INTRODUCTION TO THE SCIENCE OF CLIMATE CHANGE AND THE GREEN HOUSE EFFECT

INDIAN INSTITUTE OF SCIENCE EDUCATION AND RESEARCH, KOLKATA

SUSTAINABILITY AND CHEMISTRY: A SYSTEMS APPROACH

CH 5106 – LECTURE 2

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LECTURE OUTLINE

- Some key definitions: Weather, climate, climate change, global warming
- The Earth's energy budget and balance
- Nature of solar and terrestrial radiation
- The origin of the "Green House Effect"
- How and why does atmospheric warming vary in time and space and as a function of latitude and height?
- Why does "Green House Effect" cause warming of earth? How do Green House Gases trap heat?
- Why some gases contribute to "Green House Effect" and some do not?
- Anthropogenic GHG emissions : Origins and growth
- Measuring carbon dioxide concentration in the atmosphere

LECTURE OUTLINE

- Global carbon cycles and carbon exchange / redistribution
- Global warming and the impact on the "ocean systems": Sea-level rise and ocean acidification
- The concept of "Climate Tipping Point"
- Consequences of climate change on the Earth's systems
- Greenhouse effect, atmospheric concentration of CO_2 and climate change: The burden of proof
- The challenge of Net Zero? Why, how and by when?
- Can we pull the GHGs from the air or at the source of emission?
- How do we decarbonize the planet ? Which segment of the human activity and manufacturing industry emit the most?
- Science and technology challenges for mitigating climate change

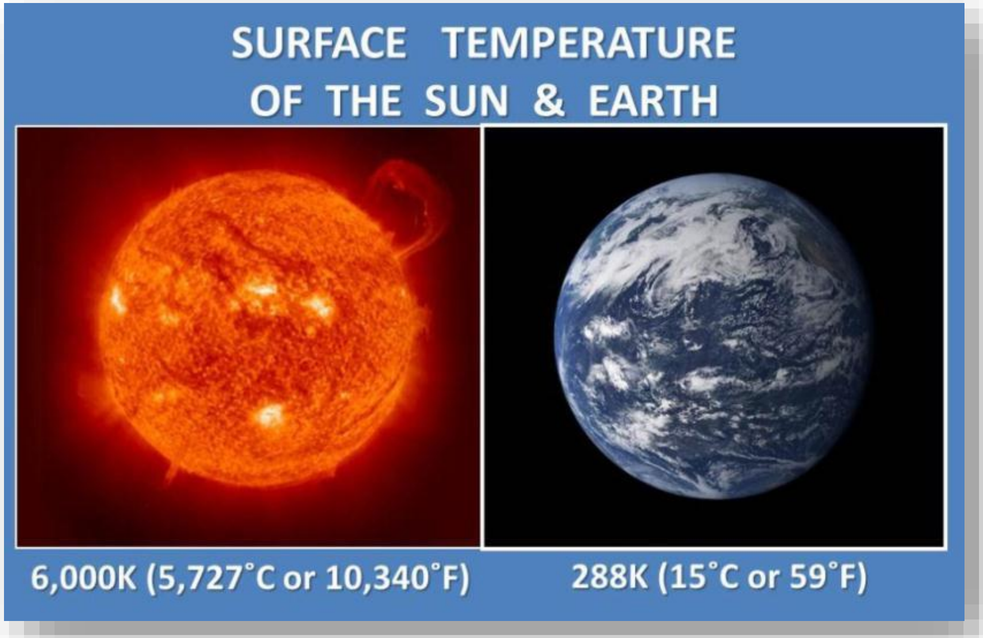
STEFAN-BOLTZMANN LAW

All objects with temperatures above absolute zero (0K or −273°C) emit radiation at a rate proportional to the **fourth power** of their absolute temperature (Black Body Radiation)

$$E = \sigma T^4$$

E - maximum rate of radiation (often referred to as energy flux) emitted by each square meter of the object's surface.

"σ" (sigma) - the Stefan-Boltzmann constant (5.67 x 10^{-8}W/m^2K^4)
W (watt) - unit used to express power (expressed in joules per second).
T - object's average surface temperature in Kelvin.



Assuming the Earth to be in thermal equilibrium

$$S_0 / 4 (1- \alpha) = \sigma T^4$$

$$T = -18^oC$$

But, the actual mean surface temperature of the earth is much higher !

MISSING FACTOR : THE GREENHOUSE RADIATIVE EFFECT

The Greenhouse effect is the Earth’s natural warming process

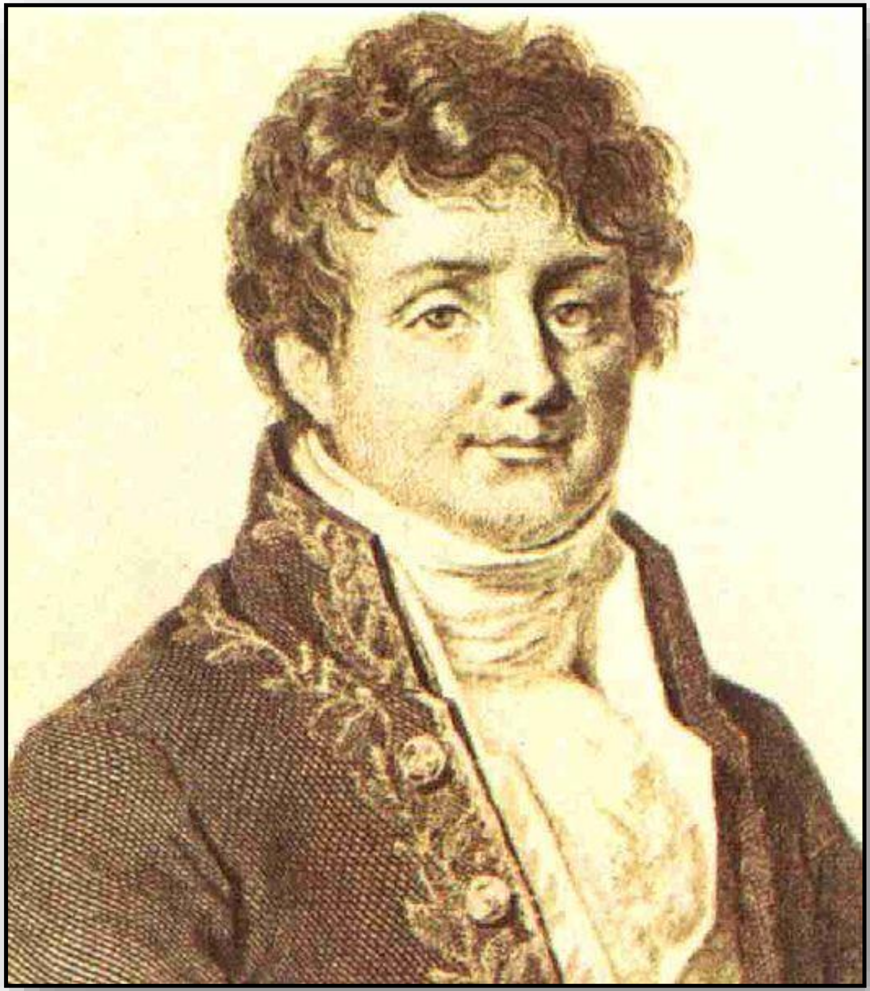
Exercise

Estimation of the global mean surface temperature of the Earth

THE GREENHOUSE EFFECT

- In 1827, Joseph Fourier, a French mathematician and physicist calculated the earth's energy budget and predicted that the average temperature on earth should be −18°C (0°F)
- He wondered why Earth's average temperature is much warmer, approximately 15°C (59°F)

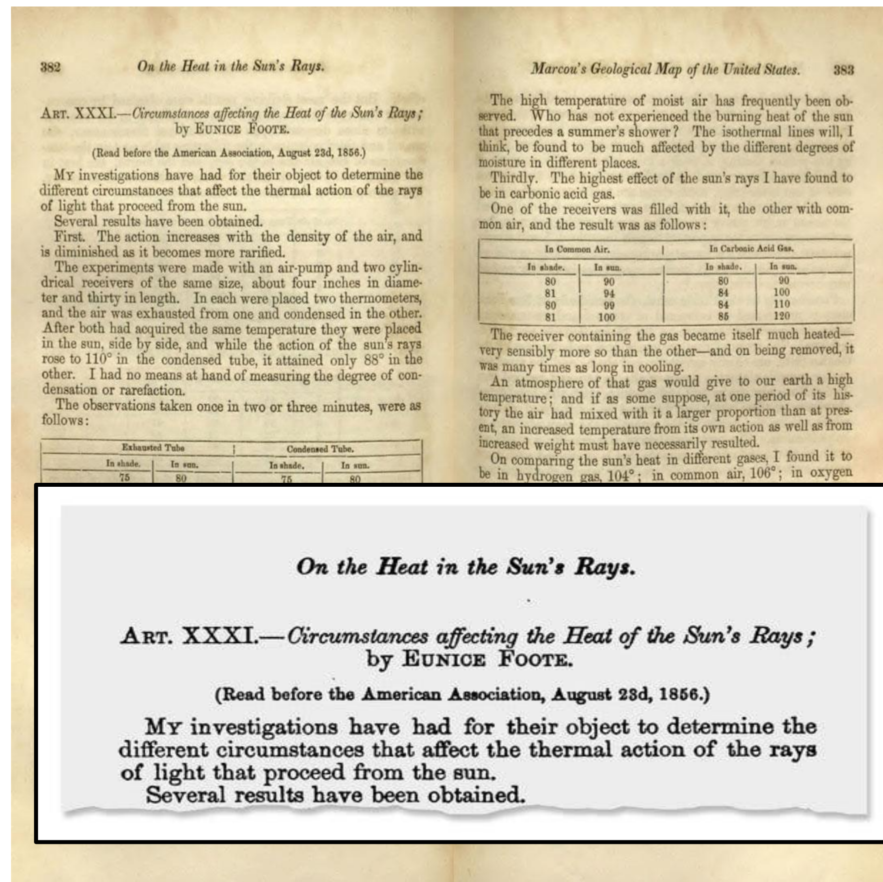
- He suggested the existence of another process occurring in the atmosphere which retains heat.



Eunice Newton, Foote, 1819-1888

"Additional carbon dioxide in the atmosphere would cause global warming and if as some suppose, at one period of [Earth's] history the air had mixed with it a larger proportion than at present, an increased temperature from its own action as well as from increased weight must have necessarily resulted."

The world's first climate scientist


382 *On the Heat in the Sun's Rays.*

ART. XXXI.—*Circumstances affecting the Heat of the Sun's Rays;* by EUNICE FOOTE.

(Read before the American Association, August 23d, 1856.)

MY investigations have had for their object to determine the different circumstances that affect the thermal action of the rays of light that proceed from the sun.

Several results have been obtained.

First. The action increases with the density of the air, and is diminished as it becomes more rarified.

The experiments were made with an air-pump and two cylindrical receivers of the same size, about four inches in diameter and thirty in length. In each were placed two thermometers, and the air was exhausted from one and condensed in the other. After both had acquired the same temperature they were placed in the sun, side by side, and while the action of the sun's rays rose to 110° in the condensed tube, it attained only 88° in the other. I had no means at hand of measuring the degree of condensation or rarefaction.

The observations taken once in two or three minutes, were as follows:

Exhausted Tube		Condensed Tube.	
In shade.	In sun.	In shade.	In sun.
75	80	75	80

Marcou's Geological Map of the United States. 383

The high temperature of moist air has frequently been observed. Who has not experienced the burning heat of the sun that precedes a summer's shower? The isothermal lines will, I think, be found to be much affected by the different degrees of moisture in different places.

Thirdly. The highest effect of the sun's rays I have found to be in carbonic acid gas.

One of the receivers was filled with it, the other with common air, and the result was as follows:

In Common Air.		In Carbonic Acid Gas.	
In shade.	In sun.	In shade.	In sun.
80	90	80	90
81	94	84	100
80	99	84	110
81	100	85	120

The receiver containing the gas became itself much heated—very sensibly more so than the other—and on being removed, it was many times as long in cooling.

An atmosphere of that gas would give to our earth a high temperature; and if as some suppose, at one period of its history the air had mixed with it a larger proportion than at present, an increased temperature from its own action as well as from increased weight must have necessarily resulted.

On comparing the sun's heat in different gases, I found it to be in hydrogen gas, 104°; in common air, 106°; in oxygen

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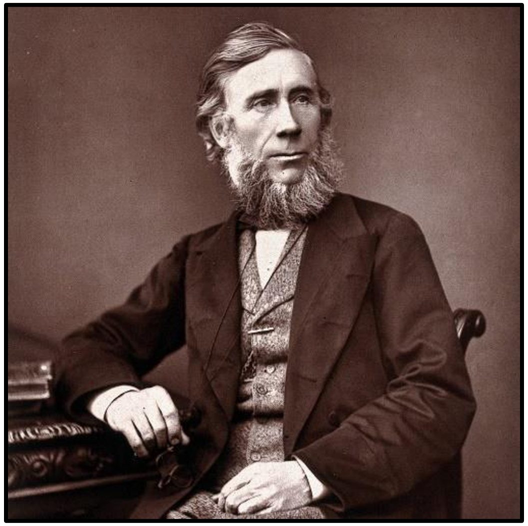
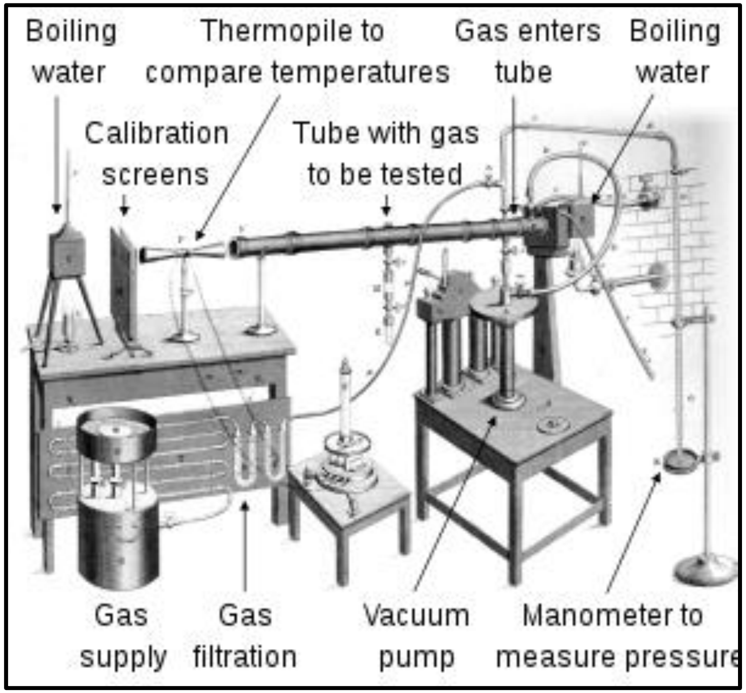


John Tyndall
1820-1893

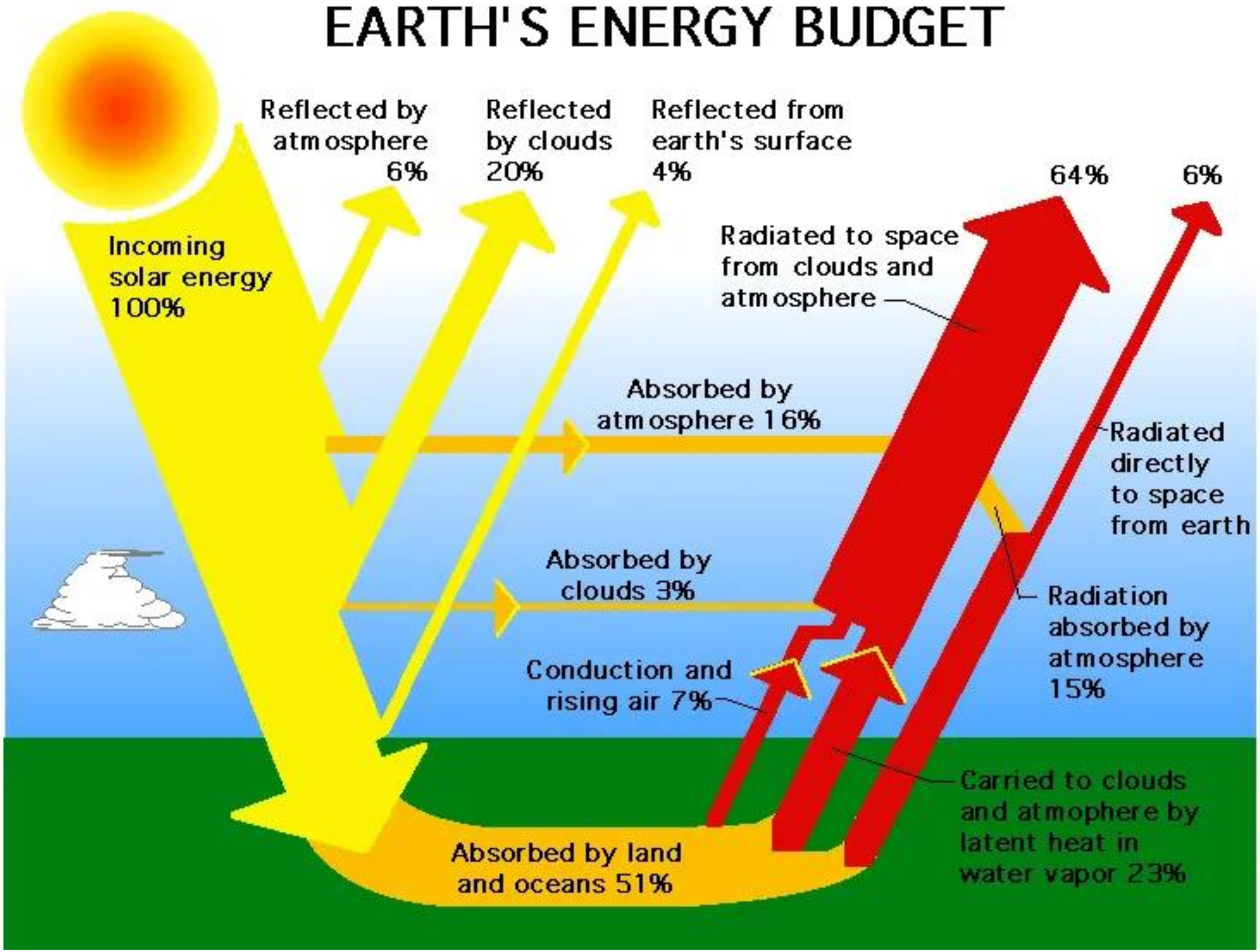


- In 1859, John Tyndall, a prominent 19th-century Irish physicist, published the first paper to directly measure the Earth's natural greenhouse effect. **He concluded it was due to absorption of longwave radiation by carbon dioxide in the upper atmosphere**
- Three years earlier, in 1856, Eunice Newton Foote had announced experiments demonstrating that water vapour and carbon dioxide absorb heat from solar radiation, but she did not attribute this to infrared absorption
- **Tyndall in 1860 was first to demonstrate and quantify that visually transparent gases are infrared emitters**
- Ultimately, full credit for the discovery of carbon dioxide's role—which is central to the understanding of climate change, weather and meteorology—was given to Tyndall, while Eunice Foote's contribution to climate science remained unknown and forgotten

Overlooked No More: Eunice Foote, Climate Scientist Lost to History, New York Times, April 21, 2020; Eunice Foote finally gets some credit, Kent Sate Magazine, Summer 2021; https://www.kent.edu/magazine/eunice-foote-finally-gets-some-credit

RADIATIVE FORCING

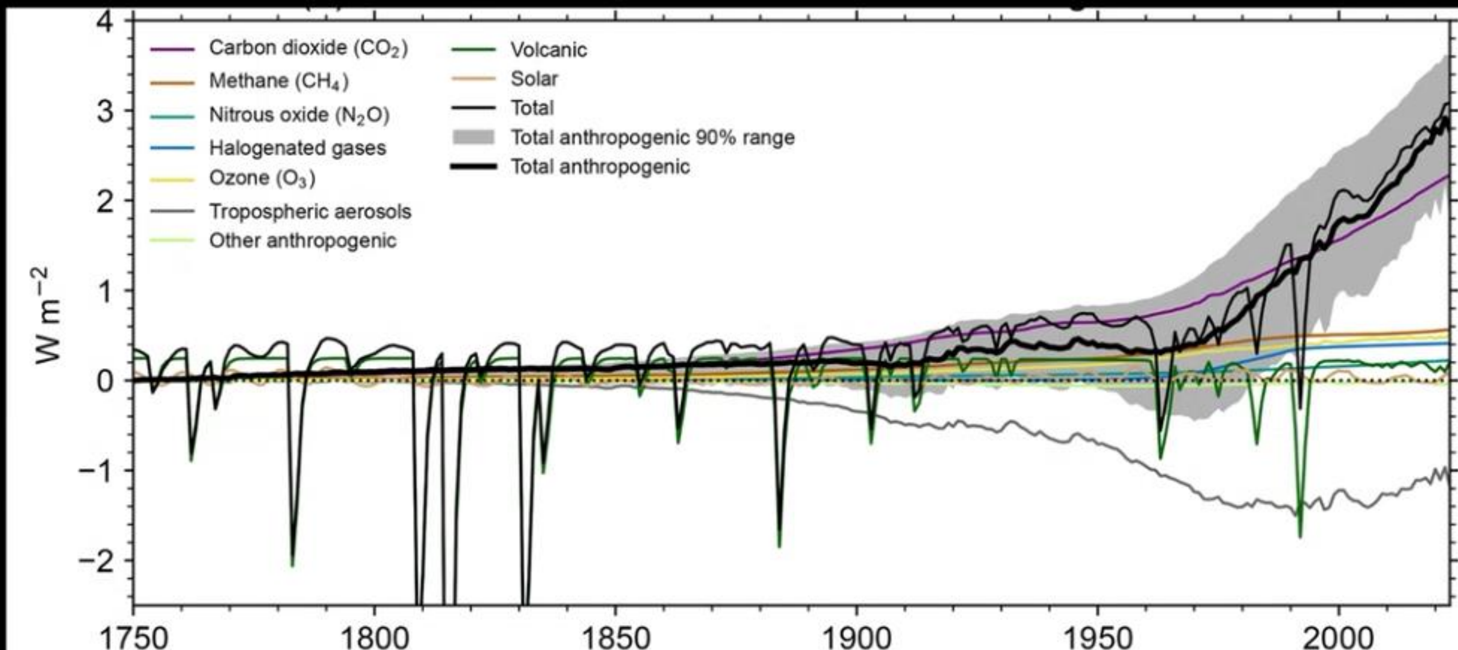
- Any factor that causes a change to Earth's energy balance is known as a **radiative forcing**. A radiative forcing is expressed in W/m^2 (watts per square meter).
  - A **positive forcing**, such as that produced by increasing concentrations of greenhouse gases, *tends to warm* the Earth's surface.
  - A **negative forcing**, such as that produced by airborne particulates that reflect solar energy, *tends to cool* the Earth's surface
  - Forcing may be either natural or human caused (also known as anthropogenic) or human induced (geoengineering)
  - Natural forcing (green house effect) makes earth habitable



This diagram of Earth’s energy budget shows incoming energy from the Sun and where that energy goes once it reaches the Earth system.

NASA GPM

Effective Radiative Forcing (1750-2023)

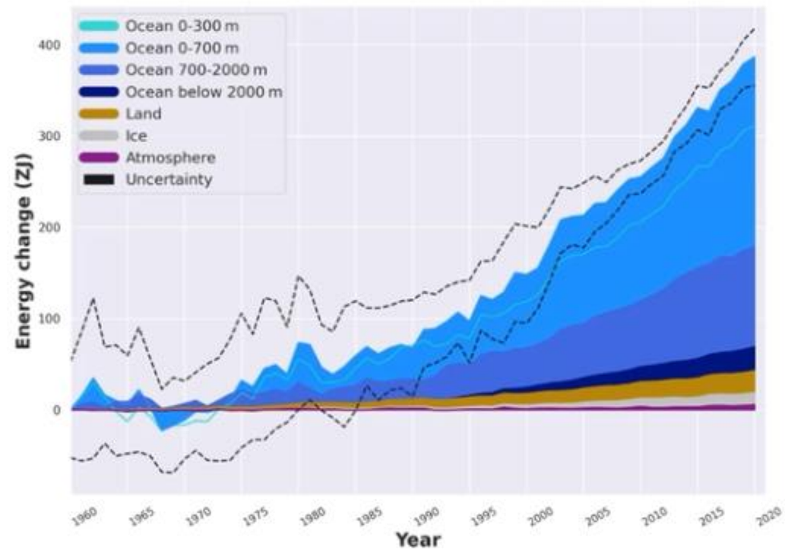


The estimate of ERF for 2023 is lower than in 2022. The main reason for the decline in 2023 relative to 2022 is a very strong contribution from biomass burning aerosol in 2023, particularly organic carbon emissions which strengthened the negative aerosol ERF. Sulfur emissions from shipping have declined since 2020, weakening the aerosol ERF and adding around +0.1 W m−2 over 2020 to 2023. However, the strengthened negative ERF from increased biomass burning likely dominated the effect of reduced shipping emissions.

Source: Forster et al. (2024)

P.M. Forster, et. al, Earth Systems Science, 2025, 17, 2641

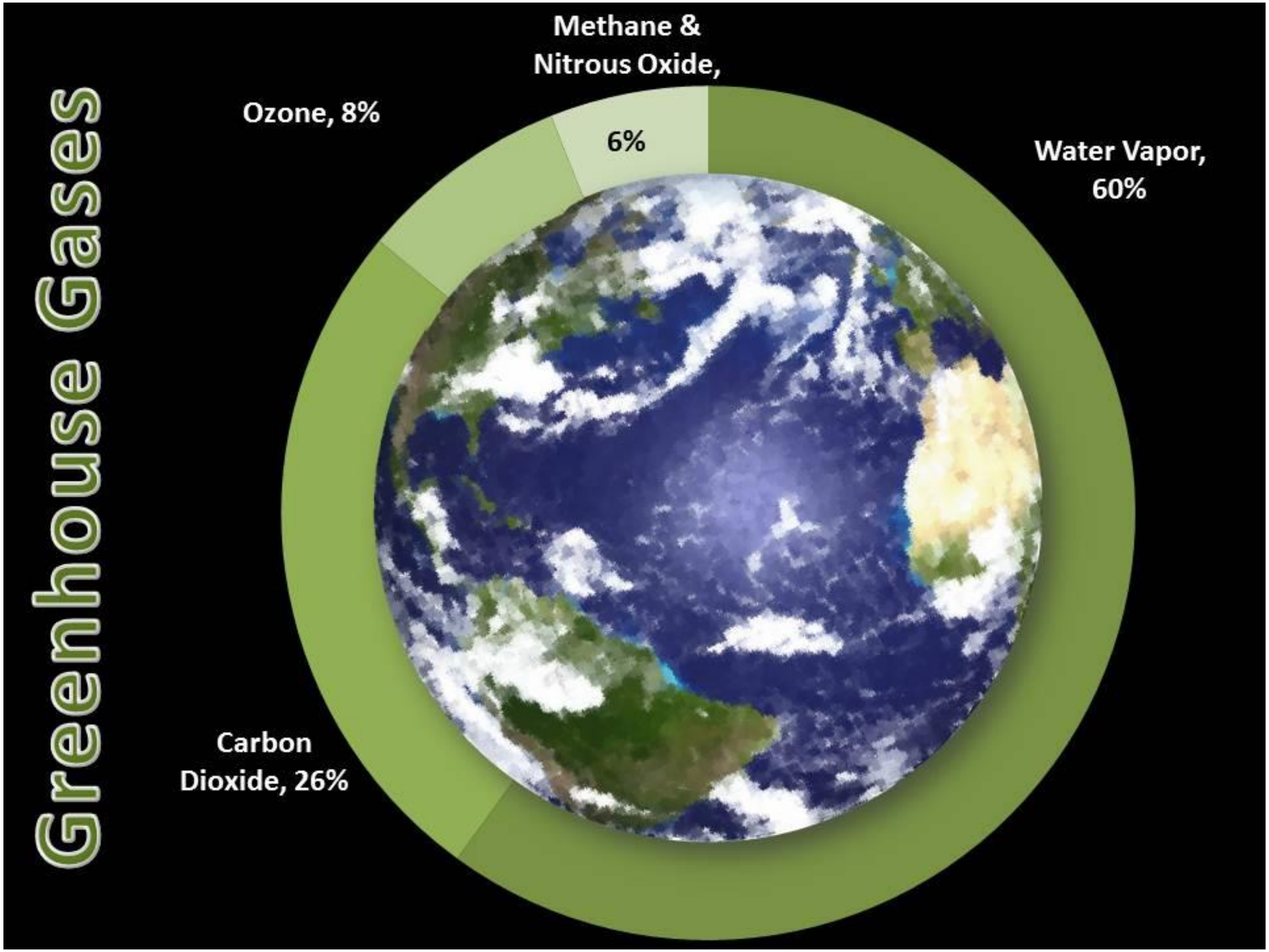
EARTH IS OUT OF ENERGY BALANCE



Schuckmann et al. 2023

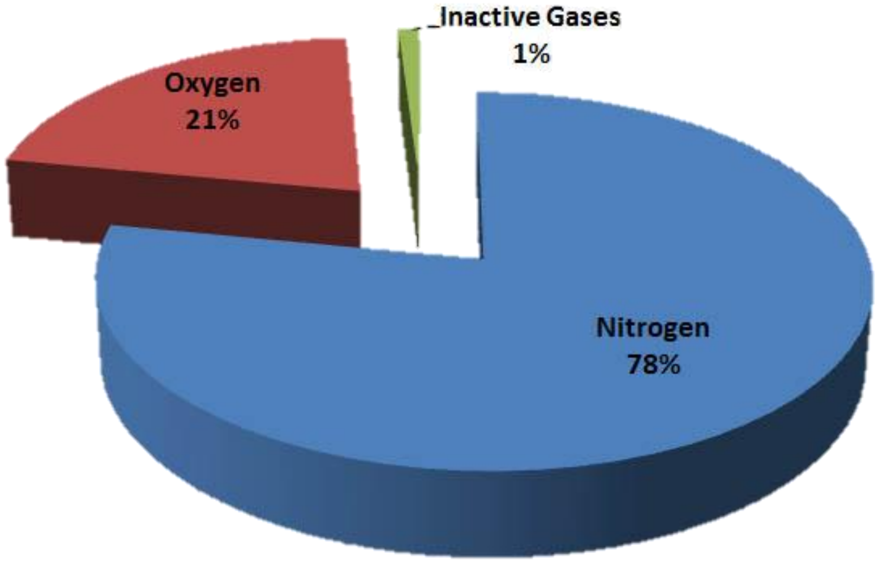
The Earth heat inventory provides a measure of the Earth energy imbalance (EEI) and allows for quantifying how much heat has accumulated in the Earth system, as well as where the heat is stored. The Earth system has continued to accumulate heat. The majority, about 89 %, of this heat is stored in the ocean, followed by about 6 % on land, 1 % in the atmosphere, and about 4 % available for melting the cryosphere. Over the most recent period (2006–2020), the EEI amounts to 0.76±0.2 W m^{-2}. The Earth energy imbalance is the most fundamental global climate indicator that we can use as the measure of how well the world is doing in the task of bringing anthropogenic climate change under control

K.V. Schuckmann et. al., Earth Systems Science, 2023, 15, 1675


Greenhouse Gases
Methane & Nitrous Oxide,
6%
Ozone, 8%
Water Vapor, 60%
Carbon Dioxide, 26%

HOW DO GREENHOUSE GASES CAUSE WARMING?

- Our atmosphere comprise of O_2, N_2, H_2, CO_2, H_2O (v), $O_{3,}$ $NO_{x,}$ $CH_{4,}$ SF_6, HFC, PFC etc.
- Of this oxygen and nitrogen make up about 99% of the atmospheric gases
- Gases contributing to global warming are about 1 %
- Why do these small proportion of gases contribute to global warming ?
- Can you rank the gases in the order of their potential GHG effect based on some fundamental property of the molecule?



Hint : Think, diatomic or triatomic, degrees of freedom, point symmetry, linear or non linear molecule

THE BENEFICIAL ROLE OF GHG EFFECT

- It is important to remember that the greenhouse effect has a beneficial side. This is referred to as the natural greenhouse effect (i.e. one that has not been affected or influenced by human activities)
- If the earth's atmosphere did not contain any greenhouse gases, the global annual average surface temperature would be about -18 °C. That's pretty cold
- The presence of greenhouse gases raises this average temperature to about + 16 °C and makes the earth a much more habitable place

CLIMATE CHANGE AND GLOBAL WARMING

CLIMATE CHANGE

a significant and sustained change from one climatic condition to another

GLOBAL WARMING

specific kind of climate change in which Earth's average temperature is increasing

THANK YOU

If you do not change direction, you may end up where we are heading: Lao Tzu