

Primary Contributors to Net Observed Anthropogenic Global Warming (AGW) From 1750 to 2018 and, Separately, the Natural Greenhouse Effect (NGE)

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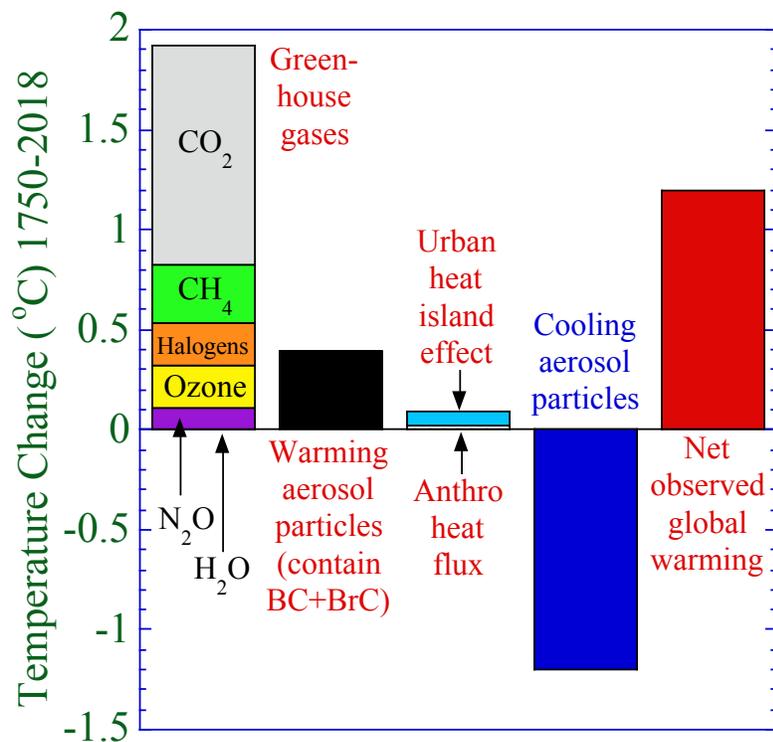
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<https://web.stanford.edu/group/efmh/jacobson/WWSBook/WWSBook.html>

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Figure 1.2. Estimated primary contributors to net observed global warming from 1750 to 2018.



Results are based on global model calculations (Jacobson and Ten Hoeve, 2012; Jacobson, 2014; Russell et al., 2018) and radiative forcing data for greenhouse gases from Myhre et al. (2013). Greenhouse gases are discussed in Section 1.2.1. Warming aerosol particles include black carbon (BC) and brown carbon (BrC) from fossil fuel, biofuel, and open biomass burning sources (Section 1.2.2). Cooling aerosol particle components include primarily sulfate, nitrate, chloride, ammonium, sodium, potassium, calcium, magnesium, weakly absorbing organic carbon, and water. Section 1.2.4 describes the urban heat island effect. Its contribution to warming is from Jacobson and Ten Hoeve (2012). Section 1.2.3 discusses anthropogenic heat fluxes. Their contribution to warming is from Jacobson (2014). Net observed warming is from NASA (2018) using November 2016 to October 2017 average surface temperatures versus 1900 to 1930 average temperatures. Of all the warming in the figure 45.7 percent is due to CO₂, 16.3 percent is due to BC+BrC, 12 percent is due to CH₄, 9.0 percent is due to halogens, 8.8 percent is due to ozone, 4.3 percent is due to N₂O, 3.0 percent is due to the urban heat island effect, 0.7 percent is due to anthropogenic heat flux, and 0.23 percent is due to anthropogenic H₂O.

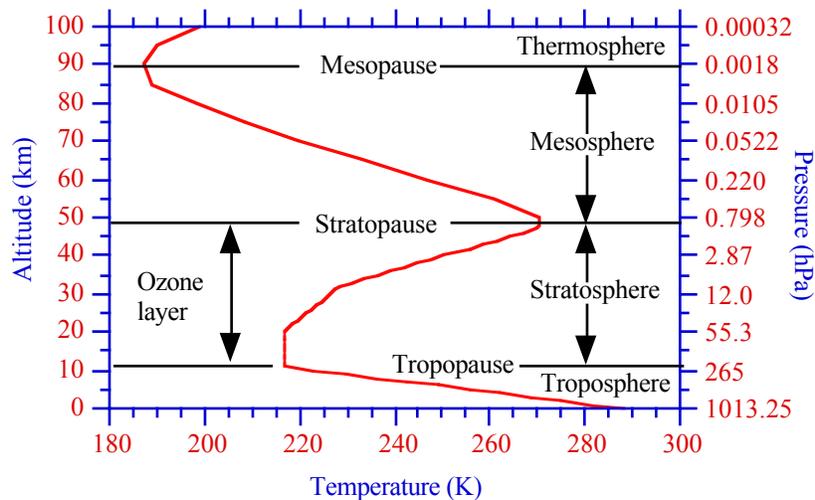
1.2. Global Warming

Greenhouse gases are naturally- and anthropogenically-emitted gases in the atmosphere that are generally transparent to **solar radiation** (sunlight) but selectively absorb certain wavelengths of **thermal-infrared (TIR) radiation (heat)** emitted by the surface of the Earth. Once a greenhouse gas molecule absorbs a specific wavelength of TIR radiation, the molecule vibrates. It then converts the vibrational energy back to TIR radiation at a different wavelength, which depends on temperature. Finally, the molecule, which is no longer vibrating, re-emits the new wave in a random direction. The probability that the new wave is emitted downward is the same as the probability that it is emitted upward.

Due to this mechanism, greenhouse gases in the lowest part of the atmosphere, the troposphere (Figure 1.1), trap a portion of the TIR (heat) radiation emitted by the surface of the Earth. The trapping increases near-surface air and ground temperatures. Because some heat is trapped near the surface, that heat does not reach higher altitudes, so the addition of greenhouse gases to the atmosphere causes temperature to decrease with increasing height in the troposphere.

The more greenhouse gas that is present, the less TIR radiation that reaches the upper atmosphere (stratosphere, mesosphere, or thermosphere in Figure 1.1). Therefore, **anthropogenic greenhouse gases emitted near the surface warm the surface, lower troposphere, and mid troposphere at the expense of cooling the upper troposphere and stratosphere**, relative to no anthropogenic emissions. This is because the additional heat trapped by the anthropogenic greenhouse gases would have otherwise radiated to the upper atmosphere where natural background greenhouse gases there would have absorbed it, heating the upper atmosphere.

Figure 1.1. Globally-averaged temperature structure in the lowest 100 km of the Earth's atmosphere.



1.2.1. The Natural Greenhouse Effect

Global warming must be distinguished from the **natural greenhouse effect**, which is the historic buildup of naturally emitted greenhouse gases in the Earth's atmosphere before humans arrived on the scene.

In the absence of any greenhouse gases in its atmosphere, the Earth's temperature can be approximated by considering a balance among the solar radiation reaching the Earth, the reflectivity of the Earth and atmosphere, and the TIR leaving the Earth, which depends on temperature. Such a balance results in an **equilibrium temperature of the Earth** of about 255 K (-18 °C). At this temperature life could not have

evolved on Earth. Fortunately, the actual average temperature of the Earth's surface prior to the Industrial Revolution was about 288 K (+15 °C) (Figure 1.1). Temperatures near this have allowed life to evolve. The difference between the pre-Industrial-Revolution temperature and the equilibrium temperature is the natural greenhouse effect. It is due to the historic buildup of natural greenhouse gases.

Table 1.1 indicates that, of the 33 K (33 °C) temperature rise above the Earth's equilibrium temperature due to the natural greenhouse effect, about 66 percent is due to **water vapor (H₂O)** and about 25 percent is due to background **carbon dioxide (CO₂)**. Several other chemicals contribute to the remainder.

Table 1.1. Primary contributors to the natural greenhouse effect and global warming on Earth.

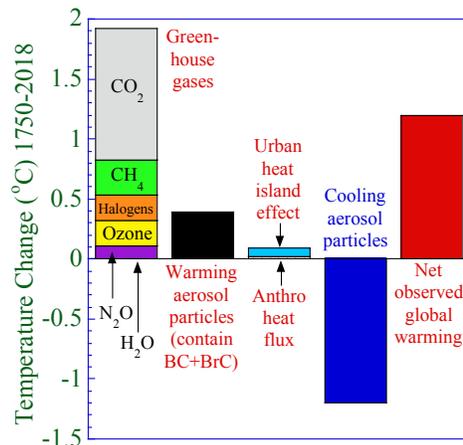
Contributor	Percent contribution to the 33 K natural greenhouse effect	Percent contribution to the 2.4 K gross global warming through 2018 before cooling subtracted
Water vapor H ₂ O	66	0.23
Carbon dioxide (CO ₂)	25	45.7
Black carbon (BC)+brown carbon (BrC)	0.2	16.3
Methane (CH ₄)	0.6	12.0
Halogens	0.0029*	9.0
Ozone (O ₃)	6.2	8.8
Nitrous oxide (N ₂ O)	1.4	4.3
Carbon monoxide (CO)	0.032	<0.01
Molecular oxygen (O ₂)	0.6	0
Urban heat island effect (UHI)	0	3.0
Anthropogenic heat flux (AHF)	0	0.7

Gross global warming (2.4 K) is warming before cooling (1.2 K) due to cooling aerosol particles is subtracted out. Net global warming (1.2 K) is gross warming minus cooling. *The halogen contributing to the natural greenhouse effect is methyl chloride from the oceans. Halogens contributing to global warming are all synthetic compounds (Section 1.2.3.3). Percentage contributions to the natural greenhouse effect are from Jacobson (2014). Percentage contributions to global warming are from Figure 1.2.

1.2.2. Global Warming

Global warming (also referred to as **anthropogenic global warming**, or **AGW**) is the net rise, caused by human activities, in globally averaged near-surface air and ground temperatures above and beyond those due to the natural greenhouse effect. The net rise in temperatures is due to four major warming processes that result in a gross global warming partially offset by one major cooling process (Figure 1.2).

Figure 1.2. Estimated primary contributors to net observed global warming from 1750 to 2018.



Results are based on global model calculations (Jacobson and Ten Hoeve, 2012; Jacobson, 2014; Russell et al., 2018) and radiative forcing data for greenhouse gases from Myhre et al. (2013). Greenhouse gases are discussed in Section 1.2.1. Warming aerosol particles include black carbon (BC) and brown carbon (BrC) from fossil fuel, biofuel, and open biomass burning sources (Section 1.2.2). Cooling aerosol particle components include primarily sulfate, nitrate, chloride, ammonium, sodium, potassium, calcium, magnesium, weakly absorbing organic carbon, and water. Section 1.2.4 describes the urban heat island effect. Its contribution to warming is from Jacobson and Ten Hoeve (2012). Section 1.2.3 discusses anthropogenic heat fluxes. Their contribution to warming is from Jacobson (2014). Net observed warming is from NASA (2018) using November 2016 to October 2017 average surface temperatures versus 1900 to 1930 average temperatures. Of all the warming in the figure 45.7 percent is due to CO₂, 16.3 percent is due to BC+BrC, 12 percent is due to CH₄, 9.0 percent is due to halogens, 8.8 percent is due to ozone, 4.3 percent is due to N₂O, 3.0 percent is due to the urban heat island effect, 0.7 percent is due to anthropogenic heat flux, and 0.23 percent is due to anthropogenic H₂O.

The four major processes that contribute to global warming are anthropogenic greenhouse gas emissions, anthropogenic aerosol particles containing sunlight-absorbing chemicals, anthropogenic heat emissions, and the urban heat-island effect. The process causing cooling is the anthropogenic emission of non-absorbing or weakly absorbing aerosol particles that cool climate by reflecting sunlight to space and by thickening clouds, which are largely reflective. The strongly absorbing particles are referred to as **warming particles**, and the weakly- or non-absorbing particles are referred to as **cooling particles**.

Warming particles include black carbon (BC) and brown carbon (BrC). Cooling particles contain primarily sulfate, nitrate, chloride, ammonium, sodium, potassium, calcium, magnesium, weakly absorbing organic carbon, and water. The sources of warming particles generally differ from those of cooling particles. Also, because cooling particles tend to be more soluble in water than warming particles, cooling particles enhance cloudiness, thus cool climate, more than do warming particles. Warming particles, on the other hand, tend to heat clouds, helping to burn them off.

Because all aerosol particles together are the leading cause of air pollution mortality, reducing both cooling and warming particles is desirable from a public health perspective. However, Figure 1.2 indicates that cooling particles cause more cooling than warming particles cause warming globally. As such, if emissions of all warming and cooling particles are eliminated together without eliminating other sources of heat, global warming will worsen.

Similarly, since cooling particles mask half of global warming (Figure 1.2), eliminating only cooling particles will roughly double net global warming.

One strategy to address global warming and human health simultaneously is to eliminate only warming particles. The downside is that this strategy permits continued global warming and ocean acidification due to greenhouse gases and air pollution mortality due to cooling particles.

Thus, Figure 1.2 suggests that the best strategy for addressing human health and climate simultaneously is to eliminate greenhouse gases, cooling particles, and warming particles simultaneously. This will also reduce some anthropogenic heat flux, the main source of which is fossil fuel combustion.

This book is about understanding and implementing that strategy – eliminating all anthropogenic emissions of greenhouse gases, warming particles, and cooling particles at the same time. This strategy will be accomplished by transitioning the world’s energy to 100 percent wind, water, and solar plus storage for everything and by eliminating remaining non-energy emissions.

1.2.3. Anthropogenic Greenhouse Gases

The primary anthropogenic greenhouse gases contributing to global warming are CO₂, **methane** (CH₄), **nitrous oxide** (N₂O), ozone (O₃), halogens, and H₂O. The first three of these are introduced briefly next, followed by the remaining three.

1.2.3.1. Carbon Dioxide, Methane, and Nitrous Oxide

The **volume mixing ratio** of a gas is the number of molecules of the gas per million molecules of air (ppmv) or per billion molecules of air (ppbv). Since the start of the **Industrial Revolution** in the mid-1700s, the volume mixing ratio of the well-mixed (on the large scale) greenhouse gas CO₂ has increased by about 50 percent, from a natural background level of 275 ppmv to 412 ppmv in 2018. The mixing ratio of CH₄ has increased by about 150 percent, from 0.715 ppmv to 1.8 ppmv and that of N₂O has increased by almost 600 percent, from 0.27 ppmv to 1.86 ppmv (Winther et al., 2018). Whereas the total mass of tropospheric O₃ has increased by about 43 percent, the mass of stratospheric ozone has decreased by about 5 percent (Myhre et al., 2013, Section 8.2.3.1).

All of these greenhouse gases, except for ozone, are emitted. Ozone is discussed briefly, followed by a discussion of halogens. Then, the relative contributions of the different major greenhouse gases to global warming are described followed by a discussion of anthropogenic water vapor.

1.2.3.2. Ozone

Ozone is not emitted. Instead, it forms by chemical reaction from other chemicals that are emitted. Ozone in the atmosphere can be separated into tropospheric ozone and stratospheric ozone. The **troposphere** is a layer of the atmosphere that extends from the surface of the Earth to the **tropopause** (Figure 1.1), which is a boundary that separates the troposphere from the stratosphere. The altitude of the tropopause above the surface is around 6 to 8 km near the poles, increasing to 18 km at the equator. In Figure 1.1, the tropopause is drawn with a mean value of about 12 km. The troposphere is characterized by a decrease in temperature with increasing altitude, except in the bottom 1 km (0.2 to 1.5 km), referred to as the **boundary layer**, where the temperature may increase or decrease with increasing altitude between night and day and under different meteorological conditions.

The **stratosphere** is the atmospheric layer between the tropopause and 48 km above the surface (**stratopause**). Ninety percent of all ozone in the current atmosphere resides in the stratosphere, and almost 10 percent resides in the troposphere. The stratosphere is characterized by a large **temperature inversion**, which is defined as an atmospheric layer where temperature increases with increasing altitude. The inversion is caused by ozone, as described next.

Stratospheric ozone densities peak between 25 and 32 km, in the middle of the stratosphere. Peak stratospheric temperatures, though, occur at the top of the stratosphere because this is the altitude at which the most intense UV wavelengths first enter the stratosphere. Ozone at the top of the stratosphere absorbs these short wavelengths, preventing them from penetrating further down. Although the ozone concentration at the top of the stratosphere is low, each ozone molecule that absorbs a short UV wavelength converts that radiation into kinetic energy and moves fast. The resulting increase in the average kinetic energy of air molecules in the upper stratosphere increases the air temperature there (since temperature is proportional to the average kinetic energy among all molecules). Because the shortest UV wavelengths do not penetrate further down, temperatures increase less and less between the top and bottom of the stratosphere.

Ozone is greenhouse gas. However, since preindustrial times, the mass of tropospheric ozone has increased by about 43 percent, whereas since the late 1970s, that of stratospheric ozone has declined by about 5 percent.

The increase in tropospheric ozone is due to the anthropogenic emissions of **nitric oxide (NO)**, **nitrogen dioxide (NO₂)**, CH₄, other organic gases, and **carbon monoxide (CO)** due to fossil fuel combustion, biofuel combustion, and open biomass burning. In the presence of UV radiation, these gases chemically produce ozone in the troposphere. Such gases usually break down or are removed from the atmosphere before they get to the stratosphere so have less of an effect in the stratosphere.

Ozone in the stratosphere is produced by UV radiation breakdown of **molecular oxygen (O₂)** into two **atomic oxygen (O)** atoms followed by reaction of an O atom with an O₂ molecule, which gives O₃. Ozone is lost by natural chemical reaction as well. Ozone's natural production and loss leads to a natural equilibrium amount of it in the stratosphere. However, since 1978, stratospheric ozone mass has declined about 5 percent. The decrease is due to the emissions of certain halogens into the atmosphere starting in 1928, the transport of those halogens to the middle stratosphere, which took up to 50 years, the breakdown of those halogens into chlorine (Cl) and bromine (Br) atoms by UV radiation in the middle and upper stratosphere, and the chemical destruction of stratospheric ozone by its reaction with Cl and Br.

1.2.3.3. Halogens

Halogens are a group of synthetic chemicals invented starting in 1928 as refrigerants, solvents, degreasing agents, blowing agents, fire extinguishants, and fumigants. They enter the atmosphere primarily upon evaporation when they leak or when the appliances containing them are drained. Many of them (**halocarbons**) can be obtained by replacing some or all of the hydrogen (H) atoms in a methane (CH₄) or an ethane (C₂H₆) molecule with chlorine (Cl), bromine, (Br), fluorine (F), or iodine (I). The first halocarbons were obtained by replacing one or two chlorine atoms with fluorine atoms in carbon tetrachloride (CCl₄). Other halogens, such as sulfur hexafluoride (SF₆), have no carbon. Below, several types of halogens are categorized.

Chlorofluorocarbons (CFCs) are halocarbons containing Cl and F. Examples are CFCl₃ (CFC-11) and CF₂Cl₂ (CFC-12), which were used primarily as refrigerants starting in 1928 (for CFC-12). Their main applications were in ice cream coolers, whole-room coolers, refrigerators, air conditioners, and automobile cooling systems. Subsequent CFCs were used as solvents, degreasing agents, and blowing agents in spray cans and during foam production.

Halons are halocarbons, such as CF₃Br (H-1301), that contain carbon and bromine and that are used in fire extinguishers.

Perfluorocarbons (PFCs) are halocarbons, such as CF₄ (PFC-14) and C₂F₆ (PFC-116), containing only carbon and fluorine.

Hydrofluorocarbons (HFCs) are halocarbons, such as CHF₃ (HFC-23), that contain carbon, fluorine, and hydrogen. PFCs and HFCs were developed primarily to replace CFCs.

Because CFCs and halons contain stratospheric ozone-destroying chlorine and bromine, most countries outlawed them through international agreement. PFCs and HFCs were developed as ozone-layer-friendly replacements. However, because many PFCs and HFCs are greenhouse gases with long lifetimes in the atmosphere, such chemicals, while not directly damaging the ozone layer, have the unintended consequence of exacerbating global warming.

1.2.3.4. Lifetimes and Global Warming Potentials

The contribution to global warming of each gas depends on how many molecules of the gas are in the atmosphere at a given time and how much warming each gas molecule causes. For chemicals that are

directly emitted from anthropogenic sources (all the greenhouse gases, except for ozone), the number of molecules of the gas in the atmosphere at a given time depends on the emission rate of the gas and the *e*-folding lifetime of the gas against its removal by all processes. For ozone, the number of molecules depends on its production rate from chemical reaction and its lifetime.

The ***e*-folding lifetime** (also called the **average lifetime**) of a chemical is the time required for the amount of the chemical to decrease to $1/e$ (36.79 percent) its original amount due to chemical reaction, biological removal, removal by rain, or removal by hitting the ground. After two *e*-folding lifetimes, the chemical has decayed to $1/e^2$ (13.53 percent) its original amount. The time required for the amount of a chemical to reach 1 percent of its initial value is 4.61 *e*-folding lifetimes.

Table 1.2 provides the *e*-folding lifetimes of several anthropogenic greenhouse gases. It indicates that most gases have lifetimes that range from a few years to 50,000 years. Tropospheric ozone, on the other hand, has an average lifetime of only 23 days. If a chemical has a short lifetime yet is an important greenhouse gas, it either has an extremely high emission rate or production rate or causes significant warming per molecule. Ozone is produced rapidly in the troposphere by chemical reaction.

The strength of warming of an emitted chemical is often quantified by its **global warming potential (GWP)**. GWP measures the time-integrated heat trapped by a chemical in the atmosphere per unit mass emission of the chemical relative to that of CO₂. Another way of thinking of it is the number of grams of CO₂ emissions that give the same time-integrated atmospheric heating as 1 g emission of the substance of interest. Thus, the GWP of chemical *x* has units of g-CO₂/g-*x*. The GWP of CO₂ is 1.

A chemical's GWP accounts for the chemical's lifetime. GWPs are usually determined by integrating over either 20 years (for examining shorter-term impacts) or 100 years (for examining longer-term impacts). A 20-year GWP of 20 means that 1 g emission of the gas results in 20 times more heat trapping (warming) than 1 g emission of CO₂, averaged over 20 years. A 100-year GWP of 5 means that 1 g emissions of the gas results in 5 times more warming than 1 g emissions of CO₂, averaged over 100 years.

Example 1.1. Calculating global warming potential

Calculate the 20- and 100-year global warming potentials of chemical A assuming (unrealistically) that (a) 1 kg of chemical A in the atmosphere at a given moment causes 100 times the instantaneous global warming of CO₂ and (b) 1 kg of A emitted in the atmosphere stays in the atmosphere exactly 20 years, at which point it is suddenly removed.

Solution:

Since the 1 kg of A emitted into the air stays there for 20 years, and the warming per unit mass of A in the air is 100 times that of CO₂, the 20-year GWP of A is 100. Over 100 years, the GWP is 100 for the first 20 years and 0 for the last 80 years, or a weighted average of 20.

Chemicals that have a greater 20-year GWP than 100-year GWP have shorter lifetimes than CO₂. Conversely, chemicals that have a greater 100-year GWP than 20-year GWP have longer lifetimes than CO₂.

Table 1.2. *E*-folding lifetimes, 20-year GWPs, and 100-year GWPs of several global warming agents.

Chemical	<i>E</i> -folding lifetime	20-Year GWP	100-Year GWP
^a CO ₂	50-90 years	1	1
^b BC+POC in fossil fuel soot	3-7 days	2,400-3,800	1,200-1,900
^b BC+POC in biofuel soot	3-7 days	2,100-4,000	1,060-2,020
^c CH ₄	12.4 years	86	34
^c N ₂ O	121 years	268	298
^c CFCl ₃ (CFC-11)	45 years	7,020	5,350
^d CF ₂ Cl ₂ (CFC-12)	100 years	10,200	10,800

^c CF ₄ (PFC-14)	50,000 years	4,950	7,350
^d C ₂ F ₆ (PFC-116)	10,000 years	8,210	11,100
^e Tropospheric O ₃	23 days	--	--
^f NO _x -N	< 2 weeks	-560	-159
^g SO _x -S	< 2 weeks	-1,400	-394

GWP=Global Warming Potential.

^aLow-lifetime of CO₂ is the data-constrained lifetime upon increasing CO₂ emissions from Jacobson (2012a, Figure 3.12); high-lifetime of CO₂ calculated from Figure 1 of Jacobson (2017), which shows CO₂ decreasing by 65 ppmv (from 400 to 335 ppmv) over 65 years upon elimination of anthropogenic CO₂ emissions. Since the natural CO₂ is 275 ppmv, the anthropogenic CO₂ = 400-275=125 ppmv, and the lifetime of anthropogenic CO₂ $\sim 65 \text{ y} / -\ln((125-65) \text{ ppmv}/125 \text{ ppmv}) = \sim 90$ years. The GWP of CO₂=1 by definition.

^bPOC is primary organic carbon co-emitted with black carbon from combustion sources. In the case of diesel exhaust, it is mostly lubricating oil and unburned fuel oil. In all cases, POC includes both absorbing organic (brown) carbon (BrC) and less absorbing organic carbon. Soot particles contain both BC and POC. The lifetime is from Jacobson (2012b) and the GWP is from Jacobson (2010a, Table 4), which accounts for direct effects, optical focusing effects, semi-direct effects, indirect effects, cloud absorption effects, and snow-albedo effects.

^cFrom Myhre et al. (2013) Table 8.7. Results from Etminan et al. (2016) suggest that the 20-y GWP of CH₄ may be up to 98.

^dFrom Myhre et al. (2013) Table 8.A.1.

^eFrom Myhre et al. (2013), Section 8.2.3.1. Tropospheric ozone is not emitted so does not have a GWP.

^fFrom Myhre et al. (2013), Table 8.A.3, including aerosol direct and indirect effects. Values are on a per kg nitrogen basis

^gFrom Streets et al. (2001) and Jacobson (2002), including aerosol direct and indirect effects. Values are on a per kg sulfur basis.

Table 1.2 indicates that the *e*-folding lifetime of PFC-14, for example, is 50,000 years. Its GWP is 4,950 over 20 years, increasing to 7,350 over 100 years. The increase in GWP from 20 to 100 years indicates that the same pulse emission of PFC-14 and CO₂ results in a greater increase in the mixing ratio of PFC-14 than CO₂ over 100 years. Not only does PFC-14 last much longer than does CO₂, each gram of PFC-14 in the atmosphere causes more warming than does each gram of CO₂, resulting in a GWP of PFC-14 that exceeds 1. The only reason PFC-14 in the air today does not cause much more global warming than CO₂ is simply because the emission rate and mixing ratio of CO₂ are much larger than those of PFC-14.

For CH₄, the 20- and 100-year GWP also exceed one, but the 100-year GWP of CH₄ is less than its 20-year GWP. This is due to the fact that CH₄ has a shorter lifetime than CO₂. As time marches on far past 100 years, CO₂'s integrated warming per unit mass emission approaches that of CH₄'s. However, a danger arises from using a 100-year or longer GWP. Such GWPs hide the fact that some chemicals, such as CH₄, cause more severe heating per unit mass emission over 20 year than does CO₂. This heating causes impacts, including melting of the Arctic sea ice, that may not easily be reversed and that may trigger additional positive feedbacks, causing more warming. As such, implementing policies using a 20-year GWP could help to delay irreversible damage, giving time for other solutions to be implemented, whereas using a 100-year GWP could result in irreversible damage.

1.2.3.5. Carbon Dioxide Equivalent Emissions

One way to compare the global warming impacts of two different energy sources is to compare the **carbon dioxide equivalent (CO₂e) emission rate** of each source. The CO₂e of an energy source equals the product of the emission rate (e.g., g/kWh for electric power sources or g/km for vehicles) of each chemical from the source and the GWP of the chemical, summed over all chemicals from the source. CO₂e emission rates can be defined over either a 20- or 100-year time frame. For a 20-year time frame, 20-year GWPs are used; for a 100-year time frame, 100-year GWPs are used (Table 1.2). Since the GWP of CO₂ itself is always 1, the CO₂e of an energy source that emits only CO₂ is simply the emission rate of CO₂.

Example 1.2. CO₂e emissions of natural gas versus coal.

Calculate the methane leakage rate (fraction of total mined methane that leaks) during its mining and transport such that the carbon dioxide equivalent emissions (CO₂e) of a natural gas electric power plant that uses the methane equals that of a coal power plant over (a) a 20-year time frame and (b) a 100-year time frame. Assume the coal plant emits 1,000 g-CO₂/kWh and nothing else; the natural gas plant emits leaked methane and 500 g-CO₂/kWh of combusted methane; the molecular weight of CO₂ is 44.0095 g/mol; and the molecular weight of CH₄ is 16.04246 g/mol. Ignore any other emissions associated with either natural gas or coal.

Solution:

Over both the 20- and 100-year time frames, the coal plant emits 1,000 g-CO₂/kWh, which is the CO₂e emission rate of the coal plant. The CO₂e emission rate of the natural gas plant is 500 g-CO₂/kWh + $L \times \text{GWP}$, where L is the leakage rate of methane (g-CH₄/kWh) and the GWP is that of methane (g-CO₂/g-CH₄). The GWPs of methane from Table 1.2 are 86 and 34 over 20- and 100-years, respectively. Equating the CO₂e from the gas and coal plants and solving for the leakage rate gives $L = 5.81$ g-CH₄/kWh over a 20-year time frame and $L = 14.7$ g-CH₄/kWh over a 100-year time frame.

L is the absolute leakage rate of methane. Next, it is necessary to calculate the leakage rate as a fraction of total methane (leaked methane plus methane combusted in the natural gas plant). This is calculated as $L / (L + B)$, where B is the mass of methane that is burned per unit electricity produced in the natural gas plant. Since 1 mole of CH₄ is burned for every 1 mole of CO₂ emitted, $B = 500 \text{ g-CO}_2/\text{kWh} \times 16.04246 \text{ g-CH}_4/\text{mol} / 44.0095 \text{ g-CO}_2/\text{mol} = 182.26 \text{ g-CH}_4/\text{kWh}$.

The fraction of total methane that leaks is therefore $L / (L + B) = 0.031$ over a 20-year time frame and 0.075 over a 100-year time frame. In other words, if the leak rate of methane equals or exceeds 3.1 percent, natural gas causes more warming than coal over a 20-year time frame, if only CO₂ and CH₄ impacts are considered. A higher GWP of CH₄ than provided in Table 1.2 would reduce this leak rate break-even point. Over a 100-year time frame, the break-even point is a 7.5 percent leak rate. However, as discussed in Chapter 3, additional chemicals must be considered when comparing the CO₂e of natural gas versus coal.

1.2.3.6. Anthropogenic Water Vapor

Anthropogenic water vapor comes from two main sources: (a) evaporation of water that is used to cool power plants and industrial facilities that run on coal, natural gas, oil, nuclear power, or biofuels; and (b) emission of water vapor during the combustion of fossil fuels, biofuels, and biomass. Water vapor emitted annually from these sources is only around 1/8,800th of the ~500 million Tg-H₂O/y emitted from natural sources (Jacobson, 2014). Nevertheless, this relatively small anthropogenic emission of water vapor contributes to an estimated 0.23 percent of global warming (Jacobson, 2014).

1.2.2. Anthropogenic Absorbing Aerosol Particle Components

Absorbing aerosol particle components, namely black carbon and brown carbon, together cause more global warming than any other chemical aside from CO₂ (Jacobson, 2000, 2001a, 2002, 2010a; Bond et al., 2013). Such particle components simultaneously cause significant air pollution mortality and morbidity.

A **particle** is an aggregate of atoms or molecules bonded together as a liquid, solid, or mixture of both. An **aerosol** is an ensemble of solid, liquid, or mixed-phase particles suspended in the air. An **aerosol particle** is a single liquid, solid, or mixed-phase particle among an ensemble of suspended particles.

Black carbon (BC) is a solid agglomerate of pure carbon spherules attached together in an amorphous shape. Its source is incomplete combustion of diesel, gasoline, jet fuel, bunker fuel, kerosene, natural gas, biogas, biomass, and liquid biofuels. Black carbon is often visible to the eye and appears black because it absorbs all wavelengths of sunlight, transmitting none to the eye. Black carbon particles convert the absorbed light to heat, raising the temperature of the particles and causing them to re-radiate some of the heat to the surrounding air.

Black carbon and greenhouse gases warm the air in different ways from each other. Greenhouse gases are mostly transparent to solar radiation. They heat the air by absorbing thermal-infrared radiation emitted by

the surface of the Earth and reemitting some of the heat back toward the surface. Black carbon particles, on the other hand, heat the air primarily by absorbing solar radiation, converting the solar radiation to thermal-infrared radiation, and reemitting the TIR back to the air. Black carbon particles also absorb and reemit TIR, but that process is less important for them unless BC concentrations are high.

Black carbon not only warms the air directly, but when it enters clouds, it can evaporate them. When BC falls on snow or sea ice, it can melt the ice or snow faster. In addition, when other aerosol material, such as sulfuric acid, nitric acid, water, or brown carbon coats the outside of a black carbon particle, the black carbon can heat the air up to 2 to 3 times faster than without a coating because more light hits the larger particle thus bends (refracts) into the particle. Inside the particle, this light bounces around until it hits and is absorbed by the black carbon core.

Brown carbon (BrC) is also an aerosol particle component that causes health problems. Major sources of brown carbon are the same as those of black carbon, except that the BrC-to-BC ratio increases with decreasing temperature of combustion. Smoldering biomass, for example, is a large source of brown carbon. BrC contains carbon, like black carbon, but also contains hydrogen (H) and possibly atomic oxygen (O), nitrogen (N), and or other atoms. In other words, it is **organic carbon** (which is defined as containing C, H, and possibly other atoms). However, not all organic carbon is brown carbon. Brown carbon is the subset of organic carbon that selectively absorbs short (blue) and maybe some medium (green) and even less frequently, red wavelengths of visible light. The remaining long wavelengths (red) and some of the green are transmitted to the viewer's eye, making the particle haze appear brown. The more green light that is transmitted (the less that is absorbed), the more yellow the particles appear.

All organic aerosol components and gases absorb the sun's ultraviolet (UV) wavelengths to some degree. UV wavelengths are shorter and more energetic than visible wavelengths. However, only a few organic aerosol components absorb visible wavelengths. Short-wavelength visible-light-absorbing organic particle or gas components include nitrated aromatics, benzaldehydes, benzoic acids, aromatic polycarboxylic acids, phenols, polycyclic aromatic hydrocarbons, and nitrated inorganics (Jacobson, 1999). In addition, tar balls are organic particles that form during the cooling of a biomass burning plume and strongly absorb visible radiation even in the red part of the visible spectrum.

Whereas the mass ratio of brown carbon to black carbon from diesel exhaust is around 1:1, that in biomass burning is around 8:1. Higher-temperature flames (e.g., in diesel engines) produce the lower ratio; lower-temperature flames produce the higher ratio. Although BrC concentrations are generally higher than are BC concentrations in the air, BC is a much stronger overall absorber so almost always dominates the impact of the two on climate. An exception is in the case of biomass burning, where the impacts of BrC may dominate those of BC.

Table 1.2 indicates that although BC plus BrC from fossil fuel and biofuel sources has an *e*-folding lifetime of less than a week, it has an extremely high GWP, even over 100 years. The reason is that BC in particular is about one million times more powerful per unit mass at warming the air than is CO₂ (Jacobson, 2002). Although a lot more CO₂ than BC exists in the air at a given time, the strong warming per unit mass allows BC plus BrC to be the second leading cause of global warming after CO₂ (Table 1.1). Methane is third.

1.2.3. Anthropogenic Heat Emissions

Anthropogenic heat emissions include the heat from the dissipation of electricity; the heat from dissipation of motive energy by friction; the heat from combustion of fossil fuels, biofuels and biomass for energy; the heat from nuclear reaction; and the heat from anthropogenic biomass burning. Such heat emissions warm the air directly. Much of the hot air eventually rises, expands, and cools, converting heat

energy (**sensible heat**) to **gravitational potential energy** (Section 3.2.2.3), which is energy embodied in air lifted to a certain height against gravity. Differences in gravitational potential energy between one horizontal location and another result in the conversion of gravitational potential energy to **kinetic energy**, or winds. The increase in temperature and wind speed both evaporate water vapor, converting sensible heat and kinetic energy, respectively, to **latent heat**, which is energy added to liquid molecules to evaporate them into gas molecules. Since water vapor is a greenhouse gas, the production of water vapor enhances the impact of the original anthropogenic heat emissions.

In sum, much of the heat from anthropogenic heat emissions is converted to other forms of energy. Since energy is conserved, the different forms of energy persist in the atmosphere (although some of the energy is transferred to the oceans and land) and cause impacts that persist for a long time. Overall, though, the impacts of anthropogenic heat emissions are less than those of greenhouse gases, which also persist for decades to centuries but cause greater warming than do anthropogenic heat emissions. Nevertheless, anthropogenic heat may contribute to about 0.7 percent of global warming to date (Figure 1.1 and Jacobson, 2014).

1.2.4. The Urban Heat Island Effect

The urban heat island (UHI) effect is the temperature increase in urban areas due to the covering of soil and vegetation with impervious surfaces. Covering surfaces reduces evaporation of water from soil and evapotranspiration from plants. Because evaporation and evapotranspiration are cooling processes, eliminating them warms the surface. Built-up areas also have sufficiently different properties of construction materials (e.g., heat capacities, thermal conductivities, albedos, emissivities) to enhance urban warming relative to surrounding vegetated areas. Worldwide, the UHI effect may be responsible for about 3 percent of gross global warming (warming before cooling is subtracted out) (Figure 1.1 and Jacobson and Ten Hoeve, 2012).

1.2.5. Impacts of Global Warming

Global warming has already caused the world significant financial losses, and the cost is expected to grow to \$25 to \$30 trillion per year by 2050 (Jacobson et al., 2017). Losses arise due to coastline erosion (from sea level rise); fishery and coral reef losses; species extinction losses; agricultural losses; increased heat stress mortality and morbidity; increased migration, famine, drought, wildfires, and air pollution; and more severe storms and weather (hurricanes, tornados, hot spells).

Higher temperatures not only increase wildfire risk and damage, increasing air pollution and infrastructure loss directly, but they also increase air pollution in cities where the pollution is already severe (Jacobson 2008, 2010b). During November 2018, for example, three major wildfires in California, enhanced by drought and unusually high November temperatures, killed dozens of people, displaced hundreds of thousands of others, rendered several thousand people homeless, and produced dangerous levels of air pollution throughout the state for over two weeks.

Similarly, global warming increases the intensity of hurricanes, increases their wind speeds, storm surge, and the resulting damage. The failure of agriculture crops has caused mass migrations in many parts of the world. Thus, global warming has already resulted in devastation and the creation of climate migrants.

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