Guide to the Science of Climate Change in the 21st Century

Chapter 15
Greenhouse Gases and Aerosols

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Chapter 15.0 Greenhouse Gases and Aerosols

15.1 Introduction

15.1.1 Greenhouse gas emissions – an overview

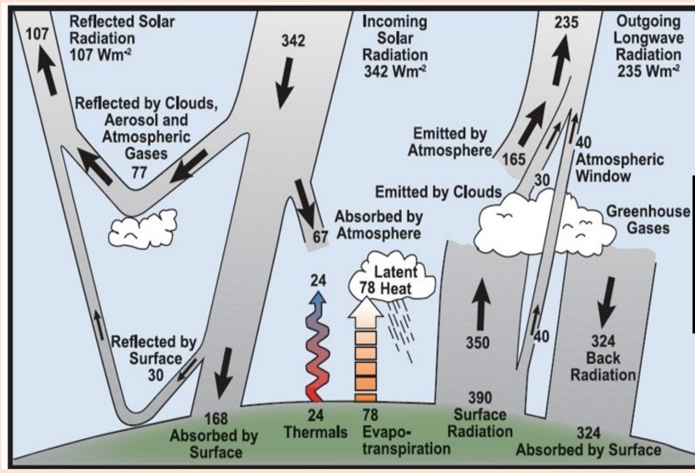
The monitoring of carbon dioxide in the atmosphere on Moana Loa, Hawaii by Dr. Keeling of the Scripps Institution of Oceanography was a huge 'wake-up call' that Earth was headed toward serious problems with global warming https://en.wikipedia.org/wiki/Charles_David_Keeling and https://sioweb.ucsd.edu/programs/keelingcurve/2013/04/03/the-history-of-the-keeling-curve/#:~:text=The%20Keeling%20Curve%20is%20a,until%20his%20death%20in%202005 . Figure 15.1 shows the 'Keeling Curve' which illustrates how the concentration of carbon dioxide in the atmosphere varies throughout the year at that location and how the concentration has increased since 1958 when the monitoring was started https://scrippsco2.ucsd.edu/ . The significant role carbon dioxide and all of the other greenhouse gases (GHGs) is beginning to play in shaping Earth's climate is fully realized https://www.epa.gov/ghgemissions/overview-greenhouse-gases , https://en.wikipedia.org/wiki/Greenhouse_gas#Atmospheric_lifetime and https://www.c2es.org/content/main-greenhouse-gases/ . This is particularly evident from examinations of carbon dioxide concentration of Earth's atmosphere captured in ice cores taken from the Antarctic ice sheet. This data goes back 800,000 years and clearly shows how unusual current increases in the concentration of carbon dioxide actually are (see Figure 15.2). Figure 15.3 shows how the global concentration of carbon dioxide in the atmosphere has changed since the mid nineteenth century.

There are now hundreds of GHG monitoring stations distributed around the world and several satellites, orbiting and geostationary, collecting information on the concentration of all GHG's (carbon dioxide, methane and nitrous oxide and others) on a continuous basis. This information is critical to the monitoring and numerical modelling of climate change and also to pinpoint opportunities to control GHG.

Figure 4.5, shown below, illustrates the global energy budget and the importance of greenhouse gases (GHGs) and aerosols. In the process of absorbing long wave (infrared) radiation emitted from the Earth, heating the atmosphere and reradiating the energy back to Earth and space, GHGs are ultimately responsible for a warmer terrestrial and atmospheric environment on Earth www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf and https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases#:~:text=Carbon%20dioxide%20concentrations%20have%20increased,is%20due%20to%20human%20activities .

Clearly, global atmospheric carbon dioxide concentration today and its rate of increase is unusual and concerning.

Anthropogenic production of GHGs is the major contribution to increases in radiative forcing and resulting global warming.

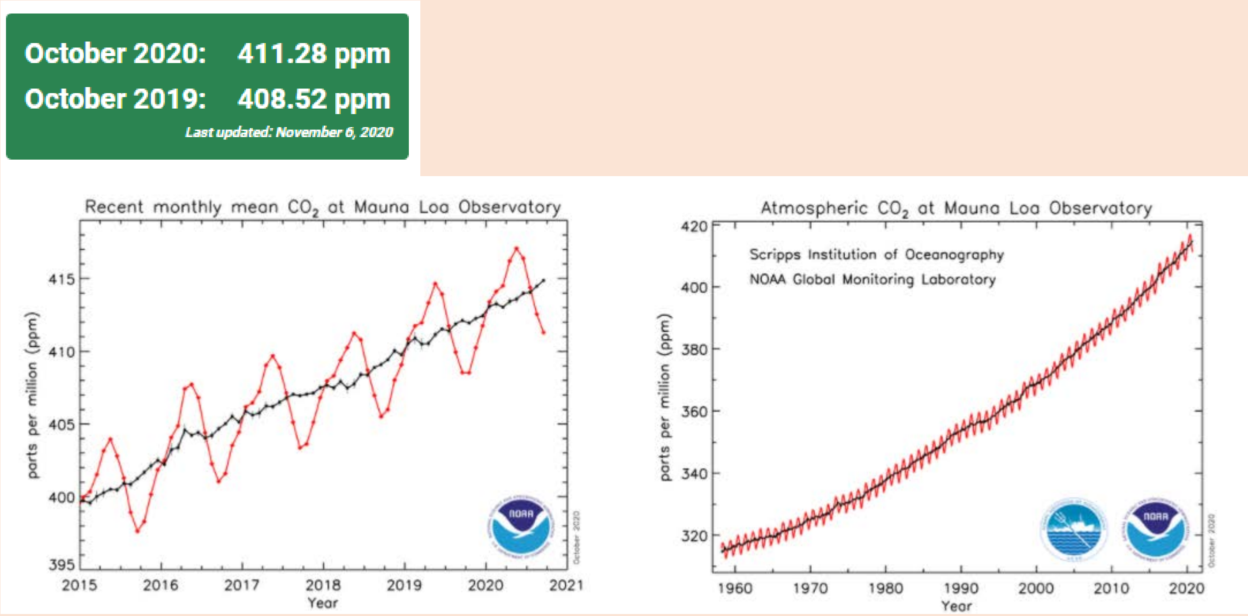


Units: Watts per square metre or Wm^{-2}

Figure 4.5 Global Energy Budget taken from http://climateknowledge.org/figures/Rood_Climate_Change_AOSS480_Documents/Kiehl_Trenberth_Radiative_Balance_BAMS_1997.pdf

The concentration of carbon dioxide in the atmosphere has increased steadily since 1958. The National Oceanic and Atmospheric Administration (NOAA) began taking measurements of the concentration of carbon dioxide in the atmosphere in 1974. The red line is a plot of average monthly values. The 'saw tooth' shape reflects the growing season in the northern hemisphere. The concentration of carbon dioxide in the atmosphere in 1958 was approximately 100 ppm less than today. NOAA observes that the observations at Mauna Loa are taken at an elevation of 3400m and may not be the same as globally averaged values at the surface.

Figure 15.2 show how carbon dioxide concentration is reflected by season (plant growth) from the far north, tropics, equator to South Pole. The South Pole exhibits no affect similar to the measurements taken near the Equator, American Samoa. The average for each is the same. Figure 15.3 shows a graph of atmospheric carbon dioxide concentration in ice cores taken from the Antarctic ice sheet – 800,000 years of record. The global average was 409.8 ppm for 2019 and 413.56 ppm for 2020 and 418.72 ppm September 17, 2023 https://www.co2.earth/daily-co2 . The highest concentration of carbon dioxide in the 800,000 years prior to 1850 was observed to be 300 ppm. Figure 15.4 shows a graph of carbon dioxide measured in millions of tons from the beginning of the industrial era to present and projected to 2040.



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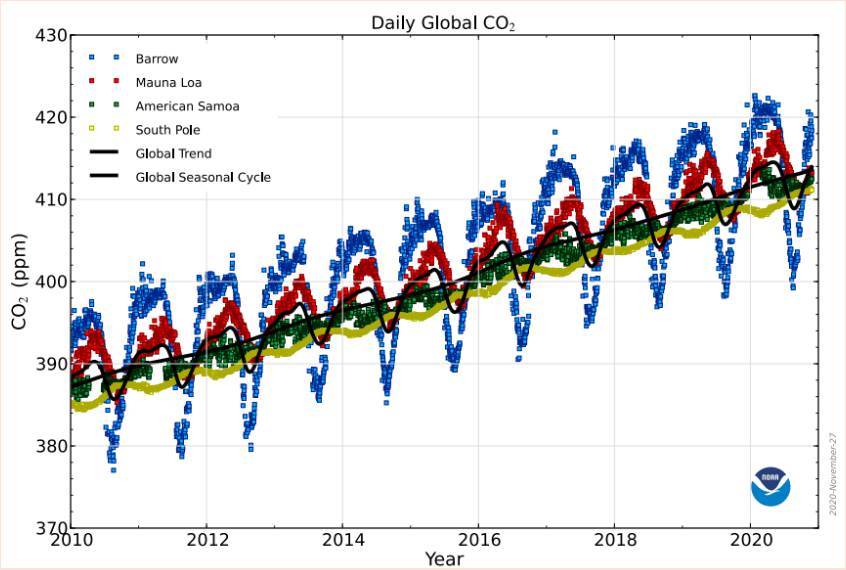

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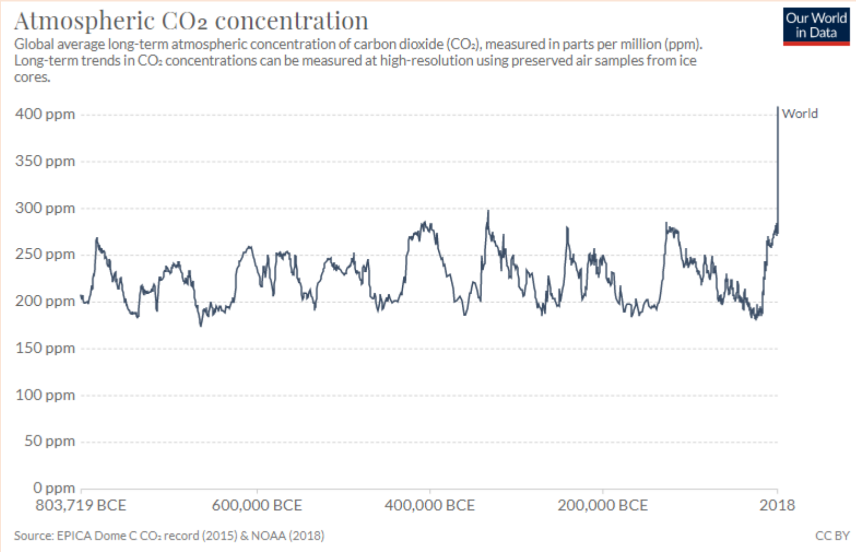
https://www.esrl.noaa.gov/gmd/ccgg/trends/gl_trend.html



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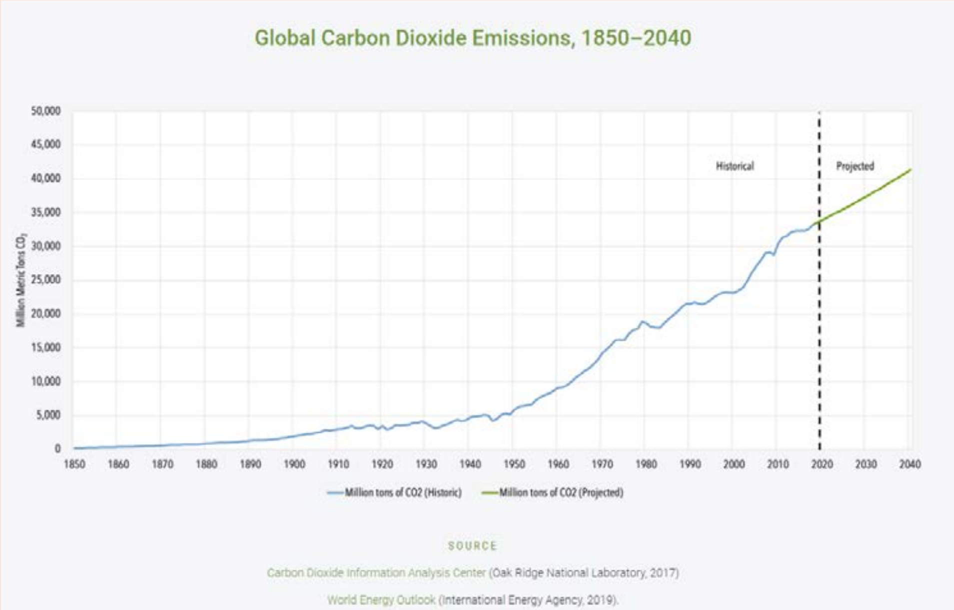
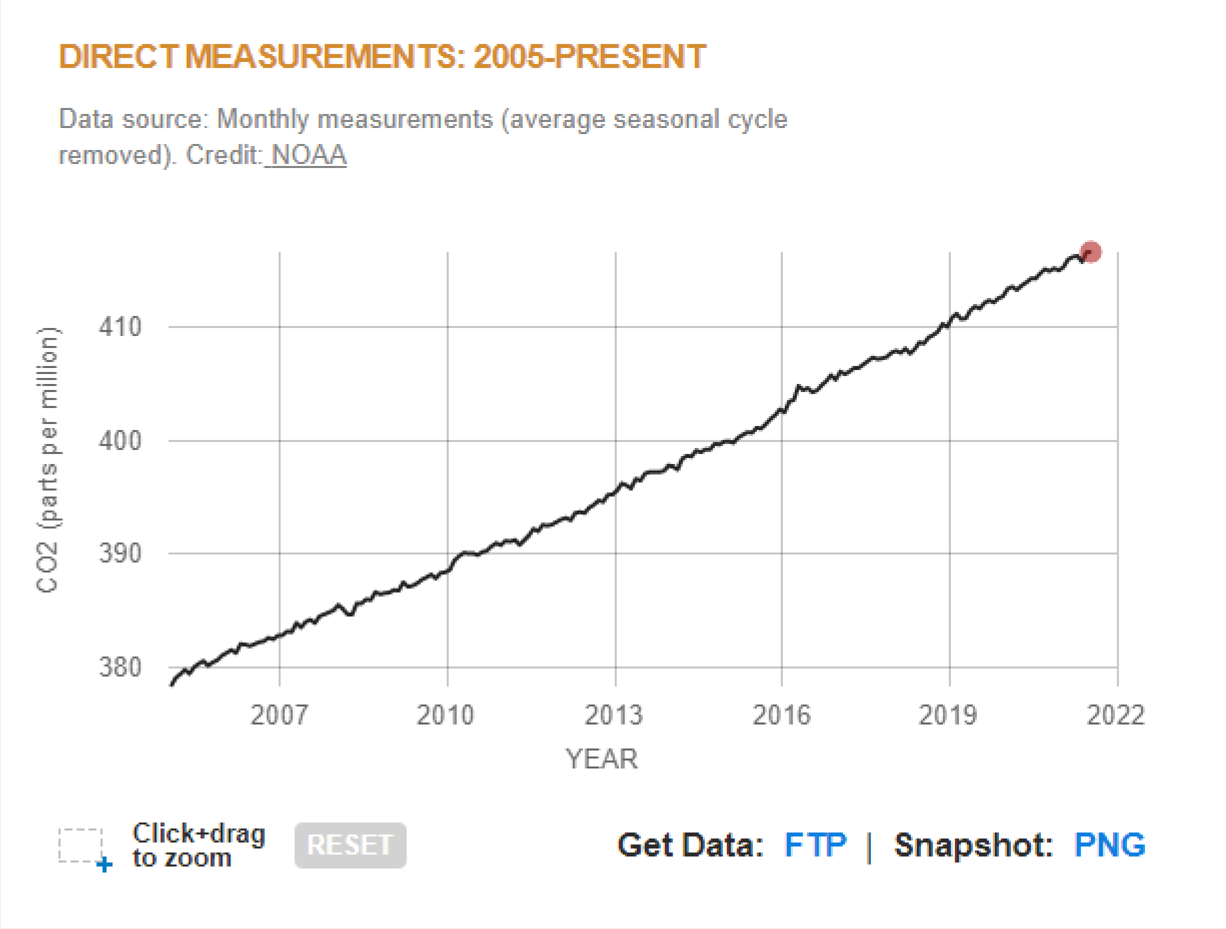


Figure 15.4 Global carbon dioxide emissions, 1850 to 2040. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions.

NASA published an interactive web site that describes the latest measurements of carbon dioxide in the atmosphere: July 2021 (417 ppm), https://climate.nasa.gov/vital-signs/carbon-dioxide/?utm_source=newsletter&utm_medium=email&utm_campaign=monthly+newsletter ; how CO2 has increased from 2005 to 2021 to present, snapshot shown in Figure 15.5, proxy measurements of CO2 in the atmosphere since 800 AD shown in Figure 15.6 and an interactive map of the world showing the mid-troposphere concentration of CO_2 2002 to 2016 based on the satellite data collected using the Atmospheric Infrared Sounder (AIRS) – same web site.



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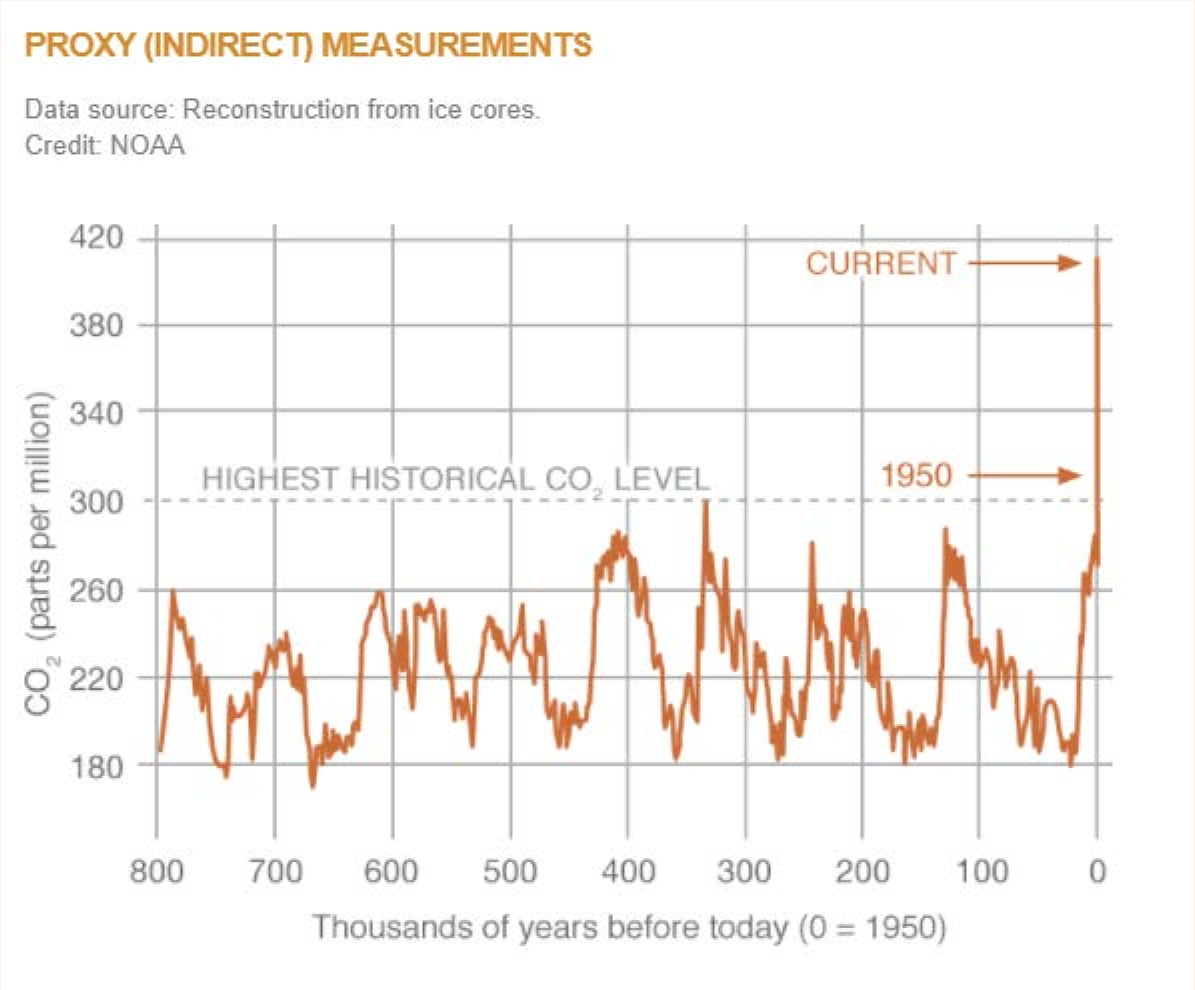


Figure 15.6 Proxy determinations of carbon dioxide in the atmosphere 800 AD to present, https://climate.nasa.gov/vital-signs/carbon-dioxide/?utm_source=newsletter&utm_medium=email&utm_campaign=monthly+newsletter

Also of interest is the Global Carbon Atlas http://globalcarbonatlas.org/en/content/welcome-carbon-atlas published by the BNP Paribas Foundation. It visually documents the most up-to-date data on carbon fluxes resulting from human activities and natural processes.

15.1.2 Aerosols

Aerosols are submicron particles suspended in the atmosphere that scatter and absorb solar radiation. Aerosols include water droplets, sulfur dioxide, ash, dust, black carbon, brown carbon and many other types of particles. The importance of aerosols in the global energy budget is shown in Figure 4.5. Clouds and fog contain water droplets. Volcanic eruptions produce ash and chemical aerosols such as sulfur dioxide. Dust may result from wind erosion. Black carbon (or soot) and brown carbon are produced by the burning of fossil fuels and natural wildfires. Black carbon are black coloured solid particles that absorb solar energy and warm the atmosphere. Brown carbon aerosols are a mixture of both black coloured and brown coloured particles that in combination both absorb and reflect solar energy. (See https://en.wikipedia.org/wiki/Brown_carbon.) The significance of brown carbon resulting from biomass burning is its affect on Arctic warming. This is discussed in detail in https://www.sciencedirect.com/science/article/pii/S2590332222000914?utm_campaign=Daily%20Briefing&utm_content=20220321&utm_medium=email&utm_source=Revue%20newsletter . Details of the chemistry, sources and formation of brown carbon, from a variety of sources, are discussed in https://manu56.magtech.com.cn/progchem/EN/abstract/abstract12362.shtml and https://www.sciencedirect.com/science/article/abs/pii/S0048969718312476.

Industrial activity produces a wide variety of other types of aerosols.

The historical occurrence, including the type of aerosols, is recorded in the ice cores obtained from the Greenland and Antarctic ice sheets and several other ice sheets around the world where glaciers originate.

The concentration of aerosols is measured in terms of the aerosol optical thickness or AOT. AOT is the degree to which aerosols prevent the transmission of light through the atmosphere by scattering or absorption. The greater the AOT the more aerosols in the atmosphere. Monitoring of the concentration of aerosols in the atmosphere is relatively recent, forty years or so, consisting of a limited number of ground-based methods and satellite and airborne platforms (https://www.intechopen.com/chapters/63154 , https://earthobservatory.nasa.gov/features/Aerosols and https://gml.noaa.gov/aero/net/aao.html)

Information on aerosols is much more limited because of the non-uniform occurrence and movement of aerosols such as those produced by volcanos, wildfires and dust storms. The methodology and utility of information collected is still being developed and evaluated. (See discussion of airborne platforms https://gml.noaa.gov/aero/net/aao.html and use of NASA satellites to monitor atmospheric rivers such as the movement of dust particles from the Sahara Desert https://climate.nasa.gov/news/3081/in-a-first-scientists-map-particle-laden-rivers-in-the-sky/ .)

15.2 Types of greenhouse gas emissions

Water vapour is the primary greenhouse gas in Earth's atmosphere, approximately two to three times carbon dioxide. Virtually all of the water vapour in the atmosphere is the result of evaporation or sublimation (liquid water or solid water to water vapor) and transpiration from plants. (See Chapter 6.) Anthropogenic sources of water vapour are negligible. The greater the temperature of the atmosphere and Earth's surface, the greater the amount of water vapor produced. The amount of water vapor in the atmosphere will increase approximately 7% for every one-degree centigrade increase of the temperature of the atmosphere. However, water vapor will not accumulate in the atmosphere because when the atmosphere cools the water vapour condenses into water droplets or ice particles and falls to the Earth's surface. A detailed discussion of water as a GHG is available from NASA, https://climate.nasa.gov/ask-nasa-climate/3143/steamy-relationships-how-atmospheric-water-vapor-supercharges-earths-greenhouse-effect/?utm_source=newsletter&utm_medium=email&utm_campaign=monthly+newsletter. Increases in the temperature of the atmosphere and Earth surface are the result of increases of all of the other GHG's which do accumulate in the atmosphere until natural processes remove them – often over decades and centuries. The duration a GHG remains in the atmosphere is called its atmospheric lifetime.

The principle GHGs (except for water) emitted in the United States for 2018 by gas are shown in Figure 15.7. Similar global emissions breakdown for 2015 is shown in Figure 15.8. The radiative forcing for CO_2, N_2O and CH_4 (carbon dioxide, nitrous oxide and methane) may be calculated based on the concentration of the gas in the atmosphere (Etminan, Myhre, Highwood and Shrine 2016 https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016GL071930).

The term, global warming potential, is used to describe the relative potency, molecule for molecule, of a greenhouse gas, taking account of how long it remains active in the atmosphere. The global warming potentials, GWPs, are those calculated over 100 years. Carbon dioxide is taken as the gas of reference and given a 100-year GWP of 1.

A carbon dioxide equivalent, or CO_2 equivalent, CO_2-eq is a measure used to compare emissions from various greenhouse gases on the basis of their global-warming potential. (For example; The GWP of methane is 25. If there are 1.5 metric tonnes of methane, the CO_2-eq is 37.5 metric tonnes. The GWP for nitrous oxide is 298.).

As shown in Figure 5.1, the carbon cycle, a principal source of carbon dioxide emissions is the burning of fossil fuel and the production of cement. The production and use of fossil fuels produce both carbon dioxide and methane. Methane is also produced from agricultural operations (rice production and livestock), biofuels, landfills, wastewater and naturally from wetlands, forest fires and thawing permafrost.

GHGs are monitored using land based, air borne and satellite instrumentation and country reporting to the UNFCC https://unfccc.int/ as per their reporting requirements https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/reporting-requirements .

There are a number of terms used to describe GHG emissions, carbon dioxide equivalents in particular. These are used to describe sources and sinks of GHG and aid in the development and implementation of strategies to limit GHG emissions.

The global warming potential and atmospheric lifetime for major GHGs is shown in Table 15.1.

Greenhouse gas	Chemical formula	Global Warming Potential, 100-year time horizon	Atmospheric Lifetime (years)
Carbon Dioxide	CO2	1	100*
Methane	CH4	25	12
Nitrous Oxide	N2O	265	121
Chlorofluorocarbon-12 (CFC-12)	CCl2F2	10,200	100
Hydrofluorocarbon-23 (HFC-23)	CHF3	12,400	222
Sulfur Hexafluoride	SF6	23,500	3,200
Nitrogen Trifluoride	NF3	16,100	500

Table 15.1 Global warming potential and atmospheric lifetime for major greenhouse gases. https://www.ipcc.ch/report/ar4/wg1/ .

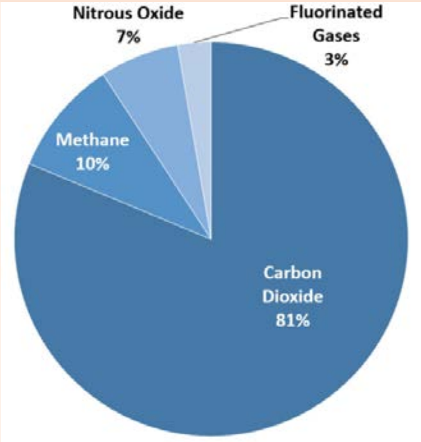


Figure 15.7 Emissions of GHGs in 2018 in the U. S. by gas.
https://www.epa.gov/ghgemissions/overview-greenhouse-gases

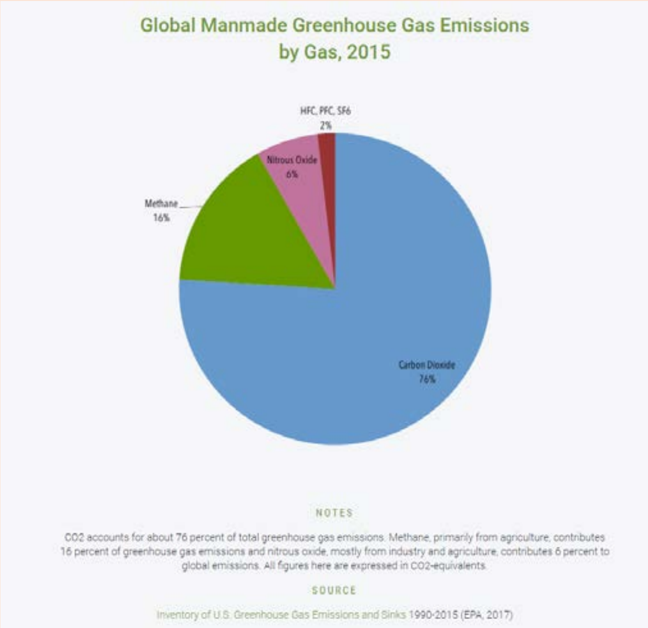


Figure 15.8 Global manmade greenhouse gas emissions by gas, 2015.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

Figure 15.9 shows how the concentration of the various GHGs have changed over the past two thousand years. The dramatic increases coincide with the beginning of the industrial revolution in the mid nineteenth century.

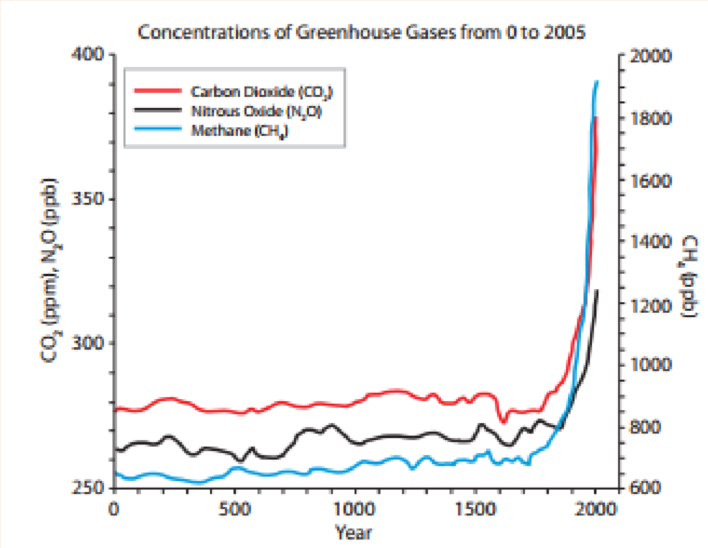


Figure 15.9 Concentration of GHGs from 0 to 2005.
https://www.canr.msu.edu/resources/greenhouse_gas_basics_e3148

15.3 Carbon dioxide emissions by fuel type

The amount of energy in a fuel is measured in terms of its energy density which is the amount of energy that can be stored in a given volume or mass of the fuel. Units might be watt-hours per litre or megajoules/litre and watt-hours per kilogram or megajoules per kilogram. Table 15.2 lists several types of fuel and their energy density.

Fuel Type	Reaction Type	Energy Density (MJ/kg)	Typical uses
Wood	Chemical	16	Space heating, Cooking
Coal	Chemical	24	Power plants, Electricity generation
Ethanol	Chemical	26.8	Gasoline mixture, Alcohol, Chemical products
Biodiesel	Chemical	38 [8]	automotive engine
Crude oil	Chemical	44	Refinery, Petroleum products
Diesel	Chemical	45	Diesel engines
Gasoline	Chemical	46	Gasoline engines
Natural gas	Chemical	55	Household heating, Electricity generation
Uranium-235	Nuclear	3 900 000	Nuclear reactor electricity generation

Table 15.2 Energy density of different fuels.
https://energyeducation.ca/encyclopedia/Energy_density

A very useful tool is the energy conversion calculator available at:
https://www.eia.gov/energyexplained/units-and-calculators/energy-conversion-calculators.php
and helpful explanations at: https://www.eia.gov/energyexplained/units-and-calculators/

The conversion of the chemical energy in fossil fuels to electricity varies from a low of 37% (or less) for coal fired plants to a potential high of 60% for combined-cycle gas fired plants, https://en.wikipedia.org/wiki/Fossil_fuel_power_station .

The efficiency of electricity production using fossil fuels may be expressed as its heat rate in terms of BTU/kilowatt hour or megajoules/kilowatt hour. For a thorough explanation see https://en.wikipedia.org/wiki/Heat_rate_(efficiency) .

The carbon dioxide emissions by fossil fuel type are listed in Table 15.3. This information is needed for the estimating carbon footprint. Note that the energy required to produce and transport the fossil fuel has not been considered.

Knowing which fossil fuel is used and its efficiency of electricity production allows emission comparison between different means of electricity production.

Carbon Dioxide Emissions Coefficients by Fuel

Carbon Dioxide (CO_2) Factors:	Pounds CO_2 Per Unit of Volume or Mass	Kilograms CO_2 Volume or Mass	Pounds CO_2 Million Btu	Kilograms CO_2 Million Btu
For homes and businesses				
Propane	12.70/gallon	5.76/gallon	139.05	63.07
Butane	14.80/gallon	6.71/gallon	143.20	64.95
Butane/Propane Mix	13.70/gallon	6.21/gallon	141.12	64.01
Home Heating and Diesel Fuel (Distillate)	22.40/gallon	10.16/gallon	161.30	73.16
Kerosene	21.50/gallon	9.75/gallon	159.40	72.30
Coal (All types)	4,631.50/short ton	2,100.82/short ton	210.20	95.35
Natural Gas	117.10/thousand cubic feet	53.12/thousand cubic feet	117.00	53.07
Gasoline	19.60/gallon	8.89/gallon	157.20	71.30
Residual Heating Fuel (Businesses only)	26.00/gallon	11.79/gallon	173.70	78.79
Other transportation fuels				
Jet Fuel	21.10/gallon	9.57/gallon	156.30	70.90
Aviation Gas	18.40/gallon	8.35/gallon	152.60	69.20
Industrial fuels and others not listed above				
Flared natural gas	120.70/thousand cubic feet	54.75/thousand cubic feet	120.60	54.70
Petroleum coke	32.40/gallon	14.70/gallon	225.10	102.10
Other petroleum & miscellaneous	22.09/gallon	10.02/gallon	160.10	72.62
Nonfuel uses				
Asphalt and Road Oil	26.34/gallon	11.95/gallon	166.70	75.61
Lubricants	23.62/gallon	10.72/gallon	163.60	74.21
Petrochemical Feedstocks	24.74/gallon	11.22/gallon	156.60	71.03
Special Naphthas (solvents)	20.05/gallon	9.10/gallon	160.50	72.80
Waxes	21.11/gallon	9.57/gallon	160.10	72.62
Coal by type				
Anthracite	5,685.00/short ton	2,578.68/short ton	228.60	103.70
Bituminous	4,931.30/short ton	2,236.80/short ton	205.70	93.30
Subbituminous	3,715.90/short ton	1,685.51/short ton	214.30	97.20
Lignite	2,791.60/short ton	1,266.25/short ton	215.40	97.70
Coke	6,239.68/short ton	2,830.27/short ton	251.60	114.12
Other fuels				
Geothermal (average all generation)	NA	NA	16.99	7.71
Municipal Solid Waste	5,771.00/short ton	2,617.68/short ton	91.90	41.69
Tire-derived fuel	6,160.00/short ton	2,794.13/short ton	189.54	85.97
Waste oil	924.0/barrel	419.12/barrel	210.00	95.25

Source: U.S. Energy Information Administration estimates.
Note: To convert to carbon equivalents multiply by 12/44. Coefficients may vary slightly with estimation method and across time.

Table 15.3 Carbon dioxide equivalent emissions by fuel type.
https://www.eia.gov/environment/emissions/co2_vol_mass.php
and https://www.eia.gov/tools/faqs/faq.php?id=73&t=11

15.4 Carbon dioxide emissions from cement production.

Depending on the source, the estimates of the contribution of the cement industry to global carbon dioxide emission varies from 5 to 10%.

A very good description of why production of cement is a significant producer of carbon dioxide emissions may be found in https://www.carbonbrief.org/qa-why-cement-emissions-matter-for-climate-change and https://en.wikipedia.org/wiki/Environmental_impact_of_concrete .

Basically, the reasons are two-fold; heating of the limestone releases carbon dioxide, (chemical reaction 60%), and the energy used to heat the limestone to produce the final product 40%.

15.5 Methane (CH_4) emissions

The major sources of methane are shown in Figure 15.10 and 15.11. (chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://projects.iq.harvard.edu/files/acmg/files/pku_methane_jacob.pdf and https://www.globalcarbonproject.org/methanebudget/)

The major natural source of methane is wetlands. The remainder comes from gas hydrates, geologic seepages, volcanic gas, melting permafrost, ocean sediments, wildfires and termites.

The major manmade sources of methane are approximately double the volume of the natural occurring sources. These include agriculture – paddy rice fields and livestock production, biofuel production, biomass burning (as distinct from naturally occurring forest and wild fires), decomposition of organic waste in landfills and wastewater and fossil methane emission during the exploration, production and transport of fossil fuels.
https://en.wikipedia.org/wiki/Methane_emissions#Natural

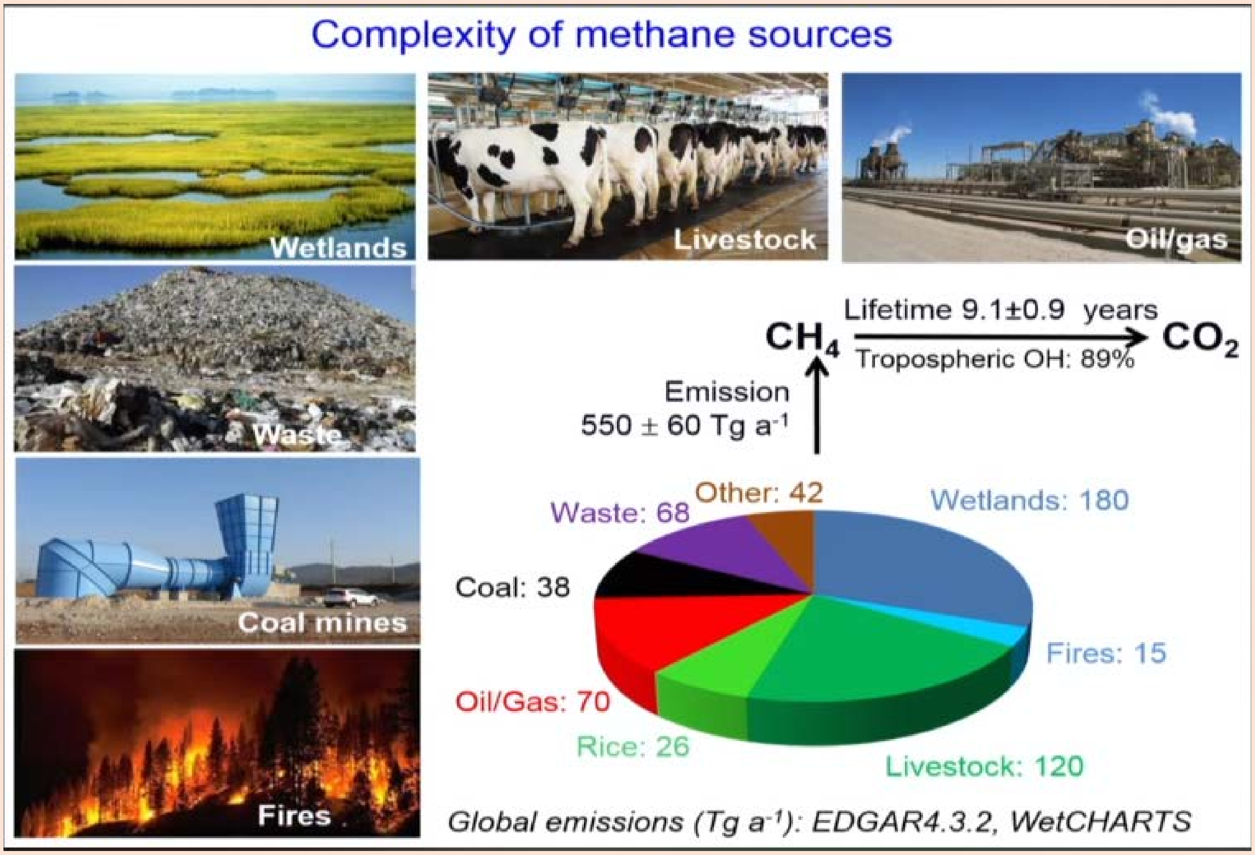


Figure 15.10 Complexity of methane sources. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://projects.iq.harvard.edu/files/acmg/files/pku_methane_jacob.pdf

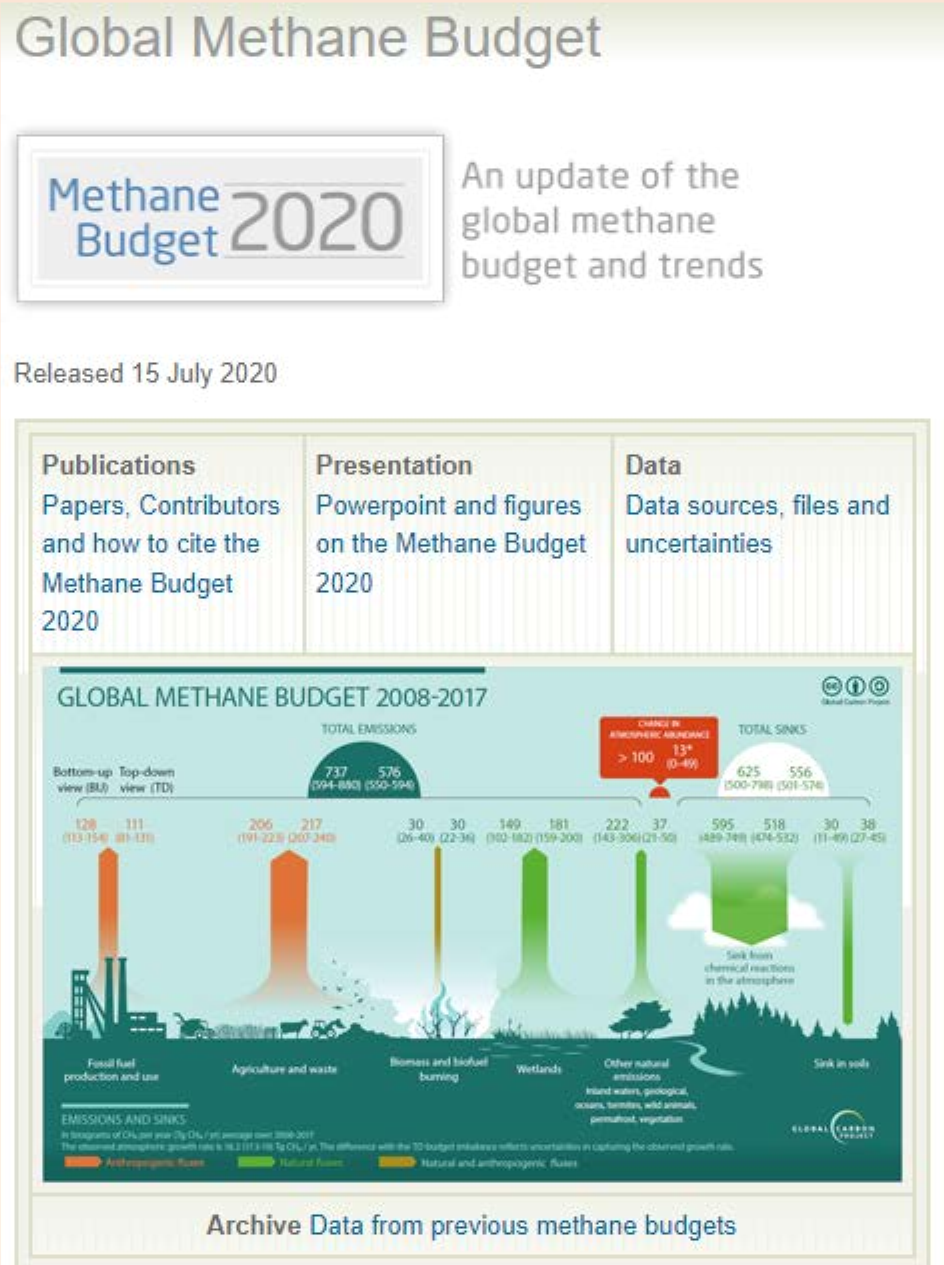


Figure 15.11 Global methane budget 2020.
https://www.globalcarbonproject.org/methanebudget/ .

The natural and anthropogenic sources of methane are listed in Tables 15.4 and 15.5.

Category	Major Sources	IEA Annual Emission[3] (Million Tons)
Wetlands	Wetland methane	194
Other natural	Geologic seepages Volcanic gas	39
	Arctic melting Permafrost	
	Ocean sediments	
	Wildfires	
	Termites	
	Total natural	**233**

Additional References: [1][18][19]

Table 15.4 Natural sources of methane.
https://en.wikipedia.org/wiki/Methane_emissions#Natural

Category	Major Sources	IEA Annual Emission[3] (Million Tons)
Fossil fuels	Gas distribution	45
	Oil wells	39*
	Coal mines	39
Biofuels	Anaerobic digestion	11
Industrial agriculture	Enteric fermentation	145
	Rice paddies	
	Manure management	
Biomass	Biomass burning	16
Consumer waste	Solid waste Landfill gas	68
	Wastewater	
	Total anthropogenic	**363**

* An additional 100 million tons (140 billion cubic meters) of gas is vented and flared each year from oil wells.[17]
Additional References: [1][18][19][20][21]

Table 15.5 Anthropogenic sources of methane.
https://en.wikipedia.org/wiki/Methane_emissions#Natural

Off gassing from landfills and fossil methane are considered the most manageable. Fossil methane includes:

- Fugitive methane emissions occur from leakages that are not intended, for example because of a faulty seal or leaking valve.

- Vented methane emissions are the result of intentional releases, often for safety reasons, due to the design of the facility or equipment (e. g. pneumatic controllers) or operational requirements (e. g. venting a pipeline for inspection and maintenance).
- Incomplete flaring methane emissions can occur when natural gas that cannot be used or recovered economically is burned instead of being sold or vented. The vast majority of the natural gas is converted into CO_2 and water, but some portion may not be combusted and is released as methane into the atmosphere.
- Suspended/ inactive, abandoned and orphaned, wells, (oil or natural gas) and pipelines or other facilities prior to decommissioning.

The International Energy Agency produces what it calls the 'methane tracker database' listing the world fossil methane emission sources. https://www.iea.org/reports/methane-tracker-2021?utm_campaign=IEA%20newsletters&utm_source=SendGrid&utm_medium=Email Methane emissions are identified and monitored using a variety of airborne and satellite platforms as discussed in later sections.

The impact of melting permafrost on release of methane from decomposing permafrost and release of fossil methane is discussed in Section 16.4.6.

The decomposition of methane in the atmosphere is described in Figure 15.12 taken from https://www.americanlaboratory.com/913-Technical-Articles/160507-Methane-A-Simple-Gas-with-Complex-Problems/ .

1. $CH_4 + OH \longrightarrow CH_3 + H_2O$
2. $CH_3 + O_2 + M \longrightarrow CH_3O_2 + M$ (M is some molecule acting catalytically and carrying off the excess energy of reaction)
3. $CH_3O_2 + NO \longrightarrow CH_3O + NO_2$

3A. $CH_3O_2 + HO \longrightarrow CH_3OOH + O_2$

3B. $CH_3OOH + h\upsilon \longrightarrow CH_3O + OH$

4. $CH_3O + O_2 \longrightarrow HCHO + HO_2$
5. $HCHO + OH \longrightarrow HCO + H_2O$

5A. $HCHO + h\upsilon \longrightarrow HCO + H$

6. $HCHO + h\upsilon \longrightarrow CO + H_2$
7. $HCO + O_2 \longrightarrow CO + HO_2$
8. $CO + OH \longrightarrow CO_2 + H$

Figure 15.12 Decomposition of methane in the atmosphere. https://www.americanlaboratory.com/913-Technical-Articles/160507-Methane-A-Simple-Gas-with-Complex-Problems/ .

15.6 Sources of greenhouse gases

The World Resources Institute clearly explains greenhouse gas emissions by country and sectors as shown in Figure 15.13 https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors It is essential to visit this web site to access and benefit from the information presented.

The data and some of the presentation is also available from Climate Watch, https://www.climatewatchdata.org/ghg-emissions?end_year=2018&start_year=1990 .

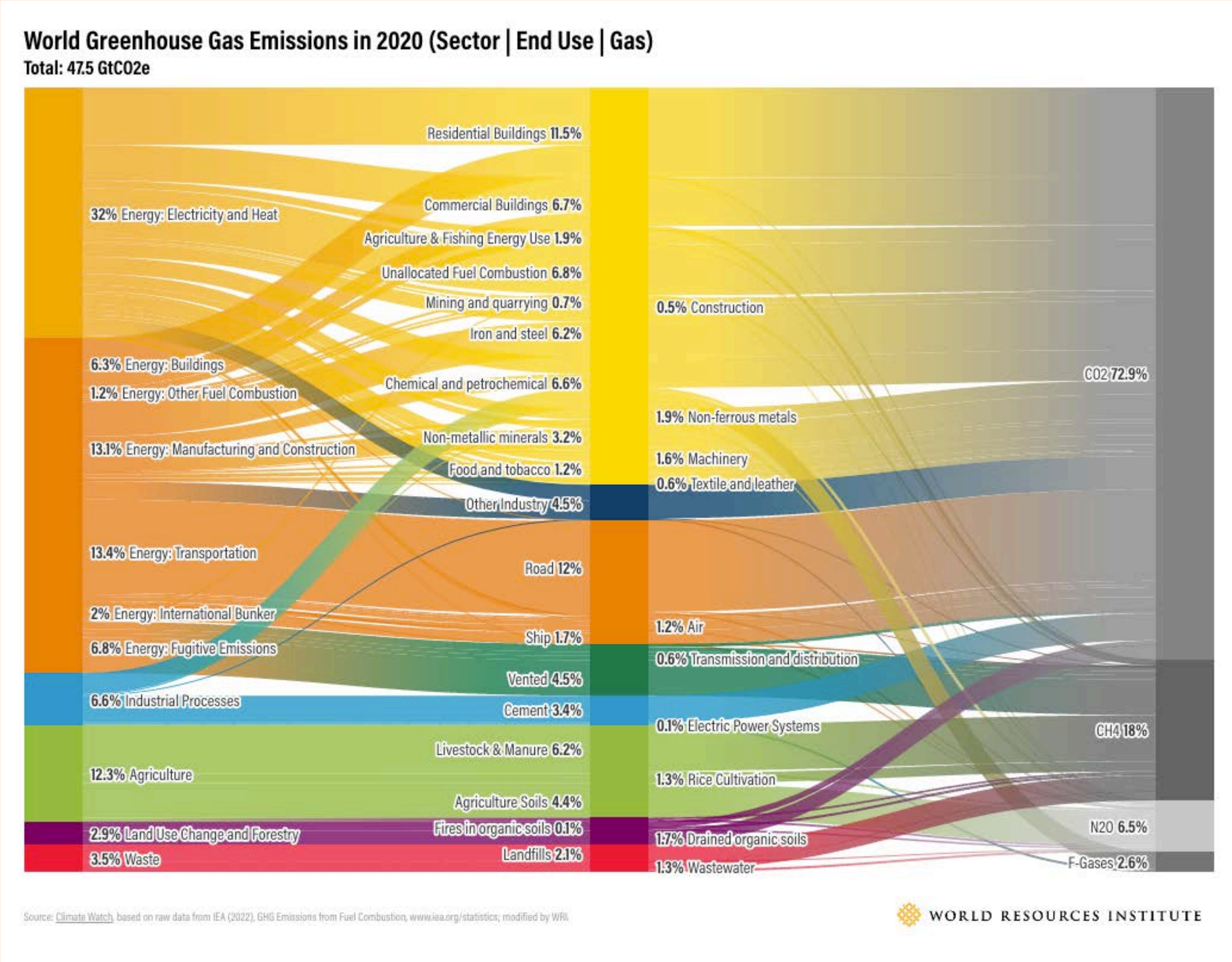


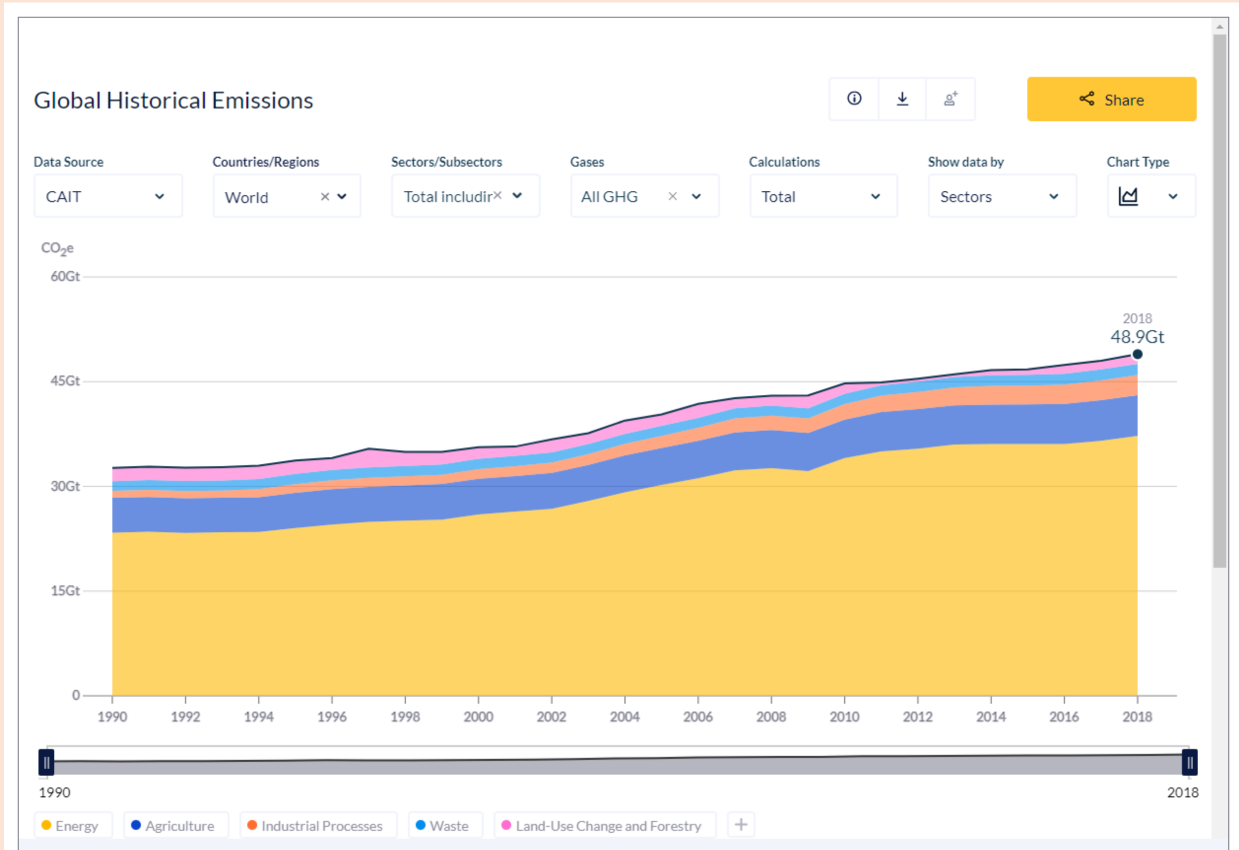
Figure 15.13 World greenhouse gas emissions in 2020 https://www.wri.org/data/world-greenhouse-gas-emissions-2020 .

15.6.1 World greenhouse gas emissions by country and sector

A snapshot of their interactive graphic is shown in Figure 15.14. The interactive graphic allows the user to focus on the country of interest and identify which sectors are the main contributors to energy-related emissions. (The data and some of the presentation is also available from Climate Watch, https://www.climatewatchdata.org/ghg-emissions?end_year=2018&start_year=1990 .)

15.6.2 Global historical emissions

In the graph shown, Figure 15.14, information is presented for the period 1990 to 2019 both as an interactive figure and in the table immediately below it. The user has the opportunity to select data source, country/ region of interest, emissions by sector and subsector, historical emissions and their method of calculation, type of information desired and method of presentation (chart type). Details are shown in Tables 15.6 to 15.12.



Sector	Unit	014	2015	2016	2017	2018
Energy	$MtCO_2e$	36053.93	36060.24	36080.14	36539.61	37224.95
Industrial Processes	$MtCO_2e$	2671.42	2678.62	2768.08	2825.88	2902.68
Agriculture	$MtCO_2e$	5669.75	5691.56	5737.28	5821.07	5817.65
Waste	$MtCO_2e$	1514.26	1543.59	1560.85	1583.86	1606.86
Land-Use Change and Forestry	$MtCO_2e$	737.94	786.46	1267.61	1220.05	1387.56

CLIMATEWATCH

Figure 15.14 Global historical emissions, https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors .

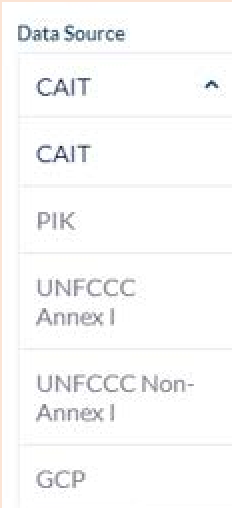


Table 15.6 Global historical emissions data source.

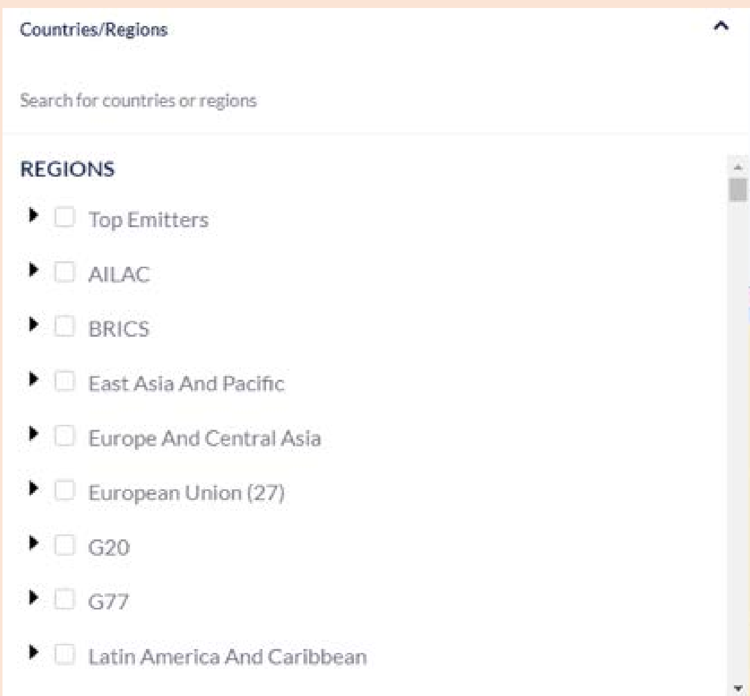


Table 15.7 Global historical emissions countries/regions.

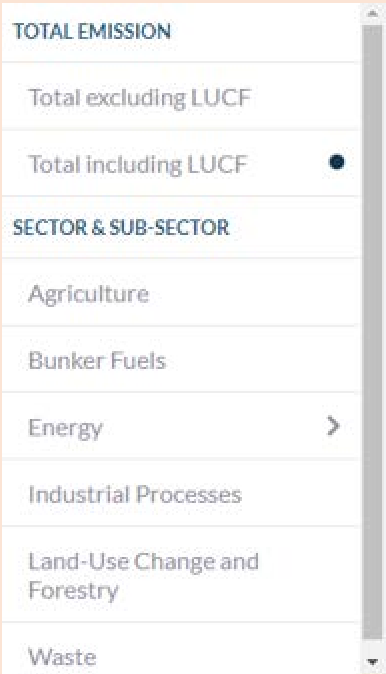


Table 15.8 Global historical emissions sectors/subsectors.

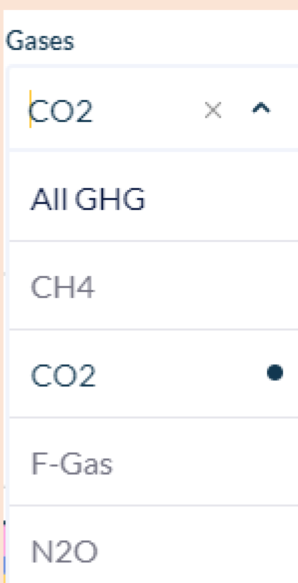


Table 15.9 Global historical emissions gases.

Calculations
Total
Total
per Capita
per GDP
Cumulative across available years
Percentage change from prior year

Table 15.10 Global historical emissions method of calculation.

Show data by
Sectors
Countries
Regions
Sectors
Gases

Table 15.11 Global historical emissions focus of information presented.

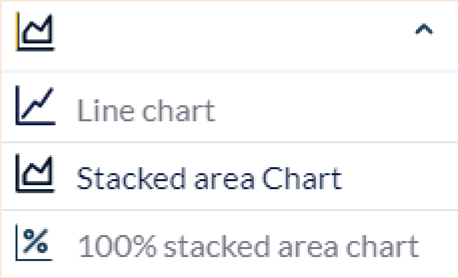
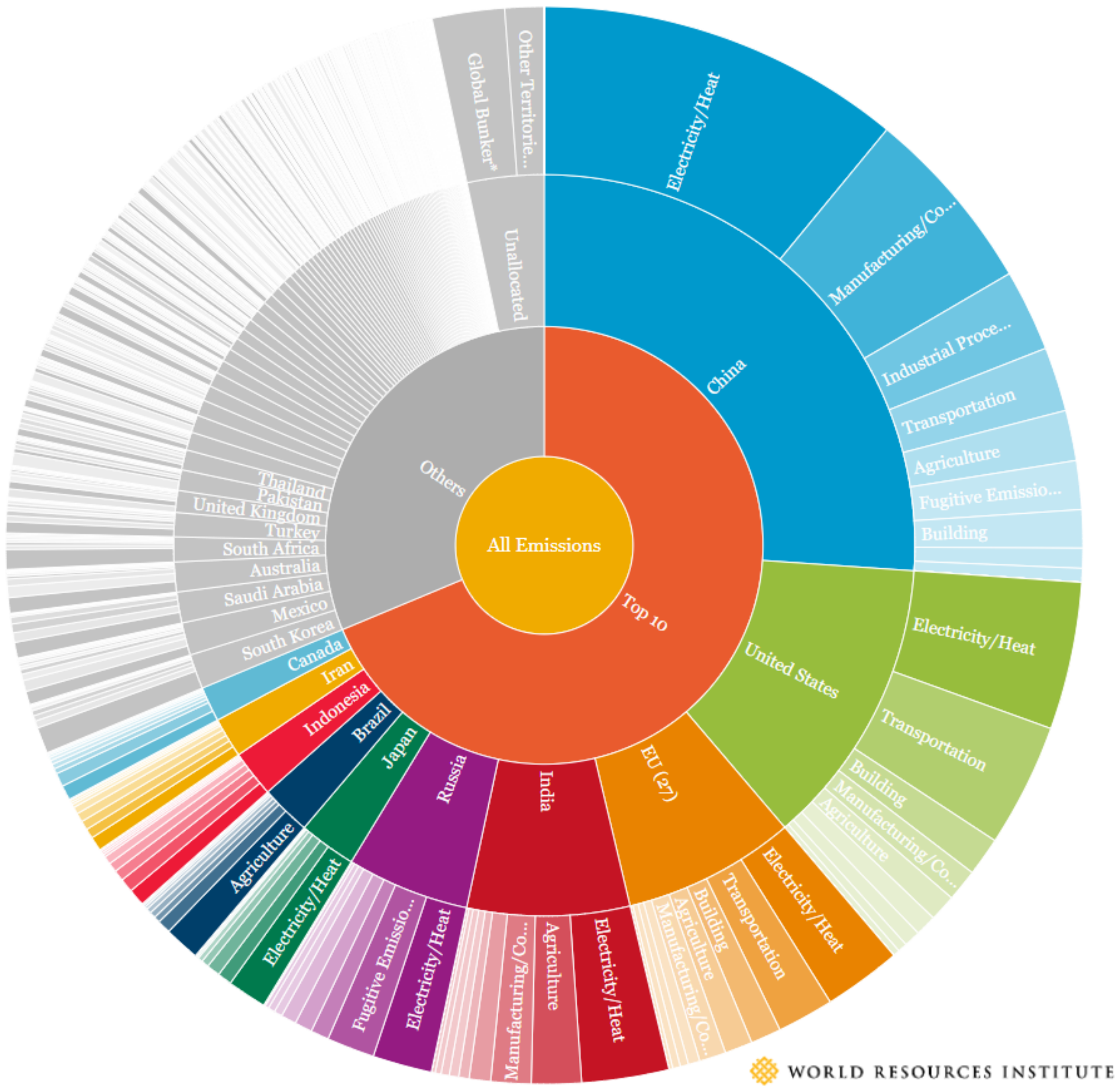


Table 15.12 Global historical emissions chart type.

15.6.3 Comparison of global greenhouse gas emissions by country by Johannes Friedrich.

A graphic in Figure 15.15 clearly shows the country source and sector within the country of greenhouse gas emissions, https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors . Note that land-use change and forestry have been excluded. Go to the web site. The greenhouse gas emitted by a country is indicated by passing the cursor over the country and emission is presented as a total and as a percentage of global greenhouse gas emissions. Note that approximately 2/3 of emissions originate from ten countries.

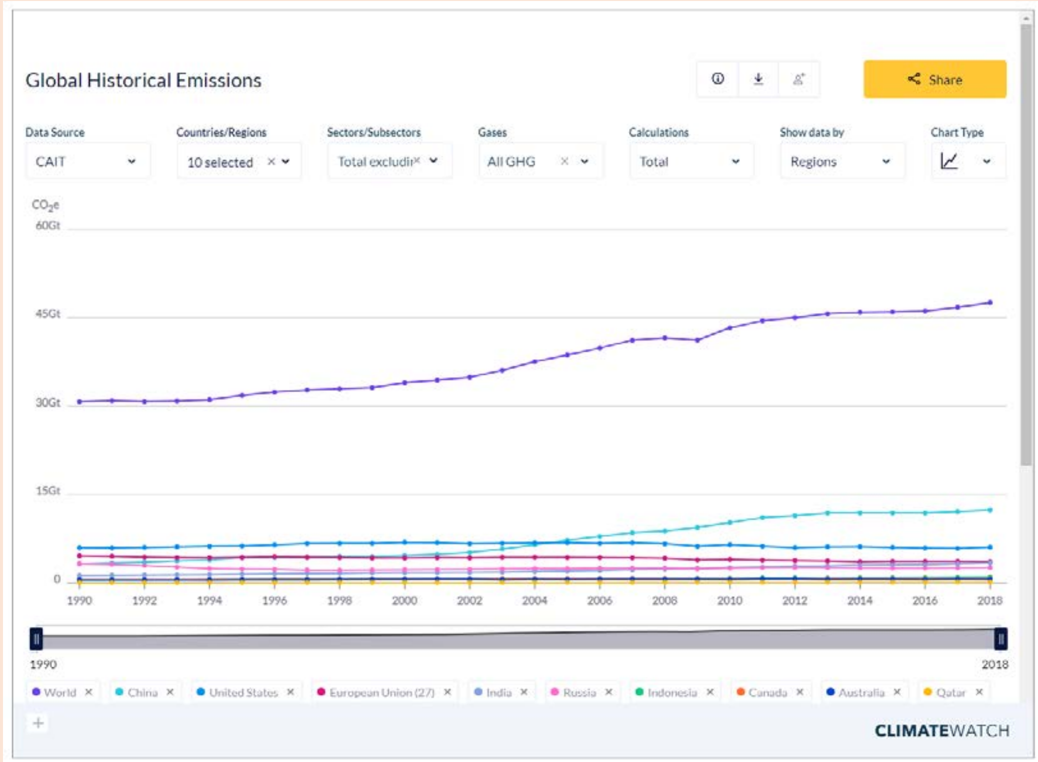


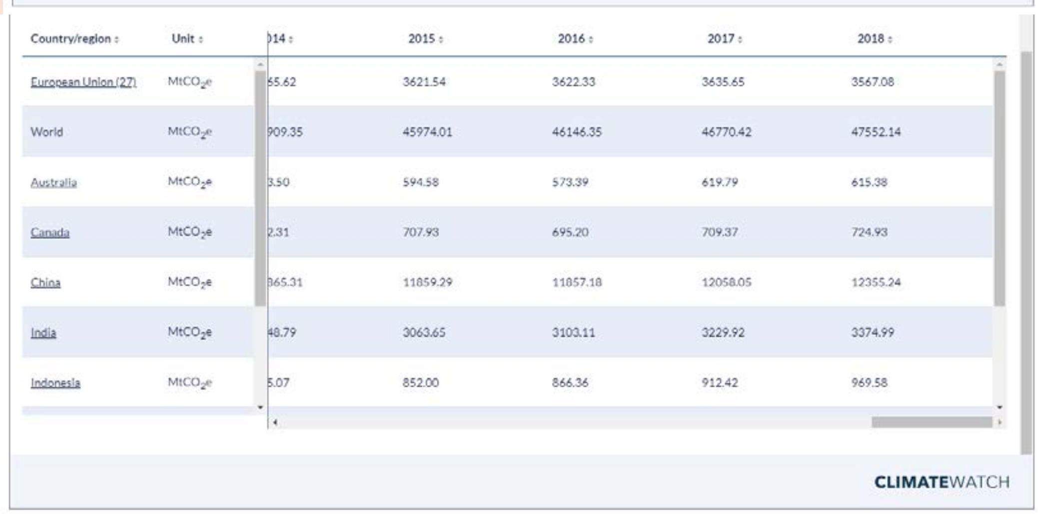
Graphic by Johannes Friedrich. Data source: Preliminary global greenhouse gas emissions 2018 excluding land-use change and forestry (LUCF) from Climate Watch.The EU 27 is considered a country.
*Bunker fuels inlcude international aviation and shipping that are not included in country totals. Other territories include regions not covered by Climate Watch country data. See Climate Watch for country level land-use change and forestry and bunker fuel emissions.

Figure 15.15 Comparison of global greenhouse gas emission by country
https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors

15.6.4 Global historical comparison of emissions by the top ten emitting countries.

Figure 15.16 shows a graph of historical emissions by the top ten greenhouse gas emitting countries for the period 1990 to 2018. The information is similar to that shown in Figure 15.14.





Country/region	Unit	)14	2015	2016	2017	2018
European Union (27)	$MtCO_2e$	55.62	3621.54	3622.33	3635.65	3567.08
World	$MtCO_2e$	909.35	45974.01	46146.35	46770.42	47552.14
Australia	$MtCO_2e$	3.50	594.58	573.39	619.79	615.38
Canada	$MtCO_2e$	2.31	707.93	695.20	709.37	724.93
China	$MtCO_2e$	365.31	11859.29	11857.18	12058.05	12355.24
India	$MtCO_2e$	48.79	3063.65	3103.11	3229.92	3374.99
Indonesia	$MtCO_2e$	5.07	852.00	866.36	912.42	969.58

Figure 15.16 Historical emissions by the top ten greenhouse gas emitting countries for the period 1990 to 2018 https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors.

The agriculture, forestry, and other land use (AFOLU) sector is very broad. Agriculture practices include soil management and the conversion of previously forested land into intensive farming or range land are recognized as significant contributors to green house gas emissions. Forest loss due to any cause has the impact of eliminating greenhouse has storage and release of previously stored greenhouse gases to the atmosphere. Changes in land use involving loss of forest and soil covered land areas eliminate opportunities for greenhouse gas storage and capture. To this has been added peatland management as reported by the International Union for the Conservation of Nature, ICUN, https://www.iucn.org/resources/issues-briefs/peatlands-and-climate-change. They describe peatlands as a type of wetlands that occur in almost every country covering 3% of the global land surface. The term 'peatland' refers to the peat soil and the wetland habitat growing on its surface. They go on to say that damaged peatlands contribute about 10% of greenhouse gases from the land use sector or 5.6% of anthropogenic carbon dioxide emissions. The damage is caused by drainage and conversion to agricultural land, fires, and harvesting as fuel. Loss of peatlands is considered to have a negative impact on local biodiversity.

Oceans are not specifically identified as a significant contributor of greenhouse gas emissions (maybe as part of 'other contributors). Oceans are normally viewed as greenhouse gas sinks. Recent studies on the impact of ocean fisheries, trawling practices in particular on ocean biodiversity and release of greenhouse gases have recently been reported, (https://www.nature.com/articles/s41586-021-03371-z, https://www.sciencedaily.com/releases/2021/03/210317141645.htm, https://www.bluemarinefoundation.com/2021/03/18/trawling-discovered-to-have-massive-climate-change-impact/, https://www.theguardian.com/environment/2021/mar/17/trawling-for-fish-releases-as-much-carbon-as-air-travel-report-finds-climate-crisis). The release of greenhouse gases is estimated to be as much as the entire airline industry and is viewed as a manageable activity.

15.7 Greenhouse gas emissions - reported

15.7.1 UNFCC country reports by country projected to 2030

Countries report the GHG emissions from industries operating in their jurisdiction to the United Nations Framework Convention on Climate Change using protocols established by the UNFCCC https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/reporting-requirements . This approach to quantifying GHG emissions is known as 'activity-based'.

It is very important to know which countries and industries are producing GHG emissions so that global strategies for mitigation and adaptation can be developed and funded. This information is also useful when assessing progress in implementing mitigation strategies. Greenhouse gas emissions for major economies 1990-present and projections from present to 2030 are shown in Figure 15.17.

Greenhouse gas emissions for the top seven emitters is shown in Figure 15.18. Cumulative GHG emissions from these emitters for the period 1751-2017 is shown in Figure 15.19. Comparison of Figure 15.18 and 15.19 highlight the change in position of China and India and the presence of a new top emitter, Brazil.

Per capita greenhouse gas emissions for the major economies and the world are shown in Figure 15.20. This figure reflects standard of living. The difference between the lower income population and the high-income population is highlighted in Figure 15.21. Figure 15.22 shows the per capita GHG emissions by country. Aspects such as climate and affluence are reflected.

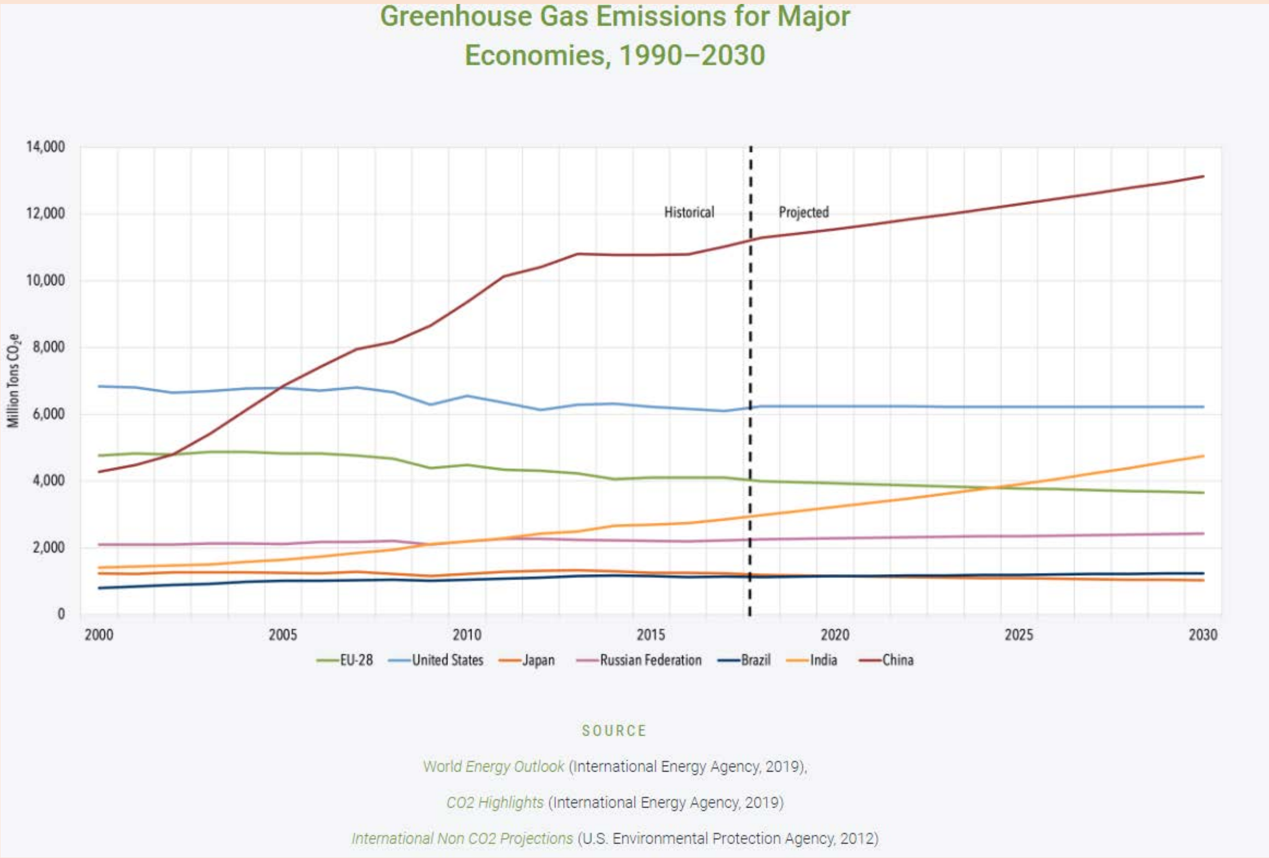


Figure 15.17 Greenhouse gas emissions for major economies, 1990-2030.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

Greenhouse gas intensity for the major economies and the world is shown in Figure 15.23. Greenhouse gas intensity is measured in tonnes of carbon dioxide equivalent per thousand dollars of gross domestic product. The lower this number the more efficient the economy in terms of use of fossil fuel. Similar information is presented in Figure 15.24 which considers a cross-section of countries worldwide.   More affluent countries tend to be more efficient.

It is clear that there is considerable information available regarding present GHG emissions by sector and by country.   This information is critical when projecting future GHG emissions.

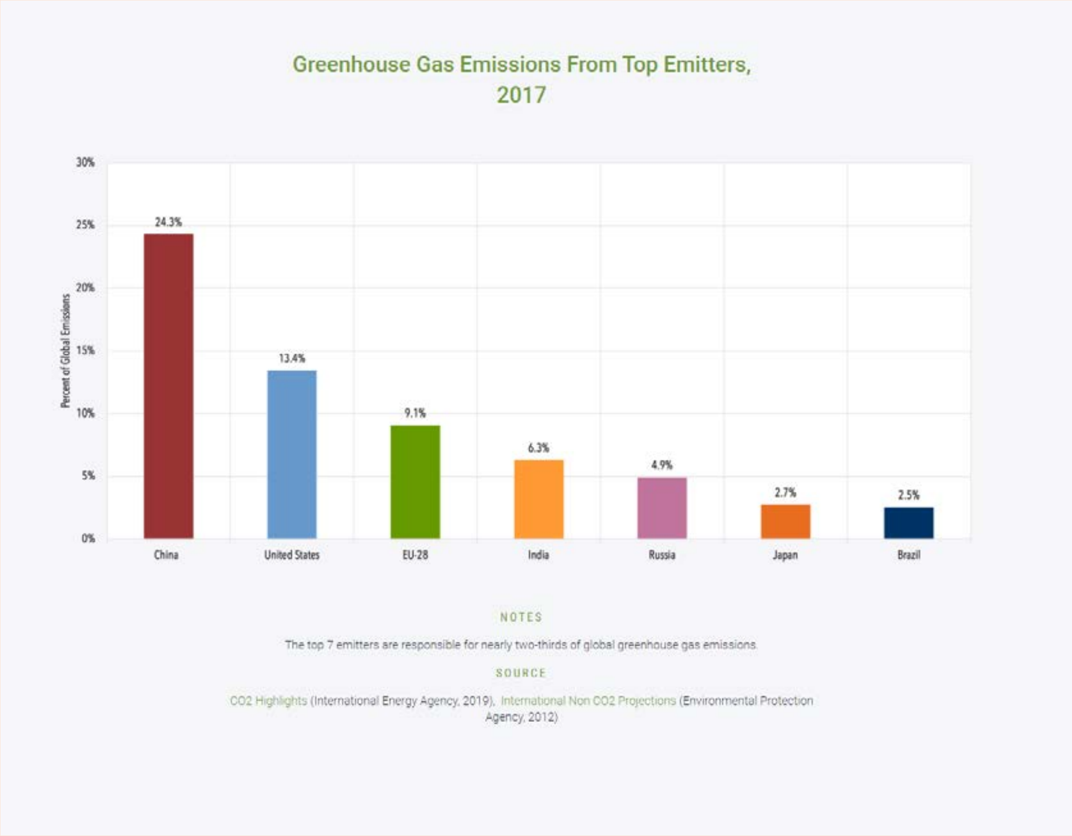


Figure 15.18 Greenhouse gas emissions for top emitters, 2017.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

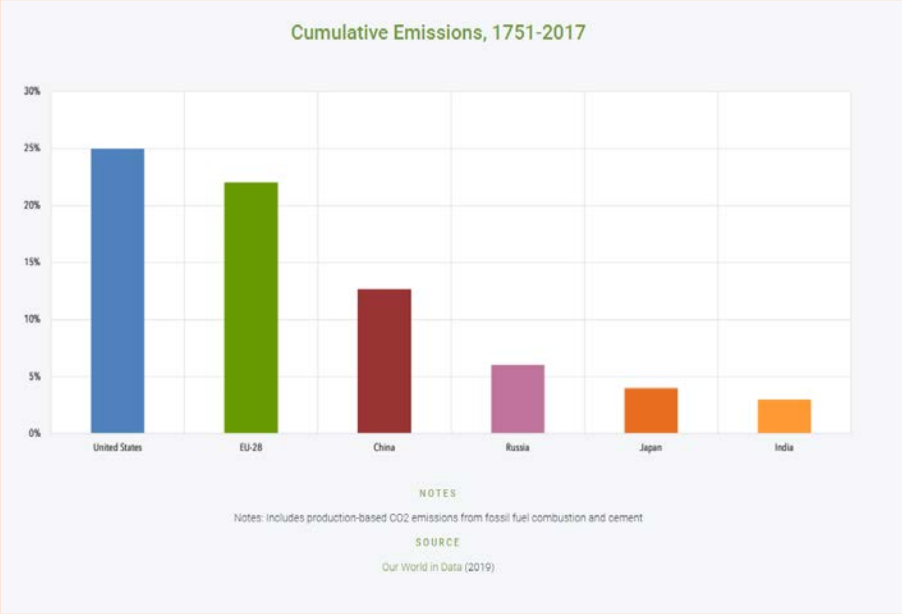


Figure 15.19 Cumulative greenhouse gas emissions for major economies, 1751-2017. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

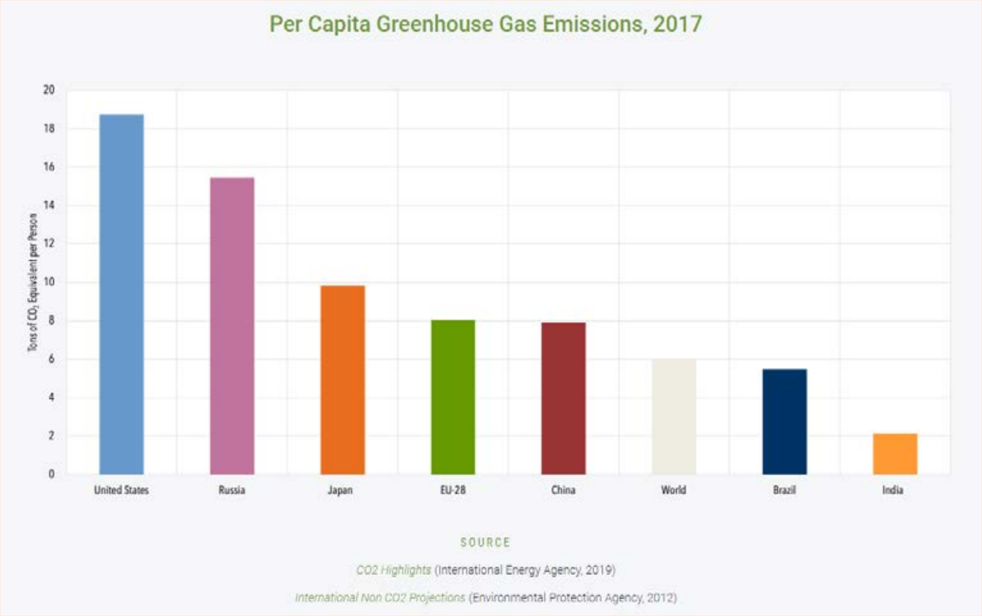


Figure 15.20 Per Capita greenhouse gas emissions for major economies, and the world, 2017.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

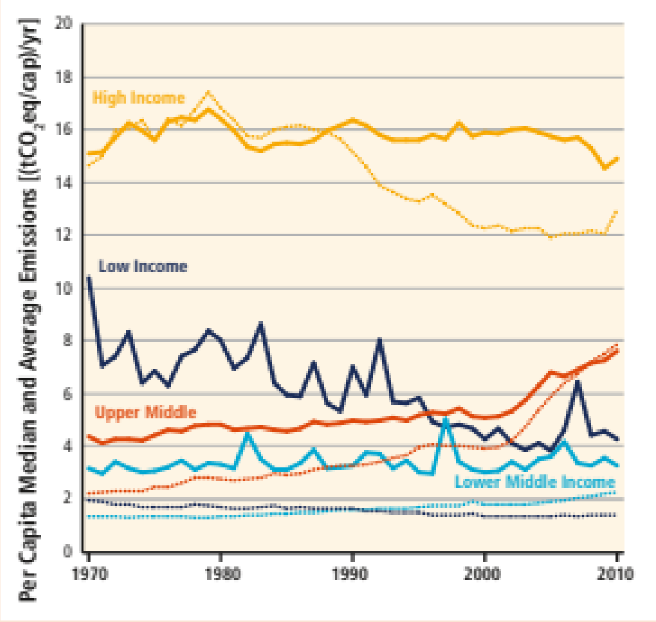


Figure 15.21 Per capita emissions for different income brackets.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

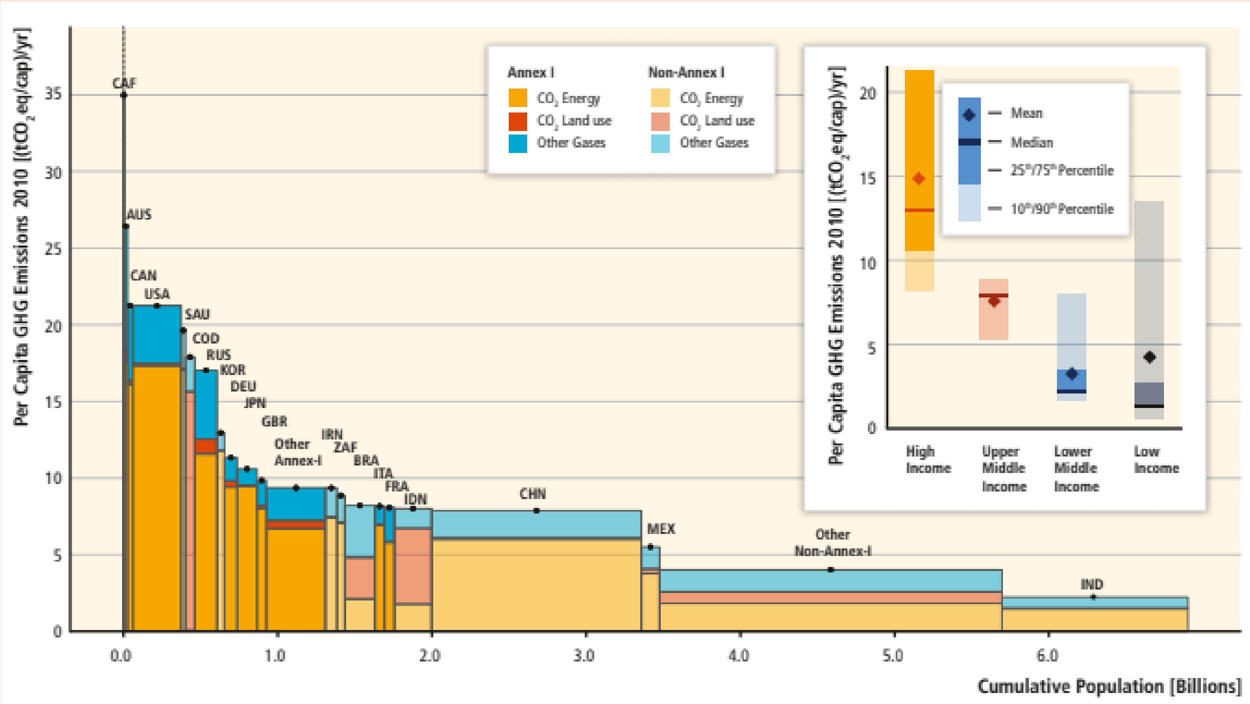


Figure 15.22 Per capita GHG emissions by country from IPCC.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

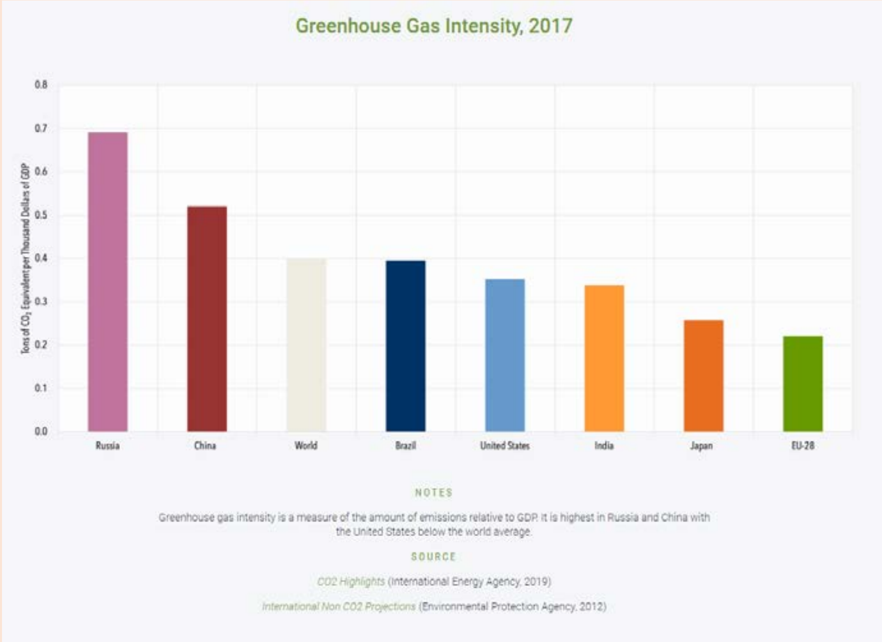


Figure 15.23 Greenhouse gas intensity for major economies and the World, 2017. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

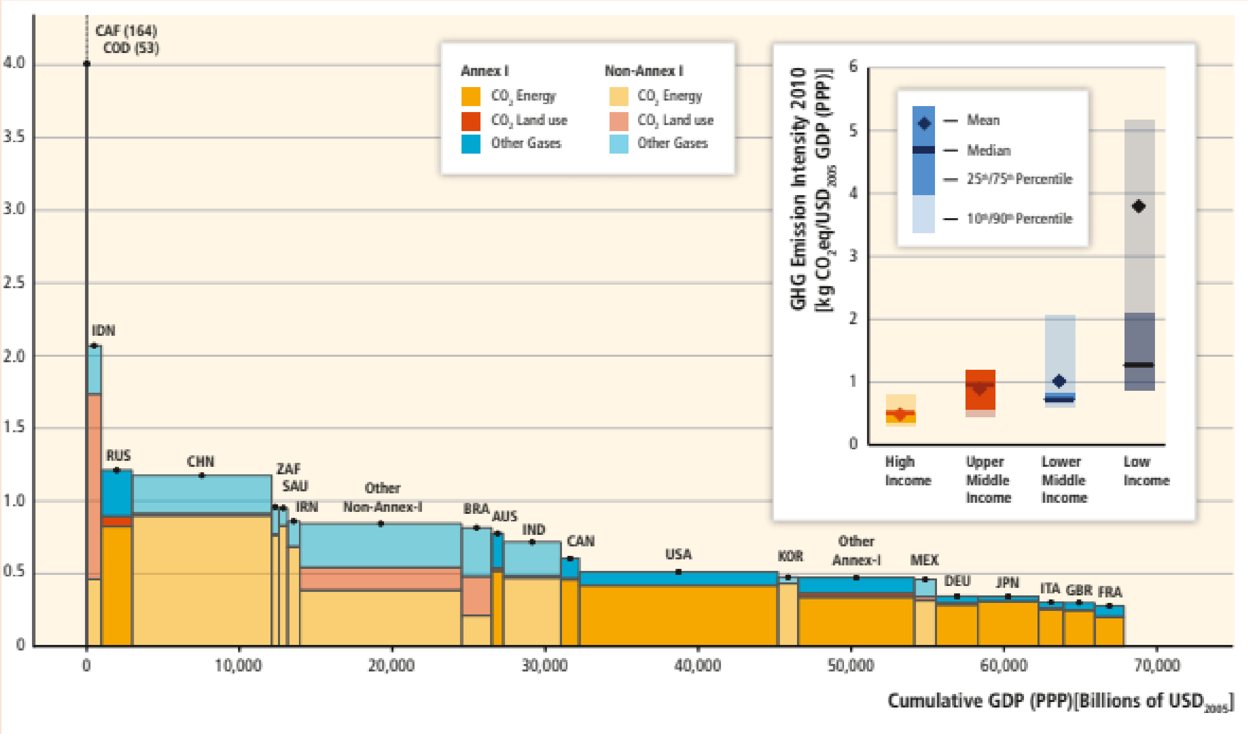


Figure 15.24 Greenhouse gas intensity for cross-section of countries.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

15.7.2 Global Carbon Project

'**The Global Carbon Project** https://www.globalcarbonproject.org/index.htm is a Global Research Project of Future Earth https://futureearth.org/ and a research partner of the World Climate Research Programme https://www.wcrp-climate.org/ . (See Section 1.3 for further information on Future Earth and the World Climate Research Programme.) It was formed to work with the international science community to establish a common and mutually agreed knowledge base to support policy debate and action to slow down and ultimately stop the increase of greenhouse gases in the atmosphere.

The overwhelming realization that anthropogenic climate change is a reality has focused the attention of the scientific community, policymakers and the general public on the rising atmospheric concentrations of the main greenhouse gases, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The GCP has approached this challenge by focusing comprehensively on the global biogeochemical cycles which govern these three greenhouse gases, including their natural and human drivers, and opportunities for low carbon pathways.

Attempts through the United Nations Framework Convention on Climate Change, first with its Kyoto Protocol and now with the Paris Agreement, are underway to stabilize the climate system which requires achieving a balance between sources and sinks of greenhouse gases.'

'The scientific goal of the Global Carbon Project is to develop a complete picture of the global carbon cycle, including both its biophysical and human dimensions together with the interactions and feedbacks between them. This will be:

- **Patterns and Variability:** What are the current geographical and temporal distributions of the major pools and fluxes in the global carbon cycle?
- **Processes and Interactions:** What are the control and feedback mechanisms - both anthropogenic and non-anthropogenic - that determine the dynamics of the carbon cycle?
- **Carbon Management:** What are the dynamics of the carbon-climate-human system into the future, and what points of intervention and windows of opportunity exist for human societies to manage this system?'

The mandate of the Global Carbon Project is;

1. To develop a research framework for integration of the biogeochemical, biophysical and human components of the global carbon cycle, including the development of data-model fusion schemes, and design of cost effective observational and research networks.
2. To synthesize current understanding of the global C cycle and provide rapid feedback to the research and policy communities, and general public.
3. To develop tools and conceptual frameworks to couple the biophysical and human dimensions of the carbon cycle.
4. To provide a global coordinating platform for regional/national carbon programs to improve observation network design, data standards, information and tools transfer, and timing of campaigns and process-based experiments.
5. To strengthen the broad carbon research programs of nations and regions, and those of more disciplinary projects in IGBP, IHDP, WCRP, and IGCO through better coordination, articulation of goals, and development of conceptual frameworks.
6. To develop a small number of new research initiatives that are feasible within a 3–5-year time framework on difficult and highly interdisciplinary problems of the carbon cycle.
7. To foster new carbon research in regions (e.g., tropical Asia) that will provide better constrains of continental and global carbon budgets through promoting partnerships between institutions and exchange visits.

15.7.3 US National Academies of Science, Engineering and Medicine

The US National Academies of Science, Engineering and Medicine, NASEM, https://www.nationalacademies.org/ has produced a report titled 'Greenhouse Gas Emissions

Information for Decision Making'
https://nap.nationalacademies.org/resource/26641/interactive/?utm_source=Division+on+Earth+and+Life+Studies&utm_campaign=a0f4d23a82-EMAIL_CAMPAIGN_2022_07_19_03_14_COPY_01&utm_medium=email&utm_term=0_3c0b1ad5c8-a0f4d23a82-278885679&mc_cid=a0f4d23a82&mc_eid=b6391f6645 . This report addresses the following questions:

1. What information do decision makers need?
2. How are GHG emissions quantified?
3. How should decision makers evaluate GHG emissions information?

15.8 Greenhouse gas emissions - observed

Observation of GHG concentration in the atmosphere is collected using a variety of platforms including land based, aircraft and satellite. The collection system is able to monitor global concentration of each of the variety of greenhouse gases and are able to pinpoint where the emissions originate. This greatly improves opportunities for better quality modelling, development of adaptation programs and development of mitigation strategies as well as management of GHG emissions, verification of reporting of GHG emissions and 'policing' of GHG emitters.

15.8.1 Land and ocean-based monitoring and sampling
Figure 15.25 shows the location of a variety of land and ocean-based sampling points for monitoring GHG's, usually carbon dioxide, ozone and aerosols. The exact nature of what is being collected is available on the NOAA web site:
https://www.esrl.noaa.gov/gmd/dv/iadv/index.php?code=mlo .

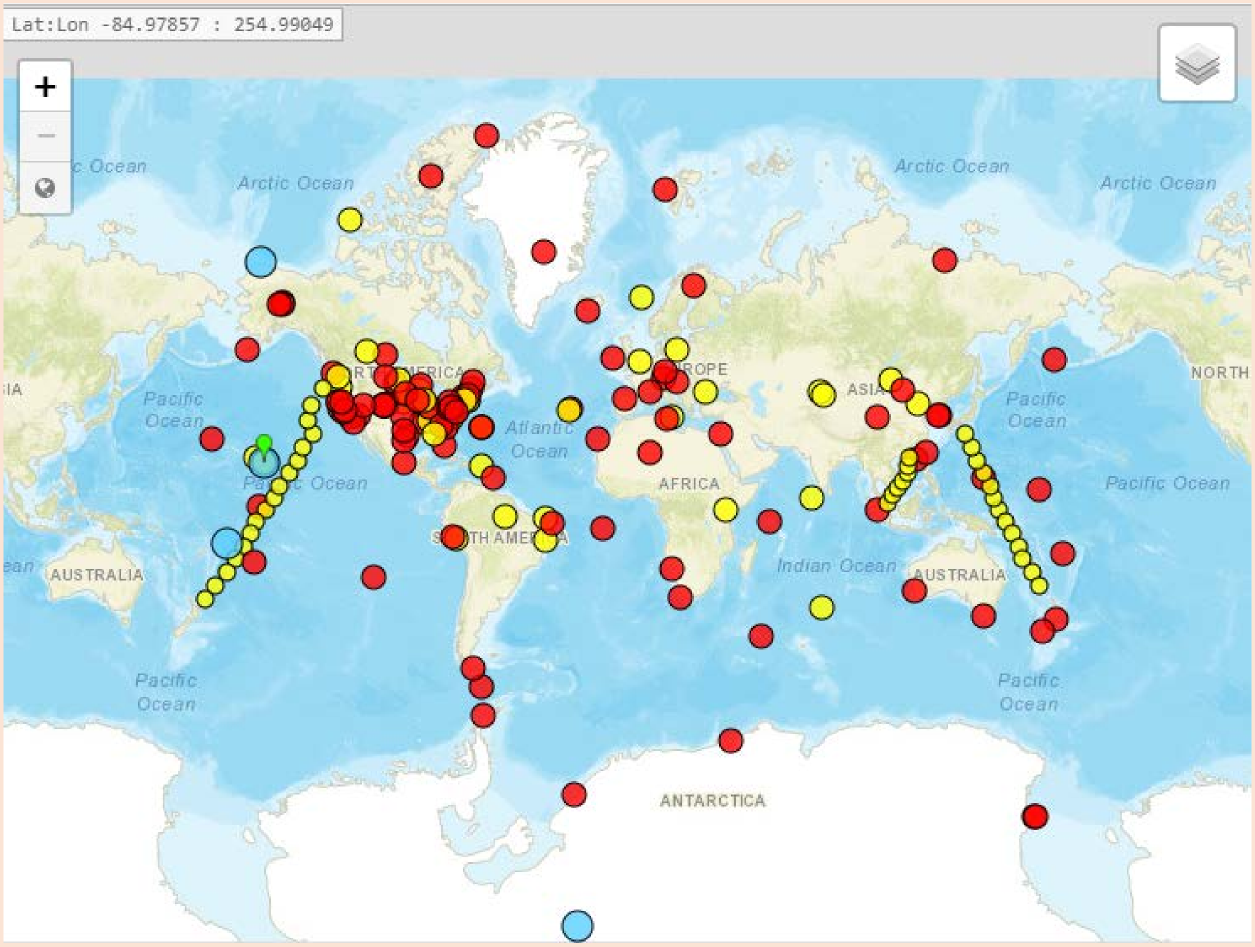


Figure 15.25 Land and ocean-based sampling of GHG's, ozone, and aerosols. https://www.esrl.noaa.gov/gmd/dv/iadv/index.php?code=mlo

15.8.2 Aircraft GHG sampling

Figure 15.26 shows the aircraft GHG sampling program. See NOAA web site for most up-to-date information, http://www.esrl.noaa.gov/gmd/ccgg/aircraft/ .

Yellow aircraft symbols represent discontinued sites.

Figure 15.26 Aircraft GHG sampling program operated by NOAA.
http://www.esrl.noaa.gov/gmd/ccgg/aircraft/

15.8.3 Satellite based monitoring

The following is a sampling of the most recent satellite based GHG monitoring platforms.

Figure 15.27 shows the Greenhouse Gases Observing Satellite, GOSAT or Ibuki (Japanese) which is the first satellite dedicated to GHG monitoring. It measures carbon dioxide and methane.

Figure 15.28 shows the NASA orbiting carbon observatory, OCO-2. Data received from this satellite shows where the carbon emissions are coming from and the intensity of those carbon emissions as shown in Figure 15.29 OCO-3 will extend NASA's carbon monitoring program from the International Space Station.

Figure 15.30 shows an image of carbon monoxide sources as observed by NASA's Atmospheric Infrared Sounder (AIRS). In this figure it has sensed carbon monoxide from the wildfires in California.

Figure 15.31 shows an instrument mounted on a communications satellite named the Geostationary Carbon Cycle Observatory (EVM-2) or (GeoCarb).   GeoCarb will collect 10 million daily observations of the concentrations of carbon dioxide, methane, carbon monoxide and solar-induced fluorescence (SIF) at a spatial resolution of about 3 to 6 miles (5 to 10 kilometers).

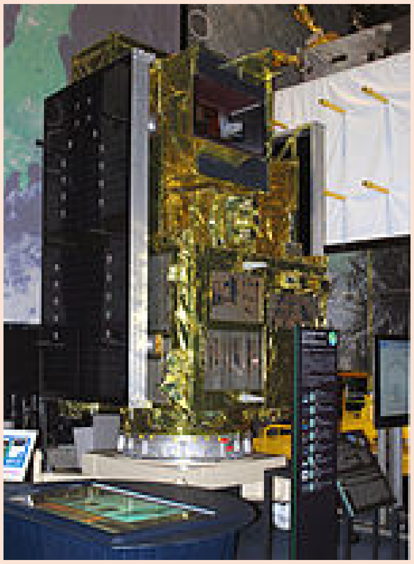
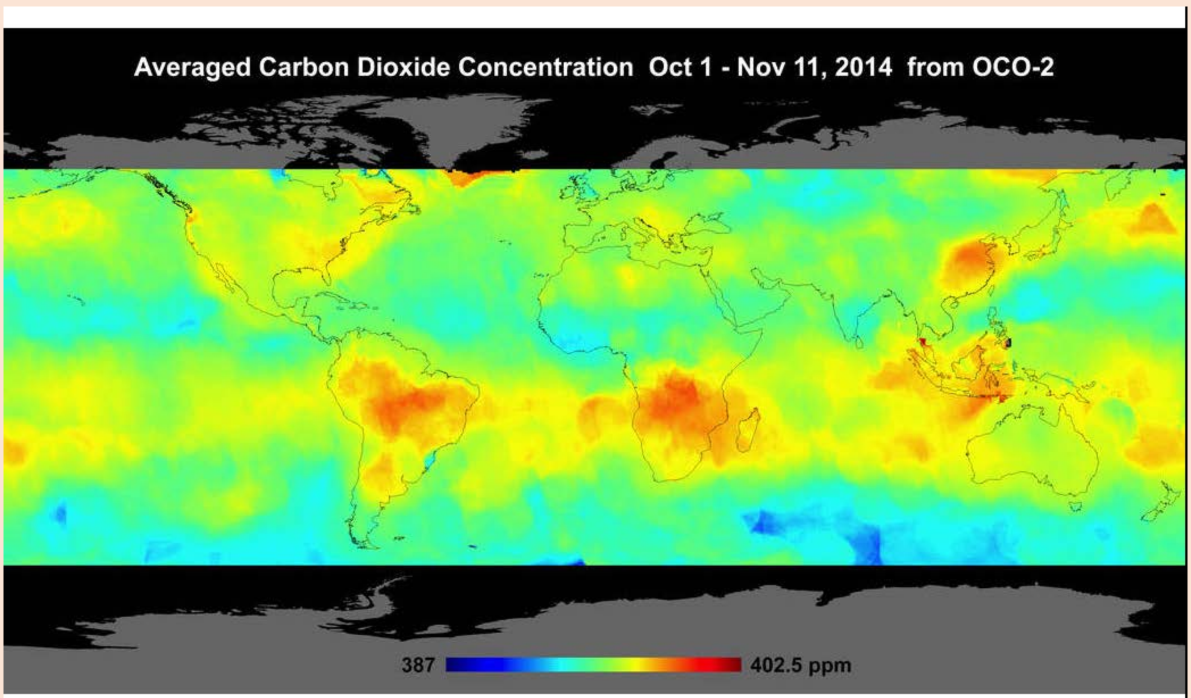


Figure 15.27 Greenhouse Gases Observing Satellite, GOSAT or Ibuki (Japanese) is the first satellite dedicated to GHG monitoring. It measures carbon dioxide and methane.
https://en.wikipedia.org/wiki/Greenhouse_Gases_Observing_Satellite

NASA's rendering of its Orbiting Carbon Observatory-2. Credit: NASA

Figure 15.28 NASA Orbiting Carbon Observatory-2.
https://www.nasa.gov/mission_pages/oco2/index.html



Global atmospheric carbon dioxide concentrations from Oct. 1 through Nov. 11, as recorded by NASA's Orbiting Carbon Observatory-2. Carbon dioxide concentrations are highest above northern Australia, southern Africa and eastern Brazil. Preliminary analysis of the African data shows the high levels there are largely driven by the burning of savannas and forests. Elevated carbon dioxide can also be seen above industrialized Northern Hemisphere regions in China, Europe and North America.

Image credit: NASA/JPL-Caltech

Last Updated: May 29, 2015
Editor: Tony Greicius

Figure 15.29 Averaged carbon dioxide concentration Oct 1 – Nov 11, 2014 from OCO-2.
https://www.nasa.gov/jpl/oco2/pia18934

Figure 15.30 Carbon monoxide measurements from NASA's Atmospheric Infrared Sounder (AIRS).
https://climate.nasa.gov/news/3019/nasa-monitors-carbon-monoxide-from-california-wildfires/

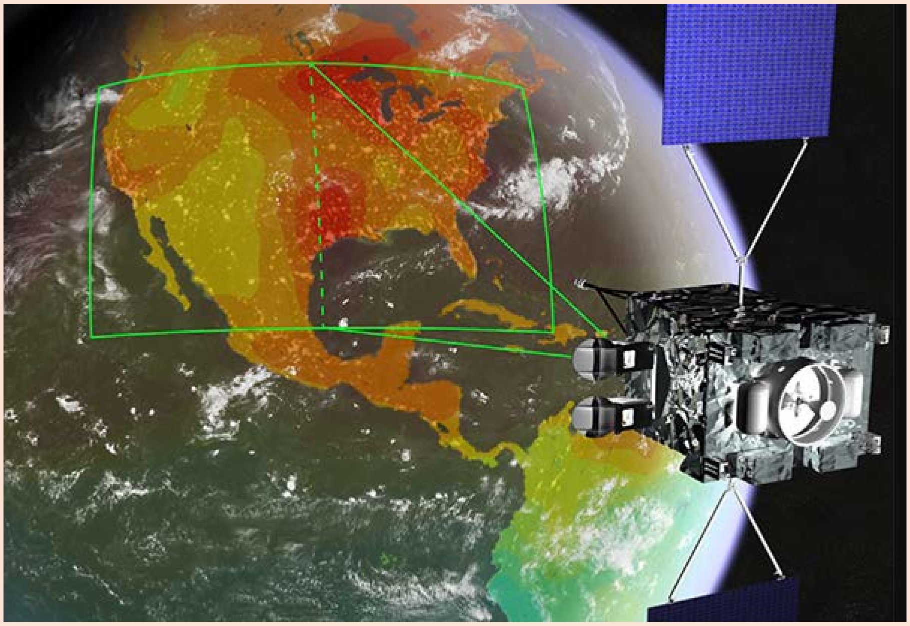


Figure 15.31 Geostationary carbon cycle observatory, EVM-2, GeoCarb.
https://eospso.nasa.gov/missions/geostationary-carbon-cycle-observatory-evm-2

Figure 15-32 shows a methane leak from space as detected by Earth Observing-1 (EO-1) satellite.

Figure 15-33 refers to NASA's 3-dimensional portrait of methane concentrations by combining multiple data sets from emissions inventories such as fossil fuel, agricultural activities, biomass burning, and biofuels and simulations of wetland sources. This project is an international success story. The full potential of this tool is described on the web site: https://climate.nasa.gov/news/2961/new-3d-view-of-methane-tracks-sources-and-movement-around-the-globe/. Methane sources can be identified and opportunities for mitigation determined.

Figure 15-34 illustrates the use of a satellite recently launched by a private company, GHGSat, named Iris detecting a methane plume (controlled release) in Alberta, Canada. This is their second satellite. The company's products and services use a proprietary multi-platform system for collecting emissions data.

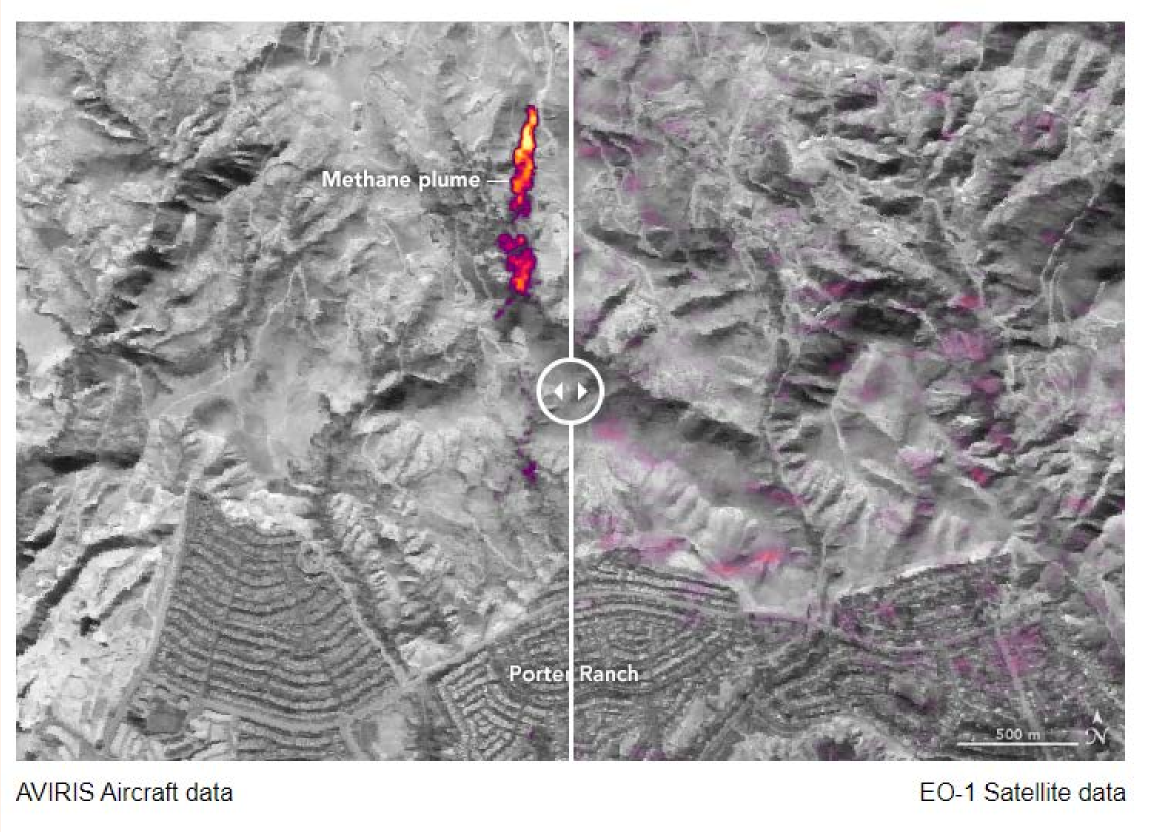


Figure 15.32 Methane leak from space as detected by Earth Observing-1 (EO-1) satellite. https://earthobservatory.nasa.gov/images/88245/imaging-a-methane-leak-from-space

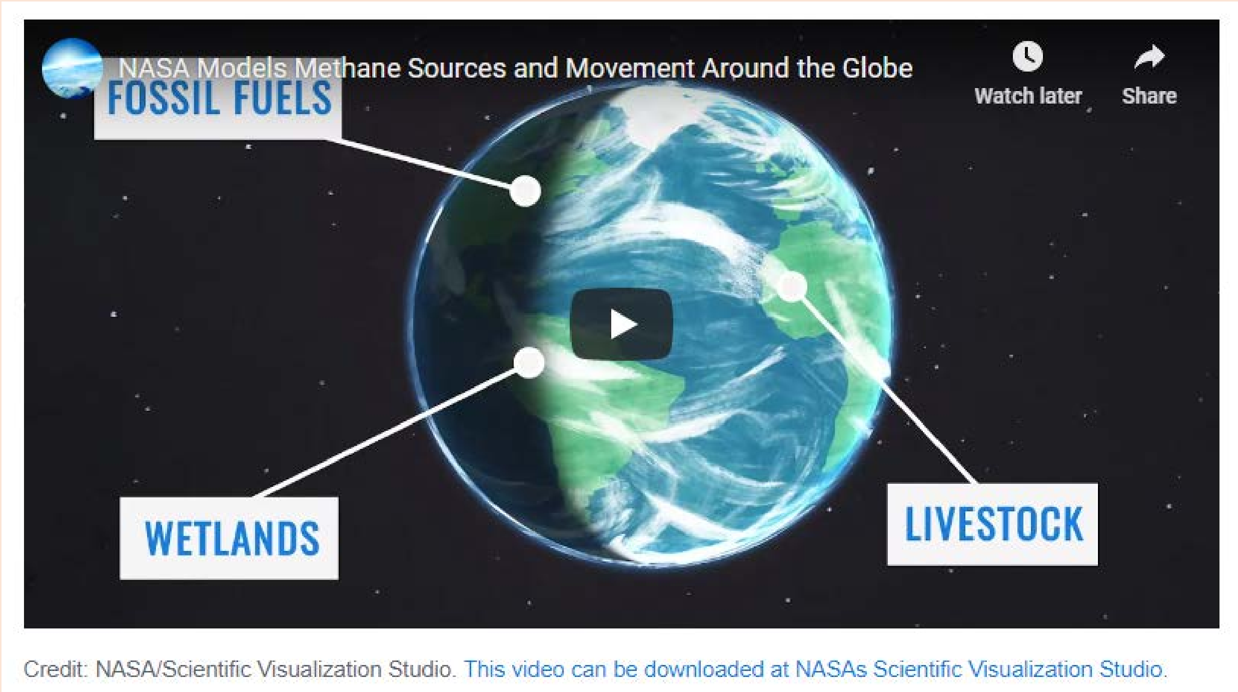


Figure 15.33 NASA Methane source model. https://climate.nasa.gov/news/2961/new-3d-view-of-methane-tracks-sources-and-movement-around-the-globe/

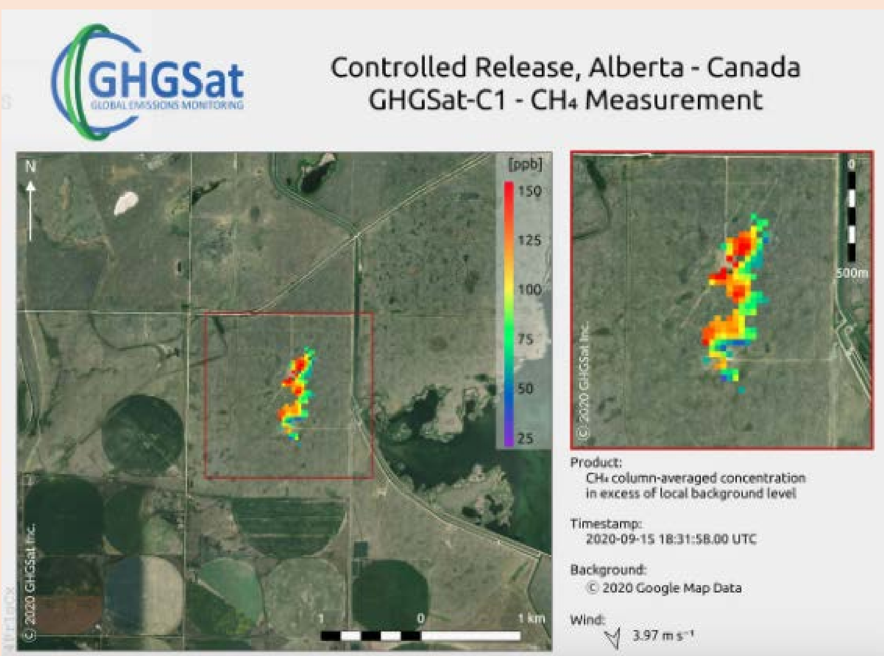


Figure 15.34 Global methane emissions monitoring https://www.ghgsat.com/

July 2022 NASA launched a new sensor, Earth Surface Mineral Dust Source Investigation, EMIT, to identify the presence of a wide variety of minerals as well as mineral weathering or alteration https://earth.jpl.nasa.gov/emit/ . The sensor is mounted on the International Space Station. The same sensor is capable of identifying methane 'super-emitters' https://earth.jpl.nasa.gov/emit/news/23/methane-super-emitters-mapped-by-nasas-new-earth-space-mission/ .

Satellite data, combined with land and ocean-based data, provide a very good quantitative statement of global greenhouse gas emissions. The ability to detect and monitor GHG emissions is steadily improving. As the resolution of satellite surveillance of GHG emissions improves their role extends beyond simple detection of GHG emissions to verification of emission and mitigation reporting (globally) to provision of opportunities for regional management of GHG emissions.

Sensor technology is also developing to better distinguish anthropogenic contributions from naturally occurring and 'see' a wider variety of parameters. A summary of methods and satellites used to observe greenhouse gases from space, methane in particular, is shown in Figure 15.35. A paper describing how methane emissions from global scale to point sources using satellite observations of atmospheric methane may be found in https://acp.copernicus.org/articles/22/9617/2022/ .

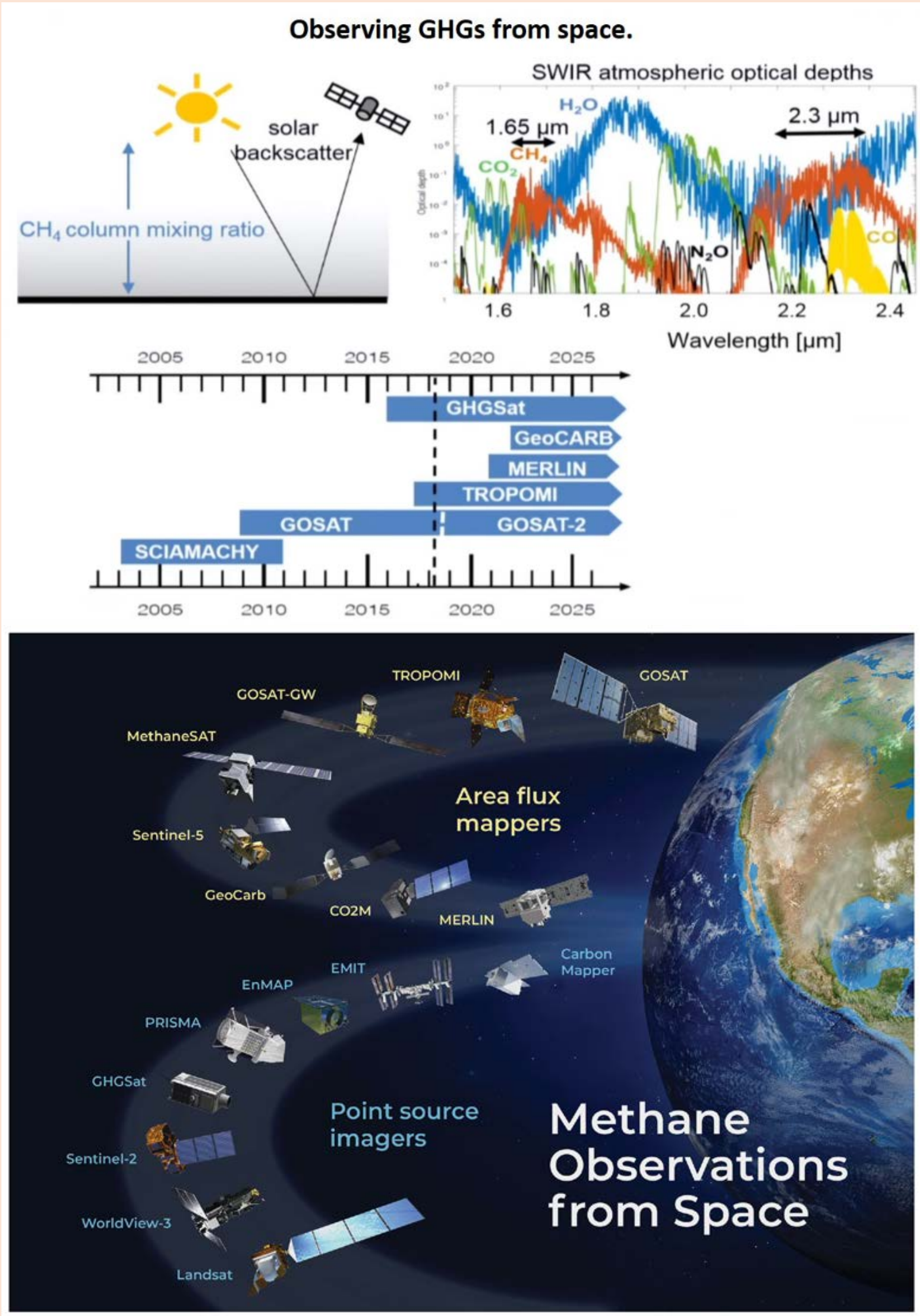


Figure 15.35 Summary of the methods for observing GHGs from space
https://acp.copernicus.org/articles/22/9617/2022/ .

15.9 Natural and anthropogenic radiative forcing

The importance of anthropogenic forces contributing to global warming as compared to natural forces is evident from the graph shown in Figure 15.36. Natural forcing or solar radiative forcing, is 0.05 Wm^{-2}. Total anthropogenic radiative forcing is 2.29 Wm^{-2} - most of which is due to GHGs.

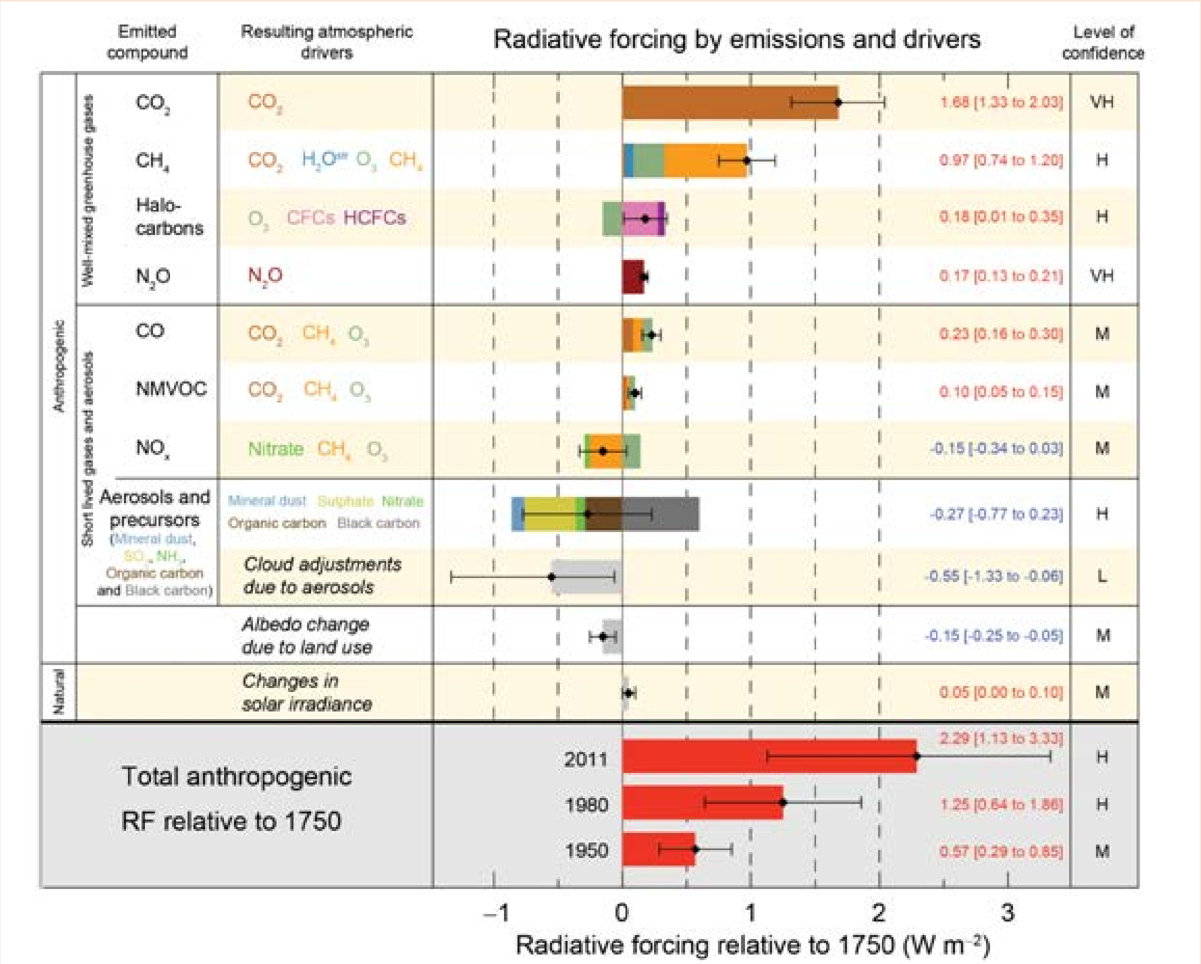


Figure 15.36 Global-average radiative forcing estimates and ranges – AR5.
https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf

15.10 Carbon footprint and auditing

A carbon footprint is the total greenhouse gas emissions caused by an individual, event, organization, service or product expressed as carbon dioxide equivalent, Wikipedia
https://en.wikipedia.org/wiki/Carbon_footprint#:~:text=A%20carbon%20footprint%20is%20the

,expressed%20as%20carbon%20dioxide%20equivalent and the University of Michigan Center for Sustainable Systems, http://css.umich.edu/factsheets/carbon-footprint-factsheet.

The carbon footprint may be determined using a variety of software available on the internet. Of course, these are estimates but some are about as good as anyone needs. Examples are:

1. Terrapass, https://www.terrapass.com/carbon-footprint-calculator?gclid=CjwKCAiAgJWABhArEiwAmNVTB1nzx5DFqZOnTKo9gTnWFUFWgbfSTpqYMUX_t4G-3TAHqw6IPBlM8BoC0gUQAvD_BwE#

2. The Nature Conservancy. https://www.nature.org/en-us/get-involved/how-to-help/carbon-footprint-calculator/

3. Carbon Footprint. https://www.carbonfootprint.com/

4. University of Michigan, Center for Sustainable Systems. http://css.umich.edu/factsheets/carbon-footprint-factsheet

5. United States EPA, Carbon footprint calculator. https://www3.epa.gov/carbon-footprint-calculator/

6. World Wildlife Fund. https://footprint.wwf.org.uk/#/

7. Science Direct. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/carbon-footprint

The determination of a carbon footprint may be complex and a 'carbon audit' might be required. The process is governed by protocols such as PAS 2050 and the World Resources Institute, GHG Protocol Standard described in https://ghgprotocol.org/sites/default/files/standards_supporting/GHG%20Protocol%20PAS%202050%20Factsheet.pdf or https://ghgprotocol.org/ . The UN FAO publishes a guide as to how to assess carbon footprint of goods and services in http://www.fao.org/sustainable-food-value-chains/library/details/en/c/266040/. The ISO 14067:2018 is a standard with which the carbon footprint of products can be determined. It outlines the requirements and guidelines for quantification. https://www.iso.org/standard/71206.html. Training courses are provided by organizations certified to provide the courses for individuals and organizations so that their assessments are accepted.

This is usually provided by companies accredited to provide the PAS and ISO assessments. One organization that provides this service and a variety of certifications is Carbon Trust, https://www.carbontrust.com/what-we-do/assurance-and-certification/product-carbon-footprint-label?kw=%20carbon-%20footprint-%20audit-Broad.

These certifications are very important for reporting requirements and for the insight they provide to design and management of production and other operations. They are also important because they determine whether a product or organizations is meeting its allowable GHG emissions (nationally or provincially established); and, perhaps the carbon offsets they may be able to contribute (valued asset) or need to acquire (expense).

15.11 Emission intensity or carbon intensity

Emission intensity or carbon intensity, (CI) are synonymous. It is the emission rate of as given pollutant relative to the intensity of a specific activity, or an industrial production process, https://en.wikipedia.org/wiki/Emission_intensity .

Another common usage of emission intensity is the ratio of greenhouse gas emissions produced to gross domestic product. It is a measure of a country's economic dependence on greenhouse gas producing activity (fuel for example). If a country transitions to the use of renewable energy while maintaining or increasing its GDP, this ratio would decrease.

Other measures could be the amount of greenhouse gas emissions produced per number of products produced, number of animals raised to harvest, resulting from production of a unity of electricity, distance traveled, etc.

The Government of British Columbia, Canada uses the term carbon intensity as follows; 'Carbon intensity is the measure of greenhouse gas (GHG) emissions associated with producing and consuming a transportation fuel, measured in grams of carbon dioxide equivalent per megajoule of energy (g CO_2-eq /MJ). Carbon intensity accounts for the GHG emissions associated with extracting, producing, transporting, and consuming a unit of energy of transportation fuel. It is a measure of the GHG emissions from the complete life cycle assessment (LCA) of a fuel.' https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/rlcf006_-_carbon_intensity_records.pdf . This is also known as the 'wells-to-wheels' carbon intensity. This definition of carbon intensity is also known as 'thermal intensity' – the specifics of what is considered must be clearly understood. This is similar to the protocol recently introduced by the Government of Canada named the 'Clean Fuel Standard'.

Whole life cycle assessments (LCA) include emissions resulting from the entire production of a given product including the machinery used to produce product, materials used in product, energy consumed during manufacturing, and energy consumed in marketing.

15.12 Carbon neutral, decarbonizing, net zero, carbon efficiency

There are a number of terms used to describe the various states of 'carbon' use by various entities including countries, companies, organizations, products, services, events or people. In this sense carbon means carbon equivalent unless explicitly defined differently.

1. Carbon neutral, (climate neutral) results when the reduction in carbon emissions equals carbon emission production. Net zero means the same as carbon neutral.
2. Decarbonizing is the process of reducing carbon emissions in a particular activity. For example, replacing energy sources from fossil fuels with energy from renewable sources such as wind or hydro. Carbon reduction potential is the maximum amount of decarbonizing possible.
3. Carbon efficiency or energy efficiency, has several definitions including carbon or emission intensity. Another is the amount of carbon emissions resulting from manufacturing a product or providing a service (relative term), again similar to intensity.

There are number of other terms that are derivatives of the above definitions such as carbon performance and carbon budget, https://www.wri.org/blog/2015/12/cop21-glossary-terms-guiding-long-term-emissions-reduction-goal .

15.13 Carbon management

Carbon management refers to the actions available to governments to limit the production of carbon emissions, that is, greenhouse gas emissions. There are several ways to regulate carbon emissions (reduce them) and several new descriptors have been introduced to describe how carbon emission management is accomplished. These concepts are important when linking mitigation strategies to the science.

Article 6.4 of the Paris Agreement (net-zero by 2050) https://unfccc.int/process-and-meetings/the-paris-agreement/article-64-mechanism is described by the UNFCC as follows:

'Article 6 of the Paris Agreement establishes three approaches for Parties to voluntarily cooperate in achieving their emission reduction targets and adaptation aims set out in their national climate action plans under the Paris Agreement (Nationally Determined Contributions, or NDCs). One of these approaches is through **the Article 6.4 Mechanism, a mechanism "to contribute to the mitigation of greenhouse gas emissions and support sustainable development"** (Paris Agreement, Article 6, paragraph 4).
The Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA), at their third session in Glasgow, adopted Decision 3/CMA.3 containing the rules, modalities and procedures for the mechanism established by Article 6, paragraph 4, of the Paris Agreement ("the mechanism"). **Through this mechanism a company in one country can reduce emissions in that country and have those reductions credited so that it can sell them to**

another company in another country. That second company may use them for complying with its own emission reduction obligations or to help it meet net-zero.
The CMA also designated a 12-member body (Supervisory Body) to supervise the mechanism under the authority and guidance of the CMA and be fully accountable to the CMA.'

15.13.1 Cap-and-trade (carbon allowance, carbon cap, carbon credits, carbon offsets, negative carbon emission, carbon insets)
The maximum net amount of carbon emissions that a particular industrial activity is allowed to produce may be established by a regulatory body (government). This is called the carbon allowance, carbon credit or cap. Penalties are assessed if the cap is exceeded. If an entity is not using all of its allowance it can bank them for use later or sell the excess to another entity which wants to increase their allowance (selling their carbon credits). (See the following web sites for more complete description of a carbon credits;
https://www.investopedia.com/terms/c/carbon_credit.asp and
https://en.wikipedia.org/wiki/Carbon_credit.)

If the entity in need of a higher allowance is unable to purchase additional allowance it might purchase a carbon offset to stay within its allowance. Carbon offsets, also called offset credits, are the amount of reduction in carbon emissions that result from an activity somewhere else which removes carbon from the atmosphere. It is a kind of negative carbon emission. The purchase of a carbon offset has the effect of increasing the purchaser's cap or cancelling some of their carbon emissions. (Tree planting is good example of an activity that produces negative carbon emission or marketable carbon offsets.) Carbon offsets are a type of carbon credit.

The David Suzuki Foundation and the Pembina Institute published a guide for purchasing carbon offsets for Canadian consumers, businesses and organizations, https://davidsuzuki.org/wp-content/uploads/2019/10/purchasing-carbon-offsets-guide-for-canadians.pdf. See https://en.wikipedia.org/wiki/Carbon_offset for full description as to what carbon offsets are, types of projects, accounting and verifying reductions, quality assurance, markets and controversies. Also see https://native.eco/2017/12/carbon-offset-vs-carbon-credit/ , and https://www.edf.org/climate/how-cap-and-trade-works .

Emissions trading (carbon market) is the name given to the activity of selling and purchasing carbon offsets and allowances.

An important discussion on carbon offsets may be found in the article, 'In-depth Q&A 'carbon offsets' help to tackle climate change?' published in the newsletter, Carbon Brief, Daily Briefing, 25/09/2023, https://interactive.carbonbrief.org/carbon-offsets-2023/?utm_source=cbnewsletter&utm_medium=email&utm_term=2023-09-26&utm_campaign=Daily+Briefing+25+09+2023 . The authors address the following questions:

- What are 'carbon offsets?

- What does science say about the need for carbon offsets?
- How are countries using carbon offsets to meet their climate targets?
- How are businesses and organisations using carbon offsets?
- Do carbon offsets overestimate their ability to reduce emissions?
- Why are there 'double-counting' risks with carbon offsets?
- Why is there a risk of greenwashing with carbon offsets?
- Why do carbon-offset projects come with side effects for Indigenous peoples and local communities?
- Could carbon-offsets be put at risk by climate change?
- Is there a way for carbon offsets to be improved?

The same Carbon Brief newsletter also provides articles titled:

- Infographic: How are carbon offsets supposed to work? https://interactive.carbonbrief.org/carbon-offsets-2023/infographic.html .
- Timeline: The 60-year history of carbon offsets, https://interactive.carbonbrief.org/carbon-offsets-2023/timeline.html .
- Glossary: Carbon Brief's guide to the terminology of carbon offsets, https://interactive.carbonbrief.org/carbon-offsets-2023/glossary.html .

Carbon insetting refers to the decarbonizing of their own value chains, https://www.weforum.org/agenda/2022/03/carbon-insetting-vs-offsetting-an-explainer/ . The International Platform for Insetting describes carbon insetting as follows: 'Insetting is a strategic mechanism used to scale effective nature-based solutions, enabling businesses to deliver against ambitious climate and sustainability goals and harmonise their operations with the ecosystems they depend upon.', https://www.insettingplatform.com/insetting-explained/#why-insetting .

15.13.2 Carbon tax

A carbon tax is a fee imposed on any company (particularly the energy, cement and other heavy industry and transportation sectors) that burns fossil fuels and produces carbon emissions. It is based on how much carbon dioxide (or equivalent) they emit. https://www.thebalance.com/carbon-tax-definition-how-it-works-4158043, https://www.carbontax.org/whats-a-carbon-tax/#:~:text=A%20carbon%20tax%20is%20a,destabilizing%20and%20destroying%20our%20climate. The incentive is to consume less fossil fuel or use fossil fuels that produce less carbon dioxide emissions and so pay less tax.

15.13.3 Carbon dividend

A carbon dividend is the distribution of the revenue of the carbon tax over the entire population (equally, on a per-person basis) as a monthly income or regular payment. This is illustrated in Figure 15.37. In this way a carbon tax is said to be revenue neutral.

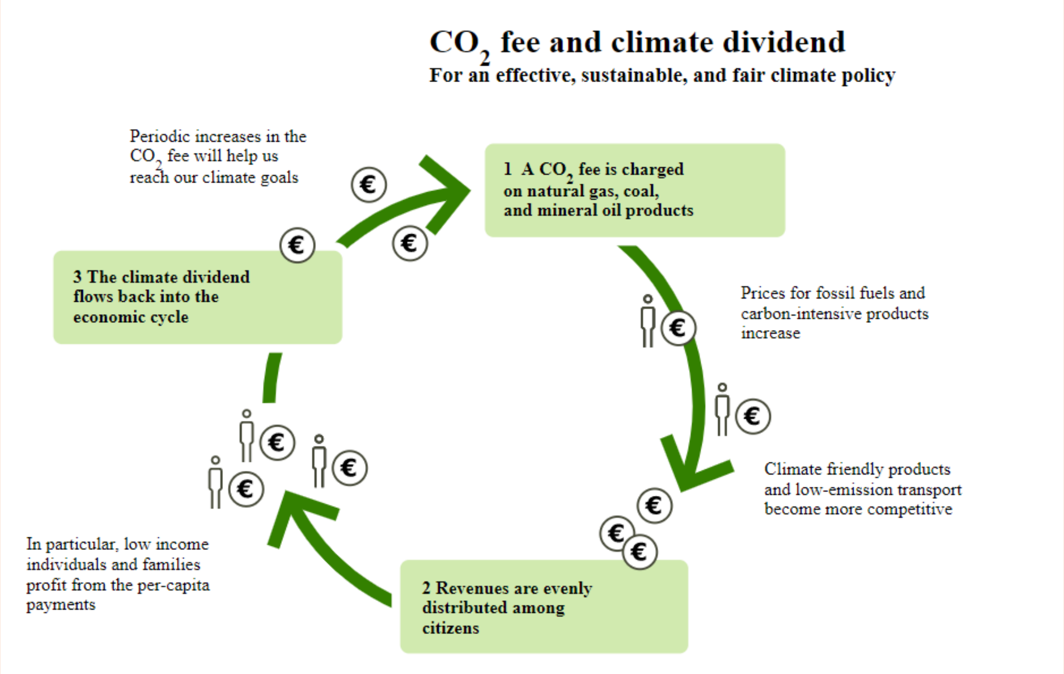


Figure 15.37 Collection of carbon tax and distribution of dividend to population. https://en.wikipedia.org/wiki/Carbon_fee_and_dividend

15.13.4 Carbon leakage

Carbon leakage refers to the situation that may occur if, for reason of costs related to climate policies, businesses were to transfer production to other countries with laxer emission constraints and bring their products back into the national economy. This type of activity could actually lead to an increase in their total emissions.

15.13.5 Carbon tariff

Other names for carbon tariff are; carbon levy, carbon border adjustment, border carbon adjustment, carbon border tariff, embodied carbon tariff, carbon border tax and green border levy.

Carbon tariffs levy a charge on goods crossing the border. While ordinary tariffs are based on the value of a good, carbon tariffs are based on the amount of greenhouse gases emitted during the production of a good; that is, the amount of carbon emissions embedded in the production of the goods. For example, the charge for a tonne of cement would be based on the amount carbon dioxide emitted during its production. The more carbon emissions that tonne of cement has caused, the higher the charge. The purpose is to strengthen domestic carbon pricing and counter the problem of carbon leakage.

It has the effect of countries extending the reach of their domestic carbon regulations; and, it may adversely affect exports from developing countries.

A carbon tariff can also have the effect of increasing the cost of production for goods that require elements that are imported.

The world's first carbon border tariff was initiated October 1, 2023 by the European Union, https://www.reuters.com/business/environment/eu-launches-first-phase-worlds-first-carbon-border-tariff-2023-09-30/?utm_source=cbnewsletter&utm_medium=email&utm_term=2023-10-02&utm_campaign=Daily+Briefing+02+10+2023 .

15.13.6 Carbon pricing

The World Bank, https://www.worldbank.org/en/programs/pricing-carbon, describes carbon pricing as follows: 'Carbon pricing attempts to capture what are known as the external costs of carbon emissions – costs that the public pays for in other ways, such as damage to crops and health care costs from heat waves and droughts or to property from flooding and sea level rise – and tie them to their sources through the price of carbon.' This is also known as the 'social price of carbon'.

A price on carbon helps shift the burden for the damage back to those who are responsible for it, and who can reduce it. Instead of dictating who should reduce emissions where and how, a carbon price gives an economic signal and polluter decide for themselves whether to discontinue their polluting activity, reduce emissions, or continue polluting and pay for it. In this way, the overall environmental goal is achieved in the most flexible and least-cost way to society. The carbon price also stimulates clean technology and market innovation, fueling new, low-carbon driver of economic growth.

Carbon (carbon dioxide emissions) pricing is a key element in cap-and-trade systems where the price the carbon is determined by the market (carbon cap and carbon offset trading) and of carbon tax and dividend initiatives.

15.13.7 Avoided emissions

Avoided emissions are emission reductions that occur outside of a product's life cycle or value chain, but as a result of the use of that product. This is explained very well on the Mission Innovation website, http://mission-innovation.net/1-5-degree-compatibility-framework/ as follows: The 1.5 C Compatibility Initiative is aligned with Mission Innovation's Delivering the Action Plan 2018-2020 and aims to support efforts to limit the global temperature increase to 1.5 degrees Celsius, as per the Paris Agreement and the IPCC 1.5 C special report. This includes the development of an avoided emissions framework that provides guidance for how to quantify the potential for clean energy innovations to reduce emissions in society.

It supports investors and funders to identify those system solutions and technologies that have significant ability or potential to contribute to reduced greenhouse gas (GHG) emissions in society, so called “avoided emissions”.

To accelerate emission reductions, companies cannot only be driven by cost and risk reductions, but must also use their capacity for innovation to deliver the solutions that we need. Hence, solutions providers need the tools and credibility to be able to demonstrate their positive impacts in society. The framework is developing, implementing and launching an initial set of tools to achieve this aim.

The framework is supporting an accelerated uptake of disruptive solutions by supporting increased transparency regarding actual and potential GHG reductions, making it easier to identify, support and invest in the next generation of solution providers.
For example, Company A manufactures a product to perform a certain function. Other products on the market use much more energy to perform the same function. Company A can claim the energy savings resulting from the use of their product in the form of avoided emissions.

The World Resources Institute, the International Energy Agency and the International Renewable Energy Agency provide additional information as how avoided emissions are determined. See https://ghgprotocol.org/estimating-and-reporting-avoided-emissions, https://www.iea.org/data-and-statistics/charts/change-in-global-energy-related-co2-emissions-and-avoided-emissions-2018-compared-to-2019-3 and https://www.irena.org/.
The International Renewable Energy Agency also provides a method for calculating avoided emissions, https://www.irena.org/climatechange/Avoided-Emissions-Calculator
Avoided emissions should not be confused with carbon offsets though they can be used in a similar way.

15.13.8 Renewable energy certificates
Investopedia (https://www.investopedia.com/terms/r/rec.asp) describes a renewable energy certificate or REC as follows:
‘Renewable Energy Certificates (RECs) are a market-based instrument that certifies the bearer owns one megawatt-hour (MWh) of electricity generated from a renewable energy resource. Once the power provider has fed the energy into the grid, the REC received can then be sold on the open market as an energy commodity. RECs earned may be sold, for example, to other entities that are polluting as a carbon credit to offset their emissions.’

RECs can go by other names, including Green Tags, Tradable Renewable Certificates (TRCs), Renewable Electricity Certificates, or Renewable Energy Credits.

An REC is a tradable market-based instrument that represents the property rights to the environmental, social and other non-power attributes of renewable electricity generation. RECs are issued when one megawatt-hour of electricity is generated and delivered to the electricity grid from a renewable energy resource. RECs can be sold separately from the physical electricity that it is associated with.

A good description of an REC is provided by Call Me Power on their web site, https://callmepower.ca/en/faq/renewable-energy-certificates-rec. RECs are certified and tracked by a third party such as the Canadian EcoLogo in https://callmepower.ca/en/faq/ecolabel .

Utilities Consumer Advocate explains how they are used in Alberta, Canada on their web site, https://ucahelps.alberta.ca/Green_Energy_Plans_Explained.aspx

15.14 Net-zero by 2050 objective and committed warming

The concepts of 'net zero' and 'committed warming' are actually part of the discussion of emission scenarios, namely, representative concentration pathways, (RCPs) which may be found in Section 18.2 and shared socio-economic pathways, (SSPs) which may be found in Section 21.3. The outcomes of following these emission scenarios are determined using various climate change models. The net zero objective is different in that it is simply the emission target for 2050. There is no attempt to describe the emission pathway to achieve this except to note that if this objective is achieved, the global temperature in year 2050 will not increase. (Intermediate emission targets for 2030 are encouraged to help ensure that the 2050 target can be achieved.) This has caused some confusion with all parties, governments at all levels, businesses and all other human activities who seem to be left to their own resources as to how they will achieve this objective (not quite true since governments at all levels are closely involved providing guidelines and incentives). The net zero objective is quite simple though and all parties are expected to achieve the objective independently following their own pathway. All stakeholders (parties) must be conversant in all aspects of greenhouse gas emissions as it relates to their activities and responsibilities. Their progress is reported and collated at a national level and so their success in achieving the 2050 objective can be monitored. A brief discussion of net zero and committed warming follows.

The UNFCC Paris Agreement (https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement), adopted by 196 Parties at COP21 in Paris on December 12 2015 and entered into force on November 4, 2016 committed the Parties (countries) to reducing their GHG emissions sufficiently to limit global warming to well below 2 °C. and preferably 1.5°C.

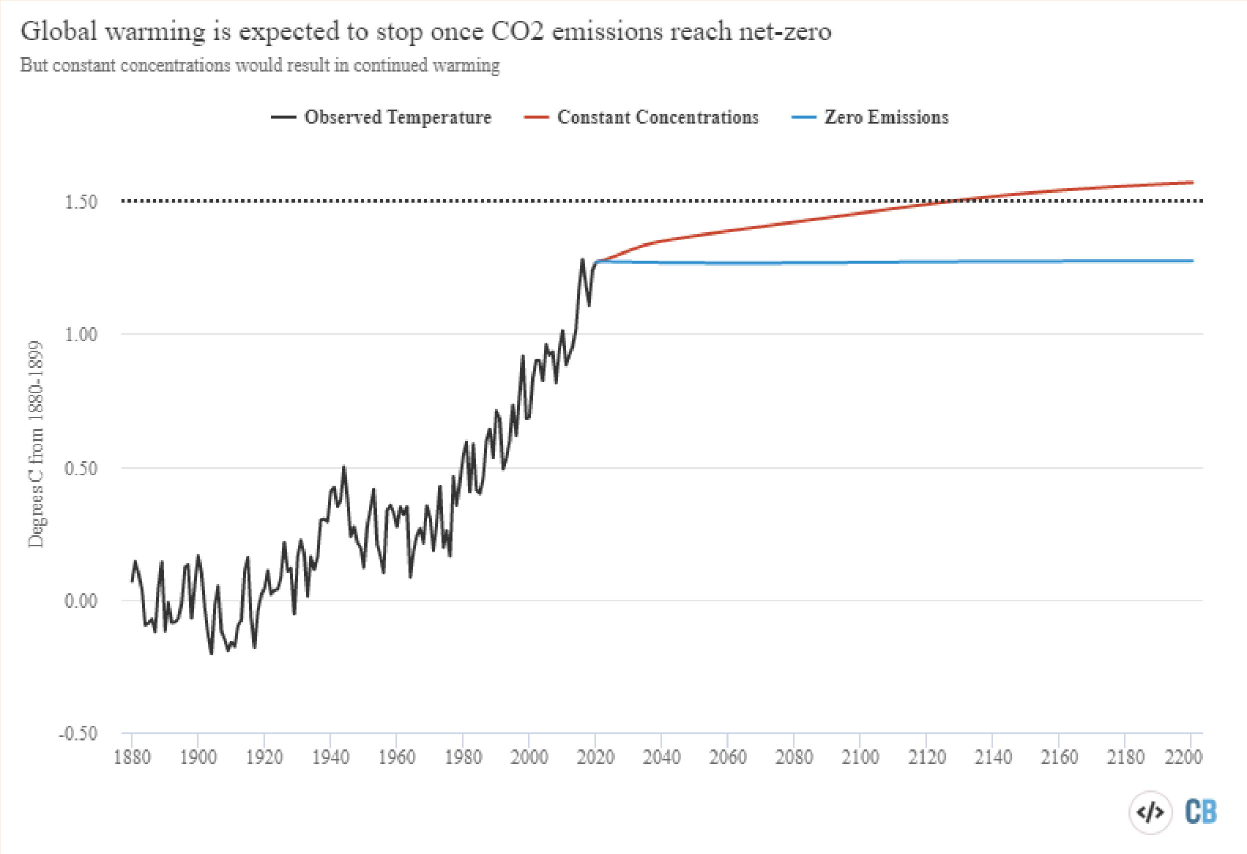
The IPCC Special Report, Global Warming of 1.5 °C, outlines the impacts of global warming above this temperature and the pathways with which this may be achieved https://www.ipcc.ch/sr15/. The pathways with which the 1.5°C objective for 2100 can be achieved is discussed in the In-depth Q&A article in Carbon Brief 08.10.2018 https://www.carbonbrief.org/in-depth-qa-ipccs-special-report-on-climate-change-at-one-point-five-c . Some involve 'over-shoot' of warming before 2100 but achieve 1.5°C by 2100 and others that do not over-shoot the temperature objective before 2100. Only those scenarios which did not over-shoot were considered acceptable; that is, aligned with the Paris Agreement's real objective of 1.5°C limit for 2100.

The 'net-zero' emission objective is the commitment by all countries to net-zero CO2 emissions by 2050. If this were achieved the global temperature at 2050 would gradually decrease from this year forward. The underlying hope is that the global temperature in 2050 will be less than 2°C and close to 1.5°C.
The 'Explainer article' in the newsletter, Carbon Brief, by Zeke Hausfather, 29.04.2021 that 'The best available evidence shows that – warming is likely to more or less stop, that is, no over-shoot, once carbon dioxide emissions reach zero', https://www.carbonbrief.org/explainer-will-global-warming-stop-as-soon-as-net-zero-emissions-are-reached?utm_campaign=Daily%20Briefing&utm_content=20220224&utm_medium=email&utm_source=Revue%20newsletter.

The author explains the difference in surface temperature between scenarios which maintain a constant concentration of CO2 and the effect of achieving net-zero. This is illustrated in Figure 15.38. Additional warming would occur, (over-shoot), if the concentration of CO2 was held constant after 2050, that is until the concentrations of CO2 in the atmosphere, land and the ocean achieved equilibrium.

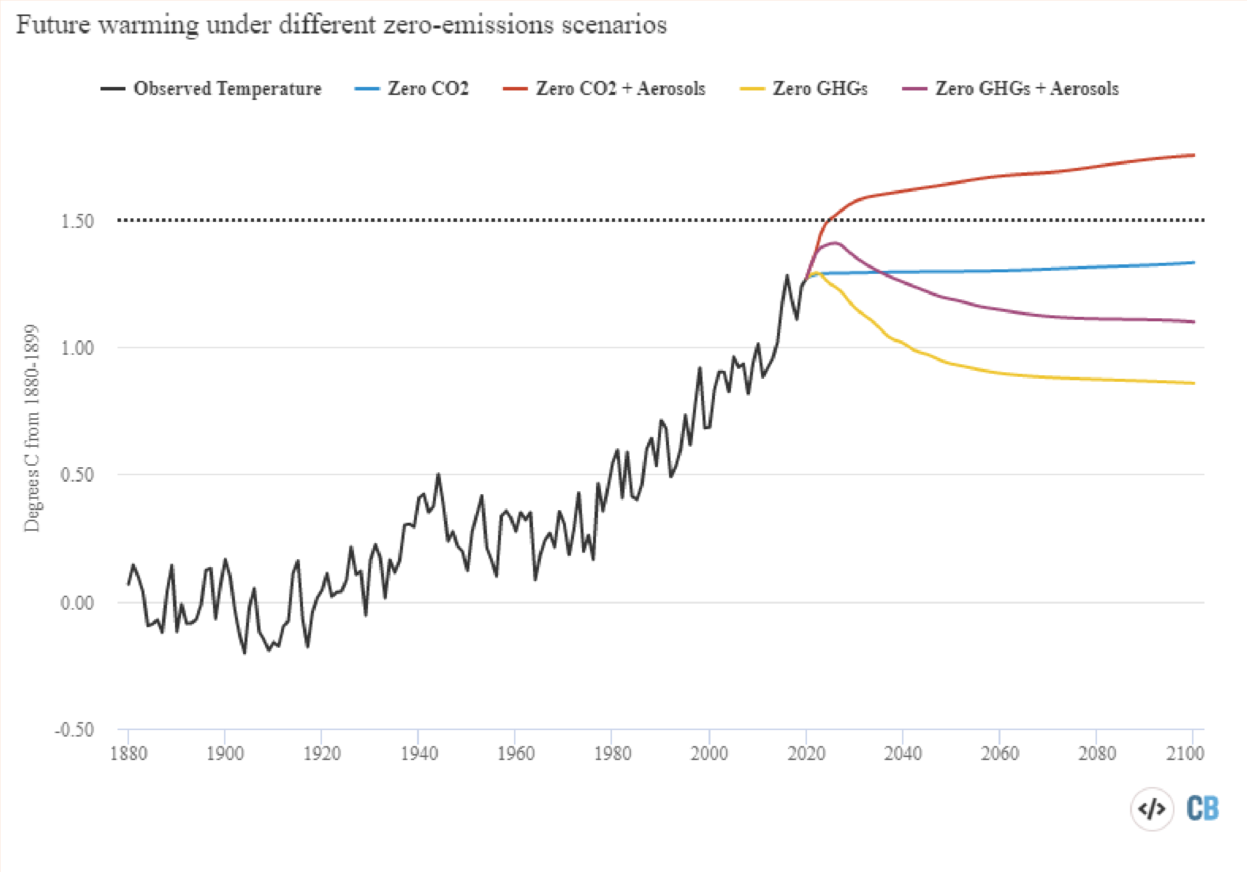
If CO2 emissions decreased as per the net-zero emission scenario, the concentration of CO2 in the atmosphere would decrease as a result of the CO2 loss to the land and oceans.
It is interesting to note that the IPCC 1.5°C objective for 2100, https://www.ipcc.ch/sr15/, can be achieved in a variety of other ways as discussed in the In-depth Q&A article in Carbon Brief 08.10.2018 https://www.carbonbrief.org/in-depth-qa-ipccs-special-report-on-climate-change-at-one-point-five-c that involve 'over-shoot' of warming before 2100 but achieve 1.5°C by 2100 and those that do not over-shoot the temperature objective before 2100. See Figure 15.39. Only those scenarios which did not over-shoot were considered acceptable; that is, aligned with the Paris Agreement's 1.5°C limit for 2100.

It is important to emphasize that net-zero CO2 will likely achieve the IPCC 1.5°C objective for 2100. The success of net-zero was determined using the models discussed in Chapter 17. The ways with which net-zero can be achieved are determined by individual governments.



Projected future warming under constant concentrations (red line) and zero-emissions scenarios (blue). Historical warming based on an average of NASA, NOAA, Berkeley, Cowtan and Way and Hadley/UEA records (black). Future warming adapted from model runs in Matthews and Weaver 2010. Model runs are combined with historical temperatures based on a 30-year local regression. Chart by Carbon Brief using Highcharts.

Figure 15.38 Committed temperature increases under the constant concentration scenario of CO2 in the atmosphere and the zero emissions scenario https://www.carbonbrief.org/explainer-will-global-warming-stop-as-soon-as-net-zero-emissions-are-reached?utm_campaign=Daily%20Briefing&utm_content=20220224&utm_medium=email&utm_source=Revue%20newsletter.



Projected global surface temperature changes under zero CO2 emissions (blue line), zero CO2 and aerosol emissions (red), zero GHG emissions (yellow) and zero GHG and aerosol emissions (purple). Chart by Carbon Brief using Highcharts, adapted from Figure 1.5 in the IPCC SR15. Historical warming values (black) and combination with model simulations are estimated using the methods described in the first figure.

Figure 15.39 Temperature increases under zero emission scenarios: zero CO_2 (no change in other GHGs or aerosols), zero CO_2 and aerosols, zero GHGs (no change in aerosols) and zero GHGs and aerosols https://www.carbonbrief.org/explainer-will-global-warming-stop-as-soon-as-net-zero-emissions-are-reached?utm_campaign=Daily%20Briefing&utm_content=20220224&utm_medium=email&utm_source=Revue%20newsletter.

15.15 Super pollutant concept

Super pollutants are discussed in the web site, https://www.americanprogress.org/article/super-pollutants-101/ . They are also known as short-lived climate pollutants, or forcers. They are potent noncarbon-dioxide global warming contaminants the most important of which are; black carbon, methane and hydrofluorocarbons or HFCs. While these super pollutants have a global warming potential much greater than CO_2, they lose their warming power relatively quickly after being emitted. This is summarized in Table 15.13.   Consider that half of carbon dioxide emitted will continue to cause increased temperatures for 50 to 100 years and 20 per cent that remains will cause temperature increases for thousands of years.

Global warming potential, lifetime, and primary source of super pollutants

Super Pollutant	Global warming potential (100-year)	Lifetime in atmosphere	Primary source
Methane	21	12 years	Agriculture, mobile sources, electricity generation
Black carbon, or soot	330-2,240	Days to weeks	Incomplete combustion of fossil fuels, biofuels, biomass
Hydrofluorocarbons, or HFCs	140-11,700	15 years on average	Substitution of ODS, electricity generation

Source: U.S. Environmental Protection Agency.

Table 15.13 Global warming potential, lifetime and primary source of super pollutants, https://www.americanprogress.org/article/super-pollutants-101/

The immediate reduction or elimination of super pollutants would provide rapid relief from extreme climate-related impacts compared to the time-line of the relief achieved by reducing carbon dioxide.

The argument is made that that the sources of the super pollutants are known and are controllable compared to carbon dioxide. The recommendation made is to immediately take steps to reduce release of super pollutants and so ‘accomplish the following: quickly decrease global warming pollution; limit temperature increase caused by climate forcers; improve health impacts caused b soot and extreme heat conditions; improve global annual crop yields; and buy some time on passing the 2-degree Celsius threshold.’

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15.16 Immortal pollutants

Immortal pollutants are greenhouse gas chemicals which have a very large global warming potential and remain in the atmosphere for up to 50,000 years https://insideclimatenews.org/news/21092022/epa-immortal-chemicals/

The immortal pollutants are a class of fluorinated gases that include the man-made chemicals, sulfur hexafluoride, tetrafluoromethane and hexafluoroethane. The collective emissions are small but because of their long atmospheric lifetimes, the emissions add up. Fortunately, it is reasonable to enact regulations to eliminate their manufacture and use.

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