The Heating of the Atmosphere

The purpose of this story is to give you an understanding of the reason why the Earth has been heating over the last two hundred years and why it will continue to heat.

This is the story of the simple molecules that constitute the Earth's atmosphere – the air we breathe!

The impact of this heating of the atmosphere on Earth's climate I will leave to others.

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Before we dive in, I need you to be aware of, two important pieces of information. You are aware of these already but possibly in not enough detail.

Light and the Electromagnetic Spectrum

"What do you think microwaves, sunlight and x-rays all have in common?"

☑ They're all made of electromagnetic waves (or photons) — just with different wavelengths and energies.

Simple Definition; Electromagnetic radiation is a kind of energy that travels in waves.

These waves move at the speed of light, and they can be:

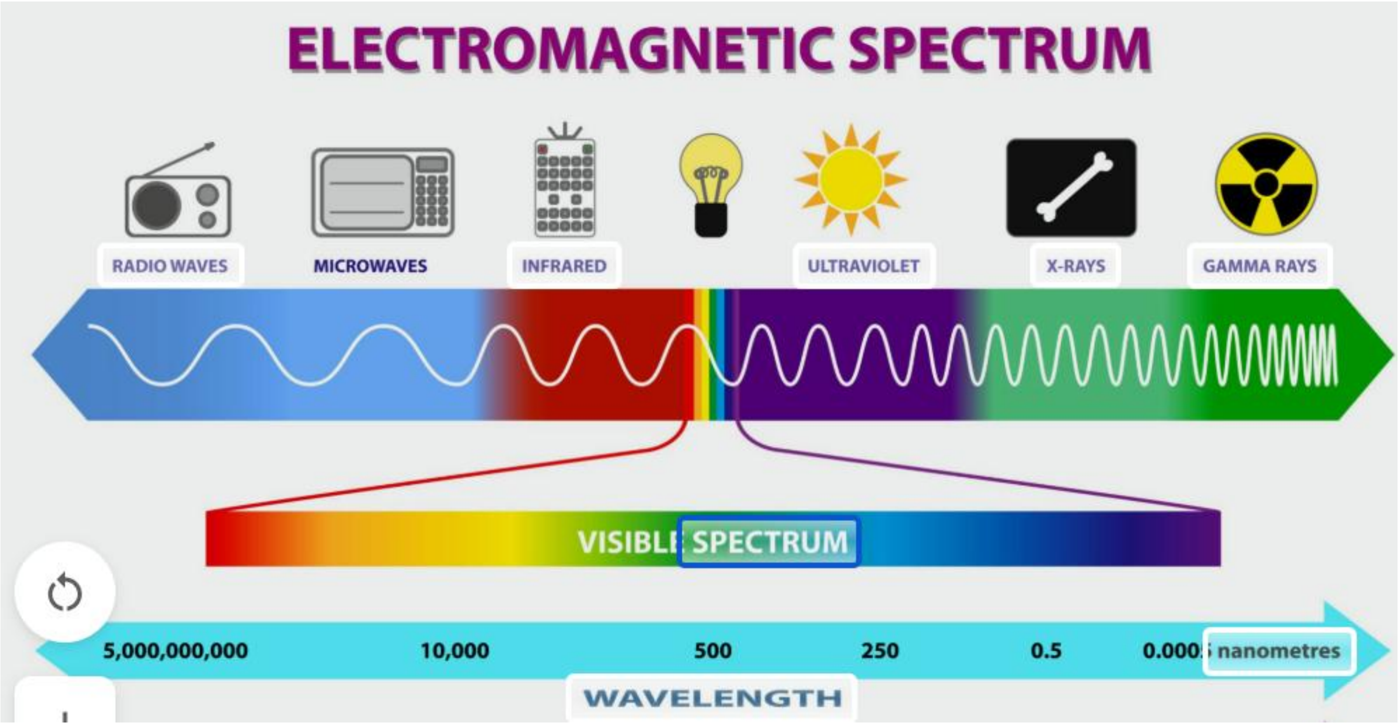
- Very short (like X-rays)
- Very long (like radio waves)
- Or in the middle (like visible light)

"Shorter waves pack more energy — like a fast, snapping whip vs. a slow, waving rope."

The Electromagnetic spectrum is used in a multitude of ways. Here are a few;

- Infrared → used in night vision and sensing heat
- Ultraviolet → causes sunburn and helps sterilize
- Microwaves → heat food and carry cell signals
- X-rays → Medical-let doctors see bones
- Radio → GPS, and communication

The Electromagnetic spectrum is the most important way of exploring the universe. Just about everything we know of the universe, its behaviour and content have been learned through the analysis of light from the depths of space.



🧠 Final Thought:

"Even though our eyes can only see a tiny part of the electromagnetic spectrum, our knowledge of the whole spectrum is understood completely.

Often, we talk about light as though it is made of particles.

A particle of light is called a **photon**.

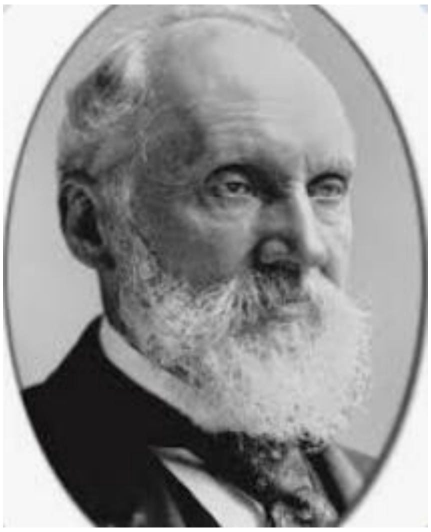
The part of the spectrum that we are most interested with respect to global warming is the **Infrared Region**. This region is invisible to our eyes but very well understood.

Although most of the spectrum is invisible to our eyes, we have built instruments that do the seeing for us.

Temperature

In the first part of the 19th Century ideas of temperature and heat (think steam engine) and their relationship to energy were being worked out. We came up with the Celsius and Fahrenheit scales of temperature. But more importantly, in 1848 William Thompson (later Lord Kelvin) came up with what we now know as the Kelvin temperature scale.

In the Kelvin scale the temperature is directly related to the thermal motion of the system being measured.



At the beginning of the 1800s, a relationship was discovered between the volume and the temperature of a gas. This relationship suggests that the volume of a gas should become zero at a temperature of -273.15°C. In 1848 the British physicist William Thompson, who later became Lord Kelvin, suggested that this observation could be used as the basis for an absolute temperature scale. On the Kelvin scale, absolute zero (0 K) is the temperature at which the volume of a gas becomes zero. It is therefore the lowest possible temperature, or the absolute zero on any temperature scale. Zero on the Kelvin scale is therefore -273.15°C.

$$0\ K = -273.15^{o}C$$

Each unit on this scale, or each *kelvin*, is equal to 1 degree on the Celsius scale. There is a subtle difference between the units on these scales, however. Because the Celsius scale is based on two arbitrary references points, the difference between the temperatures of these two points is divided into *degrees*. The Kelvin scale, however, is an absolute scale. Zero is not arbitrarily defined; it is the lowest possible temperature that can be achieved. Thus, temperatures on the Kelvin scale are not divided into degrees. Temperatures on this scale are reported in units of "Kelvin," not in "degrees Kelvin."

The Kelvin directly represents the average kinetic energy of particles.

OR

The Kelvin isn't just marking degrees on a scale - it's directly measuring energy at the molecular level, starting from the absolute minimum possible temperature.

It begs the question; What exactly are molecules doing at absolute zero (0 K)?

A bit EXTRA for those that appreciate some maths.

Is there's a direct mathematical relationship between thermal energy and temperature in Kelvins? YES.

For most practical purposes with macroscopic quantities, we often use the formula:

$$\text{Thermal Energy} = \frac{3}{2}nRT$$

Where:

- n is the number of moles of substance
- R is the universal gas constant (8.31446 joules per mole per kelvin)
- T is the temperature in kelvins

This direct proportionality between thermal energy and Kelvin temperature is precisely why the Kelvin scale is so useful in scientific calculations. When temperature doubles on the Kelvin scale (e.g., from 200K to 400K), the thermal energy exactly doubles as well, making calculations much more straightforward than with Celsius or Fahrenheit.

Atmospheric Warming

Understanding how greenhouse gases like CO_2 (carbon dioxide), CH_4 (methane), and H_2O (water vapor) can cause Earth to warm.

🌍 1. The Earth's Energy Balance

Earth receives energy from the Sun mostly in the form of visible light and ultraviolet radiation. The Earth absorbs some of this energy and re-radiates it back to space as infrared radiation (IR) — basically, heat.

If all the incoming energy were exactly balanced by outgoing heat, Earth’s temperature would stay stable.

🧊 2. Greenhouse Gases Trap Heat

Greenhouse gases absorb infrared radiation that is emitted by Earth's surface. Instead of letting that heat escape to space, they re-radiate it — in all directions, including back toward Earth.

This process is similar to how a greenhouse works (hence the name): sunlight comes in, but heat gets trapped.

🌫️ 3. How Specific Gases Work

- CO_2 (Carbon Dioxide):
  - Strong absorber of IR at specific wavelengths.
  - Long-lived in the atmosphere (centuries).
  - Its concentration directly influences Earth’s radiative balance.
- CH_4 (Methane):
  - Much more potent than CO_2 *per molecule* (over 25 times more effective at trapping heat).
  - Shorter atmospheric lifetime (about 12 years), but its warming effect is powerful while it lasts.
- H_2O (Water Vapor):
  - Not a primary cause of warming, but a feedback.
  - As the atmosphere warms from CO_2 or CH_4, it can hold more water vapor.

    - Water vapor itself is a powerful greenhouse gas, so this amplifies the warming.
    - However, it condenses and precipitates, so it doesn't accumulate like CO_2.

🔁 4. The Positive Feedback Loop

- Warming from CO_2 → more water vapor → more warming.
- Thawing permafrost → releases CH_4 → more warming.
- Melting ice → less sunlight reflected → more absorbed → more warming.

These feedbacks amplify the initial warming from human emissions.

A closer look at Carbon Dioxide CO_2

CO_2 is a linear molecule: O=C=O

And has 4 vibrational modes.

1. Symmetric stretch (does not absorb IR)
2. Asymmetric stretch
3. Bending – up/down and in/out of plane

🌊 2. IR-Active Vibrational Modes of CO_2 (absorb IR):

Mode	Wavelength	Energy (meV)	Notes
Bending	~15 µm	~82.8 meV	Strong IR absorber

📈 3. Why These Wavelengths Matter

The Earth emits most of its IR radiation in the **4–50 µm** range, with a peak around 10 µm, depending on surface temperature (~288 K = 15°C). CO_2's absorption peaks match well with parts of this IR spectrum.

- The 15 µm bending mode is right in the middle of Earth's emission range.

- That's a sweet spot — a region of the spectrum called the "atmospheric window" would otherwise let heat escape to space, but CO_2 partially blocks it.

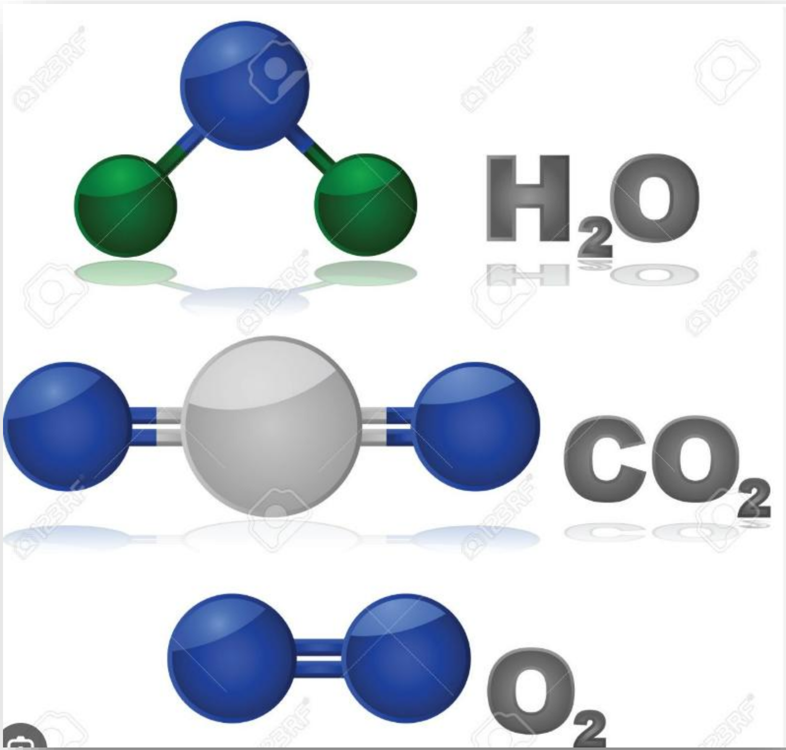
🎯 4. Mechanism of IR Absorption

- A photon of IR light hits a CO_2 molecule.
- If the photon energy matches a vibrational mode, the molecule absorbs it.
- The molecule begins vibrating more vigorously (excited).
- Later, the molecule reemits that energy — randomly in all directions — including back toward Earth, warming the lower atmosphere and surface.

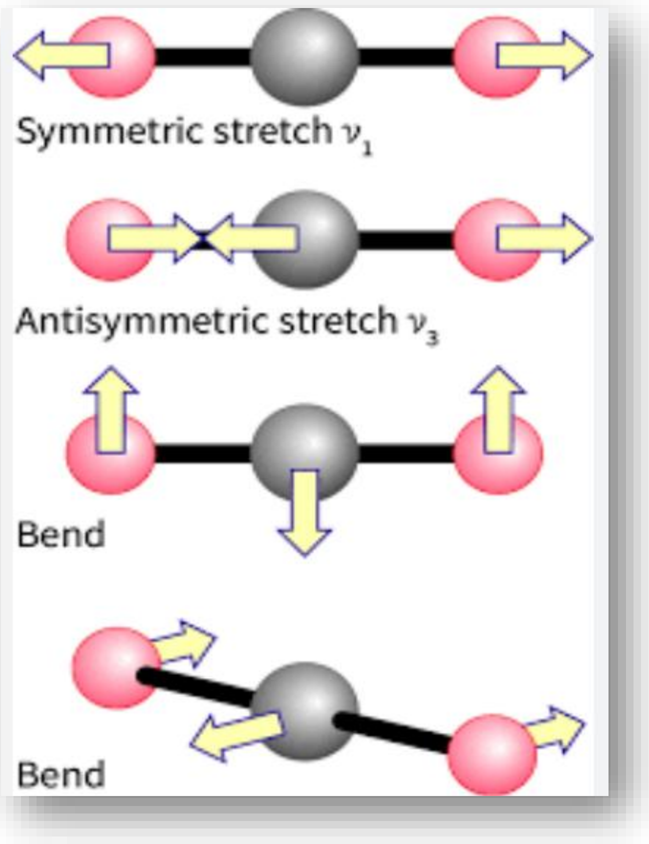
This re-emission is not always at the same wavelength or in the same direction — it's probabilistic.

💡 Bonus Thought: Why Oxygen and Nitrogen Don't Contribute

- O_2 and N_2 are diatomic and symmetric — they're invisible to IR — even though they make up 99% of the atmosphere.



Visual diagrams of the vibrational modes of CO_2

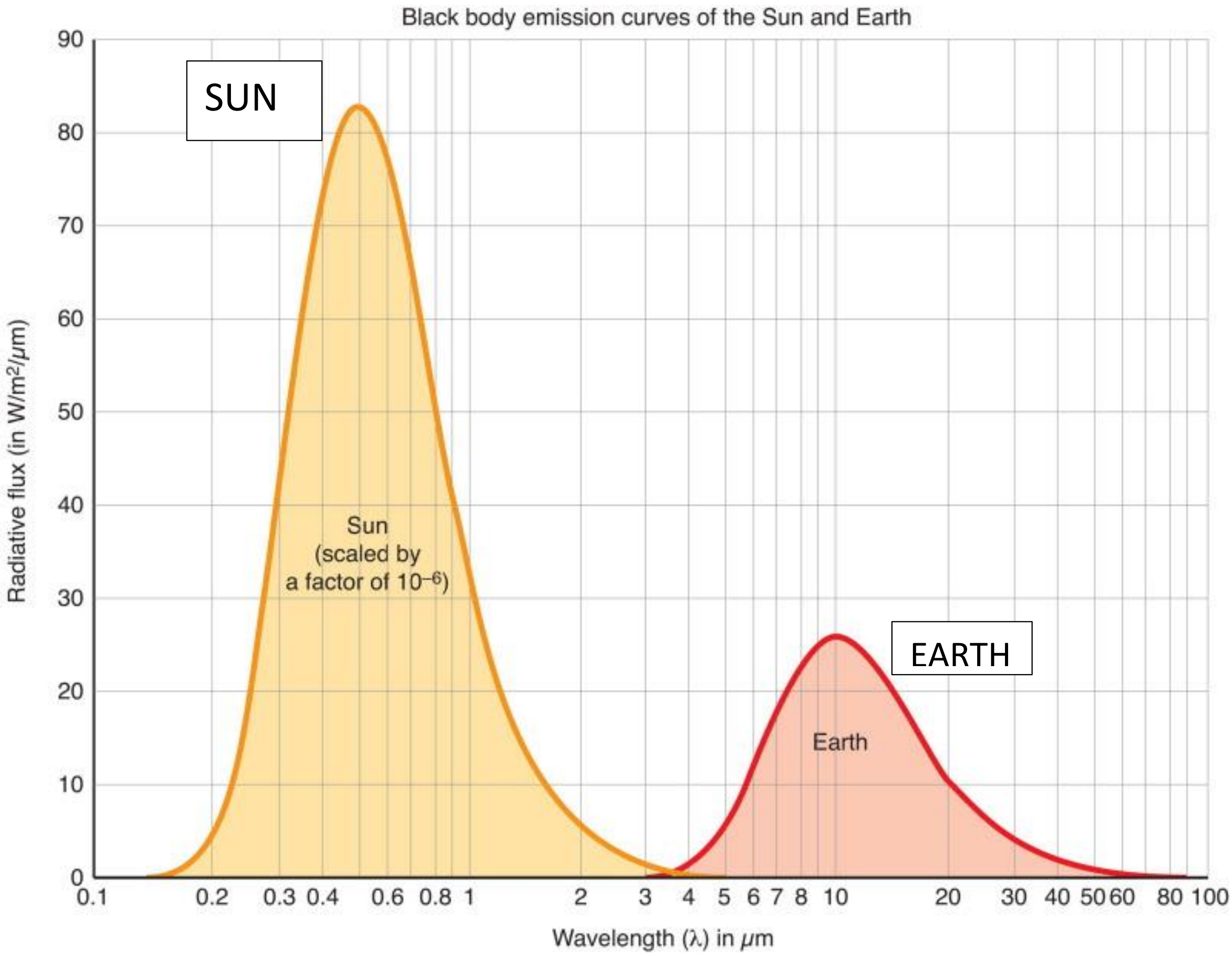


How do these vibrational modes line up with the Earth's blackbody radiation spectrum?

This is where physics, chemistry, and climate science converge. Let's dig into how the vibrational modes of CO_2 align with the Earth's blackbody spectrum, and why that alignment is critical for the greenhouse effect.

All Material Bodies Radiate

All objects whose temperature is above 0K radiate. What do they radiate? A: photons



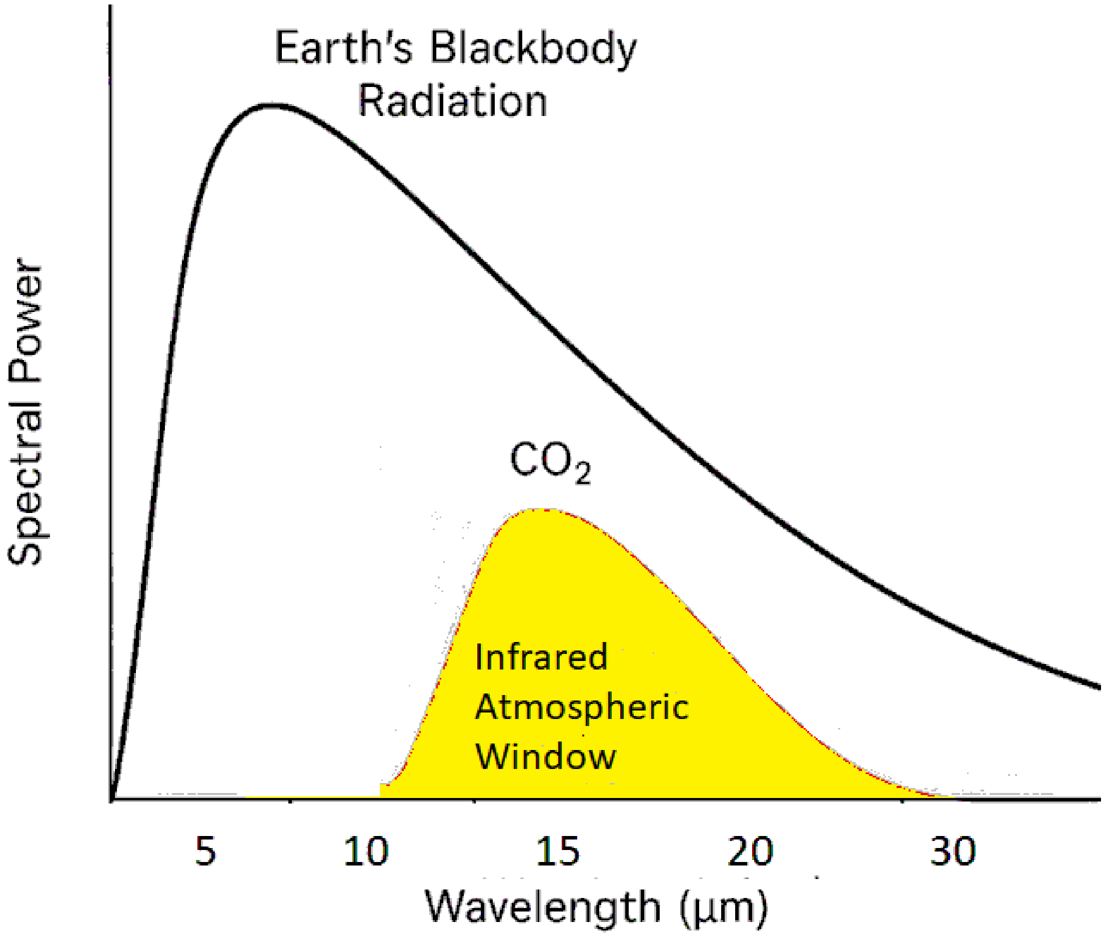
🌍 Earth's Blackbody Radiation Spectrum

1. The Basics

- Earth behaves approximately like a blackbody radiator with an average surface temperature of ~288 K (15°C).
- Earth emits infrared (IR) radiation primarily in the 4 to 50 µm wavelength range.
- The peak emission occurs near 10 µm.

🔁 🛰️ Visual Comparison

A combined spectrum plot of Earth's blackbody emission overlaid with CO_2's absorption bands? It's a great way to visually understand the overlap.



📊 Match with Earth's IR Output

- The 15 µm bending mode aligns very well with the high-energy part of Earth's outgoing IR — and it's in a region where otherwise heat would escape efficiently.
- The 15 µm bending mode strongly traps heat, making CO_2 a key player in the greenhouse effect.

Why This Matters

- When CO_2 absorbs IR at these bands, it gets vibrationally excited and then re-emits IR in all directions.

  The energy is often transferred to nearby N_2 or O_2 molecules via collisions, warming the atmosphere.

  Some of the re-emitted IR goes back down to Earth's surface, reinforcing warming — this is the greenhouse effect in action.

CO_2 Concentrations in the Atmosphere

The current concentration of carbon dioxide (CO_2) in the atmosphere is approximately **430 parts per million (ppm)**. This marks a significant increase from pre-industrial levels, which were around **280 ppm** in the late 1700s. Over the last 200 years, human activities—especially the burning of fossil fuels—have driven this rise, with CO_2 levels increasing by about **50%**.

This rapid change is unprecedented in Earth's recent history and has profound implications for climate systems.

"Our addiction to fossil fuels is pushing humanity to the brink.

We face a stark choice: Either we stop it — or it stops us.

– UN Secretary-General Antonio Guterres
