January 18, 2021

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

Chapter 15
Greenhouse Gases

David H. Manz
PhD., P. Eng., AOE, FCAE
2020

Eco-print, “Ivy”, Nora Manz 2020

Table of Contents

List of Figures

Figure 15.6 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 15.7 Concentration of GHG's from 0 to 2005.
https://www.canr.msu.edu/resources/greenhouse_gas_basics_e3148

Figure 15.8 Global manmade greenhouse gas emissions by sector, 2013.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions.

Figure 15.9 Greenhouse gas emissions by sector, U. S., 1990-2014.
https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014.

Figure 15.10 Detailed global emissions by sector.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

Figure 15.11 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.

Figure 15.12 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 15.13 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 15.14 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 15.15 Per capita emissions for different income brackets.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

Figure 15.16 Per capita GHG emissions by country from IPCC.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

Figure 15.17 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 15.18 Greenhouse gas intensity for cross-section of countries.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

Figure 15.19 Land and ocean-based sampling of GHG's, ozone, and aerosols.
https://www.esrl.noaa.gov/gmd/dv/iadv/index.php?code=mlo

Figure 15.20 Aircraft GHG sampling program operated by NOAA.
http://www.esrl.noaa.gov/gmd/ccgg/aircraft/

Figure 15.21 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

Figure 15.22 NASA Orbiting Carbon Observatory-2.
https://www.nasa.gov/mission_pages/oco2/index.html

Figure 15.23 Averaged carbon dioxide concentration Oct 1 – Nov 11, 2014 from OCO-2.
https://www.nasa.gov/jpl/oco2/pia18934

Figure 15.24 Carbon monoxide measurements from NASA's Atmospheric Infrared Sounder (AIRS).
https://climate.nasa.gov/news/3019/nasa-monitors-carbon-monoxide-from-california-wildfires/

Figure 15.25 Geostationary carbon cycle observatory, EVM-2, GeoCarb.
https://eospso.nasa.gov/missions/geostationary-carbon-cycle-observatory-evm-2

Figure 15.26 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 15.27 NASA Methane source model. https://climate.nasa.gov/news/2961/new-3d-view-of-methane-tracks-sources-and-movement-around-the-globe/

Figure 15.28 Global methane emissions monitoring.

https://www.ghgsat.com/

Figure 15.29 Global-average radiative forcing estimates and ranges – AR5.
https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf

Chapter 15.0 Greenhouse Gases

15.1 Introduction

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. 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. The significant role carbon dioxide and all of the other greenhouse gases (GHG's) is beginning to play in shaping Earth's climate is fully realized. 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 on a continuous basis. This information is critical to numerical modelling of climate change and also to pinpoint opportunities to control GHG emissions.

Figure 4.5, shown below, illustrates the global energy budget and the importance of greenhouse gases (GHG's). 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, GHG's are ultimately responsible for a warmer terrestrial and atmospheric environment on Earth.

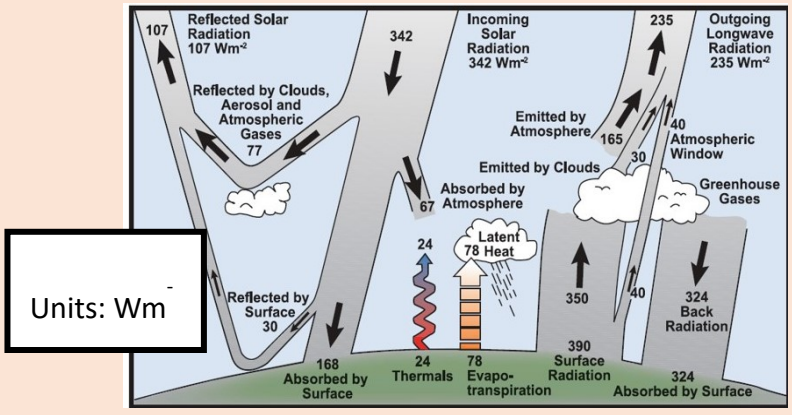


Figure 4.5 Global Energy Budget taken from
http://climateknowledge.org/figures/Rood_Climate_Change_AOSS480_Documents/Kiehl_Trenberth_Radiative_Balance_BAMS_1997.pdf

The concentration of GHG's has increased steadily since 1958 when atmospheric carbon dioxide measurements were taken at Mauna Loa Observatory in Hawaii by C. David Keeling of the Scripps Institution of Oceanography, Figure 15.1. The National Oceanic and Atmospheric Administration (NOAA) began taking measurements 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. 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.

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

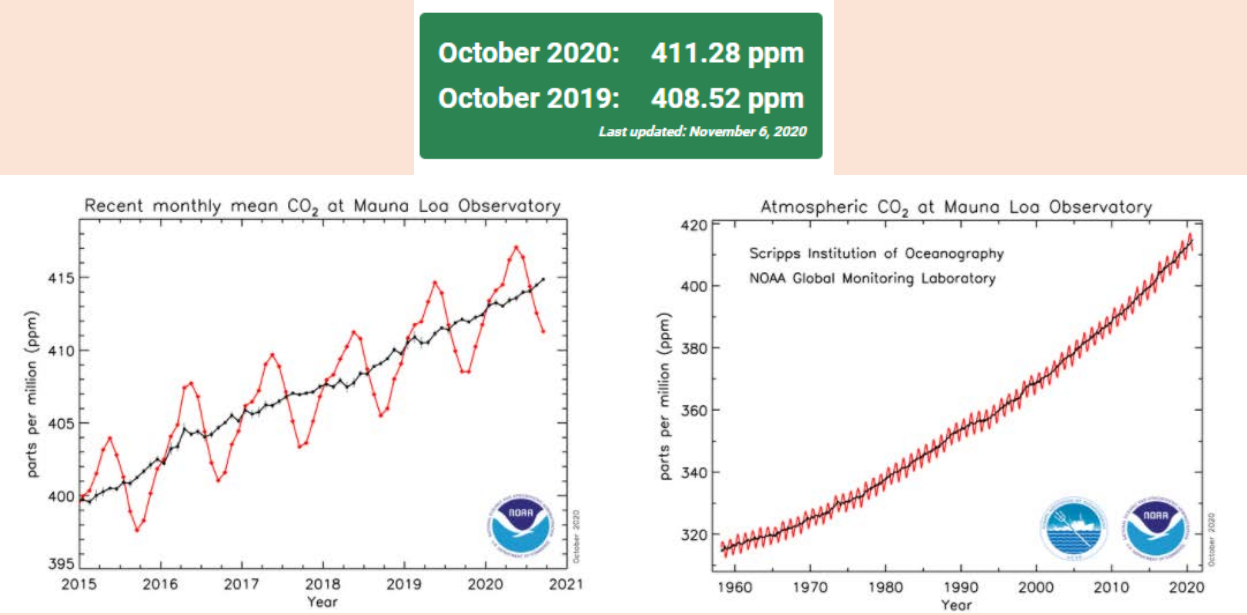


Figure 15.1 The Keeling Curve, monthly mean carbon dioxide measured at Mauna Loa Observatory, Hawaii. https://www.esrl.noaa.gov/gmd/ccgg/trends/

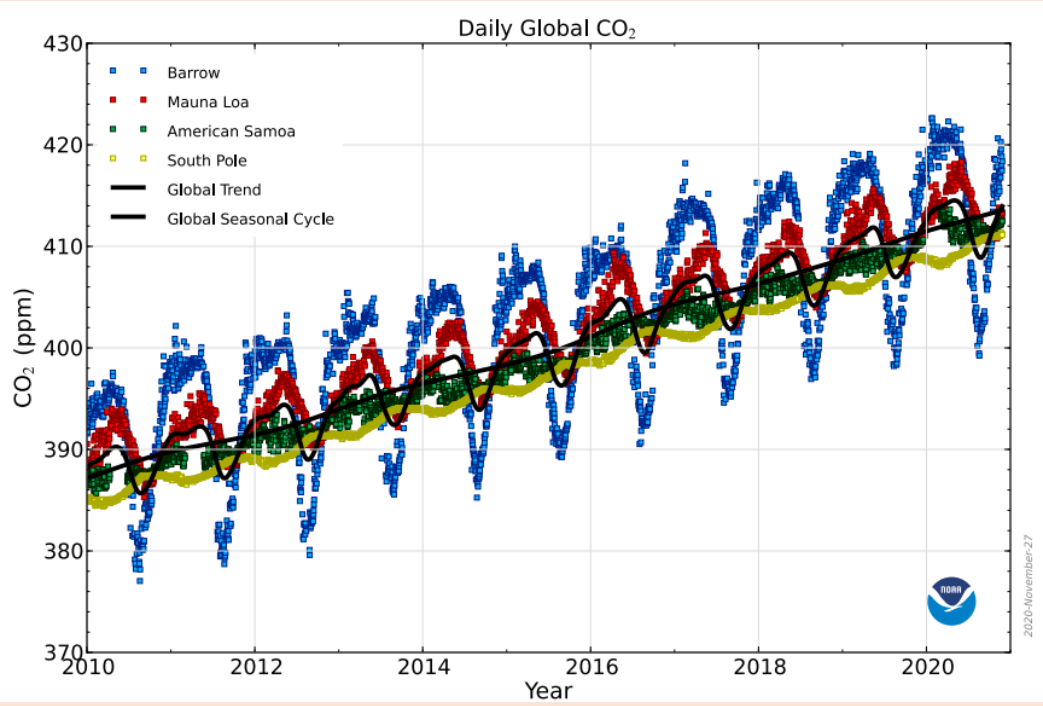


Figure 15.2 Daily averaged carbon dioxide concentration measured at Barrow, Alaska, Mauna Loa, Hawaii, American Samoa and South Pole, Antarctica.
https://www.esrl.noaa.gov/gmd/ccgg/trends/gl_trend.html

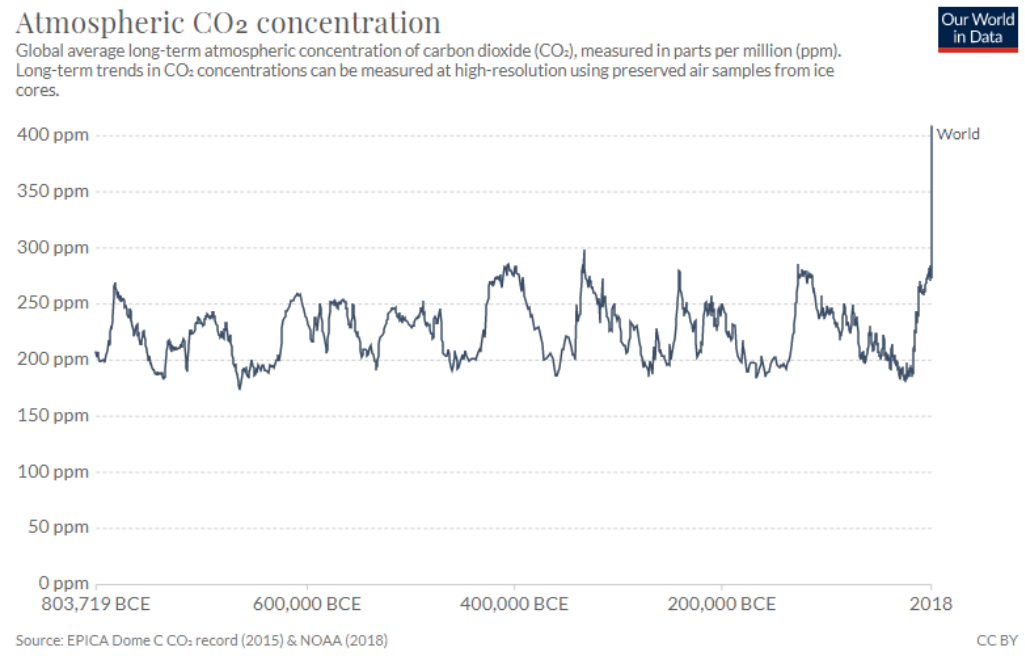


Figure 15.3 Atmospheric carbon dioxide concentration in ice cores taken from the Antarctic ice sheet. https://ourworldindata.org/atmospheric-concentrations and https://www.esrl.noaa.gov/gmd/ccgg/trends/

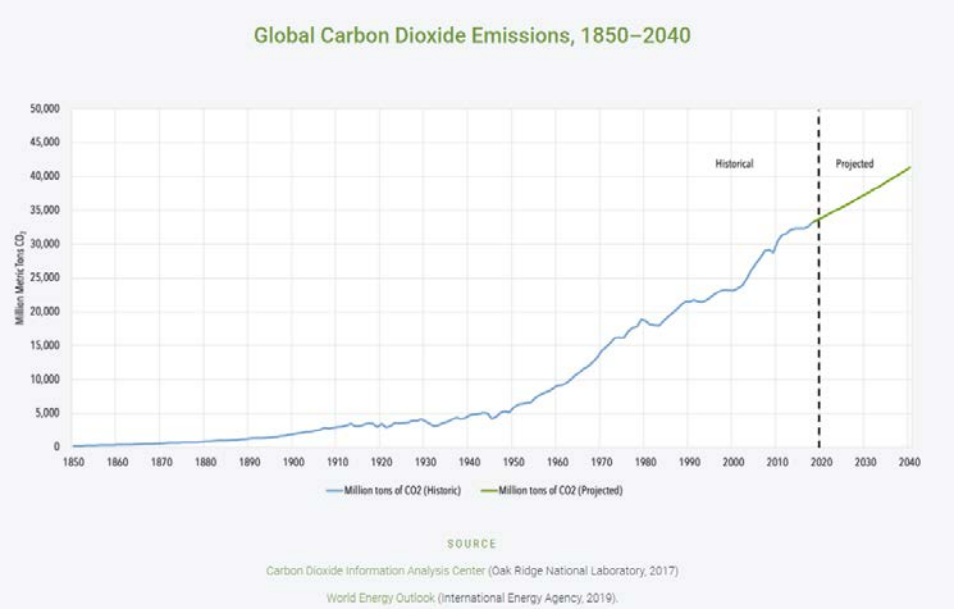


Figure 15.4 Global carbon dioxide emissions, 1850 to 2040. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions.

15.2 Types of greenhouse gas emissions.

The principle GHG's (except for water) emitted in the United States for 2018 by gas are shown in Figure 15.5. Similar global emissions breakdown for 2015 is shown in Figure 15.6. 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, used 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.).

Water vapour is the primary greenhouse gas in Earth's atmosphere, approximately two to three times carbon dioxide. The difference between water vapour and the other greenhouse gases is that when the atmosphere cools water vapour condenses into water droplets or ice particles and precipitates. Water vapour does not accumulate in the atmosphere. All of the other GHG's do. Note that anthropogenic sources of water vapour are negligible compared to natural evaporation and evapotranspiration.

Figure 15.7 shows how the concentration of the various GHG's have changed over the past two thousand years. The dramatic increases coincide with the beginning of the industrial revolution in the mid nineteenth century.

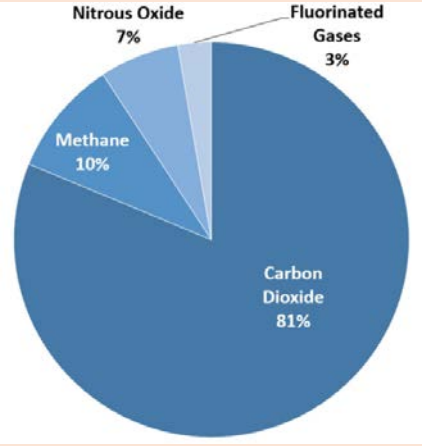


Figure 15.5 Emissions of GHG's in 2018 in the U. S. by gas.
https://www.epa.gov/ghgemissions/overview-greenhouse-gases

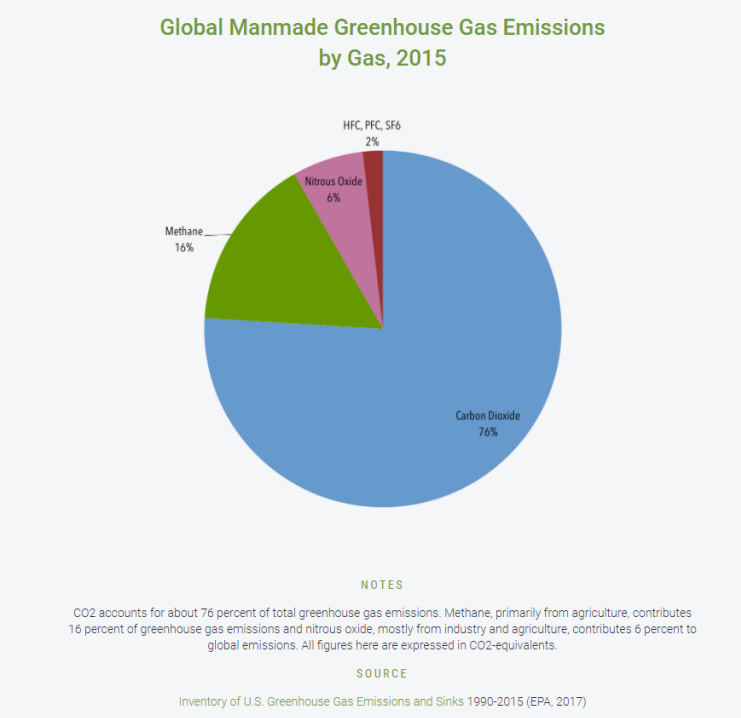


Figure 15.6 Global manmade greenhouse gas emissions by gas, 2015.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

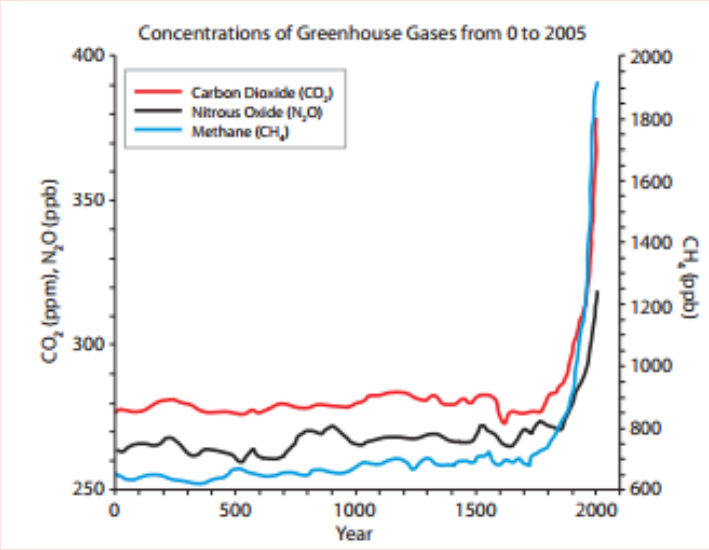


Figure 15.7 Concentration of GHG's from 0 to 2005.
https://www.canr.msu.edu/resources/greenhouse_gas_basics_e3148

15.3 Greenhouse gas emissions by sector

Global emissions of GHG's by sector are shown in Figure 15.8. Figure 15.9 shows similar information for the United States. Figure 15.10 shows detailed global emissions by sector. Details for the United States are typical for advanced western economies. This information is essential when establishing mitigation programs as discussed in Chapter 20.

All countries collect this information according to 2006 IPCC Guidelines for National Greenhouse Gas Inventories which are updated periodically, the most recent being 2019 (https://www.ipcc-nggip.iges.or.jp/index.html). This information is then provided to the United Nations Framework Convention on Climate Change, UNFCCC.

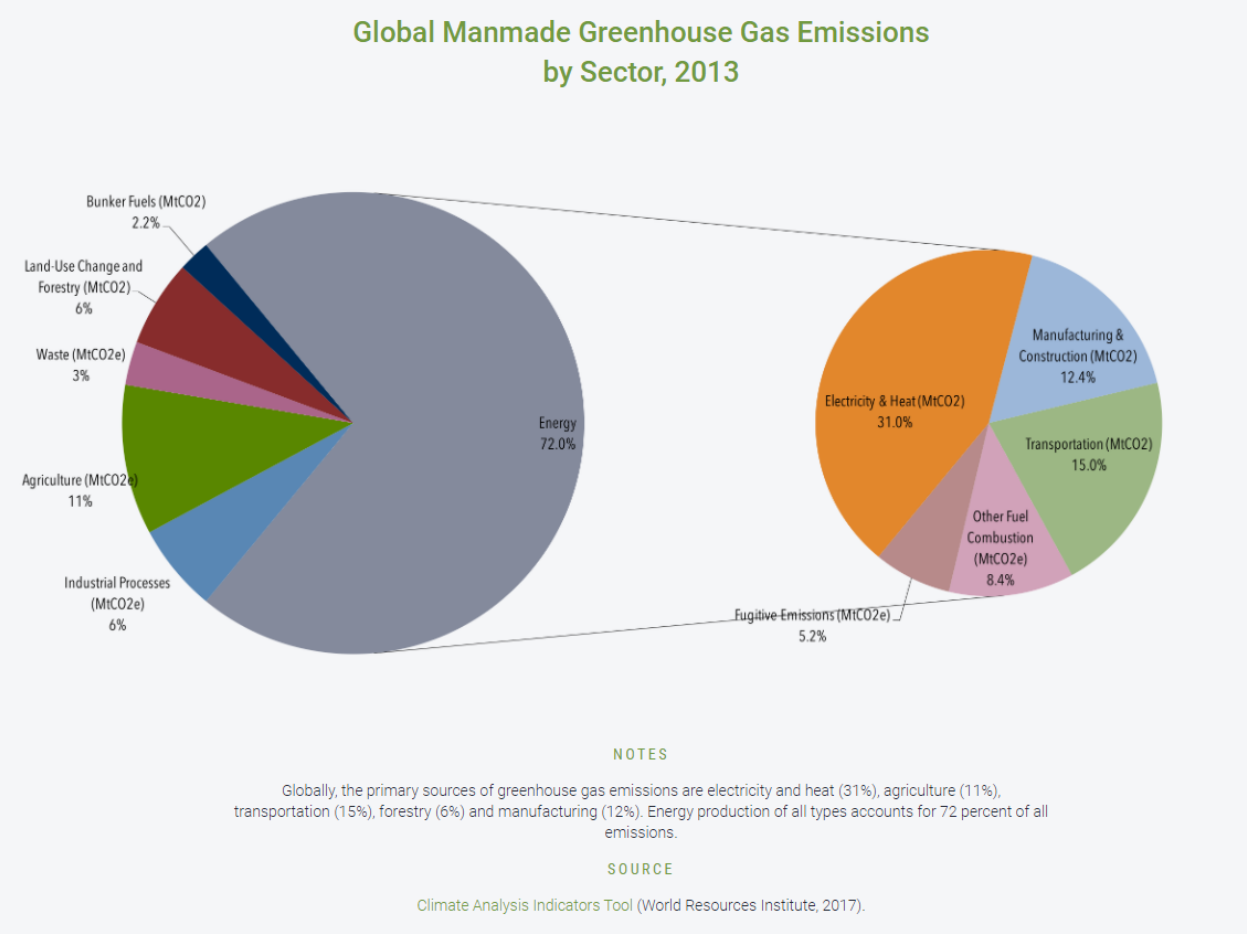


Figure 15.8 Global manmade greenhouse gas emissions by sector, 2013. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

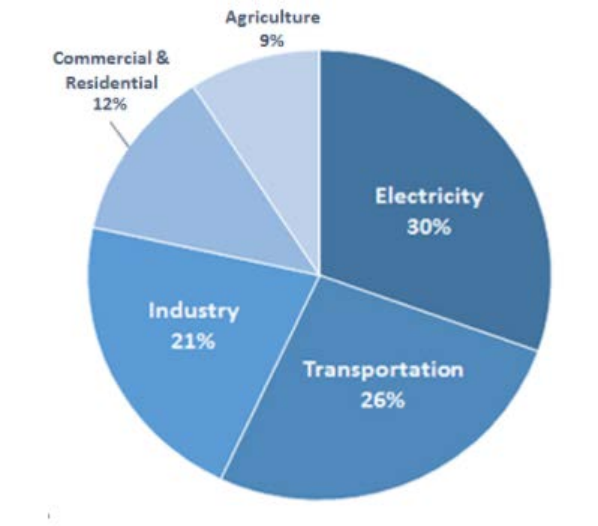


Figure 15.9 Greenhouse gas emissions by sector, U. S., 1990-2014.
https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014

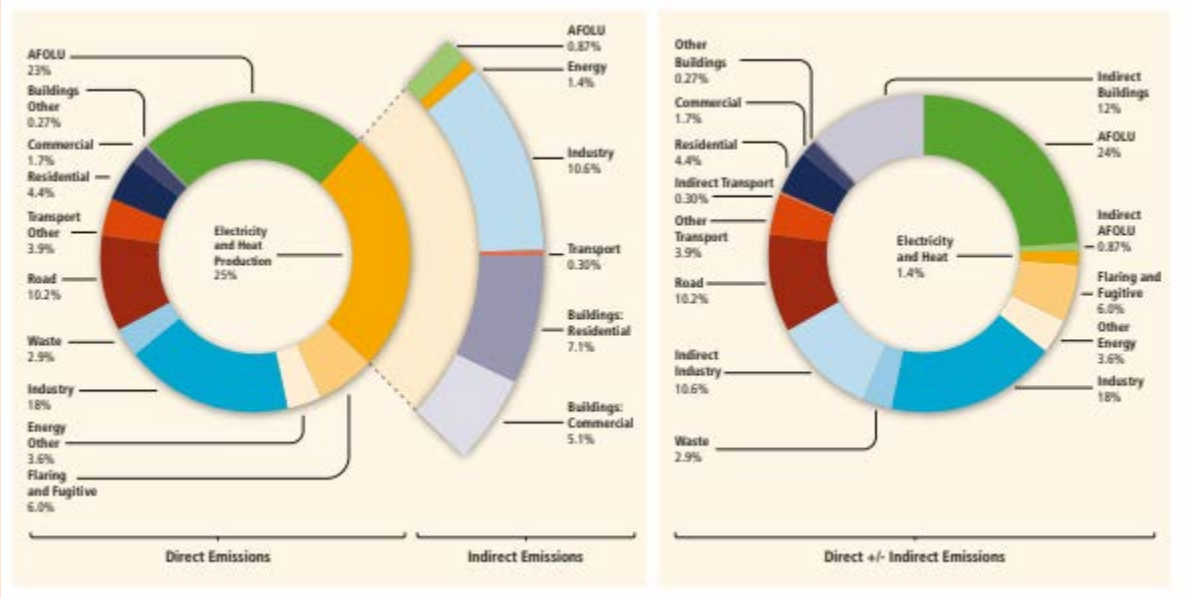


Figure 15.10 Detailed global emissions by sector.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

15.4 Greenhouse gas emissions by country

It is very important to know which countries 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 15.11.

Greenhouse gas emissions for the top emitters is shown in Figure 15.12. These emitters account for most of GHG emissions. Cumulative GHG emissions from these emitters is shown in Figure 15.13. Comparison of Figure 15. 12 and 15.13 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 15.14. This figure reflects standard of living. The difference between the lower income population and the high-income population is highlighted in Figure 15.15. Figure 15.16 shows the per capita GHG emissions by country. Aspects such as climate and affluence are reflected.

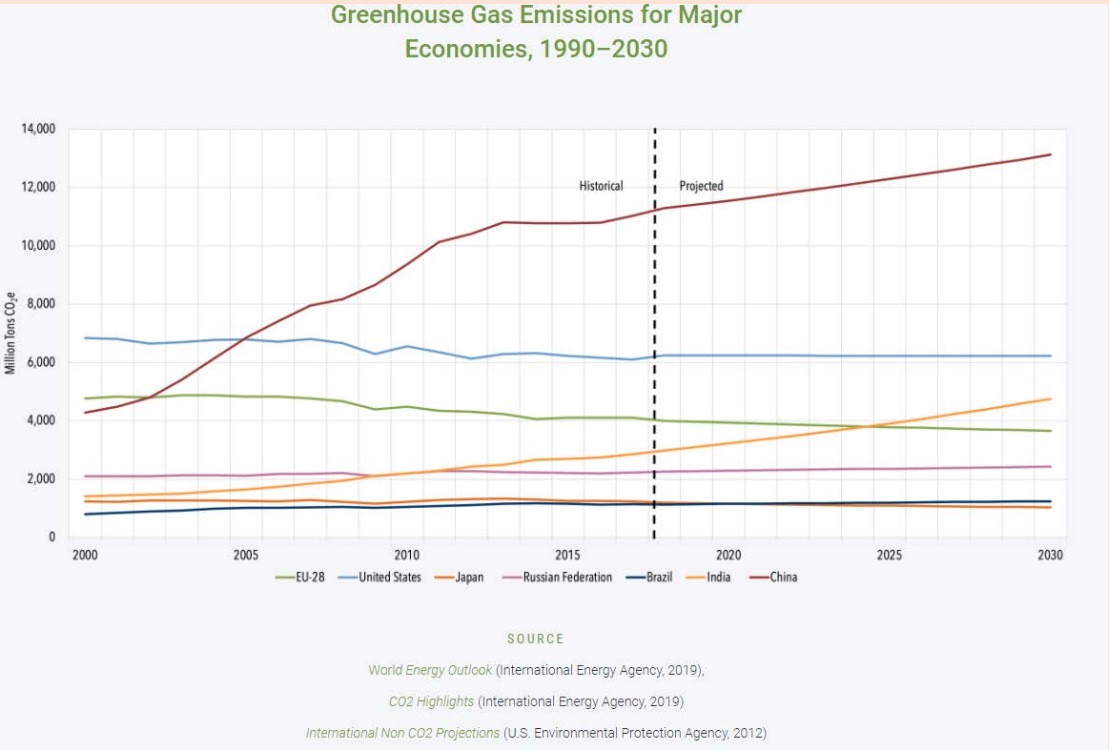


Figure 15.10 Greenhouse gas emissions for major economies, 1990-2030. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

Greenhouse gas intensity for the major economies and the world is shown in Figure 15.17. 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 15.18 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.

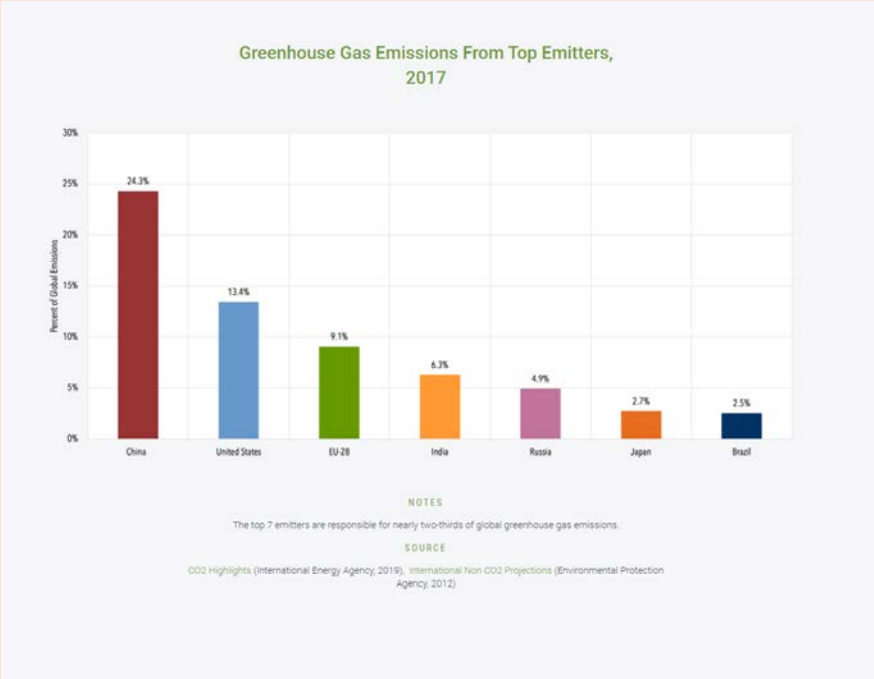


Figure 15.12 Greenhouse gas emissions for top emitters, 2017.
https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

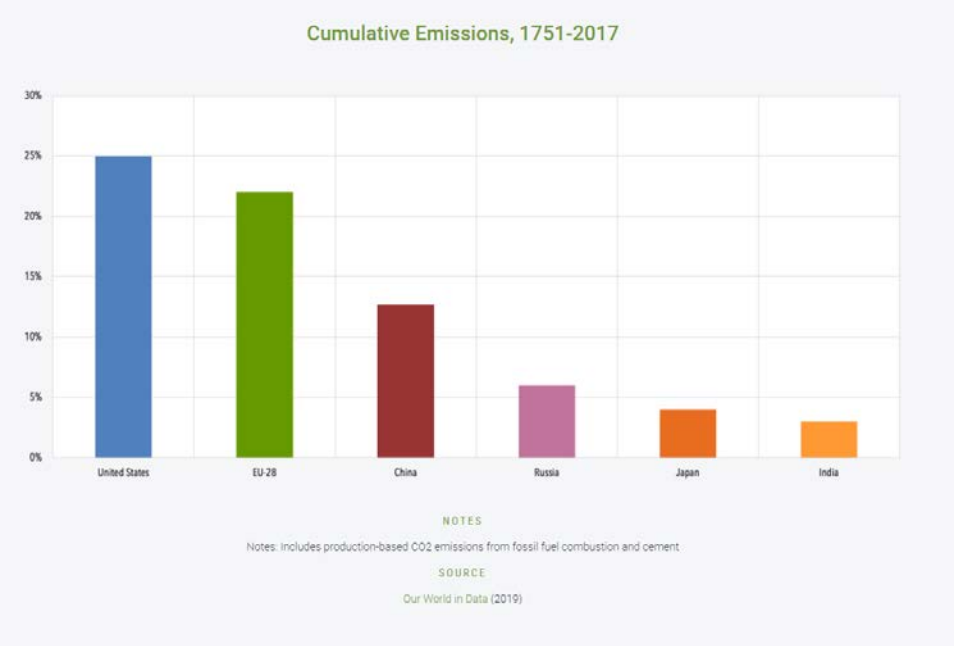


Figure 15.13 Cumulative greenhouse gas emissions for major economies, 1751-20172. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

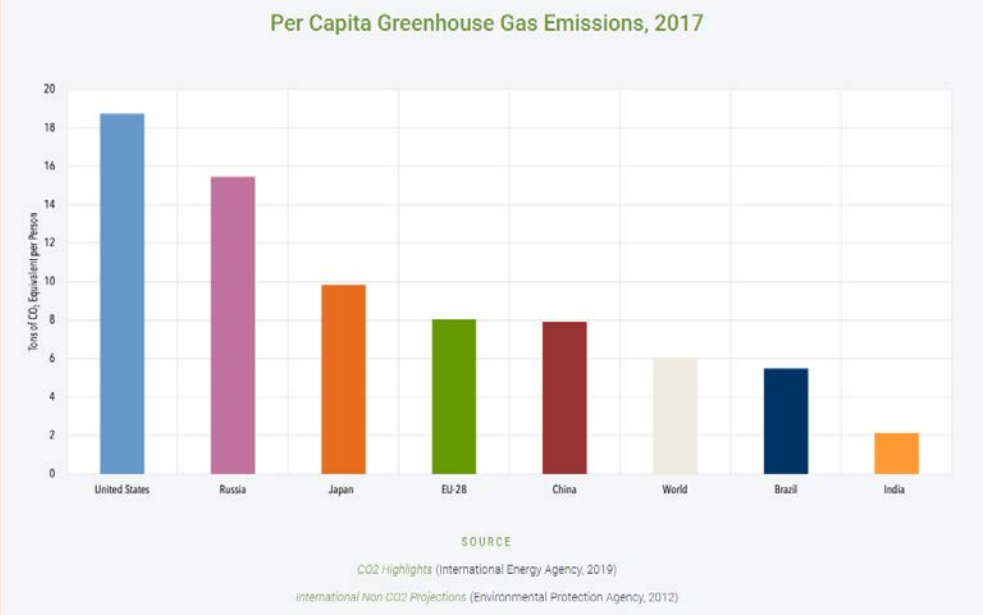


Figure 15.14 Per Capita greenhouse gas emissions for major economies, and the world, 2017. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

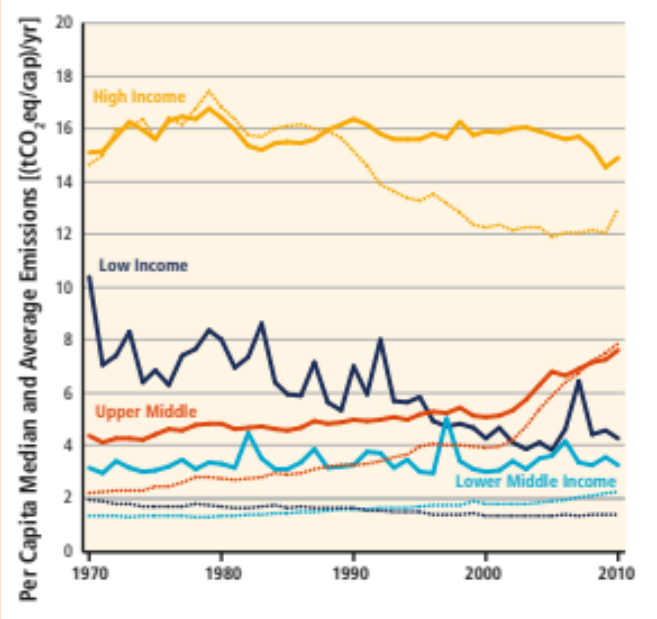


Figure 15.15 Per capita emissions for different income brackets.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

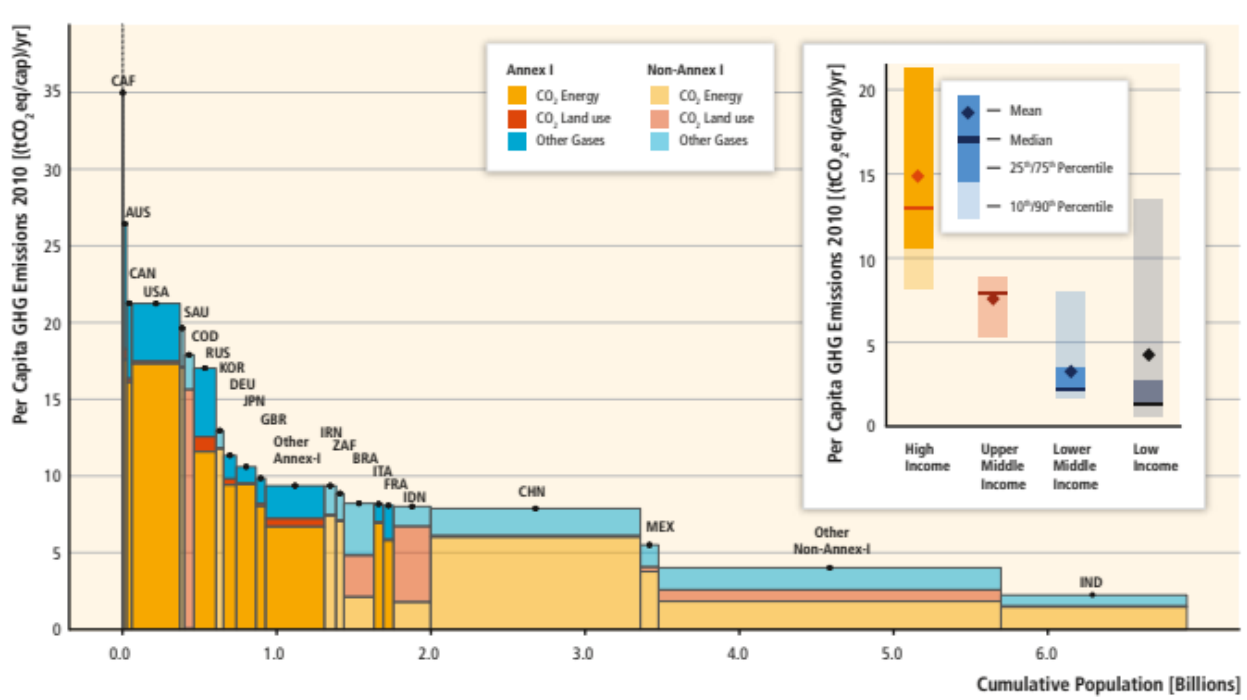


Figure 15.16 Per capita GHG emissions by country from IPCC.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

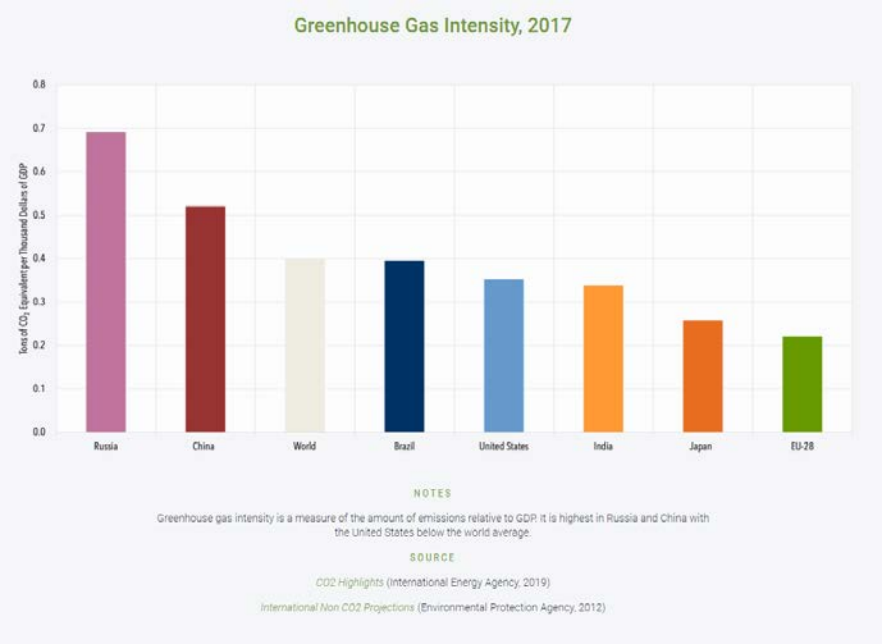


Figure 15.17 Greenhouse gas intensity for major economies and the World, 2017. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions

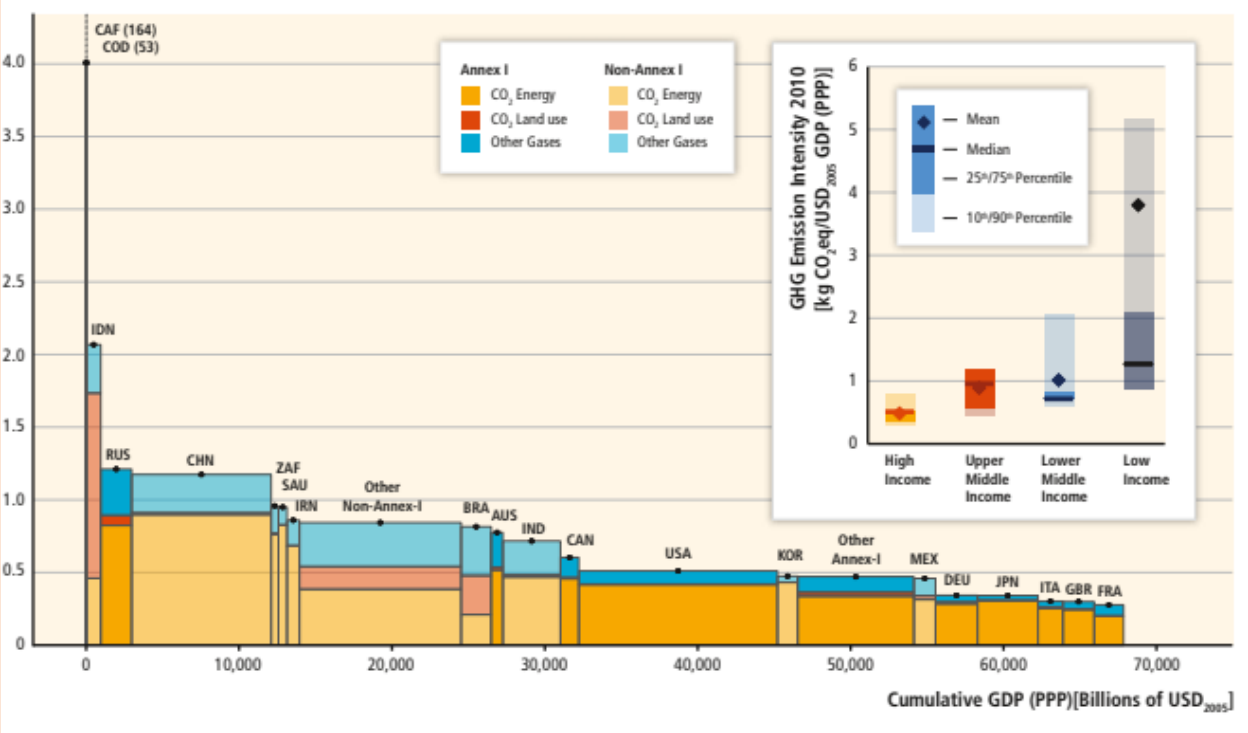


Figure 15.18 Greenhouse gas intensity for cross-section of countries.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

15.5 Collection of greenhouse gas data

Information on 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 modelling and mitigation.

15.5.1 Land and ocean-based monitoring and sampling
Figure 15.19 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 .

15.5.2 Aircraft GHG sampling
Figure 15.20 show the aircraft GHG sampling program. See NOAA web site for most up-to-date information, http://www.esrl.noaa.gov/gmd/ccgg/aircraft/ .

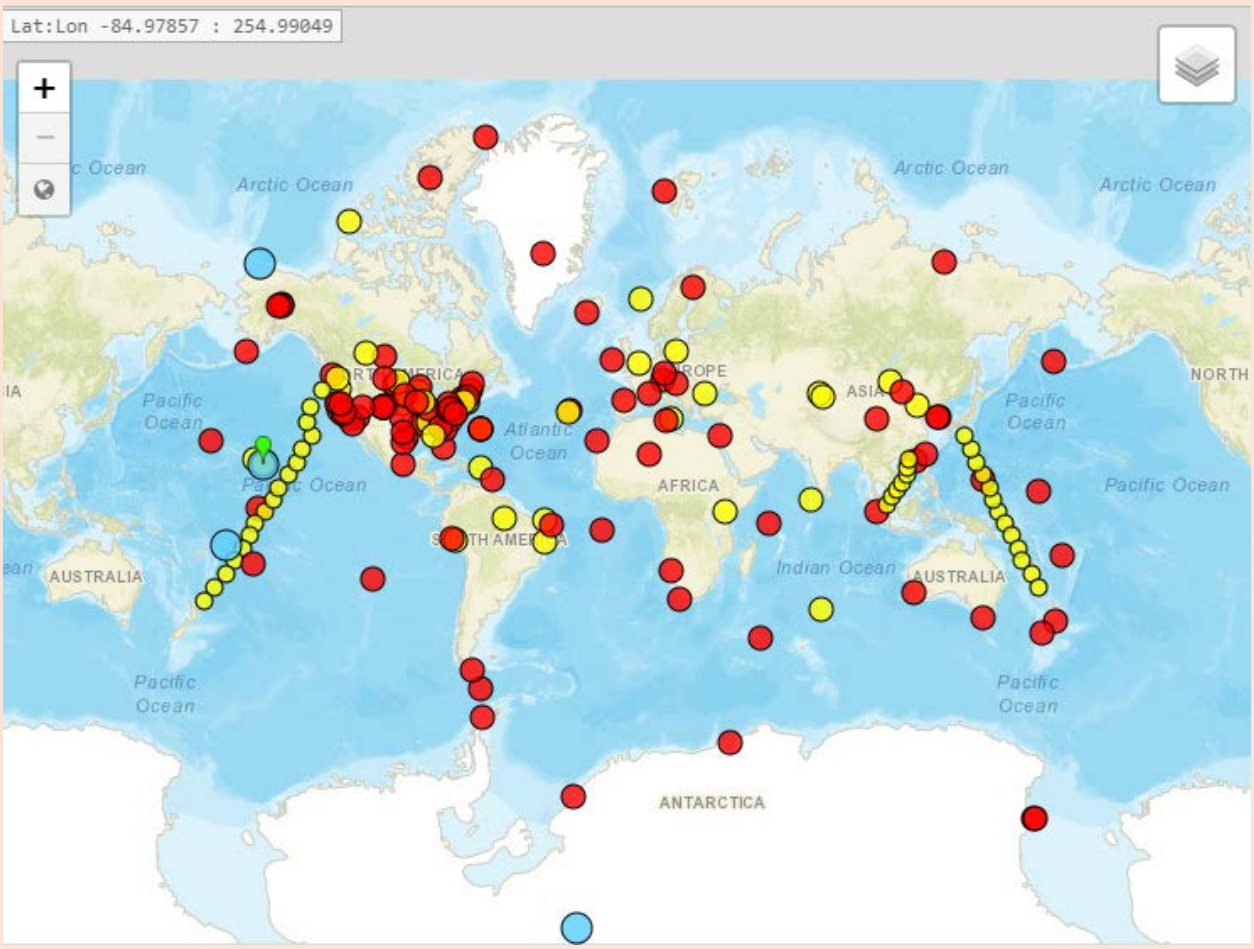


Figure 15.19 Land and ocean-based sampling of GHG's, ozone, and aerosols.
https://www.esrl.noaa.gov/gmd/dv/iadv/index.php?code=mlo

Yellow aircraft symbols represent discontinued sites.

Figure 15.20 Aircraft GHG sampling program operated by NOAA.
http://www.esrl.noaa.gov/gmd/ccgg/aircraft/

15.3 Satellite based monitoring

Figure 15.20 illustrates the NASA Earth science spacecraft and instruments in orbit. Several of these are able to monitor GHG's in Earth's atmosphere.

Figure 15.21 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 15.22 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 15.23. OCO-3 will extend NASA's carbon monitoring program from the International Space Station.

Figure 15.24 shows results from NASA's Atmospheric Infrared Sounder (AIRS) which scans for carbon monoxide sources. In this figure it has sensed carbon monoxide from the wildfires in California.

Figure 15.25 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).

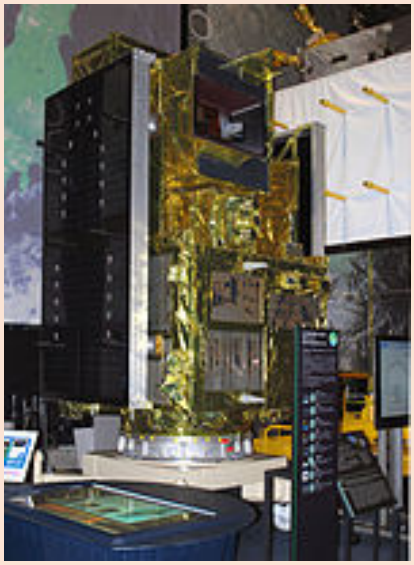
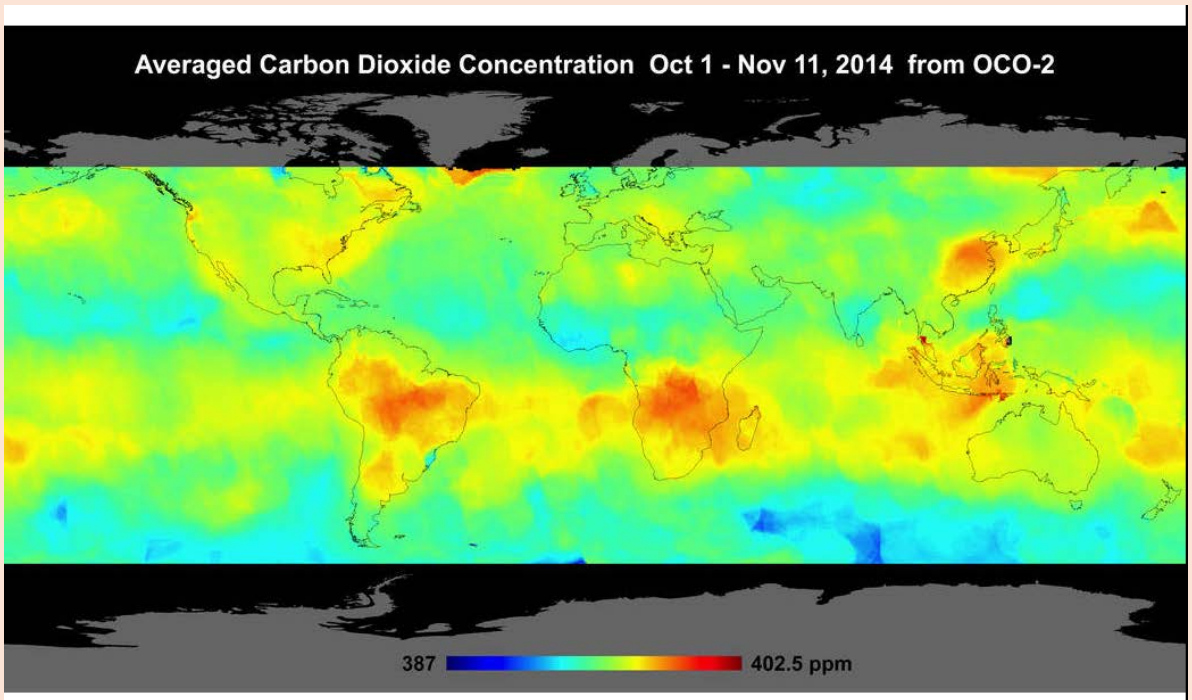


Figure 15.21 Greenhouse Gases Observing Satellite, GOSAT or Ibuki (Japanese) is the first satellite dedicated to GHG monitoring. It measures carbon dioxide and methane.
https://en.wikipedia.org/wiki/Greenhouse_Gases_Observing_Satellite

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

Figure 15.22 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 15.23 Averaged carbon dioxide concentration Oct 1 – Nov 11, 2014 from OCO-2. https://www.nasa.gov/jpl/oco2/pia18934

Figure 15.24 Carbon monoxide measurements from NASA's Atmospheric Infrared Sounder (AIRS).
https://climate.nasa.gov/news/3019/nasa-monitors-carbon-monoxide-from-california-wildfires/

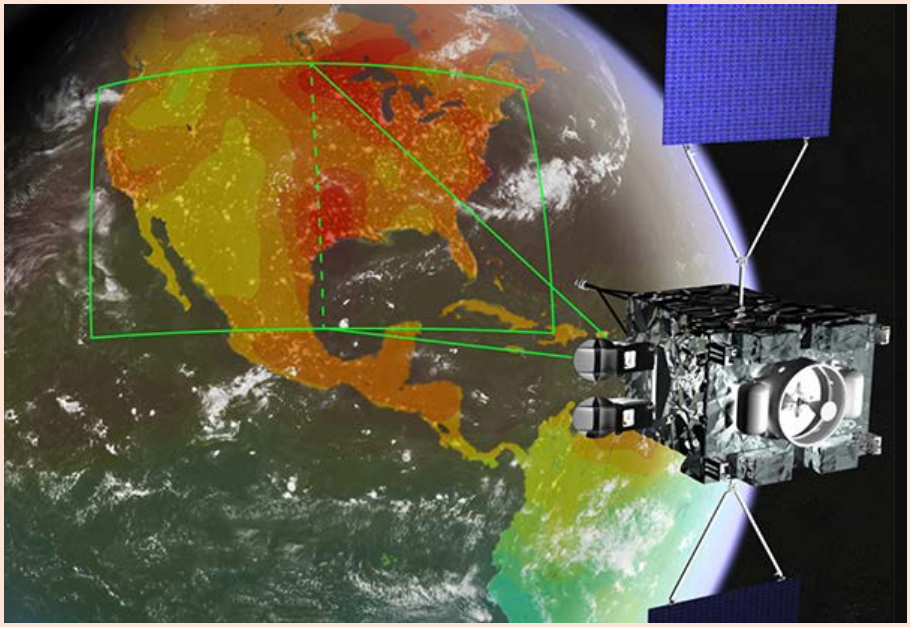


Figure 15.25 Geostationary carbon cycle observatory, EVM-2, GeoCarb.
https://eospso.nasa.gov/missions/geostationary-carbon-cycle-observatory-evm-2

15.6 Satellite monitoring of methane

Figure 15-26 shows a methane leak from space as detected by Earth Observing-1 (EO-1) satellite.

Figure 15-27 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 15-28 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.

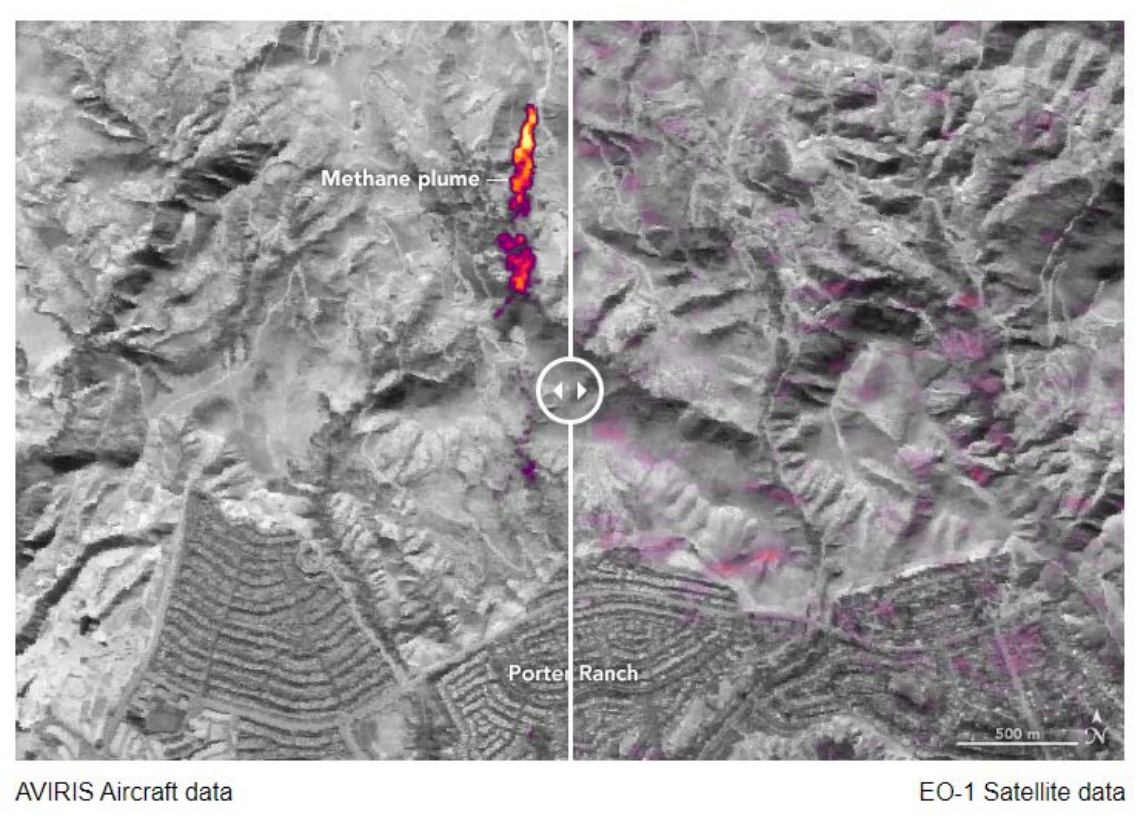


Figure 15.26 Methane leak from space as detected by Earth Observing-1 (EO-1) satellite. https://earthobservatory.nasa.gov/images/88245/imaging-a-methane-leak-from-space

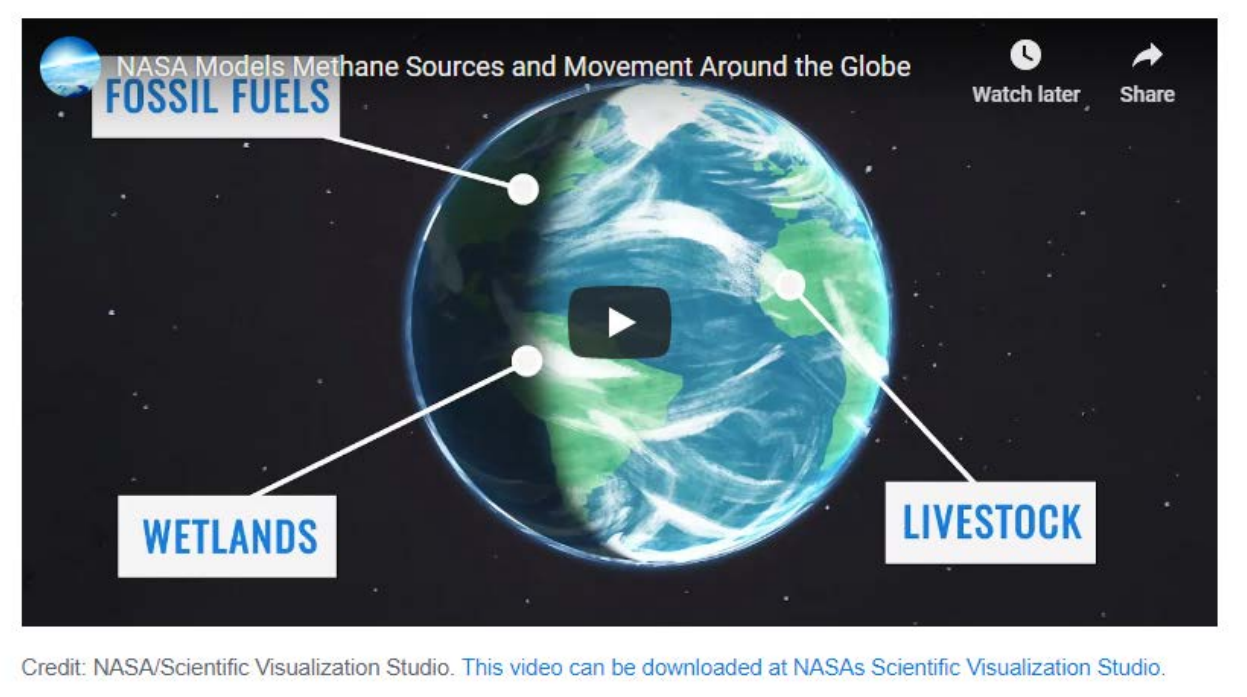


Figure 15.27 NASA Methane source model. https://climate.nasa.gov/news/2961/new-3d-view-of-methane-tracks-sources-and-movement-around-the-globe/

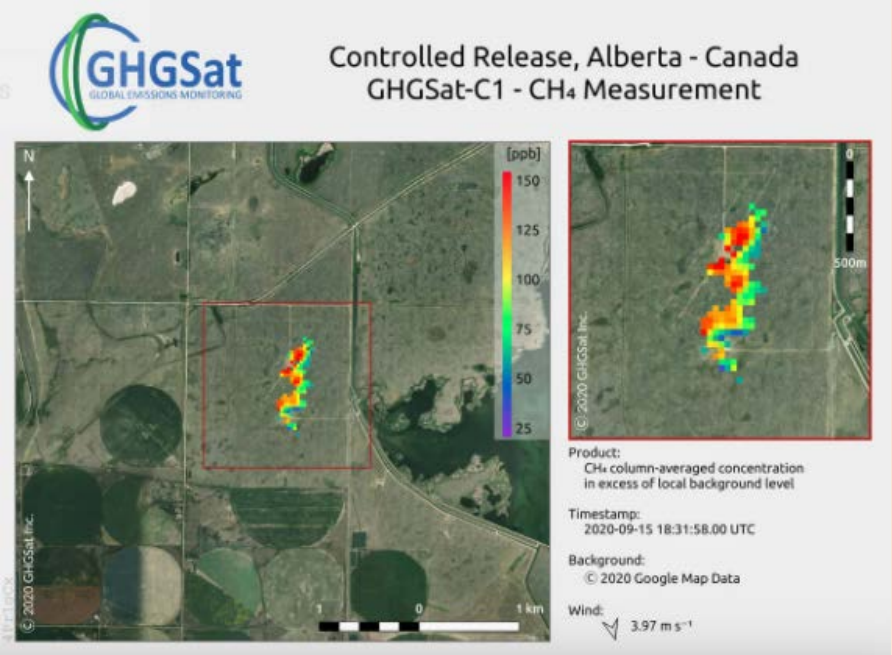


Figure 15.28 Global methane emissions monitoring.
https://www.ghgsat.com/

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 growing and so allowing greater ability to mitigate this cause of global warming and climate change.

15.7 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 15.29. 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 GHG's.

There is considerable confidence in the ability to detect, measure and monitor GHG's globally and this is steadily improving.

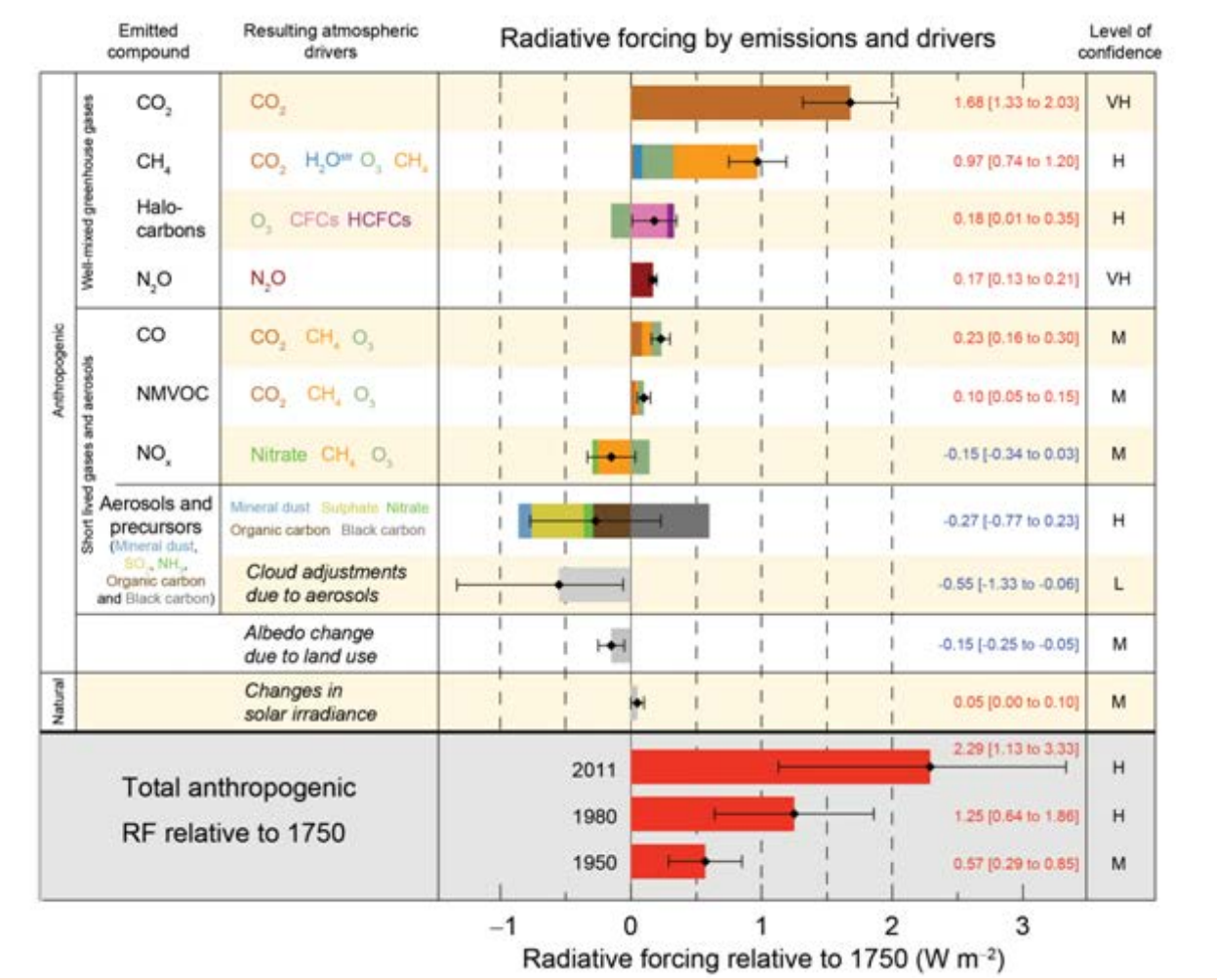


Figure 15.29 Global-average radiative forcing estimates and ranges – AR5.
https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf

15.8 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 more complex and a ‘carbon audit’ might be required. The process is governed by protocols such as PAS 2050 and the GHG Protocol Standard described in https://ghgprotocol.org/sites/default/files/standards_supporting/GHG%20Protocol%20PAS%202050%20Factsheet.pdf . 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). These issues are discussed in The Guide to Mitigation of Climate Change soon to be published in www.manzwaterinfo.ca.

15.9 Emission intensity or carbon intensity

Emission intensity or carbon intensity, (C.I.) 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.

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.

15.10 Information support

Key web sites:

1. Charles David Keeling. https://en.wikipedia.org/wiki/Charles_David_Keeling
2. Overview of greenhouse gases. https://www.epa.gov/ghgemissions/overview-greenhouse-gases
3. Greenhouse Gas Emissions. https://www.epa.gov/ghgemissions/us-greenhouse-gas-inventory-report-1990-2014
4. Changes in atmospheric constituents and in radiative forcing. https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf
5. History of the Keeling curve. 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
6. Trends in atmospheric carbon dioxide. https://www.esrl.noaa.gov/gmd/ccgg/trends/
7. Atmospheric concentrations. https://ourworldindata.org/atmospheric-concentrations
8. NASA scientists react to 400 ppm carbon milestone. https://climate.nasa.gov/400ppmquotes/
9. Climate change indicators: atmospheric concentrations of greenhouse gases. https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases#:~:text=Carbon%20dioxide%20concentrations%20have%20increased,is%20due%20to%20human%20activities.
10. Global monitoring laboratory. https://www.esrl.noaa.gov/gmd/dv/iadv/index.php?code=mlo
11. Geostationary carbon cycle observatory (EVM-2) (GeoCarb). https://eospso.nasa.gov/missions/geostationary-carbon-cycle-observatory-evm-2
12. Global atmospheric carbon dioxide. https://www.nasa.gov/jpl/oco2/pia18934
13. Orbiting carbon observatory 2. https://www.nasa.gov/mission_pages/oco2/index.html

14. Greenhouse gases observing satellite. https://en.wikipedia.org/wiki/Greenhouse_Gases_Observing_Satellite

15. New 3D view of methane, tracks sources and movement around the globe. https://climate.nasa.gov/news/2961/new-3d-view-of-methane-tracks-sources-and-movement-around-the-globe/

16. GHGSAT global emissions monitoring. https://www.ghgsat.com/

17. NASA-led study solves a methane puzzle. https://climate.nasa.gov/news/2668/nasa-led-study-solves-a-methane-puzzle/

18. NASA monitors carbon monoxide from California wildfires. https://climate.nasa.gov/news/3019/nasa-monitors-carbon-monoxide-from-california-wildfires/

19. Methane leak from space. https://earthobservatory.nasa.gov/images/88245/imaging-a-methane-leak-from-space

20. Global precipitation measurement mission. https://www.nasa.gov/mission_pages/GPM/overview/index.html

21. Climate watch. http://cait.wri.org/

22. Global emissions. https://www.c2es.org/content/international-emissions/#:~:text=Globally%2C%20the%20primary%20sources%20of,72%20percent%20of%20all%20emissions.

23. IPCC Task Force on National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/index.html

24. IPCC guidelines for national greenhouse gas inventories 2006. https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/0_Overview/V0_1_Overview.pdf

25. 2019 refinement to 2006 guidelines. https://www.ipcc.ch/site/assets/uploads/2019/12/03COP25_2019-Refinement.pdf

26. See page 123. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter1.pdf

27. Calculation of radiative forcing, Etminan, M., Myhre, G., Highwood, E. J. and Shrine, K. P. 2016. https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016GL071930

28. Carbon dioxide equivalent. https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Carbon_dioxide_equivalent

29. Global warming potential. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Global-warming_potential_(GWP)

30. Anthropogenic and natural radiative forcing. https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf

31. Carbon footprint. https://en.wikipedia.org/wiki/Carbon_footprint#:~:text=A%20carbon%20footprint%20is%20the,expressed%20as%20carbon%20dioxide%20equivalent.

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

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

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

35. Carbon footprint calculator, USEPA. https://www3.epa.gov/carbon-footprint-calculator/

36. Environmental Footprint, World Wildlife Fund. https://footprint.wwf.org.uk/#/

37. Carbon Footprint, Science Direct. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/carbon-footprint

38. Guide to PAS 2050, UNFAO. http://www.fao.org/sustainable-food-value-chains/library/details/en/c/266040/

39. ISO 14067:2018. https://www.iso.org/standard/71206.html

40. Company which provides carbon footprint certifications, Carbon Trust. https://www.carbontrust.com/what-we-do/assurance-and-certification/product-carbon-footprint-label?kw=%20carbon-%20footprint-%20audit-Broad

41. Emission intensity, Wikipedia. https://en.wikipedia.org/wiki/Emission_intensity

42. Carbon intensity for fuel, Government of British Columbia, Canada. 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

Videos:

1. NASA atmospheric chemistry. https://www.youtube.com/watch?v=54ECqX2tq9k&feature=emb_rel_end

2. Our particulate atmosphere: aerosols and black carbon in a changing climate. https://www.youtube.com/watch?v=oadRn0BrzLU

3. Black carbon. https://www.youtube.com/watch?v=fNoBBObL5tM

4. Fresh water in the Arctic. https://www.youtube.com/watch?v=FxXaT7yO4TQ