K37: Climate Forcing and Climate Time Scales

- The concept of climate forcing, and some Basic understandings of Heat, Temperature, Feedbacks, and physics time scales

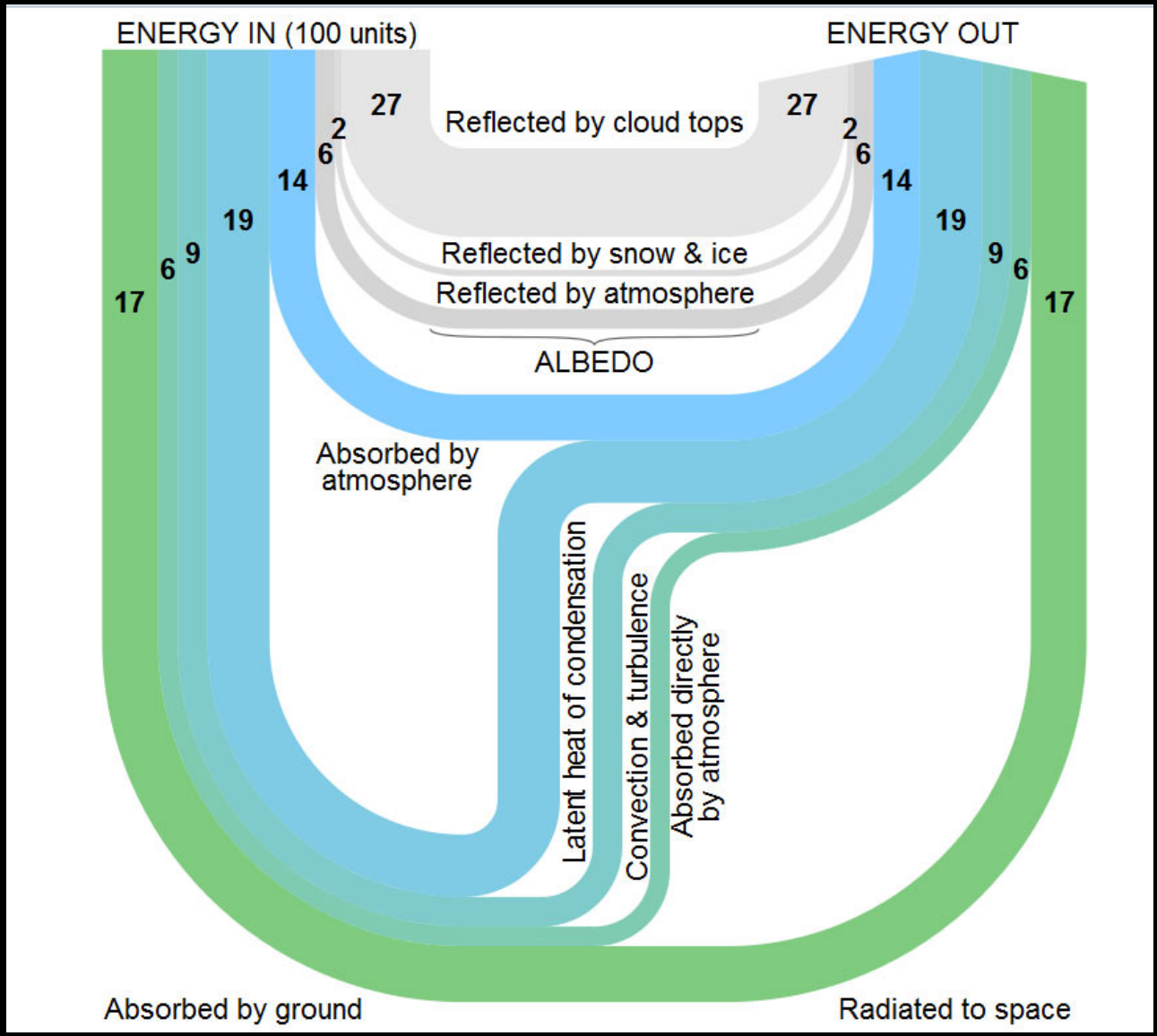
The Earth Climate System is Ultimately in Contact with Our Astronomical Surroundings

- Heat arrives from the sun at nearly a constant rate. If the Earth system's ability to absorb and emit heat remains unchanged for long periods, the Earth will come to a state whereby we emit as much energy to outer space as we get from the sun (Internal Earth heat arrival rate at surface is only 0.03% of solar).
- We are then said to be in **"Radiative Equilibrium"**

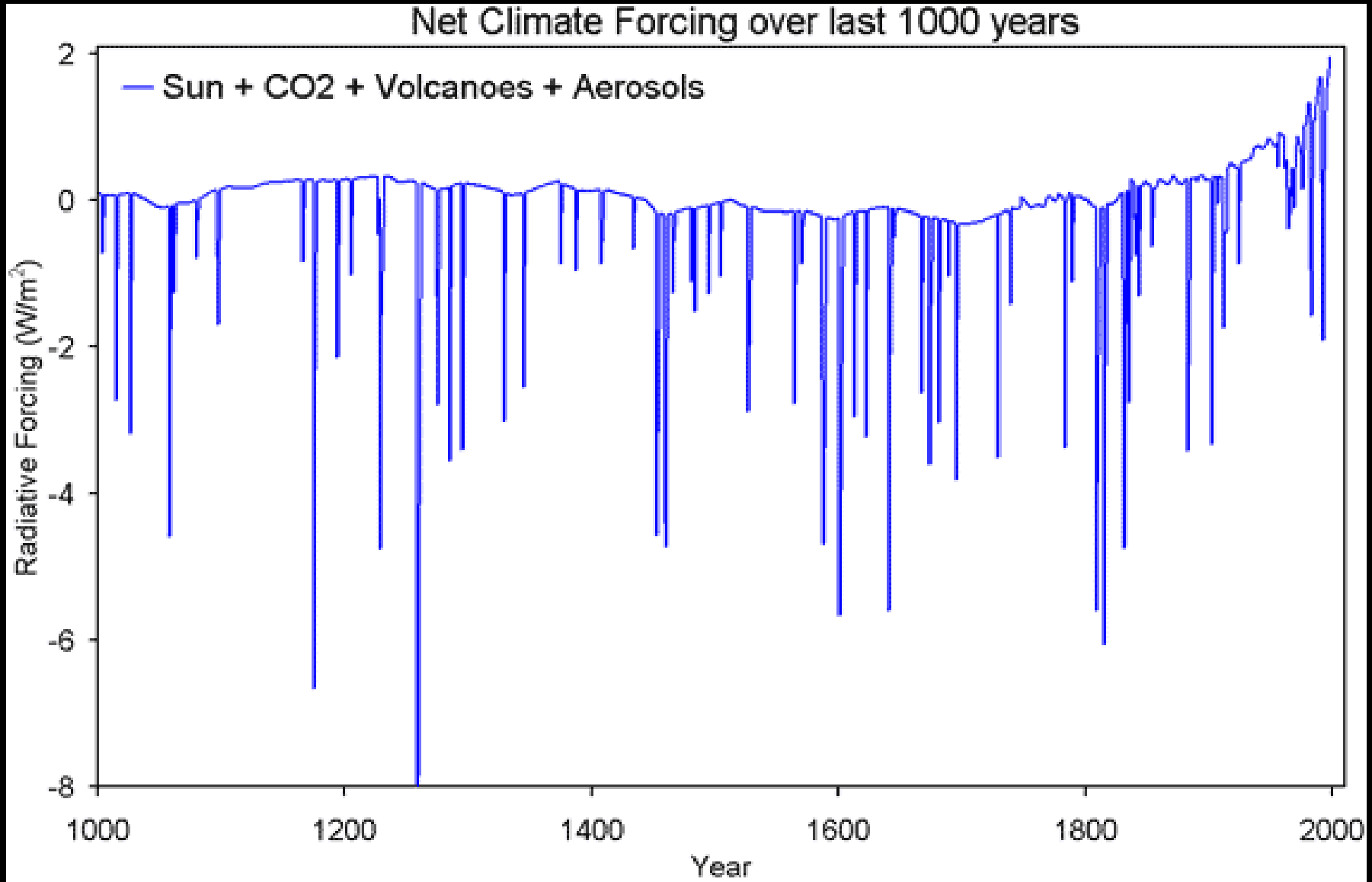
If the Earth System Experiences a Change from Equilibrium: in Either Heat Input, or in the Ability of the Earth to Radiate Back Out to Space…

- … we say the Earth system is experiencing **Radiative Forcing.**
- And, the global average surface temperature will rise or fall as a result.

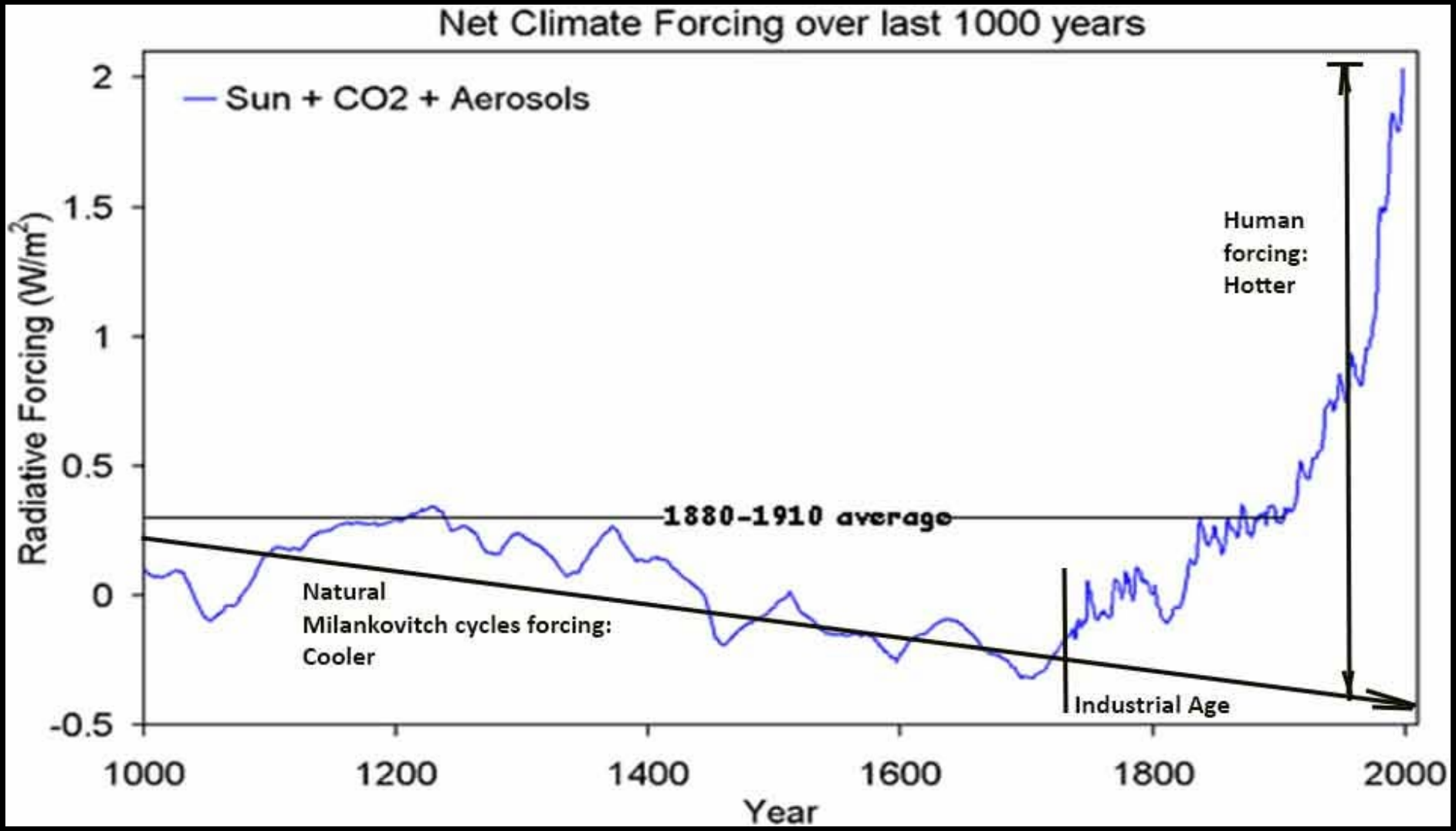
Heat In = Heat Out… and if not: you've got "Radiative Forcing"



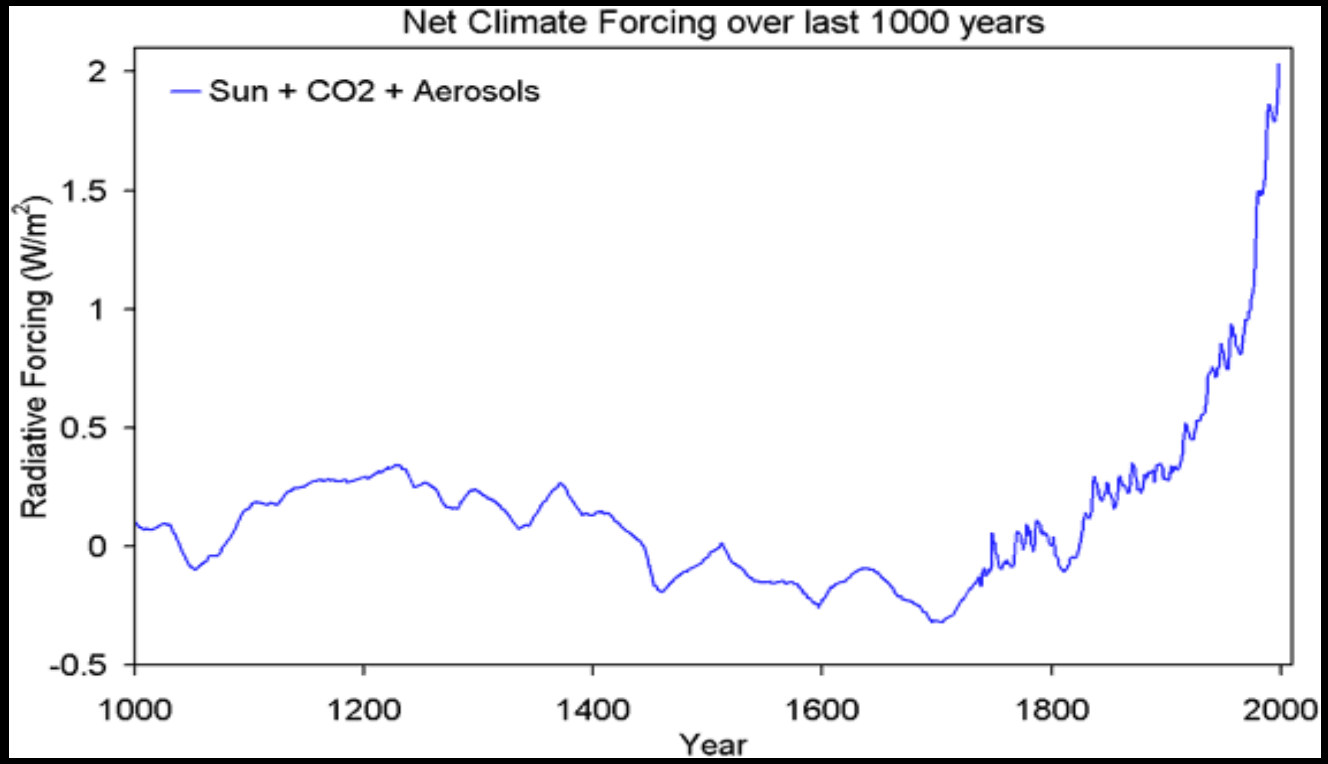
Net Climate Forcing for the Past Millennium, Volcanic Eruptions are Quick Negative Forcings = cooling). Lately, we're Forcing temperatures UP

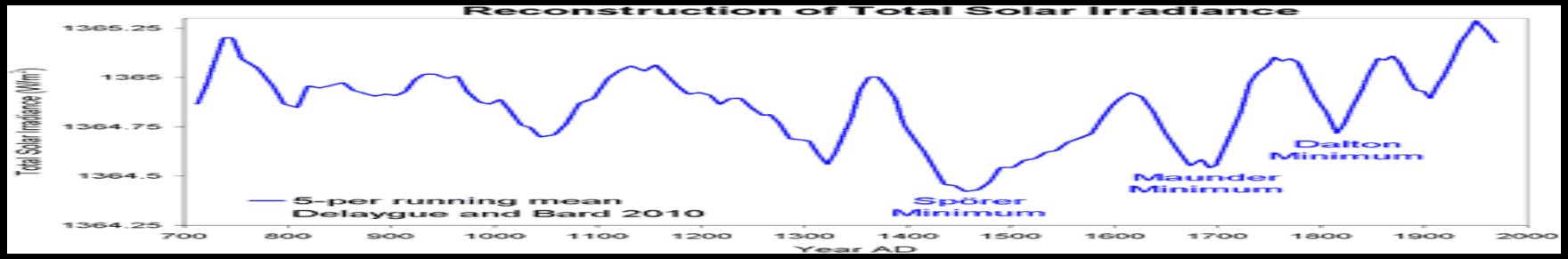


Net Climate Forcings to year 2000, Volcanic Eruptions Removed. Even the 1880-1910 average, when temperatures are conventionally defined to be "pre-industrial", coal burning was already forcing us by +0.3 W/m^2.



Bottom Image: The Sun's forcing alone. (Vertical scale compressed to Agree with "Net Forcing" Slide's Scale also reproduced here). Prior to the Fossil Fuel Era, the sun's influence was fairly important. There's a clear correlation - Sun's irradiance and Net Climate Forcing – no surprise. Yet clear too that there's more forcing than just the sun after dawn of Industrial Age. Also, graphs will likely be redone based on new analysis recalibrating sunspot numbers; sun has been MORE CONSTANT than shown here, since 1700





CO2, Water Vapor, Methane, etc. Trap Outgoing Earth's Thermal Radiation

- There are broad absorption bands for both CO_2 and water vapor in the long wavelengths at which the 280K Earth is attempting to radiate its heat back out into space
- CO_2 concentrations have risen 46% since pre-industrial times, and the atmosphere has also become more humid, as CO_2-warmed air holds more unsaturated water vapor
- **These forcings continue, at a pace much faster than the Earth can come back into radiative equilibrium.**

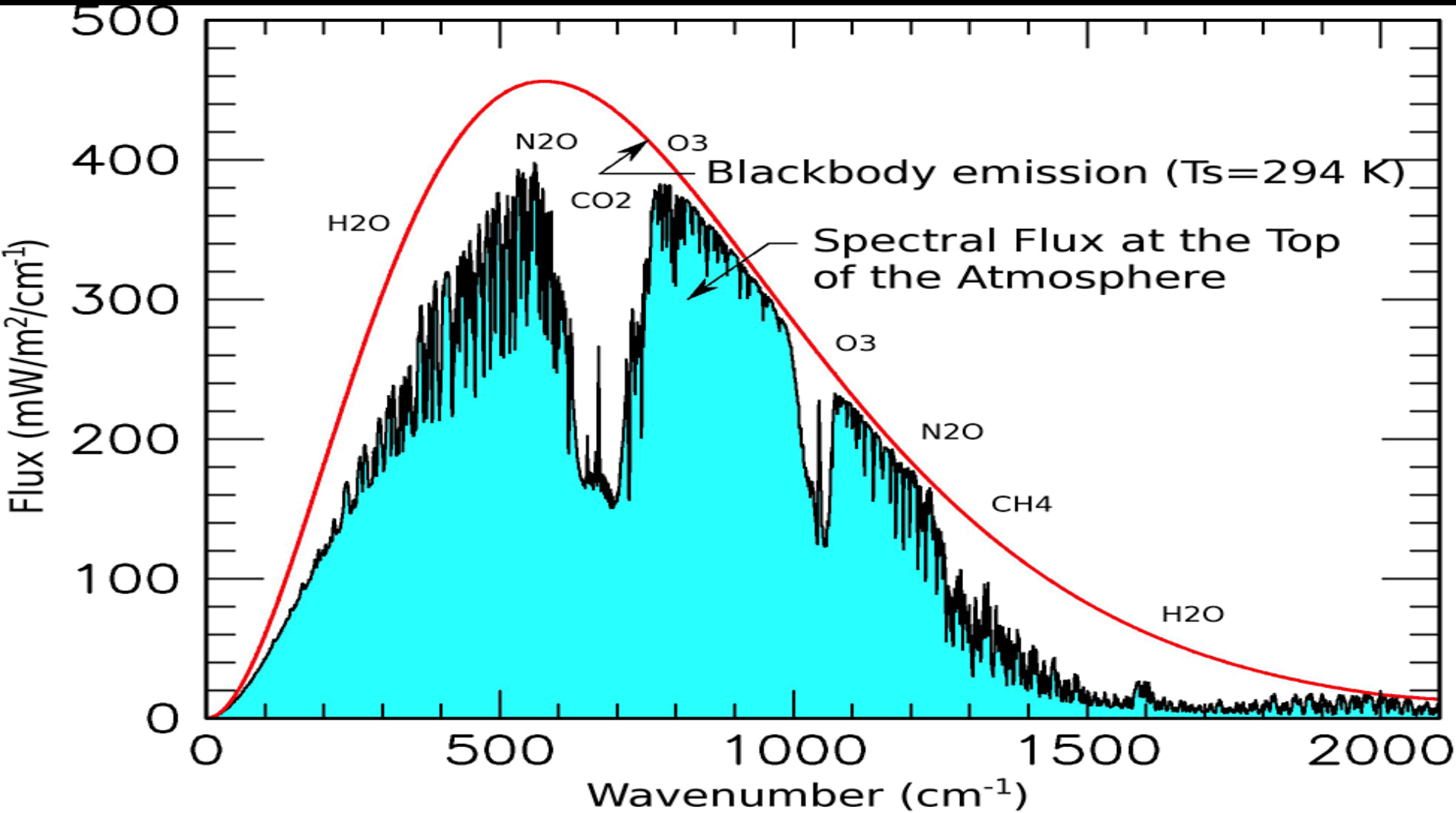
This Animation Shows A Global Map Color Coded by CO2 emissions, Advancing from 1750 to 2008

- **Time history (YouTube 1:10) of Global CO2 emissions by location**
- By ~1910 global emissions were already ~10% of today's. Prof Michael Mann makes a good case (**Schurer, Mann, *et al.* 2017**) that we should take "pre-industrial" temperature baseline over the stable centuries before this, not the more common 1880-1910, or 1850-1900 averages.
- Granted the 1880-1910 average has better data coverage and quality (which is why it is usually used), but data quality was already usable starting at 1750, and our prior graphs show non-volcanic, non-solar forcings were indeed already on the rise by that time.

This is Important: Our Modelled Future Climate Depends Critically on Knowing True Paleo (non-human forced) Data.

- The **Schurer, Mann, *et al.*** paper finds this gives a baseline temperature 0.25C lower than the conventional 1880-1910 average, and therefore today's temperatures referred to pre-industrial average should have another 0.25C added to them. It makes a large difference in "carbon budget" (as we'll talk about) available for us to avoid +2C conventional policy limits, reducing that carbon budget by some 40%

CO_2 Absorbs Near the Center of the Earth's Outgoing Thermal Radiation Spectral Peak, and Water Vapor, CH4, dominate in the Wings



So - The Earth System is being Forced Warmer

- It's like continually throwing on more and more blankets. You will get warmer and warmer until finally the surface of the top blanket is giving off as much heat as you are creating by your metabolism. Until that moment comes, you will continue to get warmer, until you stop throwing on more and more blankets and then wait a bit.
- Due to continually rising CO2 and resulting other forcings, the Earth cannot keep up and remains OUT of RADIATIVE EQUILIBRIUM; and getting worse.
- This is the difference between the incoming solar heating and the outgoing radiation back out to space

Graph here isn't total CO2 emissions, it's the RATE of Emissions per year! Total CO2 emissions would be the Integral of this dramatic curve, rising rapidly, overwhelming the ability of the Oceans and Land to absorb CO2

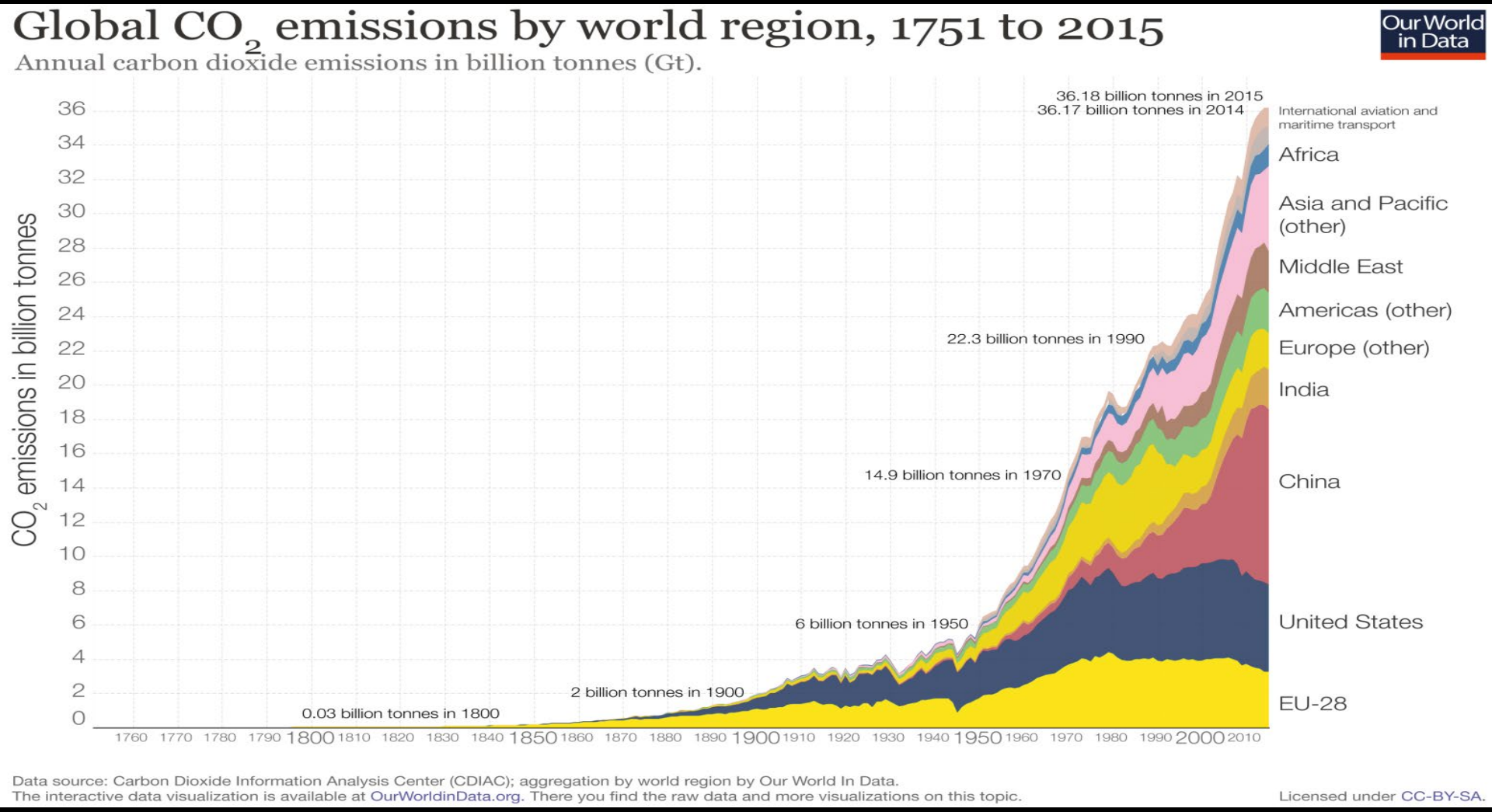
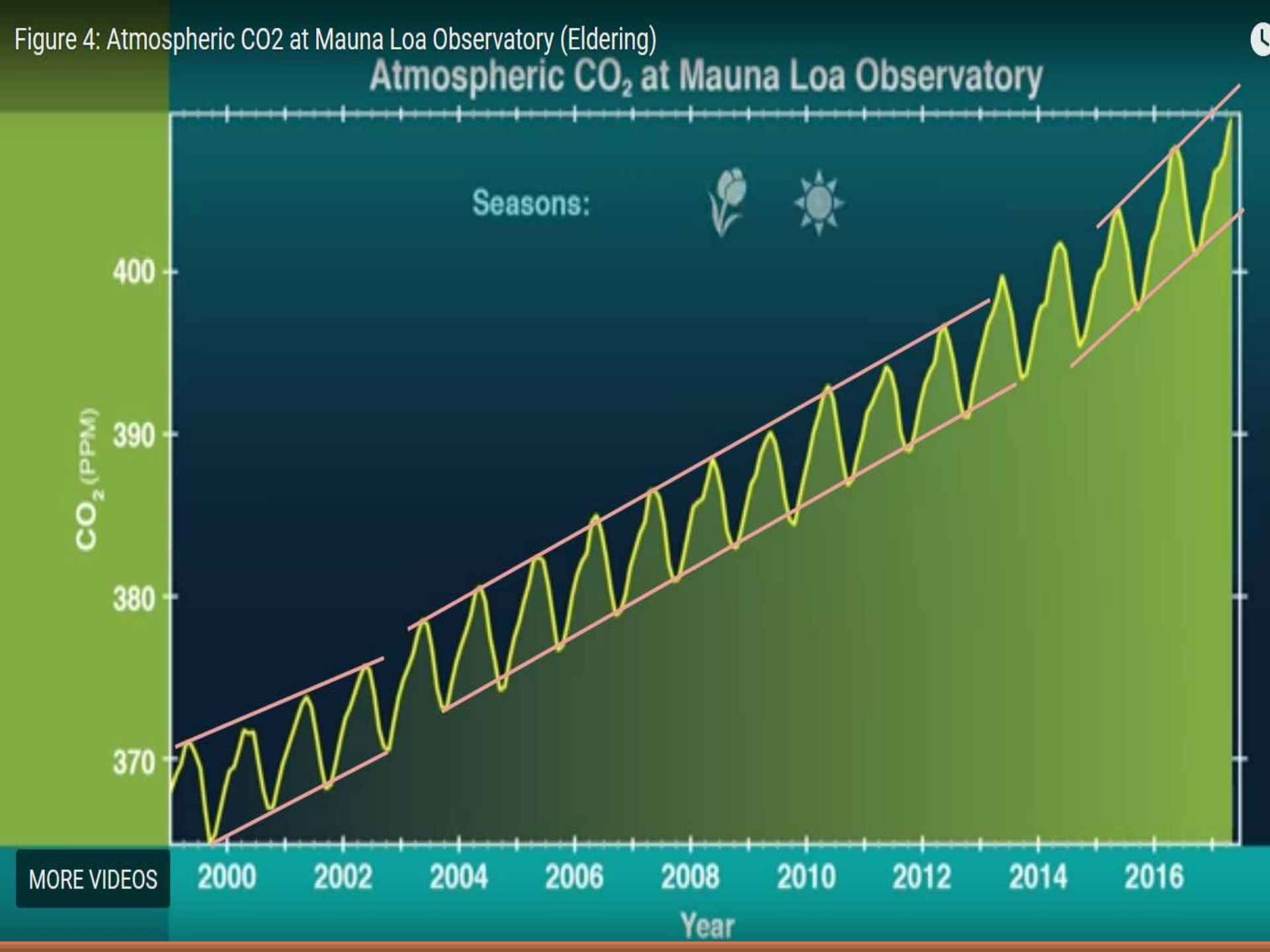


Figure 4: Atmospheric CO2 at Mauna Loa Observatory (Eldering)



Human-Generated Greenhouse Gas Radiative Forcings as of 2014 (IPCC AR5)

- 1.88 w/m^2 (58%) - CO2 (mainly fossil fuels)
- 0.49 w/m^2 (15%) - **Methane**
- 0.40 w/m^2 (12%) - Ozone in the troposphere (pollution)
- 0.17 w/m^2 (5%) - N_2O (mainly Ag fertilizers) (but ocean badly under-estimated says 2020 recent work
- 0.33 w/m^2 (10%) - CFC's and HFC's; complex industrial chemicals used in refrigeration, and some other uses.
- Total = **3.27 w/m^2**
- **We also have human-caused cooling, from smog (aerosols) so the total net heat forcing is 2.6 w/m^2, less than the 3.27 w/m^2**
- **Now, the Earth has warmed, raising its ability to radiate to space – the only sink the Earth has to get rid of its heat. The hotter Earth, though, is still unable to radiate enough, because we keep "raising the bar" – we keep pumping more GHGs into the atmosphere.**
- **The radiative imbalance now in the 2020's is rapidly rising upward from this +0.58 W/m^2 to far higher.**

Human Climate Forcings as of 2015: 3.7W/m^2 warming, -1.2W/m^2 cooling = 2.5W/m^2 Net Warming

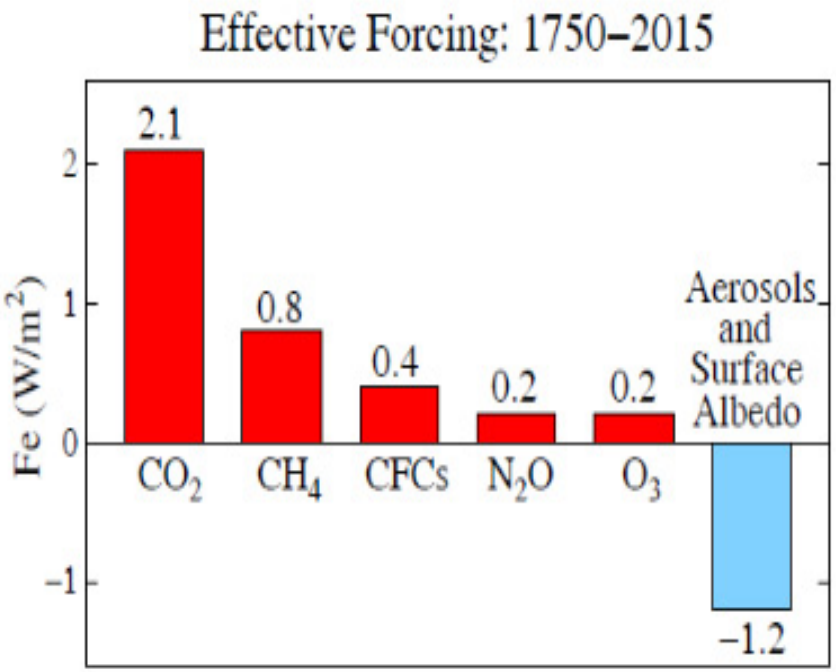


Fig. 4. Estimated effective climate forcings (update of Hansen et al 2005 through 2015). Forcings are based on actual changes of each gas, except CH_4-induced changes of O_3 and stratospheric H_2O are included in the CH_4 forcing. Oscillatory and intermittent natural forcings (solar irradiance and volcanoes) are excluded. CFCs include not only chlorofluorocarbons, but all Montreal Protocol Trace Gases (MPTGs) and Other Trace Gases (OTGs).

How Much does Modern Agriculture and Livestock Management Force Climate?

- Food, agriculture and land use changes, including livestock, account for up to 33% of global greenhouse gas emissions (**Gilbert, in *Nature* 2012**), but see next slide.
- This is from deforestation, methane emission, NO_2 and N_2O from artificial fertilizers, among the dominant sources

Unfortunately, new research shows estimated methane and nitrous oxide radiative forcings pre-2016 are too low

- **Etminan *et al.* 2016** did more accurate calculations of the radiative forcings for methane and nitrous oxide, including the short-wavelength contributions neglected earlier.
- They find both GHG's radiative forcings are about 23% HIGHER than the IPCC values, and the others in the published literature up till then.
- Methane, for example, is now calculated to contribute fully 1/3 of GHG forcing, not ¼ as thought before. **This is not in the figures in this PowerPoint**

Even Newer Work in 2019 Shows…

- Estimates of N_2O emissions were under estimated (**Thompson *et al.* 2019**),
- And true ocean emissions are up 200-500% higher than thought, based on earlier much more limited sampling (**Wilkerson *et al.* 2019**). Prior to this new work, we'd thought the oceans contributed 26% of N_2O emissions
- **This is a major change to forcing, not yet reflected in published climate modelling.**
- These studies are too new to have been incorporated into any climate models or better Radiative Forcing calculations.

Climate Feedbacks: Definitions

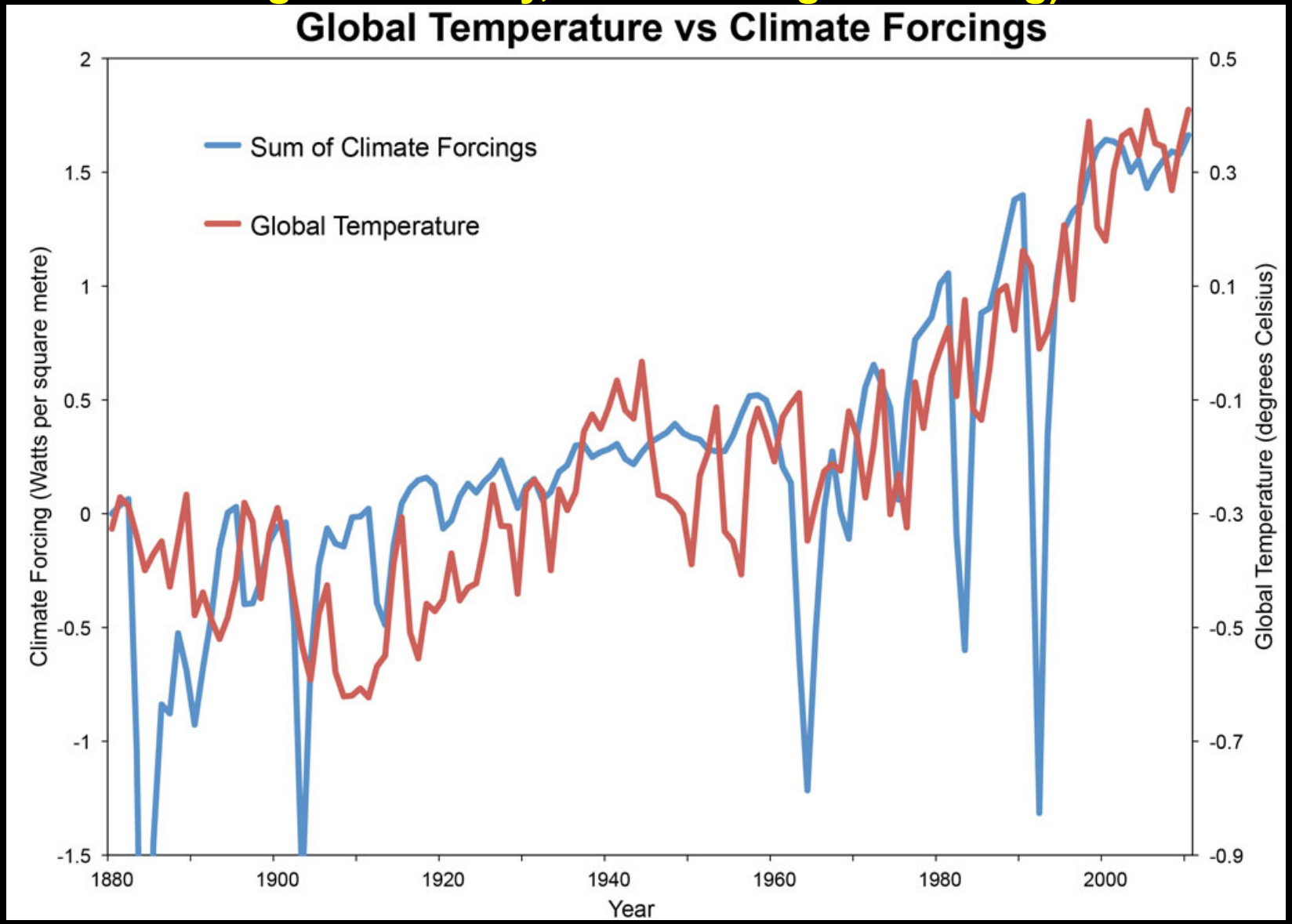
- **A Positive Feedback** = a response to the forcing of a system which increases the direction it is already being forced. For example in climate – a warming effect which is made warmer by the feedback. ***Amplifies initial forcing direction***
- **A Negative Feedback** = a response to the forcing of a system which opposes the direction of forcing. ***Reduces initial forcing direction***
- ***Unfortunate terms in this sense:***
- ***POSITIVE feedbacks are destabilizing and therefore BAAD.***
- ***NEGATIVE feedbacks are stabilizing and therefore GOOD.***
- ***Alas, nearly all climate feedbacks are amplifying feedbacks= positive feedbacks, until things get pretty far advanced***

Negative Feedbacks, Even when they Exist, Can Only Moderate the Forcing, They Cannot set it to zero and then reverse it.

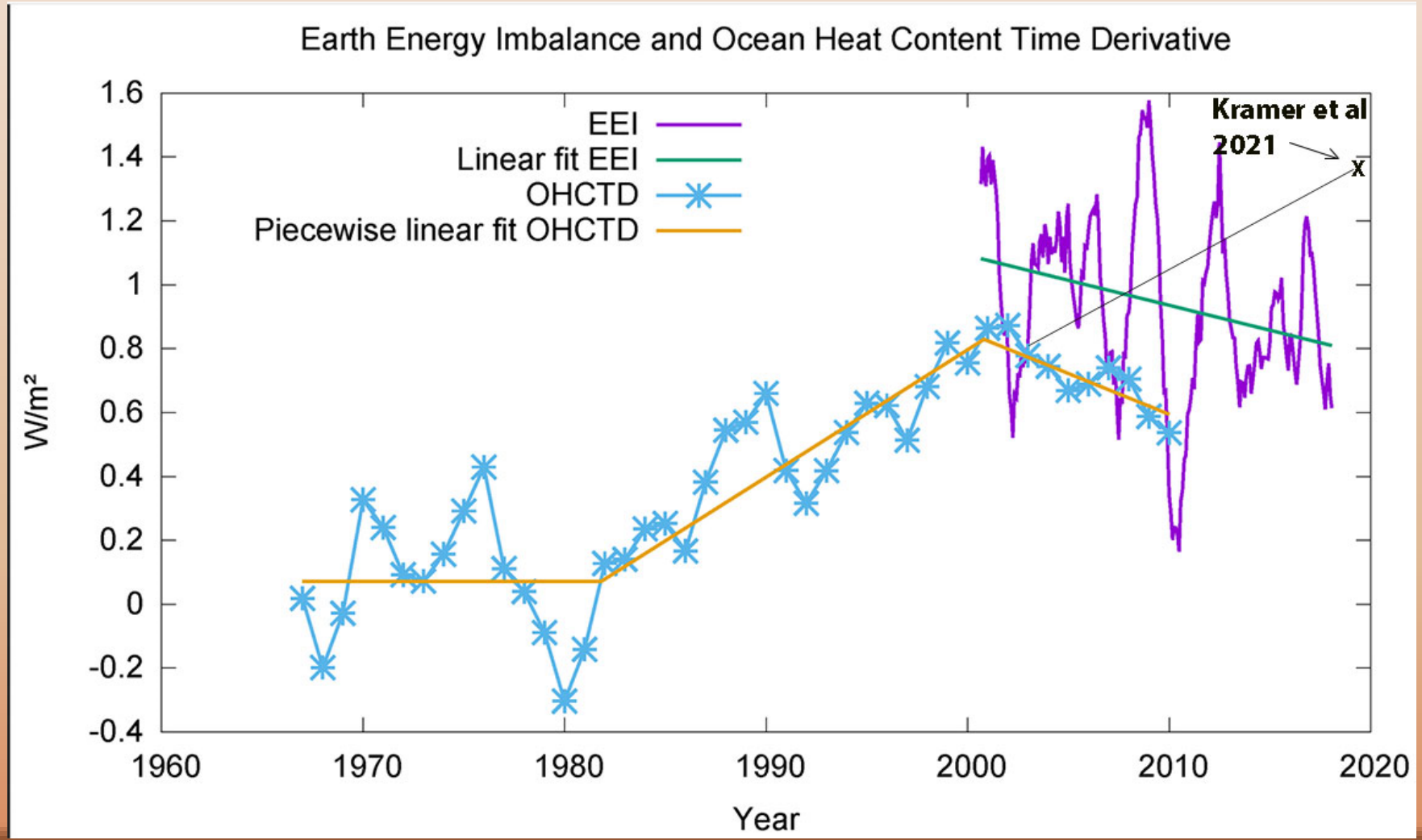
Meaning: A negative feedback cannot REVERSE CO2 warming, the negative feedback only makes warming less than it would have been, but it is still warming

- Meaning – don't expect any negative feedbacks (if we can find any) to cure Global Warming, only slow it.
- So. Do clouds show a negative feedback to greenhouse warming? At the relatively small warming we've seen so far, the evidence indicates clouds have a net POSITIVE feedback, amplifying warming.
- However, Garrett, Glenn and Krueger **(2017)** suggest in fact tropical convective cloud feedbacks to climate change may be zero, on theoretical grounds.

Note the close correlation between forcings and global average surface temperature (vertical scales differ; It is the forcing that is dragging the temperature upward, with feedbacks from the higher temperature, like higher humidity, accentuating the forcing)



From Dewitte *et al.* 2019 combined with Kramer *et al.* 2021. The Earth's energy imbalance has increased a strong 0.53 watts/m² in just the 2003 – 2018 interval due to rising GHG's and falling aerosol pollution, mainly.



GHG Forcing Rise RATE is not only rising, it's accelerating (Hansen *et al.* 2017)

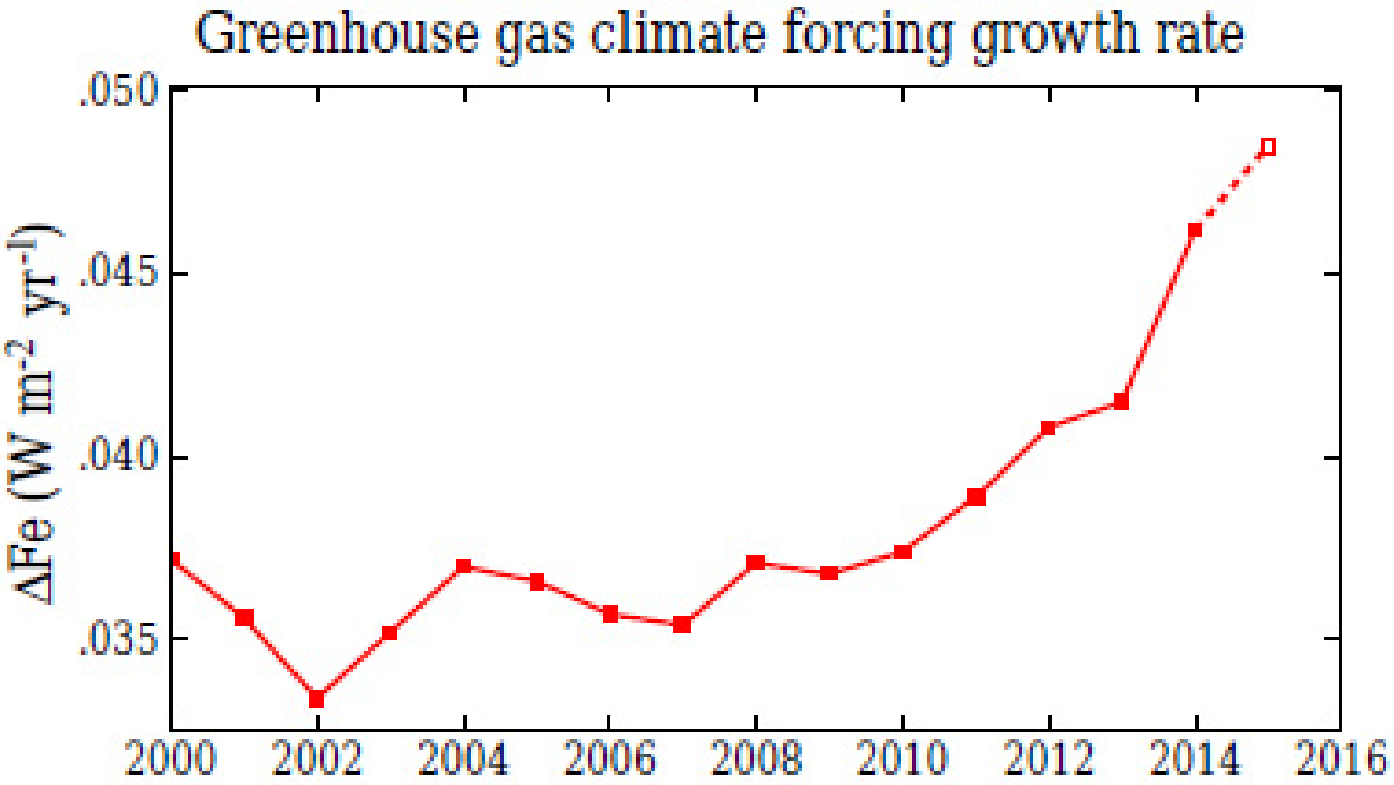
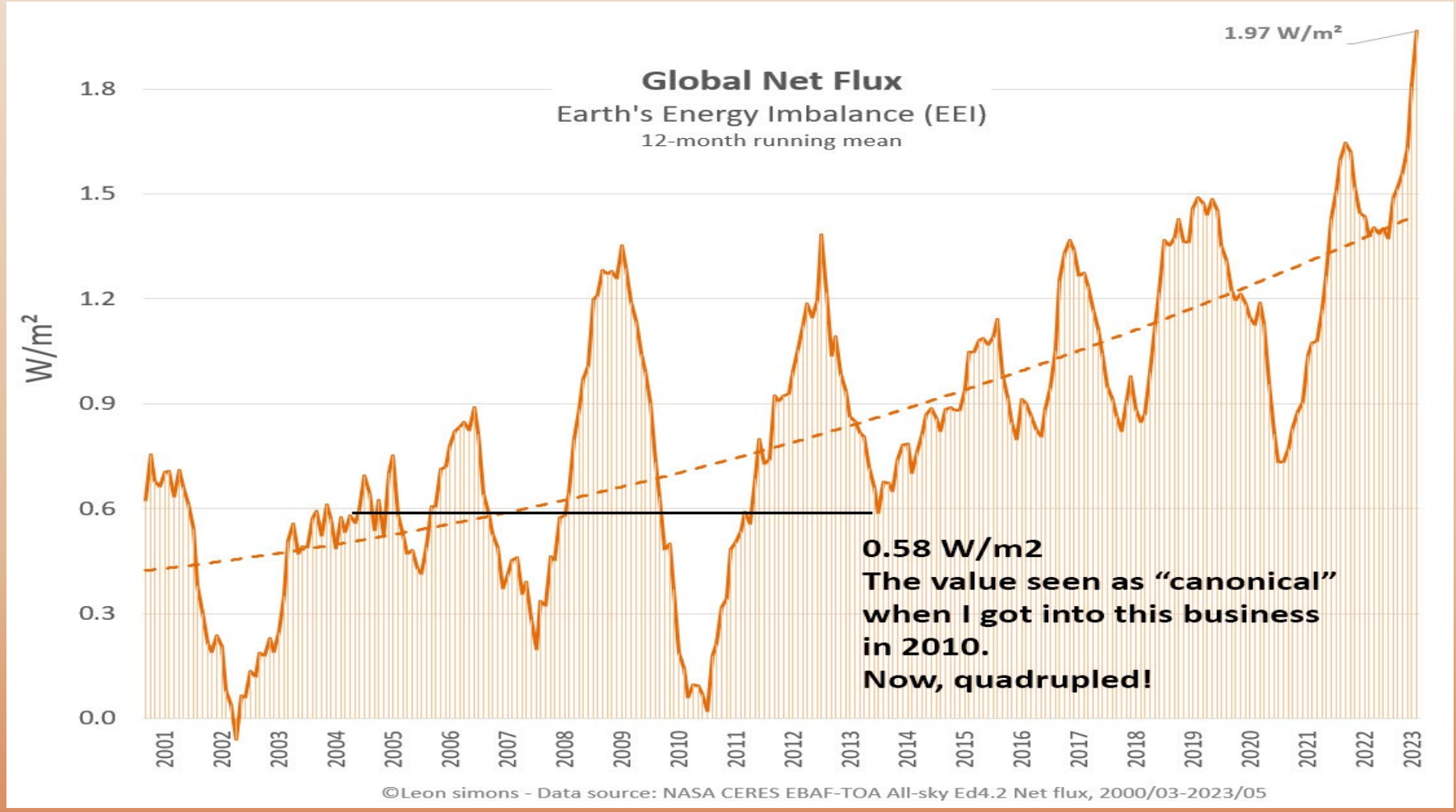


Figure 14. Recent growth rate of total GHG effective climate forcing; points are 5-year running means, except for 2015, which is a 3-year mean. See Fig. 8 for individual gases.

As of 2023, EEI has skyrocketed in just the past 2 years. Most likely due to drop in aerosol-induced cloud cooling



Cleaner air = fewer aerosols = fewer clouds = higher solar absorbed radiation. Left graph, note aerosol cooling has been diminishing since ~2006

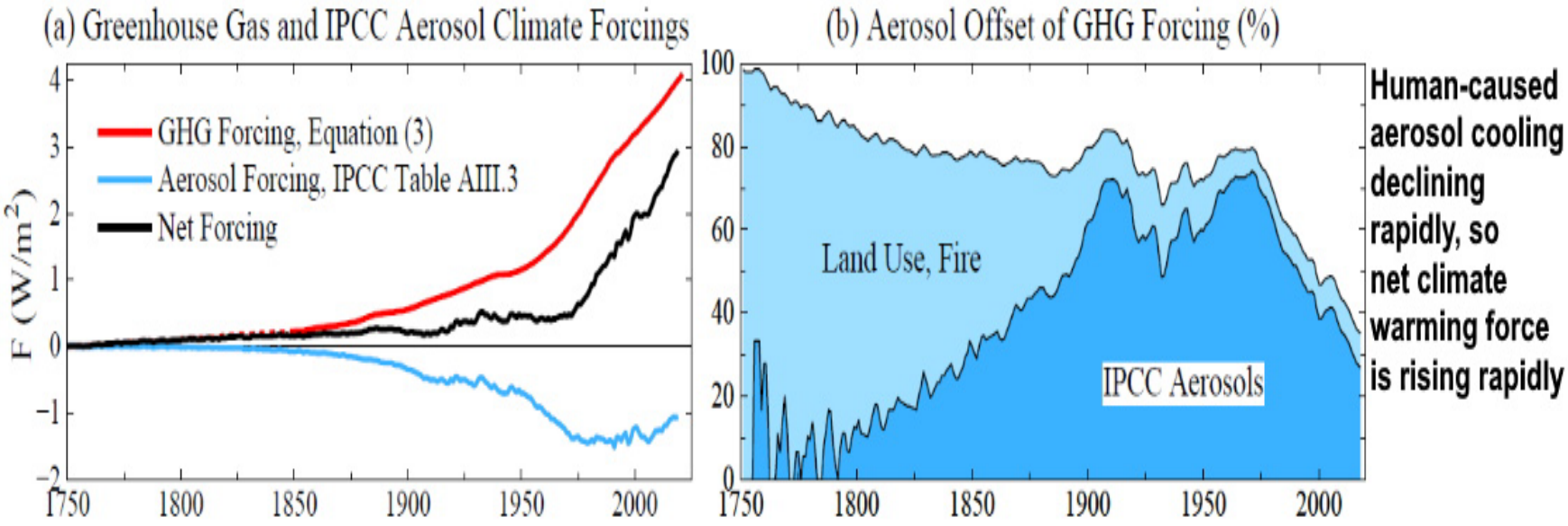
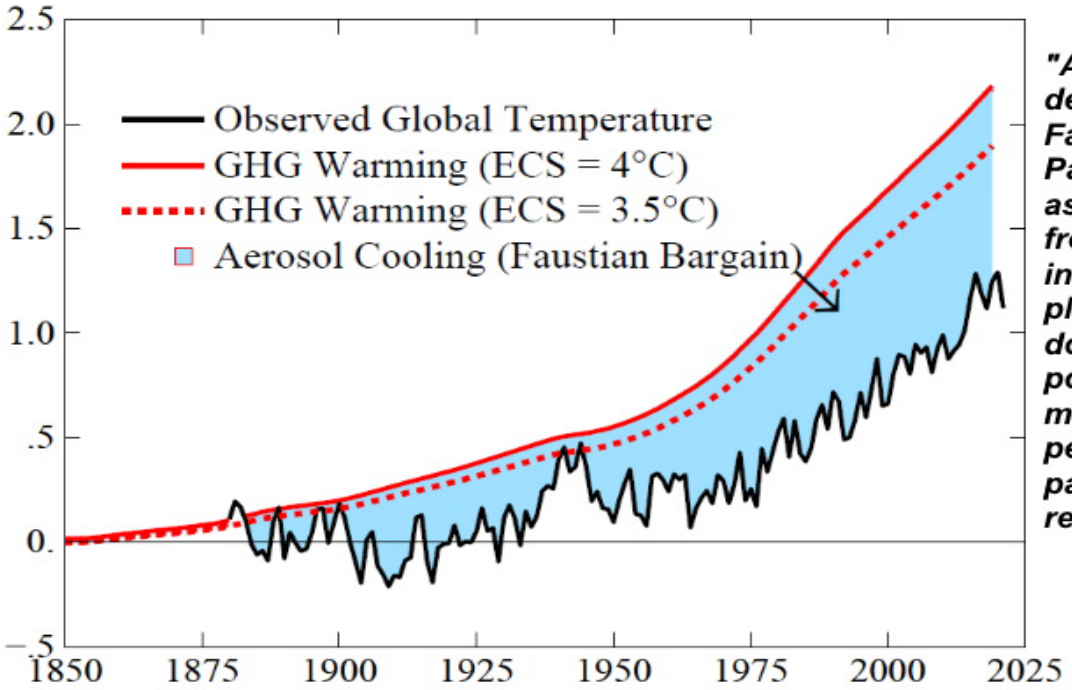


Fig. 11. (a) Estimated greenhouse gas and aerosol climate forcings relative to 1750 values. (b) Aerosol climate forcing as percent of GHG forcing that it offsets. Aerosol and GHG forcings for dark blue area are relative to 1750 values. Light blue area is added when the GHG and aerosol forcings are defined relative to their values 6000 years ago, with GHG and aerosol forcings both reaching 0.5 W/m^2 by 1750.

Faustian Bargain: Aerosols cool, but also cause millions of lung related deaths per year



"Aerosol cooling is described as a Faustian bargain. Payment comes due as we reduce pollution from shipping, vehicles, industry, and power plants, which we must do because ambient air pollution causes millions of deaths per year, with particulates most responsible"

Fig. 6. Observed global mean surface temperature (black line) and expected warming from observed GHG changes with two alternative choices for ECS. The difference (blue area) is an estimate of the cooling effect of the (unmeasured) aerosol forcing. The temperature peak in the World War II era is in part an artifact of inhomogeneous ocean data during that period.[54]

Time Scales – Human *vs.* Physics

A big source of trouble… Most policy makers and voters just don’t get it

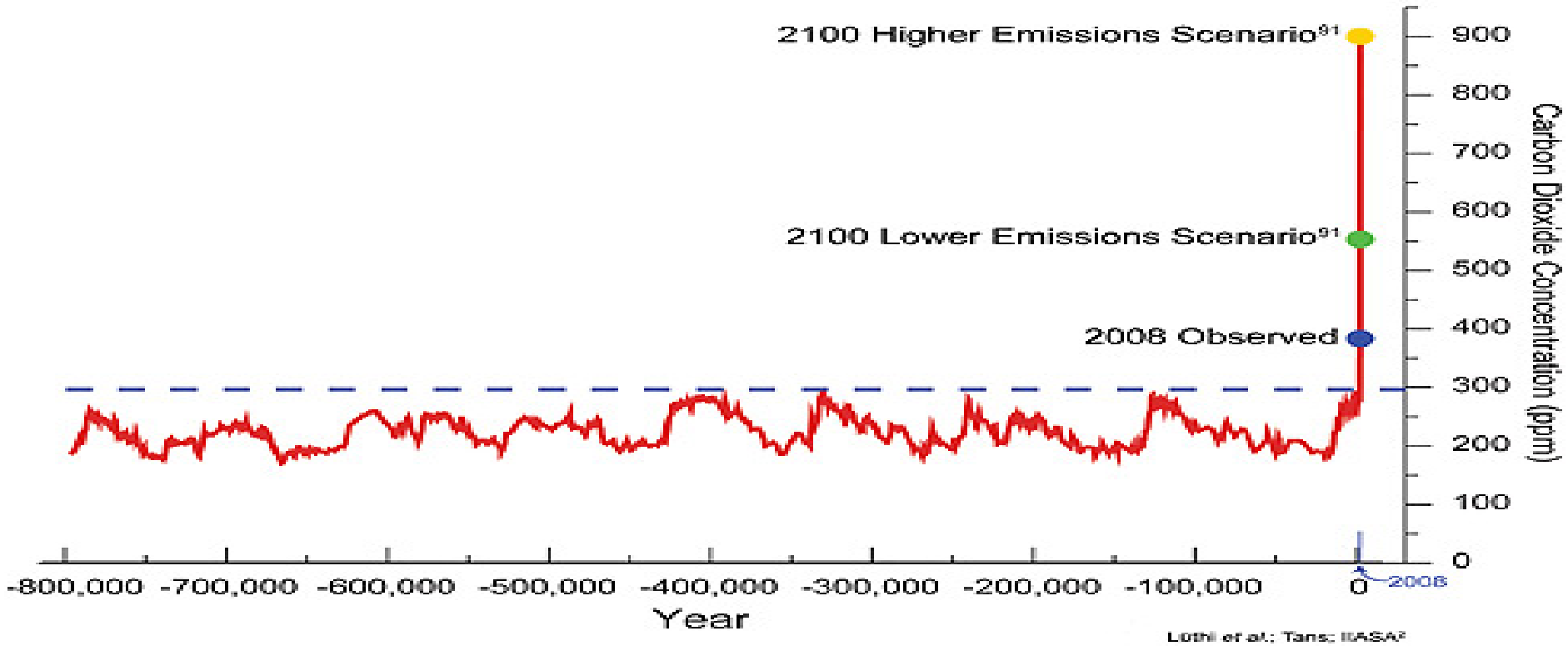
The Ability to Achieve Radiative Equilibrium Takes Time

- So, if the forcing is happening on a significantly shorter time scale than the physics time scale of the system, equilibrium may be impossible to reach and the system may get farther and farther from equilibrium.
- **If** the system were being forced on a time scale which is relatively long compared to the natural physics time scale of the system, **then** the system would proceed through a series of approximately equilibrium states.
- … and if the forcing stops, would allow the system to quickly stop changing and be in a new equilibrium.

But this is NOT the situation for current climate change!

- The forcing being applied is very strong and happening on **short** time scales, while the time scales to reach equilibrium are long, due to thermal mass and inertia of the oceans in contact with atmosphere.
- **Earth climate will remain out of radiative equilibrium for centuries, unless all heating forcing is eliminated and cooling forcing is created and applied quickly.**
- If you're speeding towards a cliff, it's not enough to just take your foot off the gas. Eliminating CO2 emissions is essentially only taking the foot off the gas pedal.

Look at how fast current gas pedal CO_2 forcing is being applied, even compared to Ice Age forcings which were already very rapid compared to earlier climate.



Analysis of air bubbles trapped in an Antarctic ice core extending back 800,000 years documents the Earth's changing carbon dioxide concentration. Over this long period, natural factors have caused the atmospheric carbon dioxide concentration to vary within a range of about 170 to 300 parts per million (ppm). Temperature-related data make clear that these variations have played a central role in determining the global climate. As a result of human activities, the present carbon dioxide concentration of about 385 ppm is about 30 percent above its highest level over at least the last 800,000 years. In the absence of strong control measures, emissions projected for this century would result in the carbon dioxide concentration increasing to a level that is roughly 2 to 3 times the highest level occurring over the glacial-interglacial era that spans the last 800,000 or more years.

What is the Physics Time Scale for Earth Climate?

- It's roughly several centuries.
- If you stop forcing climate, it will take roughly a few centuries to reach a new approximate equilibrium, heat input once again equaling heat radiated away
- The oceans take ~1000 years to fully turn over and circle the globe top to bottom
- The atmosphere would otherwise come to equilibrium much sooner, but the fact that it is in intimate thermal contact with the much more **thermally massive ocean (700 times more thermal mass)** will lengthen the climate physics time scale, to centuries
- But for the very large forcings we are doing, a thousand times stronger and faster than anything in prior Earth history, the time scale for **significant climate change** looks to be only about 50 years

Imagine a cast iron skillet in equilibrium with a low gas flame. Now you crank up the flame to “high”. The skillet surface will take time to reach a new equilbrium. The flame has to stop getting bigger, and then that added heat has to diffuse through the mass of iron

Time scales of physical processes roughly scale with size – bigger size = longer time scale

- "Size" can be…. Length, mass, thermal capacitance, thermal mass...
- Let's use conventional mechanics as an analogy
- …For significant changes in velocity to happen, we look at Newton's 2nd Law **which says…**

--- acceleration = Force/mass

For Movement under the Influence of Force… Isaac Newton!

$$\mathbf{F} = m\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = m\mathbf{a},$$

- Solving for **dt ~ time scale**, gives…
- **Time scale ~ (m/F) * dv**
- So, to make a significant change (a “delta”) in velocity, ***dv***, larger mass means longer time scale, for a given forcing = **Harder to push big things**!
- Time scale for what? For “significant” change in velocity!

Mass Goes up Very Rapidly with Physical Size… For any Given Shape of Any Material of a Given Density…

$$Mass \sim (size)^3$$

- Therefore, time scale goes up rapidly with physical size (here size means length).
- --Microbes dance around like crazy
- --People move like “normal”
- --Big things like oceans and atmospheres take months up to years up to centuries to change visibly.
- **For TEMPERATURE change, it’s THERMAL MASS that’s Important**

For Temperature Change, It's THERMAL MASS, which includes Thermal Capacitance, which is Important (sorry to get wonky!)

$$\frac{\partial u}{\partial t} = \frac{k}{c_p \rho}\left(\frac{\partial^2 u}{\partial x^2}\right)$$

- This is the "heat equation". The rate of change of the temperature ***u*** of an object is proportional to the conductivity ***k*** divided by the **thermal capacitance** times density, times the gradient of the gradient of the internal energy over space
- Reminder; complex molecules like CO_2, CH_4, H_2O, have lots of internal motion possibilities which can absorb and emit energy, giving them **HIGH THERMAL CAPACITANCE – they can absorb and emit heat energy without changing their temperature very much**

The Essence of the Physics is this…

- – that the time scale for significant change in the thermal energy of the system is proportional to the **thermal mass M_t** which is to be forced… in other words - **add the same heat to something twice as thermally big, it'll change temperature only half as fast, in everyday language**
- …and inversely proportional to the amount of thermal forcing **F_t**.
- **(Force it twice as hard, it'll change in half the time, in everyday language)**

- **The time scale = amount of time to see significant change, is proportional to M_t/F_t**

- **Remember This, in case of a quiz!**

Implications for Today?

- The atmosphere is a tiny fraction of the ocean's thermal mass – about 1/700th. Its time scale for change is therefore much faster
- fast… but alas, not fast enough to be a good thing, as we'll see
- **The time scale for the ocean to completely turn over and come to equilibrium with a constant atmosphere (if we had one) is roughly 1000 years**
- The time scale for "significant change" in the atmospheric forcing due to human-caused CO2 is a few decades because the forcing is so large in a geological context. CO2 levels in the atmosphere have increased by ~45% in only 100 years. The strong coupling of the atmosphere to the ocean lengthens the time scale. We cannot achieve thermal equilibrium with the existing CO2 levels for another century or more.
- **Unfortunately, a current climate change time scale of ~50 years falls "between the cracks" for us humans…**

It's a Very Unfortunate Time Scale

- **~50 years for significant climate change – is <u>the worst possible time scale</u>**
- **If it were many centuries**, we could legitimately neglect it and let smarter, more emotionally mature, more technologically advanced people of the future deal with it before irreversible damage was assured.
- **If it were just a few years**, like *e.g.* impending WW II, we'd **motivate**. We'd do what was necessary – spending 10%, 20% even 30% of world GDP to slow or perhaps halt climate change before it wrecked our world.
- **If it were less than 4 years**, even our politicians might be motivated to focus on the **truth**, instead of pay-offs from Big Oil, or pressure from right-wing ideologues

Economists, Studying How Aggregate Human Behavior Values Rewards in the Present vs Future…

- …have devised a mathematical concept called the "discount rate" to quantify this.
- Average global human / economic behavior fits a discount rate of about 3% per year. Meaning, that each year into the future, we value rewards happening then to be 3% less valuable to us, 3% less important to our current planning and decision-making, than a year earlier would be.
- By this math, 50 years in the future is valued at only $(1.03)^{-50}$ =23% of what today is valued, for decision-making. And year 2100 is valued at only 8% of today

In other words, ~50 years is long Compared to Human Attention Spans

- And it's long enough that ordinary people can feel *"if this was serious, it'd be changing really obviously right now. People on the street would be panic'ing." They're not panic'ing; so things can't be bad"*, in this kind of mindset.
- **Our Climate Time Scale: It's too long to get our attention, but too short to, in fact, justify ignoring it; Critical human values are at stake now.**
- **It's too short because Forcing happening NOW will only be obvious decades in the future, and so we must act NOW, not later, when it's obvious**
- That's Unfortunate – for our children and future generations. We just don't deal well with this kind of time scale. The risk is that we'll do little things in order to salve our conscience; but avoid the big changes necessary to actually head off disaster.

Nature Gave us Foreheads

- A neo-cortex for advanced thought. For grasping the concept of the future and the ability to abstract principles, then predict our future. Virtually unique among animals.
- We invented a category of work – called SCIENCE, done by scientists – and it is their job to do this prediction well, and inform the rest of us who will want to know so we can act on it.
- And…..?
- **We just don't LIKE what they're telling us. So we throw rocks at them and ignore them. Only if they produce more Bling, do we smile at them.**

It's Worse Than One May Think…

- …Because the climate feedbacks we'll discuss assure that the physics happening NOW will be locked in, to a large extent, for the future.
- Many of these feedbacks were **not included in IPCC** modelling and remain under-appreciated by far too many people.
- **To Look Ahead in our Course** … While we can change the RATE-of-change of climate by heroic massive action, yet even if we halted all CO2 emissions today, temperatures will not go back down.
- **~Ever (in any human relevant time scale).**
- And they show every indication of being too high already, for most of the polar ice caps and Earth's permafrost stored carbon to be melted and released.
- The term for this is **"committed climate change"**

Spoiler Alert:

- So, the warm and comforting notion that…
  "if we just stop hurting the Earth, then the Earth will forgive us, and heal"
  … **is just not true**, not in the case of climate
- For bringing back the condors and the tigers. And the big fishes (well, maybe), this feeling has more validity. But…
- **<u>Not climate</u>. We'll see this in the segments on "Current Climate Change"**
- **I'm Sorry**.


Oh, crap!
Was that
TODAY?
REGAN

Key Points: K37- Forcing and Time Scales

- Forcings take the climate system away from radiative equilibrium
- Forcings can have feedbacks, whereby the initial forcing is either amplified (positive feedback) or reduced (negative feedback)
- Nearly all climate feedbacks are, when near thermal equilibrium, positive feedbacks (harder to say yet, when far from equilibrium)
- Negative feedbacks can't change the forcing direction's sign (can't change a forcing to the opposite direction) if it's a true feedback
- Time scales for physical climate processes are longer for systems of higher thermal mass $\mathbf{M_t}$ and faster for stronger forcings $\mathbf{F_t}$ …
- **Time Scale ~ $\mathbf{M_t/F_t}$**
- Physics time scale for Earth climate change, for current forcing, ~50-80 years for big change, and centuries for new equilibrium to happen. VERY unfortunate - too long to get our attention, too short to afford luxury of waiting for needed policy action
- Earth climate heating, out of radiative equilibrium by +0.58 W/m²