The solar spectrum

- The sun has its strongest output in the green.
- Our eyes are most sensitive in the green.
- Plants look green, because they reflect green light. They actually use red and blue.
Planck’s law of radiation

- A hot body (such as the Sun) emits electromagnetic radiation with a characteristic spectral shape (blue curve on the previous slide).

- The peak frequency of the spectrum is proportional to the absolute temperature $T$. And the peak wavelength is inversely proportional to $T$, since $\lambda = c/f$.

- The surface of the Sun radiates at 6000 K. Its thermal radiation peaks in the visible (green).

- The surface of the Earth radiates at 300 K. Its thermal radiation peaks in the far infrared.
Absorption and emission of light

- A **strong absorber** of light is also a **strong emitter**.
- A weak absorber either reflects or transmits light.

Light is absorbed or emitted by electrons jumping up or down between two energy levels $E_1, E_2$. 

![Diagram showing absorption and emission of light](image)
Greenhouse gases $(\text{CO}_2, \text{H}_2\text{O}, \ldots)$

Greenhouse gases consist of molecules that absorb and emit radiation in the far infrared, similar to the thermal radiation of the Earth.

These molecules contain two types of atoms with opposite charges. They oscillate like the electrons in an antenna (which absorbs and emits radio waves).
What gets through?

What gets absorbed?

By which molecules?
The greenhouse effect

Step 1: Absorption of outgoing thermal radiation

Without atmosphere:

- visible in
- infrared out

cooling

The glass roof of a greenhouse absorbs infrared.

Greenhouse gases absorb infrared.
The greenhouse effect

Step 1: Absorption of outgoing thermal radiation

- The earth absorbs visible light from the hot sun and emits it into space as infrared (thermal radiation). The Earth “glows” and thereby loses heat.

- Greenhouse gases absorb part of the thermal radiation and prevent it from getting lost in space. The roof of a greenhouse does the same.
The greenhouse effect
Step 2: Emission of thermal radiation, up and down

visible in

\( \frac{1}{2} \times \text{infrared up} \)

\( \frac{1}{2} \times \text{cooling} \)

\( \frac{1}{2} \times \text{infrared down} \)

\( \frac{1}{2} \times \text{warming} \)

Greenhouse gases
The greenhouse effect
Step 2: Emission of thermal radiation, up and down

- Greenhouse gases also emit thermal radiation, since a strong absorber is also a strong emitter (Slide 3).

- Half of the heat radiation goes up into space to be lost, but the other half comes back to the ground. So we still get half of the warming out of it.

- Adding more greenhouse gases increases this warming.
The greenhouse effect

Refined model: Complex, but computers can handle it.

Greenhouse gases strengthen the orange path. More energy stays on the Earth’s surface. ⇒ Warming
The greenhouse effect: Summary

Greenhouse gases

1) absorb outgoing thermal radiation
2) radiate half of it back to Earth
Secondary effects reinforce warming

• The ice cover of the Arctic Sea shrinks and exposes more water, which absorbs sunlight. Indeed, the Arctic warms more quickly than other regions (next slide).

• Meltwater seeps to the bottom of glaciers and lubricates their slide into the ocean (Greenland, Antarctica).

• Methane, another greenhouse gas, is released by global warming from being trapped in arctic permafrost and in slush-like clathrates at the bottom of the ocean.
Evidence of global warming:
Temperature increase

http://ngm.nationalgeographic.com/climateconnections/climate-map
Global warming and extreme weather

11 year running average

Shifting Distribution of Summer Temperature Anomalies

http://svs.gsfc.nasa.gov/vis/a000000/a003900/a003975/
Global warming and extreme weather

More extremely warm weather in the last decade
Warmer oceans produce more water vapor, the fuel of storms

Green curve is from previous decades
Global warming versus CO₂
Two similar “hockey stick” curves

Temperature

Carbon dioxide
Again very similar curves. There is some debate over cause versus effect. But temperature and CO₂ levels are unlikely to decrease anytime soon. The real question is: How do we mitigate the consequences.
Conclusions by the IPCC

- The Intergovernmental Panel on Climate Change (IPCC) consists of hundreds of climate scientists, who prepare a consensus report on climate change about every 5 years. It received the Peace Nobel Prize in 2007. Some quotes from the summary of the 2007 report:

  - “Warming of the climate system is unequivocal.”
  - “Global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years.”
  - “Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations.”
  - “Anthropogenic warming and sea level rise would continue for centuries due to the time scales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilised.”

Result of global warming:
Dry/wet zones are moving
Global warming moves climate zones

Hot, moist air rises at the Equator, cools off, and releases its moisture as rain.

Cold, dry air flows away from the Equator at high altitude and comes back down in the desert belts.

With global warming, all climate zones move away from the Equator towards the poles. The Northern desert belt reaches the Southwestern US and the Mediterranean countries.
Consequences of moving climate zones

- More pine beetles survive the winter and invade trees in the mountains of North America. Together with a fungus that they spread they have done unprecedented damage.

- CO$_2$ dissolves in the oceans and forms an acid that attacks the shell of corals.

- Corals overheat, die. Can’t move fast enough to escape. Coral reefs form the nurseries for young ocean fish.

- Can trees and crops follow fast-moving climate zones?

- A mass extinction of species has started already.

- Try to transplant corals, plants to cooler climate zones.
Staghorn and elkhorn coral populations in the Florida Keys, the Dry Tortugas and the U.S. Virgin Islands have declined by more than 97%. Underwater nurseries grow transplants to revive degraded coral reefs.
Global warming increases ocean levels

- Last ice age: -130 m, 15,000 years ago
- Last century: +1.5 mm increase per year
- Now: +3 mm increase per year
- In 100 years: +0.3 m, at the current rate
- Greenland melts: +7 m, when?
- Antarctica melts: +60 m, when??
Paleoceanographer James Zachos holds a replica of a sediment core that shows an abrupt change in the Atlantic Ocean 56 million years ago, at the onset of the Paleocene-Eocene Thermal Maximum (PETM). White plankton shells vanished from the seafloor mud, shifting its color from white to red (bar below). As planet-warming CO₂ surged into the atmosphere, Zachos says, it also seeped into the seas, acidifying the water and dissolving the shells.
$\text{CO}_2$ dissolves in ocean water, forms an acid, which attacks the shells of corals and foraminifera.

**DEEP-SEA EXTINCTIONS**

This species of foraminifera—sand-grain-size creatures that abound in seafloor mud—survived the PETM by shrinking. But many other forams went extinct, victims of water that was too corrosive, low in oxygen, or hot: Even in the deep it warmed by 9°F.

- **Late Paleocene epoch**
  - Normal size and shape

- **Early PETM**
  - Erodes and shrinks in the acidified water

- **Mid-PETM**
  - Slowly increases in size

- **Early Eocene epoch**
  - Survives PETM but never regains original size

Sharp species losses mark the Paleocene-Eocene Thermal Maximum (PETM), followed by a slow recovery.
It happened suddenly. It took 150,000 years to recover:

A mass of carbon roughly the size of today’s coal, oil, and natural gas deposits entered Earth’s atmosphere during the PETM. From where is unclear—but Earth, already warm, warmed another 9°F on average. It took more than 150,000 years for oceans and forests to absorb the excess carbon and the planet to cool.

We are on track for a repeat:

Measured from atmospheric gases trapped in Antarctic ice cores

Measured at Mauna Loa Observatory, 1959-2010 (2010: 390 ppm)

Projected spike as of 2100*
Can such a scenario still be avoided?

- We will be there in about 2100 by continuing business as usual.

- The main culprit is CO₂, which is emitted in huge quantities by burning coal, oil, gas (2.4 million pounds of CO₂ every second!).

- Coal, oil, and gas (=fossil fuels) are our main sources of energy. Thus, global warming is tied to the energy problem (Lect. 32).

- Human civilization depends on readily-available energy. It is unlikely that everyone will stop consuming more energy. Humans have a track record of taking resources until they run out completely (deforestation of the Mediterranean and Easter Island).

- Gradually replace fossil fuels by renewable energy (solar, wind). The Sun provides plenty of energy for the whole planet. It does not pollute.
A success story: The ozone hole

- Ozone in the upper atmosphere absorbs ultraviolet light (which causes skin cancer).
- Some molecules cause a chemical reaction that breaks down ozone.
- An international treaty in 1987 phased these chemicals out by the year 2000.
- We are starting to see the ozone hole shrinking.
- But it will take more than 100 years to get back to normal.