

Lab 8: Climate change

Purpose of the lab:

- Better understand the sources of anthropogenic (human generated) CO₂
- Learn about the Earth's energy budget
- Study how greenhouse gases drive climate change
- Study the potential implications of climate change

PART 1: Carbon footprint

In this lab, we will study modern anthropogenic (human induced) climate change. In subsequent sections, you will look at the Earth's energy budget, how greenhouse gas emissions modify this budget and some potential impacts of climate change.

The most important human related greenhouse gas is carbon dioxide (CO₂). To develop a better sense of the sources of CO₂ emissions, in this section you will look at carbon emissions related to daily life, using a couple of online carbon calculators:

The Nature Conservancy:

<https://www.nature.org/en-us/get-involved/how-to-help/carbon-footprint-calculator/>

United Nations International Civil Aviation Organization (ICAO):

<https://www.icao.int/environmental-protection/Carbonoffset/Pages/default.aspx>

We will look at the amount of CO₂ generated by specific activities. *You are welcome to use the calculators to determine your total carbon footprint, but that is not required for the lab.*

A. Household energy use

Use the Nature Conservancy carbon calculator to determine the CO₂ emitted by **four** people living in a three-bedroom house.

- Go to The Nature Conservancy carbon footprint website.
- Scroll down to the calculator. On the first page, click on the city tab and enter your location as Santa Barbara, CA. Set the number of people in your household to 4. *You do not need to enter your salary.*
- Click on the Home icon.
- Assume the house spends \$600 a year on electricity (0% clean energy sources), \$300 on natural gas, \$0 on Heating Oil and Other Fuels, has 1300 sq. ft. of living space and uses a water value of 1x; note that these are relatively low values for a house of four.
- Scroll down and read of "Your Home Footprint". How much CO₂ does this home generate per year? _____ tons CO₂/year (one metric ton is equal to 1,337 pounds) [1].
- How much CO₂ is generated per person? _____ tons CO₂/year [1]
- Feel free to try values that are more realistic for your own energy consumption.

B. Transportation

Now, we will look at the CO₂ emissions related to travel.

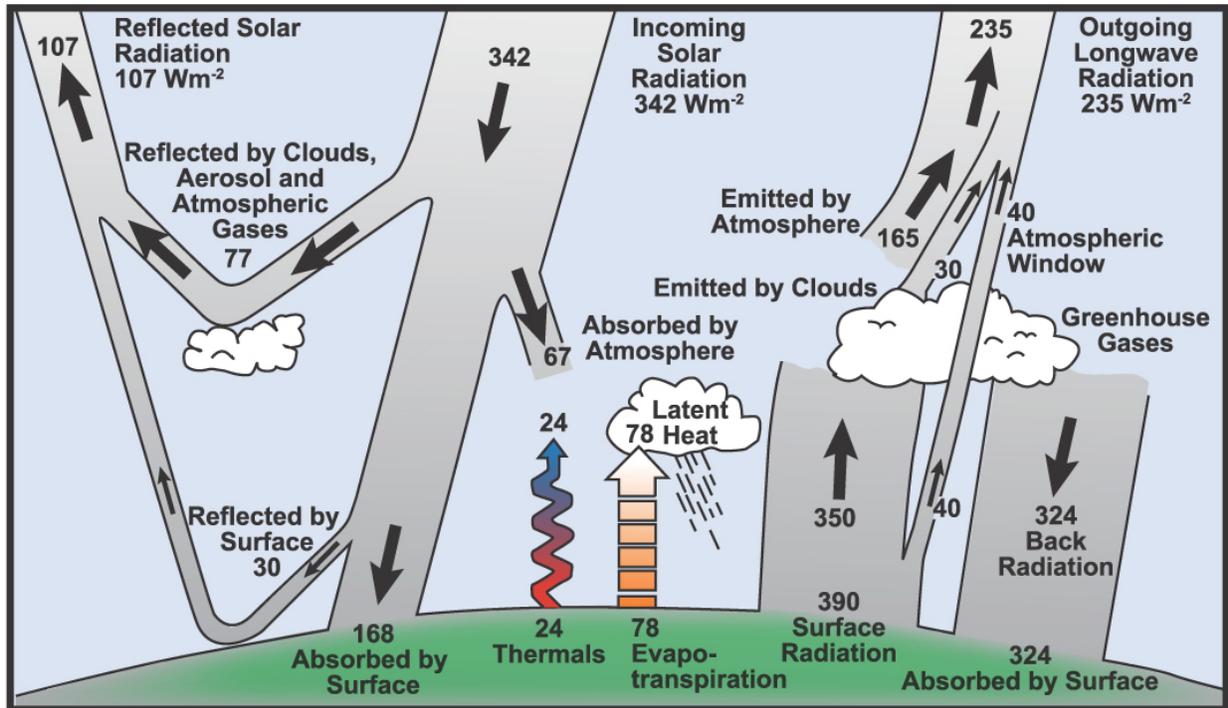
- i. Go to the ICAO carbon calculator.
- ii. Calculate how much CO₂ is emitted per passenger on a **one-way, economy** flight from Santa Barbara (SBA) to San Francisco (SFO) (use the metric setting): _____ kg [1]
- iii. A car that averages 30 miles per gallon will emit 296 kg of CO₂ every 1000 miles. It is a 326-mile drive from Santa Barbara to San Francisco. How much CO₂ will a driver emit on a drive to San Francisco? _____ kg [1]
- iv. Does driving or flying to San Francisco generate more CO₂? _____ [1]
- v. If there were four people in the car, how much CO₂ is emitted per passenger on the same drive? _____ kg [1]
- vi. Next use the ICAO calculator to determine how much CO₂ is emitted on a **one-way, economy** flight from Los Angeles (LAX) to Boston (BOS): _____ kg [1]
- vii. How much CO₂ is emitted for the same flight, if you have a layover in Denver (Use the add a new leg button, then set the first leg for LAX to DEN and the second for DEN to BOS): _____ kg [1]
- viii. How does the amount of CO₂ released compare between the direct flight to Boston and the flight with one stop over? What explains the difference?

_____ [1]
- ix. How much CO₂ would be emitted driving from LA to Boston (use the values above and a distance of 3,000 mi)? _____ kg [1]
- x. For a group of four, is it more energy efficient to fly or drive from LA to Boston? _____ [1]
- xi. Now determine the CO₂ emitted by a **round trip, non-stop, economy** flight from Los Angeles (LAX) to Boston (BOS): _____ kg [1]
- xii. How does the CO₂ released by a round trip, cross country flight compare to the per person home energy use you calculated above (1 ton of CO₂ = 1000 kg CO₂)? State your answer as a percentage or fraction (e.g., The flight is equivalent to XX% of the annual home energy use).

_____ [2]

PART 2: Earth's energy balance

The surface temperature of Earth reflects a balance between incoming solar radiation and heat lost due to energy radiated from the Earth's surface and atmosphere. The wavelength of electromagnetic radiation emitted by a planet or star is dependent on the temperature of the body. Higher temperatures (e.g., the sun) lead to emission of shorter wavelength, higher energy radiation, whereas cooler surface temperatures (e.g., Earth) lead to lower energy, longer wavelength radiation.



The figure above from the United Nations Intergovernmental Panel on Climate Change (IPCC) fourth assessment report shows Earth's energy balance.

- A. We will first focus on the incoming energy from solar radiation.
 - i. What is the total energy of incoming solar radiation? [1]
 - ii. A portion of this radiation is reflected back to space by clouds, aerosols and gases in the atmosphere. What percentage of the total incoming solar radiation is reflected back by these processes? (% = reflected/total * 100) [1]
 - iii. An additional percentage of the incoming solar radiation is reflected back by the surface of the Earth. The reflectivity of the Earth's surface is referred to as the albedo. What percentage of the total solar radiation is reflected back by the Earth's surface? [1]

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- iv. How much total solar energy is absorbed by the Earth's atmosphere and surface (be sure to add both together)? What percentage of the total incoming radiation is this? [2]

- v. The incoming solar radiation heats the Earth's surface. The Earth then re-emits energy as longer wavelength infrared radiation. How much energy is emitted from the Earth's surface as long wavelength radiation (surface radiation)? [1]

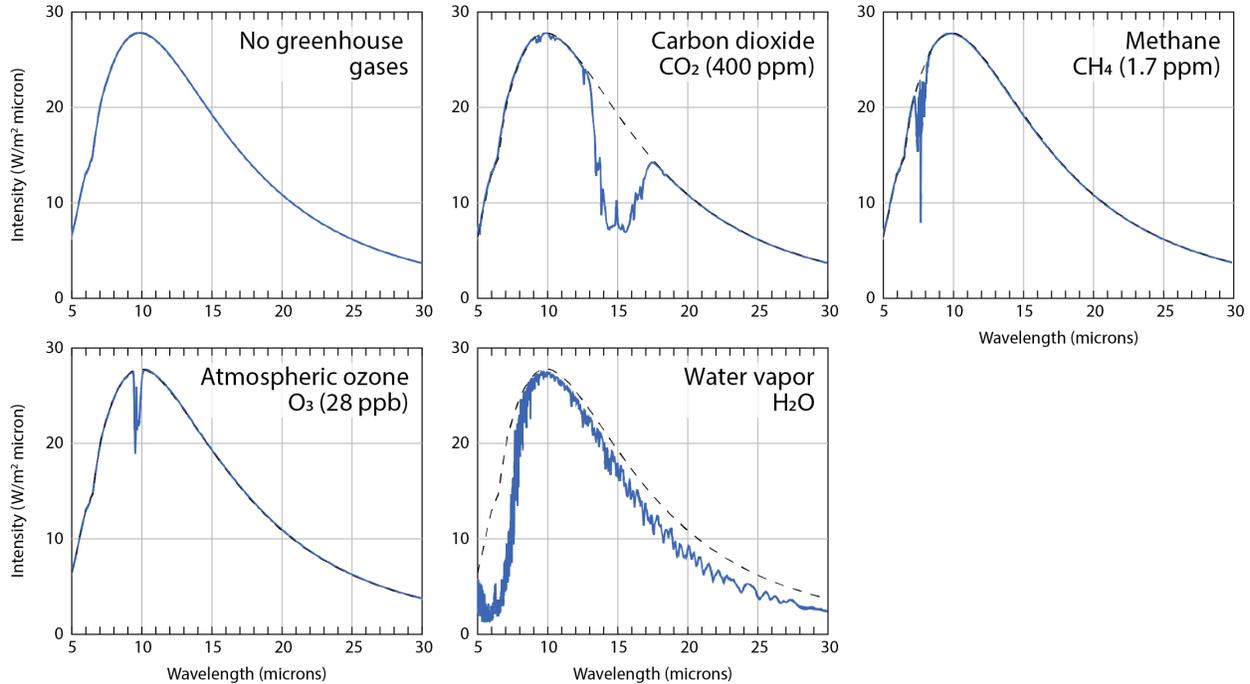
- vi. Much of the long wavelength electromagnetic radiation emitted by the surface of the Earth is absorbed and re-emitted by greenhouse gases and clouds in the Earth's atmosphere. As a result, only a fraction of the energy emitted by the Earth's surface makes it out of the atmosphere and into space. What is the total loss of energy from the Earth's surface and atmosphere into space? [1]

- vii. How does the amount of solar energy absorbed by the Earth's atmosphere and surface (part iv) compare to the amount of energy lost to space (part vi)? [1]

When the incoming solar energy is balanced by outgoing radiation, the Earth is in equilibrium and the surface and atmosphere will not warm or cool. Changes to this balance can lead to climate change. Radiative forcing is a change in this energy balance due to an external perturbation.

PART 3: Greenhouse gases

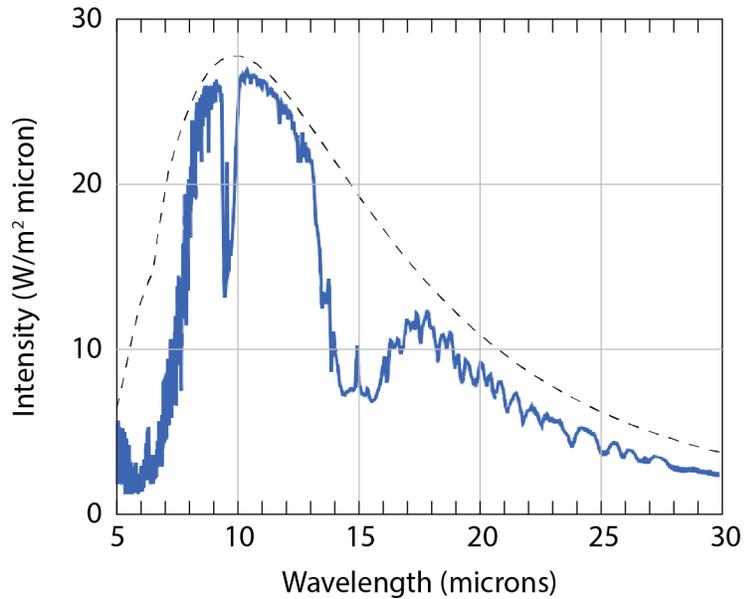
Greenhouse gases are important agents of climate forcing on Earth. In this section we will look at how greenhouse gases impact the Earth's energy balance.



- A. As discussed above, energy is radiated from the Earth as electromagnetic radiation in the infrared spectrum. Much of this energy is absorbed within the Earth's atmosphere, before it can escape to space. The plots above are models of the predicted intensity for different wavelengths of infrared radiation at a height of 70 km above the Earth's surface (above most of the Earth's atmosphere). The plot on the upper left shows the expected spectrum of infrared radiation emitted by the Earth if there were no greenhouse gases in the Earth's atmosphere. The other plots show the predicted spectrums with different greenhouse gases in the atmosphere (the dashed line in these plots corresponds to the greenhouse-free line from the upper left plot).

Based on the plots, determine what wavelengths of infrared radiation each greenhouse gas preferentially absorbs.

- i. Carbon Dioxide (CO₂): _____ microns [1]
- ii. Methane (CH₄): _____ microns [1]
- iii. Atmospheric ozone (O₃): _____ microns [1]
- iv. Water vapor (H₂O): _____ microns [1]



- B. The figure above shows the true spectrum of infrared radiation measured at the top of the Earth's atmosphere.
- Above the figure, show the range of wavelengths absorbed by the greenhouse gases you studied in part A. Draw and label the range for each gas separately. [2]
 - Based on this spectrum, which of the greenhouse gases are important in the Earth's atmosphere (i.e. what gases have affected the shape of the measured spectrum). [1]
 - Methane is an important greenhouse gas, but it is difficult to make out the signature of methane on the above spectrum. Why? [1]
 - Greenhouse gases (and clouds) are important because they absorb energy released from the Earth's surface before it is lost to space, then reemit it in all directions. Some of the reemitted energy warms the Earth's atmosphere and surface. Based on the figure at the beginning on Part 2, how much energy is back radiated toward the Earth's surface from greenhouse gases and clouds? [1]

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- v. What percentage of the energy emitted by the Earth's surface is returned by back radiation? ($\% = \text{back radiation} / \text{total emitted} * 100$) [1]
- vi. Will an increase in the concentration of CO₂ in the atmosphere lead to an increase or decrease in the amount of back radiation? What impact will this have of the temperature of the Earth's atmosphere and surface? [1]
- vii. An atmospheric window is a portion of the spectrum where there is not much energy lost in the atmosphere and those wavelengths of infrared light are transmitted to space. Based on the figure in part B, what wavelengths are most efficiently transmitted through the atmosphere (i.e. are least impacted by greenhouse gases)? [1]
- viii. This atmospheric window allows some infrared radiation emitted by Earth to leave the atmosphere. According to the figure in Part 2, how much energy is lost through the atmospheric window? [1]
- ix. Based on your lecture notes, why is solar radiation able to pass through the atmosphere and warm the surface of the Earth, while infrared radiation emitted by the surface of the Earth is captured by greenhouse gases? [2]

PART 4: Feedbacks

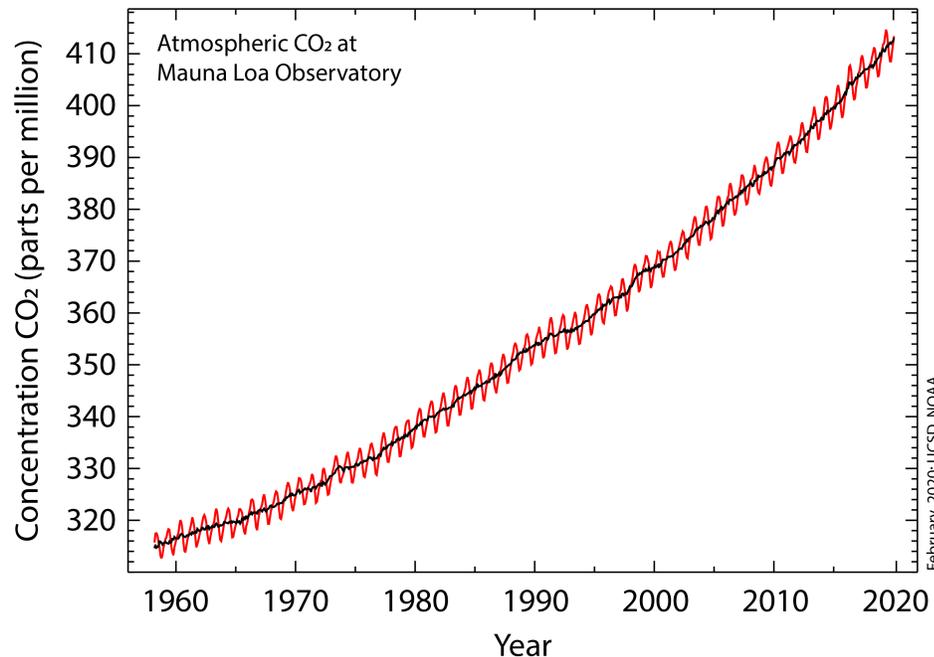
Climate change is the result of changes in radiative forcing **and** amplification of these changes by feedback loops.

A. In lecture, we discussed several feedback mechanisms.

- i. As you saw in Part 3, water vapor is an important greenhouse gas, but it is not added to the atmosphere in large quantities by human activities. Explain the link between global warming and water vapor. Is this a positive or negative feedback (positive = enhances warming, negative = slows down warming)? [2]

- ii. The Earth's albedo is a measure of how reflective the surface of the Earth is (high albedo = very reflective). Explain how global warming can increase or decrease the Earth's albedo. Is this a positive or negative feedback? [2]

PART 5: Rates and implications of climate change



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The plot above, known as the Keeling curve, shows variations in the measured CO₂ concentrations at the Mauna Loa Observatory in Hawaii from 1958 to the present. The red, squiggly line records the measured data, while the smoother curve shows the average values. The annual oscillations in the red line reflect natural changes in the abundance of CO₂ in the atmosphere in the summer and winter seasons.

A. Use the above plot to calculate how the rate of change in CO₂ in the atmosphere has changed since 1958.

i. First calculate the rate of change from 1960–1980. Use the average value for each year in your calculation. [2]

Average CO₂ in 1960: _____ (ppm)

Average CO₂ in 1980: _____ (ppm)

Rate of change from 1960–1980: _____ ppm/year

ii. Now calculate the rate of change from 1980–2000. [2]

Average CO₂ in 1980: _____ (ppm)

Average CO₂ in 2000: _____ (ppm)

Rate of change from 1980–2000: _____ ppm/year

iii. Now calculate the rate of change from 2000–2020. [2]

Average CO₂ in 2000: _____ (ppm)

Average CO₂ in 2020: _____ (ppm)

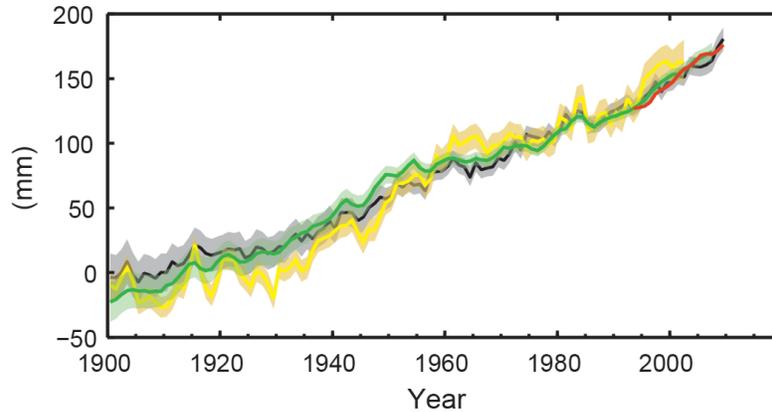
Rate of change from 2000–2020: _____ ppm/year

B. The Paris Agreement is a global plan to address climate change. The goal of the Paris Agreement is to keep "the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursue(e) efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (Paris Agreement).

i. According to the United Nation's IPCC 5th Assessment Report, keeping the global temperature increase below 2° above pre-industrial levels will require keeping atmospheric CO₂ below 450–500 ppm. Based on your calculations above, if CO₂ emissions continue at the same rate as from 2000–2020, how long will it be before we reach atmospheric CO₂ concentrations of 500 ppm? [2]

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- C. One impact of climate change is a rise in global sea level, as continental ice sheets and glaciers melt, and importantly, as ocean water thermally expands due to increased global temperatures. The most recent IPCC report predicts between 0.2–0.8 m of sea level rise (including uncertainties) by 2100.



The plot above shows global sea level change since 1900 (IPCC, 5th Assessment Report, 2013).

A recent paper used satellite measurements to estimate that the Greenland ice sheet has lost $3,902 \pm 342$ billion tons of ice from 1992 and 2018 (IMBIE Team, Nature, 2019).

- i. One metric ton = 1000 kg, so the total weight of ice lost is 3.902×10^{15} kg. Water has a density of ~ 1000 kg/m³. Calculate the volume of melt water produced (volume of melt water = total weight/water density).

Volume of water added to the oceans: _____ m³ [2]

- ii. The global oceans have a surface area of approximately 3.62×10^{14} m². How much has the volume of ice lost in Greenland raised global sea level? (sea level rise = volume of melt water/ocean surface area). Convert your answer from meters to millimeters.

Rise in global sea level: _____ mm [2]