Climate Science 101

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MIT IAP 2017

MIT JOINT PROGRAM

SCIENCE POLICY

GLOBAL CHANGE

Purpose of these lectures

- Develop a broad understanding of Earth’s climate system
- Understand how Earth’s climate responds to changes that are natural and human-induced

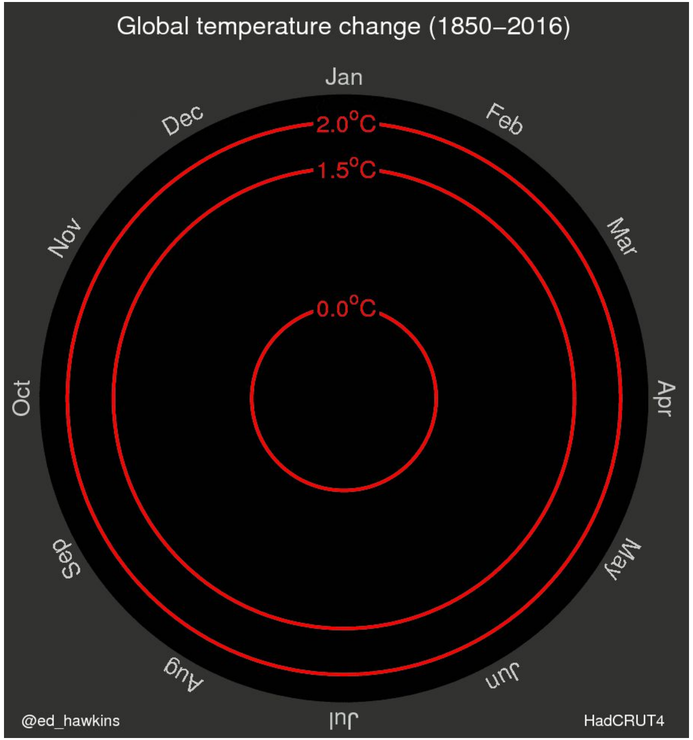
What these lectures are not

- Not about the politics or policies surrounding the issue of climate change

Today's topics

- History of climate science
- Structure and composition of Earth's atmosphere
- Earth's energy budget
- The greenhouse effect
- Variability in the climate system
- Emissions of greenhouse gases and their long-lived persistence

The world is warming. Why?



Global temperature change since 1850 to present day.

Since 1850, the global mean temperature has increased by around 0.8 degrees Celsius.

NASA/Goddard Space Flight Center Scientific Visualization Studio Data provided by Robert B. Schmunk (NASA/GSFC GISS)

Definition of “Climate”

Popular definitions:

- Climate is the average weather
- Climate is what you expect, weather is what you get

Scientific definition:

- **Climate is the statistics of weather**
    - Not just the mean weather, but the statistics of its variability
    - Aggregation over time scales of more than one year so that seasonal cycle is not considered

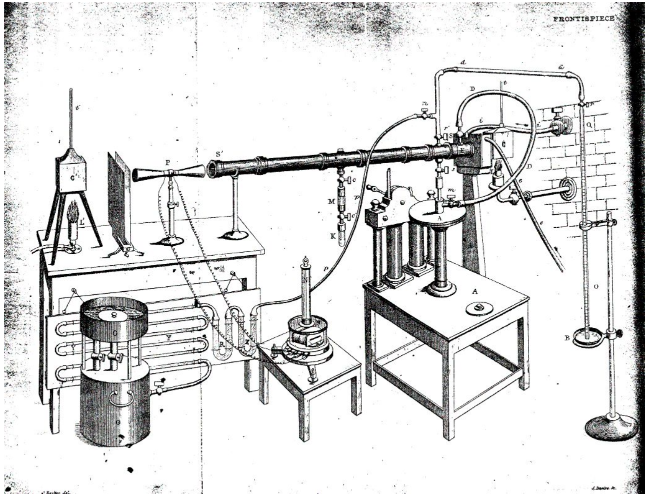
Examples climate variability:

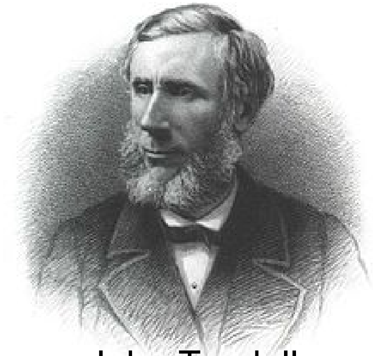
- El Nino/La Nina (2-4y), “Little ice age” (100y), Glacial cycles (20,000y)

History of climate science

Jean Baptiste
Joseph Fourier
(1768-1830)

The Greenhouse Effect





John Tyndall
(1820-1893)

History of climate science

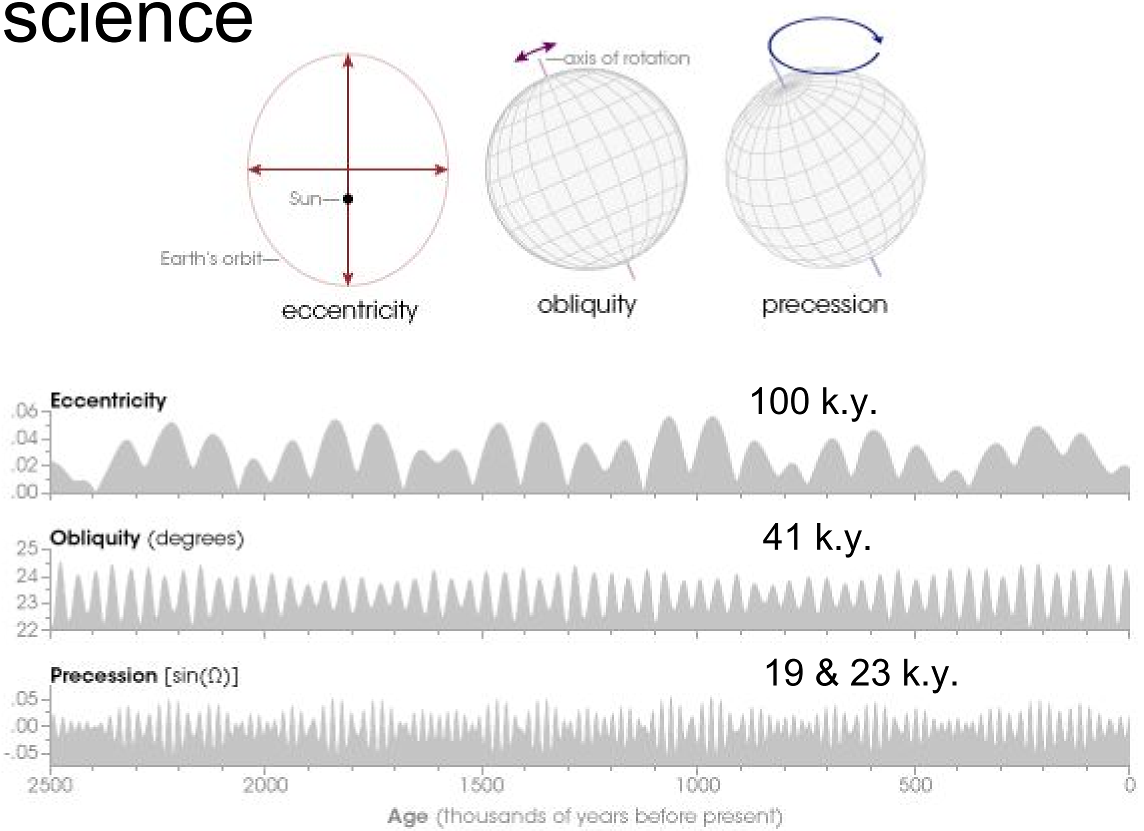
Svante Arrhenius
1859-1927

"If the quantity of carbonic acid [CO_2] in the air should sink to one-half its present percentage, the temperature would fall by about 4°; a diminution to one-quarter would reduce the temperature by 8°. ***On the other hand, any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4°;*** *and if the carbon dioxide were increased fourfold, the temperature would rise by 8°."*

Världarnas utveckling, 1906. p.53

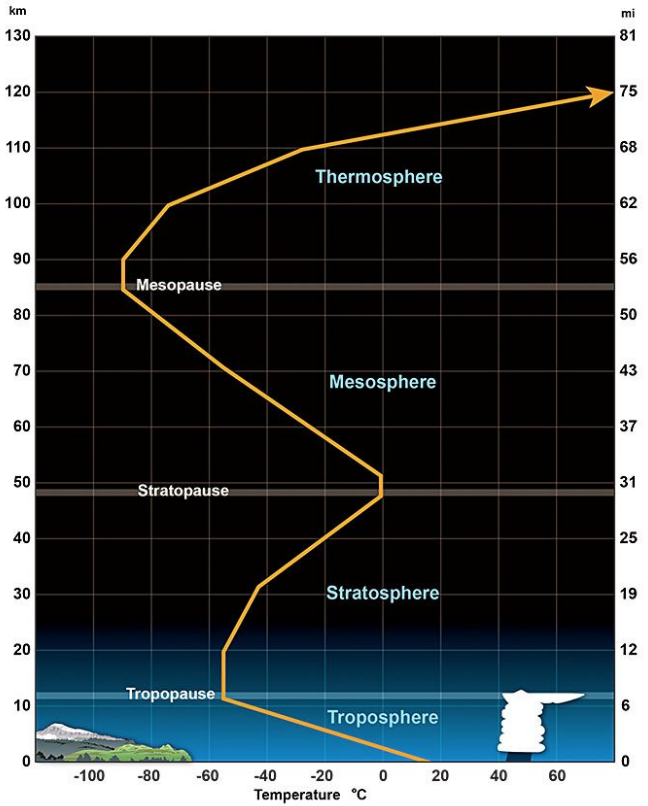
History of climate science

Milutin Milankovic
1879-1958



http://earthobservatory.nasa.gov/Features/Paleoclimatology_Evidence/

Structure of the atmosphere



Thermosphere: hot from solar charged particle interactions

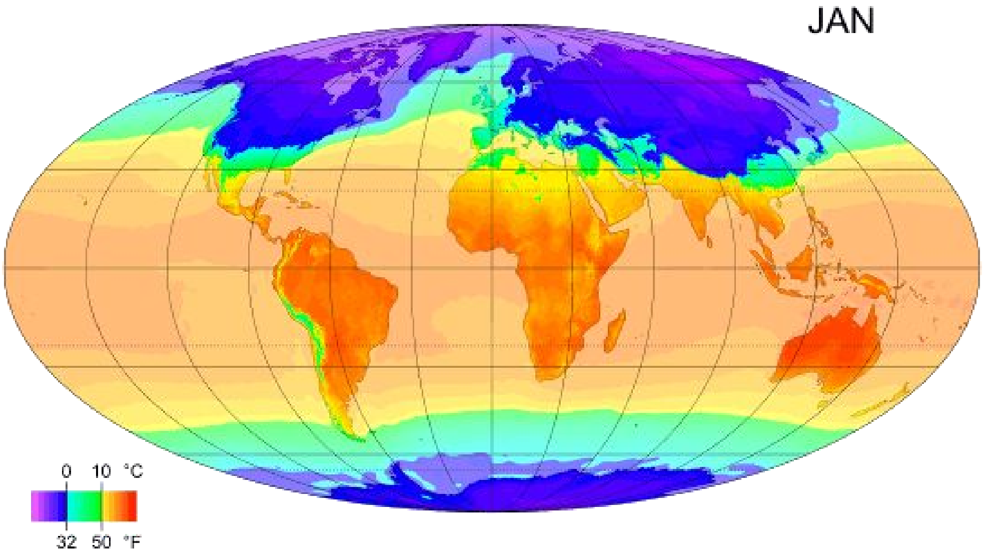
Middle atmosphere: stratosphere and mesosphere

Troposphere: ‘weather’ layer

http://www.srh.noaa.gov/srh/jetstream/atmos/layers.html

Atmosphere is very thin compared to the radius of Earth (6,300 km)

Temperature climatology



Mean surface temperatures:

- Warm temperature belt in tropics migrates North and South with the seasons.
- Most extreme variations are in high latitudes of Northern hemisphere

https://en.wikipedia.org/wiki/File:MonthlyMeanT.gif

Temperature climatology

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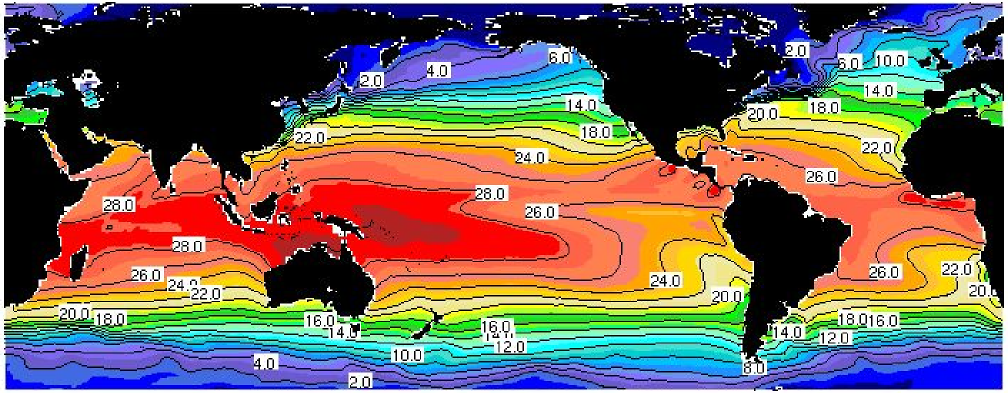
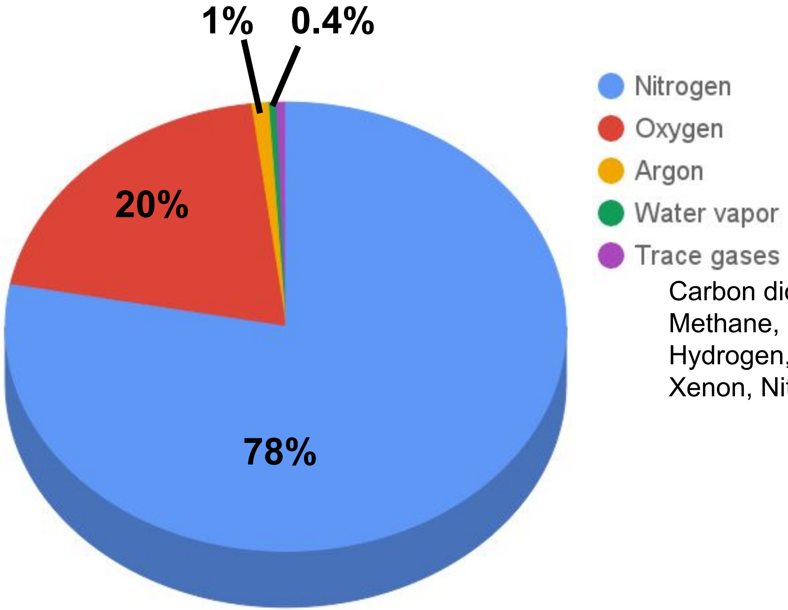


Sea surface temperatures:

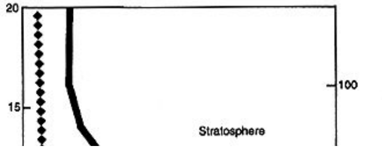
- Highest temperatures around equator, but not zonally symmetric
- Many interesting features/currents you can see

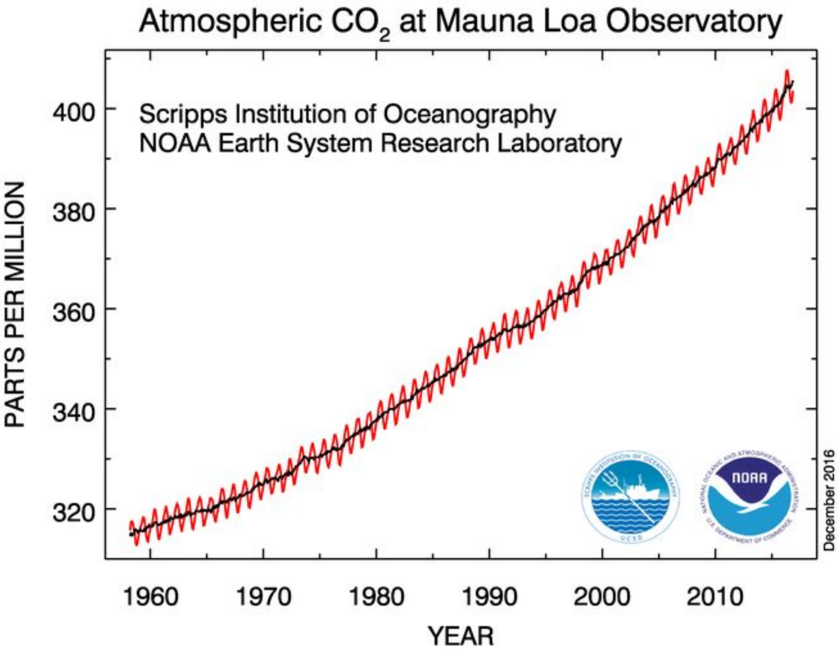
http://iridl.ldeo.columbia.edu/maproom/Global/Ocean_Temp/Monthly_Temp.html?T=Dec%202012

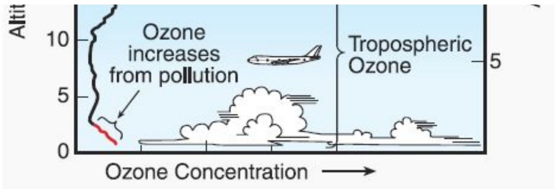
Atmospheric composition



Carbon dioxide (0.04%)
Methane, Helium, Kryptor
Hydrogen, Ozone, Neon,
Xenon, Nitrous oxide

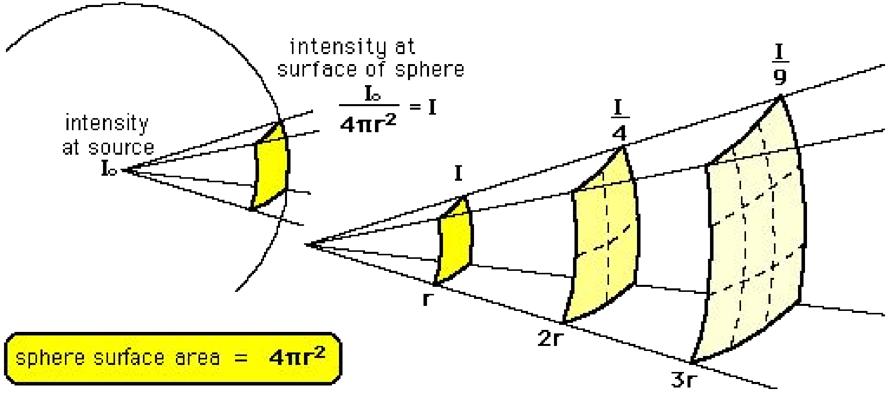


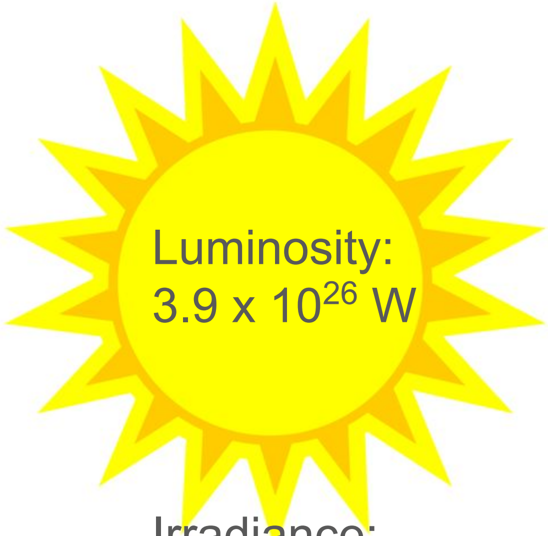




http://www.esrl.noaa.gov/gmd/ccgg/trends/full.html/on, et al., 2007

Earth energy balance





Luminosity:
3.9×10^{26} W

Irradiance:
6.4×10^{7} W/m^2

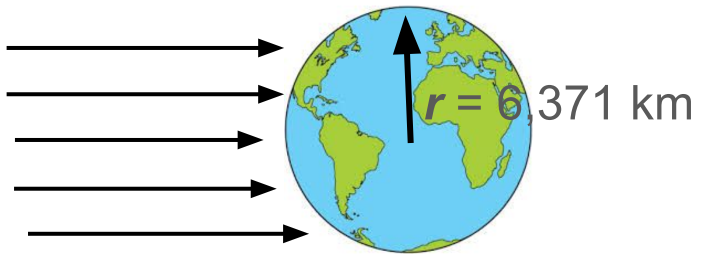
1.5×10^{11} m

Irradiance:
1370 W/m^2

↓

Solar constant S_0

Earth energy balance



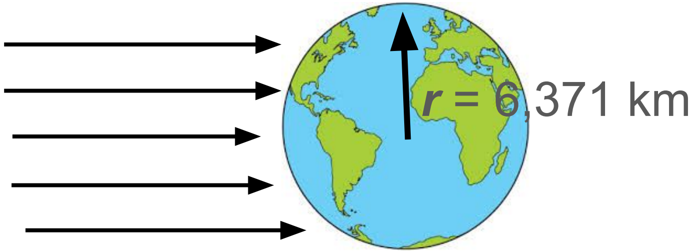
Total absorbed solar radiation: $S_0(1-a_p)\pi r^2$

$a_p \simeq 0.30$

Absorption per unit area: $\frac{S_0}{4}(1-a_p)$

Planetary albedo is the fraction of incident radiation reflected to space

Earth energy balance



Case of no atmosphere:

Can estimate Earth's surface temperature using Stefan Boltzmann law:

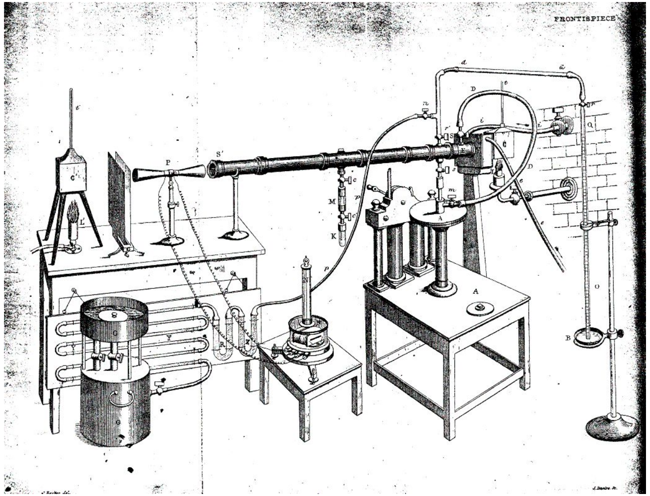
$$F = \sigma T^4 \qquad \sigma = 5.67 \times 10^{-8} W/m^{-2} K^{-4}$$

$$\sigma T_e^4 = \frac{S_0}{4}(1 - a_p)$$

The effective emission temperature of Earth is 255 K (**-18°C**) if we had no atmosphere. Observed average surface temperature is 15°C. Way too cold!!!

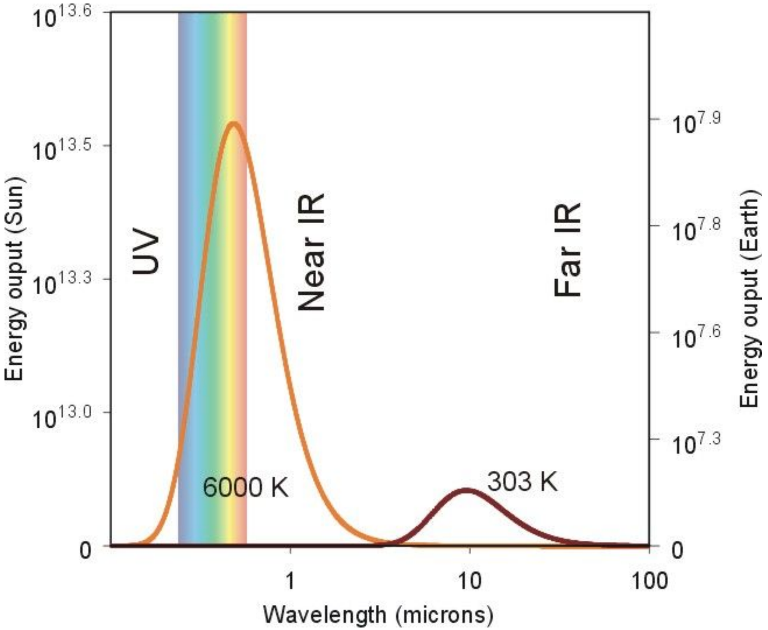
Greenhouse effect

John Tyndall
(1820-1893)



Measured infrared (IR) absorption of atmospheric gases

Wien's law

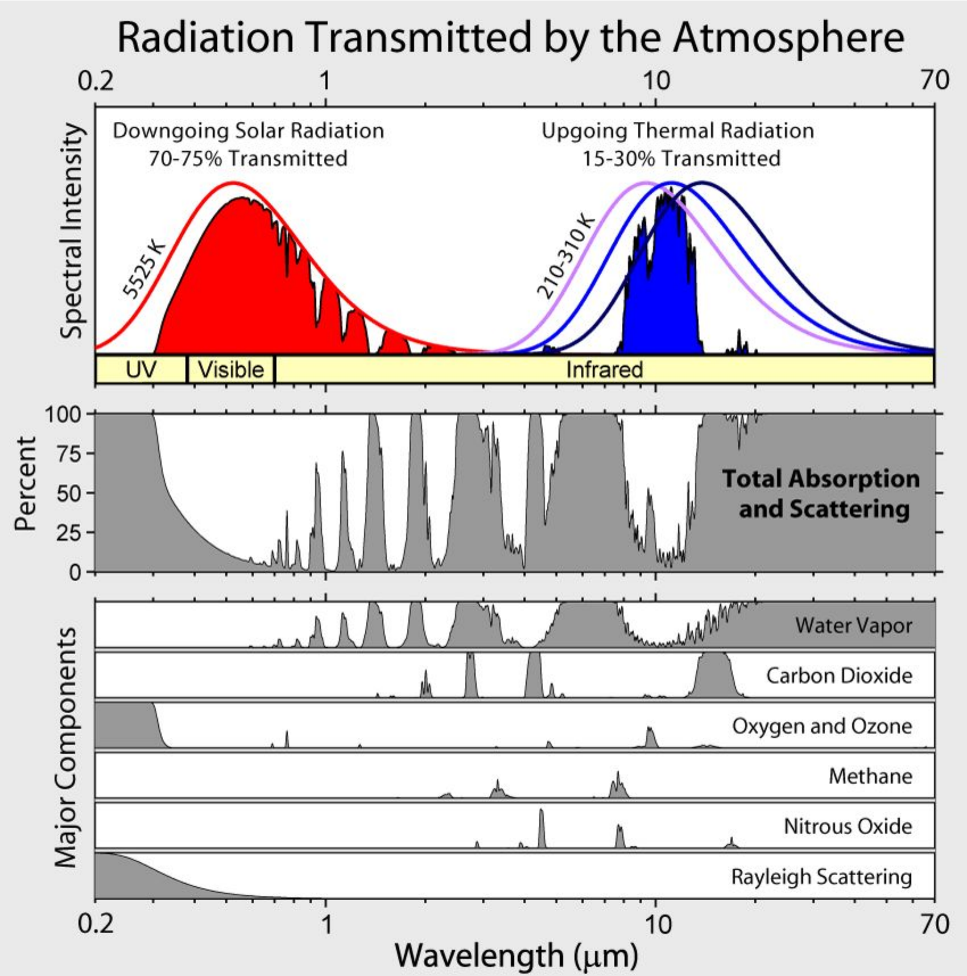


Greenhouse effect

Solid lines are the Planck blackbody emission spectra, as function of temperature.

The solid filled parts show the spectra of the incoming solar radiation transmitted through the atmosphere to the surface, and the outgoing terrestrial radiation transmitted through to the top of the atmosphere.

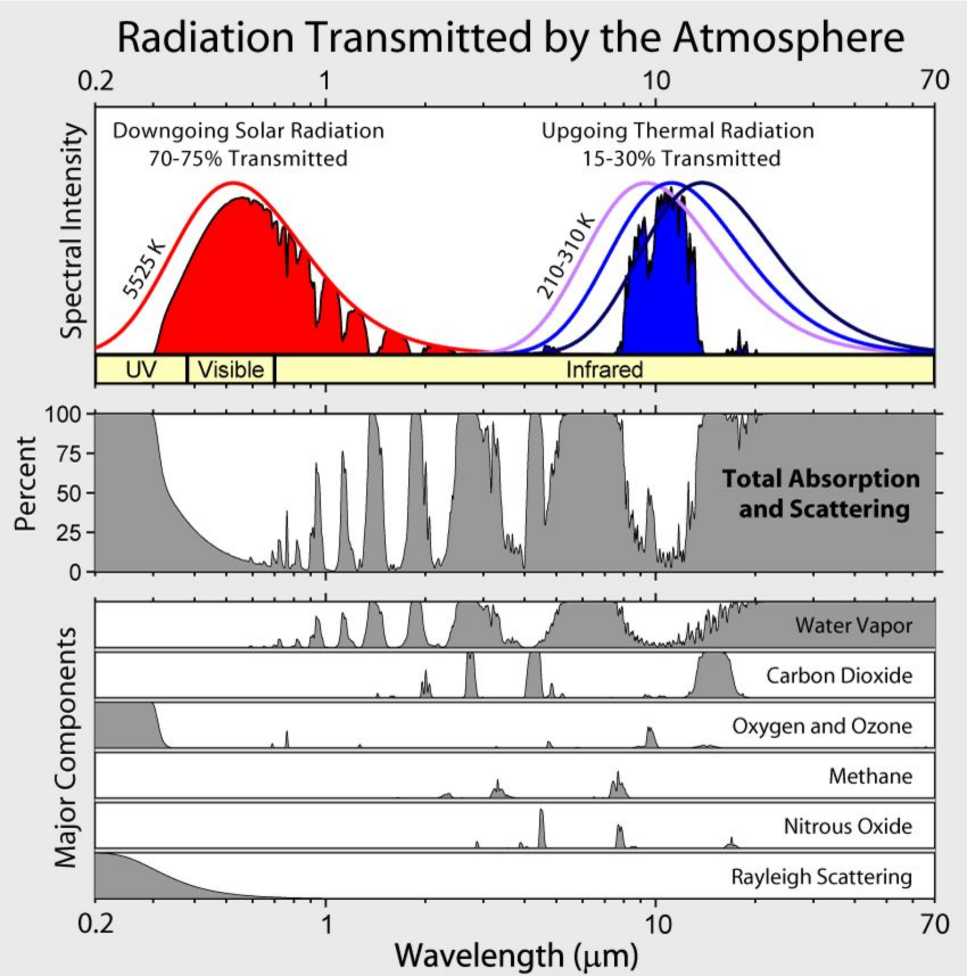
The difference between the two shows the wavelengths at which the solar/terrestrial radiation is absorbed, and by what gas/process.



https://en.wikipedia.org/wiki/File:Atmospheric_Transmission.png

Greenhouse effect

- Only 15-30% of terrestrial IR radiation escapes to space, with almost all the far IR being absorbed by the atmosphere.
- Water vapor is strongest absorber of IR heat like Tyndall concluded.
- Carbon dioxide bands do not completely overlap with water vapor.



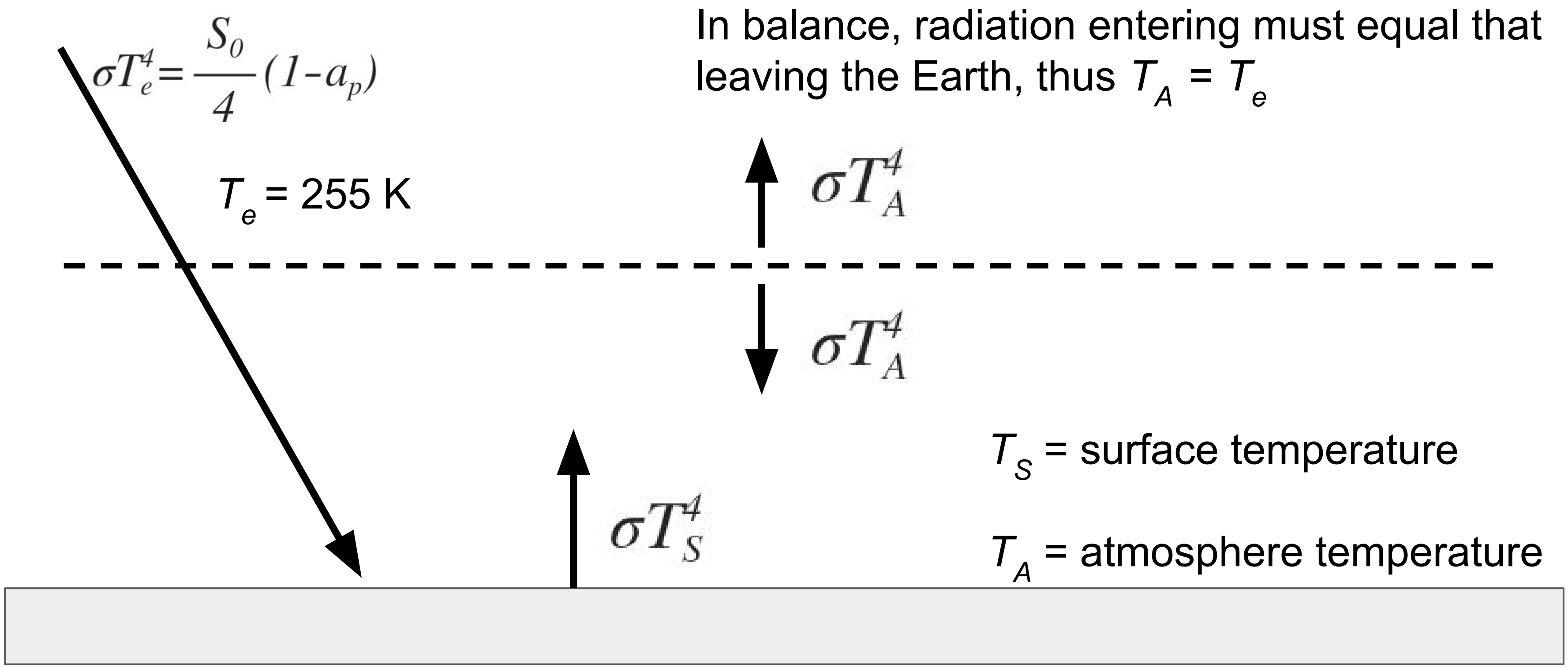
https://en.wikipedia.org/wiki/File:Atmospheric_Transmission.png

Simple model with the greenhouse effect

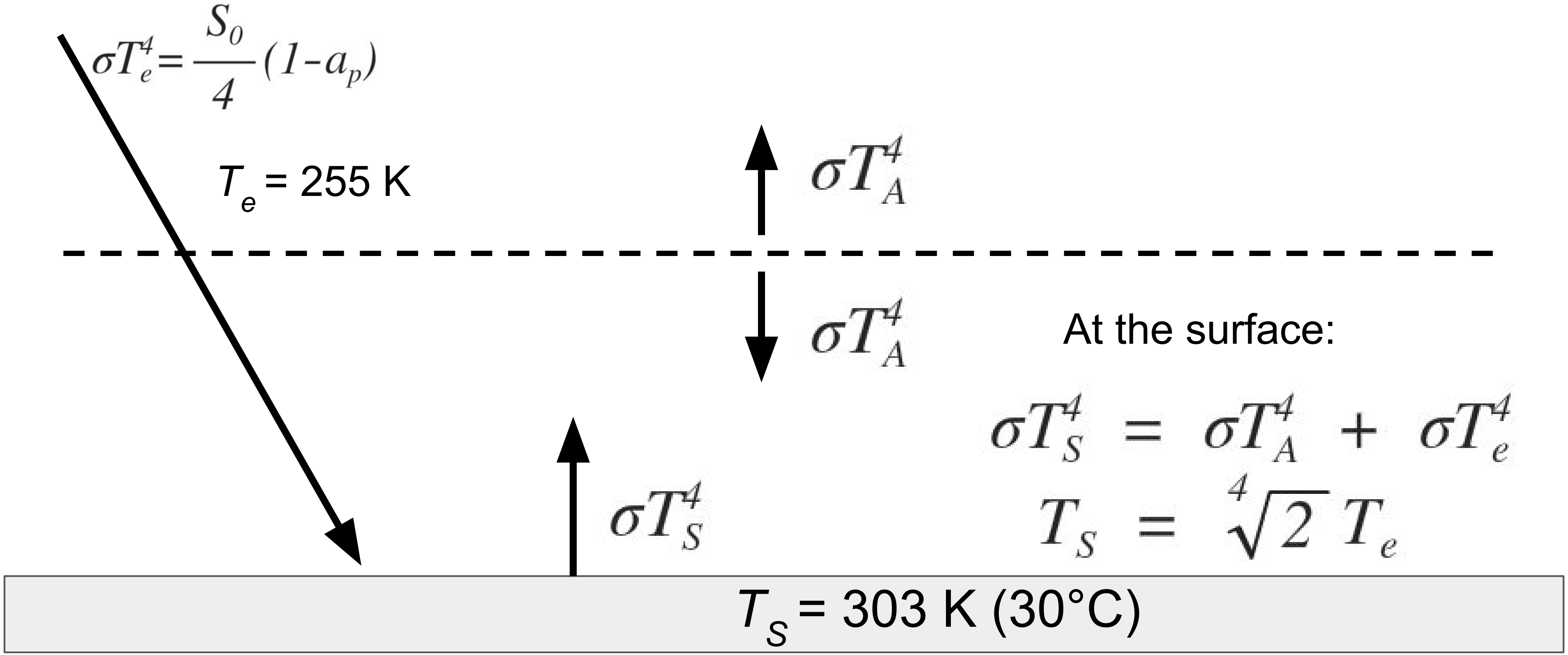
Assumptions:

- Atmosphere is completely transparent to solar radiation
- Atmosphere is opaque to infrared radiation
- Infrared emission is from surface and the atmospheric layer
- Atmosphere is a single slab

Simple model with the greenhouse effect



Simple model with the greenhouse effect



Simple model with the greenhouse effect

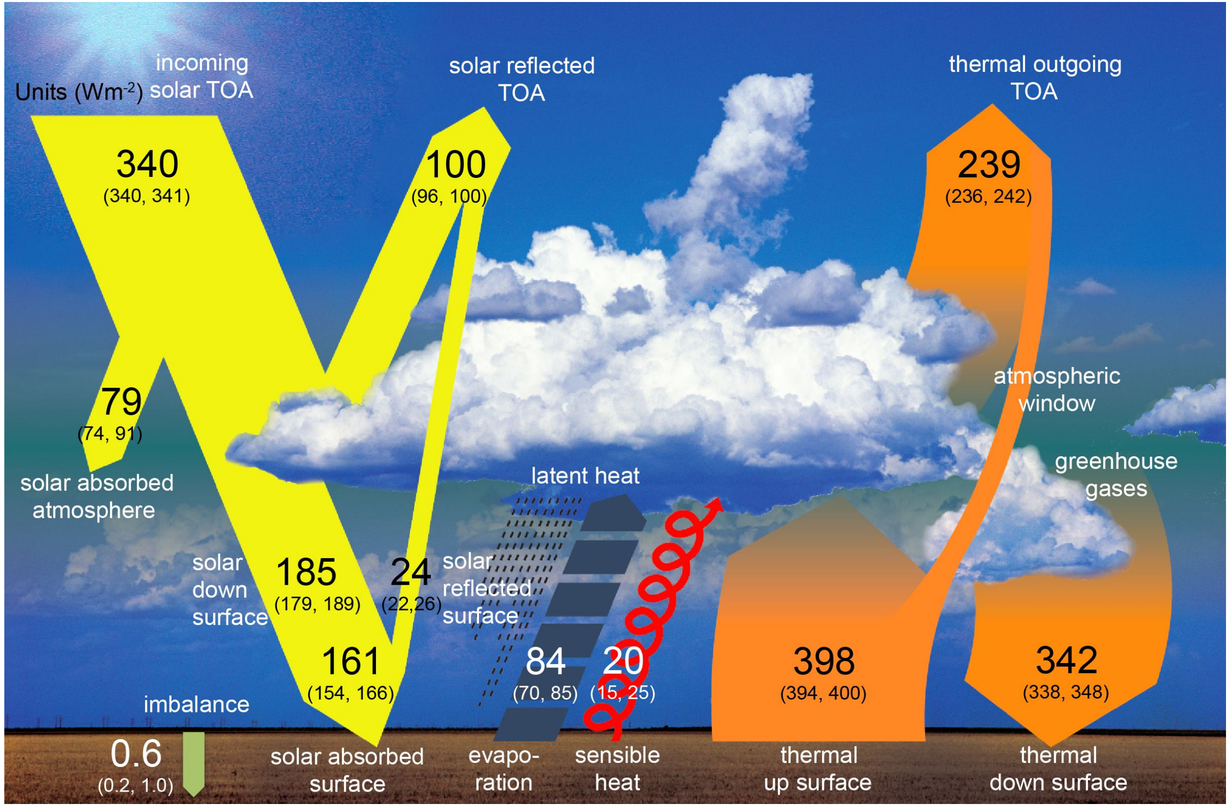
- Due to greenhouse effect, the surface must warm enough to balance both incoming sunlight and the radiation from the atmosphere back to the surface

Limitations:

- Atmosphere is not completely opaque to infrared radiation, consider ‘leaky’ greenhouse, and more than one layer

- Heat transported by convection as well as radiation

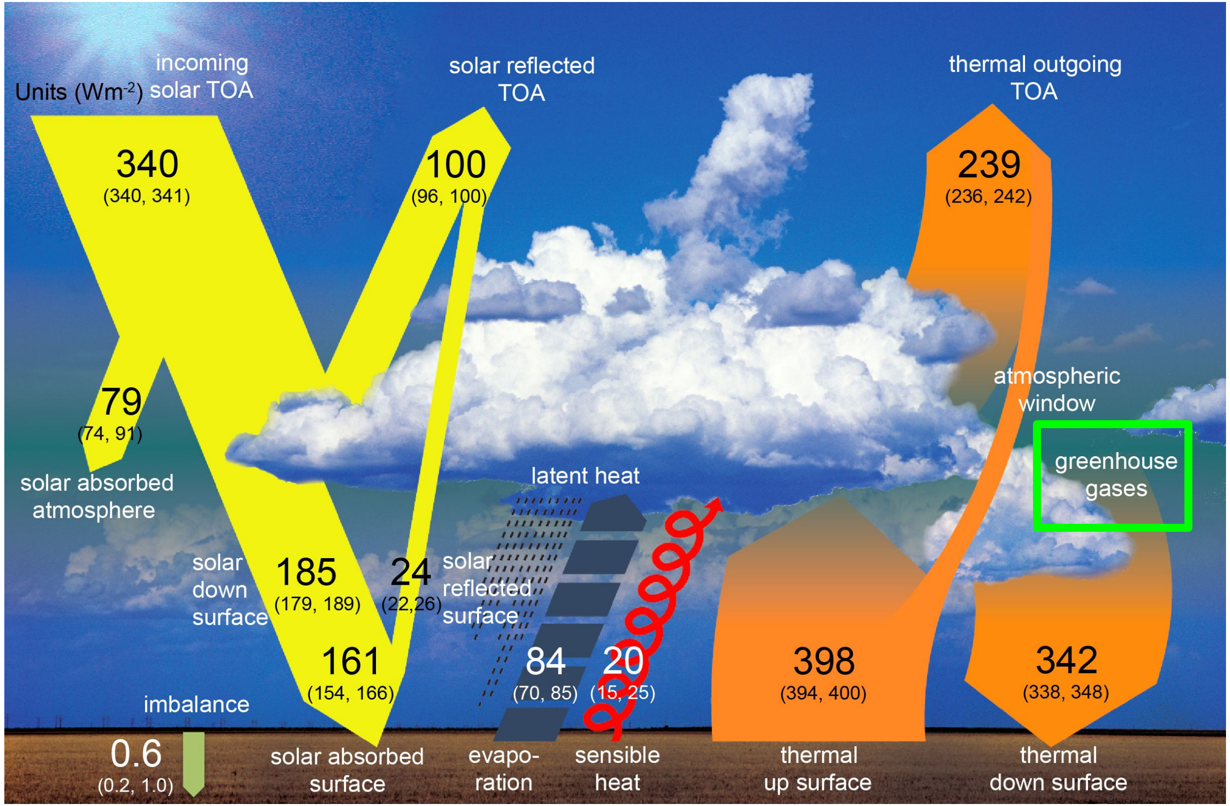
Earth's radiative budget



Global mean energy budget

IPCC AR5, Chapter 2, p.181

Earth’s radiative budget



Increasing greenhouse gases, increases IR emission back to the surface, which must adjust, i.e. by warming up.

IPCC AR5, Chapter 2, p.181

Climate variability

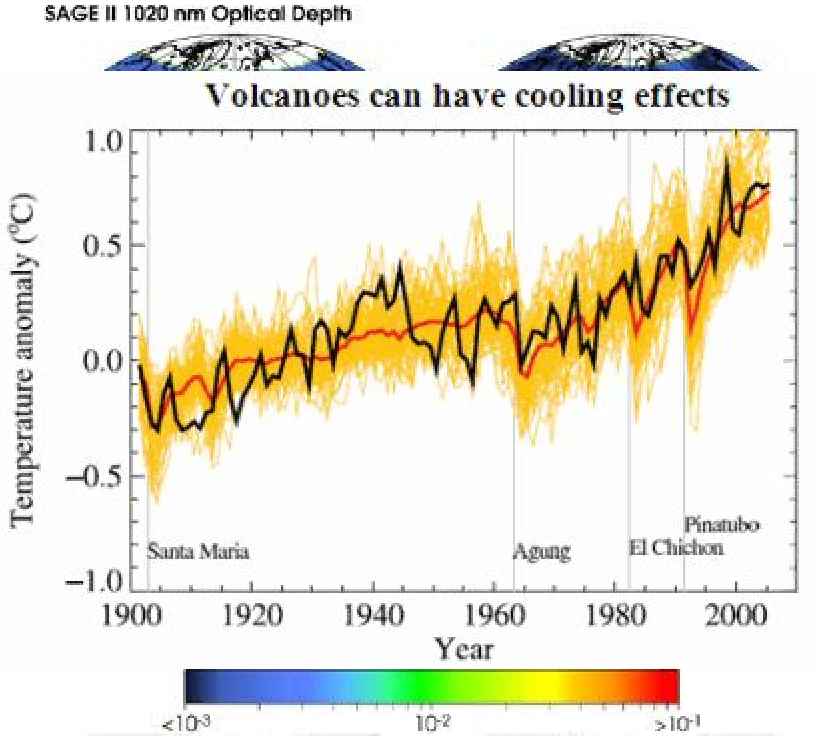
Causes of natural climate variability

- ‘External forcing’ of the climate system:
    - Glacial periods caused by changes in Earth’s orbit ~10,000 - 100,000 years
    - Large volcanic eruptions
    - Solar variability

- ‘Internal’ climate variability (chaos due to nonlinear interactions of a complex system)
    - El Niño, North Atlantic Oscillation

Volcanic eruptions impact climate

Mount Pinatubo, Philippines 1991



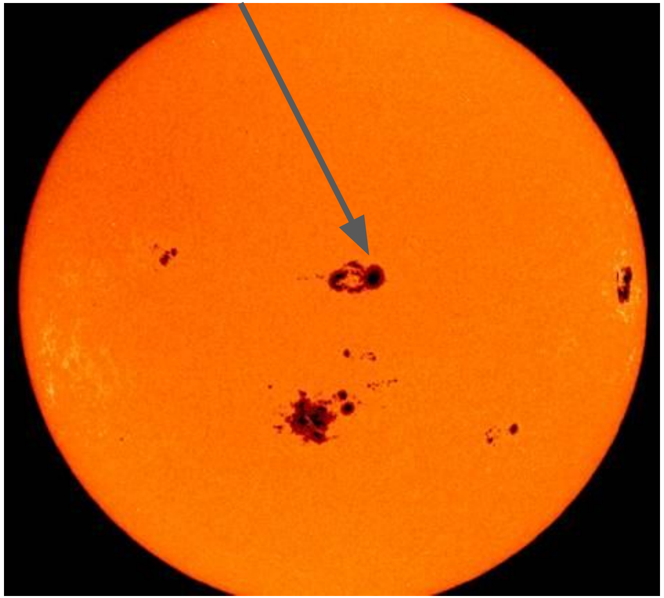
USGS Photo, 6/12/1991

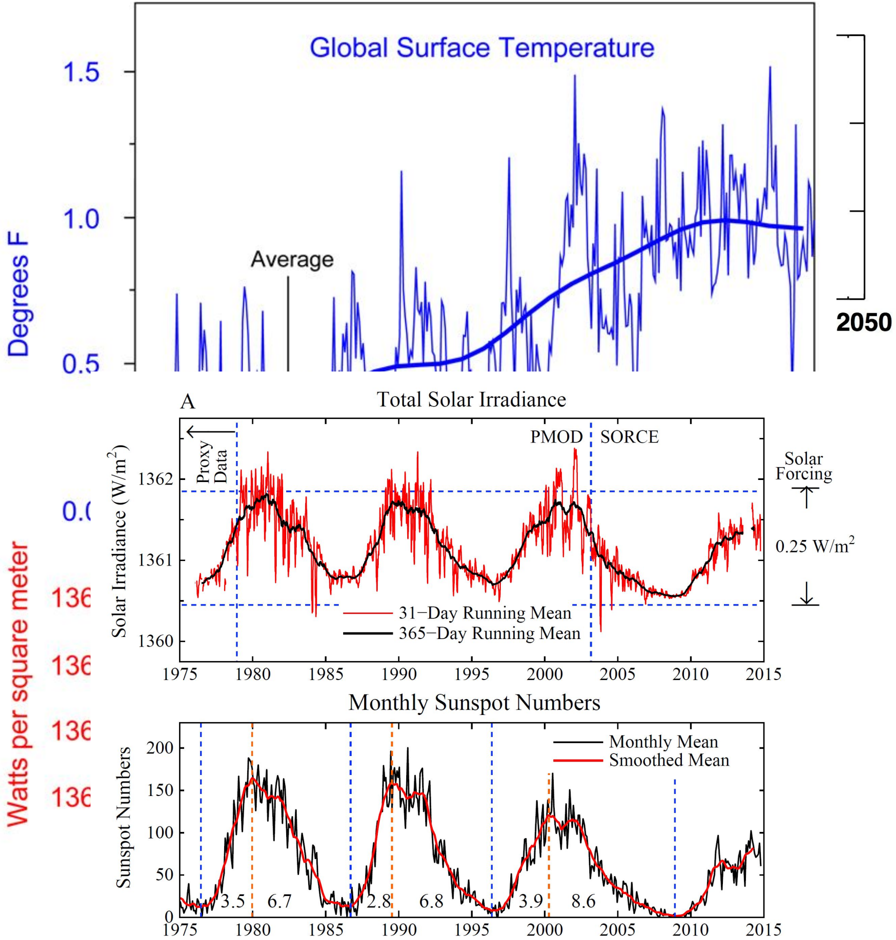
IPCC AR1, Ch 8

NASA

Solar forcing of climate

Energy output of the Sun shows slight fluctuations as the number of sunspots varies



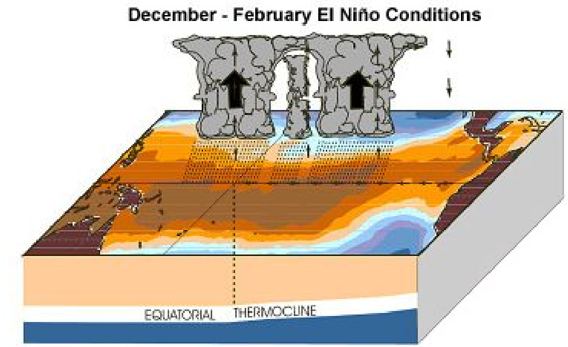


National Weather Service

NASA

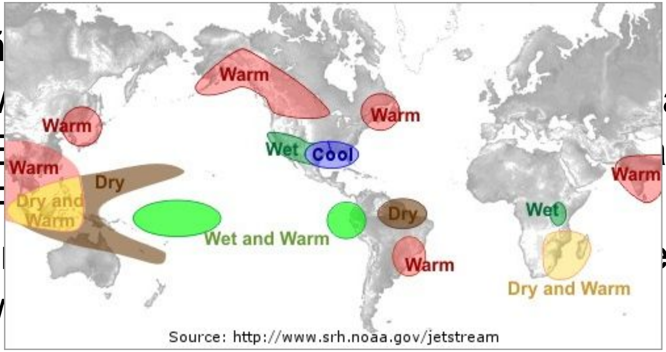
El Niño Southern Oscillation (ENSO)

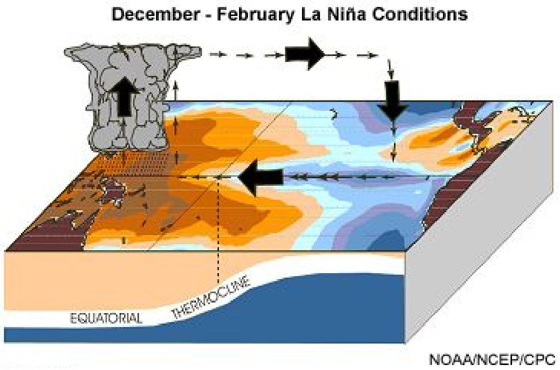
The ENSO cycle describes the fluctuations in temperature between the ocean and atmosphere in the Pacific that lead to large-scale weather pattern changes across many regions of the world.



El Niñ

- V ator
- E torial F
- Ir er w





La Niñ

- S
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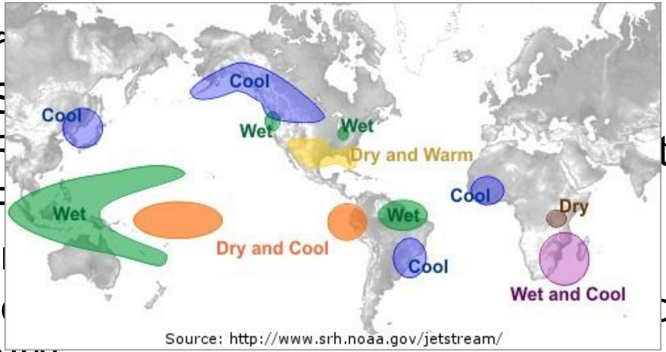
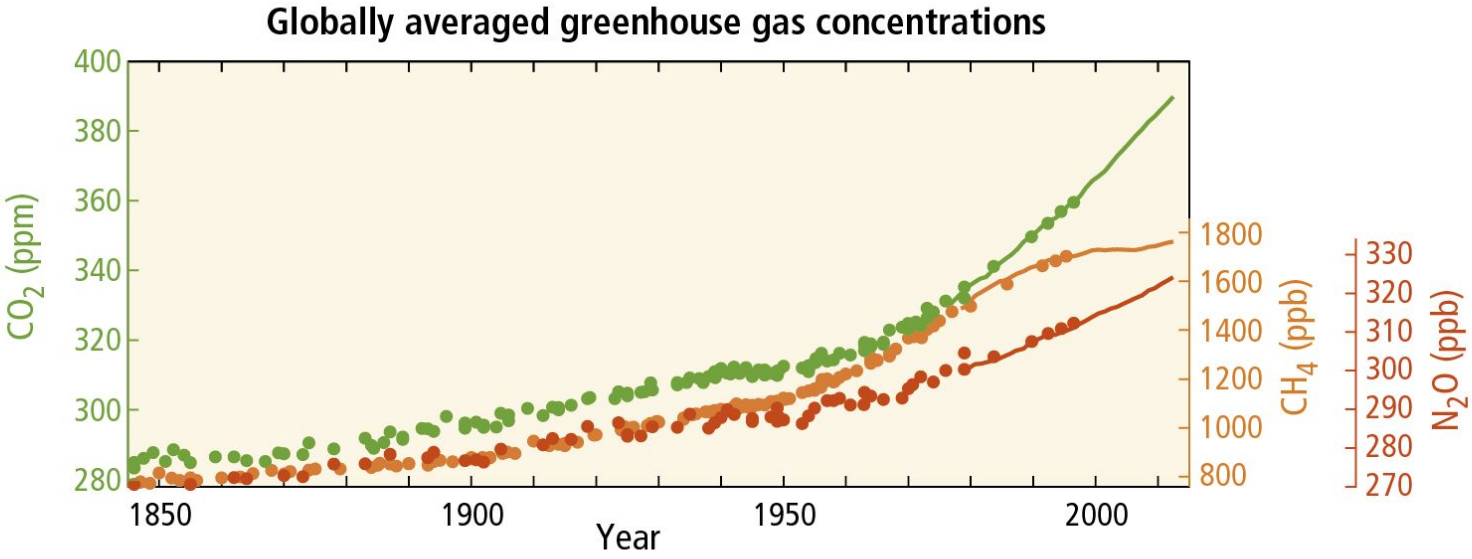
- Ir t pler in NW



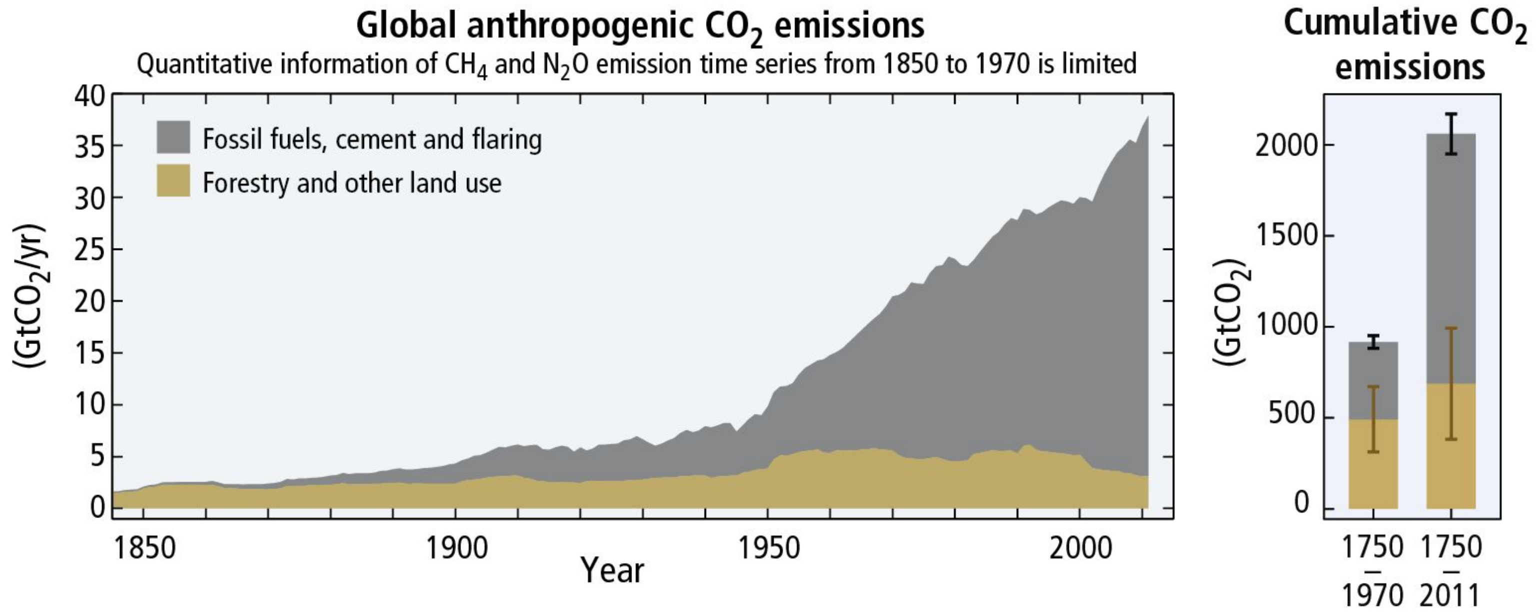
Greenhouse gas concentrations in the atmosphere



Increase in greenhouse gases in the atmosphere are primarily from increases in carbon dioxide, methane and nitrous oxide.

IPCC AR5, SPM11_rev1-01

Greenhouse gas changes in the atmosphere

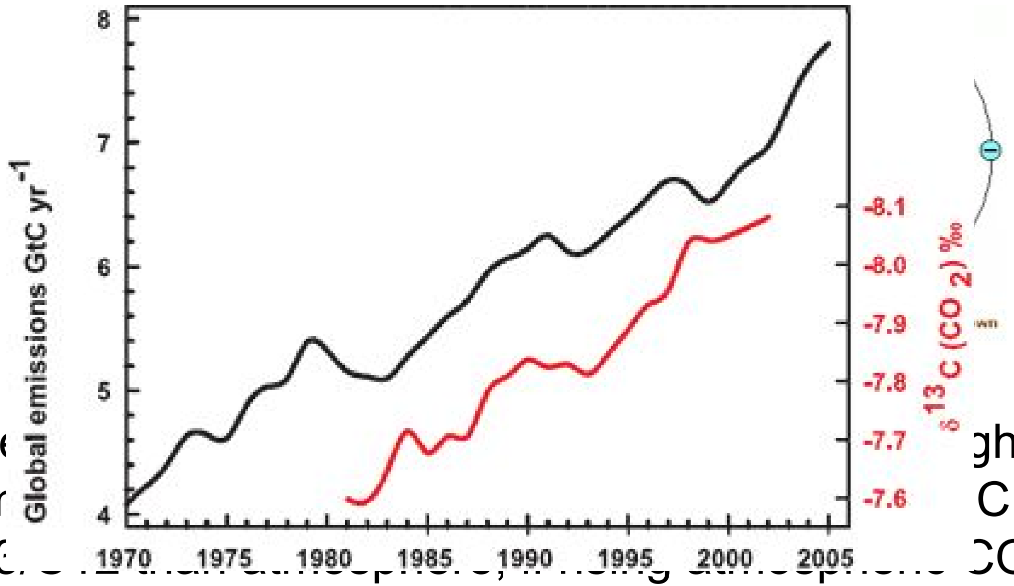


Global anthropogenic CO_2 emissions

IPCC AR5, SPM11_rev1-01

Greenhouse gas changes in the atmosphere

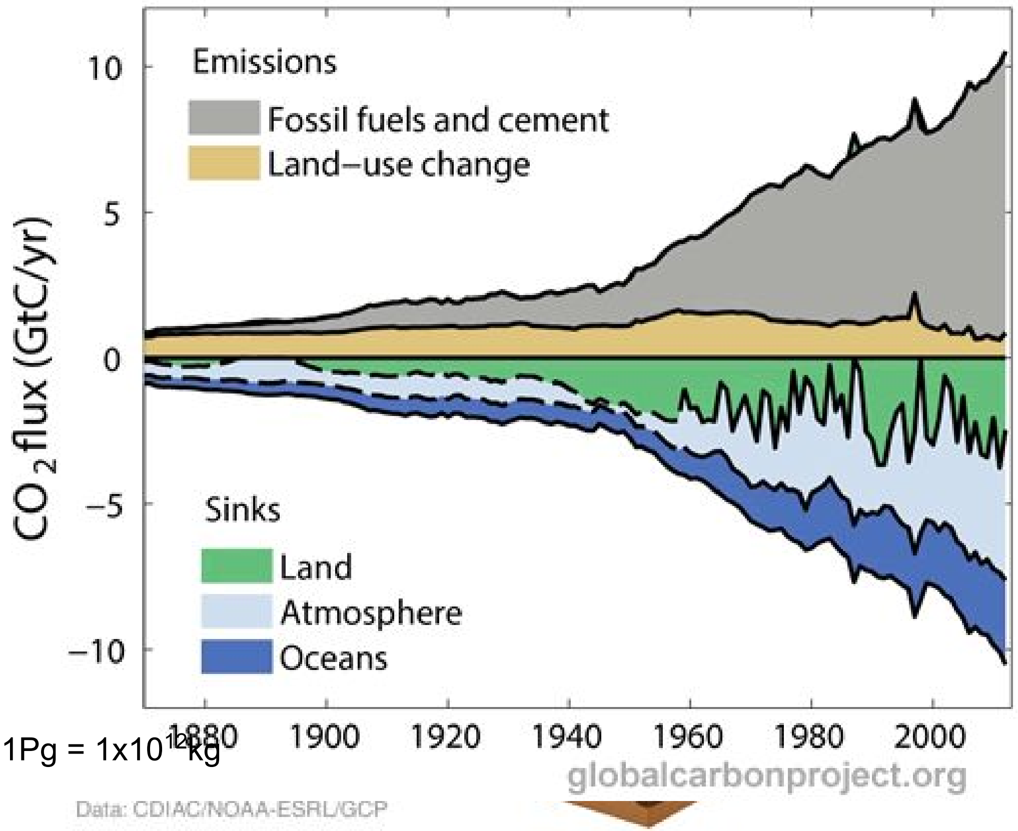
Can examine the ratio of different carbon isotopes, to show that CO_2 rise in atmosphere is from human fossil-fuel combustion.



Carbon is prese… ghter carbon
C12, when plar… C12. Plants
have lower C1… CO_2 comes
from fossil fuels, C13/C12 should be falling.

IPCC AR4, Fig 2.3

Carbon cycle

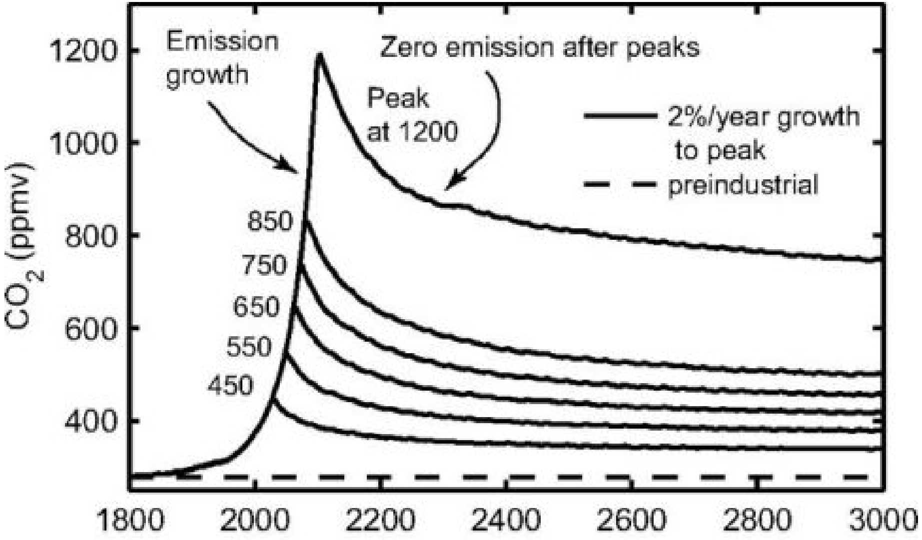


$1Pg = 1x10^{12} kg$

Global carbon budget from 1870 to 2012

Perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2006–2015 (GtCO2/yr)

Permanent CO_2 removal is slow



Solomon et al., 2009, PNAS.

Processes	Time scale (years)	Reactions
Land uptake: Photosynthesis–respiration	$1–10^2$	$6CO_2 + 6H_2O + \text{photons} \rightarrow C_6H_{12}O_6 + 6O_2$ $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{heat}$
Ocean invasion: Seawater buffer	$10–10^3$	$CO_2 + CO_3^{2-} + H_2O \rightleftharpoons 2HCO_3^-$
Reaction with calcium carbonate	$10^3–10^4$	$CO_2 + CaCO_3 + H_2O \rightarrow Ca^{2+} + 2HCO_3^-$
Silicate weathering	$10^4–10^6$	$CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$

Summary

- Trace gases in the atmosphere (H_2O, CO_2, CH_4, N_2O…) are opaque to outgoing infrared radiation and responsible for the greenhouse effect.
- Due to greenhouse effect, the surface must warm enough to balance both incoming sunlight and the radiation from the atmosphere back to the surface
- Climate system has ‘internal’ and ‘external’ modes of variability that can span from 1-100,000 years.
- Increase in CO_2 concentrations since from pre-industrial levels is from human fossil-fuel emissions, and permanent removal from the atmosphere is a slow process

That’s it for today!

Tomorrow in Climate 102 we will look at how to quantify the climate system response to both natural and human-caused forcings, and how scientists can detect and attribute observed changes in the climate system to human activity.

Other resources:

Check out http://globalchange.mit.edu/news-events/education#resources