Climate change: a summary for policy-makers

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Climate change: a summary for policymakers

- How rising atmospheric CO_2 causes global warming
- How global temperatures and sea level respond
- Quantifying human influence on climate and weather
- The fate of CO_2 and other anthropogenic emissions
- Global impact functions and the social cost of carbon
- Mitigation costs and pathways
- Policy options from carbon pricing to geo-engineering
- Capstone activity: design a robust climate policy

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The argument we want to avoid...

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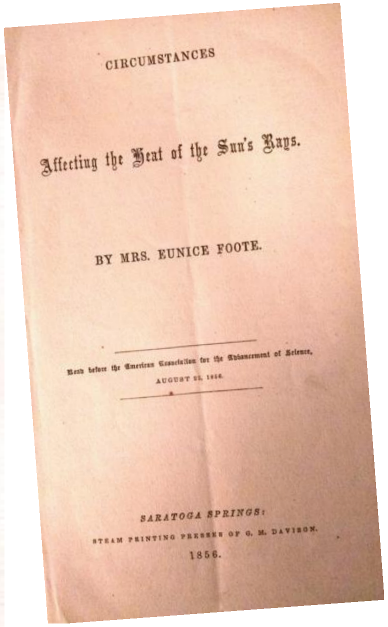
1824-1860s: Fourier, Foote and Tyndall

- Identified CO_2 as one of the trace gases responsible for the blanketing effect of the atmosphere, absorbing and emitting infra-red radiation, keeping Earth's surface warm.



CIRCUMSTANCES

Affecting the Heat of the Sun's Rays.

BY MRS. EUNICE FOOTE.

Read before the American Association for the Advancement of Science,

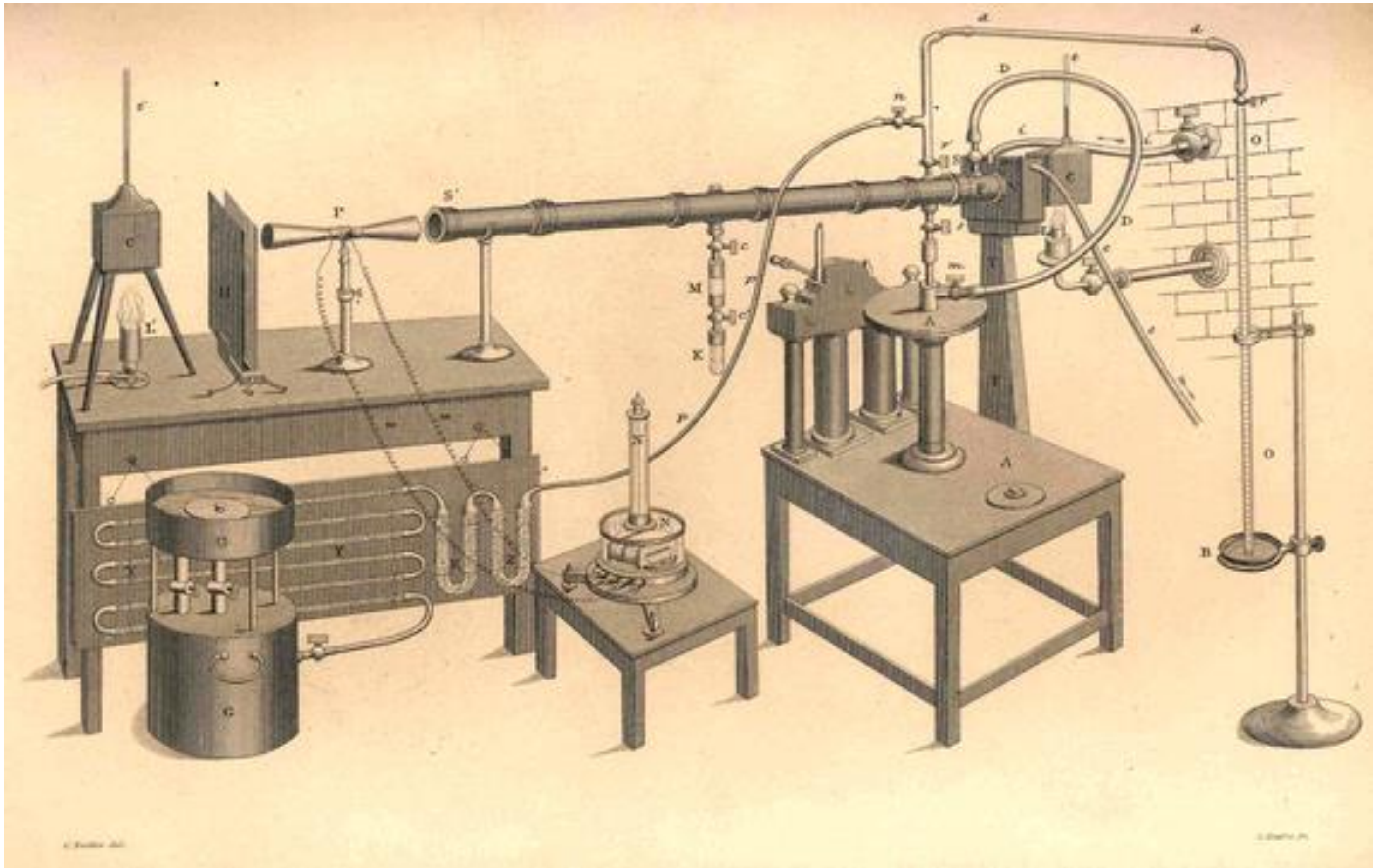
AUGUST 23, 1856.

SARATOGA SPRINGS:

STEAM PRINTING PRESSES OF G. M. DAVISON.

1856.

Tyndall's experiments



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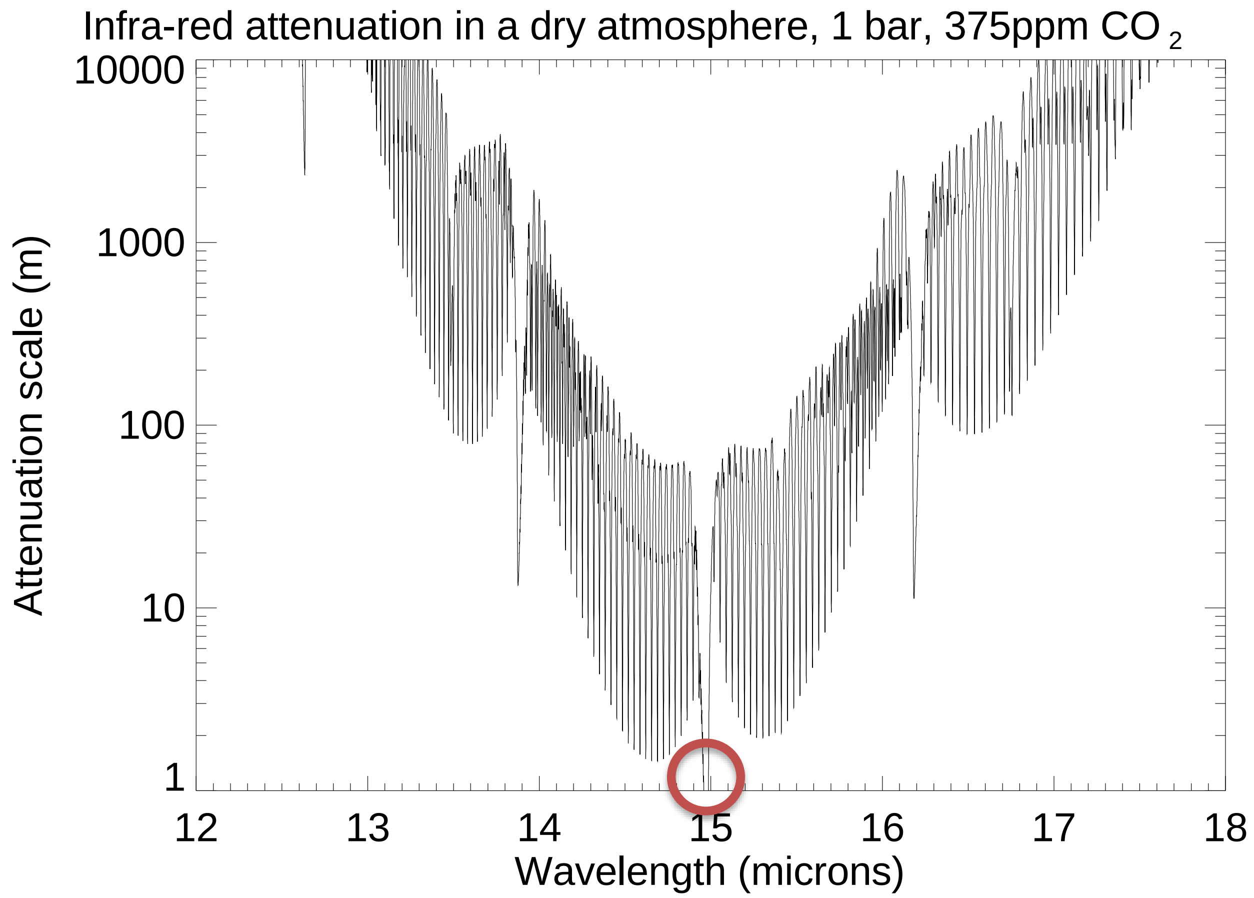
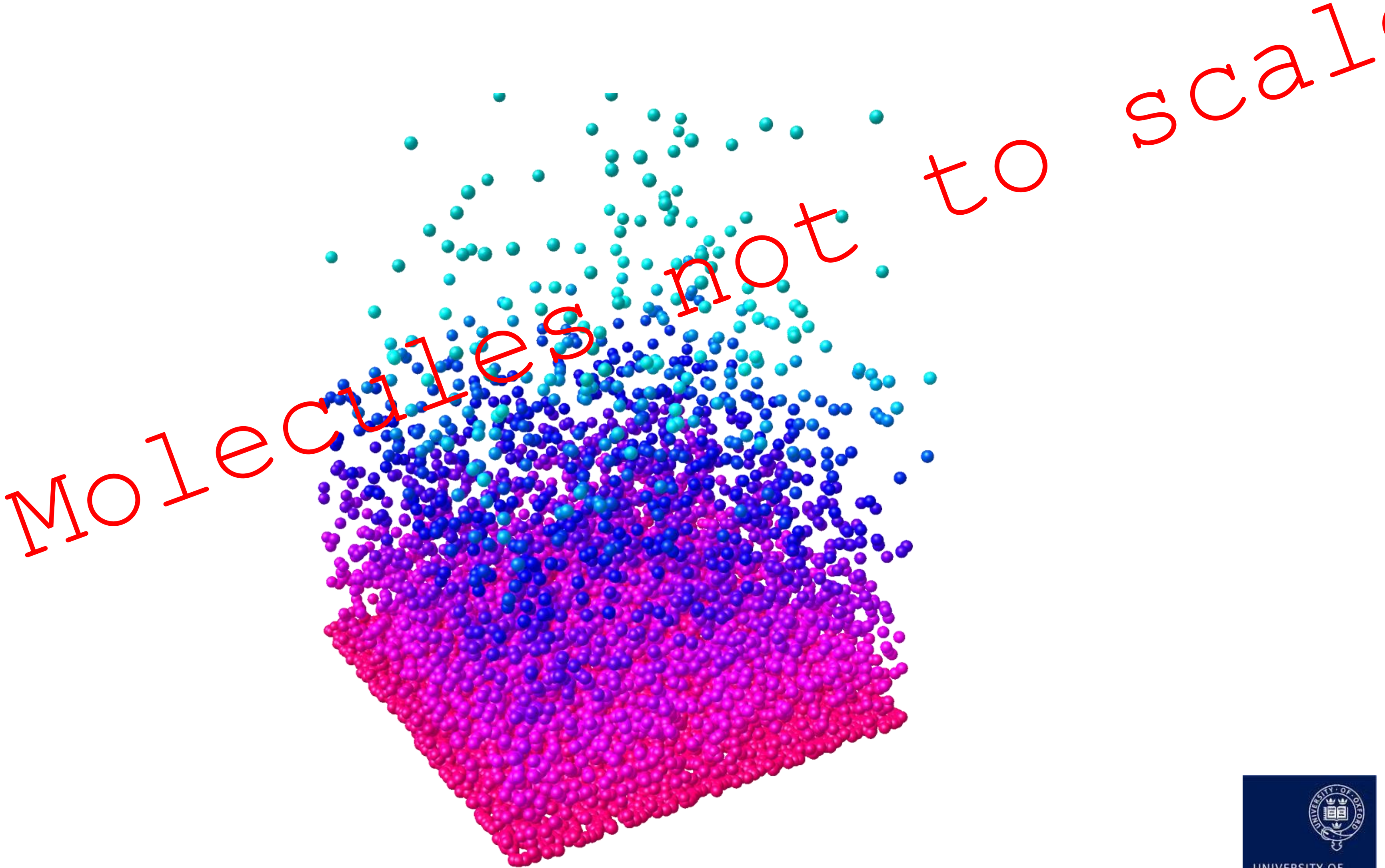
If your eyes worked at 14-16 microns, you would barely be able to see down the street

Max distance you could see clearly at this wavelength

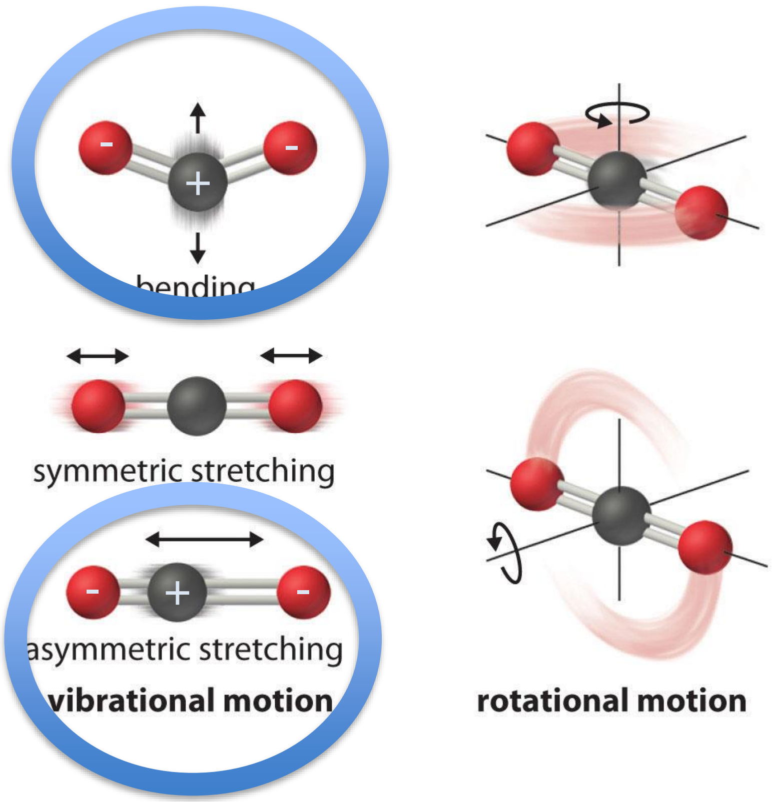


Wavelength (1 micron = 1/1000th of a millimetre)

CO_2 molecules in the atmosphere: 400 "parts per million by volume" (0.04% of air molecules)

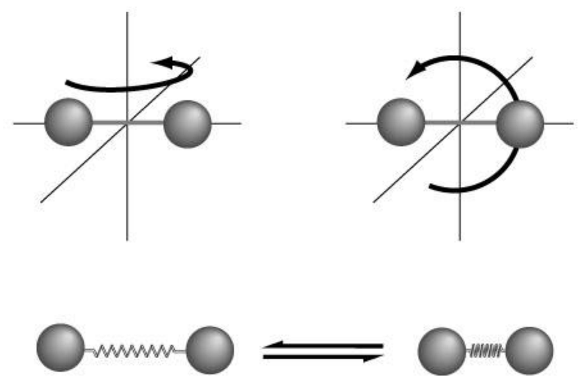


The reason CO_2 matters: how air molecules interact with electromagnetic radiation



Some of the many modes of motion of a CO_2 molecule

Some of these modes create asymmetrically-charged "dipoles" which interact with electromagnetic radiation, particularly in the infra-red part of the spectrum.



The fewer modes of motion of an O_2 or N_2 molecule

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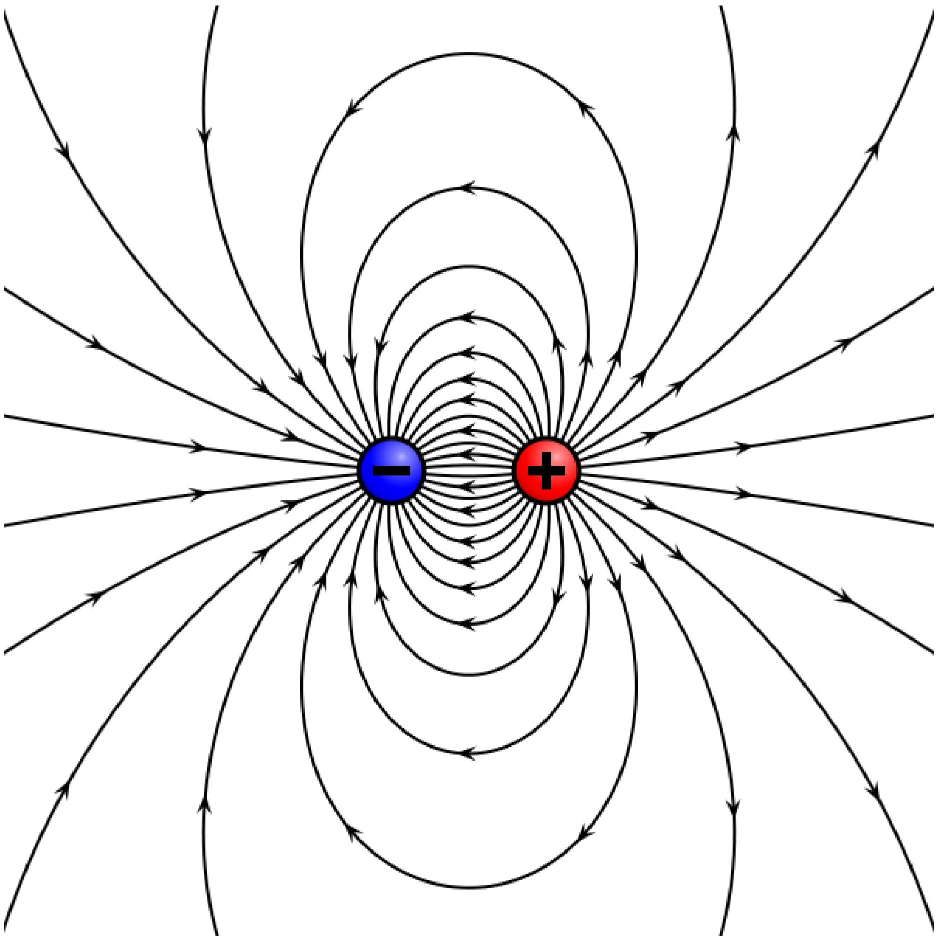
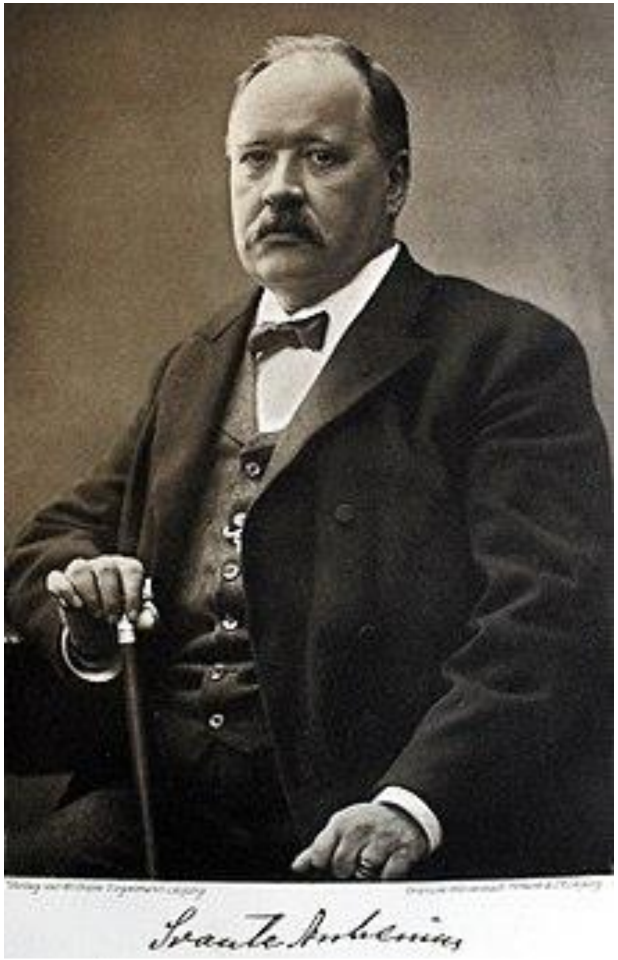
Molecular dipoles may be small, but they have far-reaching influence



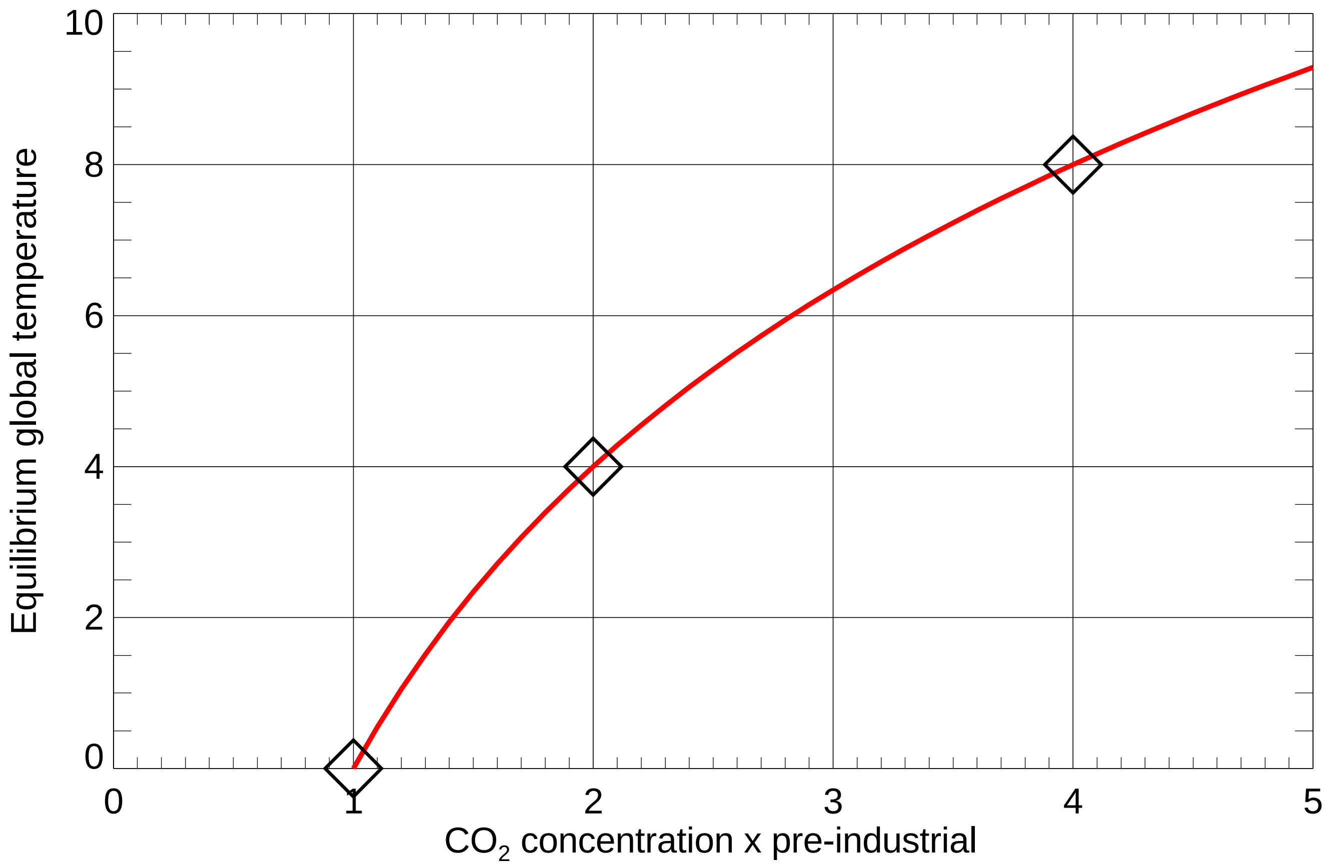
Electric field lines around a dipole

The first quantitative account of the impact of rising CO_2 on temperature: Svante Arrhenius

- "Any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4° C; and if the carbon dioxide were increased fourfold, the temperature would rise by 8° C."

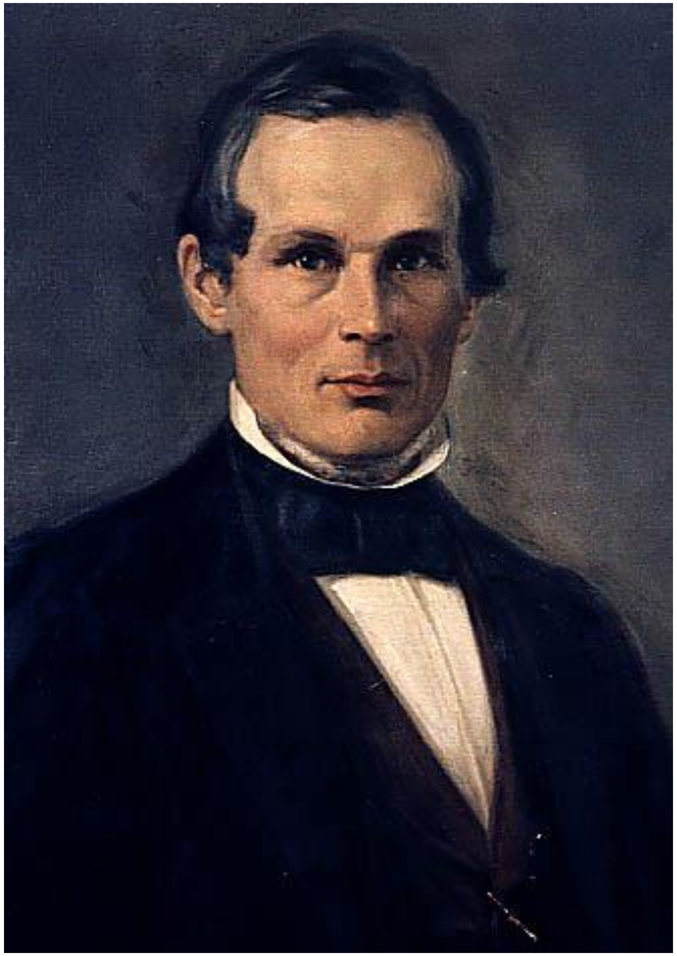


Arrhenius' non-obvious prediction



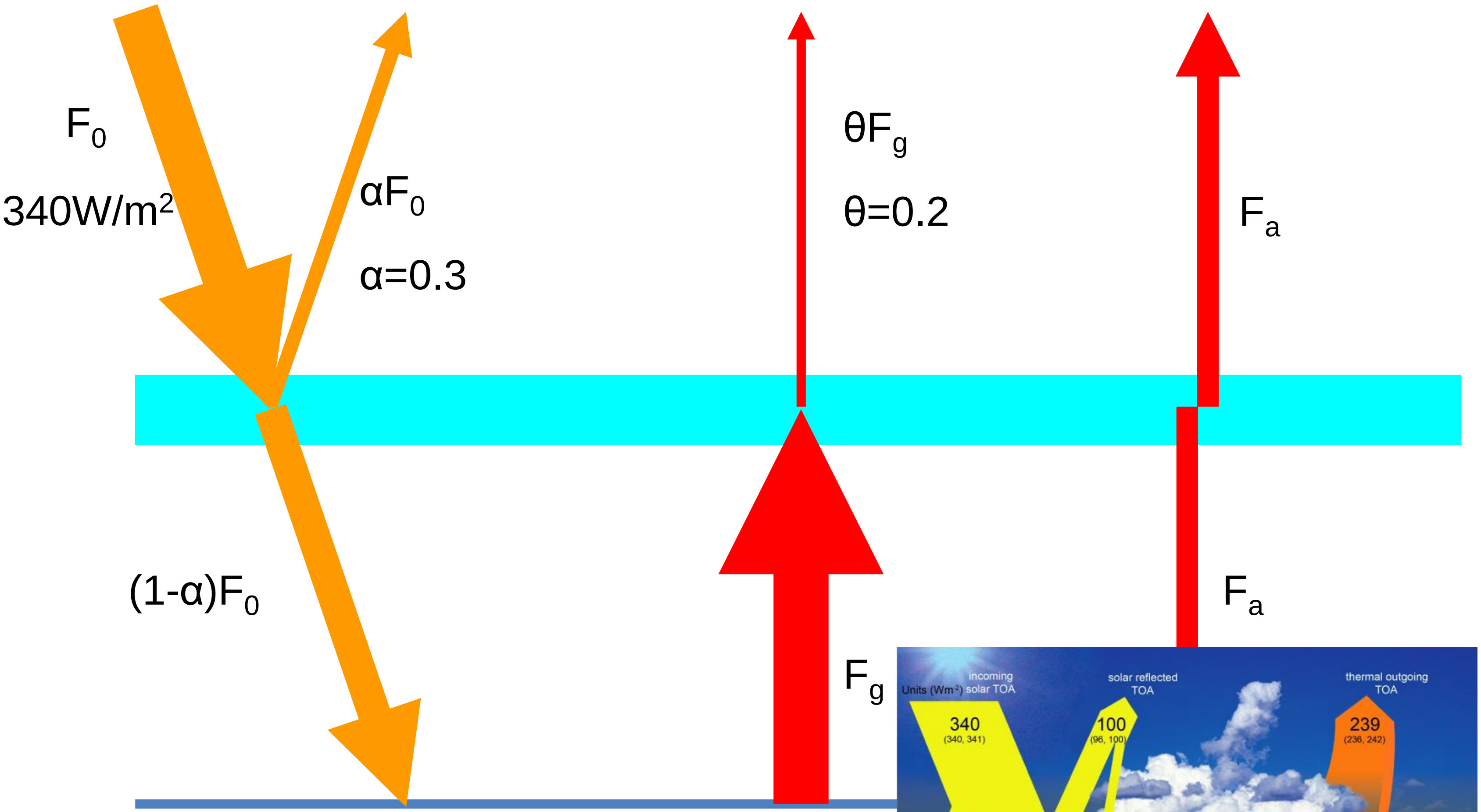
Ångström intervenes

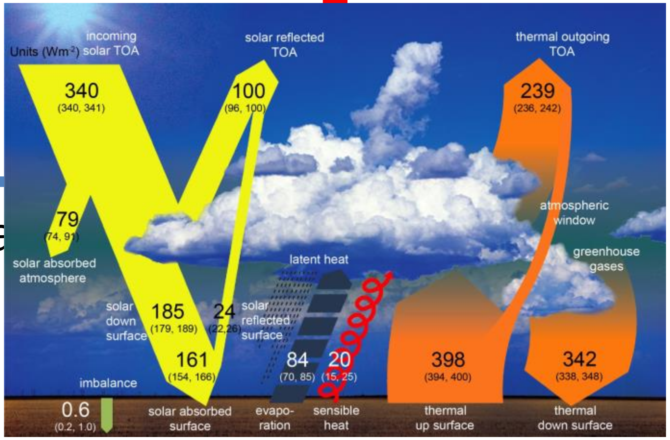
- Repeated a variant of Tyndall's experiment, varying the amount of CO_2 in the tube, and showed very little change in IR absorption: the "saturation" argument, still surprisingly popular today.



Even with a broadband infrared camera, you certainly couldn't see through the atmosphere

The schoolbook model of the “greenhouse effect”





Making sense of the schoolbook model

- Surface energy balance (1) $$F_0(1-\alpha) = F_g - F_a$$
- Planetary energy balance (2) $$F_0(1-\alpha) = \theta F_g + F_a$$
- Simultaneous equations (1)+(2) $$2F_0(1-\alpha) = (1+\theta)F_g$$
- Stefan's law: $$\frac{2F_0(1-\alpha)}{(1+\theta)} = F_g = \sigma T_g^4$$

  Energy radiated proportional to 4th power of the temperature in Kelvin

- Rearranging $$T_g = \sqrt[4]{\frac{2F_0(1-\alpha)}{\sigma(1+\theta)}}$$
- Plugging in the numbers $$= \sqrt[4]{\frac{2 \times 340 \times (1-0.3)}{5.67 \times 10^{-8} \times (1+0.2)}}$$
- Result (only 1° C out!) $$= 289\mathrm{K} = 16°\mathrm{C}$$

But is this really how it works?

- Try doubling CO_2 in a realistic atmospheric radiative transfer model (don't take my word for it):

  Go to http://forecast.uchicago.edu/Projects/modtran.html, select "Show Raw Model Output" & look for "average transmittance" at bottom

- MODTRAN tropical atmosphere:

  $\theta(400\text{ppm } CO_2) = 0.1393$

  $\theta(800\text{ppm } CO_2) = 0.1360$

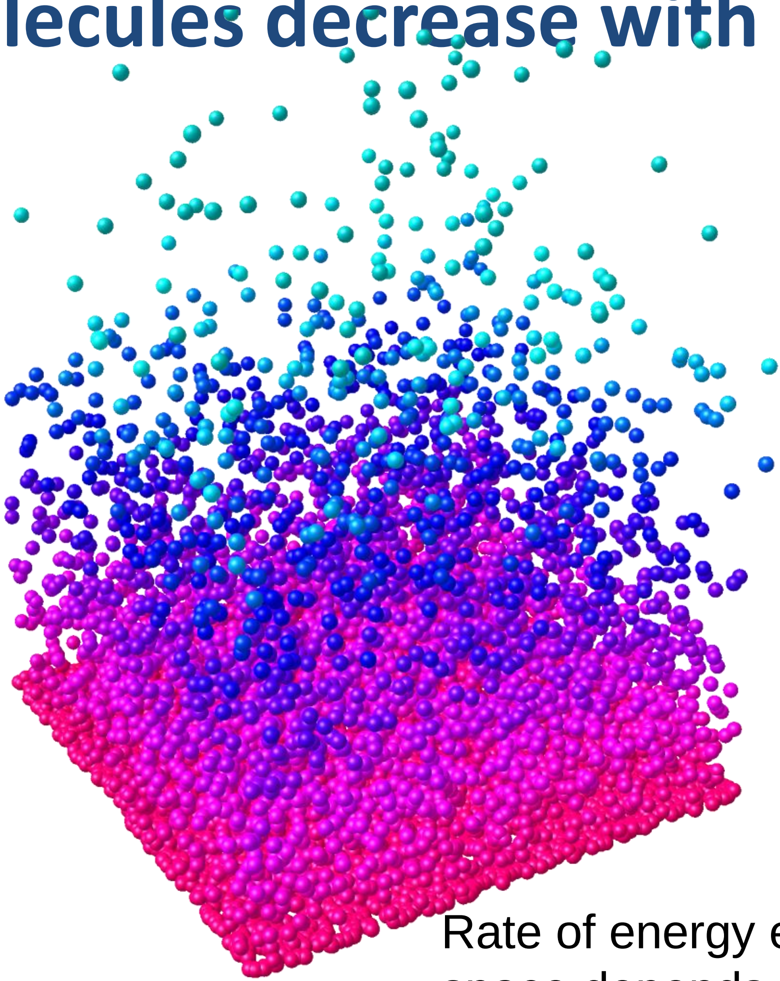
- Implying warming ΔT_g due to doubling CO_2 is $<0.3^oC$
- So was Ångström right?

Gilbert Plass (1955) and the role of water vapour

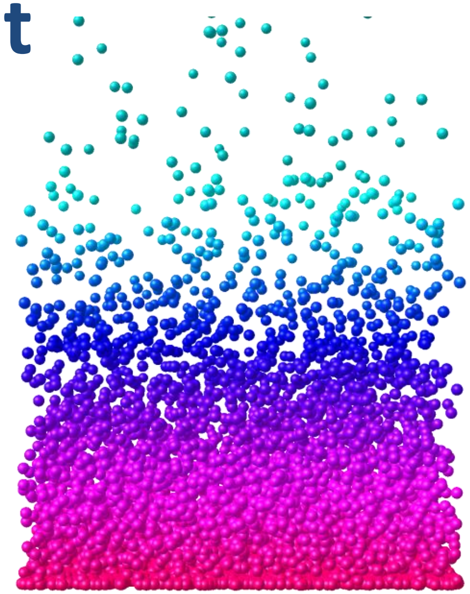
- Noted "the CO_2 theory" had been criticized because of CO_2 saturation argument and strong absorption of infra-red radiation by water vapor.
- Correctly observed that at the altitudes from which radiation escapes to space, above the humid lower atmosphere, CO_2 is the dominant greenhouse gas and absorption is not saturated.


Scanned at the American Institute of Physics

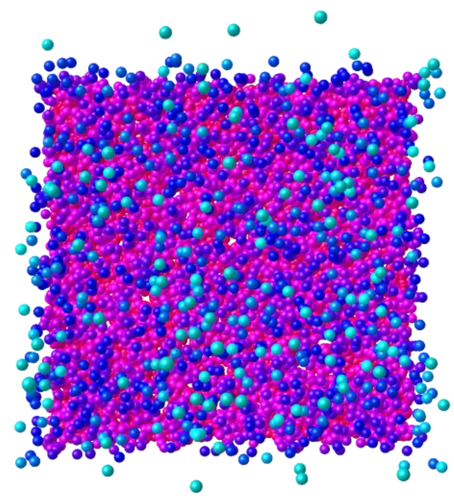
Both temperature (colour) and density of CO_2 molecules decrease with height



Rate of energy emitted to space depends on the average temperature of molecules as seen from above

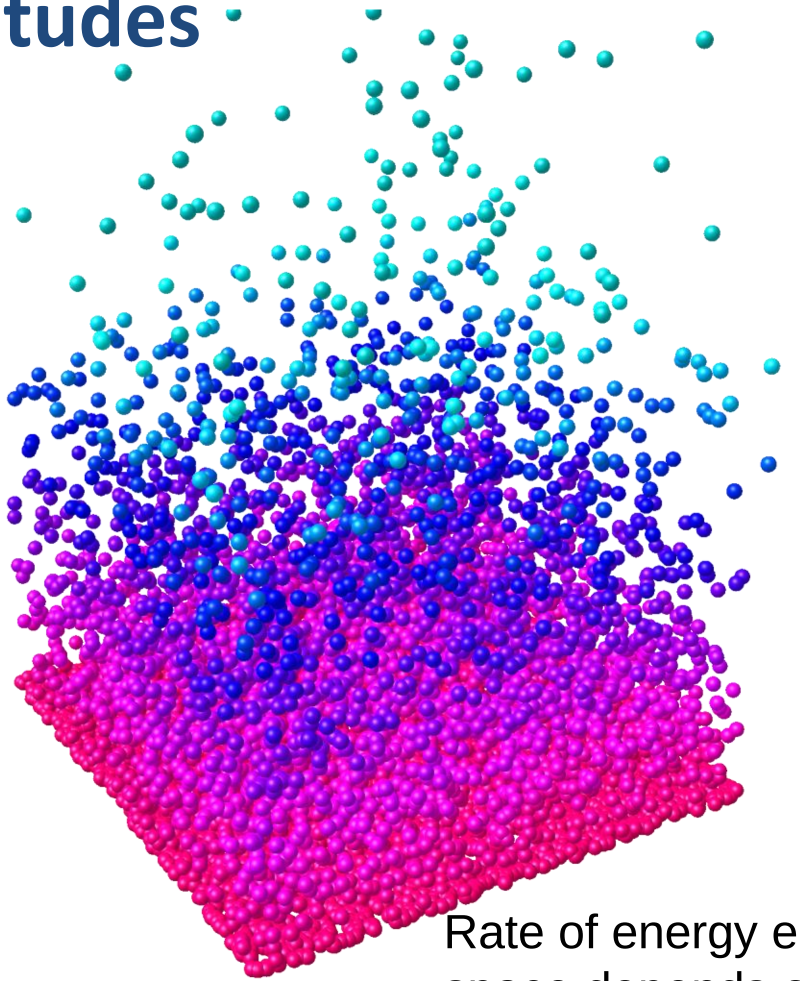


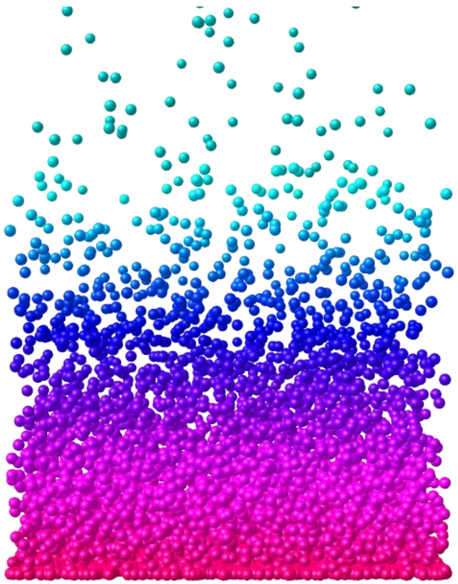
View from side



View from above

Increasing CO_2 forces energy to escape from higher altitudes





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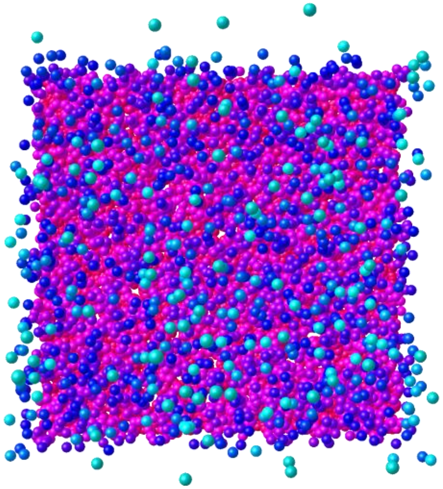

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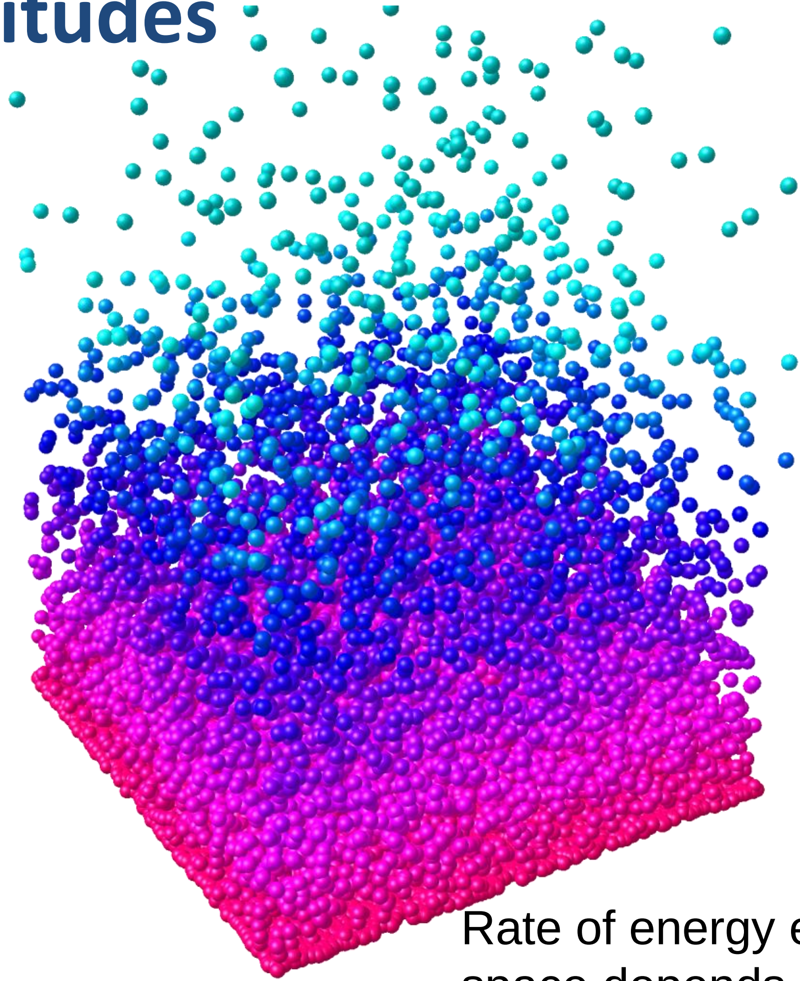

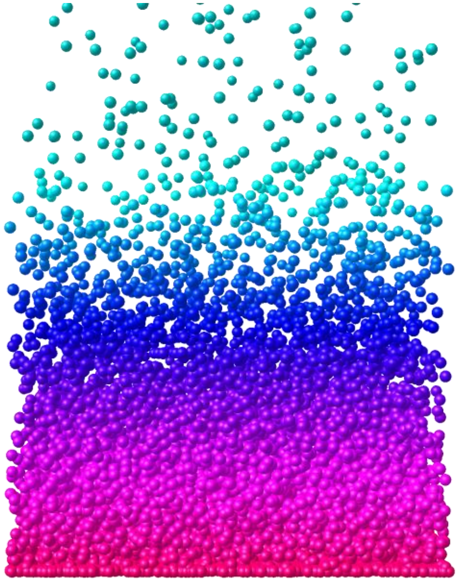

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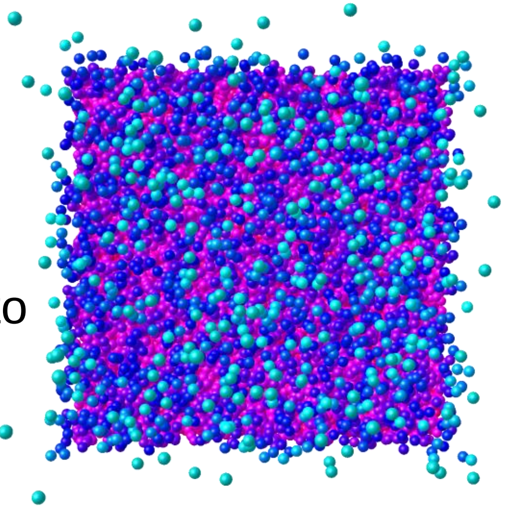

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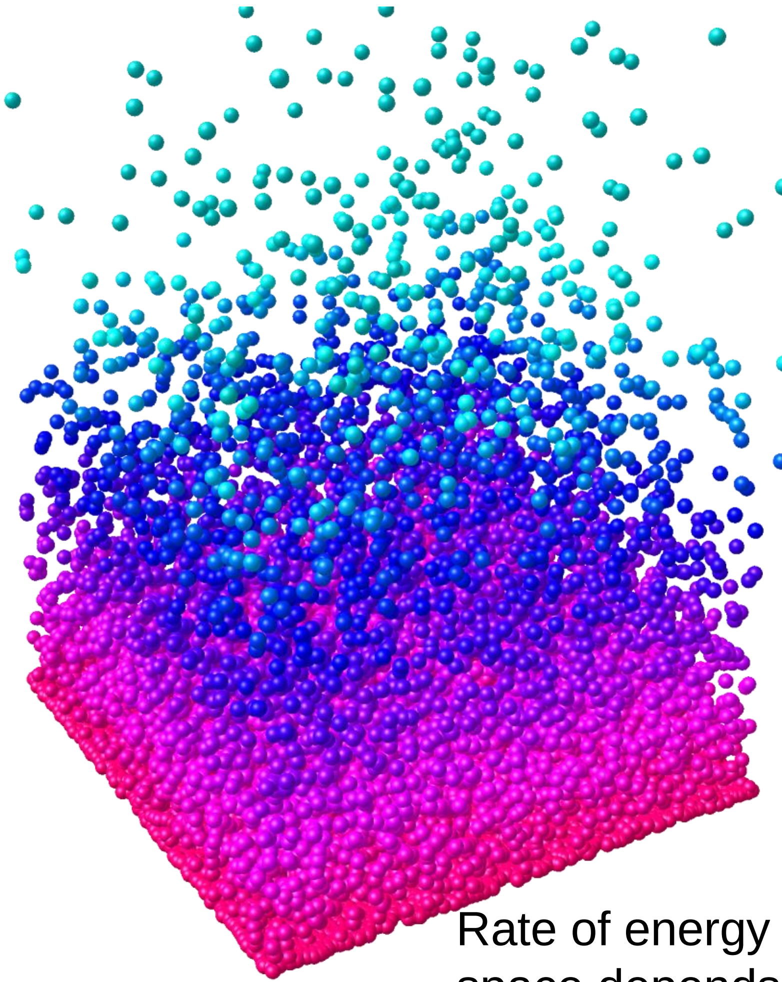
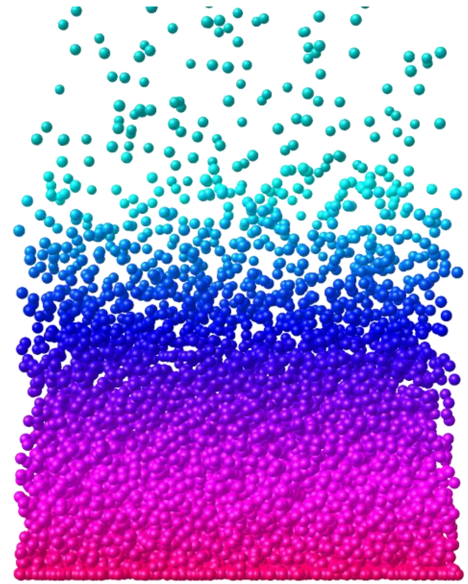
Higher air is colder, and so radiates less energy





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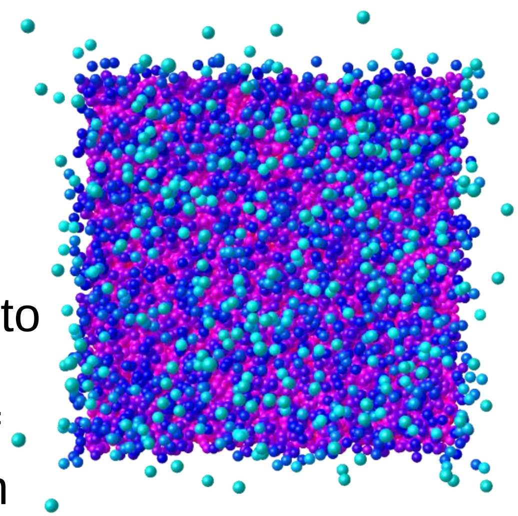

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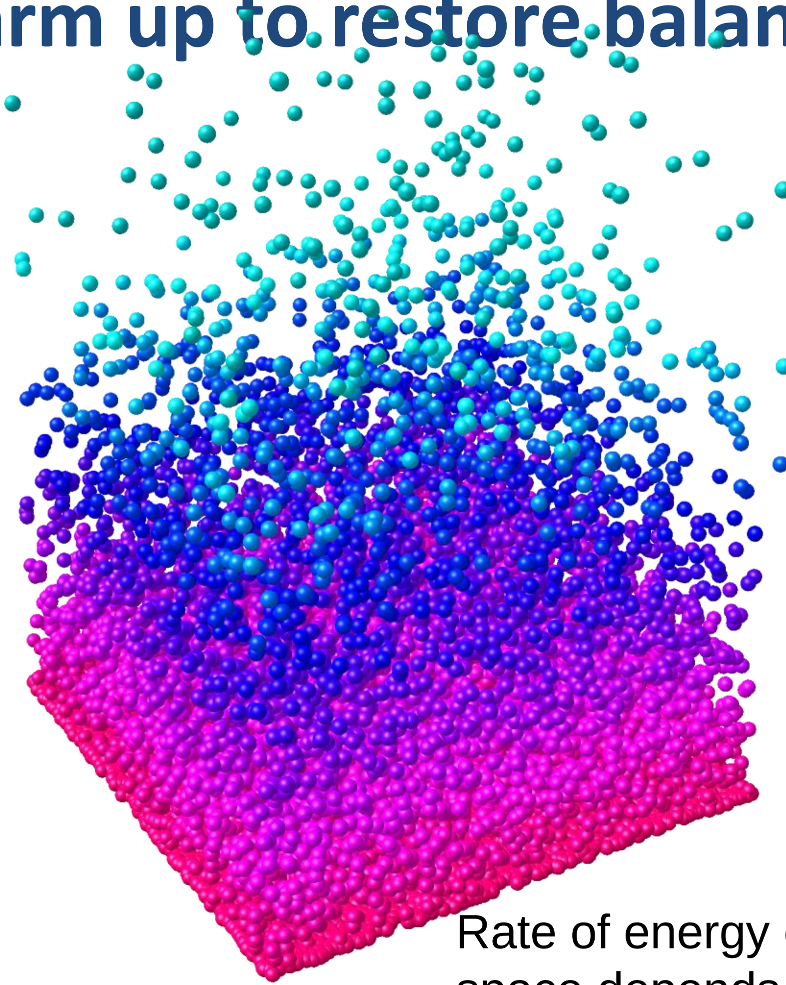
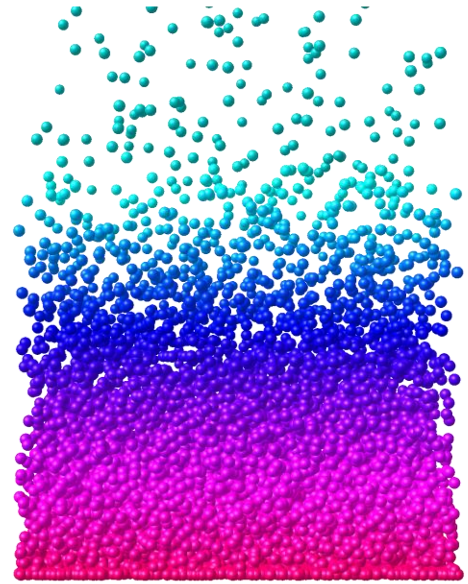
So the surface and lower atmosphere have to warm up to restore balance





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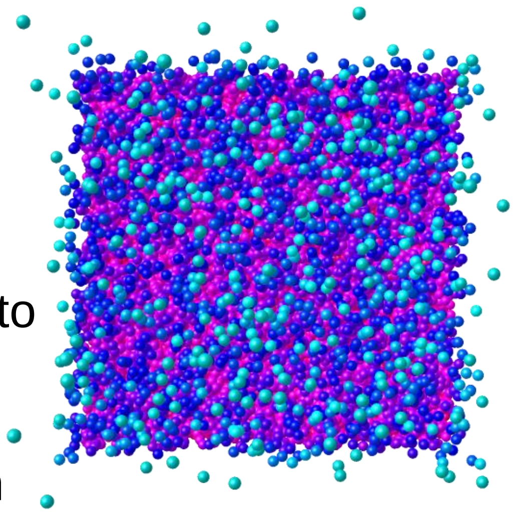

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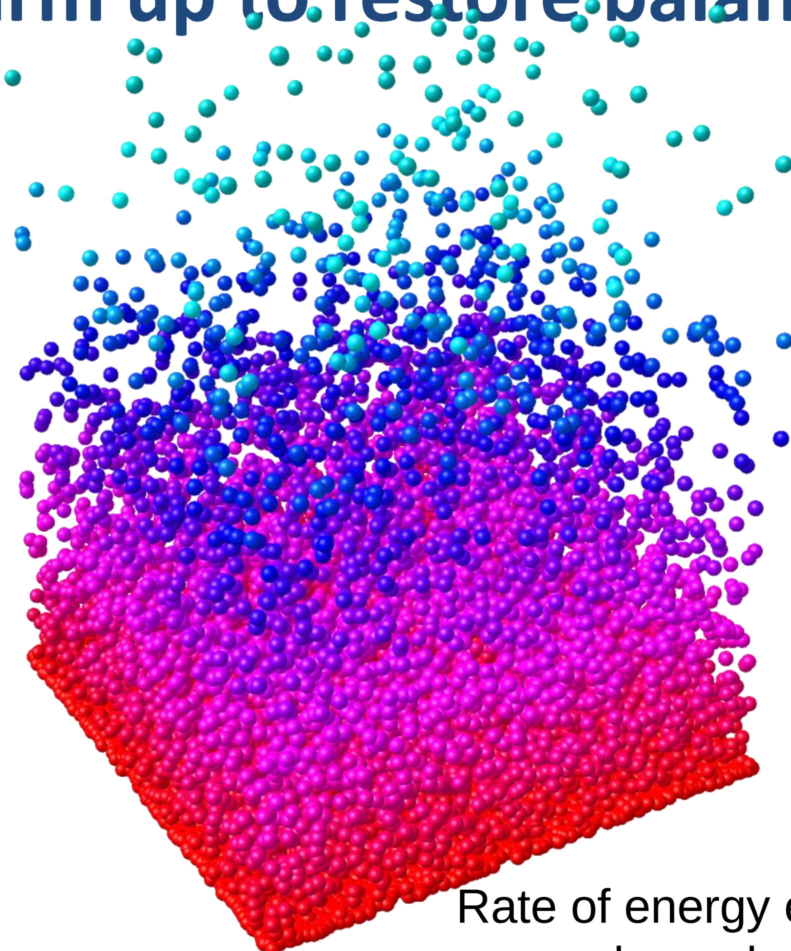

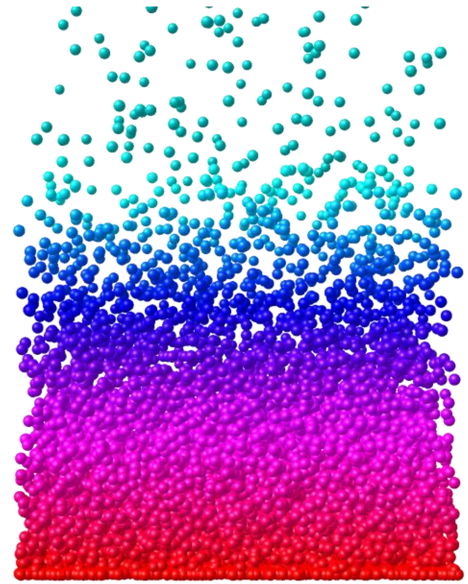

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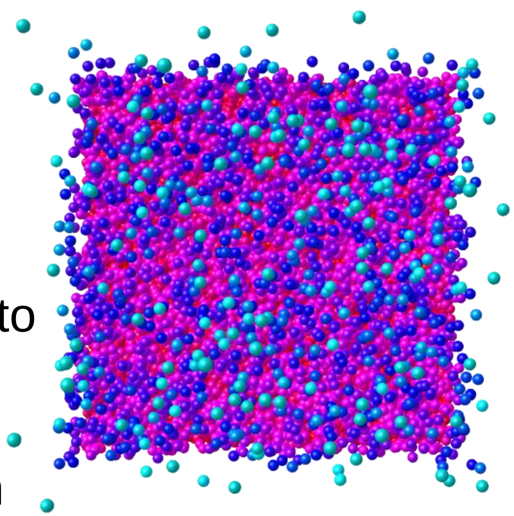

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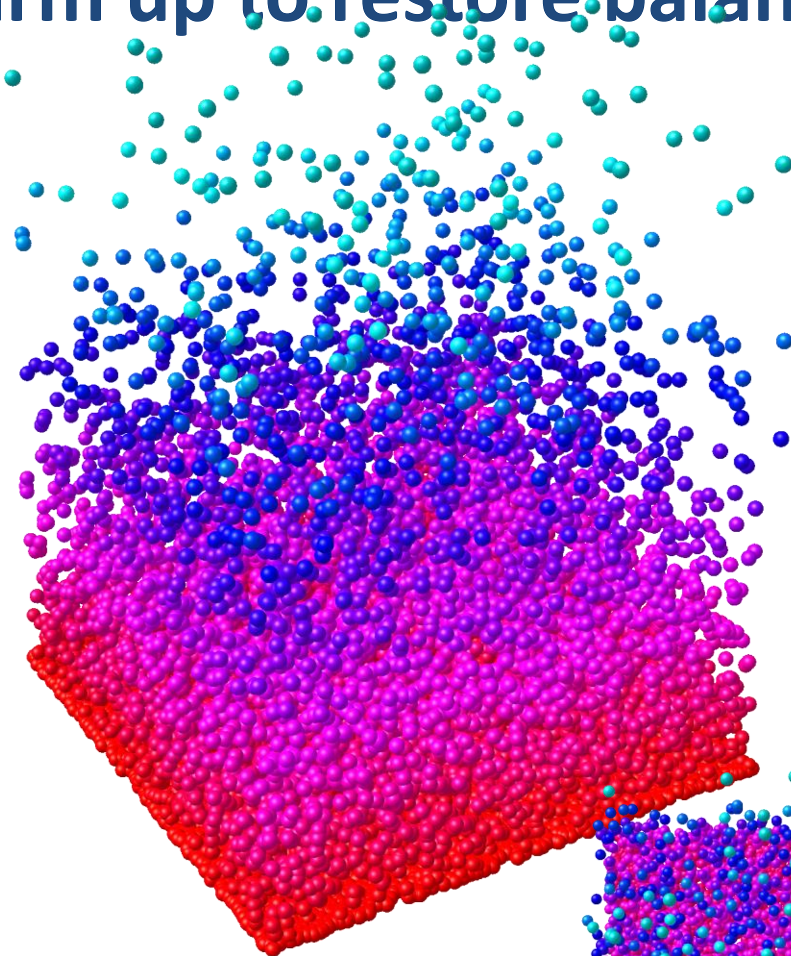

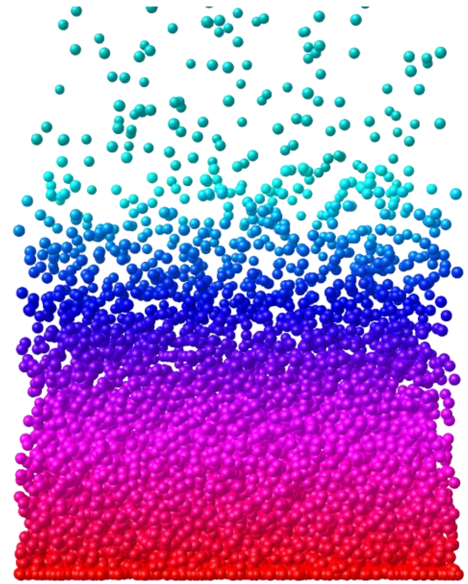

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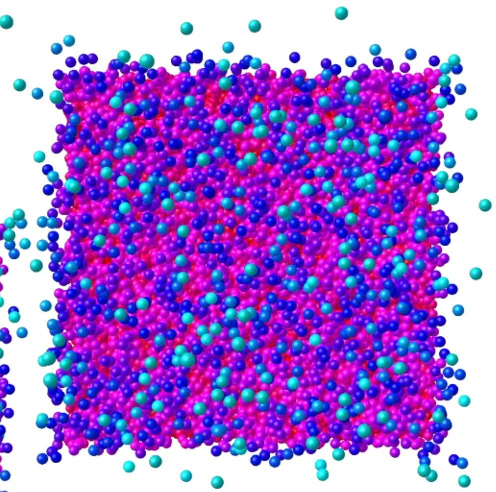
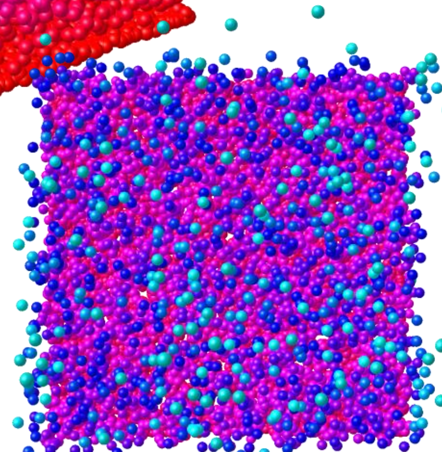
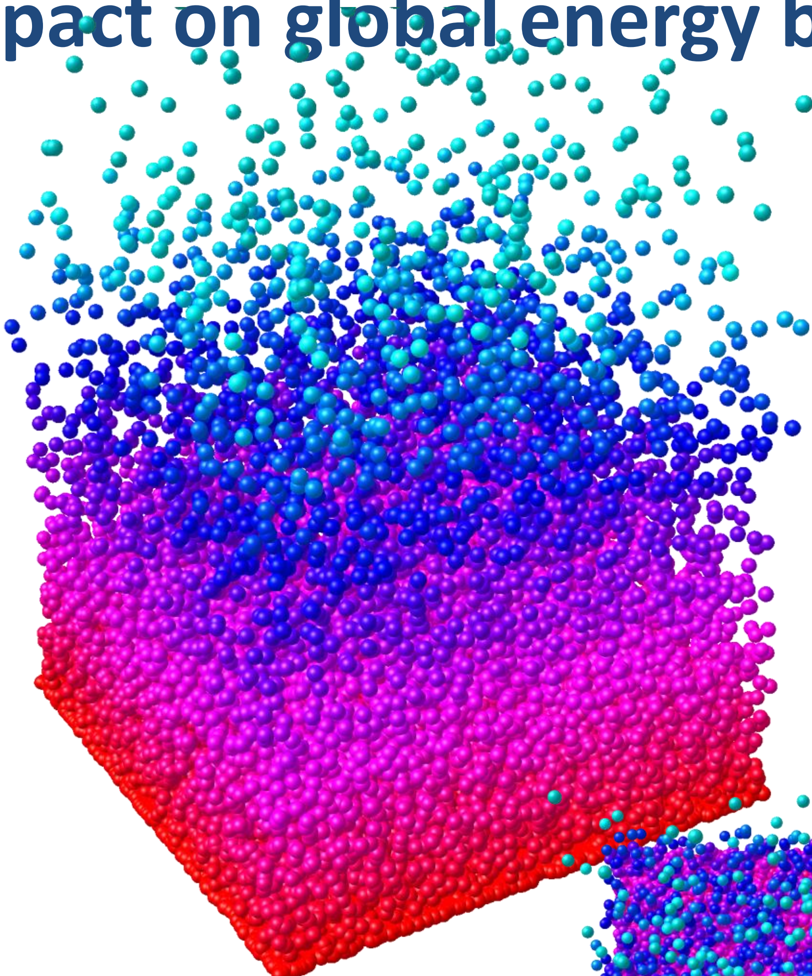


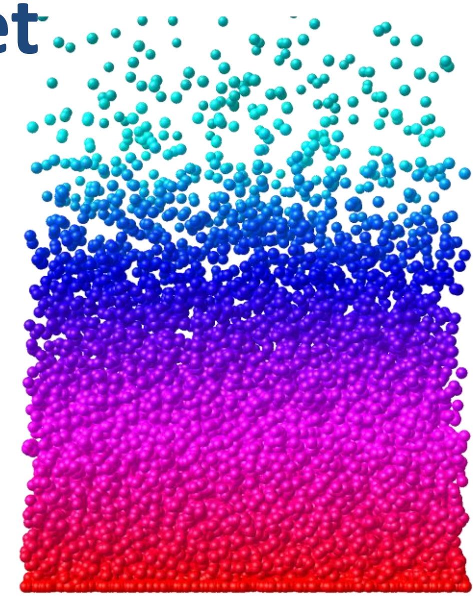


View from above

Original state before CO_2 increase & warming

Successive CO_2 doublings have about the same impact on global energy budget





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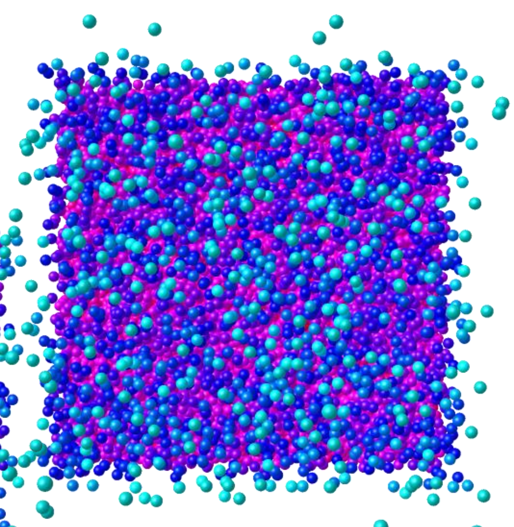

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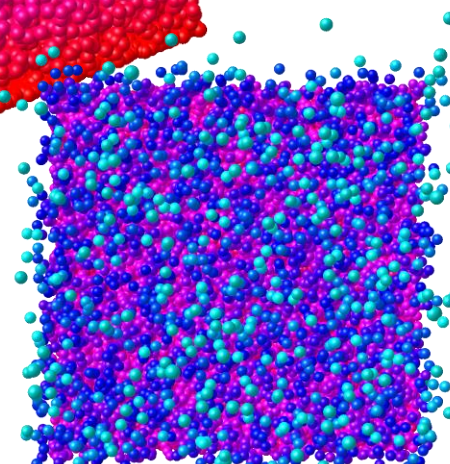
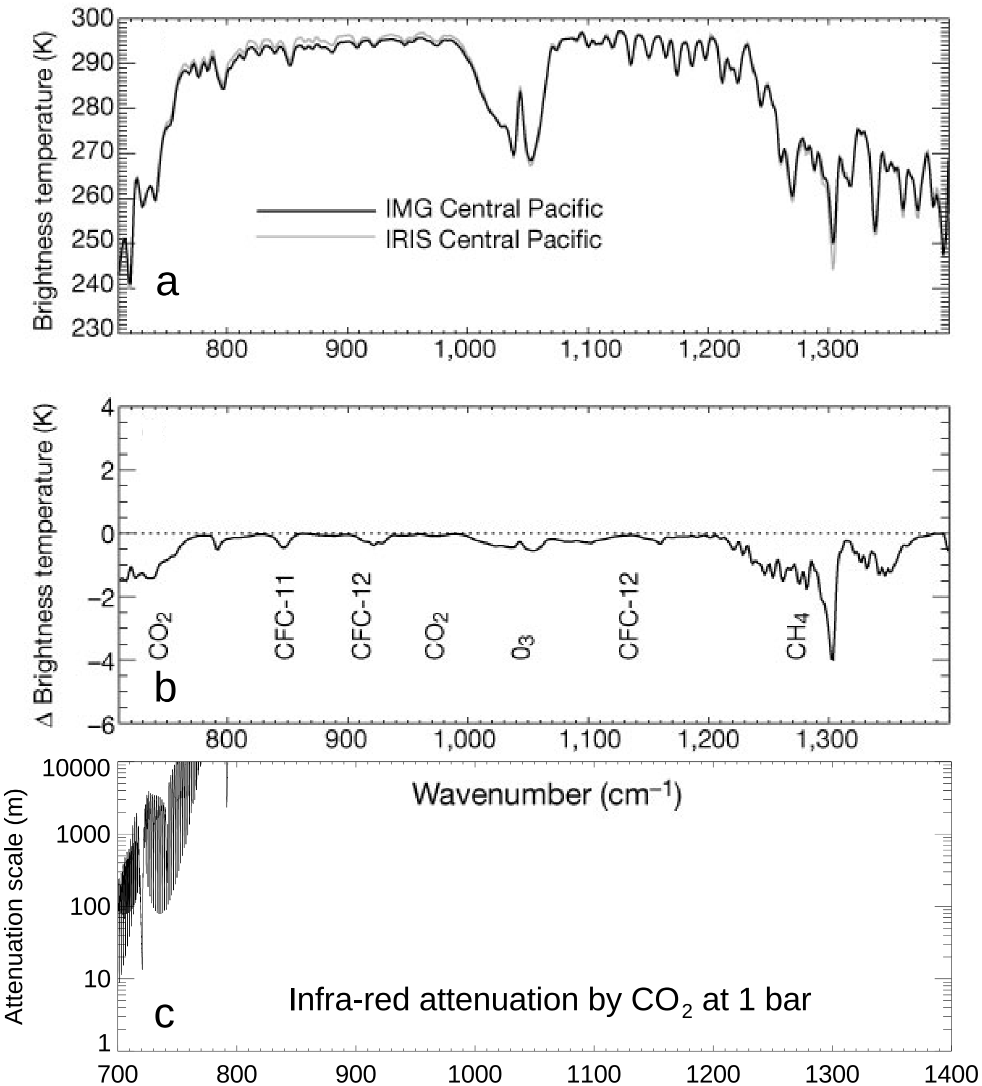


After the first CO_2 doubling and before warming

Impact of rising GHGs on the spectrum of outgoing energy has been directly observed from space

Nimbus 4 spacecraft, 1970



Comparison of outgoing spectra, IMG (1997, 367 ppm) versus IRIS (1970, 323 ppm).

Change in outgoing spectrum after correcting for impact of temperature. Reductions of about 1.5° C in wavelengths affected by CO_2.

Harries et al (2001)

How much will the world warm up?

- Averaged over the surface, seasons, weather conditions etc., a sudden doubling of atmospheric CO_2 would reduce outgoing infra-red energy by about 4 W/m^2
  - Current imbalance due to past emissions is >3 W/m^2
- How much would the world have to warm up to restore balance between incoming and outgoing energy?

$$\Delta T_{2xCO2} = \frac{F_{2xCO2}}{\lambda}$$

- "Sensitivity parameter" λ is the extra energy emitted to space per degree of warming

Lots of things change as the world warms: "Feedbacks" affecting the sensitivity parameter

• Simple thermal "blackbody" effect:	+4	$W/m^2/°C$
• Increased water vapour:	−2	$W/m^2/°C$
• Reduced lapse rate:	+0.75	$W/m^2/°C$
• Changes in clouds:	−0.5	$W/m^2/°C$
• Reduced albedo (less snow/ice):	<u>−0.25</u>	$W/m^2/°C$
• Net sensitivity parameter λ:	+2	$W/m^2/°C$

How the uncertainties add up

- $\lambda = \lambda_{BB} + \lambda_{WV} + \lambda_{LR} + \lambda_C + \lambda_A = 2(\pm 1)\ W/m^2/°C$
- Equilibrium climate sensitivity depends on forcing (well known) divided by sensitivity parameter (uncertain):

$$DT_{2xCO2} = \frac{F_{2xCO2}}{/}$$

- Round numbers: $F_{2xCO2} = 4\ W/m^2$ & $\lambda = 2 \pm 1\ W/m^2/°C$
- Best estimate $\Delta T_{2xCO2} = 2°C$
- Uncertainty range = 1.3 – 4°C
- Upper limit is more uncertain than lower limit.

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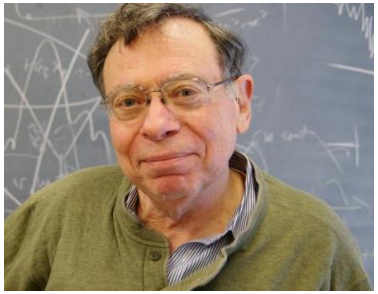
The 1979 National Academy of Sciences Report chaired by Jules Charney

- Gave a range of 1.5-4.5° C for ΔT_{2xCO2}, emphasizing:
  - Oceans "could delay the estimated warming for several decades" (warming reached 1° C around 2017)
  - "We may not be given a warning until the CO_2 loading is such that an appreciable climate change is inevitable."
  - These are the topics of the next lecture.



What we have learned about the enhanced CO_2 greenhouse effect

- Air temperature decreases with height through the lower atmosphere.
- Density of absorbing CO_2 molecules falls of exponentially.
- Increasing CO_2 raises altitude at which absorber is thin enough for radiation to escape to space.
- Each CO_2 doubling has same impact as the last: for twice as many tonnes of additional atmospheric CO_2.
- Feedbacks make the equilibrium response uncertain, particularly the upper bound.

What we have learned about climate models

- Any statement about unobservable quantities, including future climate, requires modeling.
- “All models are wrong, some are useful” (Box)
- Even very simple models can be misleading if they get the right answers for the wrong reason.
- “Bottom up” approaches to climate modeling don’t usefully constrain future climate: need observations.
- Determining a “safe” CO_2 concentration is hard, perhaps impossible.