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Planetary Physiology

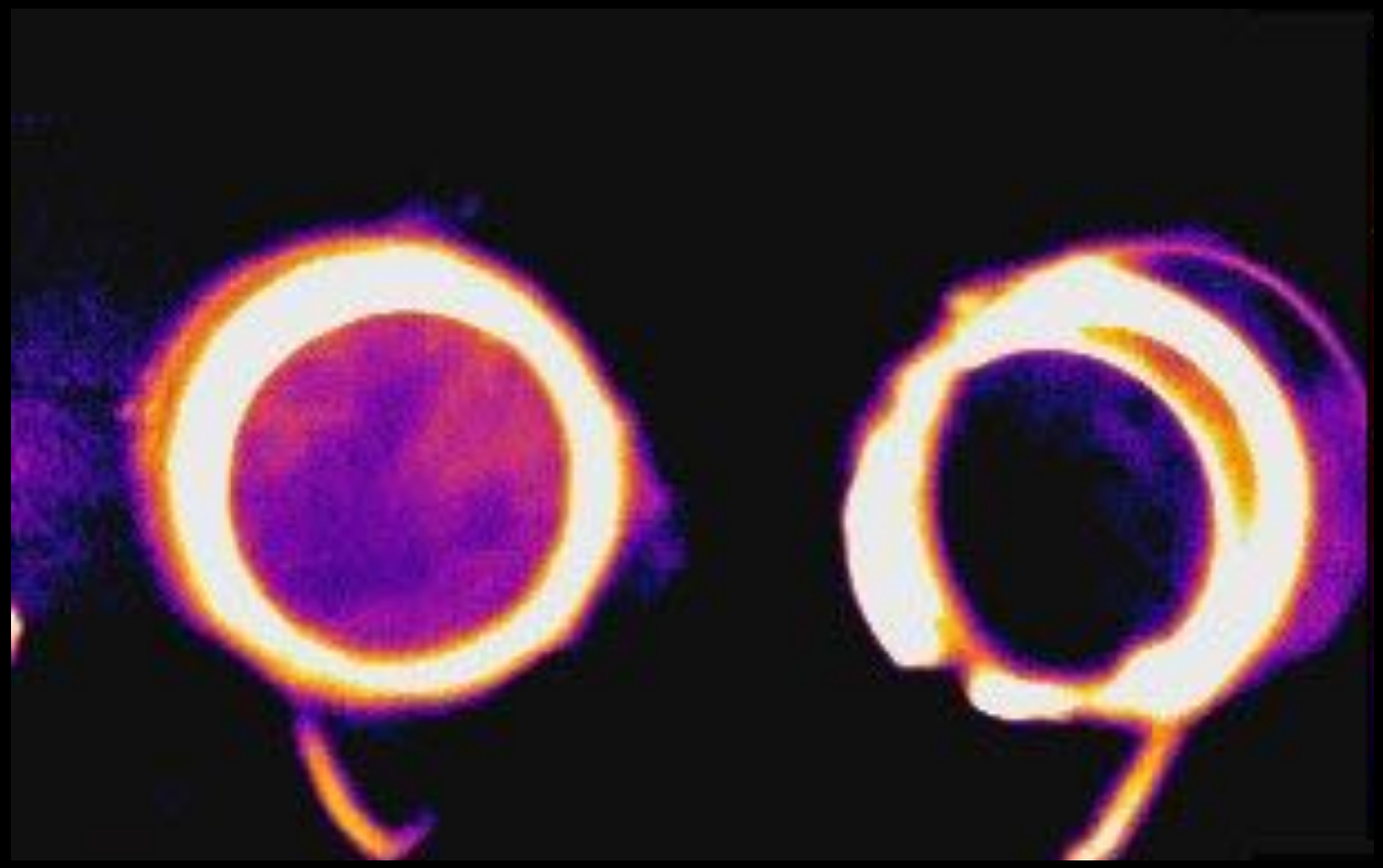


Image Philip Sieg.

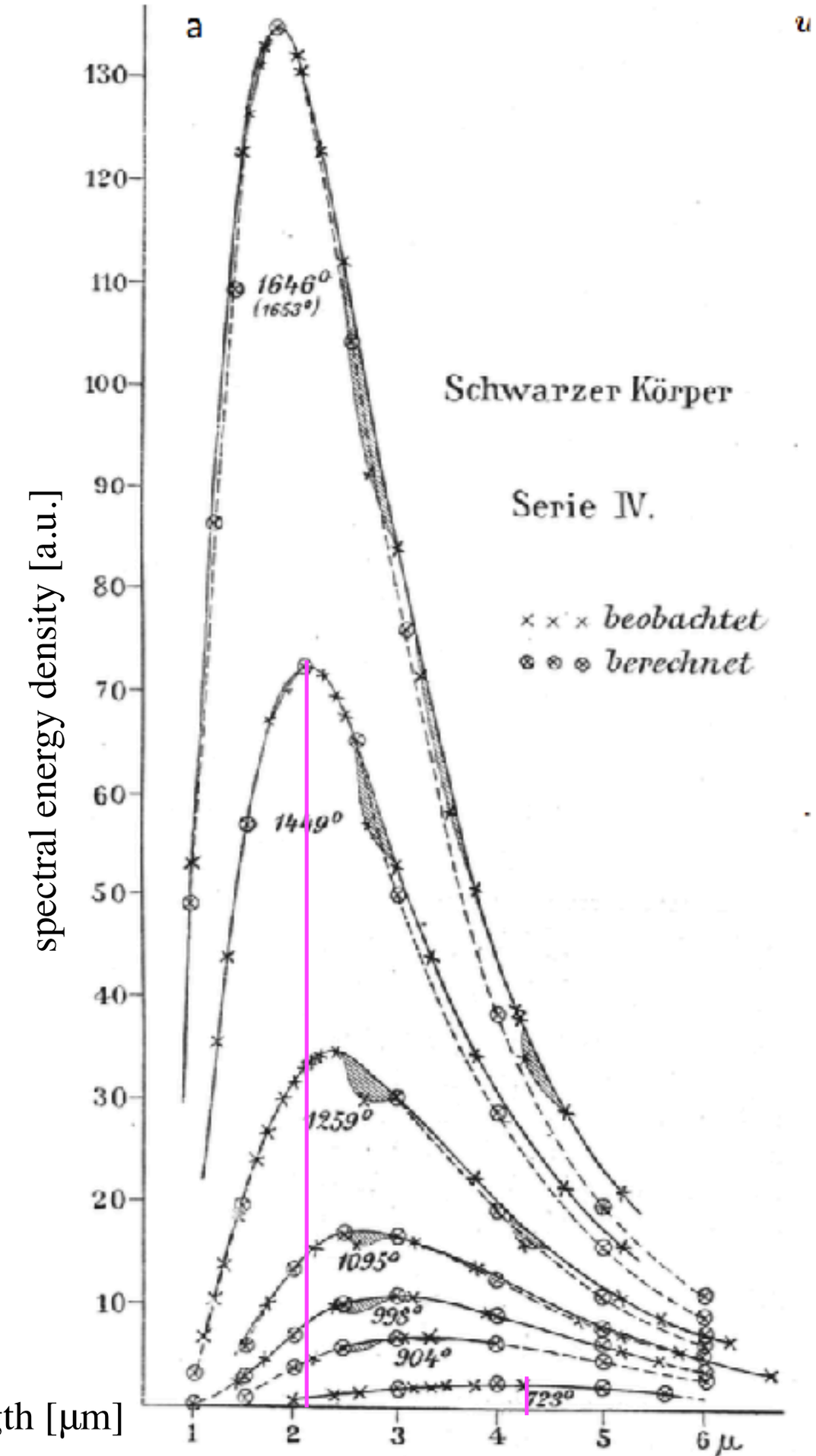
Thermal radiation

Experiments showed that doubling the absolute temperature shifts the peak wavelength to 1/2 of its value. Doubling temperature also increases total power output (area under the curve) *16-fold*:

$$\text{power} \propto T^4$$

Can we understand these spectra via some simple calculation?

Lummer & Pringsheim, 1899.



That simple physical recipe can be turned into various analytic formulas:

term	description	formula
spectral energy density	energy per volume per frequency interval	$u_\nu = \left(16\pi^2\hbar\nu^3/c^3\right)/\left(\mathrm{e}^x - 1\right)$
spectral photon density	photons per volume per frequency interval	$u_\nu/(2\pi\hbar\nu)$
photon PDF	probability per frequency interval	$u_\nu \Big/ \left(\nu \int \mathrm{d}\nu' u_\nu(\nu')/\nu'\right)$
spectral irradiance	power per area per frequency interval	$B_\nu = u_\nu c/4$
spectral photon arrival rate	photons per time per frequency interval	$B_\nu \Sigma/(2\pi\hbar\nu)$
spectral energy density	energy per volume per wavelength interval	$u_\lambda = \left(16\pi^2\hbar c/\lambda^5\right)/\left(\mathrm{e}^x - 1\right)$
spectral photon density	photons per volume per wavelength interval	$u_\lambda\lambda/(2\pi\hbar c)$
photon PDF	probability per wavelength interval	$u_\lambda\lambda \Big/ \int \mathrm{d}\nu' u_\lambda(\lambda')\lambda'$
spectral irradiance	power per area per wavelength interval	$B_\lambda = u_\lambda c/4$
spectral photon arrival rate	photons per time per wavelength interval	$B_\lambda\lambda\Sigma/(2\pi\hbar c)$

Various forms of the Planck formula for the spectrum of thermal radiation. In these formulas, $x = 2\pi\hbar\nu/(k_\mathrm{B}T) = 2\pi\hbar c/(\lambda k_\mathrm{B}T)$ and Σ is the area of a patch of emitting surface.

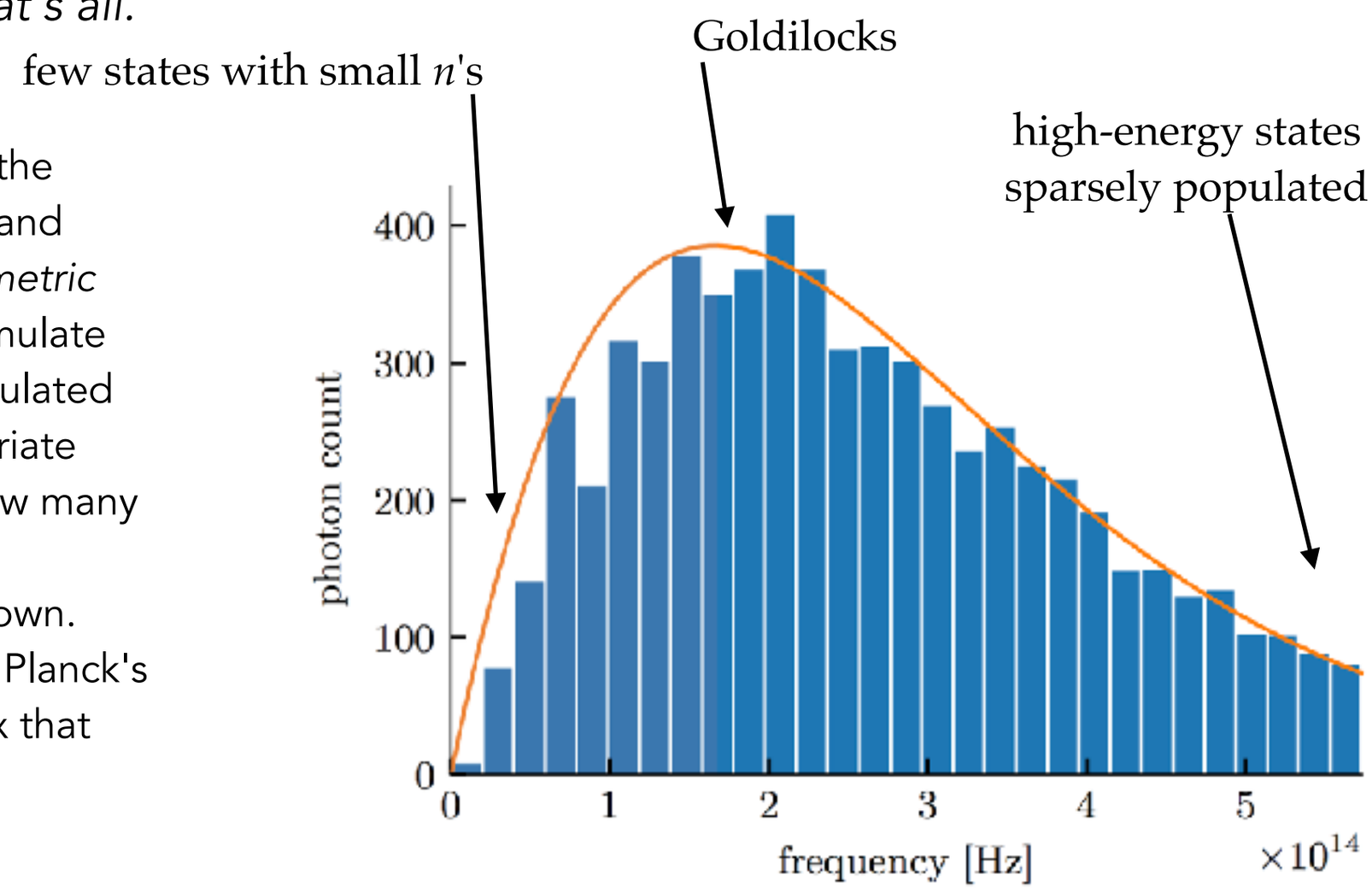
Before you glaze over: Isn't there some simple way to *understand* such formulas??

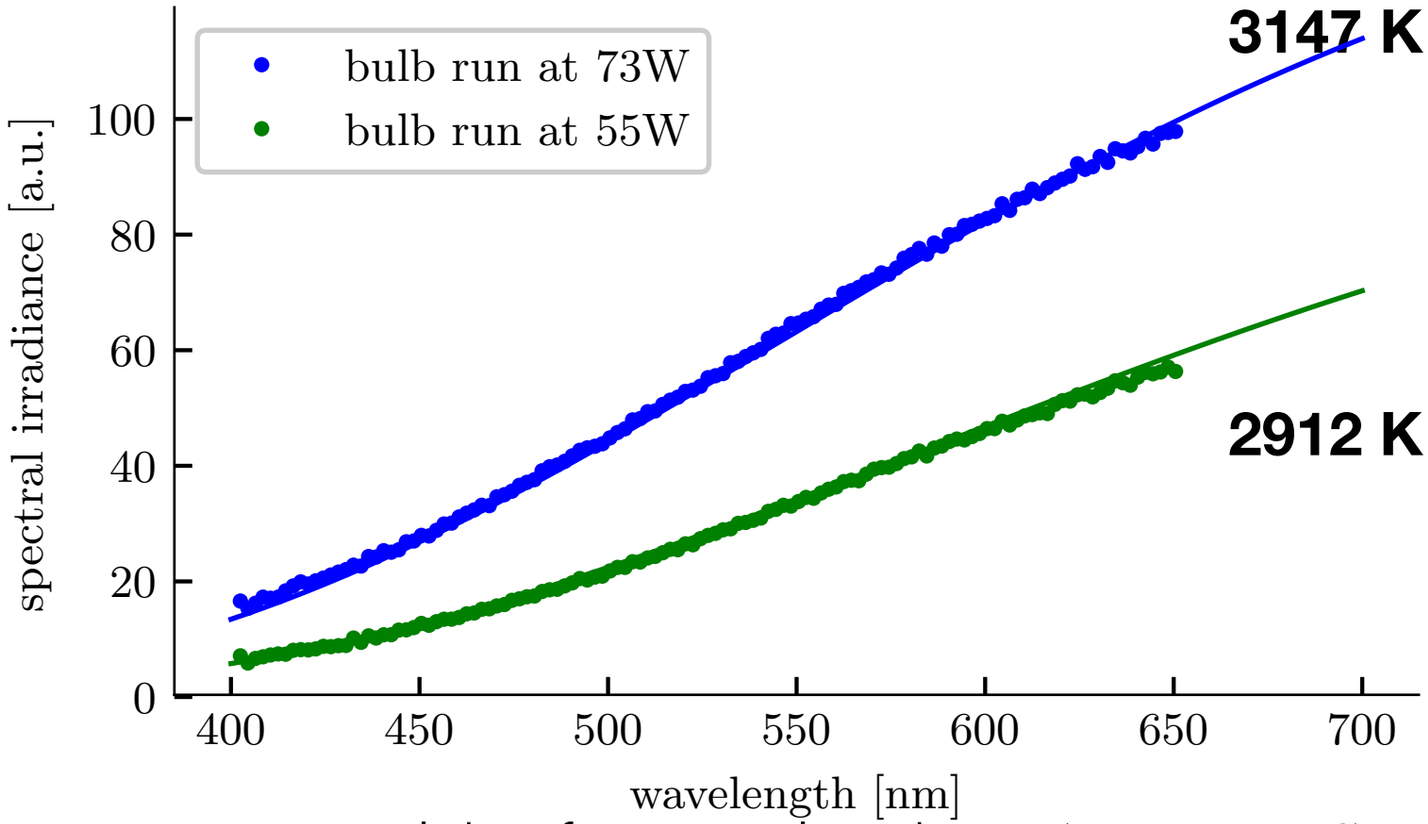
Origin of the thermal spectrum

Those curves were a mystery for a long time, but it's surprisingly simple to predict them once we grant four hypotheses, each of which can be supported from biophysical phenomena:

- Light comes in lumps ("photons").
- Where light will land in a spectrum ("frequency") determines how much energy is carried per photon via a simple linear relation: $E = h\nu$. *So:* to find the spectral energy density, we need the *populations* of each class of photon.
- In a cubical box of side L, there is a class of photons for each set of 3 integers (n_x, n_y, n_z). Photons in a particular class land in the spectral region with frequency $(c/L)\|\vec{n}\|$.
- Photons appear/disappear until each class is separately in thermal equilibrium at the temperature of the box. States 'n weights. *That's all.*

Thus, for each frequency and direction, the number of photons with that frequency and direction is a *random variable with geometric distribution.* I made a simple code to simulate draws from those distributions, and populated each possible photon state with appropriate random numbers. Then I counted up how many photons were present in each range of frequencies and made the bar graph shown. The orange curve is the prediction from Planck's formula. For concreteness, I chose a box that was a cube with edges of length 14 micrometers, and temperature 5000K.



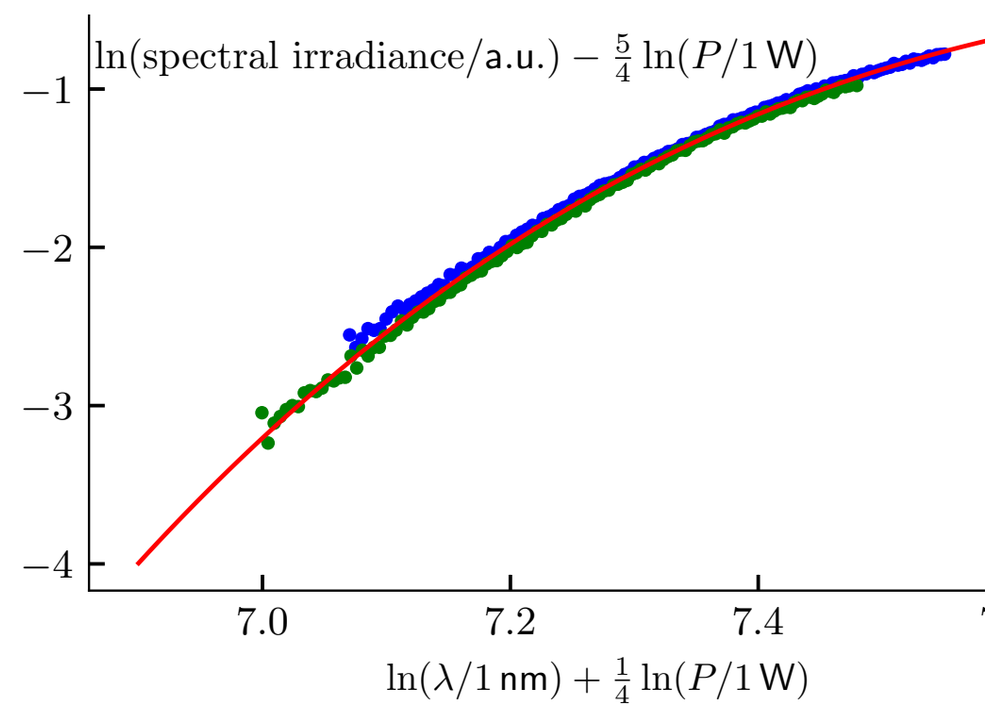


A hot tungsten wire is not obviously analogous to a cavity, and yet its emitted radiation turns out to be very close to thermal form (at least in the visible range).

Dots are experimental data for spectral irradiance (watts per m^2) times an overall scale factor that is common to both curves.

Solid curves are the Planck functions for the indicated temperatures. Indeed we find that the total power dissipation, which we measured, is related by 73/55 = $(3147/2912)^4$, as predicted by the Stefan–Boltzmann law, even though most of that power goes into wavelengths we didn't measure.

How to get that fit: First confirm that the experimental data "collapse" onto a single curve, as predicted by the model. Then fit that one curve to the model.
Finally, undo the transformation that gave the collapse to see what the predictions are for the data as given to us (above).



What is the biggest organism?

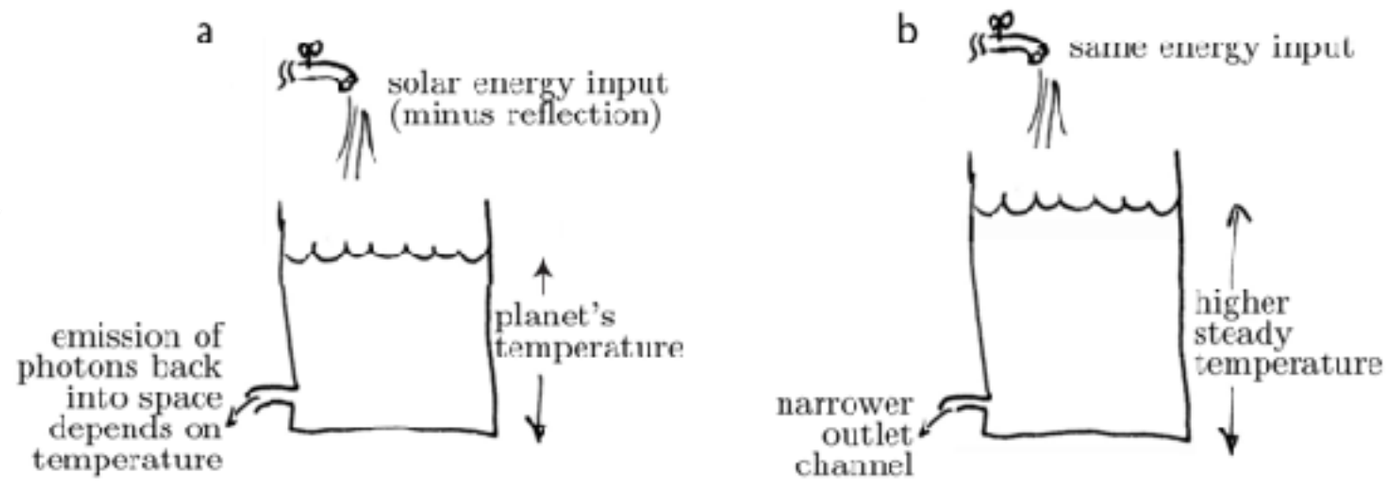
- Blue whale? Sequoia tree? That monster fungus?
- The Earth system is complex and self-regulating. It transduces solar energy into structure. Living organisms do that.
- It is true that the Earth system does not reproduce and hence did not evolve by descent with modification in the presence of natural selection. So if that's part of your definition of a living organism, it's not an example.
- But it is full of organisms that did so evolve. And it has a physiology that is replete with interesting feedbacks, as do we. And the organisms it hosts have themselves made major modifications to its physiology.
- And whether or not we call it "bio," methods and concepts of biophysics are highly relevant.
- Rather amazingly, quantum physics, usually thought of as relevant to the world of very tiny things, plays *two decisive roles* in this story.

Climate change is scary

- You can't think about climate *change* without appreciating some aspects of *climate* itself.
- And those guys seem to know and care about trade winds... continents... Earth orbit wobble... *basically all of science*. From 17th–21st century.
- And everything seems to rely on monster simulations full of assumptions normal people can't understand.
- Is there any entry-level aspect, maybe supported by a nontrivial observation I could make myself?
- This is a school about modeling – is there any entry-level model we could write that at least gives a vista on the real thing?

A simple feedback sets the temperature of a "naked" planet (like Mars)

- In the water metaphor, outflow from the leak depends on the overall water level.
  - If we increase the inflow then the system finds a new, higher steady level.
- The planetary system is similar:
  - Here the input ("net insolation") is solar radiation minus a fraction reflected by clouds and polar ice.
  - The "leak" is IR radiation back out to space, which we saw is faster at higher temperature.
  - Simple because there's only one way for energy to leave.
  - If we increase the insolation, then the system finds a new, higher steady level.



- This simple analysis works well for Mars. [First entrance of quantum mechanics in the story.]
- But it fails for Earth, and fails *spectacularly* for Venus.

The naked and the clothed

Some planets have atmospheres. But the atmospheres of Earth and Venus are mostly transparent to the solar spectrum, apart from the reflection that we already accounted for, so they have little effect on surface insolation. Why then did our estimate fail so badly for Earth and Venus?

We missed a big part of the energy budget for the *surface* (where we live):

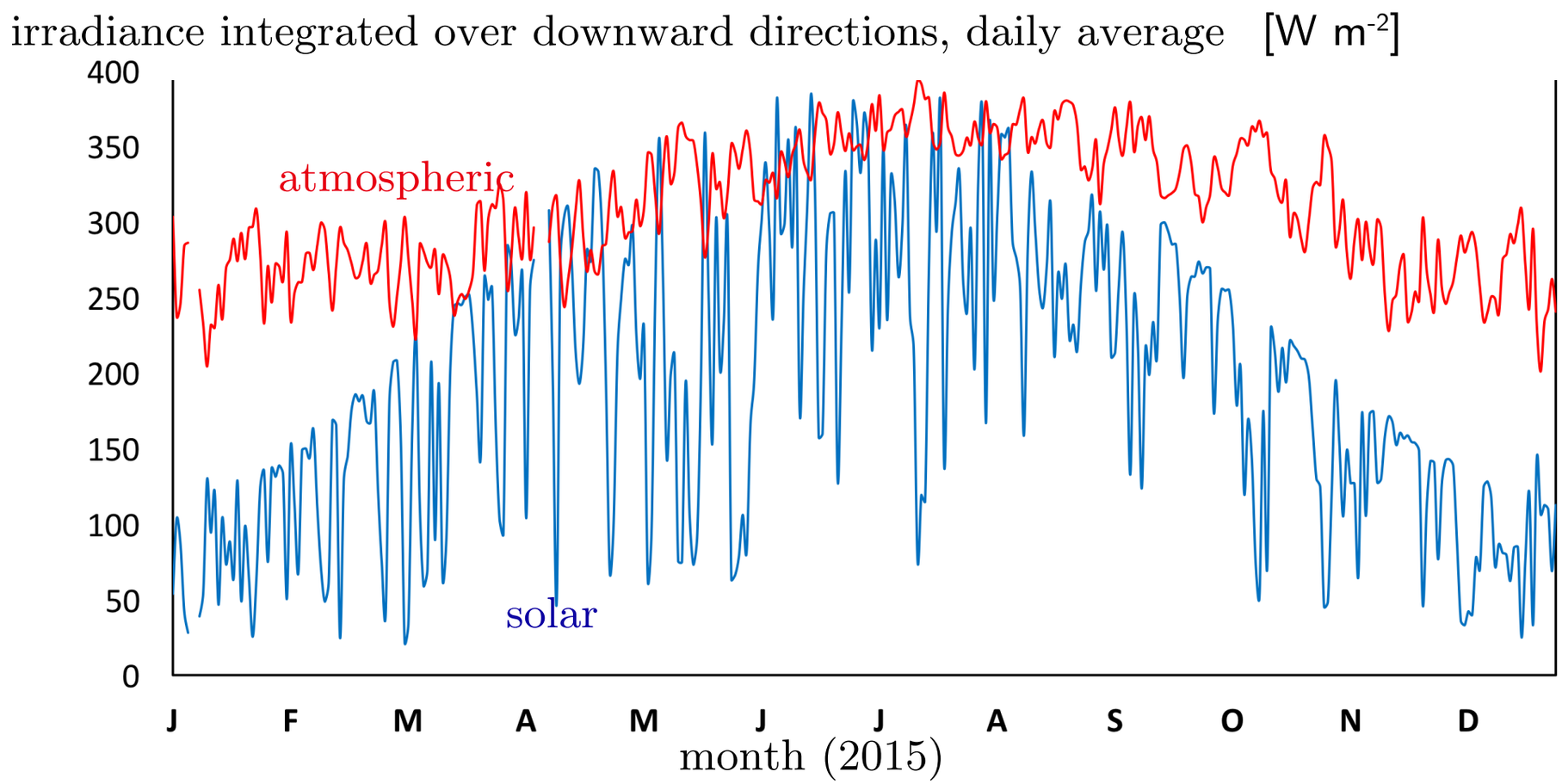
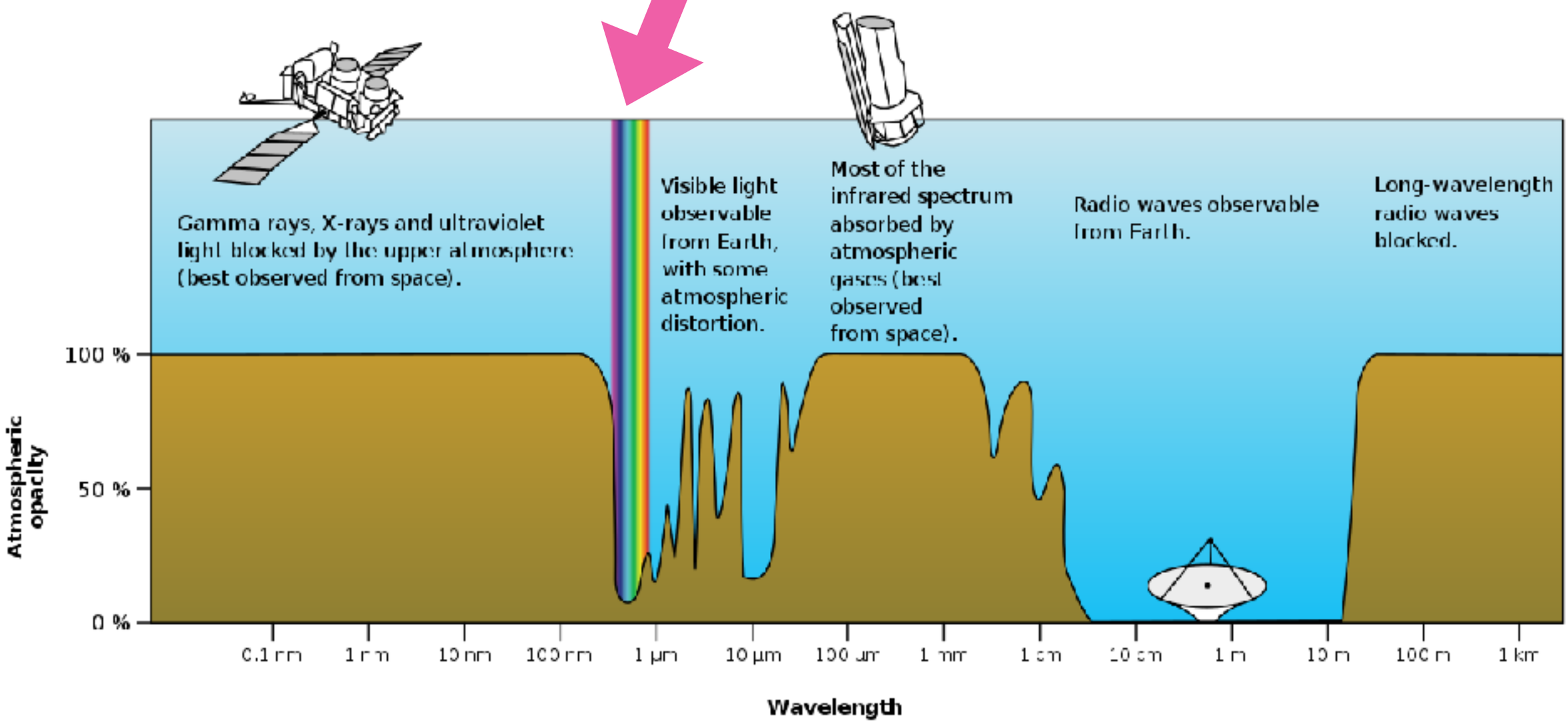


Figure 15.2: [Experimental data.] **Solar and atmospheric radiation arriving at one point on Earth surface.** The *lower (blue) curve* shows the irradiance integrated over all downward directions in the band 300 to 2800 nm, which includes nearly all light coming directly from the Sun but excludes nearly all thermal radiation at Earth's temperature (see Figure 15.1). The *upper (red) curve* shows the irradiance integrated over all downward directions in the band 4500 to 42 000 nm, which excludes nearly all light coming directly from the Sun but includes nearly all thermal radiation at Earth's temperature. [Data courtesy Peter Pilewskie.]

Where is all that extra radiation coming from?

Most solar energy is arriving in a band that passes right through the atmosphere. So where does atmosphere get that energy?



Well – when that light hits the surface, or penetrates the ocean, it *warms it.*
Then the surface radiates energy in a *different* wavelength band.
Then what?

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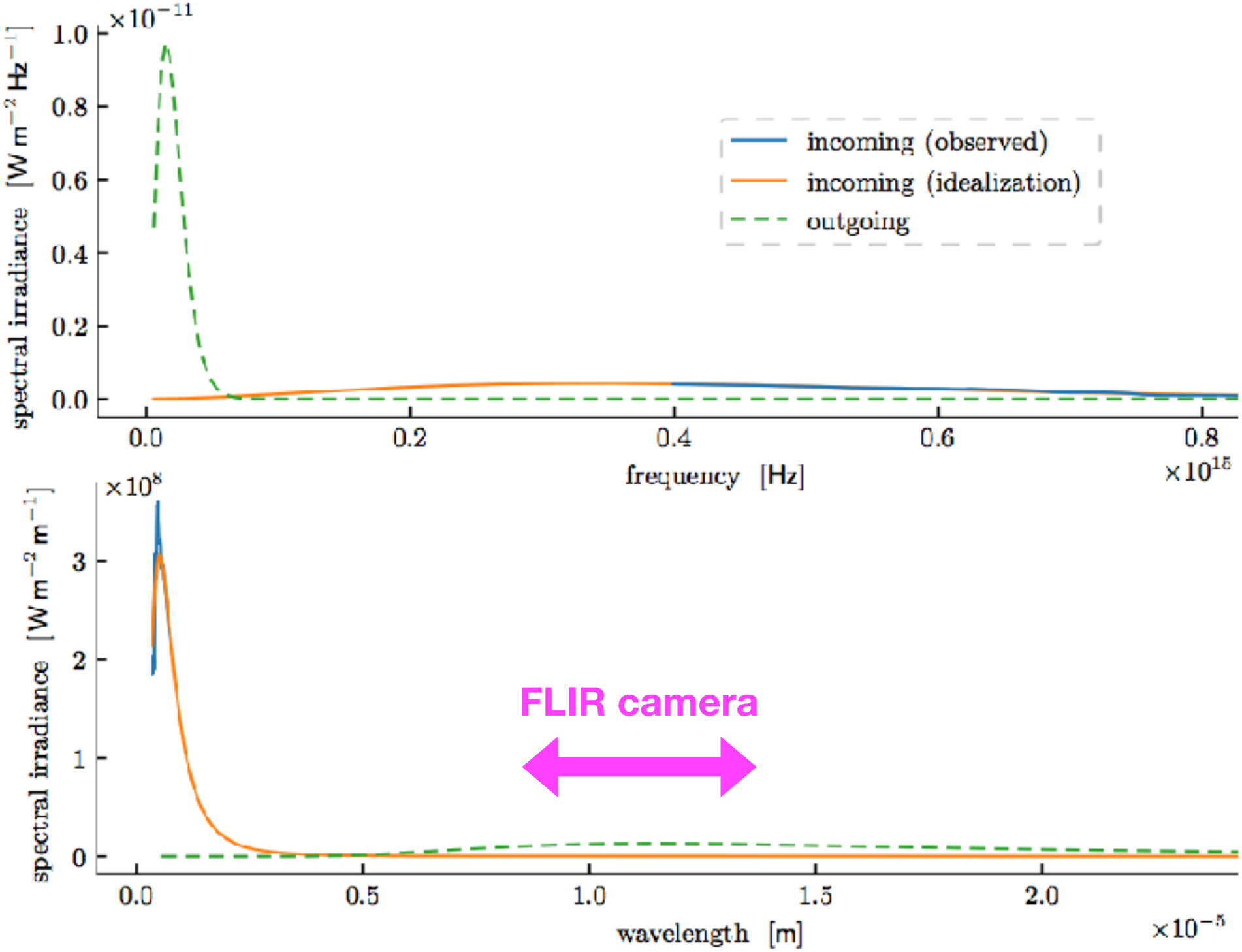
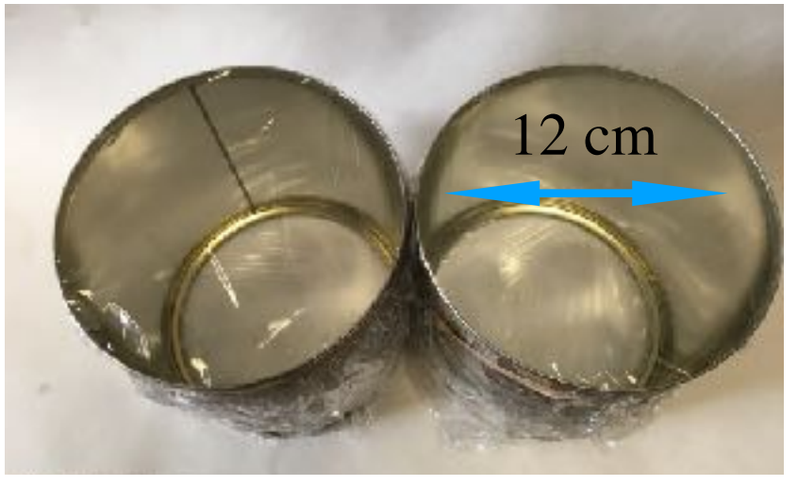


Figure 15.1: [Experimental data; mathematical functions.] **Earth without an atmosphere.** *Solid blue curves:* Observed spectral irradiance of light arriving at Earth from the Sun. The normalization of this curve includes a reduction for reflection (albedo), as well as averaging over surface position, time of day, and season. *Solid orange curves:* Planck spectral irradiance function at temperature 5760 K, also averaged and reduced by the geometrical and reflectivity factors in Equation 15.3. *Dashed green curves:* Planck spectral irradiance function with temperature $T_e = 254$ K chosen to match the total incoming irradiance (area under the orange curve); see Your Turn 15B. This curve has negligible overlap with the others. (a) Spectral densities in terms of frequency. (b) The same spectral densities in terms of wavelength. Problem 3.2 (page 142) works out how to convert between these two representations of a spectrum. [Experimental data from Thekaekara et al., 1969.]

Just Try It

www.youtube.com/watch?v=0eI9zxZoipA

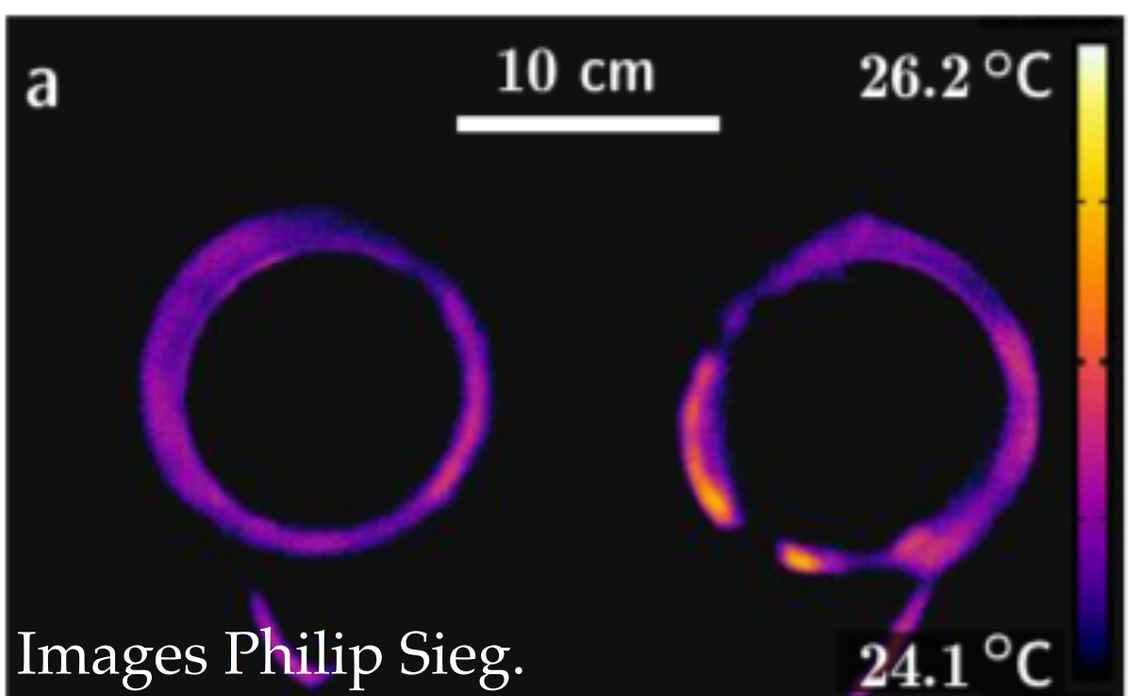


Two identical cylinders were prepared and sealed at the ends with thin plastic wrap. They looked the same to the eye.

The one on the left contained air at room temperature. The one on the right was filled with carbon dioxide gas. Below *left* we are viewing them with a camera sensitive to the wavelength range 7.5–13 μm. The color bar is a rough guide to what kind of light is being emitted. We see that initially they looked about the same. Reading the false-color scale gives apparent temperature 24°C, same as the wall behind them.

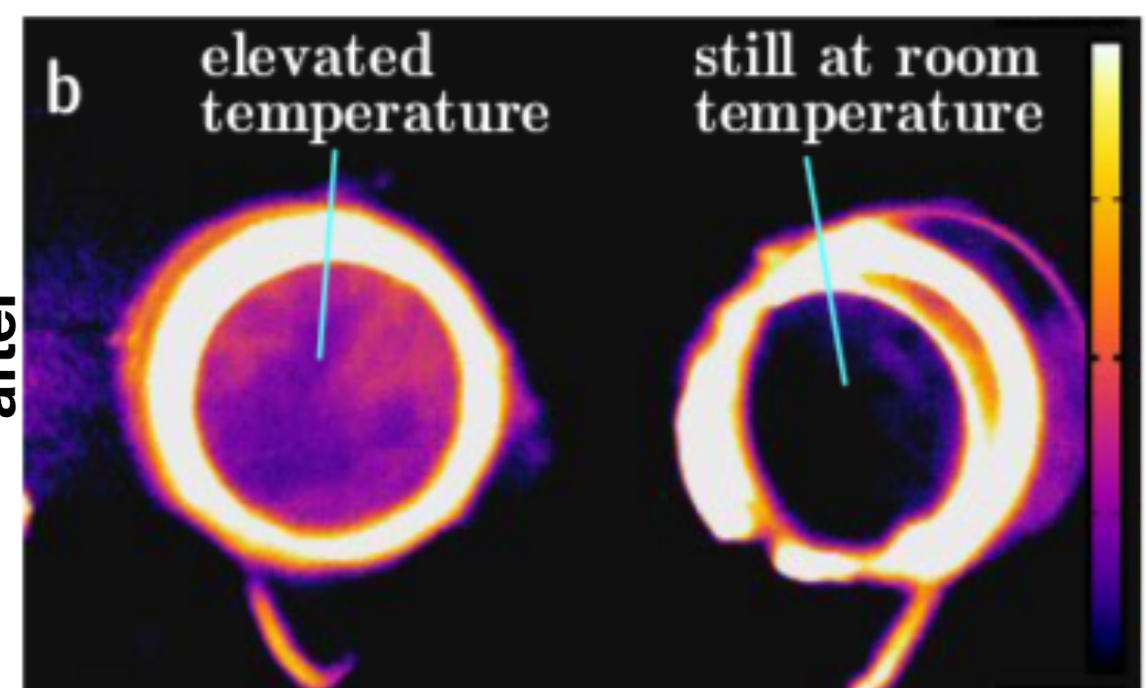
Each cylinder was exposed to a source of IR radiation through its thin window for two minutes, then the source was removed. Both cans got warmer, but the apparent temperature of the CO_2 was higher than the air (*right* below), and a measurable difference persisted even a minute later.

before



Images Philip Sieg.

after



(Let's not call it "greenhouse effect."
People have an emotional response to that phrase. They may call you bad names and tune you out. Nor is it accurate.

- A real greenhouse, or any house, has walls to suppress convection, advection (wind), etc. which carry heat away from the interior (in winter).
  The main difference between a greenhouse and your house is where the heat comes from:
  - Your house: furnace brings in energy from gas line, oil delivery, electric wires.
  - Greenhouse: glass that is transparent to visible light brings it in from the Sun; then it lands on the interior objects and turns into heat.
  - Either way, if you take away the house, it gets colder because of convection/advection, not primarily by IR radiation.

- It is true that, as in a greenhouse, Earth's surface is warmed by the absorption of visible light from the Sun. But that's got nothing to do with "greenhouse" gases! The same happens on Mars.
  - A planet like Earth or Venus has an atmosphere that absorbs IR emitted by the surface and that also radiates IR, some of it back to the surface. There is no need to suppress loss of heat to space by convection/advection, because no air in space.
  - If you take away the atmosphere, it gets colder at the surface because of IR loss.

Let's instead call it "IR trapping.")

Why are CO_2 and H_2O so different from O_2, N_2 (and Ar)?

- A homonuclear, diatomic molecule can't have any electric dipole moment (nor can a monatomic noble gas).
- H_2O has a dipole moment, so its rotational states can couple to photons. [Second entrance of quantum mechanics in the story.]
- CO_2 has no dipole moment, but it can acquire one by bending. O_2 , N_2 cannot bend.

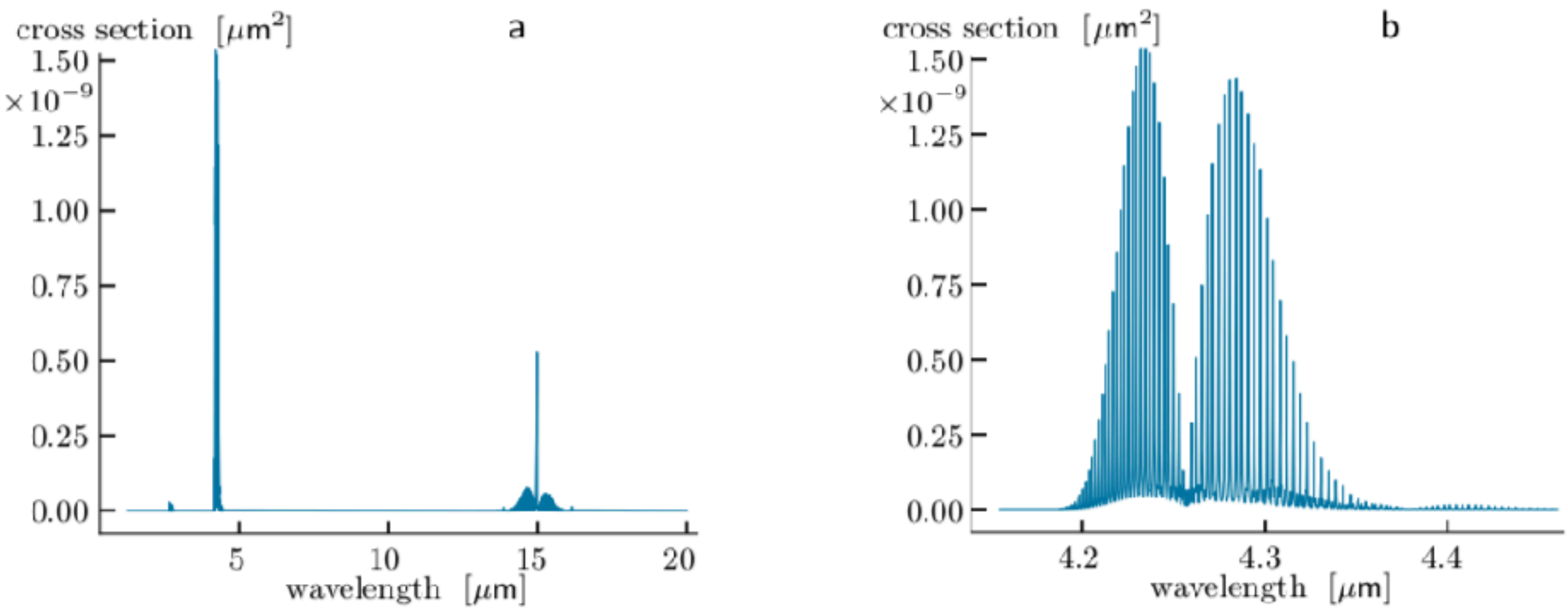
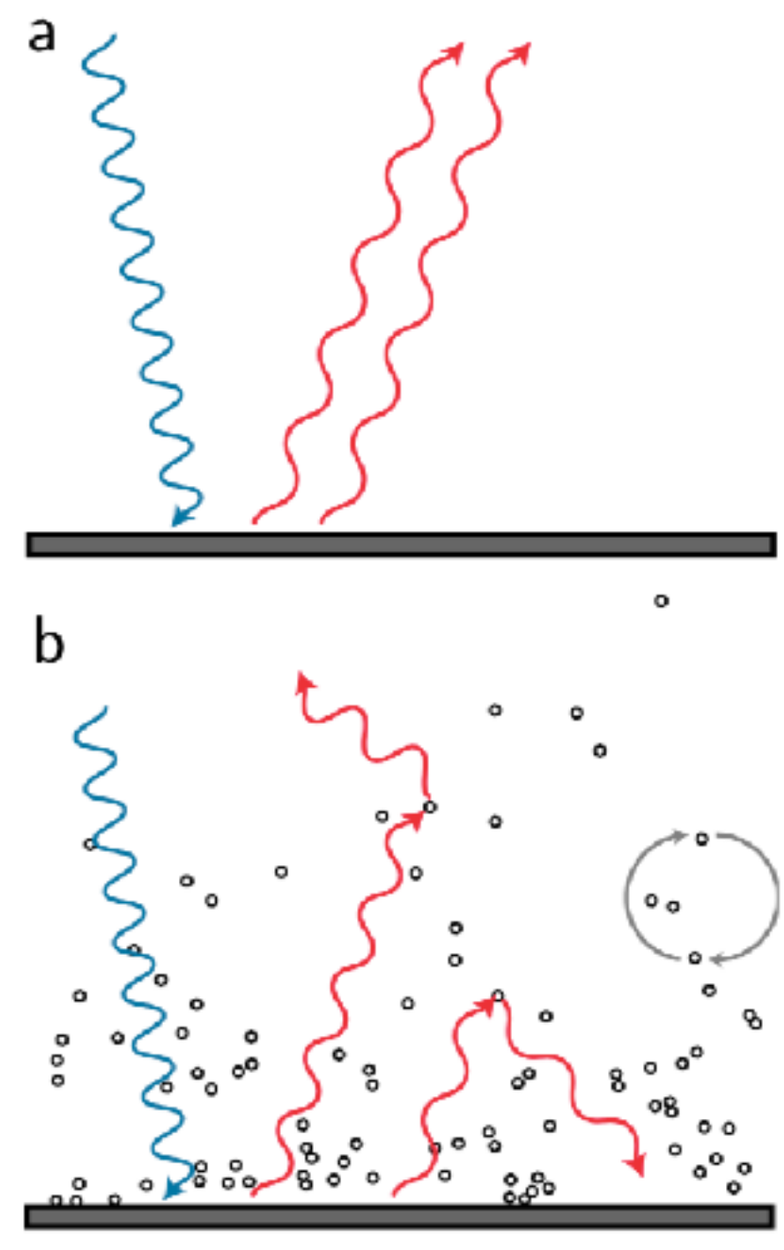


Figure 15.11: [Experimental data.] **Absorption spectrum of CO_2.** (a) Absorption cross section at atmospheric pressure and room temperature, as a function of wavelength. (b) Detail of the largest peaks in (a).

A cartoon idea:

A slightly more realistic cartoon idea:



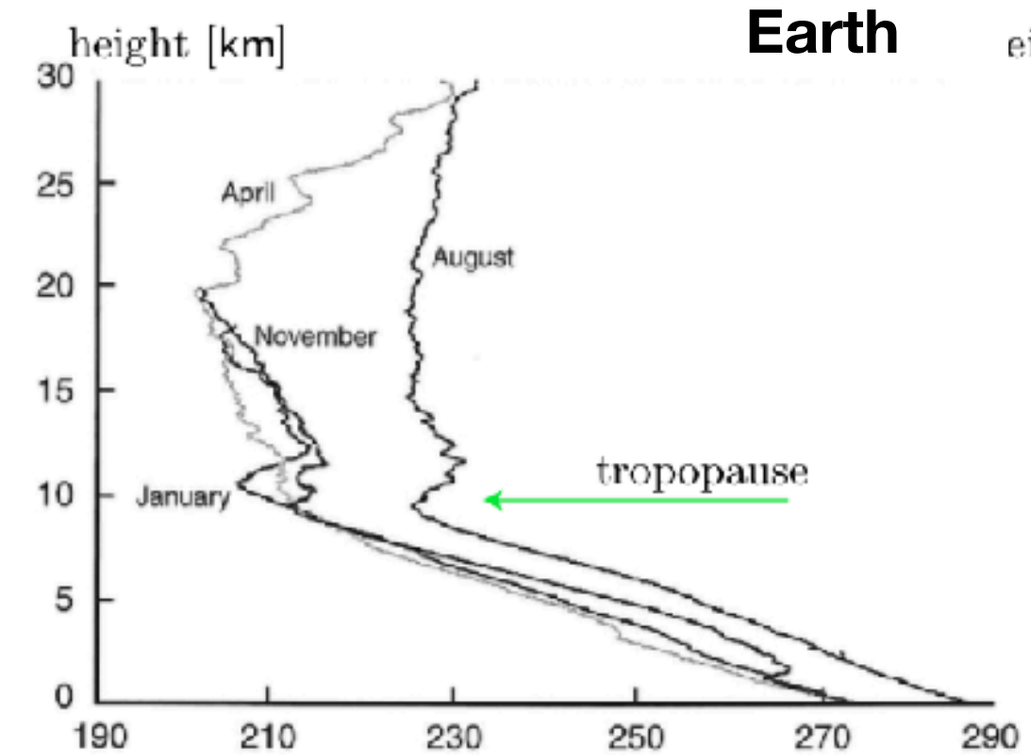
The amount of energy that must exit is fixed. If we obstruct its exit, then a hotter surface is needed in to achieve the same total flow of energy.
Before we can be really realistic, we need to think about convection (far right of cartoon).

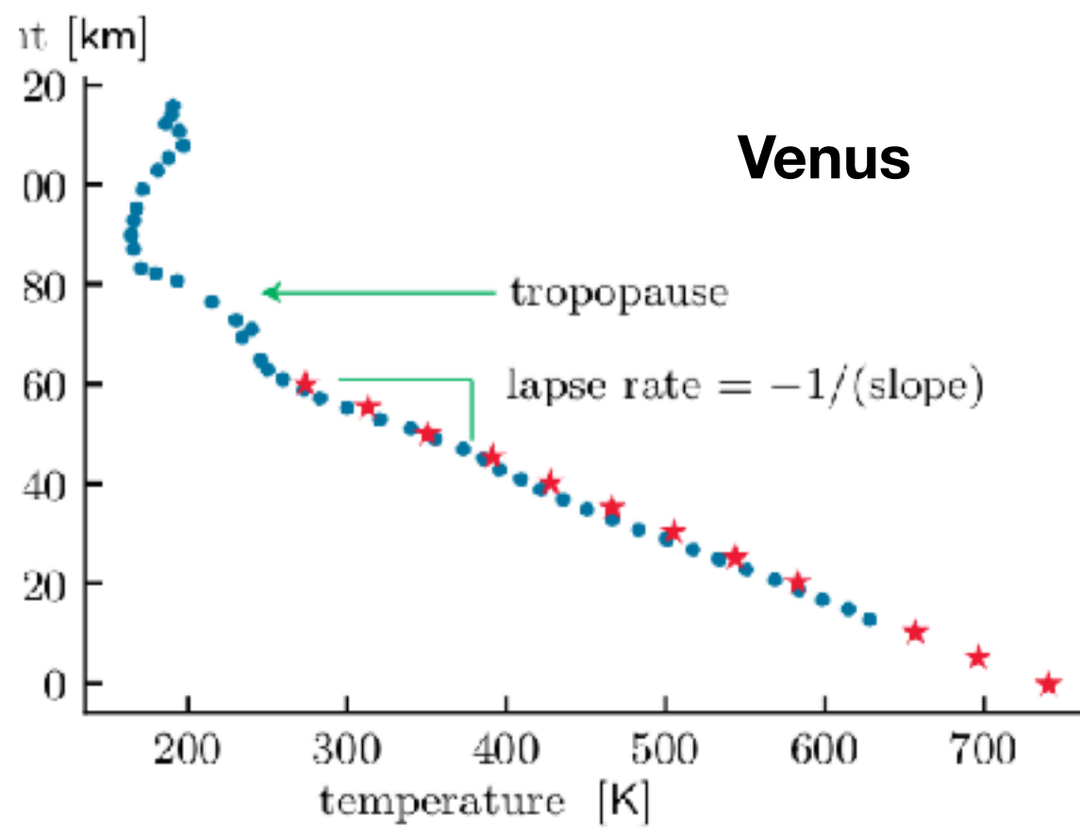
Convection sets a constant temperature gradient in the lower atmosphere

In the lower part of the atmosphere ("troposphere"), where it is still dense enough to be opaque to IR, temperature depends linearly with altitude, with slope of the graph called the "lapse rate."

For example, dry air (a mixture of gases roughly obeying the ideal gas law, without any component that can condense upon cooling) will have lapse rate $-g/c_{\mathrm{p}}$, where g is the acceleration of gravity at the surface and c_{p} is the specific heat at constant pressure, per mass. This formula is nearly independent of gas density, because c_{p} is constant for an ideal gas. The formula just given predicts its value as around $10\,\mathsf{K/km}$, and similar values even on such different planets as Mars and Venus.

Similar but more accurate formulas can be written to account for an atmosphere with a condensing component, such as water vapor on The actual observed lapse rate in the troposphere is about $65\,\mathsf{K}/(10\,\mathsf{km})$ on Earth.





Effect of changing IR-active gas concentration, Part I

More IR-active gas means the height of the last opaque layer goes up.

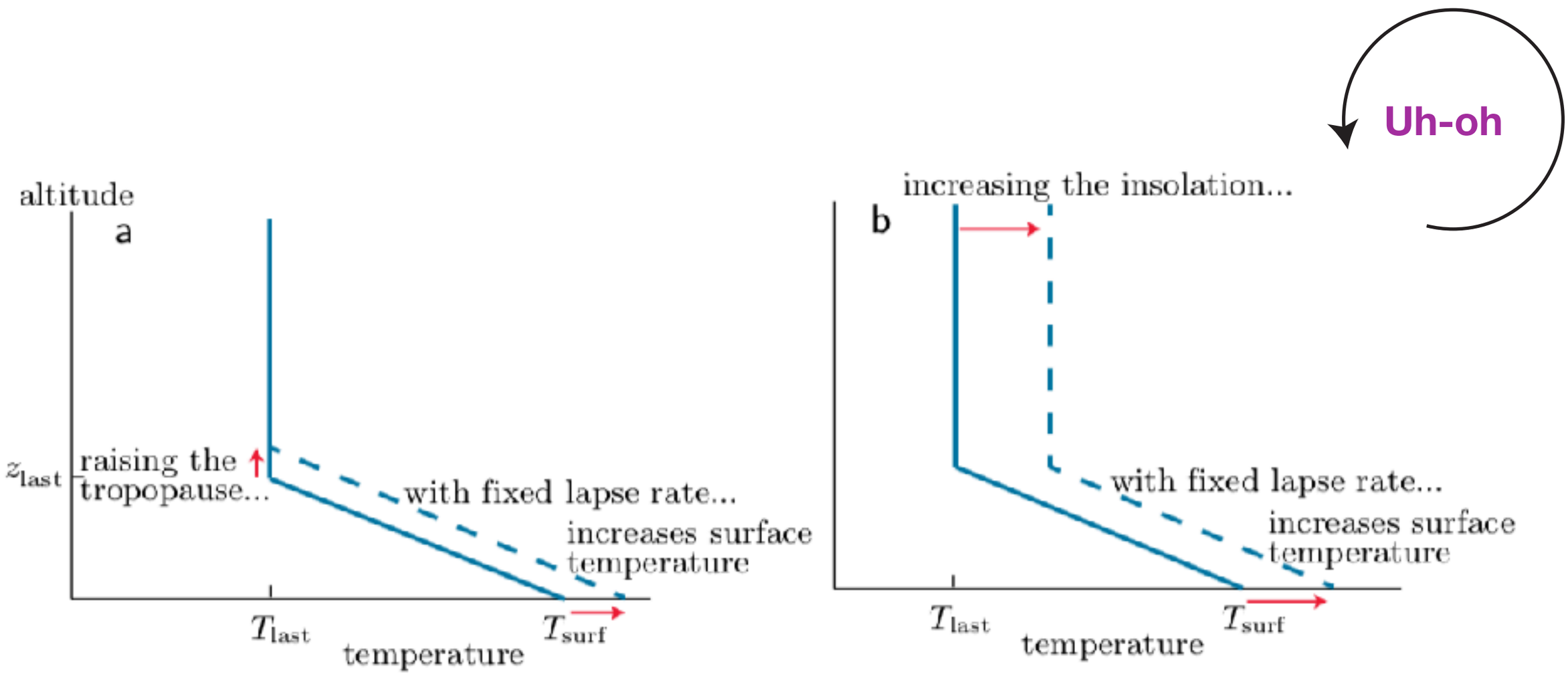


Figure 15.10: [Sketch graphs.] **Effects of changes to atmospheric composition or surface reflectivity on surface temperature.** (a) A change in atmospheric composition, with no change in reflectivity, can raise surface temperature by moving the tropopause upward (Figure 15.9b). (b) A decrease in reflectivity, with no change in composition, can raise surface temperature by increasing the net insolation and hence T_{last}.

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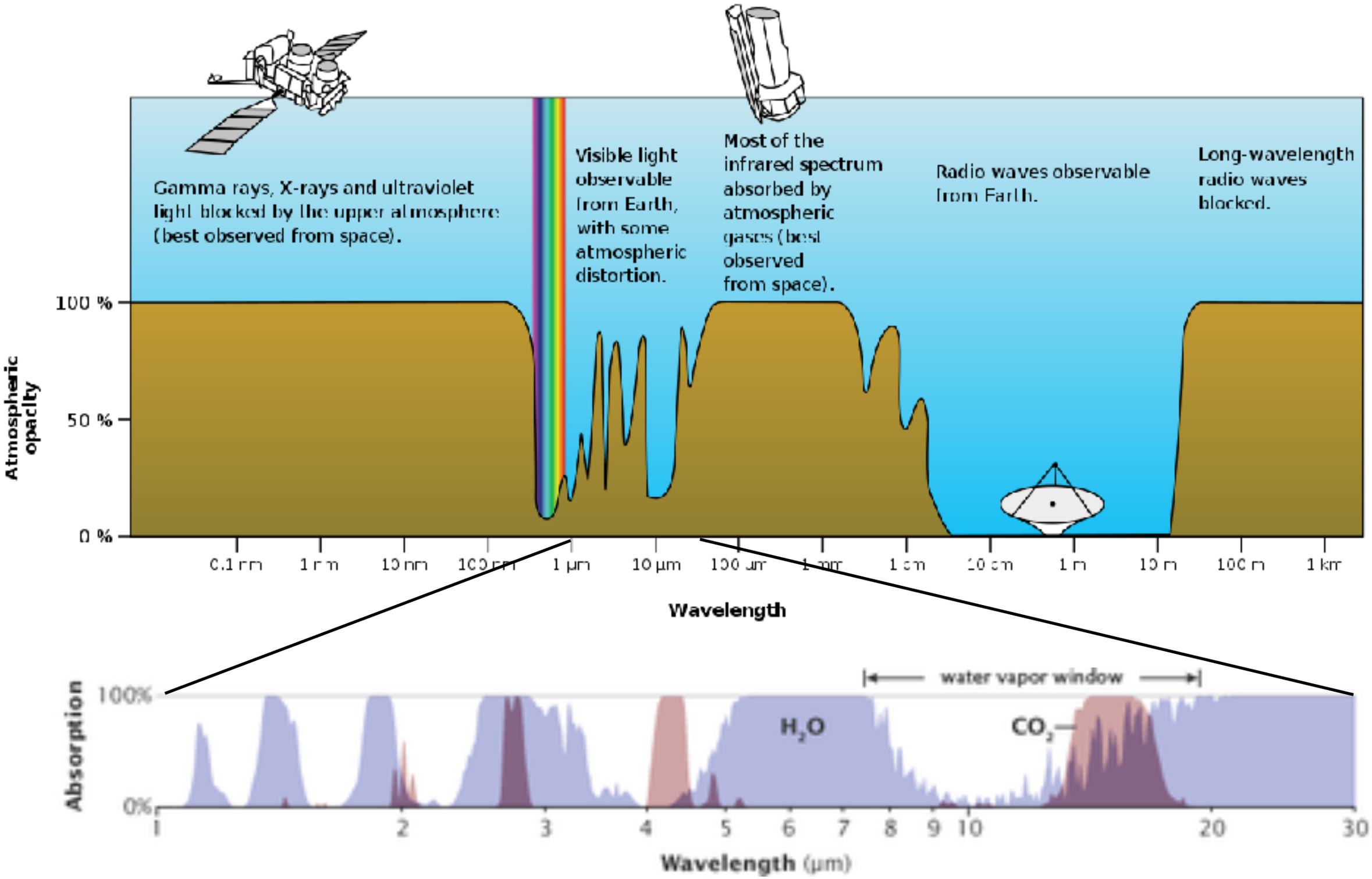
Effect of changing IR-active gas concentration, Part II

Narrowing the "window" would also lead to more absorption. What could cause that?



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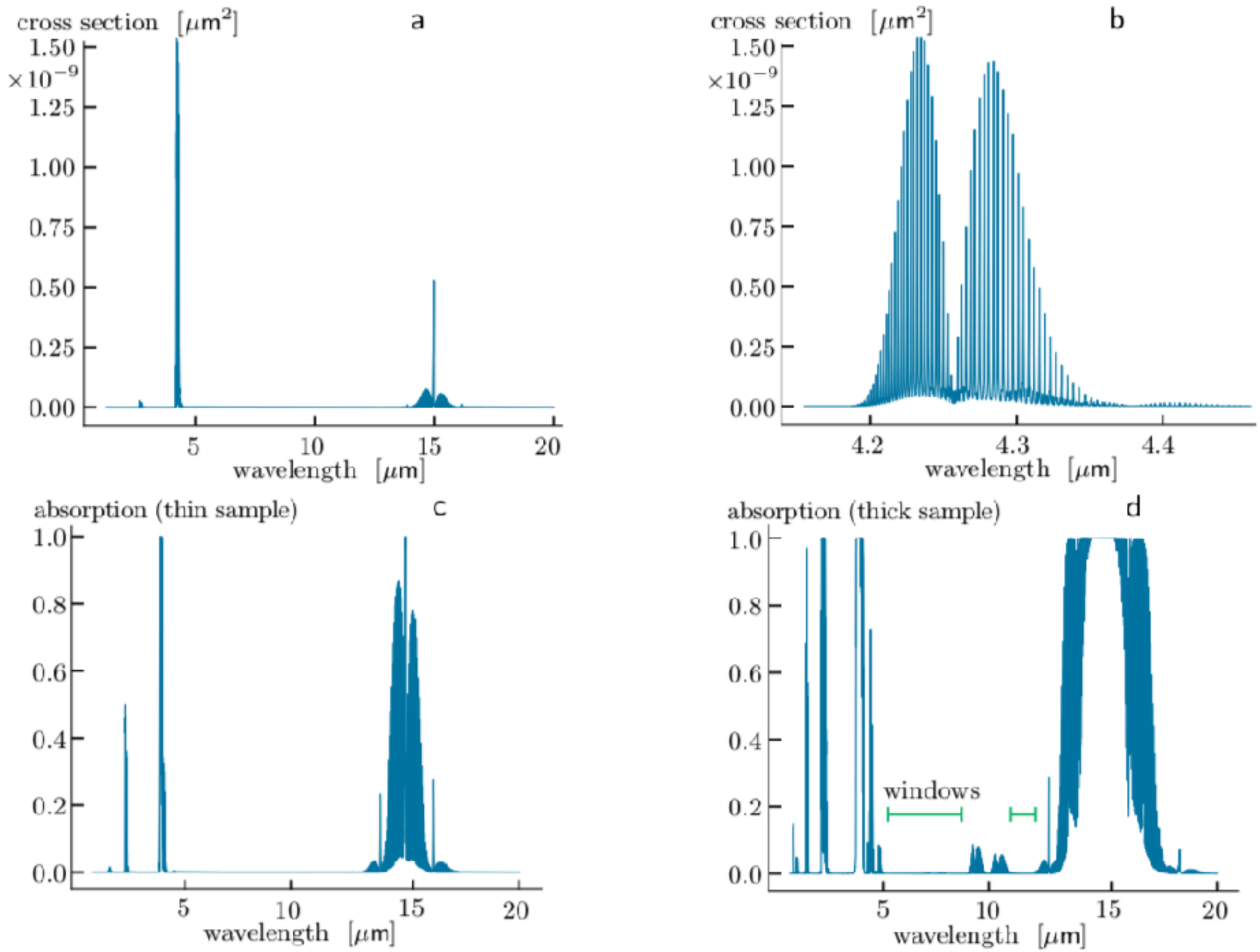

Figure 15.11: [Experimental data.] **Absorption spectrum of CO_2.** (a) Absorption cross section at atmospheric pressure and room temperature, as a function of wavelength. (b) Detail of the largest peaks in (a). (c) Absorption of a sample of pure CO_2 with depth 0.01 m. The graph was obtained by applying Equation 9.7 (page 329) to the data in (a). (d) Absorption of a sample of pure CO_2 with depth 0.23 m, for example, the sample shown in Figure 15.5. For this thick sample, the absorption bands are wider than in (c): Features that are scarcely visible in (a) have large effects (see Section 15.5.2). The *green bars* show two "windows," that is, bands of low absorption. [Data courtesy Eugene Clothiaux; see Bohren & Clothiaux, 2006, Fig. 2.12.]

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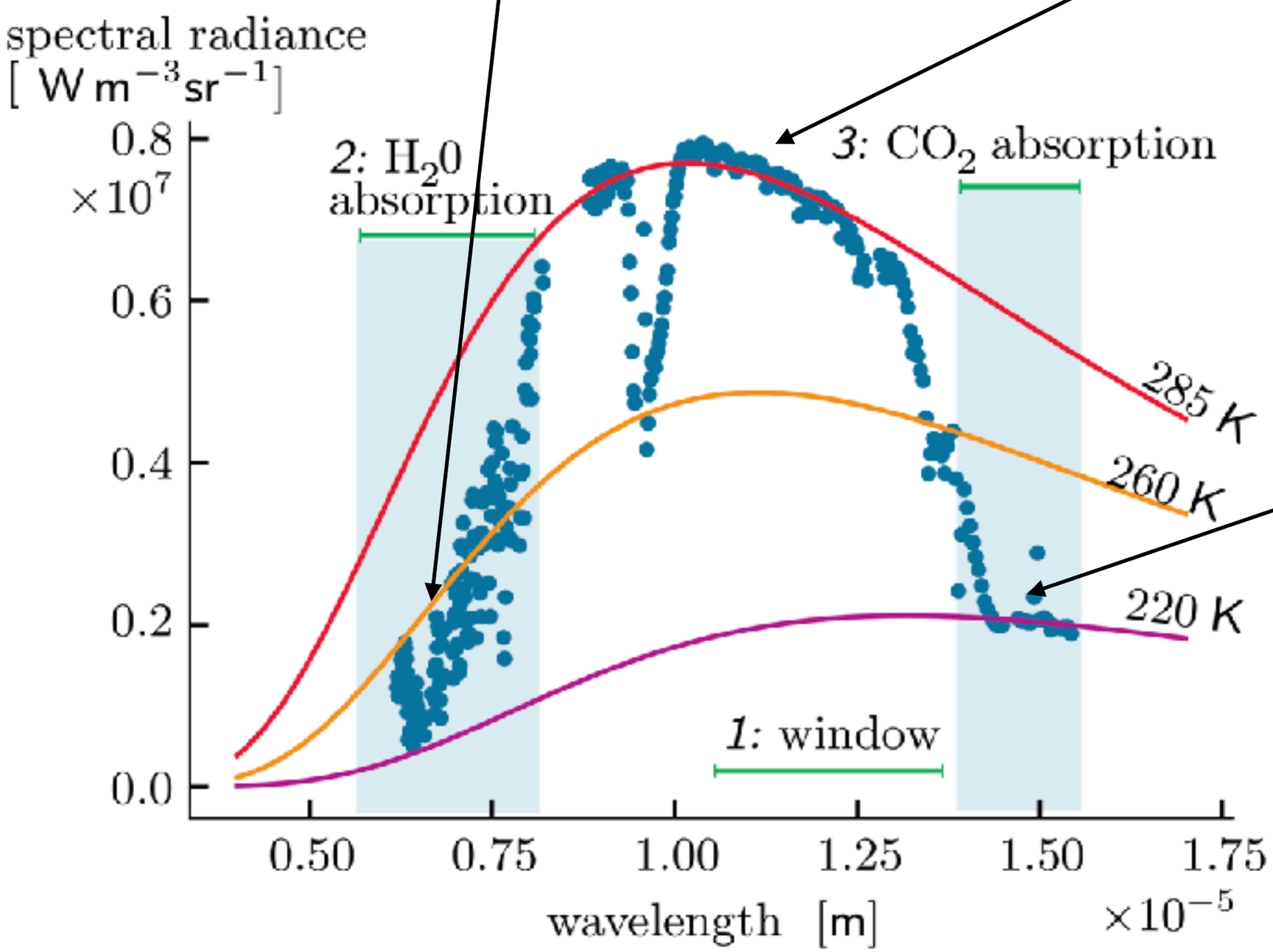
Spectrum of Earth seen from space

Water condenses out so its last IR-opaque layer is midway up.

In the IR window we see the surface temperature



The last IR-opaque layer is high in the troposphere.

repository.upenn.edu/physics_papers/645/

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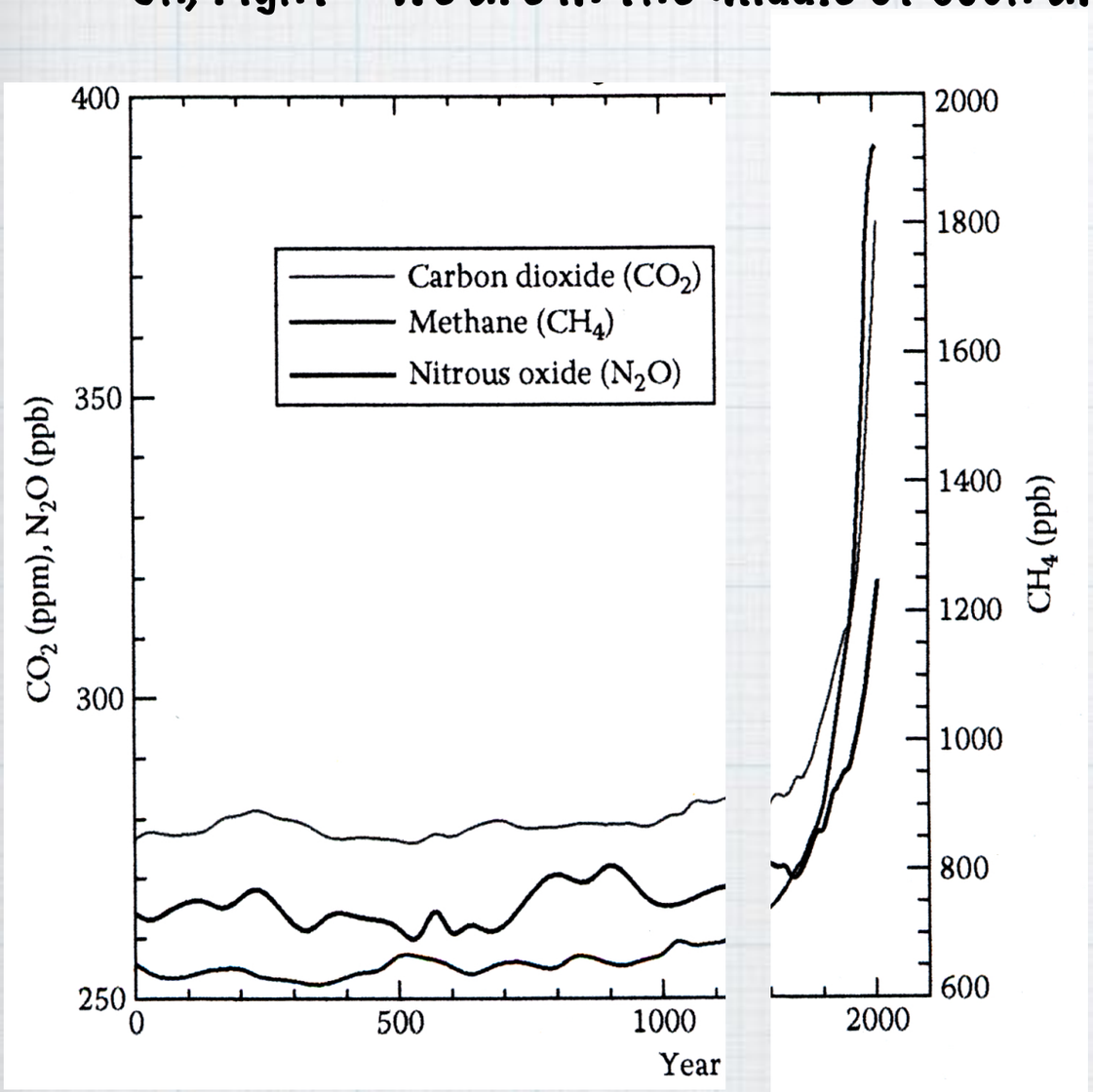
Disclaimer

* From here on, I am an amateur. If this interests you, find an expert. Experts don't know the answers yet either. If they did, it wouldn't be the Most Important Question in Science.
* In a normal science talks, the speaker describes experiments and/or calculations she did herself – first replicating and/or correcting prior work, then doing new things.
  * I can't do that yet. So, no authority. You'll have to use your judgement. I'm going to tell you what's on the minds of certain people.
  * But "lots of people believe this" is not a scientific argument. Science is about being quantitatively right, not about consensus.
  * My goal is just to bring a particular set of issues to your attention.
* At the least, I should keep it short.

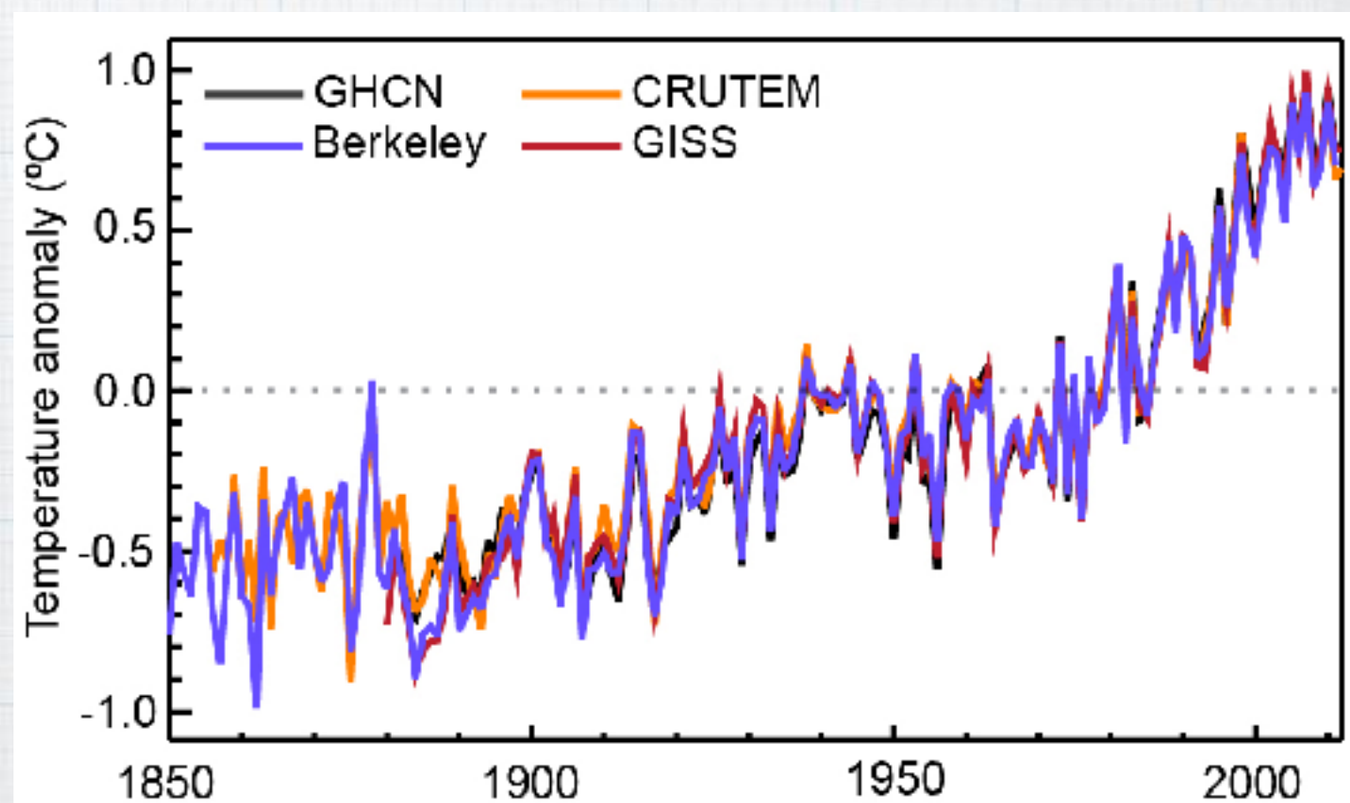
Big organism, big experiment

Is there any evidence that dumping CO_2 et al. "causes" change in global mean temperature?
It's hard to establish causation from a historical record. Correlation of A with B could mean one caused the other, or the other way round, or some other C causes changes in both.
What's needed is an experiment where we artificially crank one and see if the other responds.

Oh, right – we are in the middle of such an experiment right now.

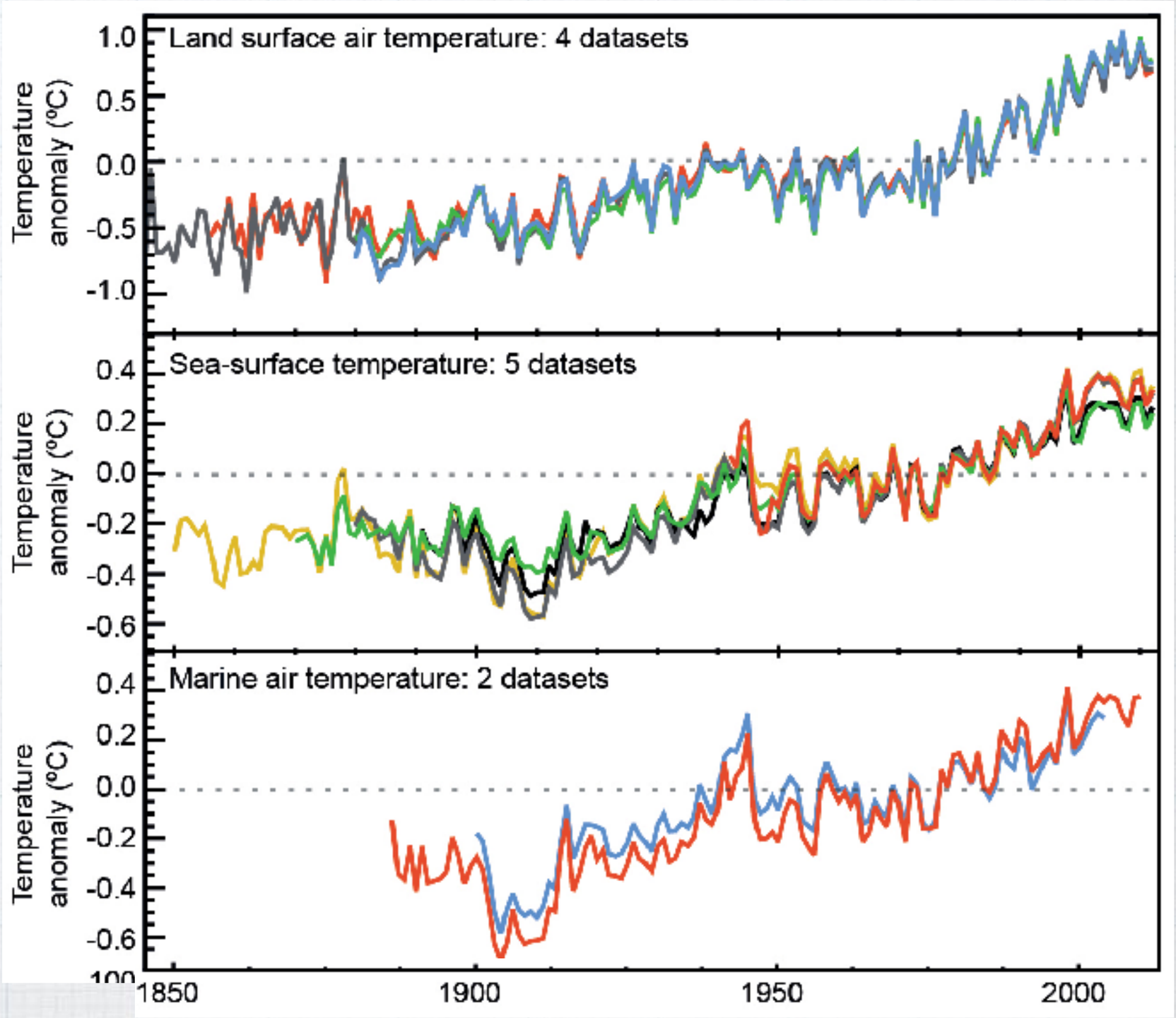


IPCC Climate Change 2007



IPCC Climate change 2013 fig 2-14 p187

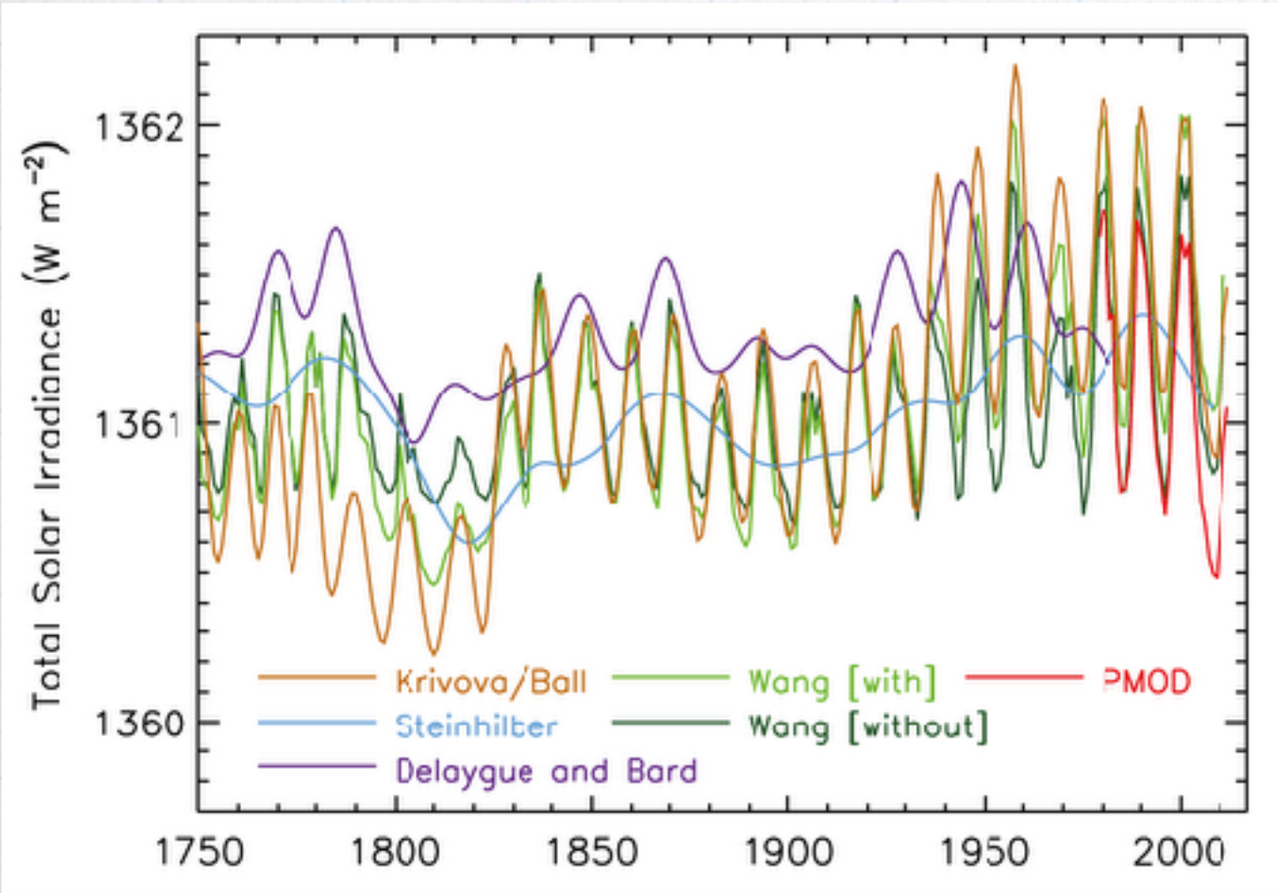
Other measures agree



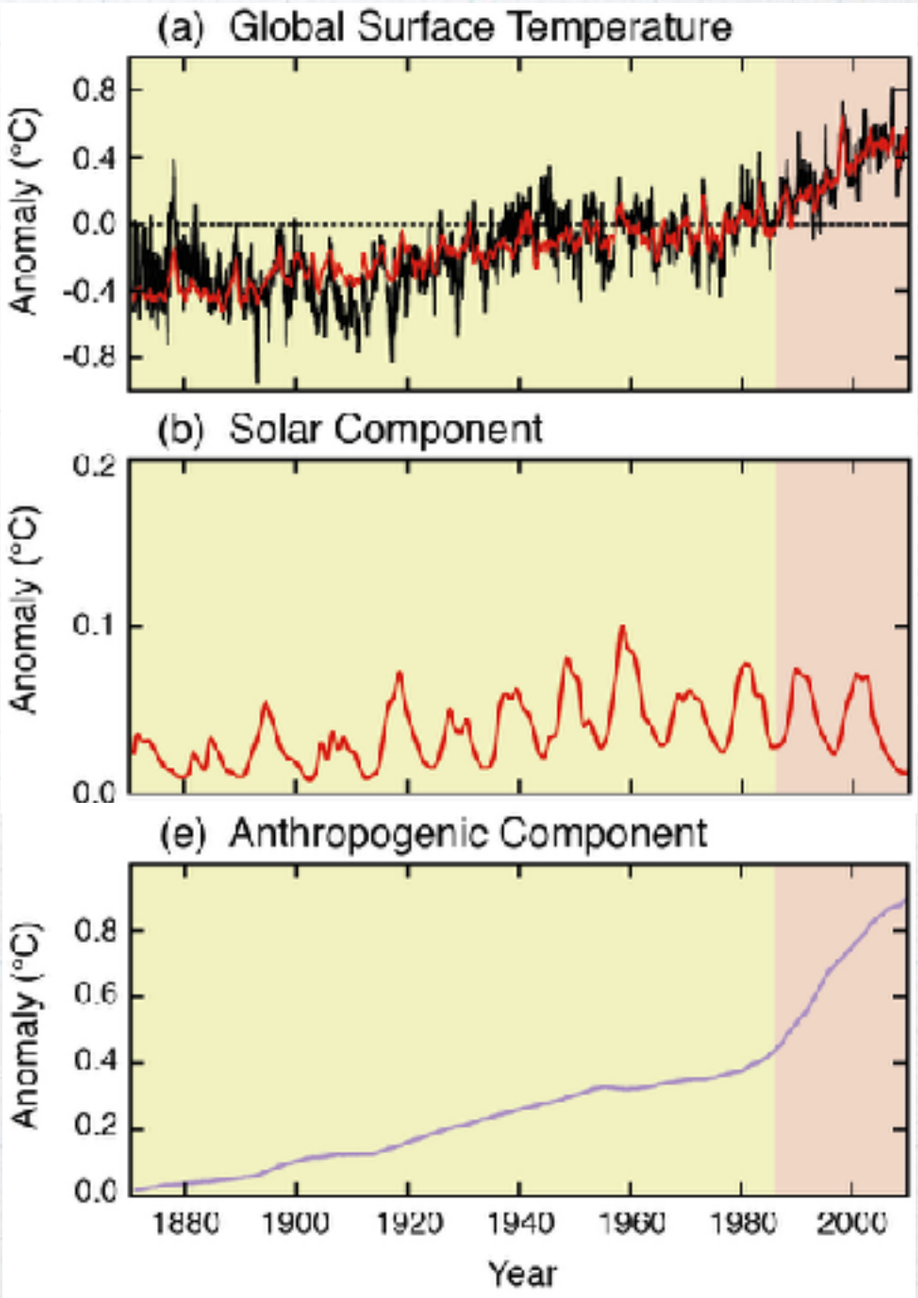
IPCC Climate change 2013 fig TS1 p38

Maybe it's the Sun?

Solar output does change. But not much over recorded history, and anyway it's almost predictable, not very random, so we know how to remove this effect.



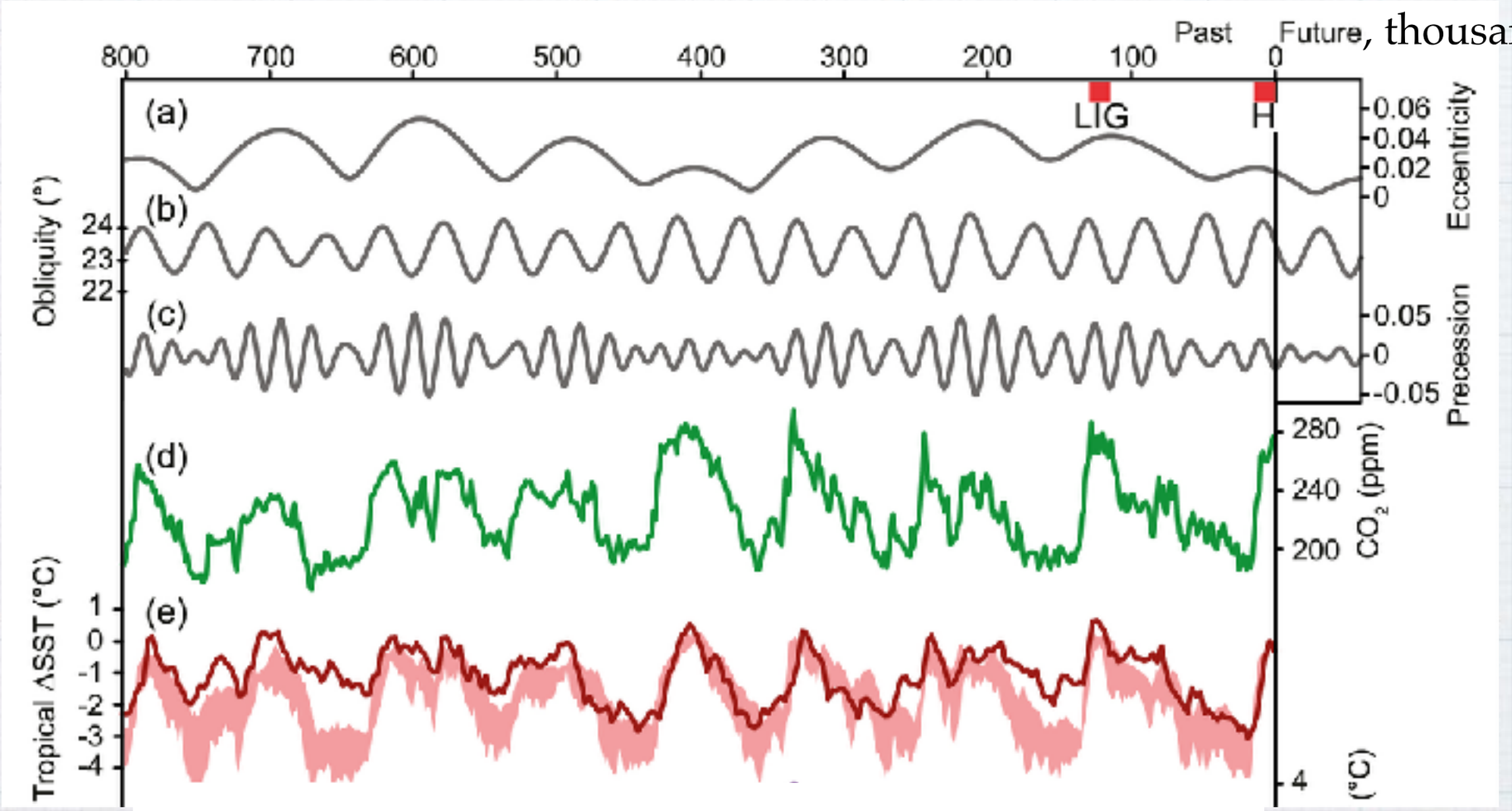
Above: IPCC Climate change 2013 fig 8.11 p689



Right: Red line in (a) is the sum of solar and other known natural variables (b–d), plus anthropogenic component (e). The estimated temperature response to anthropogenic forcing included both a warming component from greenhouse gases, and a cooling component from most aerosols. IPCC Climate change 2013 fig FAQ5.1 page 393.

Maybe it's Earth's orbit?

We could imagine that some other agency affects temperature, and rising temperature forces CO_2 out of solution in the oceans, leading to correlated fluctuations not caused by the CO_2 rise.



It is true that over huge time scales, both CO_2 and temperature correlate with changes in Earth's orbit, not anthropogenic. But the current spike is not associated to a bump in orbital eccentricity, and in any case is happening much faster than orbital changes.

IPCC Climate change 2013 fig 5.3

Earth's atmospheric composition has been stable, and very far from chemical equilibrium (e.g. very different from Mars), despite episodes of volcanic CO_2 dumping etc. Why?

* Known negative feedbacks:
  * Physical:
    * Hotter surface -> more evaporation -> more clouds -> more reflection (but see later).
  * Biological:
    * Plants capture CO_2 and emit O_2, so reduce warming. And more CO_2 -> more plants eating CO_2.
  * Biogeochemical:
    * Weathering of rocks, with the help of plants, is another negative feedback (pulls CO_2 out of atmosphere). But very slow.

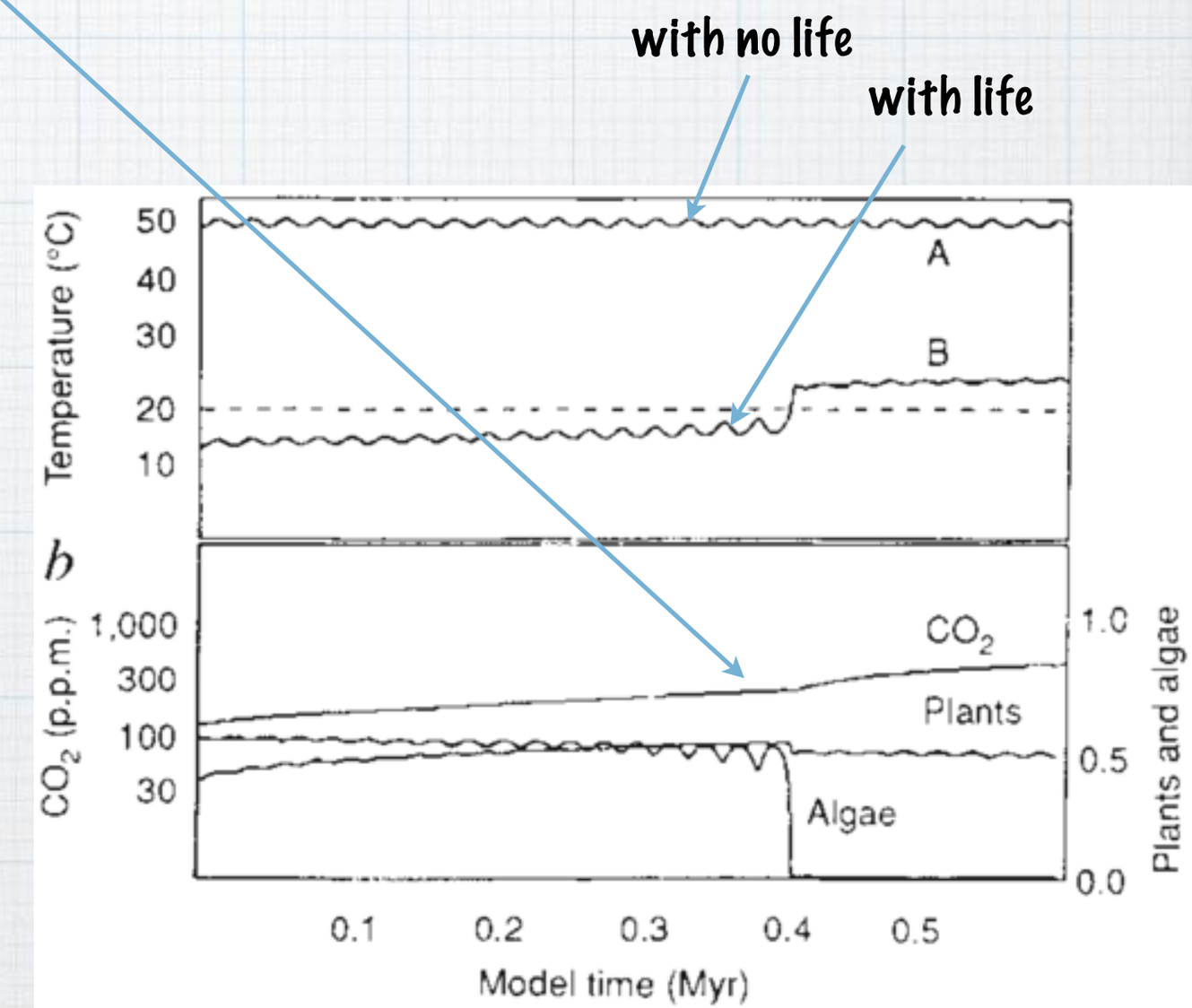
However, there are also positive (destabilizing) feedbacks:

* Warm temp brings more water vapor into air; water vapor, too, is an IR-active gas. When all the liquid water evaporates, then weathering of rocks, which removes CO_2 but requires liquid water, is suspended. That's Venus.
* Ocean circulation: Hotter means no turnover (thermocline) means no algae means no photosynthesis. That's why tropical seas are clear; that's why whales have to migrate annually to cold seas. A hotter world would have bigger dead areas of ocean. It's happening already.
    * Less photosynthesis means more CO_2 -> Energy trapping effect -> hotter.
    * Less algae also means less sulfide release means reduced clouds, reducing solar reflection (albedo) and increasing insolation.
    * Less mixing of shallow with deep also decreases effective ocean volume available to dissolve extra CO_2.
* Warmer ocean -> CO_2 less soluble -> more stays in air, trapping more IR.
* Greenland and other glacier ice: warmer temp means less ice -> less reflection -> increased solar input.
    * And warming lowers ice altitude -> increased surface temp -> more melting.
    * Warming means liquid H_2O on the surface, which wedges open cracks, which breaks off chunks, which accelerates loss.
    * Also liquid H2O falls down cracks to underlying land, lubricating faster flow or even floating the ice sheet.
* Warm temperature activates soil bacteria that release CO_2.
* Warm -> melt boggy tundra -> activate methanogen bacteria -> release CH_4 -> IR-active gas. Similarly for clathrate releasing CH_4 from seabed.
* Less rainforest -> less rain inland -> drier -> fires -> dead trees, CO_2 release.
* More methane -> depletes OH radical needed to remove methane -> longer residence time of methane in atmosphere -> enhanced IR-trapping.

Is there a tipping point? Are we close? If so what is the other equilibrium like?

* That is, could the positive feedbacks overwhelm the negatives? That could – maybe – lead to "abrupt climate change," defined as occurring "when the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause" (NRC 2002).
* Kump and Lovelock's 1994 model incorporates some of these mechanisms. They assumed steady solar input but **gradual** dumping of extra CO_2, e.g. by us. The specific feedback involved release of dimethyl sulfide by marine algae, which affects cloud formation and hence planetary reflectivity.

* Despite a very gradual increase in CO_2, the system suddenly flips to a new, hotter, steady state.
* A few degrees in global average temp is a lot.
* Sorry -- there is no reason to think that Earth "wants" to save us from the consequences of our actions.
* And there is no reason to believe that the change that follows a tipping point will be gradual. Some past changes have been very abrupt.
* And a tipping point may not be obvious until well past the point of no return, due to delays.



CO_2 : Input increasing from 1.0 to 3.0 in 20 kyrs

Kump, L. R., & Lovelock, J. E. (1994). Failure of climate regulation in a geophysical model, 369, 732–734. See update in Ayers and Cainey 2007.

Things one hears

* "Water is also an IR-active gas, and there's vastly more of it than CO_2. So CO_2 is irrelevant."
  * We have no control over how much the oceans evaporate nor over how much the clouds precipitate. That's fixed by the temperature and other things outside our control. We DO have control over how much carbon we burn, how many cattle we raise, how well we cap natural gas wells, etc. The role of water is to AMPLIFY changes wrought by changes in CO_2, methane, CFCs, etc.
* "Plants love CO_2–it's their food. They will flourish, pulling out more CO_2 and also feeding us."
  * Most of Earth's photosynthesis is by organisms in the ocean. They rely on turnover to supply nutrients. Tropical oceans don't turn over, and indeed they are nearly dead. If they grow at the expense of the productive midlatitude oceans, then the whole system can crash.
  * Land plants do pull out CO_2, but then they die and decay, returning most of that to the atmosphere. Oceans are key to long-term sequestration, via sedimentation followed by subduction.
  * Anyway, "It's a bit like hearing that your chemotherapy is slowing the growth of your tumor by 25 percent." – Carl Zimmer

* "The atmosphere is already opaque to IR light, so adding more CO_2 won't change anything."
  * The atmosphere is only opaque in certain bands; absorption falls off as we move to nearby frequencies. So increasing an IR-active gas may not affect the absorptivity at its maximum, but will increase it in the wings of the distribution.
  * Also, we saw that increasing the **depth** of the IR-opaque atmosphere is what raises surface temperature. More precisely, increasing the depth of the atmosphere that is opaque to any kind of radiation–for example in the wings of an absorption band–will raise surface temperature.

* "It may not be anthropogenic. Gigantic climate changes are always happening naturally."
  * If I'm on a prairie and I see a wall of flame coming at me, it's a little academic to ask if this was caused by an accidentally dropped cigarette, or a natural cause. I want to know WHAT TO DO (and what not to do). Let's get over this irrelevant obsession with whether we are Bad People or not, and focus on survival.
  * Anyway, even if 7 billion people (and their cattle) haven't yet done it yet, 9 billion may. Especially when a few billion more of them acquire cars.

* "It's not simple and fundamental, so physicists shouldn't study it."
  * It's true that physicists like problems with few relevant kinds of actors; few couplings; lots of identical copies of each actor; many identical repeats of each experiment; everything well controlled and/or well measured.
  * Sorry, this problem isn't like that.
  * Maybe we should change the definition of physics if that's what's getting in the way.
* "Those guys can't even predict the weather."
  * Right, complex stochastic systems are hard to predict. You got a lot of experience with this sort of thing in biophysics. We MAY be able to estimate the probability per time that a system will make a transition given its state and history.
* "Maybe change will be good! Maybe Siberia and Saskatchewan will bloom."
  * Yup. Maybe. If we warm without hitting a tipping point. Even then, civilization might not survive if 2 billion people suddenly need to relocate.
* "We're in an interglacial. Maybe we actually should be furiously burning MORE fuel to avert an ice age!"
  * OK, the stakes are high, and indeed Nature isn't necessarily going to do what's best for us. Let's just not go straight from uncertainty to magical thinking.

* "It would cost too much to fix."
  * It would cost more to relocate the entire population of Bangladesh, Singapore, Florida, NYC... Rationality is a bargain.
* "Life has overcome much more drastic challenges in the past."
  * Right. Life will endure. Even our species will endure, as we survived Ice Ages. But human **civilization**... that's much more fragile.
  * It looks like at one point in the past all but about 10000 humans were wiped out, probably for a climate-related reason. That was too close for comfort. Maybe we should study this stuff. Maybe it's more important than the search for beautiful theories of everything.
* "There are so many uncertainties. Maybe it'll all be OK despite the predictions."
  * Right. That is not impossible. But if there's even a small chance of catastrophic sudden change... that's much too high. The cautious IPCC predictions of "most probable" outcomes will be irrelevant if we position ourselves to where a less-probable fluctuation can put us over the edge, becaue eventually such a fluctuation will come.
* "It's hopeless because people are people and can never cooperate."
  * I refuse to believe in hopelessness. Anyway, humans already found a Pandora's box in 1945 that offered us the opportunity to extinguish our civilization. In our clumsy, awful way we have (so far) (just barely) avoided that.
* "Scientists should stay out of politics."
  * Scientists try to find what's demonstrably true, regardless of their or others' initial hunches. That's the **opposite** of politics. Some scientists set a higher bar and try to find what's true about questions that are also **important**.

* "It's just theory."
  * Scientists don't often articulate this, but the propositions we desperately wish to be true are the ones we must mistrust the most, the ones requiring most proof.
  * It's true there are still big uncertainties, e.g. concerning clouds. But uncertainty can go either way. Mere uncertainty is not evidence that things are OK; it's just an opportunity for wishful thinking.
  * It's true that many theories are wrong. OK, Uncle Harry, so let's see YOUR evidence that it WON'T happen. Even if there's just a 1% chance it's right -- that's too much. Are we willing to bet EVERYTHING that it won't happen?
  * ANYWAY, you can't trust my generation any longer. We're the ones who handed you this situation. You will have to evaluate this for yourself.
* "Lots of smart people are already taking care of this."
  * But maybe YOU are the one who can have one of the many big ideas that are desperately needed.
* "It's probably already too late, so let's party on while we can."
  * Um, tell that to your children, nieces, nephews 30 years from now.

Science provides us with a rich vocabulary of metaphors, which may be better for understanding a new phenomenon than our non-scientific metaphors.

For example, a lot people don't get beyond:

* "Mother Earth set it up, and She will take care of it."
  * I can't disprove this passive attitude. But "mother" is a poor metaphor compared to:
* "Earth is a host organism for humans."
  * That's suggests three possibilities:
  * Humans can choose to act like infection/parasite/cancer. The infection (us) could kill the host organism. Unlikely.
  * The host organism could eliminate the infection. A few million years stuck on "hot" will purge us right out of the system. (Even a few decades.)
  * Humans can choose symbiosis. That's really our ONLY option.
    How do you "choose" symbiosis? You study the relevant physiology and see how to fit in.

Wrap

Some of this material was taken from a recent textbook:

From photon to neuron: Light, imaging, vision (Princeton Univ. Press, 2017): www.physics.upenn.edu/biophys/PtN .

Mostly it's in a new, extra chapter freely available online:

repository.upenn.edu/physics_papers/645/ .

Here is the demo:

www.youtube.com/watch?v=0eI9zxZoipA .

Get it from an expert:

Andrews, D G. ***An introduction to atmospheric physics.*** 2nd ed. (Cambridge Univ. Press. 2010).

Pierrehumbert, R. T. (2011). Infrared radiation and planetary temperature. Physics Today, 64(1), 33–37. doi.org/10.1063/1.3541943 .