

# Global climate change:

the broad scientific story

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# Motivation for this talk



- We constantly hear that climate change is caused by human activities
- and is dangerous & consequential

- Yet we all know climate has changed **naturally** in Earth's past!
- Changes were **massive**



- (How) does this all fit together?
- Is the **current** climate change a big deal? And if so, **why**?



# A note on terminology



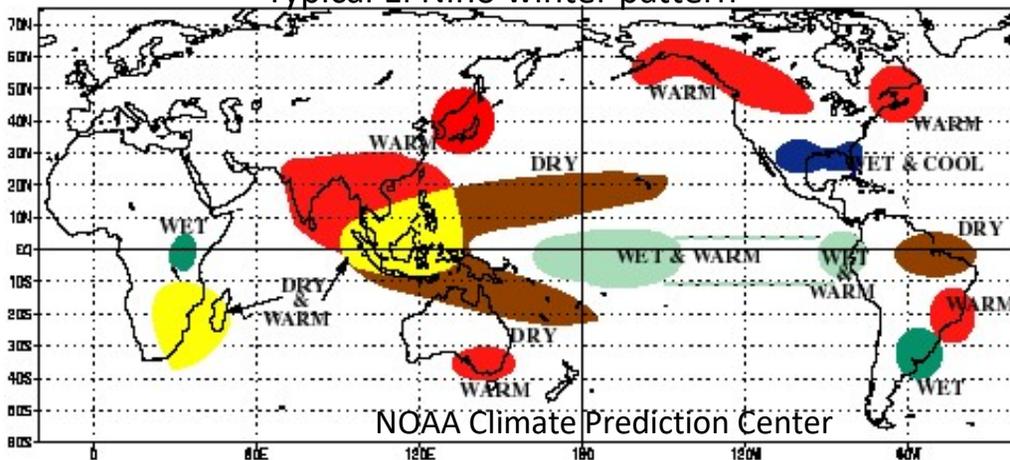
- By "climate change" we are often speaking of two different things:
- 1) Short-term cycles that temporarily make, e.g., one place wetter and another place drier... or one place cold and another place warm
- Ex: El Niño, La Niña, the Atlantic Multidecadal Oscillation, the weather...

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Typical El Niño winter pattern

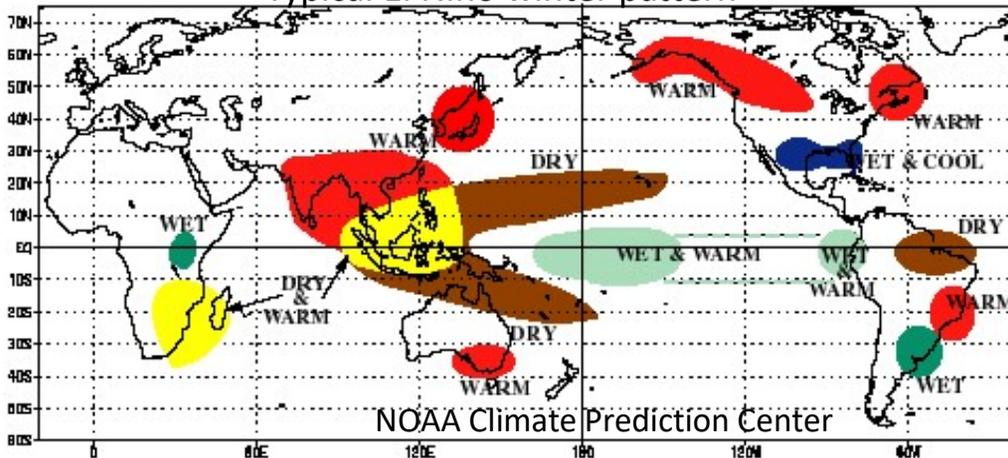


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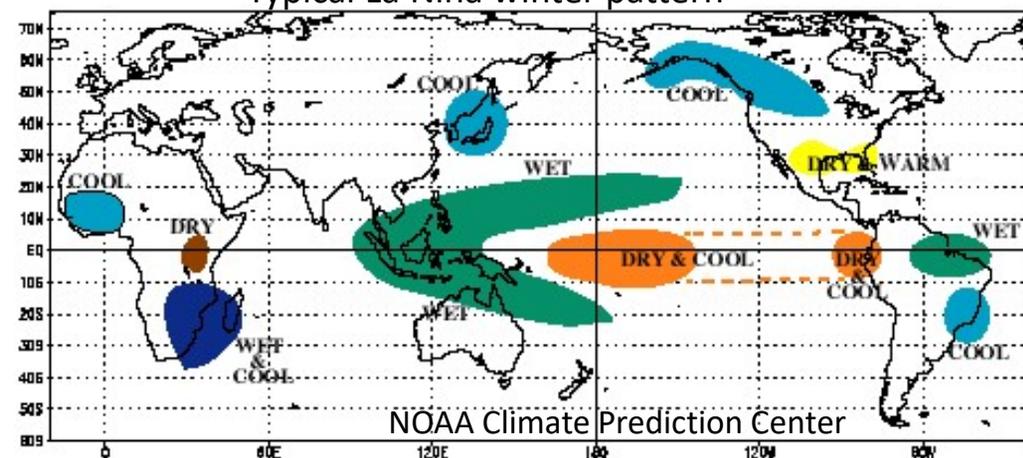
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- Ex: El Niño, La Niña, the Atlantic Multidecadal Oscillation, the weather...
  
- These are always, and will always be, happening.
- Not our focus today.

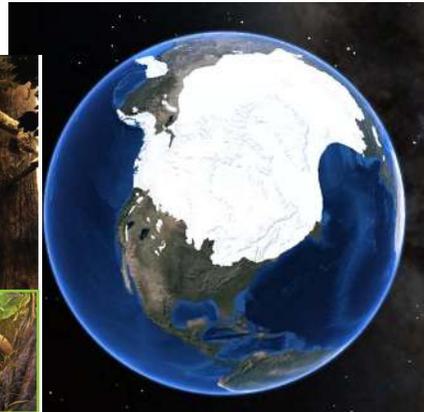
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- By “climate change” we are often speaking of two different things:
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- That is, long periods when the *entire Earth* cools down, or warms up
- This is what I will mean today when I say “climate change”

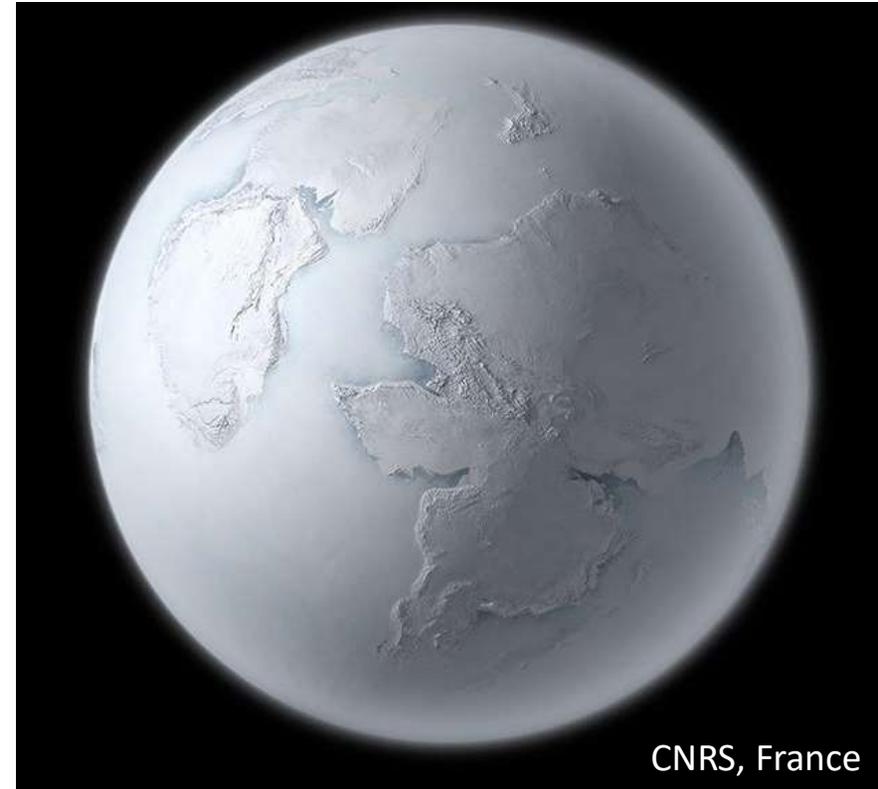
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# Examples of climate change

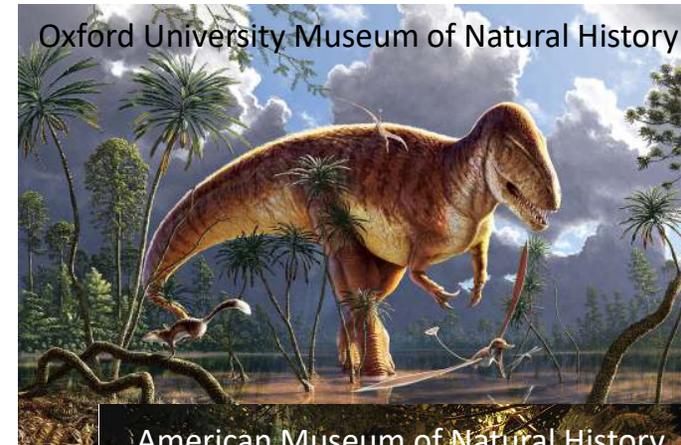
- "Snowball Earth" periods
- Huronian (2.4-2.1 billion years ago)
- Cryogenian (720-635 million years ago)
- Entire planet froze over
- "Sea-glaciers" floated on the oceans
- Multi-cell life then exploded post-Cryogenian
- (Ediacaran, Cambrian...)



CNRS, France

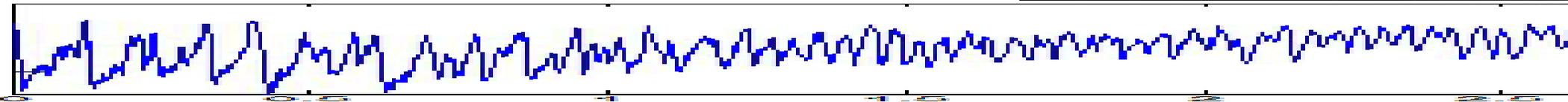
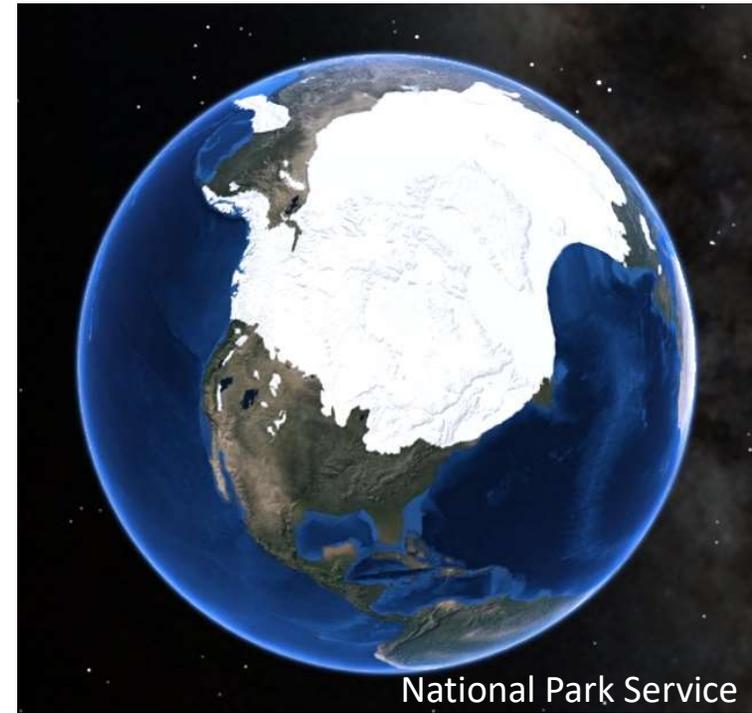
# Examples of climate change

- **Extreme global warmth** during much of late dinosaur & early mammal eras
- ~100 to 40 million years ago
- No polar ice! **Forests** grew in Antarctica & the Arctic
- Crocodiles on Ellesmere Island (80°N)
- Tropical oceans may have been **95-100°F or hotter**
- By 5 million years ago, Earth had gotten much cooler



# Examples of climate change

- **Pleistocene Ice Ages** began 2.6 million years ago
- Planet *repeatedly* cooled and warmed by a lot
- Every 40,000 to 100,000 years
- We are currently in a warm phase (interglacial)
- During cold phases (glacials) Canada & north US are covered with miles-thick ice.
- Sea level is ~400ft lower than today.

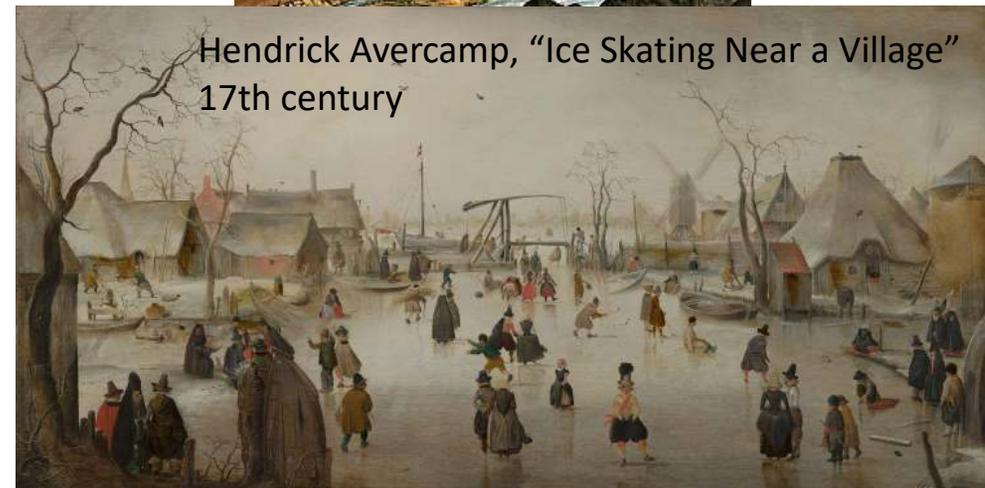


# Examples of climate change

- 1600-1850 A.D. “Little Ice Age” cooling
  - Somewhat cooler than earlier & later centuries
  - originally thought to be North Atlantic only
  - Now understood to be **global** in scope!
- 
- Frequent canal freezes in Holland
  - Glacier advances in the Alps & Rockies
  - Very cold winters in China
  - 1816 “Year Without a Summer”



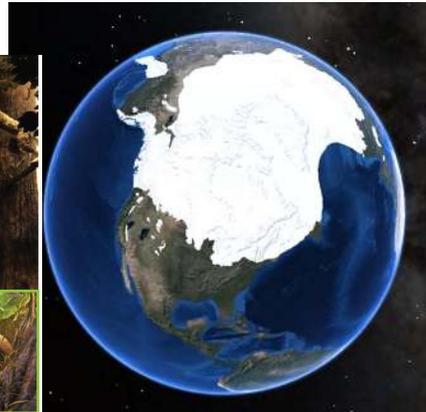
Rhone Glacier, 1870 (unknown)



Hendrick Avercamp, “Ice Skating Near a Village”  
17th century

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# Why does this happen??



- **Why** does Earth as a whole **cool down** or **warm up** at all?
- After all, we've remained the same distance from the sun – and sun's intensity has changed very little since the dinosaur era.
- We need to think about the Earth's **energy balance** a.k.a. **heat balance**.

# Energy Balance of Earth - or any planet



- **Sun** is main source of heat to Earth
- Sun's **heat** is largely carried by **sunlight** itself (**visible** photons; 0.4-0.7  $\mu\text{m}$ )
- About  $\sim 30\%$  of sunlight is reflected away by clouds, dust, ice, snow, etc and doesn't heat the planet. This  $\sim 30\%$  is called planetary **albedo**.
- But remaining 70% does heat Earth.



# *Energy Balance of Earth - or any planet*

Visualizing Earth's albedo



(NASA DISCOVR satellite)



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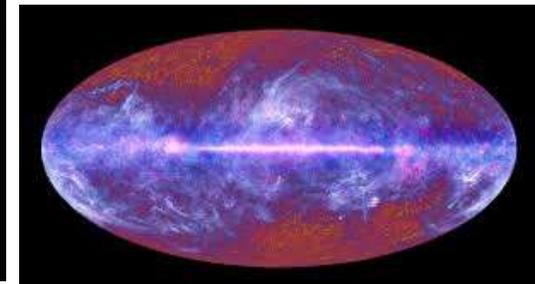
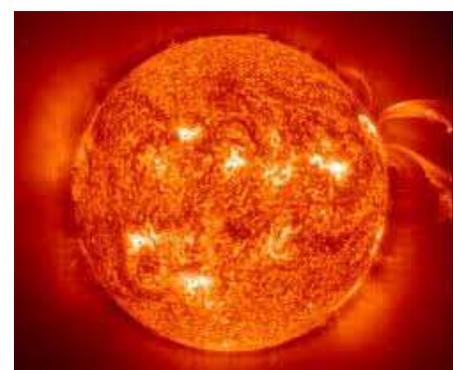
- Amount of energy is massive: Sun heats Earth at a rate of  $\sim 1.2 \times 10^{17}$  Watts
- This is 50,000 times humanity's total electrical consumption
- **Would boil the oceans away in months!!**
- Why doesn't this happen?
- Earth must be **cooling off** somehow.



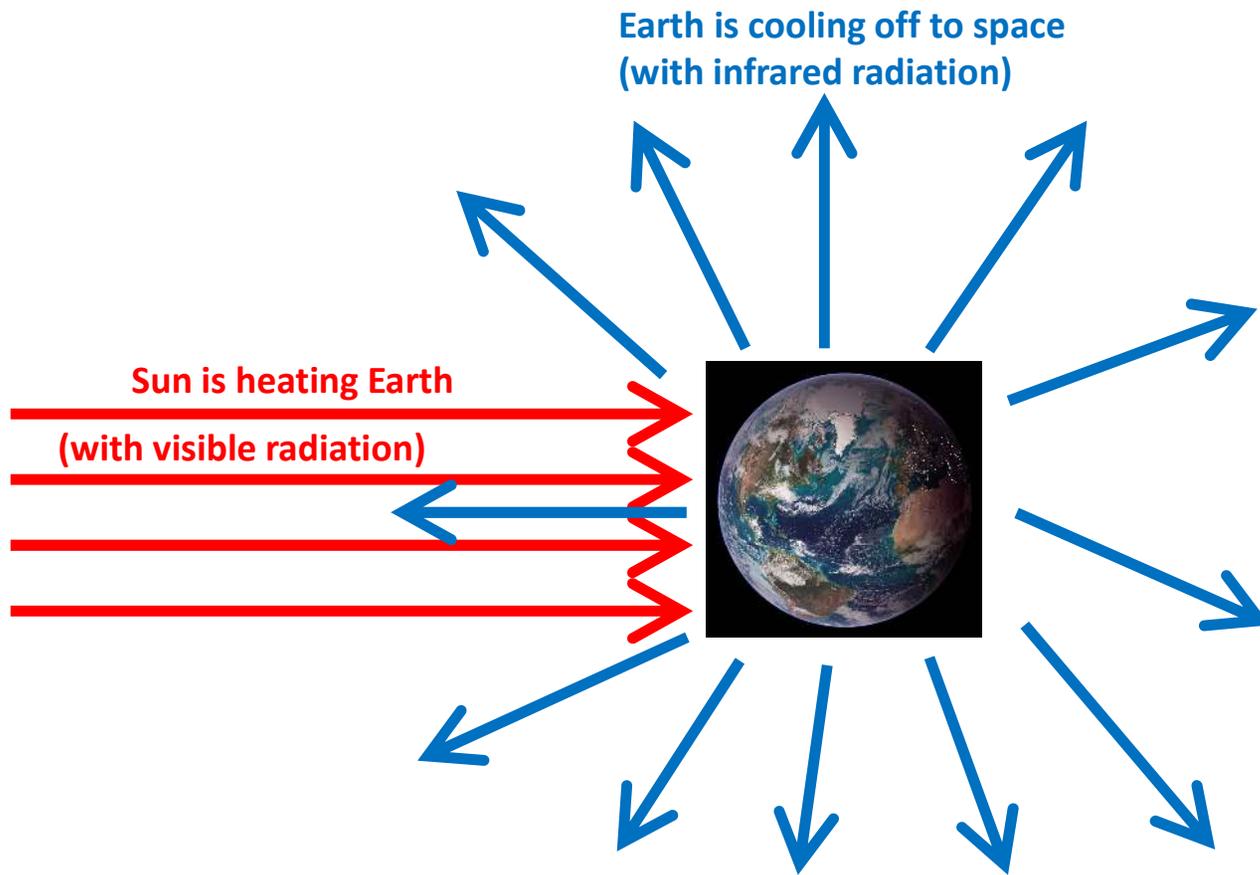
# Energy Balance of Earth - or any planet



- Everything in the universe **glows** with radiation. Hotter objects glow brighter.
- For Earth, this glow is **infrared** (& thus invisible) but *is the key cooling process*.
- Infrared light constantly leaves Earth for outer space, carrying energy away.



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- Infrared light constantly leaves Earth for outer space, carrying energy away.
  
- So, how warm is Earth?
- **However warm it needs to be** to **glow** brightly enough to **get rid of the sun's excess heat**.
- In other words, Earth's *energy balance* sets its **temperature**.

# *Energy Balance of Earth - or any planet*



- If Earth's albedo (reflectivity) decreases, it **absorbs more sun**.
- So **must get warmer** in order to **glow** "bright" enough to regain balance!
- Similarly if Earth's albedo increases, it must cool.

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Low reflectivity -- absorb **more** sun -- **warmer**



High reflectivity -- absorb **less** sun -- **cooler**

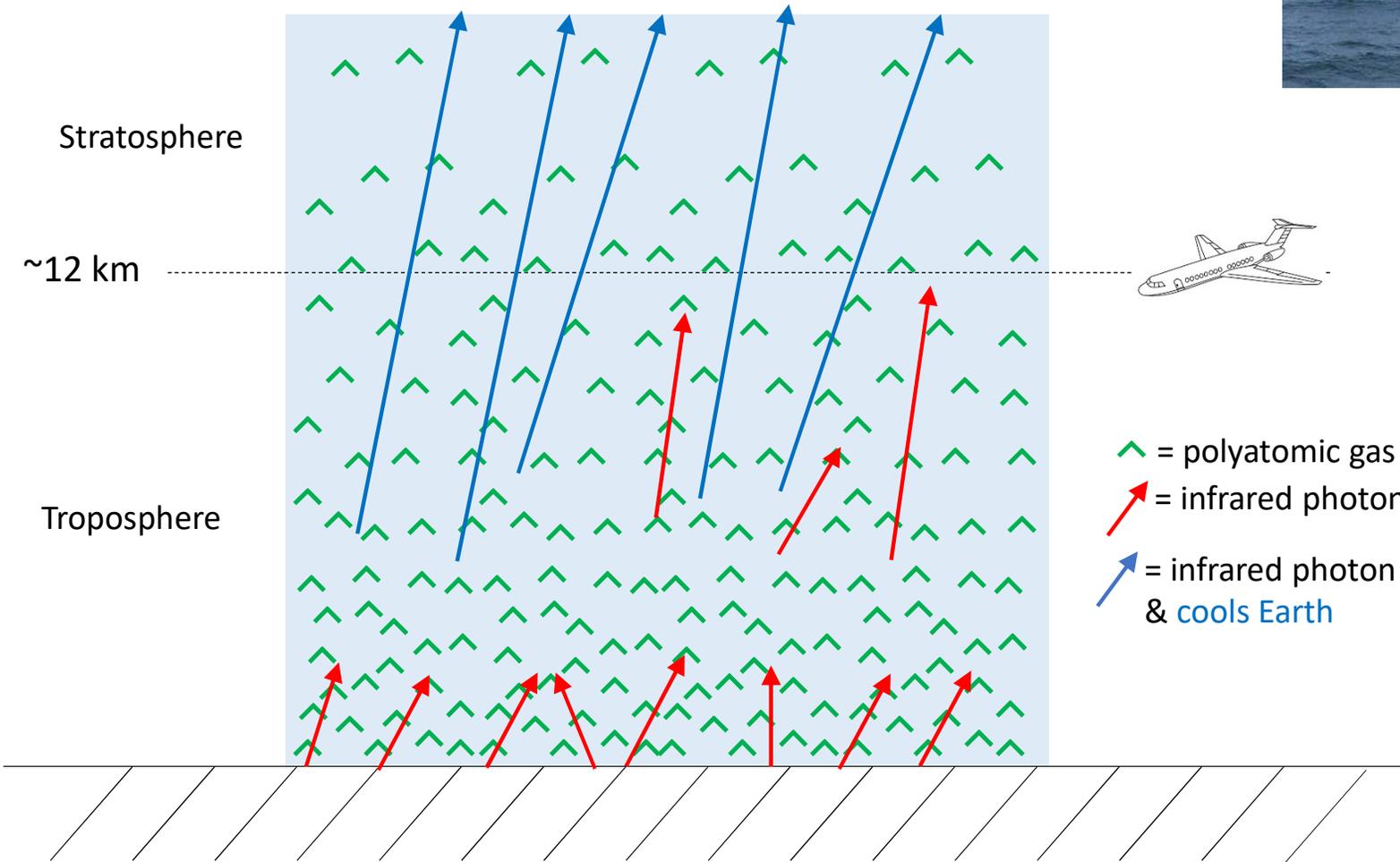


# Energy Balance of Earth - or any planet



- One more (key) twist on this story:
- The **cooling infrared glow** can be (partially) **stopped** on its way out to space.
- Diatomic & monatomic gases ( $N_2$ ,  $O_2$ , Ar – most of the air) cannot absorb infrared light – so they cannot do so.
- But **polyatomic** gases ( $H_2O$  vapor,  $CO_2$ ,  $CH_4$ ,  $O_3$ , ...) are great **absorbers** of infrared light! So are certain types of *clouds*.
- They “get in the way” of the escaping infrared, even in limited quantities.

# Energy Balance of Earth - or any planet



- ↗ = polyatomic gas molecule (H<sub>2</sub>O, CO<sub>2</sub>, etc)
- ↗ = infrared photon that is **stopped** by gases
- ↗ = infrared photon that **makes it out to space** & **cools Earth**

# Energy Balance of Earth - or any planet



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- They “**get in the way**” of some escaping infrared, even in limited quantities.
- So the **more polyatomic gas molecules are in the atmosphere**, the **warmer the surface has to be** in order to get rid of the same amount of heat.

# *Energy Balance of Earth - or any planet*



- This is exactly like why **putting on a jacket or blanket** warms you up!
- The jacket blocks your body heat from leaving, so your body needs to become warmer to give off the same amount of heat.
- Or the **insulation on your home**. “Gets in the way” of the heat leaving.
- Or, (most famously) **the glass on top of a greenhouse** keeping the heat in.
- Thus, the polyatomic gases have been dubbed “**greenhouse gases.**”
- Almost all are **naturally** occurring ( $\text{H}_2\text{O}$  vapor,  $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{O}_3$ , ...)

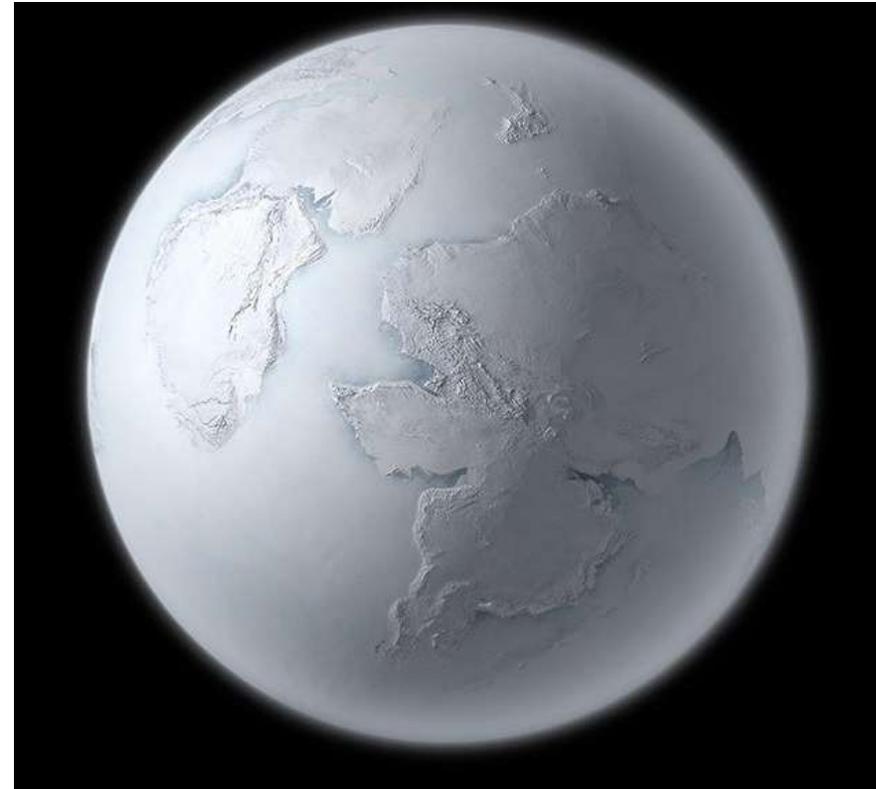
# Energy Balance of Earth - or any planet



- So to **sum up**, Earth's overall surface temperature is controlled by:
- 1) its *albedo* (reflectivity to sunlight)
- and 2) the amount of *polyatomic gases* (greenhouse gases) in its atmosphere.
  
- Less reflective -> warmer. More reflective -> cooler.
- (“T-shirt color effect”)
- More polyatomic gases -> warmer. Fewer polyatomic gases -> cooler.
- (“Jacket effect”)
- **Almost all true climate changes can be explained by this simple framework!**

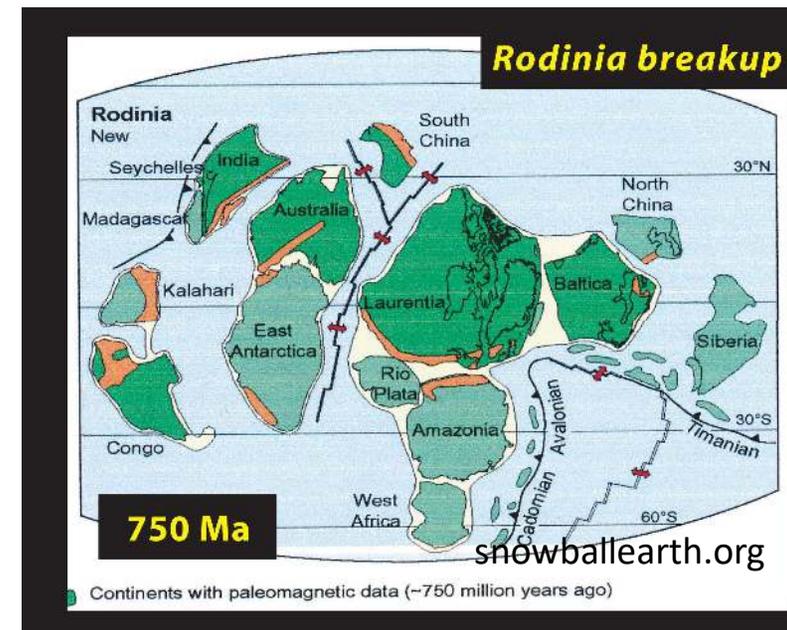
# Examples of climate change

- Huronian “Snowball Earth” (~2.3 billion y.a.)
- Caused by the “Great Oxygenation Event”
- Photosynthetic life developed, increasing  $O_2$
- As a result almost all  $CH_4$  in the air oxidized.
- Dramatic drop in  $CH_4$  levels.
- Planet froze over.
  
- Only melted after volcanoes emitted enough  $CO_2$  to warm us back above freezing. Took ~200 million years to do so!

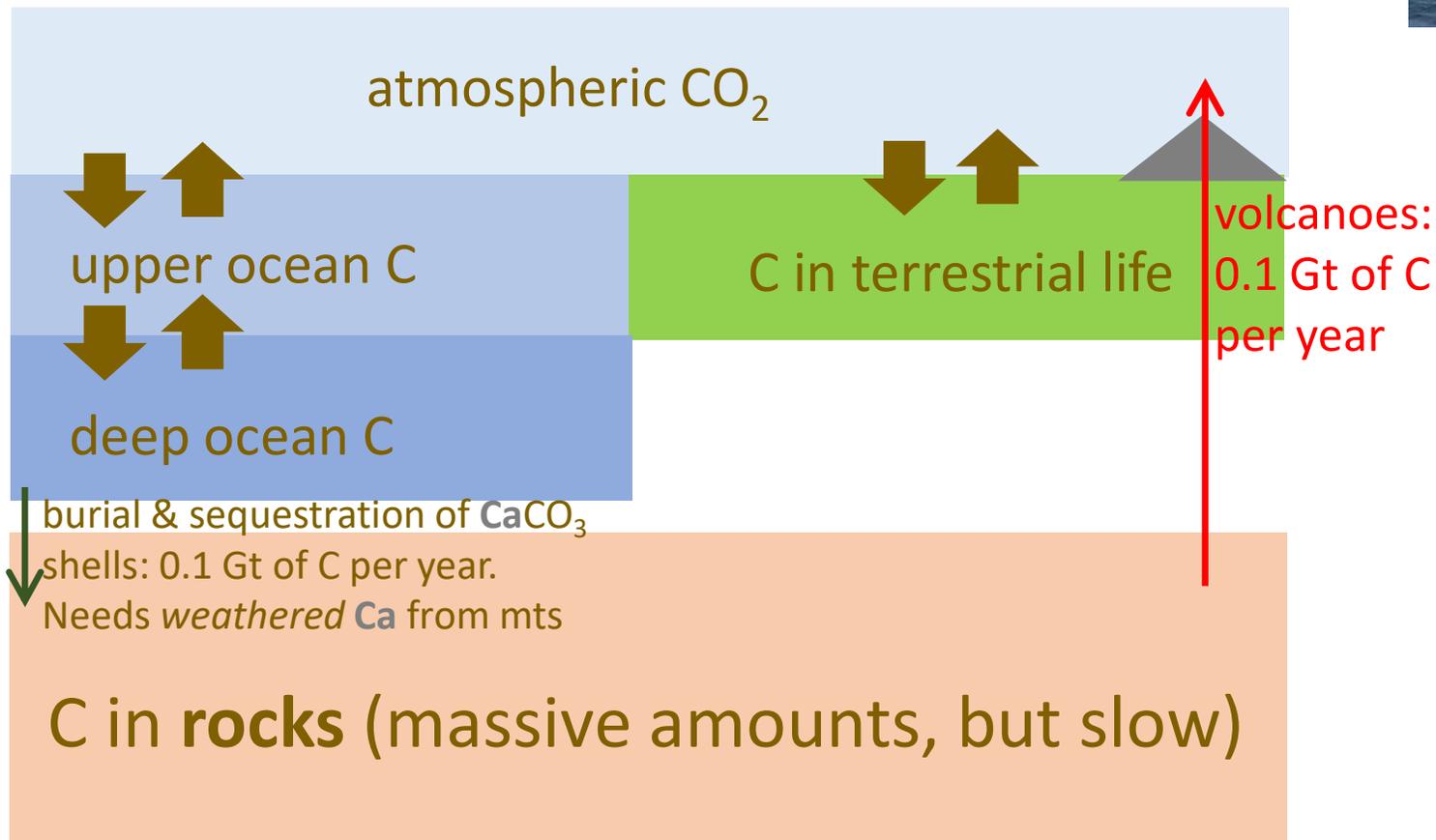


# Examples of climate change

- Cryogenian Snowball Earth (~700 million y.a.)
- Caused by movement of Earth's **continents** into the **tropics**.
- Huh?
- **Continents** are more reflective than **oceans**
- so more continents where it's **sunny** -> **more light reflected away**. Earth **cools**!
- Also, continents in the **tropics** -> more rain on rock -> more *weathering* of calcium, which **sequesters CO<sub>2</sub>** in on ocean floors...

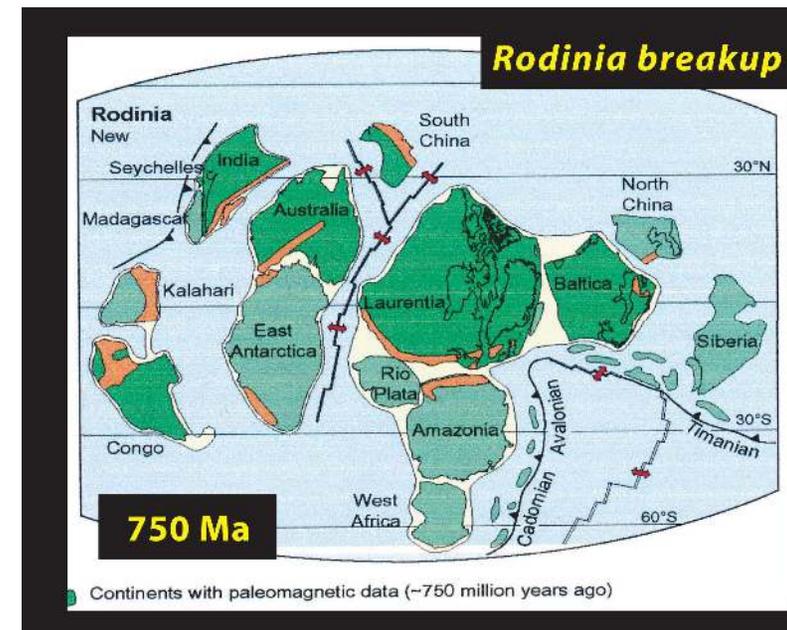


# Deep Carbon Cycle:



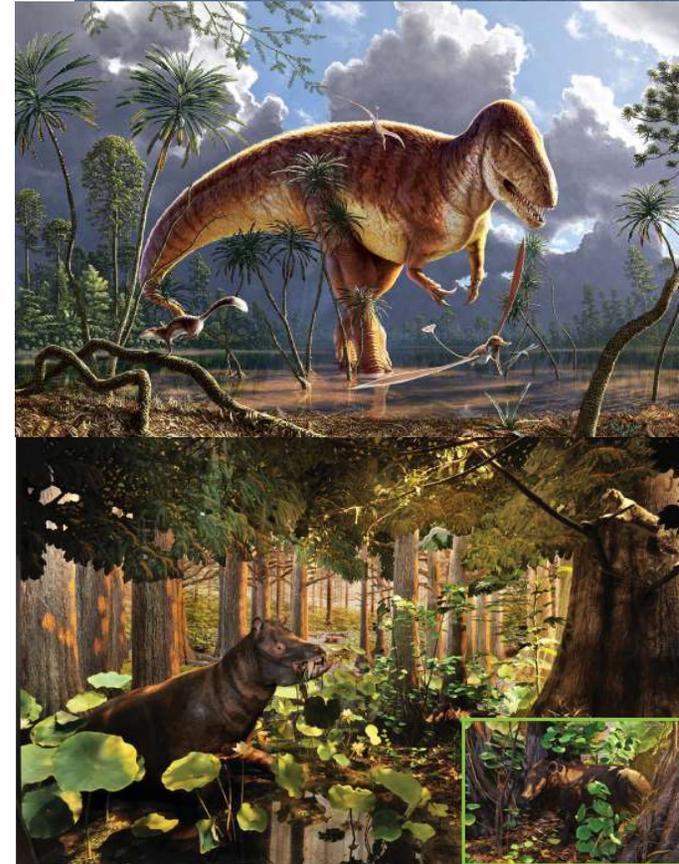
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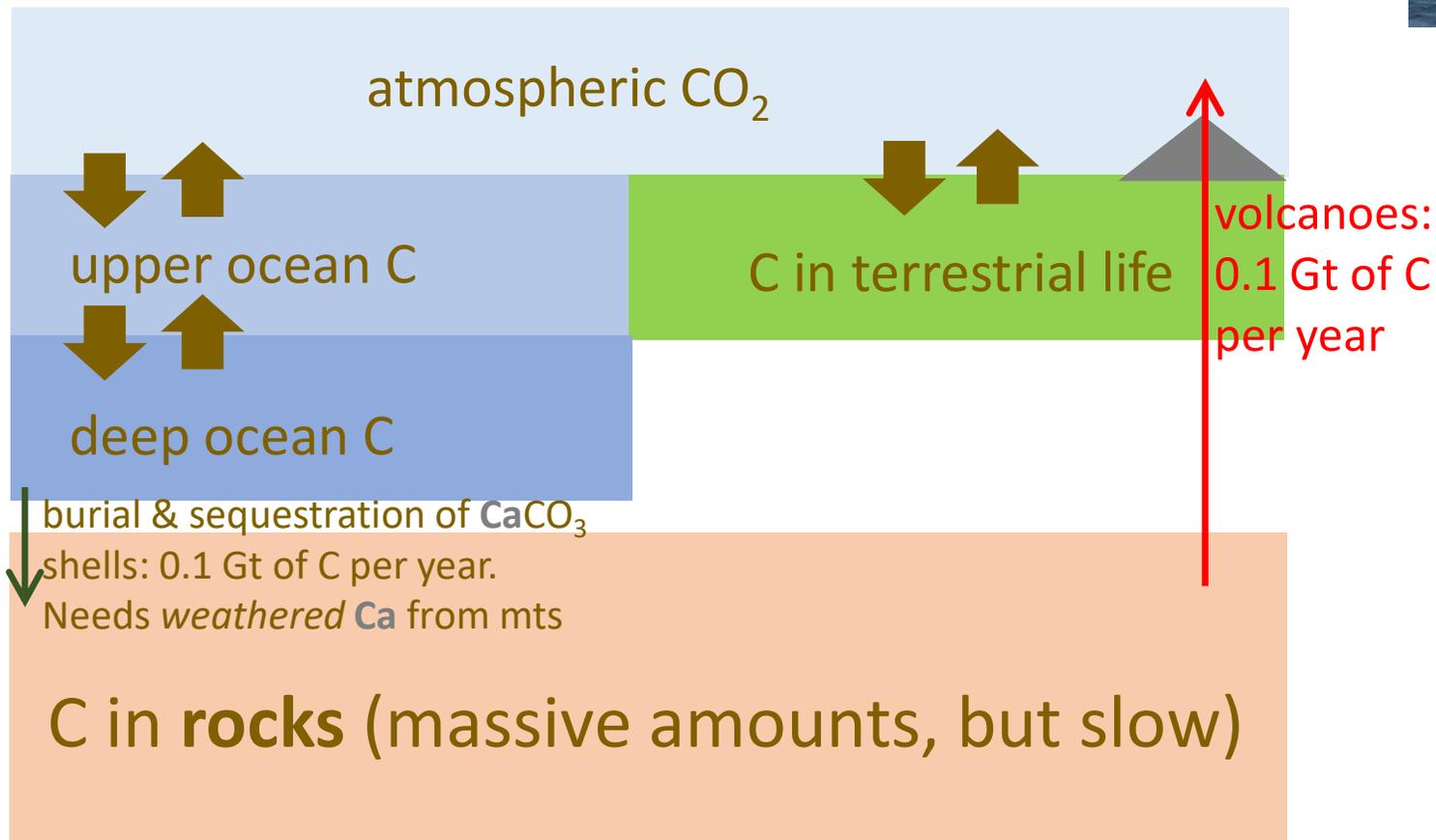


# Examples of climate change

- **Warm Mesozoic/Cenozoic (100-40 million years ago)**
- Cause: long prior period of **volcanism** > **weathering**.
- **CO<sub>2</sub> slowly built up** in air ~200-100 million years ago.
- Stayed high (with fluctuations) until **rise of Rockies, Andes, Alps, Himalayas etc.** ~50 million years ago
- which increased **Ca** weathering again & **buried CO<sub>2</sub>**.
- Planet then **cooled**.



# Deep Carbon Cycle:



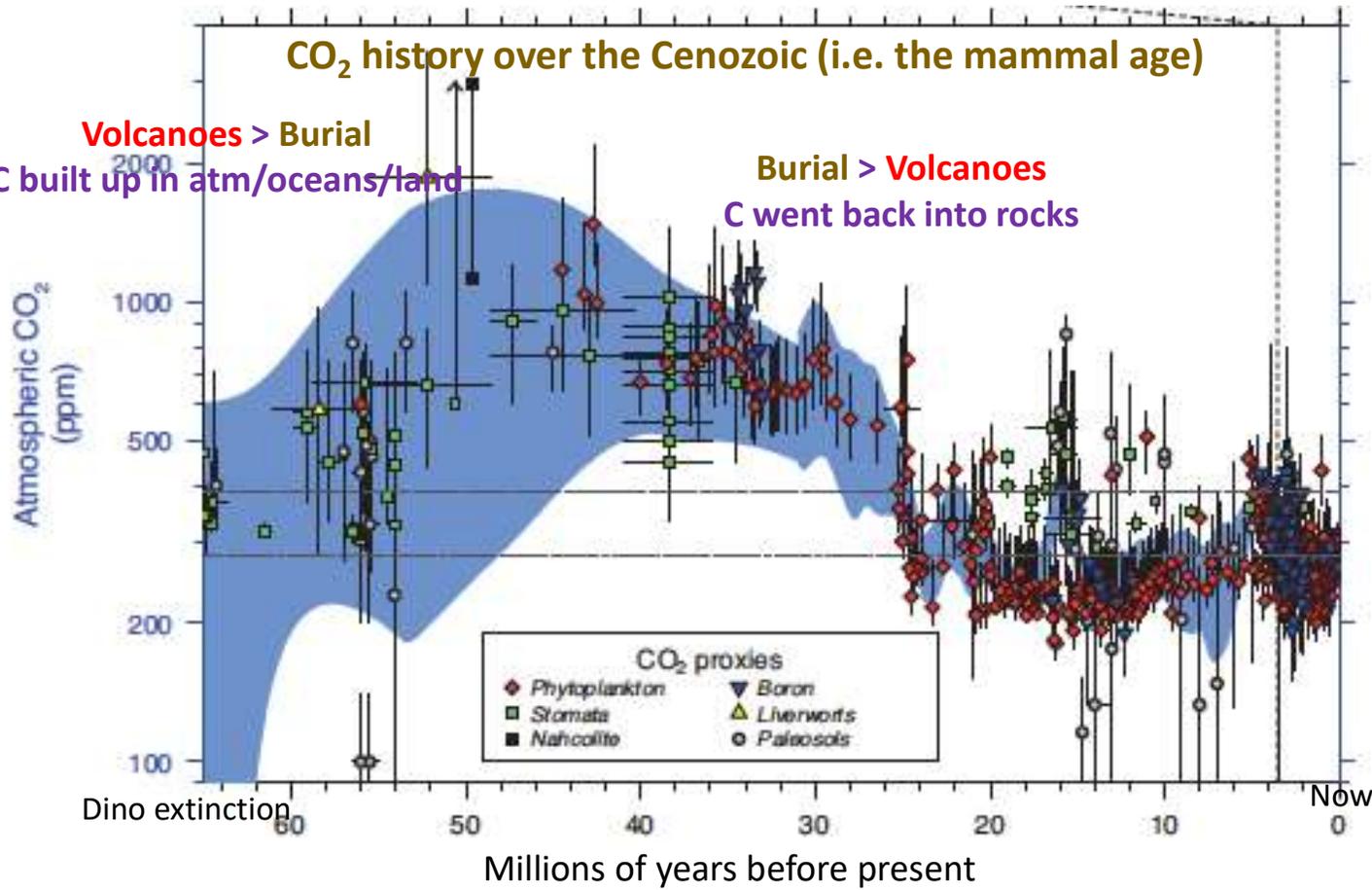
# Examples of climate change



CO<sub>2</sub> history over the Cenozoic (i.e. the mammal age)

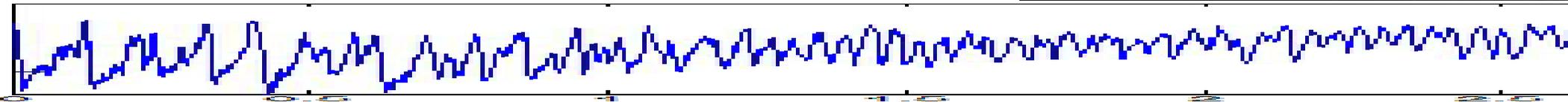
Volcanoes > Burial  
C built up in atm/oceans/land

Burial > Volcanoes  
C went back into rocks



# Examples of climate change

- **Pleistocene Ice Ages** 2.6 million years ago-present
- Caused by changes in Earth's orbit! *Milankovitch cycles* at periods of 40,000 & 100,000 years.
- **Canadian snow can survive summer** if axis's tilt angle is small, or if we're far from Sun in summer.
- This **increases Earth's albedo!** Cools planet, allowing more snow to survive. Vicious cycle.
- Eventually a **great ice sheet** grows in Canada.
- Melts once too big to be stable. Starts over.



# Examples of climate change

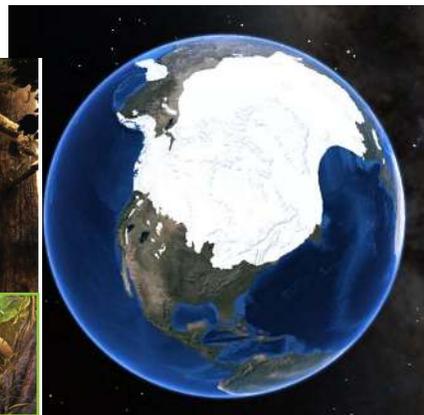
- 1600-1850 A.D. “**Little Ice Age**” cooling
- Long seen as **mysterious** – sunspot changes??
- Now finally recognized as the result of **volcanism**
- Huge tropical eruptions (e.g. Huaynaputina 1600 A.D. and Tambora 1815 A.D.)
- **Volcanic sulfur** polluted stratosphere
- Decades of **increased albedo!**
- “Year without a Summer” 1816 A.D.



# Examples of climate change



- **Point** is that almost all natural climate changes are well-understood through the framework of Earth's *energy balance*.
- More polyatomic gases (jacket effect): warmer, e.g. dino/mammal eras
- Fewer polyatomic gases: cooler, e.g. Snowball Earths
- More albedo (white T-shirt effect): cooler, e.g. Ice Ages, “little ice age”



# Examples of climate change



- In other words, **natural climate change is no mystery!**
- **Makes sense** given the changes in atmospheric gases & albedo that have occurred.
- This is a relatively recent understanding. 60 years ago geologists spoke in terms of changes in ocean currents, etc.

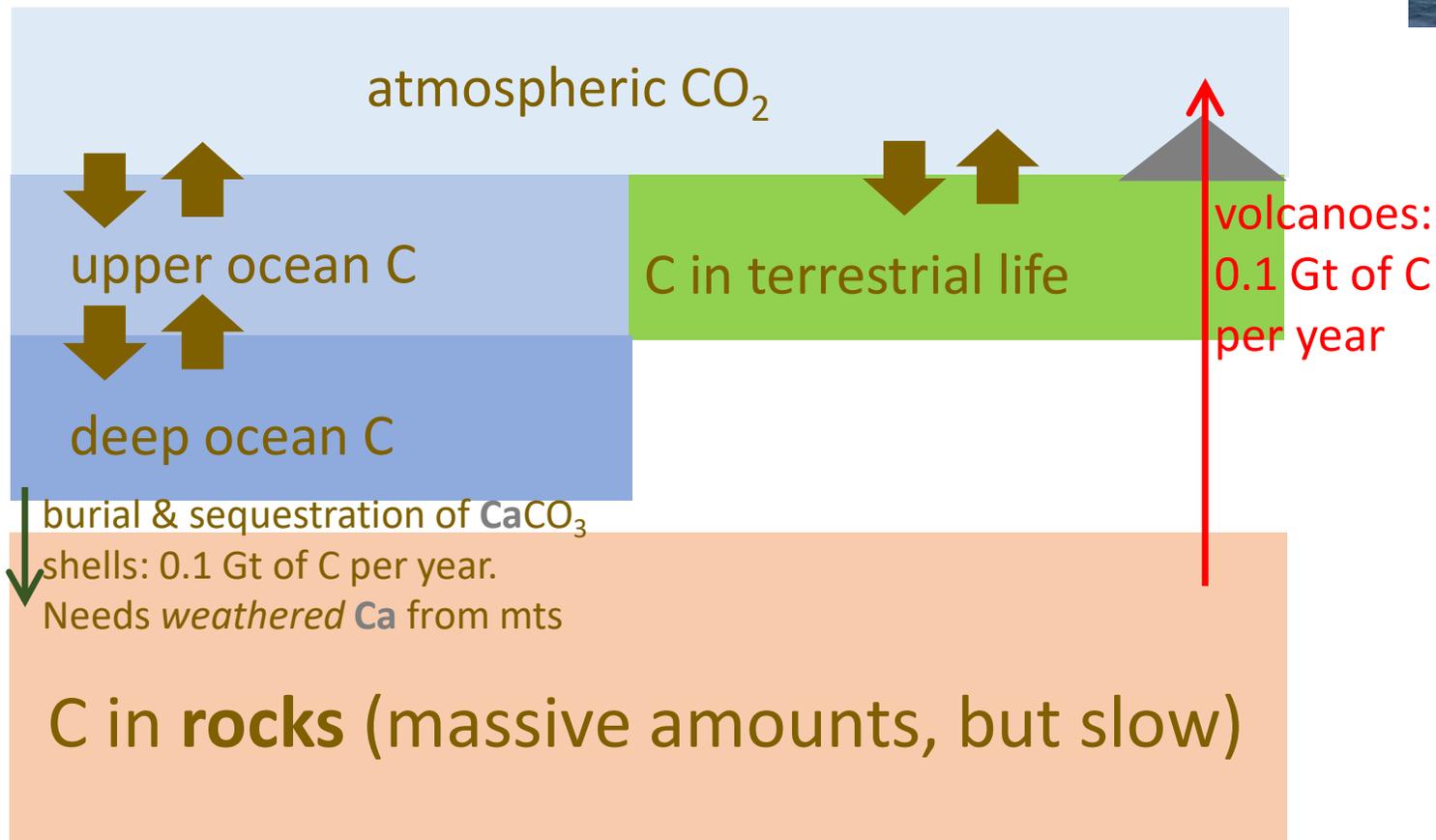


# Current climate change

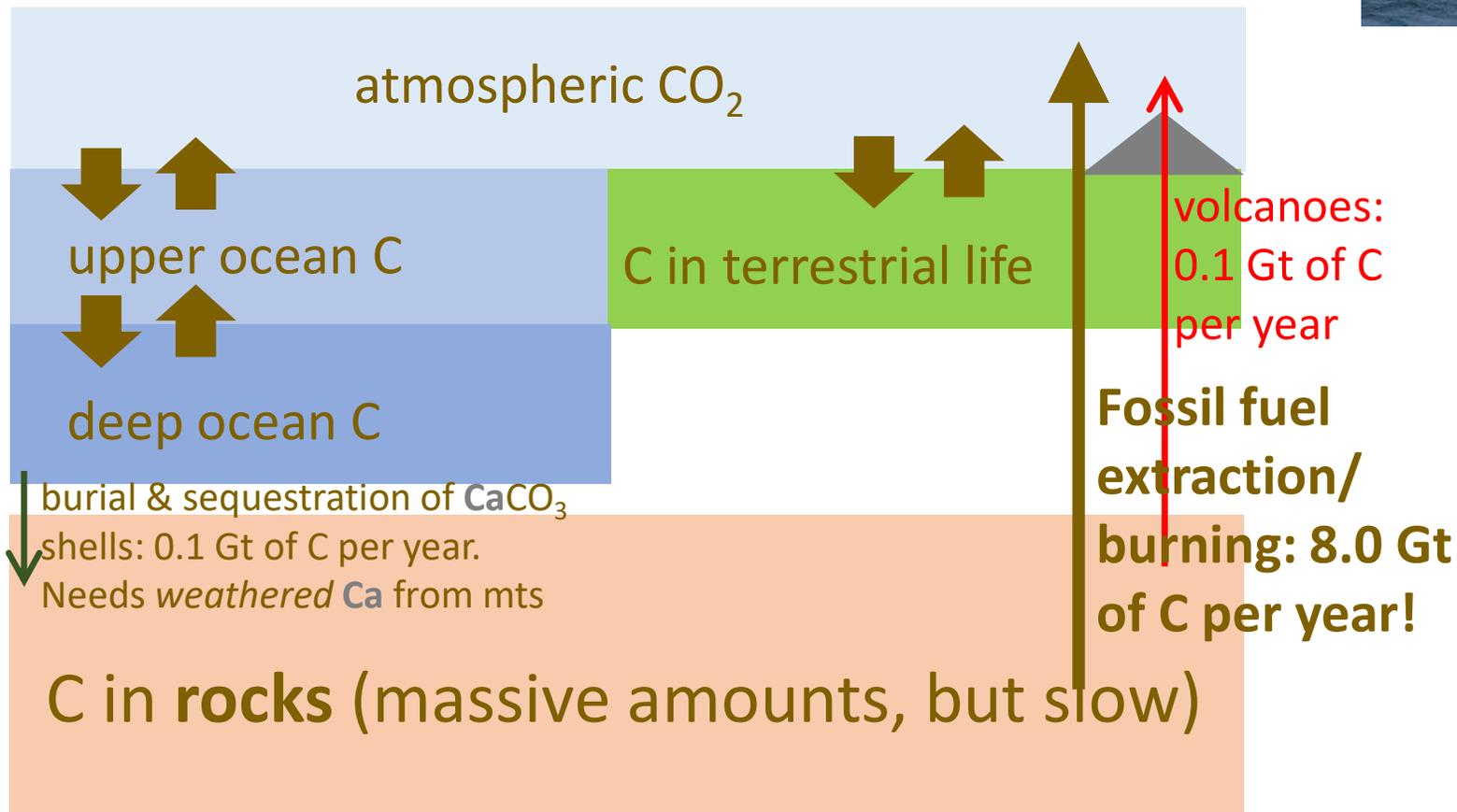


- So where do **we** fit in?
- Can we possibly compete with Nature's geologic forces?
- Most of our actions *do not*. But one currently does:
- the **extraction of fossil fuels (gas, oil, coal) from the ground & combustion of those fuels into atmospheric CO<sub>2</sub>.**
- Why??
- Because it's so much **faster** than the natural way CO<sub>2</sub> increases:

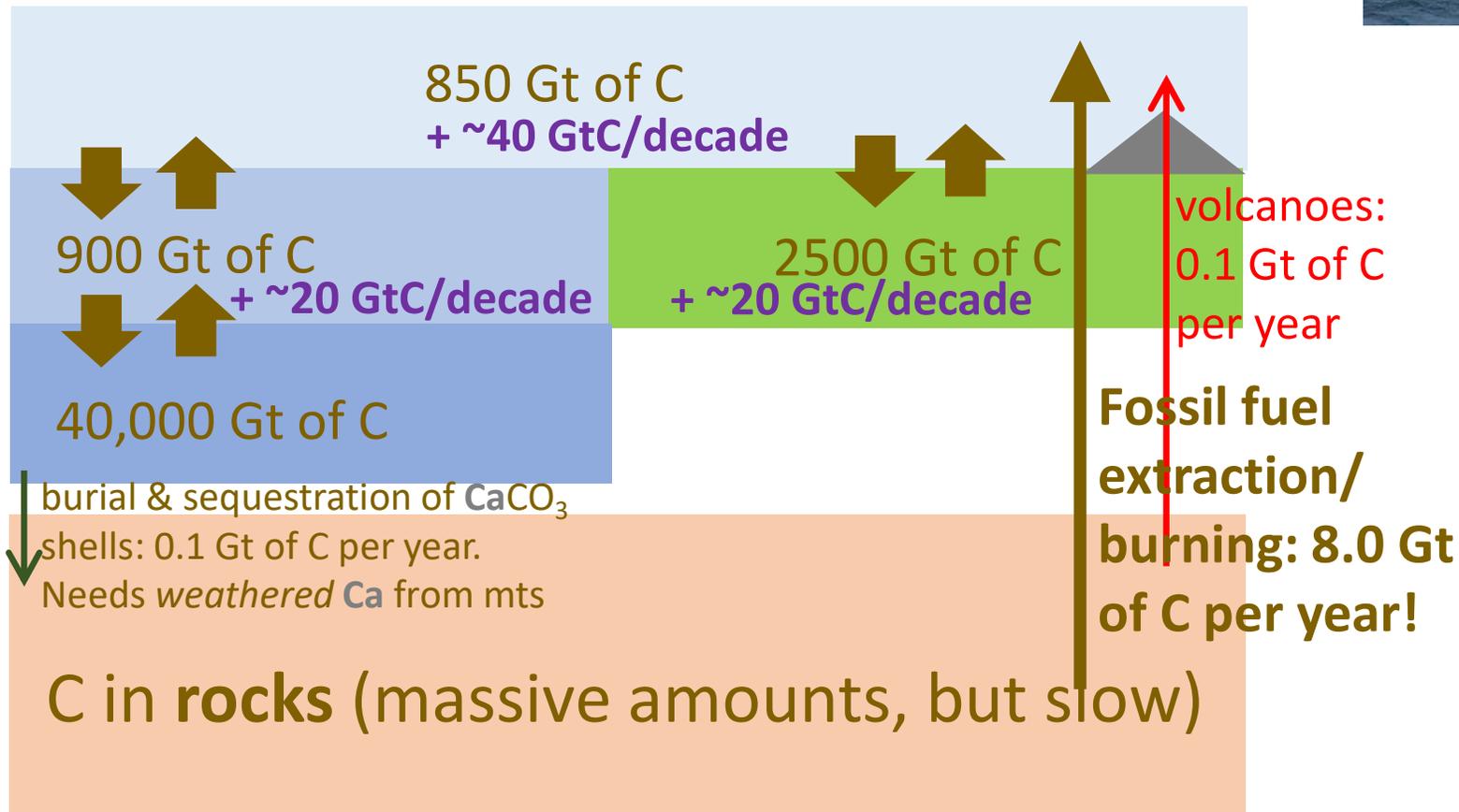
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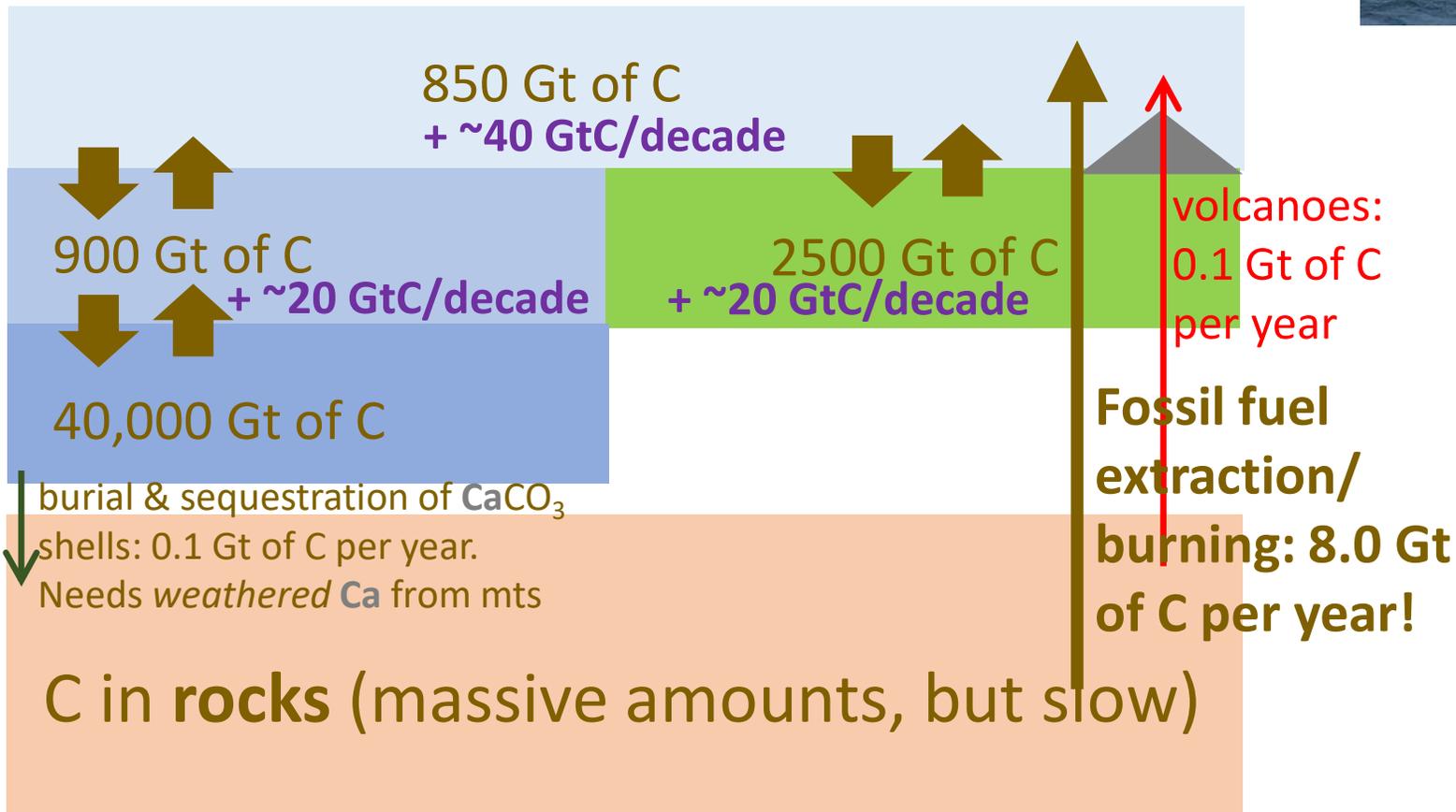
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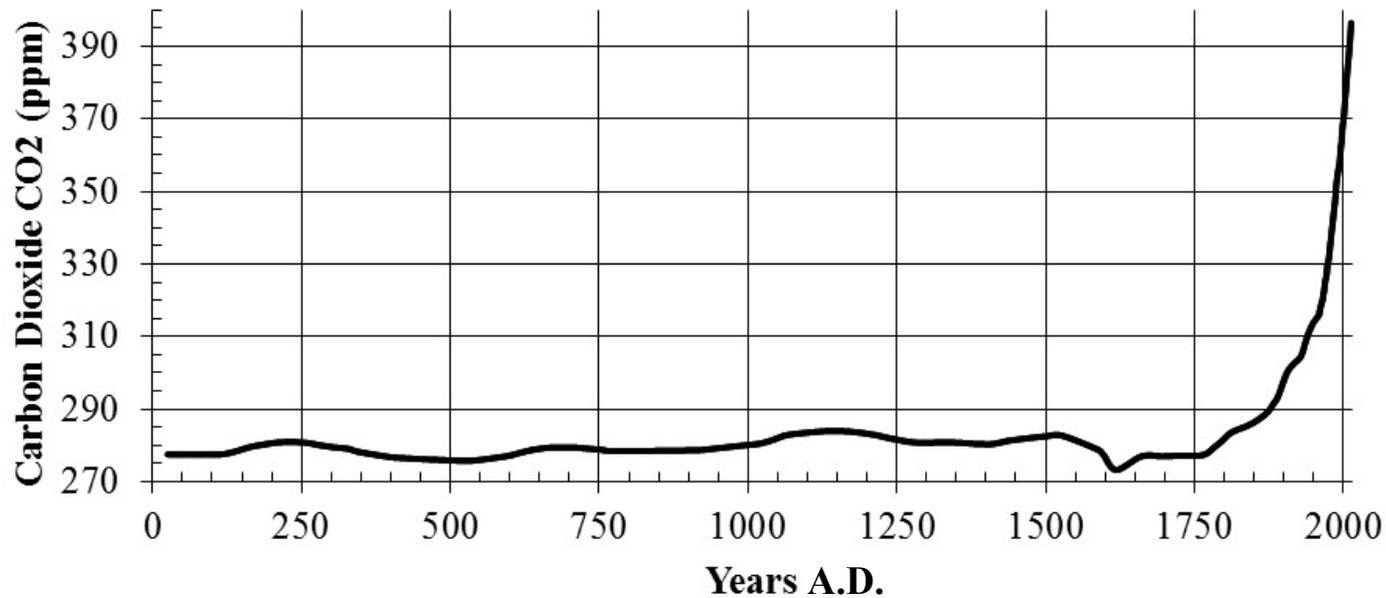


Excess C has been rapidly building up in air, oceans, land since industrial revolution.

Far faster than Ca weathering and burial can remove it!

# Deep Carbon Cycle:

**Atmospheric CO<sub>2</sub>** history over the past 2000 years (from ice core air bubbles)

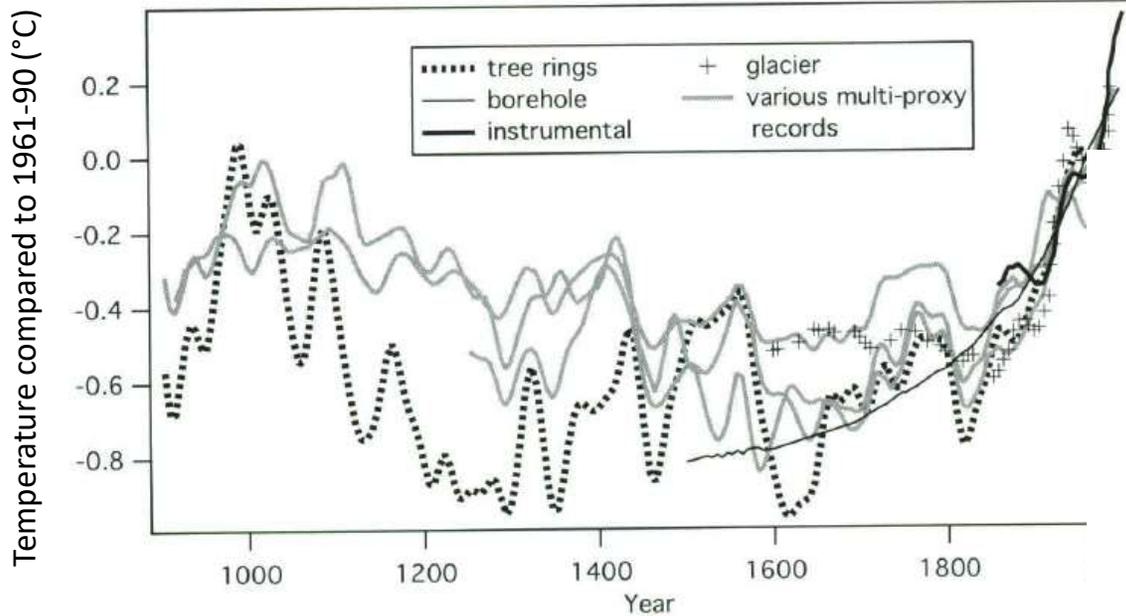


Data source: [http://www.ipcc.ch/publications\\_and\\_data/ar4/wg1/en/faq-2-1.html](http://www.ipcc.ch/publications_and_data/ar4/wg1/en/faq-2-1.html)

Also see <http://www.esrl.noaa.gov/gmd/dv/iadv/> or <http://keelingcurve.ucsd.edu/>

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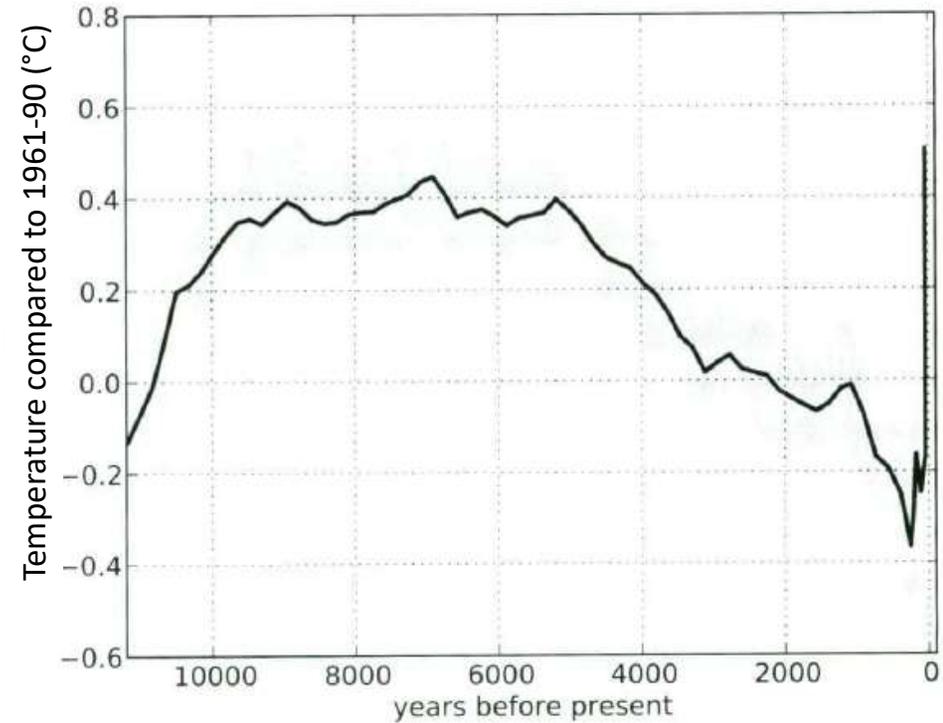
Global temperature history since medieval times



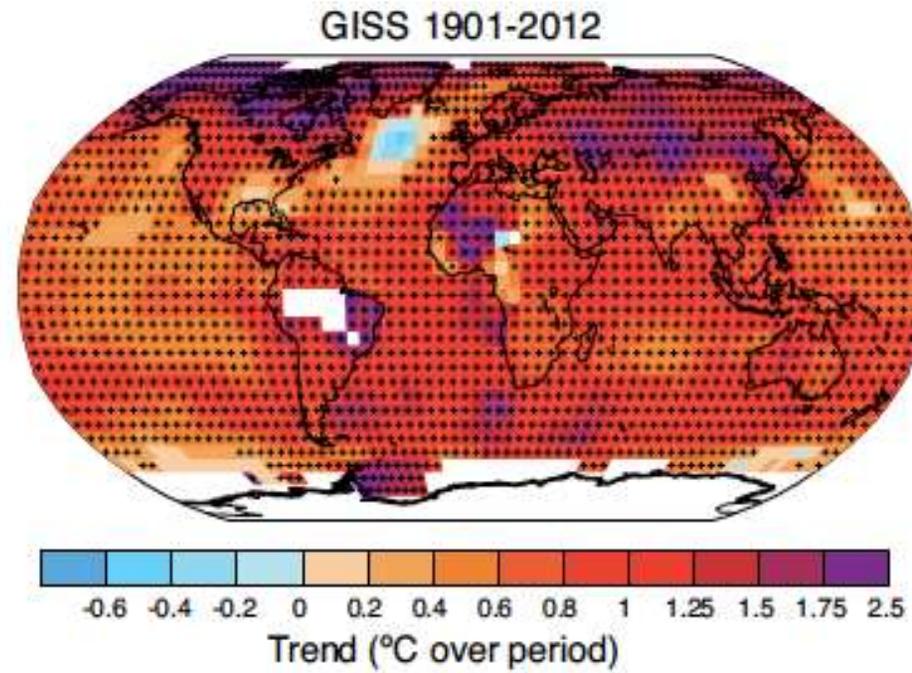
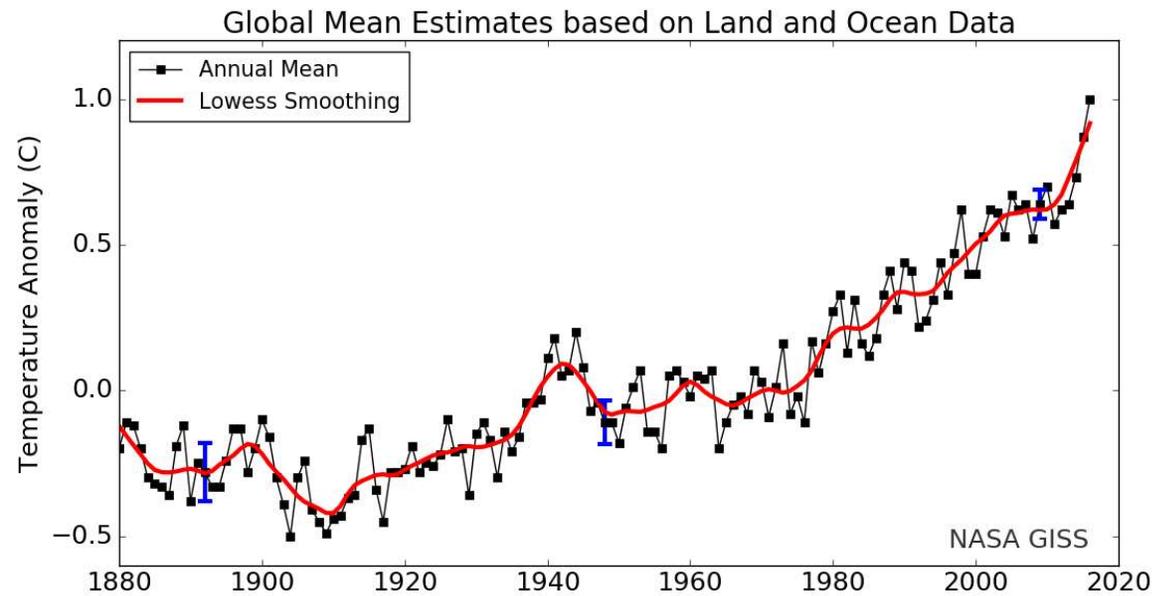
(Dessler, *Introduction to Modern Climate Change*, 2014)



Global temperature history since end of last Ice Age



# Current climate change



Local climate histories at: <http://paldhous.github.io/climate-change/>

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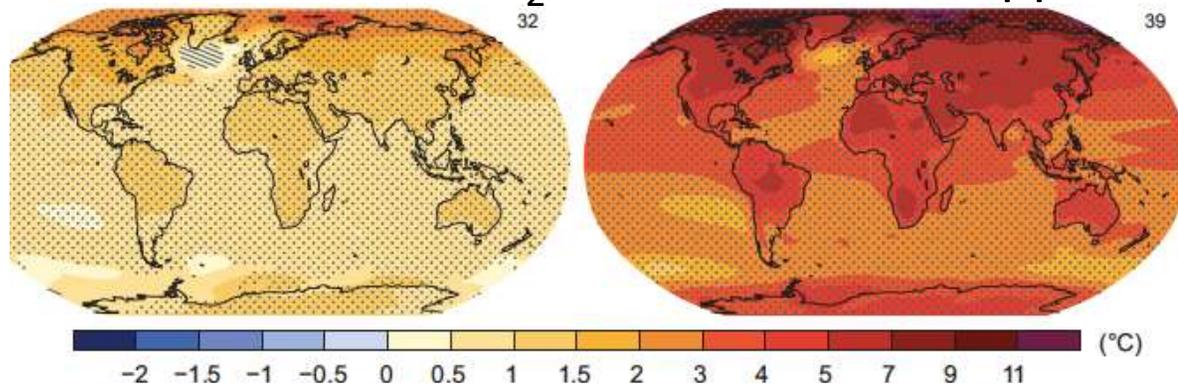


- In other words, since the industrial revolution (~19th century) we've been **unwittingly pulling one of Nature's climate levers – *hard***.
- More CO<sub>2</sub> -> thicker insulating “jacket” for Earth -> warmer.
- CO<sub>2</sub> level is now ~410 parts per million (was ~280 before fossil fuels)
- global warming so far ~ **2°F** (1°C)
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Coupled Model  
Intercomparison Project,  
phase 5

# Current climate change



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- After all, Earth has been through much larger climate changes than this!
- And humanity dealt with the end of the last Ice Age (~20,000-10,000 years ago) just fine.

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- After all, Earth has been through much larger climate changes than this!
- And humanity dealt with the end of the last Ice Age (~20,000-10,000 years ago) just fine.
- Earth warmed **~9°F** at that time – but wasn't a catastrophe for us...

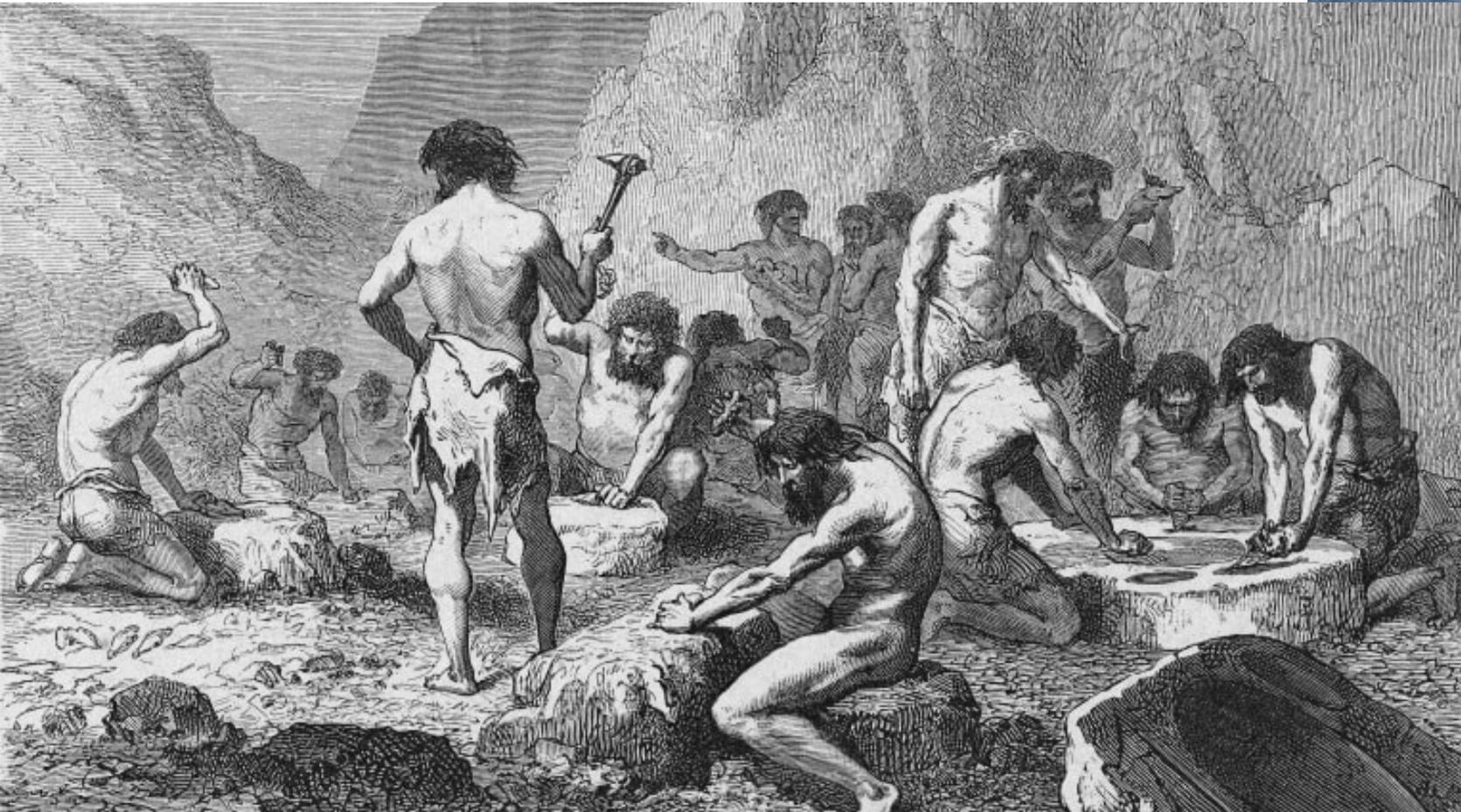


# Current climate change



- **Why does this warming matter?**
- Because this is the first significant global climate change to impact *agriculture and human infrastructure*.
- When the last Ice Age ended, we were all **running around hunting big game** and living in caves! Cro-Magnons, etc.
- Could easily move away from sea level rise, changing ecosystems, etc.
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- Could easily move away from sea level rise, changing ecosystems, etc.
- Occupy new land, hunt new game.
- It also helped that the Ice Age took **~10,000 years** to end.
- Equal amount of future warming could take just 100 years.

# Current climate change

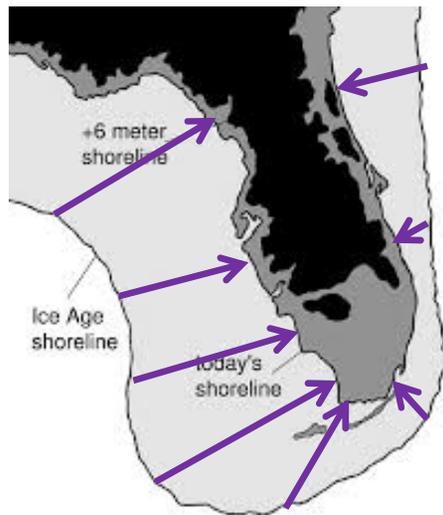
- E.g. sea level rose ~400 feet over those 10,000 years – 4 feet/century



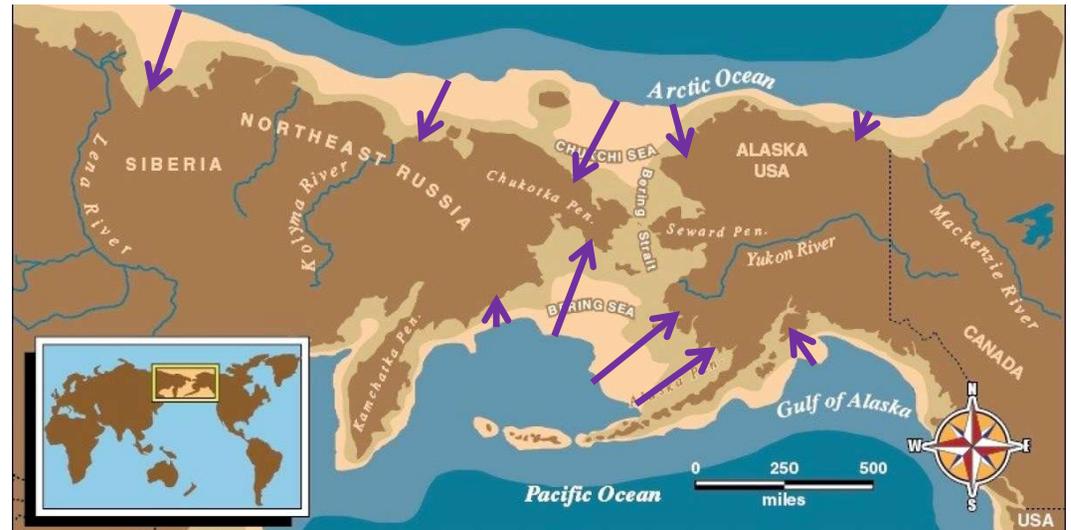
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University of Miami



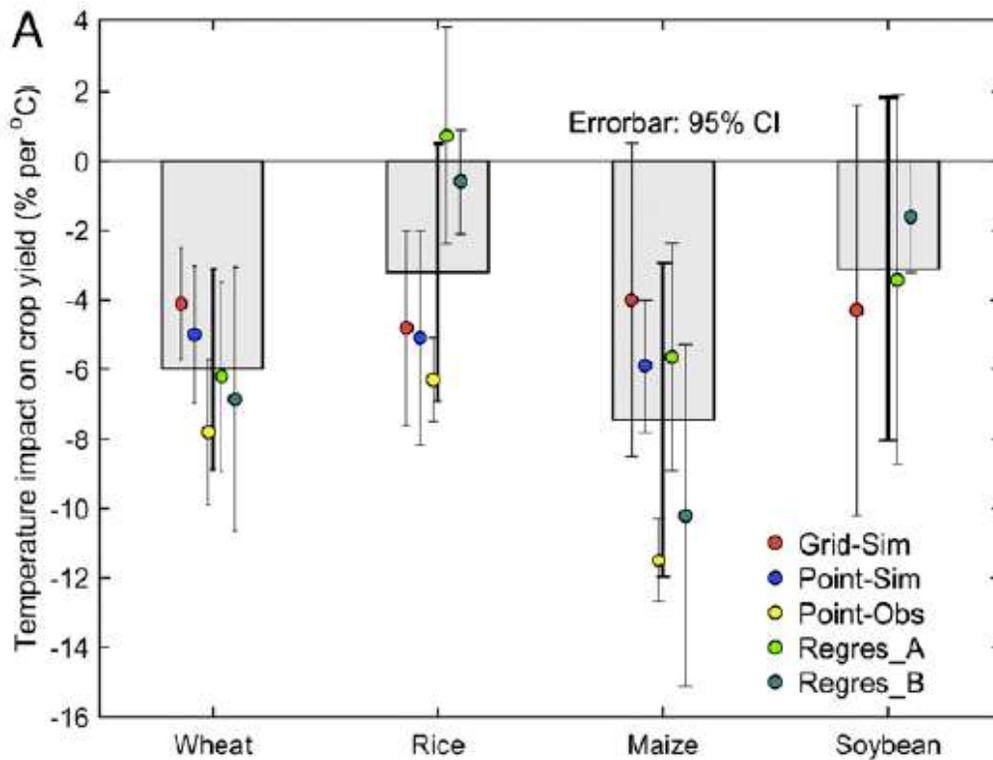
National Park Service

# Current climate change



- E.g. sea level rose ~400 feet over those 10,000 years – 4 feet/century
- But Ice Age people were **mobile** – would have hardly noticed!
- 4 feet of sea level rise *this* century would be **catastrophic** in Miami, Charleston, almost whole country of Bangladesh, etc. [coast.noaa.gov/slr](https://coast.noaa.gov/slr)
- Similarly, we were **growing no crops** then – so no climate change impact to our food supply. Could just follow game across the Bering Strait.
- Today, **most of our staple crops are very sensitive to high temperatures.**
- Crop yields could be **25-40% less** in a future warm climate due to temperature alone!

# Current climate change



Scenario	Yield changes (%) due to temperature changes by the end of century				
	Wheat	Rice	Maize	Soybean	Mean
RCP2.6	-6.9 [-15.0, -1.4]	-3.3 [-9.2, 0.8]	-8.6 [-18.6, -1.8]	-3.6 [-11.2, 1.7]	-5.6 [-14.4, -0.1]
RCP4.5	-11.4 [-21.7, -3.9]	-5.5 [-13.8, 1.0]	-14.2 [-27.9, -4.9]	-5.9 [-17.0, 3.1]	-9.2 [-21.2, -0.3]
RCP6.0	-14.0 [-25.7, -5.1]	-6.8 [-16.8, 1.3]	-17.4 [-33.1, -5.8]	-7.2 [-20.2, 3.6]	-11.3 [-25.6, 0.1]
RCP8.5	-22.4 [-40.2, -8.5]	-10.8 [-25.3, 2.4]	-27.8 [-50.4, -9.7]	-11.6 [-31.0, 6.0]	-18.2 [-38.6, -0.7]

Proceedings of the National Academy of Sciences of the USA

# Current climate change

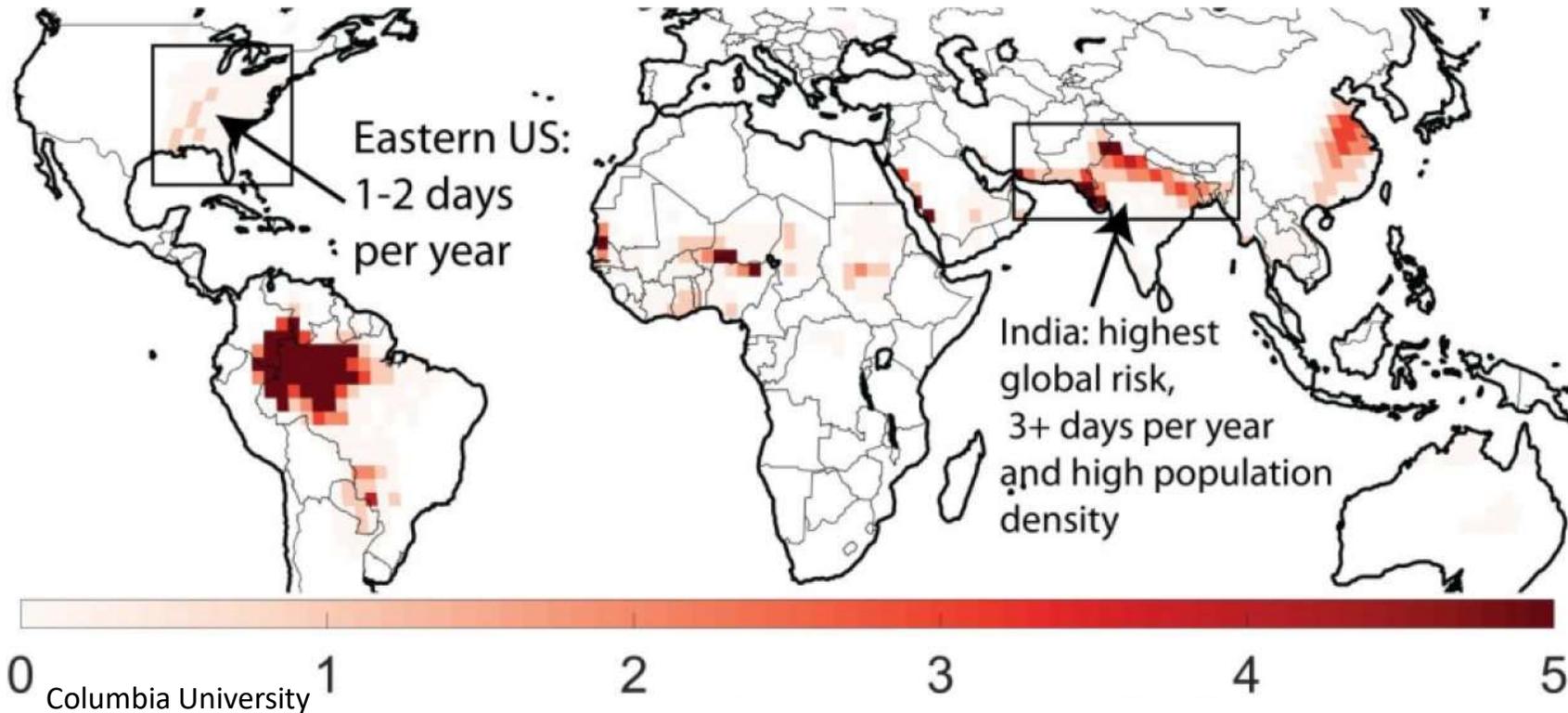


- Same reasoning applies to water in river systems, natural disasters, ecological change, etc.
- One more key impact of present/future warming:
- human and animal **heat stress/ heat stroke risk** in warm/humid places
- If we burn a lot of fossil fuel, there will be multiple days per year **so hot/humid that going outside will be dangerous**. Esp in India, China.

# Current climate change



How often it would be **too hot/humid** to safely go outside, if we warm up the planet  $\sim 7^\circ\text{F}$



# Current climate change



- Same reasoning applies to water in river systems, natural disasters, ecological change, etc.
- One more key impact of present/future warming:
- human and animal **heat stress/ heat stroke risk** in warm/humid places
- If we burn a lot of fossil fuel, there will be multiple days per year **so hot/humid that going outside will be dangerous**. Esp in India, China.
- Yes, Earth was much hotter than this in early mammal era – but mammals had tens of million years to **evolve** and **adapt** to it. **We will not have that.**

# Current climate change



- So, present climate change is so consequential because it's *fast* compared to evolution – and because it impacts our *built infrastructure* & *crops*.
- Past climate changes were much slower and we were more adaptable and mobile (or, in most cases, weren't even around yet!)

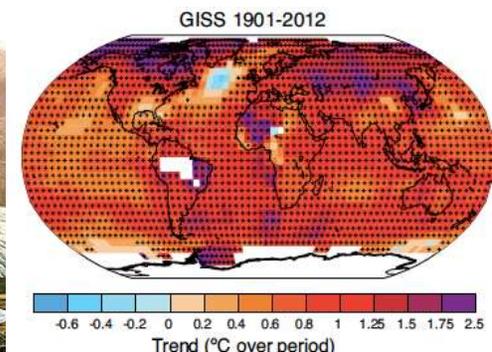
## Where to go from here?



- If we don't want any further warming, need to either:
  - **Phase out** the use of fossil fuels (*decarbonization*)
  - or,
  - figure out how to **capture** fossil fuels' CO<sub>2</sub> and re-bury it
- So many options for doing this! But there needs to be a framework for it to be **profitable** (or else massive intervention is required.)
- Just **hoping** companies will do it isn't enough...

## To sum up:

- Earth has two key natural climate change “knobs” throughout its history!
- Reflectivity to sunlight (*albedo*)
- and, amount of polyatomic gases in atmosphere (*greenhouse effect*)
- We are inadvertently increasing the latter, via fossil-fuel-combustion CO<sub>2</sub>
- Resulting global warming will be mostly business-as-usual for Nature
- But not for modern human infrastructure, agriculture, and civilization



Thank you!

