Climate change, climate sensitivity and feedback processes

Anthropogenic Climate Change

- *What factors may cause anthropogenic climate change?*
  - Increasing concentration of greenhouse gases (i.e., greenhouse effect)
  - Aerosols (such as black carbon, sulfate aerosols)
  - land use/land cover change (urbanization, farming and deforestation)
- In this section, we will focus on the greenhouse effect. The greenhouse effect can be due to increasing levels of carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), chlorofluorocarbons (CFCs), and tropospheric ozone (O3).

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Carbon Dioxide (CO2)

- Regular measurements of the atmospheric CO2 concentration were established at the Mauna Loa Observatory (elev. 3400 m) in Hawaii in 1958. The record of CO2 concentration is known as the Keeling curve.
- The Keeling curve in panel (a) shows a seasonal cycle superimposed on a clear increasing trend.
- Panel (b) shows the CO2 concentration over the South Pole. We can see the clear positive trend, but the seasonal cycle is weaker.
- The ice core record shows that the CO2 concentration oscillates with glacial periods between 200-280 ppm.
- The residence time of CO2 ranges from 5-300 years, which is much longer than the global mixing time scale. CO2 is thus well mixed.
- The largest source of anthropogenic atmospheric CO2 is the burning of fossil fuels.

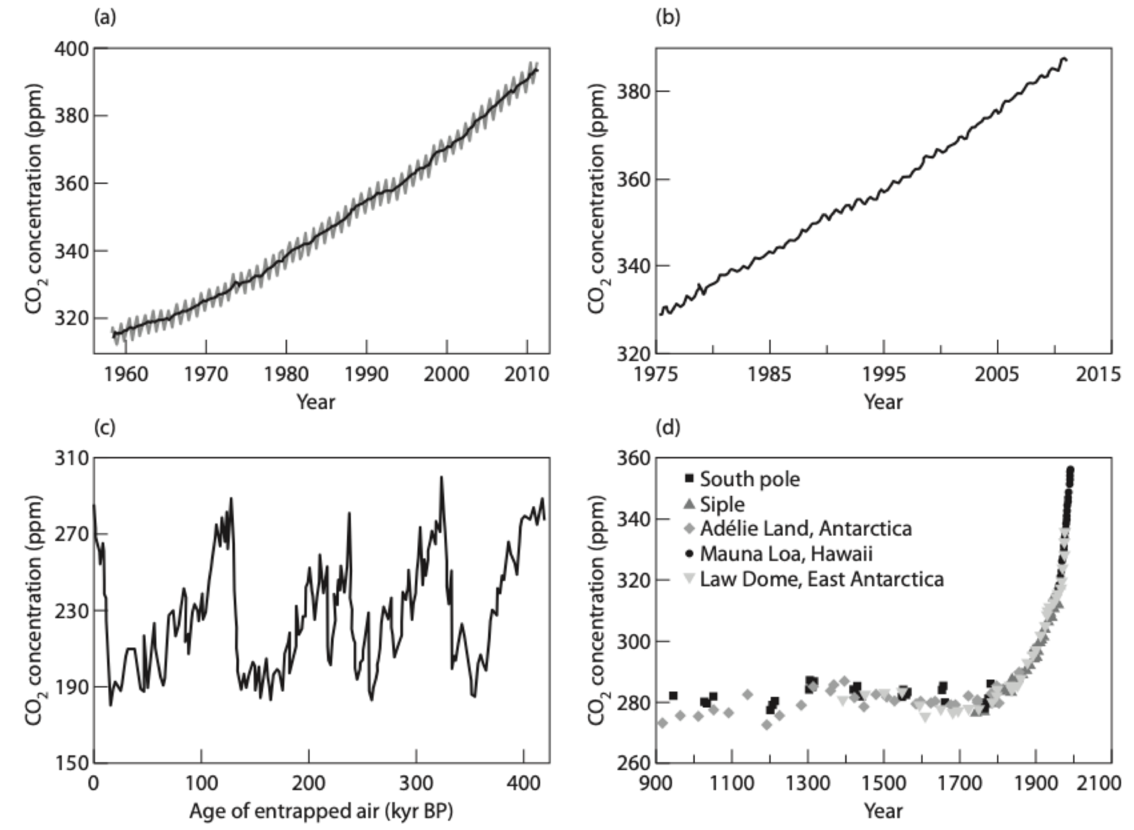

Figure 10.1 (a) Direct atmospheric CO_2 measurements from the (a) Mauna Loa Observatory and (b) South Pole. (c) Values for 400,000 years of atmospheric CO_2 from the Vostok, Antarctica, ice core. (d) Values of atmospheric CO_2 for the last 1100 years from various ice cores and Mauna Loa.

ppm = parts per million

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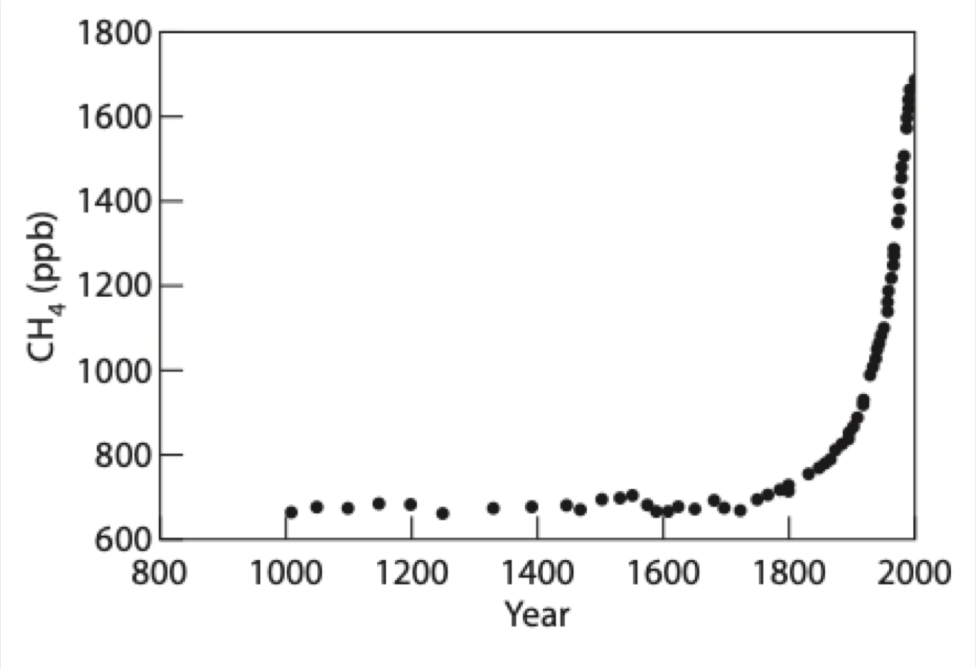
Methane (CH4)



Methane concentrations from the Antarctic and Greenland ice cores.

- Methane is a powerful greenhouse gas with various sources and sinks.
- Its primary sources are emissions from wetlands and rice paddies. Other sources include animals, termites, biomass burning, landfills, and fossil fuel production. The primary sink is its photochemical oxidation by the hydroxyl radical (OH) in the troposphere.
- The residence time scale of Methane is 12 years, and it is not well mixed globally.
- Methane has the glacial-interglacial oscillation similar to CO2.
- Methane concentration has increased exponentially in recent years from the pre-industrial level of ~700 ppb to ~1700 ppb.

ppb = parts per billion

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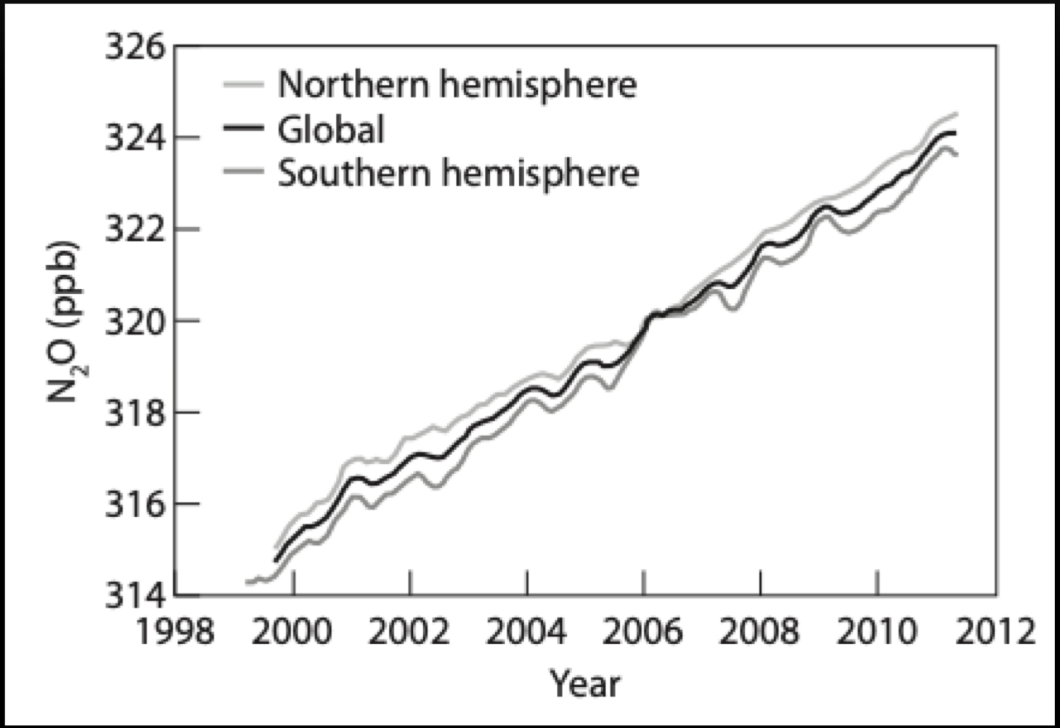
Nitrous Oxide (N2O)

- Nitrous oxide is a powerful greenhouse gas with a residence time in the troposphere of more than 100 years.
- Its concentration has increased from the pre-industrial level of ~260 ppb to ~324 ppb in 2010 (at a rate of 0.26% per year).
- Important anthropogenic sources are related to soil and manure management in agricultural practice, sewage treatment, and fossil fuel combustion.



Global and hemispheric trends in concentration of atmospheric N2O estimated from direct measurements.

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Aerosols

- Atmospheric aerosols are suspended solid particles and liquid droplets, including smoke, water droplets, sulfate particles, organic carbon, black carbon, mineral dust, nitrates, smog, and sea salt.
- Natural sources of aerosols include volcanic eruption and wind lifting over dry regions and deserts.
- Anthropogenic sources include fossil fuel combustion and biomass burning.
- Most aerosols in the troposphere have relatively short residence times (under a few weeks) and can be removed through both wet and dry deposition. Aerosols in the stratosphere have longer residence times—often a year or more.
- Aerosols produce direct radiative forcing on climate due to both absorption and scattering and exert an indirect effect on the earth's radiation budget when they interact with and modify clouds.

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Radiative Effects of Greenhouse Gas Increases

- Two methods of expressing the influence of changes in the atmosphere's composition are regularly used.
  - *direct radiative forcing*: measures the amount of radiative energy (W/m2) added to the troposphere due to a given change in a greenhouse gas
  - *global warming potential* (GWP): evaluates the implications over time of releasing a unit mass of a given greenhouse gas compared with the release of a unit mass of CO2.
- As shown in the figure on the right, aerosols have a cooling effect and tend to offset the greenhouse gas-induced warming, but the aerosol effects, especially the indirect effects, have a large uncertainty.

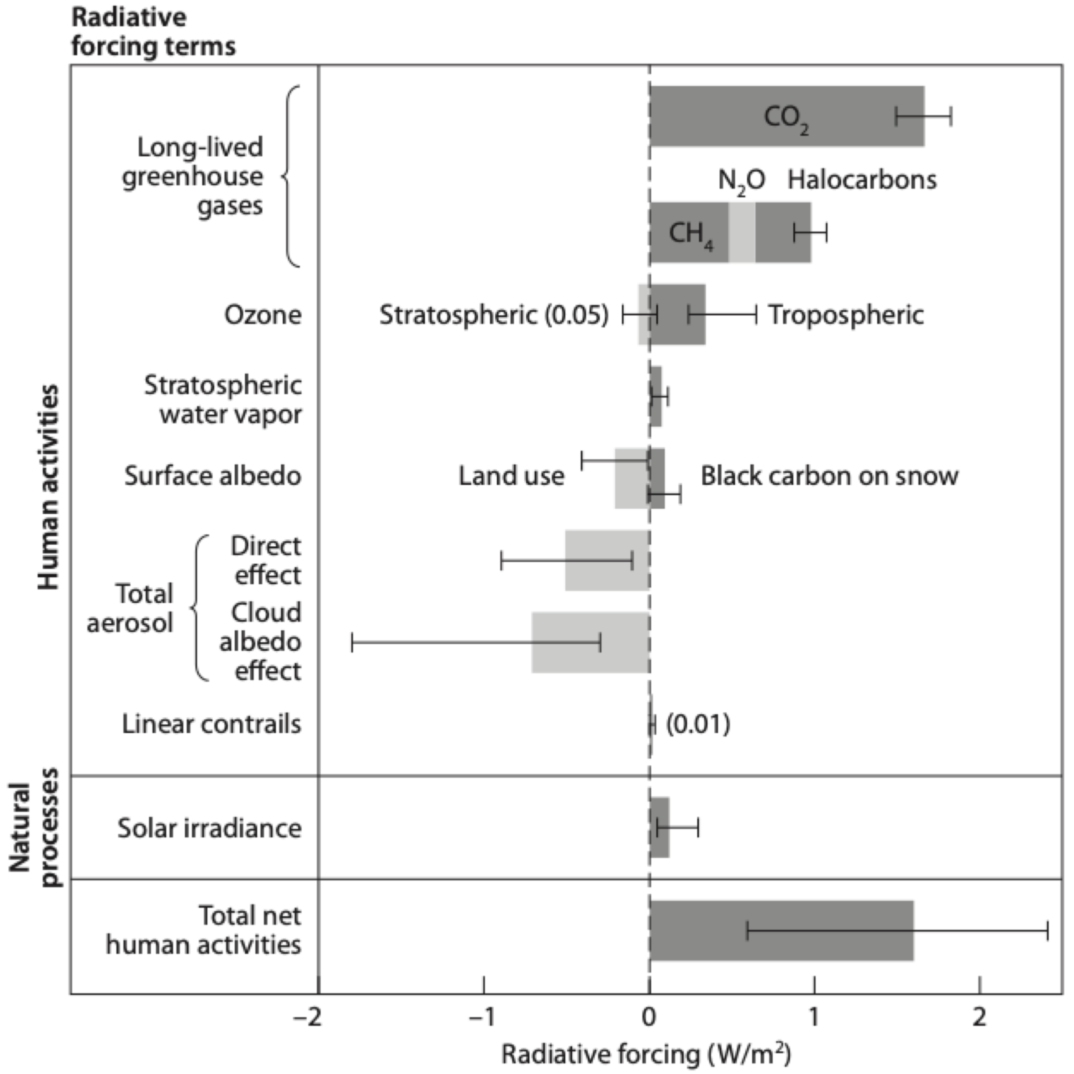

Figure 10.6. Summary of the principal components of the radiative forcing of climate change. Values represent the forcings in 2005 relative to the start of the industrial era (about 1750). From Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

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Climate Sensitivity

- Climate sensitivity measures the rate of change of the global, annual mean surface air temperature T* to a certain forcing factor F. We are essentially asking how sensitive our climate is to anthropogenic forcing, such as increases in CO2.

$$\lambda \equiv \frac{\partial T^*}{\partial F},$$

where F represents various forcing factors

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Climate Sensitivity: Example

In the state of radiative equilibrium the energy emitted is equal to the energy absorbed. The energy balance at the top of the atmosphere is

$$\frac{S_0(1-\alpha)}{4} = \varepsilon\sigma T_E^4,$$

Where sigma is the Stefan-Boltzmann constant; S_0 is the solar constant, alpha is the planetary albedo, and T_E is the radiative equilibrium temperature.

$$T_E = \left[\frac{S_0(1-\alpha)}{4\sigma}\right]^{1/4}.$$

The sensitivity of T_E to changes in the solar constant is then

$$\lambda_{S_0} = \frac{\partial T_E}{\partial S_0} = \frac{S_0^{-3/4}}{4}\left[\frac{(1-\alpha)}{4\sigma}\right]^{1/4}.$$

For S_0 = 1368 W/m^2 and alpha = 0.31, we have

$$\lambda_{S_0} = \frac{\partial T_E}{\partial S_0} = 0.046\ \mathrm{K/(W \cdot m^{-2})}.$$

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Transient Climate Response and Equilibrium Climate Sensitivity

- There are different ways of defining climate sensitivity, depending on the timescales of interest.
  - **Transient Climate Response (TCR)**: The temperature increase at the instant that atmospheric CO_2 has doubled (following an increase of 1% each year) gives us the Transient Climate Response. This is useful as a gauge for what we might expect over the current century when atmospheric concentrations of CO_2 are changing.
  - **Equilibrium Climate Sensitivity (ECS)**: The climate system will continue to warm for some time after the TCR point, largely as the oceans are very slow to respond. Therefore we can also consider the temperature increase that would eventually occur (after hundreds or even thousands of years) when the climate system fully adjusts to a sustained doubling of CO_2 – this is called the Equilibrium Climate Sensitivity.

https://www.metoffice.gov.uk/research/climate/understanding-climate/climate-sensitivity-explained

How to estimate climate sensitivity to CO2?

- **Historical climate records**: instrumental records of T combined with estimates of greenhouse gas can be used to assess the global temperature response to emissions of CO_2 by human activities to date.
- **Climate models**: we can use climate models to predict future climate sensitivity. These mathematical models are built around our understanding of the physics which underpin our climate system.
- **Paleoclimate records**: ice cores and other records can be used to estimate natural changes in temperature and atmospheric CO_2 over thousands of years. These can be used for estimates of the past relationship between the two factors.

https://www.metoffice.gov.uk/research/climate/understanding-climate/climate-sensitivity-explained

Climate Feedbacks

- When evaluating the climate sensitivity using the following equation, the factors other than *F* are held constant.

$$\lambda \equiv \frac{\partial T^*}{\partial F},$$

  However, changes in one radiative forcing often triggers other changes in the climate system that can amplify or reduce the response of T*.

- Examples of climate feedbacks:
  - Water vapor-temperature feedback
  - Ice albedo-temperature feedback
  - Cloud-radiation feedback
- In the following two sections, we will see how climate feedback processes contribute to the Arctic amplification and extreme weathers.

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References

- Cook, K., 2013: Chapter 10, Chapter 11
- IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Chapters 10 and 11
- TAR Climate Change 2001: The Scientific Basis, Chapter 7