure 1.2, p. 46). Oceanic sediments are thought to contain 4%. Ocean surface waters and the atmosphere each hold about 2% of the Earth system's carbon reservoirs. Oil, gas, and coal reserves are thought to contribute another 3%. Soils and permafrost hold 5% and 4% of global carbon, respectively, while carbon stored in vegetation adds about 1%.

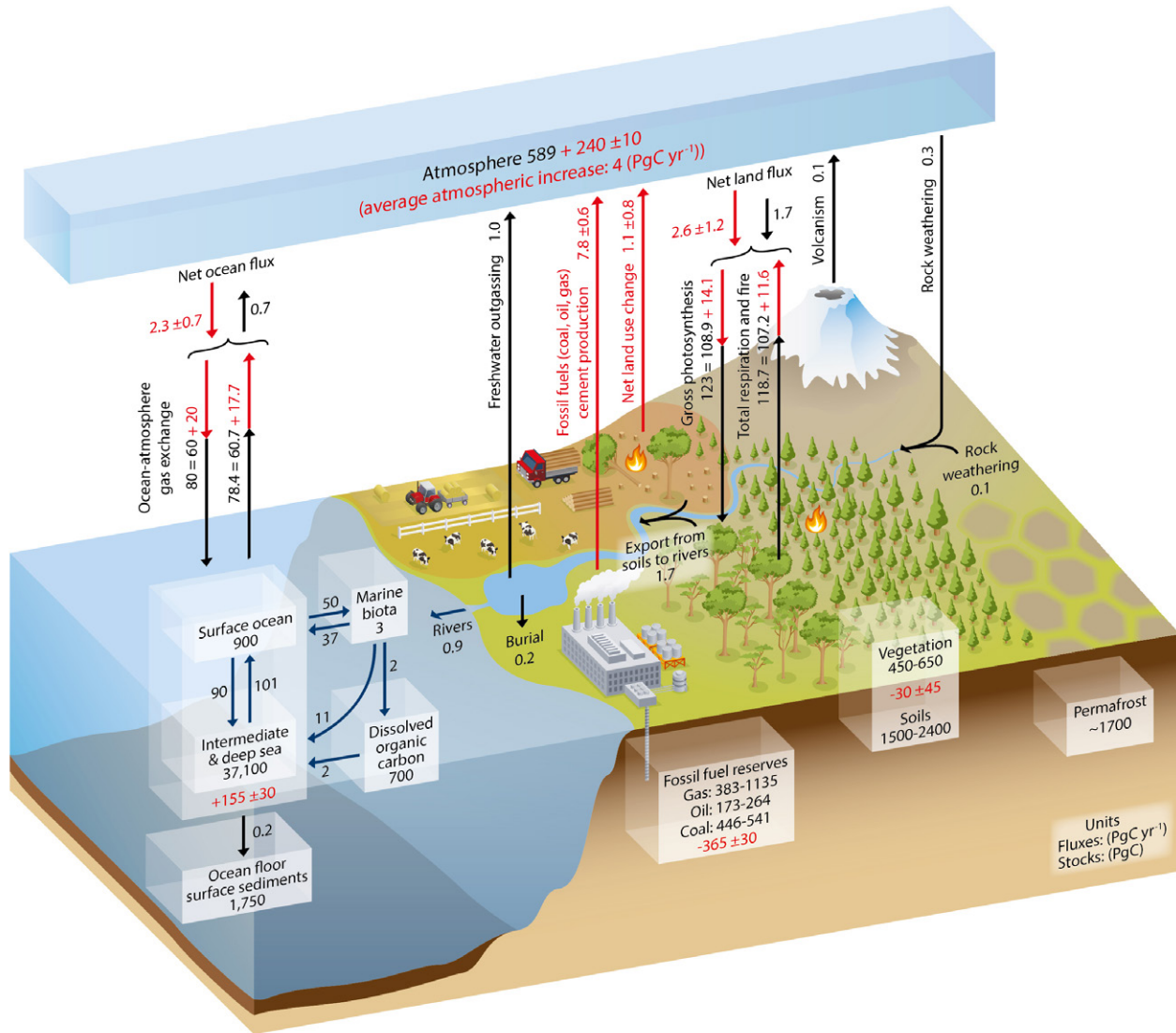


Figure 1.2. A Simplified Pictorial Illustration of the Global Carbon Cycle. The boxed numbers represent reservoir mass or carbon stocks in petagrams of carbon (Pg C). Arrows represent annual exchange (fluxes) in Pg C per year. Black numbers and arrows represent preindustrial reservoir masses and fluxes, while red arrows and numbers show average annual anthropogenic fluxes for 2000 to 2009. The red numbers in the reservoirs denote cumulative changes of anthropogenic carbon for the industrial period. Uncertainties are reported as 90% confidence intervals. [Figure source: Reprinted from Ciais et al., 2013, Figure 6.1. Copyright IPCC, used with permission.]

The global carbon cycle includes the mechanical, chemical, and biological processes that transfer carbon among these reservoirs (see Figure 1.2, this page). Reservoirs of carbon in the Earth system often are also referred to as “pools” or “stocks,” and transfers of carbon between reservoirs are known as “fluxes.” Some of these carbon fluxes are sensitive

to climate, and their resulting responses to climate change are known as “carbon cycle–climate feedbacks.” A positive feedback can occur when carbon fluxes to the atmosphere increase as a result of, for example, increasing temperatures. More carbon in the atmosphere leads to further climate warming, possibly further increasing carbon fluxes to the



atmosphere. Carbon cycle–climate feedbacks will be discussed further in Section 1.4, p. 56.

1.2.1 Carbon Dioxide

The global carbon cycle comprises a *fast* carbon cycle, having relatively rapid exchanges among the ocean, terrestrial biosphere, and atmosphere, and a *slow* carbon cycle, involving exchanges with geological reservoirs such as deep soils, the deeper ocean, and rocks. Equilibration between the terrestrial biosphere and ocean occurs on millennial timescales, while redistribution of CO₂ among geological reservoirs requires tens to hundreds of thousands of years or longer. Figure 1.2, p. 46, provides a pictorial representation of the exchanges of carbon among the main reservoirs, together with associated timescales.

Reservoirs for the fast components of the carbon cycle include the ocean, land vegetation and soils, freshwaters, shallow oceanic sediments, and the atmosphere. Based on estimates from the *Intergovernmental Panel on Climate Change Fifth Assessment Report* (IPCC AR5; IPCC 2013), about 830 petagrams of carbon (Pg C; 2000 to 2009 average) were present in the atmosphere, while 450 to 650 Pg C are stored in the terrestrial biosphere. Larger reservoirs of carbon exist in soils (1,500 to 2,400 Pg C; IPCC 2013), and soil organic carbon (SOC) densities are highest in moist boreal and tropical latitudes. Scharlemann et al. (2014) pointed out that these numbers are uncertain due to limited depth and sparse distribution of sampled or observed SOC profiles. The Arctic permafrost soils are estimated to contain 1,339 to 1,580 Pg C in the top 3 m of the soil column, with another 400 Pg C possible in deep soils (Schuur et al., 2015). Ocean waters and shallow sediments contain about 40,500 Pg C. The “fast-exchange” reservoirs of the ocean surface and marine biota hold only 900 Pg C and 3 Pg C, respectively. Turnover times for these fast- and slow-exchange reservoirs range from decades to millennia.

Exchange of carbon between the atmosphere and the terrestrial biosphere occurs via photosynthesis and respiration. Carbon is removed from the atmosphere by photosynthesis and fixed in leaves, roots,

stems, and woody biomass. It is returned to the atmosphere through autotrophic (plant) respiration and heterotrophic (microbial) respiration of plant litter and soil carbon. Fire and other disturbances such as insect outbreaks and timber harvesting can be thought of as accelerated respiration processes, and the amount entering the atmosphere from these processes varies from year to year. Removal of CO₂ by photosynthesis is thought to have been slightly higher in the preindustrial atmosphere than emissions added from respiration and natural disturbances. Global total photosynthesis at that time is thought to have exceeded global respiration and emissions from natural disturbances so that net removal from the atmosphere by the land was about 1.7 Pg C per year. This removal is estimated to have been approximately in balance with outgassing from the ocean and freshwaters (Ciais et al., 2013; see Figure 1.2).

Gas exchange between the atmosphere and ocean depends on the difference between the partial pressure of CO₂ in surface water and that of CO₂ in the atmosphere ($\Delta p\text{CO}_2$). Carbon dioxide dissolves in ocean water to form carbonic acid (H₂CO₃), which then forms bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻). These coupled reactions chemically buffer ocean water, thus regulating ocean *p*CO₂ and pH. Because *p*CO₂ can vary spatially, carbon outgasses from the ocean waters in some regions and is taken up in others. In regions where there is upwelling of nutrient-rich water and ocean waters are warm (e.g., in parts of the tropics), carbon is outgassed. In the North Atlantic, cold, sinking water removes carbon from the atmosphere. The Southern Ocean (latitudes south of 44°S) is another area where carbon is taken up. Carbon also is exchanged between land and ocean reservoirs via river transport to the coastal ocean.

Year-to-year variability of the global ocean CO₂ sink was thought to be small, at only about ±0.2 Pg C per year or 9% of annual ocean uptake (Wanninkhof et al., 2013); however, recent work by Landschutzer et al. (2016), based on comprehensive measurements of global $\Delta p\text{CO}_2$ of ocean



surface water, suggests that substantial decadal and interannual variability can exist. They found that during the 1990s, the global ocean sink was likely to have been significantly smaller than after year 2000 (-0.8 ± 0.5 Pg C per year and -2.0 ± 0.5 Pg C per year, respectively). They proposed 1) that these decadal variations are driven by extratropics and are linked with the atmospheric northern and southern annular modes and 2) that interannual variability is driven by the tropical ocean. The variability of the global land sink is larger, varying by 3 to 4 Pg C per year, and most of this variability likely occurs in the tropics (Baker et al., 2006). This global atmospheric CO₂ interannual variability arises primarily from land sink variability because of the strong anticorrelation between CO₂ and $\delta^{13}\text{C}$ (e.g., Alden et al., 2010). Terrestrial net carbon exchange gives rise to significant $\delta^{13}\text{C}$ variability, whereas air-sea gas exchange does not. The El Niño Southern Oscillation (ENSO) is thought to be a significant driver of tropical carbon flux variability for both the ocean and terrestrial ecosystems. During the warm phase of ENSO, the ocean takes up more carbon because of reduced upwelling and outgassing from the eastern Tropical Pacific. On land, ENSO is associated with outgassing from the terrestrial biosphere, a phenomenon likely associated with drought and warmer global temperatures. Indeed, the strong ENSO of 2016 pushed measured CO₂ concentrations at Mauna Loa to above 400 ppm, where they have remained (Betts et al., 2016).

The slow, or geological, carbon cycle operates on timescales of tens of millennia and longer. Fluxes to the atmosphere from volcanism, CO₂ removal from the atmosphere by chemical weathering, and ocean sediment formation together are a factor of 10 smaller than the fluxes of the fast carbon cycle. A vast amount of carbon is also stored in sedimentary rocks (100×10^6 Pg C), with an estimated 4,000 Pg C stored as hydrocarbons (Ciais et al., 2013).

Ice core evidence suggests that during glacial periods atmospheric CO₂ was present at about 180 to 200 ppm. During interglacial periods, atmospheric CO₂ abundance was higher, between 270 to 290 ppm

(Lüthi et al., 2008; Petit et al., 1999). The current atmospheric levels of 400 ppm are well outside the range that existed during the period resolved by ice cores; that is, 800,000 years before present. The most recent glacial period ended about 12,000 years ago, with the most recent glacial maximum occurring about 22,000 years ago. Even older evidence from Arctic lake sediments suggests that around 3.5 million years ago, Arctic summer temperatures were about 8°C warmer than today with atmospheric CO₂ levels around 400 ppm (Brigham-Grette et al., 2013). Contemporary CO₂ has surpassed 400 ppm, suggesting that the current Arctic is not yet in equilibrium with rapidly rising greenhouse gas concentrations and may become much warmer in the future.

Estimates for recent decades show significant trends and variability in the main components of the global carbon cycle (see Table 1.1, p. 49). Only about half of human-driven emissions from fossil fuel burning, industry (e.g., cement manufacturing), and land-use change remains in the atmosphere, although the growth in atmospheric CO₂ is highly variable depending on emissions and the strength of uptake by land and ocean (see Table 1.1). Emissions have risen by about 70% from the 1980s to the most recent decade (2007 to 2016), while land and ocean have taken up 3.0 ± 0.8 and 2.4 ± 0.5 Pg C per year, respectively (Le Quéré et al., 2017). Of this amount, North America represents a rather substantial share of global carbon uptake (0.31 Pg C per year; see Ch. 2: The North American Carbon Budget, p. 71). Figure 1.3a, p. 50, shows global average atmospheric CO₂ derived from *in situ* surface air samples. The steep rise in CO₂ reflects anthropogenic emissions, while the annual cycle reflects the seasonal uptake of vegetation, predominantly in the Northern Hemisphere.

1.2.2 Methane

Total global CH₄ emissions are approximately 550 teragrams (Tg) of CH₄ per year (1 Tg CH₄ per year = 10^{12} grams of CH₄ per year; Saunio et al., 2016). Of this, roughly 40% comes from natural sources. The largest (and most uncertain) natural



Table 1.1. Historic^a and Decadal^b Global Mean Emissions and Their Partitioning to the Carbon Reservoirs of Atmosphere, Ocean, and Land

	1750–2011 Cumulative Pg C ^c	1980–1989 Pg C per Year	1990–1999 Pg C per Year	2000–2009 Pg C per Year	2007–2016 Pg C per Year	2016 Pg C per Year
Emissions						
Fossil Fuels and Industry	375 ± 30	5.5 ± 0.3	6.3 ± 0.3	7.8 ± 0.4	9.4 ± 0.5	9.9 ± 0.5
Land-Use Change	180 ± 80	1.2 ± 0.7	1.3 ± 0.7	1.2 ± 0.7	1.3 ± 0.7	1.3 ± 0.7
Partitioning to Carbon Reservoir						
Growth in Atmospheric CO ₂ ^c	240 ± 10	3.4 ± 0.1	3.1 ± 0.1	4.0 ± 0.1	4.7 ± 0.1	6.0 ± 0.2
Ocean Uptake	160 ± 80	1.7 ± 0.5	1.9 ± 0.5	2.1 ± 0.5	2.4 ± 0.5	2.6 ± 0.5
Land Uptake	155 ± 30	2.0 ± 0.6	2.5 ± 0.5	2.9 ± 0.8	3.0 ± 0.8	2.7 ± 0.9

Notes

- a) Historic cumulative emissions and partitioning from the *Intergovernmental Panel on Climate Change Fifth Assessment Report* (Ciais et al., 2013).
 b) Decadal means from the Global Carbon Project (Le Quéré et al., 2017).
 c) Pg C, petagrams of carbon; CO₂, carbon dioxide.

emissions of CH₄ are from wetlands, defined as regions that are permanently or seasonally water-logged. Natural wetlands include high-latitude bogs and fens, tropical swamps, and temperate wetlands. Saturated soils in warm tropical environments tend to produce the most CH₄. However, warming Arctic temperatures raise concerns of increasing emissions from high-latitude wetlands and future decomposition of carbon currently stored in frozen Arctic soils (e.g., Schaefer et al., 2011; Schuur et al., 2015). Figure 1.4, p. 51, provides a pictorial representation of the main components of the global methane cycle.

Estimates of global CH₄ emissions from wetlands range from 127 to 227 Tg CH₄ per year (Saunois et al., 2016), with most probable values between 167 and 185 Tg CH₄ per year. Most emissions occur in tropical regions (Matthews 1989; Melton et al., 2013; Saunois et al., 2016). Currently, only about 25 Tg CH₄ per year (i.e., 4% of global emissions) are thought to be emitted from high northern latitudes (AMAP 2015; Saunois et al., 2016). Because emissions are sensitive to temperature and precipitation,

they exhibit significant seasonal cycles, especially at high latitudes, as well as interannual variability caused by moisture and temperature variability. Smaller amounts of CH₄ are emitted from fires, the ocean, and enteric fermentation in termites and wild animals (20 Tg CH₄ per year or less for each). In addition, up to 60 Tg CH₄ per year may be emitted from geological sources, such as seeps, clathrates, mud volcanoes, and geothermal systems (Etiope et al., 2008; Schwietzke et al., 2016).

Unlike CO₂, CH₄ has an atmospheric chemical sink that nearly balances total global emissions. Removal of atmospheric CH₄ by reaction with the hydroxyl radical (OH) results in a CH₄ atmospheric lifetime of about 9 to 10 years. Observationally constrained estimates of CH₄ lifetime suggest either small decreases of about 2% from 1980 to 2005 (Holmes et al., 2013) or stable CH₄ lifetimes with the possibility of interannual variability of about 2% (Montzka et al., 2011). CH₄ is a much more powerful greenhouse gas than CO₂ (on a per mass basis and over 100 years, CH₄ is about 25 times more effective at trapping heat than CO₂).

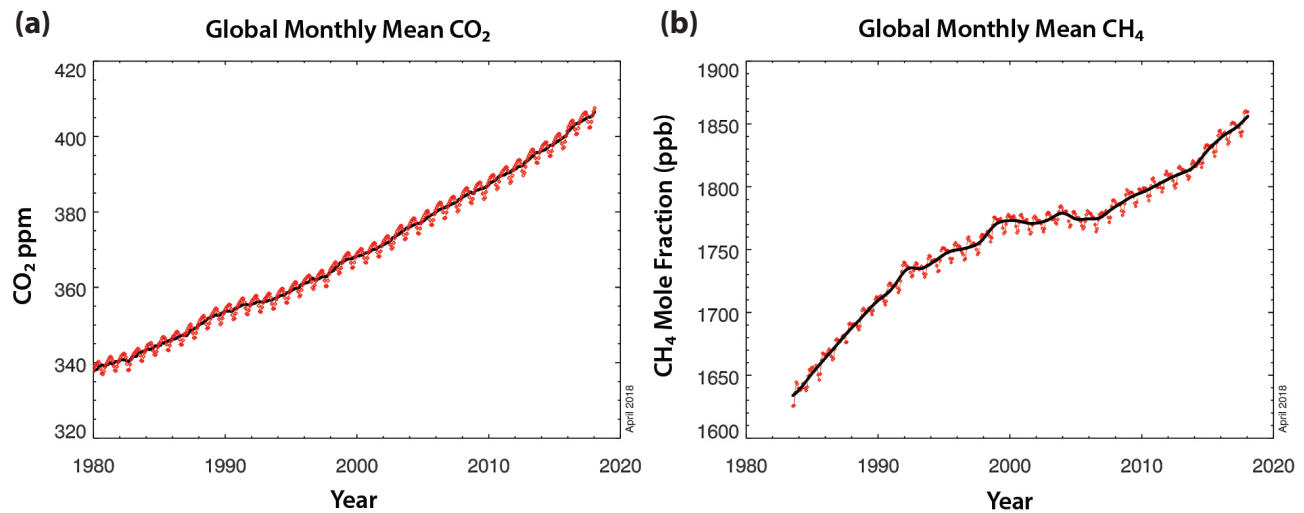


Figure 1.3. Global Averages of Atmospheric Gases Derived from Surface Air Samples. (a) Carbon dioxide (CO₂) in parts per million (ppm). **(b)** Methane (CH₄) in parts per billion (ppb). [Figure source: Redrawn from NOAA-ESRL-GMD 2017.]

As shown in Figure 1.3b, this page, atmospheric CH₄ increased rapidly during the 1980s and early 1990s before its growth leveled off between the mid-1990s and early 2000s. Methane has resumed its increase in the atmosphere since 2006, and observations show that this growth has even accelerated since 2014. The changing atmospheric CH₄ growth rate has been the subject of much debate, questioning why growth rate slowed for a decade starting in the mid-1990s. Several studies suggested that this slower rate was due to decreases in fugitive emissions from fossil fuel production (Aydin et al., 2011; Simpson et al., 2012) or to decreased emissions from anthropogenic microbial sources, such as rice agriculture (Kai et al., 2011). On the other hand, Dlugokencky et al. (1998, 2003) proposed that the slowing of CH₄ growth in the atmosphere was due to an approach to a quasi-steady state, reached when global sources and sinks are in balance. Consistent with this view, the study of Schwietzke et al. (2016) found that emissions from oil and gas production have remained stable over the past several decades, implying increasing efficiency in fossil fuel production industries while their production was increasing over time.

Dlugokencky et al. (2003) predicted that CH₄ would approach a steady state in the atmosphere of about 1,780 ppb by the 2010s if there were no major changes in its budget. The methane budget did change, however, because the atmospheric growth of CH₄ resumed its rise in 2006. The cause of the recent increase in CH₄ growth also has been much debated. Based on global observations of the CH₄ isotope, ¹³CH₄, the global growth in CH₄ appears likely to have been dominated by microbial sources in the tropics (wetlands or agriculture and waste), rather than fossil fuel production (Nisbet et al., 2016; Schaefer et al., 2016), as suggested by some studies (e.g., Rice et al., 2016). Other studies have argued that ¹³CH₄ may not be a very strong constraint on the global methane budget and that changes in the atmospheric CH₄ chemical sink are responsible for the global methane changes (Rigby et al., 2017; Turner et al., 2017). However, plausible chemical mechanisms that could explain the changes in the CH₄ sink have not been identified. Using space-based retrievals of carbon monoxide, Worden et al. (2017) argued that the isotopic data record also can be consistent with increased fossil fuel emissions if global biomass-burning emissions have decreased twice as much as estimates based

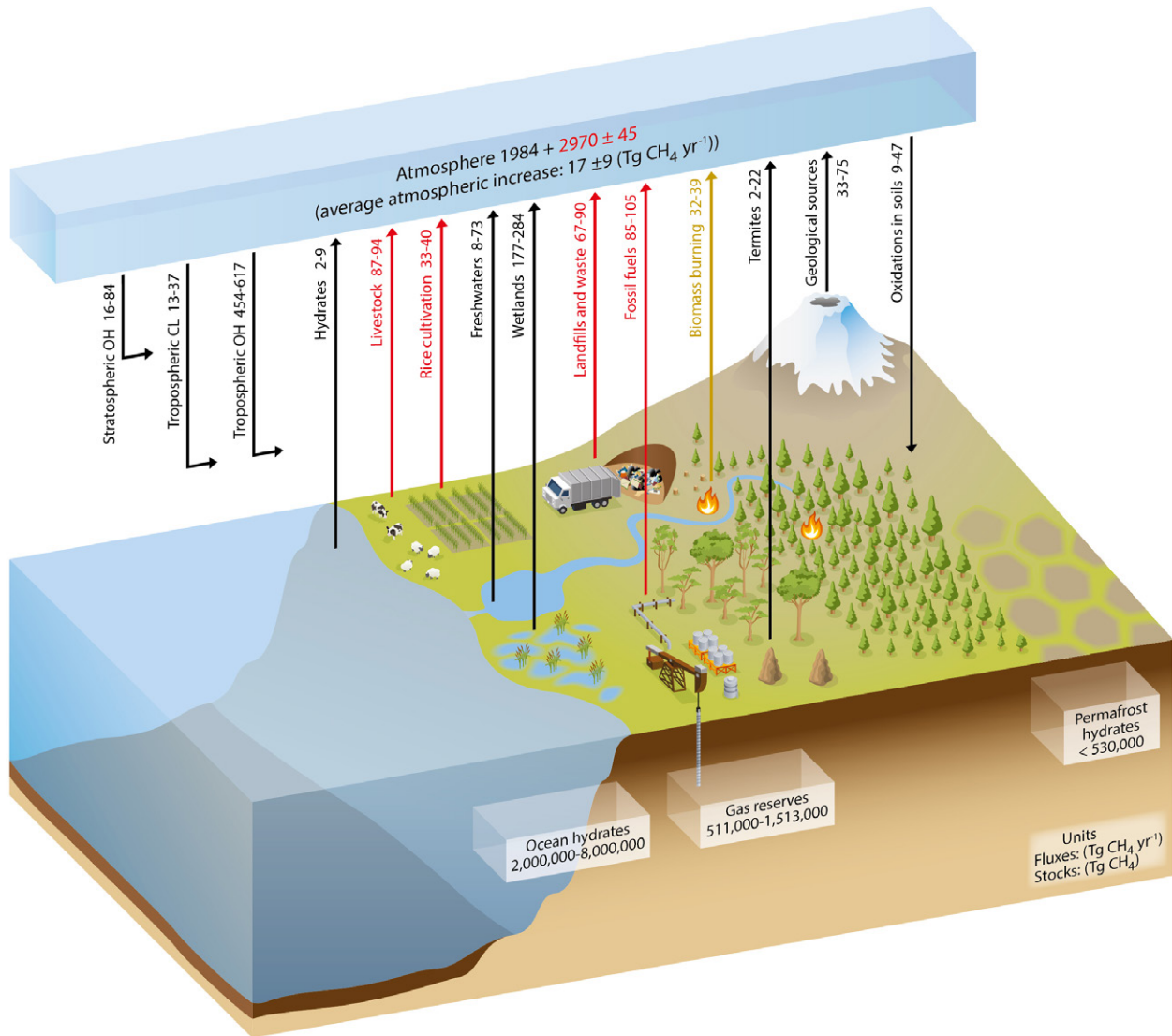


Figure 1.4. A Pictorial Illustration of the Global Methane (CH₄) Cycle. The arrows and boxed numbers represent annual fluxes in teragrams (Tg) of CH₄ per year estimated from 2000 to 2009 and CH₄ reservoirs in Tg CH₄. Reservoirs include the atmosphere and three geological reservoirs (i.e., hydrates on land and in the ocean floor and gas reserves). The black arrows show natural emissions, while red arrows show anthropogenic fluxes. The brown arrow represents total anthropogenic and natural emissions. [Figure source: Reprinted from Ciais et al., 2013, Figure 6.2. Copyright IPCC, used with permission.]

on space-based observations of burned areas. If the recent rise of global atmospheric CH₄ is indeed due to increases in microbial emissions, then the question becomes whether anthropogenic or natural microbial sources are responsible. Some studies have suggested that anthropogenic microbial

sources, such as livestock, are behind the increased atmospheric growth of CH₄ (Schaefer et al., 2016; Saunio et al., 2016). If the increase is due to emissions from wetlands, especially in the tropics, then this raises the possibility that changing climate could be changing natural emissions.



1.3 Perturbations to the Global Carbon Cycle

The carbon cycle undergoes perturbations caused by a variety of natural processes such as wildfires, droughts, insect infestations, and disease. These processes can themselves be affected by human activities, for example through GHG emissions that change climate, wildfire suppression, and land-use change. During longer periods, variations in the Earth's orbit also drive significant perturbations to the global carbon cycle. Over the recent several centuries, human activity has resulted in perturbations to the carbon cycle that have no precedent in geological records. Anthropogenic emissions also can directly alter the chemistry of the atmosphere, possibly affecting its ability to remove pollutants. These human-caused carbon cycle perturbations are discussed in this section.

Since the dawn of the Industrial Age over 250 years ago, humans have significantly altered the global carbon cycle, chiefly by combustion of fossil fuels, but also by perturbing the natural carbon cycle. An example is the large-scale conversion of forests to agricultural land and rangeland. As a result, atmospheric concentrations of CO₂ and CH₄ have increased dramatically. Atmospheric CO₂ has increased from a preindustrial abundance of 280 ppm of dry air (MacFarling Meure et al., 2006) to more than 400 ppm in recent years (NOAA-ESRL-GMD Trends 2017),² an increase of 43%. Methane has increased from a preindustrial abundance of about 700 ppb of dry air to current values of over 1,850 ppb, an increase of over 160%. Current understanding of the sources and sinks of atmospheric carbon supports the dominant role played by human activities, especially fossil fuel combustion, in the rapid rise of atmospheric carbon. For example, Tans (2009) demonstrated that accumulated carbon in the atmospheric and oceanic reservoirs since preindustrial times is approximately equivalent to the total amount emitted by fossil fuel combustion. If

fossil fuel emissions were abruptly terminated, 20% to 40% of this carbon would remain airborne for millennia (Archer et al., 2009; Archer and Brovkin 2008; Solomon et al., 2009). Increases in atmospheric carbon, along with smaller contributions from other GHGs emitted by humans, have led to annual global mean temperatures that have risen by 0.85°C during 1880 to 2012 (IPCC 2013). If recent years are included, the global average temperature has increased by about 1.25°C since 1880 (Hansen et al., 2017).

1.3.1 Anthropogenic Emissions

By burning coal, oil, and gas, humans are accelerating the part of the geological carbon cycle that transfers carbon in rocks and sediments to the atmosphere. From 1870 to 2017, humans emitted 430 ± 20 Pg C as CO₂ to the atmosphere (Le Quéré et al., 2018). Global fossil fuel emissions of CO₂ increased at a rate of about 4% per year from 2000 to 2012, when emissions growth decreased to about 1% per year. In subsequent years, the growth of CO₂ emissions continued to decline, leveling off in 2015 (see Figure 1.4, p. 51; Le Quéré et al., 2018), when global carbon emissions from fossil fuel use and cement production—an industry which releases CO₂ as a by-product of the chemical process that produces lime from limestone—was estimated to total 9.9 Pg C (about 100 times faster than natural geological fluxes; see Figure 1.2, p. 46). This leveling off of emissions occurred even as the global economy was expanding (see Figure 1.5, p. 53). In 2017, global CO₂ emissions rose again by an estimated 2%, likely due to faster economic growth and lower fossil fuel prices (Le Quéré et al., 2018).

Humans also can affect the global carbon cycle through land-use change, mainly by conversion of forests to agricultural land. Often deforestation is accomplished through use of fire. Emitted during the land-use conversion process from forest to other uses, CO₂ thereafter reduces carbon uptake. Reforestation of formerly agricultural land can cause increased carbon uptake over time. Cumulative emissions of carbon from land-use change (mainly

² National Oceanic and Atmospheric Administration Global Monitoring Division, Trends in Atmospheric Carbon Dioxide; esrl.noaa.gov/gmd/ccgg/trends/global.html.

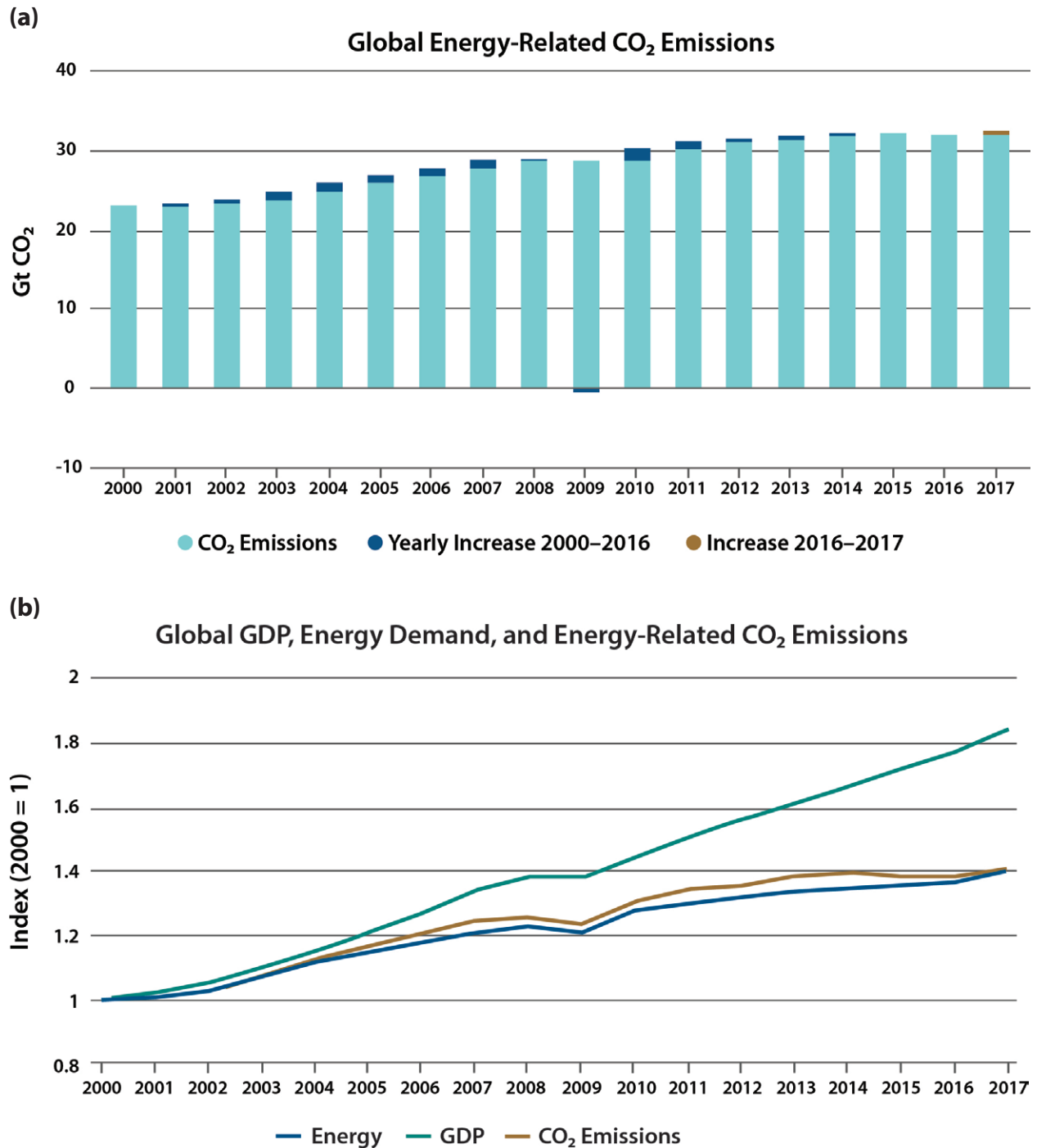


Figure 1.5. Global Energy-Related Carbon Dioxide (CO₂) Emissions. (a) Fossil fuel CO₂ emissions in gigatons (Gt) and their yearly increase. (b) Growth in CO₂ emissions, energy demand, and global gross domestic product (GDP) normalized to 2000. [Figure source: Redrawn from International Energy Agency (IEA) data in the *Global Energy & CO₂ Status Report 2017* (IEA 2017). Copyright Organisation for Economic Cooperation and Development/IEA, used with permission.]



clearing of land for agriculture) since 1750 are estimated at 225 ± 75 Pg C (Le Quéré et al., 2018).

Atmospheric CH₄ also is influenced by diverse human activities, ranging from food production (e.g., ruminants and rice) to waste (e.g., sewage and landfills) to fossil fuel production (e.g., coal, oil, and gas). Future increases in population likely will increase CH₄ emissions from agriculture and waste as demand rises for more food production. Furthermore, the current boom in shale oil and gas exploitation has focused attention on leakage from drilling, storage, and transport of fossil fuel (e.g., Peischl et al., 2015; Pétron et al., 2014). Chemical reaction with OH accounts for about 90% of the total CH₄ sink (Ehhalt 1974). These OH radicals, produced through the photolysis of ozone (O₃) in the presence of water vapor, are destroyed by reactions with CH₄ and other compounds. Uncertainty in the sink due to chemical loss by OH is 10% to 20%, because the OH distribution remains uncertain at regional to global scales (Saunois et al., 2016).

Relative to CO₂, CH₄ and other short-lived climate forcers such as black carbon have short atmospheric lifetimes; thus, estimates project that their mitigation potentially could reduce global mean warming by about 0.5°C by 2050, with air quality and agricultural productivity as co-benefits. Such mitigation, however, would not significantly limit maximum warming beyond 2050 (Shindell et al., 2012; Rogelj et al., 2014; National Academies of Sciences, Engineering, and Medicine 2018). Various strategies are possible for reducing emissions or enhancing the CH₄ sink. For example, some increases in agricultural and waste emissions possibly could be avoided through improved practices and changed dietary trends (Hall et al., 2009; see Ch. 5: Agriculture, p. 229, for more information on agricultural and food emissions). In addition, humans potentially can alter the chemical lifetime of CH₄ through emissions that affect the abundance of OH. Naik et al. (2013) found that OH might be about 10% lower than in preindustrial times, although with large uncertainty.

Current estimates reported by Saunois et al. (2016) for anthropogenic emissions average 328 Tg CH₄ per year (ranging from 259 to 370 Tg CH₄ per year). Extraction and processing of fossil fuels account for 32% to 34% of all anthropogenic emissions. Livestock, agriculture, landfills, and sewage together account for another 55% to 57%, with the remainder due to biomass and biofuel burning. A recent study using observations of the isotopic composition of CH₄ suggests that emissions from fossil fuel production and geological emissions may be 20% to 60% higher than previously thought. This increase would require a compensating reduction in microbial emissions from natural and anthropogenic sources (Schwietzke et al., 2016) for the atmosphere to be in balance with the observed global average CH₄ abundance.

Current CH₄ levels are unprecedented in over at least 800,000 years (Loulergue et al., 2008). Recent National Oceanic and Atmospheric Administration atmospheric network observations have shown that global CH₄ increased rapidly through the late 1990s, leveled off during the early 2000s, and began to increase again in 2007 (Dlugokencky et al., 2009; Rigby et al., 2008). These changes in global CH₄ are not well understood and are under debate. Although Dlugokencky et al. (1998, 2003) suggested that the plateau in CH₄ growth resulted from an approximate balance between global sources and sinks, some studies suggested that decreases in anthropogenic emissions (Aydin et al., 2011; Kai et al., 2011; Simpson et al., 2012) led to the period of slow CH₄ growth. Isotopic evidence points toward increased emissions from microbial sources as an explanation for the recent rise in global CH₄ (Nisbet et al., 2016; Schaefer et al., 2016; Schwietzke et al., 2016). However, increases in anthropogenic emissions also have been proposed (Rice et al., 2016), as well as decreases in the chemical loss (Rigby et al., 2017; Turner et al., 2017). Worden et al. (2017) have recently suggested a significant role for fossil fuel emissions in the recent growth of atmospheric CH₄ based on decreases in biomass burning that could change the interpretation of methane isotope observations. This result is based on space-based



observations of atmospheric CO₂, which itself may be responding to changes in other sources besides biomass burning.

Figure 1.1, p. 45, shows that CH₄ contributed just over 0.5 W/m² in 2017 to global total anthropogenic radiative forcing, an amount which is about one-fourth of that from CO₂. Although CH₄ is much more effective at absorbing infrared radiation (Hofmann et al., 2006; Myhre et al., 2013),³ it is about a hundred times less abundant in the atmosphere than CO₂.

1.3.2 North American Emissions in a Global Context

Historically, North America has been one of the world's largest producers of human-caused CO₂ emissions. Between 1850 and 2011, the United States has added 27% of the cumulative emissions, compared with 25% from European Union (EU) countries and 11% from China, currently the world's largest emitter (World Resources Institute et al., 2014).⁴ In 2015, North America emitted almost 15% (1.5 Pg C) of the 9.9 Pg C emitted globally (Olivier et al., 2016). Of North America's annual total emissions, a majority (84%) came from the United States, while Canada and Mexico emitted 8.7% and 7.3%, respectively. Since the 2007 publication of the *First State of the Carbon Cycle Report* (SOCCR1), China has replaced the United States as the world's top emitter of CO₂, adding 2.8 Pg C to the atmosphere in 2014, about twice U.S. emissions (Olivier et al., 2016). In terms of cumulative emissions, the United States is responsible for 100 Pg C out of a global total of 378 Pg C (UNFCCC 2013; World Resources Institute 2017). If land-use change and forestry are taken into account, U.S. contributions have totaled 134 Pg C out of a global total of 572 Pg C of net emissions. For comparison, historical emissions (including land-use change and forestry) of EU countries and China are 114 and 74 Pg C, respectively.

³ Hofmann et al. (2006), updated at www.esrl.noaa.gov/gmd/aggi/.

⁴ World Resources Institute, wri.org/blog/2014/11/6-graphs-explain-worlds-top-10-emitters/.

Both inventory (i.e., field measurements) and modeling techniques have been used to estimate land-based carbon sinks for North America (King et al., 2015). These estimates show that human-caused carbon emissions in North America are significantly higher than the land's capacity to absorb and store them. For example, estimates suggest that between 2000 and 2009, only 15% to 49% (with a mean estimate of 26%) of North American fossil fuel emissions were absorbed by North American lands (King et al., 2015). As a result, North America is considered to be an overall net source of carbon to the atmosphere. However, the ability of North American land to take up and store carbon is significant. Globally, estimates suggest that over the past decade (2006 to 2015) 2.4 ± 0.5 Pg C per year were taken up by the ocean and 3.0 ± 0.8 Pg C per year were taken up by the terrestrial biosphere (Le Quéré et al., 2017). Of these totals, the amount taken up by the terrestrial biosphere in North America is estimated to be about 0.47 Pg C per year (King et al., 2015), or 15% of global terrestrial uptake.

Carbon uptake by North American lands is driven largely by the regrowth and recovery of forests from earlier human-driven changes in land cover and land use, such as forest clearing and harvesting (King et al., 2015), as well as increases in forest area from improved forest management practices (Melillo et al., 2014). Environmental influences on plant growth, such as the fertilizing effects of rising concentrations of atmospheric CO₂ and nitrogen, along with changes in climate including longer growing seasons in northern midlatitude regions also have contributed to increased carbon uptake in North America over the past two decades (King et al., 2015; Melillo et al., 2014; see Ch. 2: The North American Carbon Budget, p. 71).

However, the emissions of other GHGs, primarily CH₄ and N₂O, partially offset the potential climate cooling induced by the uptake of CO₂ in North America (Tian et al., 2016). North America accounts for about 10% of natural (e.g., wetlands) and 12% of human-driven (e.g., agriculture and fossil



fuels) global CH₄ emissions (Kirschke et al., 2013; see Ch. 2: The North American Carbon Budget).

1.4 The Future Carbon Cycle: Emissions, Sinks, and Carbon Cycle–Climate Feedbacks

Coupled carbon cycle–climate models forced with future “business as usual” emissions scenarios suggest that the changing carbon cycle will be a net positive feedback on climate, reinforcing warming, but the size of the projected feedback is highly uncertain (Friedlingstein et al., 2014). Besides the uncertain trajectories of human factors such as fossil fuel emissions, land use, or significant mitigation efforts, various natural processes can lead to the carbon cycle being a positive feedback. For example, a warming climate can lead to increased fires and droughts and less storage of carbon in the terrestrial biosphere. In particular, warming is expected to decrease carbon uptake in the tropics and midlatitudes. In the high latitudes, a warmer climate is expected to lead to a more productive biosphere and more uptake but also may result in increased respiration and release of stored CO₂ and CH₄ in soils and lakes. Negative feedbacks also are possible, such as increased atmospheric CO₂, leading to increased carbon storage in the terrestrial biosphere (e.g., Schimel et al., 2015), although the relative roles of this effect relative to land-use change, nitrogen deposition, and temperature increases on the cumulative land carbon sink over the last century are not fully understood (Huntzinger et al., 2017).

Human impacts on land use can directly impact climate. Deforestation and agriculture can affect carbon storage in soil and biomass. Fertilizer use also affects the global nitrogen budget and can increase carbon storage. Large-scale drainage of wetlands and conversion to agricultural land can reduce CH₄ emissions from anaerobic respiration while potentially increasing faster soil carbon loss through aerobic respiration.

The ocean carbon sink is driven primarily by the partial pressure difference of CO₂ between the

atmosphere and the ocean surface ($\Delta p\text{CO}_2$). Although this mechanism would imply that increasing atmospheric CO₂ concentrations would, therefore, lead to increased uptake of CO₂ in the ocean, there actually is substantial uncertainty in future uptake due to uncertainty in future changes to ocean circulation, warming, and chemical changes, all of which would impact the ocean sink (Lovenduski et al., 2016; Randerson et al., 2015). In addition, the sequestration of CO₂ in ocean water also can lead to undesirable impacts as the ocean becomes more acidic. For example, ocean acidification disrupts the ability of organisms to build and maintain calcium carbonate (CaCO₃) shells, substantially perturbing ocean ecosystems.

Frozen Arctic soils compose another potential carbon cycle–climate feedback (see Ch. 11: Arctic and Boreal Carbon, p. 428, and Ch. 19: Future of the North American Carbon Cycle, p. 760). An estimated 1,460 to 1,600 Pg C are frozen in Arctic soils, and warming has proceeded in the Arctic faster than in any other region. Current understanding suggests that approximately 146 to 160 Pg C, primarily as CO₂, could be vulnerable to thaw and release to the atmosphere over the next century (Schuur et al., 2015; see Ch. 11: Arctic and Boreal Carbon). This release of carbon from permafrost is likely to be gradual and occur on century timescales (Schuur et al., 2015). If the amount of carbon estimated to enter the atmosphere by Schuur et al. (2015) were released annually at a constant rate, emissions would be far lower than annual fossil fuel emissions (about 9 Pg C per year) but comparable to land-use change (0.9 Pg C per year).

Factors that will affect the carbon cycle are explored in much more depth in respective chapters of this report, and Ch. 19 describes future projections and the results of different IPCC scenarios on the North American carbon cycle in a global context.

1.5 The Carbon Cycle and Climate Mitigation

Concern about the effects of climate change, on the one hand, and the difficulties of reducing emissions



of carbon from fossil fuel use, on the other, have led to a target of limiting global average warming to no more than 2°C, with a more conservative target of 1.5°C to reduce the risks of the most serious effects of climate change (USGCRP 2017). The choice of 2°C reflects a balance between a realistic threshold and one that would result in a presumably tolerable amount of climate change. However, as Knutti et al. (2015) points out, no proof exists that this threshold maintains a “safe” level of warming, and the definition of “safe,” as well as the components of the Earth system that the term applies to, are themselves subjective. Several recent studies have suggested that the accumulated carbon in the atmosphere already may have committed the climate system to 2°C or more of global average temperature increase (Mauritsen and Pincus 2017; Raftery et al., 2017).

The relationship of cumulative carbon emissions to global temperature increase depends on the data constraints or model used to simulate the temperature response. Gillett et al. (2013) reports an observationally constrained range of 0.7 to 2.0°C per 1,000 Pg C (5% to 95% confidence interval) and a range of 0.8 to 2.4°C per 1,000 Pg C based on 15 models from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Similarly, IPCC (2013) estimates that limiting the warming with a probability of >33%, >50%, and >67% to less than 2°C since the period 1861 to 1880 will require cumulative emissions from all anthropogenic sources to stay below about 1,570 Pg C, 1,210 Pg C, and 1,000 Pg C since that period, respectively. Cumulative emissions since 1850, including land-use change and forestry, are 572 Pg C (Global Carbon Project 2016; Peters et al., 2015; World Resources Institute 2017). However, this amount includes only the carbon from CO₂ emissions and does not include non-CO₂ emissions (i.e., primarily CH₄ and N₂O), which amount to an additional 210 Pg C equivalent from non-CO₂ sources, bringing the total to 779 Pg C equivalents (Peters et al., 2015). This amount implies that, to achieve a >33%, >50%, and >67% warming probability limited to below 2°C, amounts of no more than 791, 431, or 221 Pg C equivalent, respectively, can be emitted from 2017

forward. Current annual global emissions of CO₂ from fossil fuel combustion and cement production are 10.7 Pg C per year (Le Quéré et al., 2017), so this limit could be reached in less than 80, 40, or 20 years. Although technically achievable (Millar et al., 2017), the most conservative emissions reductions would require immediate and concerted action.

These simple estimates of cumulative emissions and their effect on future global temperature, however, have many uncertainties. Uncertainties in climate models include cloud, aerosol, and carbon cycle feedbacks. Carbon-climate feedbacks, such as the effect on carbon emissions from permafrost thaw, are highly uncertain and may significantly lower the cumulative amount of carbon that can be emitted before exceeding the 2°C global temperature increase.

Attempts to avoid the most severe impacts of climate change through management of the carbon cycle rely on reducing emissions and increasing storage in land and ocean reservoirs. Other means that focus on adaptation are not specifically addressed in this report. Evaluating and predicting the success of these strategies require an understanding of all the natural and anthropogenic components of the global carbon cycle because decreases in emissions or increases in sinks from mitigation activities may be offset partially or wholly by changes in other components. Globally, land and ocean sinks have averaged between 3.9 and 4.7 Pg C per year since 2000 (Le Quéré et al., 2016), growing over time in proportion to emissions (Ballantyne et al., 2012). The sink on land, accounting recently for about 25% of total emissions (Le Quéré et al., 2016), is consistent with the measured increase in carbon stocks of forests (Pan et al., 2011). In North America, the forest sink is currently about 223 Tg C per year (see Ch. 9: Forests, p. 365), but increases in the frequency of wildfires and insect infestations in the western continent threaten to reduce that sink. The sink in Canadian forests, though much smaller than that in the United States, also is threatened by insects and wildfire and could become a significant source (Kurz et al., 2013), as has happened recently. Mexican forests also are thought to be a small sink



based on estimates of regrowth of previously disturbed forests that exceed emissions from deforestation and forest degradation (see Ch. 9: Forests, p. 365).

Options for managing emissions of carbon and other GHGs include 1) reduction or cessation of the use of fossil fuels, replacing them with renewable sources of energy (e.g., solar, wind, and water); 2) climate intervention via carbon dioxide removal (CDR), including carbon capture and storage (CCS), which involves absorption of emissions at point sources; and 3) negative emissions, using approaches to remove previously emitted CO₂ by increasing storage in terrestrial and ocean reservoirs. Climate intervention via albedo modification does not affect the carbon budget directly but is an attempt to counteract climate change by directly influencing the global radiation balance. For example, introducing aerosols into the stratosphere potentially could provide a global cooling effect but would not address other issues such as ocean acidification. Climate intervention will not be discussed here further; rather, the focus of this section is on actions that directly involve the carbon cycle.

The study of MacDonald et al. (2016) estimated that U.S. carbon emissions from the power sector could be reduced by as much as 80% relative to 1990 use without significantly increasing energy costs and using existing technology. Although some studies have argued that a complete transition to decarbonized energy systems is feasible (Jacobson et al., 2015), other authors have pointed out that a transition to a low-carbon energy system is likely to be difficult and expensive without using a range of options (Clack et al., 2017), including some contribution from fossil fuels. This issue is complex, and full discussion of it is beyond the scope of this report.

For the CCS option, there are many unknowns about its implementation and permanence. A special example of CCS involves renewable energy, in this case bioenergy CCS (BECCS), where energy is derived from burning biomass, capturing and storing the resulting CO₂, and then re-growing the

biomass. Although BECCS is appealing because it replaces fossil fuels *and* removes carbon from the atmosphere, there is only one experimental biomass plant of this type and its technology suffers from the same uncertainty as other CCS types (Anderson and Peters 2016; Fuss et al., 2014).

Estimates of the potential for negative emissions are in the range of 1.6 to 4.4 Pg C per year or 34 to 105 Pg C by 2100 (Griscom et al., 2017; Houghton and Nassikas 2018). Achieving the potential of negative emissions, however, has other constraints involving competition for land area, water availability, albedo changes, and nutrient limitations (Smith et al., 2015). Most negative emissions activities on land are useful either as a bridge to a low-carbon emissions energy system for developing and implementing CCS or for assistance with future removals of previously emitted CO₂, but effects are limited in implementing long-term solutions because forests and soils cannot accumulate carbon at high rates indefinitely. The most rapid rates of carbon removal occur in the first 50 to 100 years of forest growth. Soils generally are slow to accumulate carbon, although that process in forests may last for centuries if the forests remain undisturbed (Luyssaert et al., 2008). Thus, negative emissions are a part of the portfolio of mitigation activities, but the timing of impacts needs to be considered. These negative emissions cannot compensate for future emissions that either continue at current rates or increase (Gasser et al., 2015). Furthermore, the effects of climate change on the carbon balance of terrestrial ecosystems are uncertain, as suggested by the increased mortality of U.S. forests from droughts, insects, and fires.

Another unknown is how much of an overshoot is possible—that is, by how much and for how long emissions could exceed the limit imposed by a 2°C ceiling and their effects still be reversible. Moreover, questions include: How would they be reversed with only limited, available negative emissions? What are the tipping points? For example, warming already is thawing permafrost and thereby exposing long-frozen organic carbon to oxidation. Estimates



are that emissions of carbon from thawing permafrost could be 146 to 160 Pg C by 2100 (Schuur et al., 2015), enough to counter negative emissions. Similarly, disruption of tropical and subtropical ecosystems could lead to substantial releases of

carbon into the atmosphere. Avoidance of tipping points is a paramount challenge to civilization. Only by continuing to seek a better understanding of the carbon cycle can the predictability of these events be improved.



SUPPORTING EVIDENCE

KEY FINDING 1

Atmospheric carbon dioxide (CO₂) has increased from a preindustrial abundance of 280 parts per million (ppm) of dry air to over 400 ppm in recent years—an increase of over 40%. As of July 2017, global average CO₂ was 406 ppm. Methane (CH₄) has increased from a preindustrial abundance of about 700 parts per billion (ppb) of dry air to more than 1,850 ppb as of 2017—an increase of over 160%. The current understanding of the sources and sinks of atmospheric carbon supports the dominant role of human activities, especially fossil fuel combustion, in the rapid rise of atmospheric carbon (*very high confidence*).

Description of evidence base

Preindustrial concentrations of CO₂, CH₄, and other trace species are known from measurements of air trapped in ice cores and firn from Greenland and Antarctica (e.g., MacFarling Meure et al., 2006). These measurements show that preindustrial levels of CO₂ and CH₄ were 280 ppm and 800 ppb, respectively. Contemporary global measurements of CO₂ and CH₄ are archived and documented at esrl.noaa.gov/gmd/ccgg/trends/global.html. Estimates of cumulative carbon emissions, along with atmospheric observations and estimates of net uptake by ocean or land, show that human emissions dominate the observed increase of CO₂ (Tans 2009). Analyses of “bottom-up” estimates of the CH₄ budget and atmospheric observations also support a strong role for anthropogenic emissions in the contemporary atmospheric CH₄ budget (Saunois et al., 2016).

Major uncertainties

There is a high degree of confidence in the overall increases in CO₂ and CH₄ since the preindustrial era. Attribution of these increases to anthropogenic emissions or natural emissions is subject to uncertainty (e.g., Saunois et al., 2016; Tans 2009). However, these uncertainties are unlikely to change the central conclusion that anthropogenic emissions have caused the significant increases in CO₂ and CH₄ since preindustrial times.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Observations clearly show substantial increases in greenhouse gas (GHG) concentrations since preindustrial times resulting from anthropogenic GHG emissions and land-use change.

Summary sentence or paragraph that integrates the above information

For Key Finding 1, there is very high confidence that CO₂ and CH₄ have increased by over 40% and 160%, respectively, since preindustrial times and that this increase is due to anthropogenic emissions. Uncertainties in natural exchanges among the atmosphere, ocean, and terrestrial biosphere and in anthropogenic emissions are unlikely to change the latter conclusion.

KEY FINDING 2

In 2011, the total global anthropogenic radiative forcing resulting from major anthropogenic greenhouse gases (not including anthropogenic aerosols) relative to the year 1750 was higher by 2.8 watts per meter squared (W/m²). As of 2017, the National Oceanic and Atmospheric Administration’s Annual Greenhouse Gas Index estimates anthropogenic radiative forcing at 3.1 W/m²,



an increase of about 11% since 2011. In 2017, CO₂ accounted for 2.0 W/m² and CH₄ accounted for 0.5 W/m² of the rise since 1750. The global temperature increase in 2016 relative to the 1880 to 1920 average was over +1.25°C, although this warming was partially boosted by the 2015–2016 El Niño. Global temperature, excluding short-term variability, now exceeds +1°C relative to the 1880–1920 mean in response to this increased radiative forcing (Hansen et al., 2017; *very high confidence*).

Description of evidence base

Global anthropogenic radiative forcing was extensively reviewed in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (Myhre et al., 2013). The change in radiative forcing since 2011 and the contributions from CO₂ and CH₄ are based on global observations of radiatively active trace species and computed using empirical expressions derived from atmospheric radiative transfer models. Details are available at esrl.noaa.gov/gmd/aggi/aggi.html. Changes in global average temperature over the last century are based on the Goddard Institute for Space Studies surface temperature analysis (GISTEMP, data.giss.nasa.gov/gistemp; Hansen et al., 2017).

Major uncertainties

The uncertainty of radiative forcing calculations is about 10% (Myhre et al., 2013), including uncertainty of the atmospheric radiative transfer model and the global abundance of trace species. Uncertainty of global average temperature trends is determined by the distribution, type, and length of surface observation sites. The effects of these factors are discussed extensively by Hartmann et al. (2013) and also by Hansen et al. (2010, 2017).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Observations and models clearly demonstrate that radiative forcing has increased substantially since preindustrial times and that this increase is ongoing, resulting primarily from the observed increase in atmospheric GHG concentrations.

Summary sentence or paragraph that integrates the above information

For Key Finding 2, there is very high confidence in the value of global anthropogenic radiative forcing (2.8 W/m²) and the fact that CO₂ accounts for the largest share of anthropogenic forcing, with CH₄ accounting for half the remainder. There is very high confidence that this increased radiative forcing has led to global average temperature increases since the preindustrial era.

KEY FINDING 3

Global fossil fuel emissions of CO₂ increased at a rate of about 4% per year from 2000 to 2013, when the rate of increase declined to about 2% per year. In 2014, the growth in global fossil fuel emissions further declined to only 1% per year (Olivier et al., 2016). During 2014, the global economy grew by 3%, implying that global emissions became slightly more uncoupled from economic growth, likely a result of greater efficiency and more reliance on less carbon intensive natural gas and renewable energy sources. Emissions were flat in 2015 and 2016 but increased again in 2017 by an estimated 2.0% (*high confidence*).

**Description of evidence base**

Quantification of global fossil fuel emissions relies mainly on energy consumption data collected by multiple international organizations such as the International Energy Agency (IEA), the Carbon Dioxide Information Analysis Center (CDIAC), the United Nations (UN), and the Energy Information Administration (EIA). UN energy statistics are used to estimate the amount of CO₂ released by gas flaring, and production statistics are used to quantify emissions from cement production. More details on estimation of global fossil fuel emissions are given by Le Quéré et al. (2016) and Ciais et al. (2013).

Major uncertainties

Uncertainty of global fossil fuel emissions is approximately 5% when expressed as a standard deviation (Le Quéré et al., 2016). This assessment of uncertainties includes the amounts of fuel consumed, the carbon and heat contents of fuels, and the combustion efficiency. Although typically considered as constant in time, the uncertainty expressed as a percentage of total emissions is in reality growing in time, as a higher fraction of total emissions come from emerging economies and developing countries with less sophisticated accounting (Le Quéré et al., 2016; Marland et al., 2009). The majority of the uncertainty is likely to be in the form of systematic errors for individual countries, resulting from biases inherent to their energy statistics and accounting methods (Le Quéré et al., 2016).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Energy consumption data clearly show that global fossil fuel emissions have grown over the past decades, with only slight decreases in certain individual years.

Summary sentence or paragraph that integrates the above information

For Key Finding 3, there is high confidence that fossil fuel emissions increased at a rate of 4% per year, until recently when they began to slow even as the U.S. economy grew. The slowing of emissions occurred even as the global economy was growing, implying greater reliance on lower carbon-emitting energy sources.

KEY FINDING 4

Net CO₂ uptake by land and ocean removes about half of annually emitted CO₂ from the atmosphere, helping to keep concentrations much lower than would be expected if all emitted CO₂ remained in the atmosphere. The most recent estimates of net removal by the land, which accounts for inland water emissions of about 1 petagram of carbon (Pg C) per year, indicate that an average of 3.0 ± 0.8 Pg C per year were removed from the atmosphere between 2007 and 2016. Removal by the ocean for the same period was 2.4 ± 0.5 Pg C per year. Unlike CO₂, CH₄ has an atmospheric chemical sink that nearly balances total global emissions and gives it an atmospheric lifetime of about 9 to 10 years. The magnitude of future land and ocean carbon sinks is uncertain because the responses of the carbon cycle to future changes in climate are uncertain. The sinks may be increased by mitigation activities such as afforestation or improved cropping practices, or they may be decreased by natural and anthropogenic disturbances (*high confidence*).



Description of evidence base

Using observations of CO₂ accumulation in the atmosphere and statistics on fossil fuel and cement production, the total uptake of carbon by the terrestrial ecosystem and the ocean can be resolved as residual. Inland waters are implicitly included in the terrestrial component through this process. The partitioning of the residual uptake between land and ocean is more complicated and requires the use of upscaled quantities such as partial pressure of CO₂ ($p\text{CO}_2$) measurements in seawater or measurements of atmosphere-land biosphere fluxes to understand contemporary fluxes and their variability. Among these two major sinks, the oceanic sink generally is understood to be better constrained by independent observations. In terms of interannual variability, substantial uncertainty remains for both oceanic and terrestrial sinks. In terms of the cumulative sink, cumulative oceanic uptake is best constrained by interior data for the ocean (e.g., Khatiwala et al., 2009, 2013), while the cumulative land uptake typically is understood as the difference between cumulative emissions and the estimated cumulative oceanic sink. In addition to the more direct data-based constraints, models of oceanic circulation often are used with $p\text{CO}_2$ measurements to estimate oceanic fluxes, and inverse modeling techniques also are used to estimate carbon uptake by global land and ocean. Inverse modeling combines information from atmospheric observations, atmospheric transport models, and best-available estimates of carbon fluxes from land and ocean via models and observations. Recent synthesis studies by Le Quéré et al. (2016 and 2017) overview the recent carbon budget. Future uptake by land and ocean is estimated using models of the terrestrial and oceanic carbon cycle coupled to climate simulations (e.g., Friedlingstein et al., 2014).

Major uncertainties

The partitioning of carbon fluxes between land and ocean has significant uncertainty resulting from sparse observational coverage of atmospheric concentration and fluxes. Models of ocean-land carbon exchange must be evaluated against observations of carbon fluxes and storage in ecosystems, but in general there is not enough global coverage. Similarly, large regions that are important for understanding the global carbon budget, such as the tropics and Siberia, are not covered by atmospheric observations. This lack of observational coverage makes accurate estimates of the partition of carbon uptake between global land and ocean difficult to achieve using inverse modeling. Uncertainties in atmospheric transport models add to the problem of sparse observational coverage. Increased observational coverage offered by space-based instruments may improve the situation in the future, assuming technical limitations can be understood and overcome. The future evolution of the carbon cycle, including climate-carbon cycle feedbacks, is highly uncertain (e.g., Friedlingstein et al., 2014), and the use of inverse techniques to understand the carbon budget over recent decades could help to improve simulations of the future carbon budget. Future carbon cycle-climate feedbacks are expected to be positive (Ciais et al., 2013).

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Observations and models clearly demonstrate that about half of annually emitted CO₂ is absorbed by the terrestrial biosphere and by oceans. However, the exact partitioning between the land and ocean sinks is somewhat uncertain, while projections of the future of this uptake are highly uncertain.

**Summary sentence or paragraph that integrates the above information**

For Key Finding 4, there is very high confidence that the land and ocean are absorbing a significant amount of carbon emitted by fossil fuel use. The partitioning of this uptake between the land and ocean is more uncertain. The future evolution of the global carbon cycle is also uncertain.

KEY FINDING 5

Estimates of the global average temperature response to emissions range from +0.7 to +2.4°C per 1,000 Pg C using an ensemble of climate models, temperature observations, and cumulative emissions (Gillett et al., 2013). The Intergovernmental Panel on Climate Change (IPCC 2013) estimated that to have a 67% chance of limiting the warming to less than 2°C since 1861 to 1880 will require cumulative emissions from all anthropogenic sources to stay below about 1,000 Pg C since that period, meaning that only 221 Pg C equivalent can be emitted from 2017 forward. Current annual global CO₂ emissions from fossil fuel combustion and cement production are 10.7 Pg C per year, so this limit could be reached in less than 20 years. This simple estimate, however, has many uncertainties and does not include carbon cycle–climate feedbacks (*medium confidence*). These conclusions are consistent with the findings of the recent *Climate Science Special Report* (USGCRP 2017).

Description of evidence base

Cumulative carbon emissions are quantified for Key Finding 5 using energy consumption statistics as described for Key Finding 3. The cumulative emissions required for staying below 2°C are estimated using climate models.

Major uncertainties

There is a range of plausible responses of global temperature to carbon emissions as a result of uncertainty in climate models, especially modeling cloud, aerosol, and carbon cycle feedbacks. In particular, the range of climate model sensitivity to a doubling of CO₂ is 1.5 to 4.5°C, suggesting uncertainty in the amount of cumulative carbon emissions that cannot be exceeded to stay below a global temperature increase of no more than 2°C. In addition, some potential carbon cycle–climate feedbacks, such as the effect of carbon emissions from permafrost thaw, are highly uncertain and may significantly lower the cumulative amount of carbon that can be emitted before the 2°C global temperature increase limit is exceeded.

Assessment of confidence based on evidence and agreement, including short description of nature of evidence and level of agreement

Based on climate models, temperature observations, and inventories of cumulative GHG emissions, it is clear these emissions have resulted in the observed global temperature increase. However, there remains some uncertainty about the exact temperature response to future emissions due to uncertainty about climate feedbacks.

Summary sentence or paragraph that integrates the above information

For Key Finding 5, carbon emissions would have to be slowed and reduced within a few decades to avoid a high probability of global temperature increases that exceed 2°C. Over half the cumulative emissions allowable for a 67% chance to stay below 2°C may already have been emitted, and current emissions rates suggest that emitting the remainder may take as little as 20 to 40 years. There is a medium degree of confidence in the remaining emissions available to keep temperature increases below a given level.



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