THE SCIENCE OF CLIMATE

Dan Hooper – Fermilab

Saturday Morning Physics

A Few Preliminaries

- In the past, I've given Saturday Morning Physics lectures on cosmology, quantum mechanics, and relativity
- There are two major differences between those lectures and this one
  1) I'm an expert on cosmology, quantum mechanics, and relativity
  2) Cosmology, quantum mechanics, and relativity are apolitical topics

Blue: Universally agreed upon by virtually all scientists

Green: A near consensus, but with some room for debate

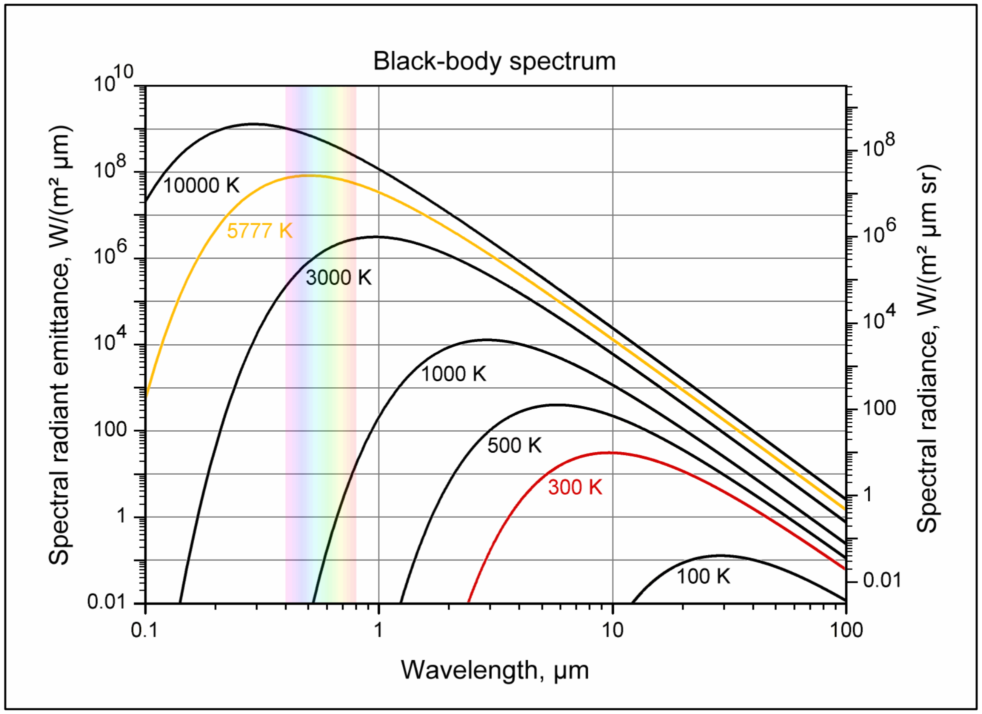
Yellow: Controversial or speculative

Heat and Temperature

- Objects radiate energy in the form of light, with a spectrum and intensity that depends on their temperature and surface area
- Two things to keep in mind:

  1) The wavelength (and frequency) of the radiation emitted depends on the temperature of the source: $\lambda_{peak} \propto 1/T$

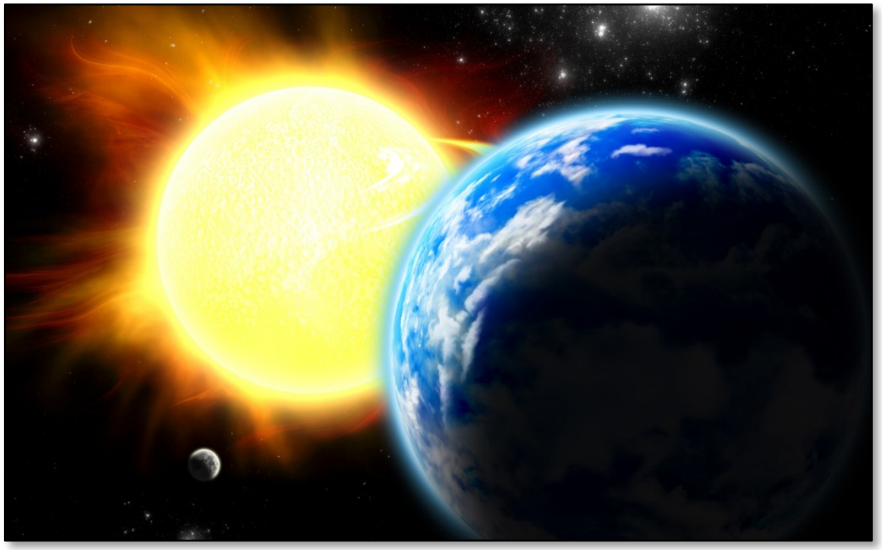
  2) The total intensity of the radiation emitted depends strongly on the temperature of the source: $I \propto T^4 \times A$



The Sun and the Earth

Consider a simple (and unrealistic) example, assuming that all of the radiation emitted by the Earth escapes (neglecting atmospheric absorption):

- At the Earth's distance from the Sun, the average power in sunlight is 340 watts/m^2, for a total of 1.7×10^{17} watts incident on the Earth's surface
- About 64% of this energy is absorbed by the Earth (the rest is reflected); in other words, the Earth's geometric albedo is 0.36
- If the average temperature of the Earth were *higher* than about -17°C, the Earth would radiate away more energy than it takes in, causing it to cool; if it were *lower* than about -17°C it would *heat up*
- The actual (average) temperature of the Earth is about 15°C



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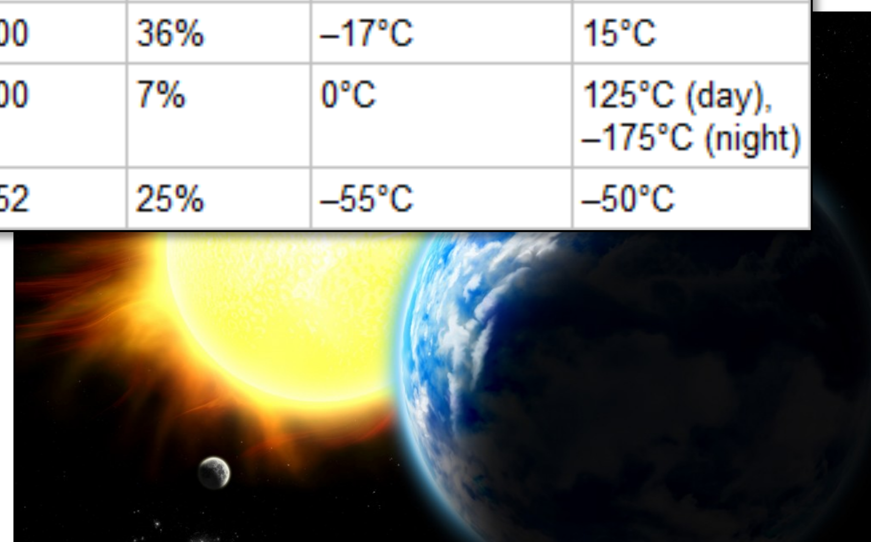
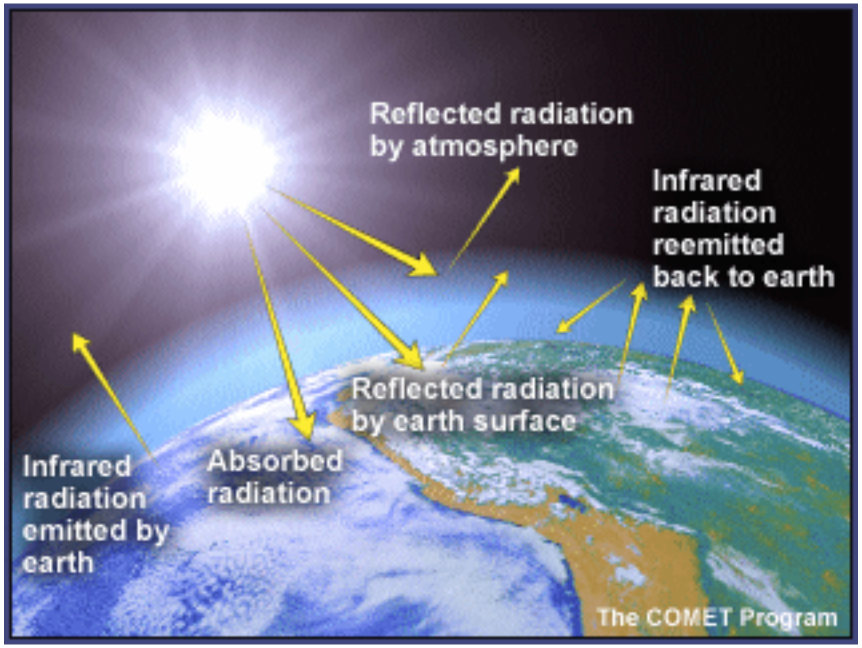
- If the average temperature of … he Earth would radiate away mo … ; if it were *lower* than about -17 … would *heat up*
- The actual (average) tempera… of the Earth is about 15°C
- We can perform similar estimates for other planets and moons

World	Average Distance from Sun (AU)	Reflectivity	"No Greenhouse" Average Surface Temperature*	Actual Average Surface Temperature
Mercury	0.387	11%	164°C	425°C (day), –175°C (night)
Venus	0.723	72%	–43°C	470°C
Earth	1.00	36%	–17°C	15°C
Moon	1.00	7%	0°C	125°C (day), –175°C (night)
Mars	1.52	25%	–55°C	–50°C



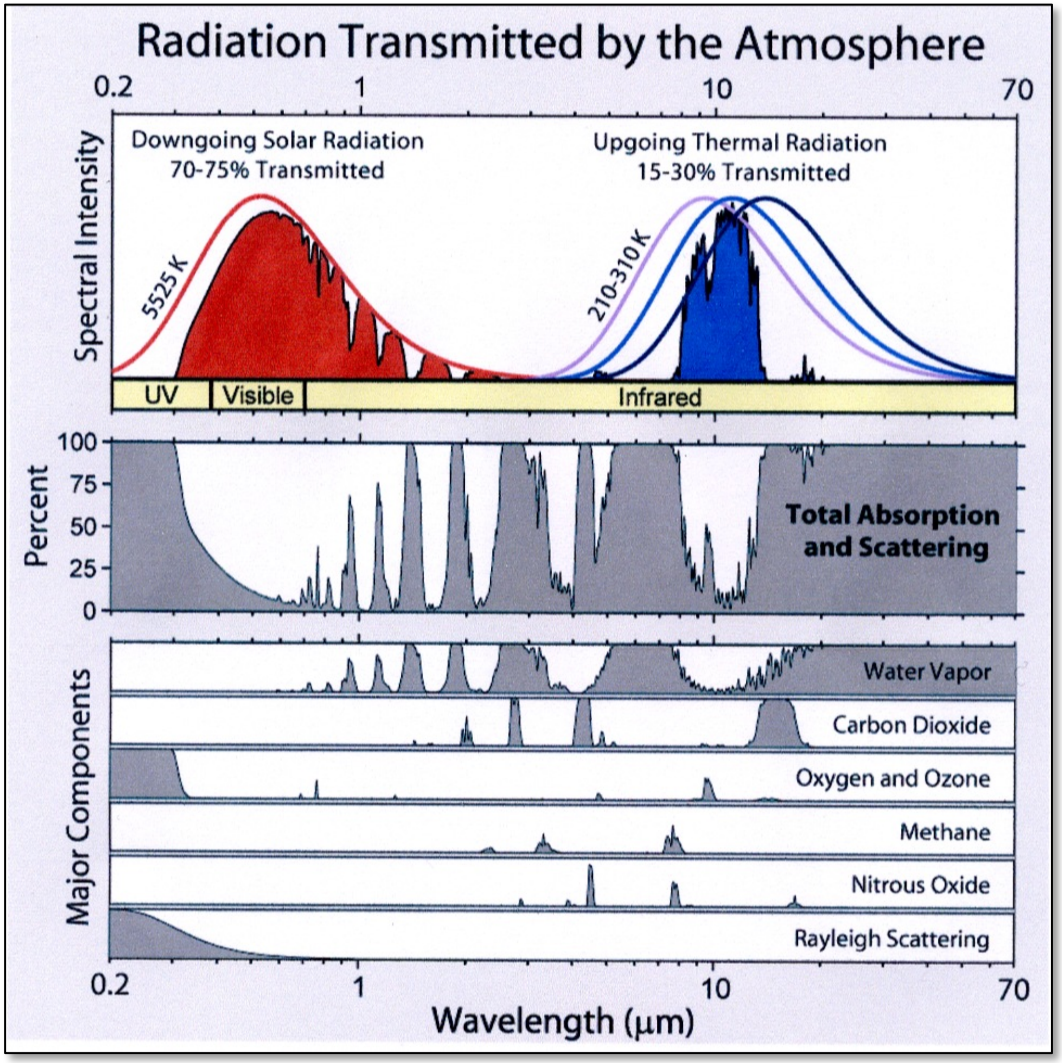
What are we missing?

- Although these estimates are sometimes in the right ballpark, they are not consistently accurate; the reason for this is that it does not take into account the fact that an atmosphere can absorbs some of the radiation that a planet gives off
- Most of the sunlight passes through the atmosphere, although some is reflected by the Earth's atmosphere, clouds, and surface (thus the albedo)
- The radiation emitted by the Earth can also be absorbed, or reflected back toward the Earth making the true temperature higher than in our simple estimate – this is known as the "greenhouse effect"



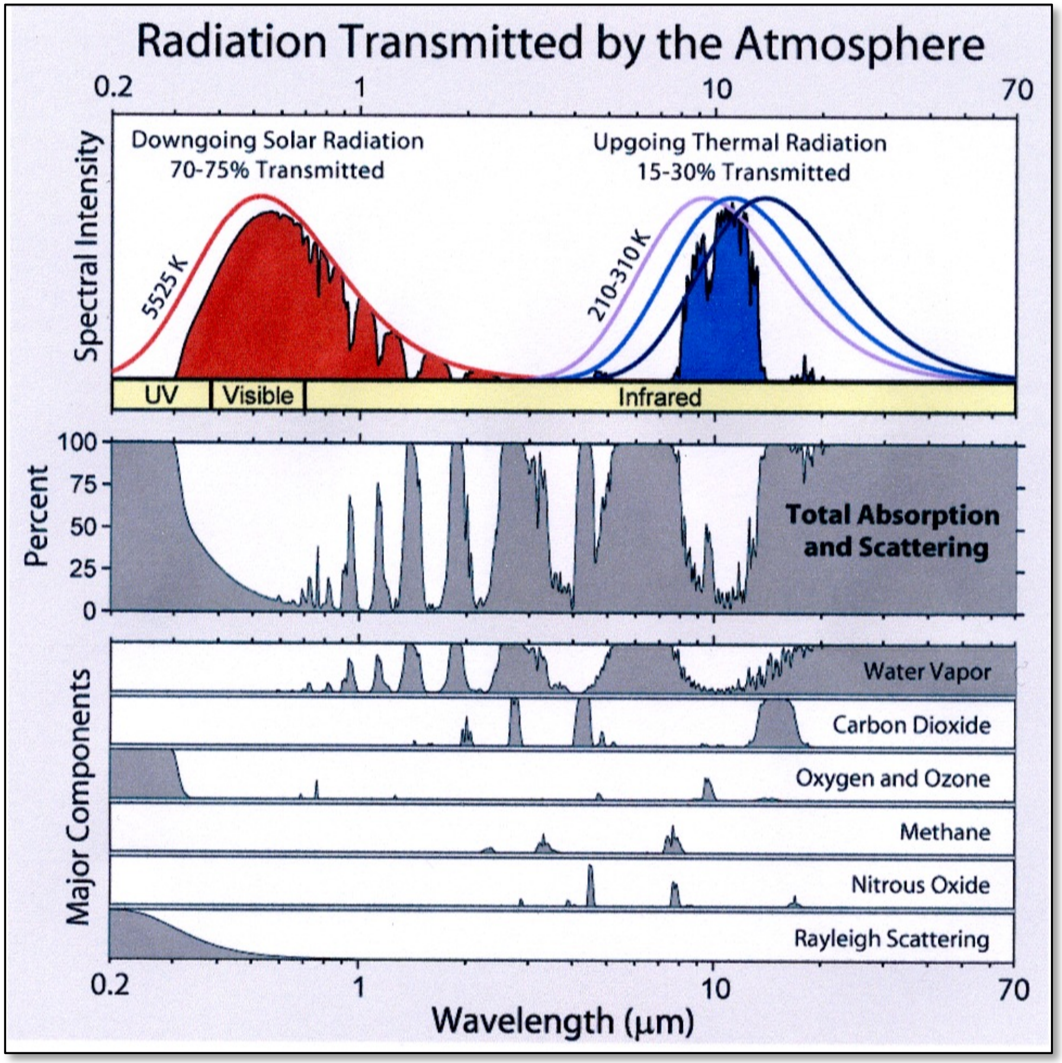
Greenhouse Gases

- The radiation given off by the Earth is mostly at infrared wavelengths; the fraction of this energy that is absorbed before escaping the Earth depends significantly on the chemical composition of the atmosphere



Greenhouse Gases

- The radiation given off by the Earth is mostly at infrared wavelengths; the fraction of this energy that is absorbed before escaping the Earth depends significantly on the chemical composition of the atmosphere
- Carbon dioxide (CO_2) is the most often discussed greenhouse gas, although water vapor (H_2O) and methane (CH_4) are also important greenhouse gases (water is a significantly stronger absorber than CO_2)



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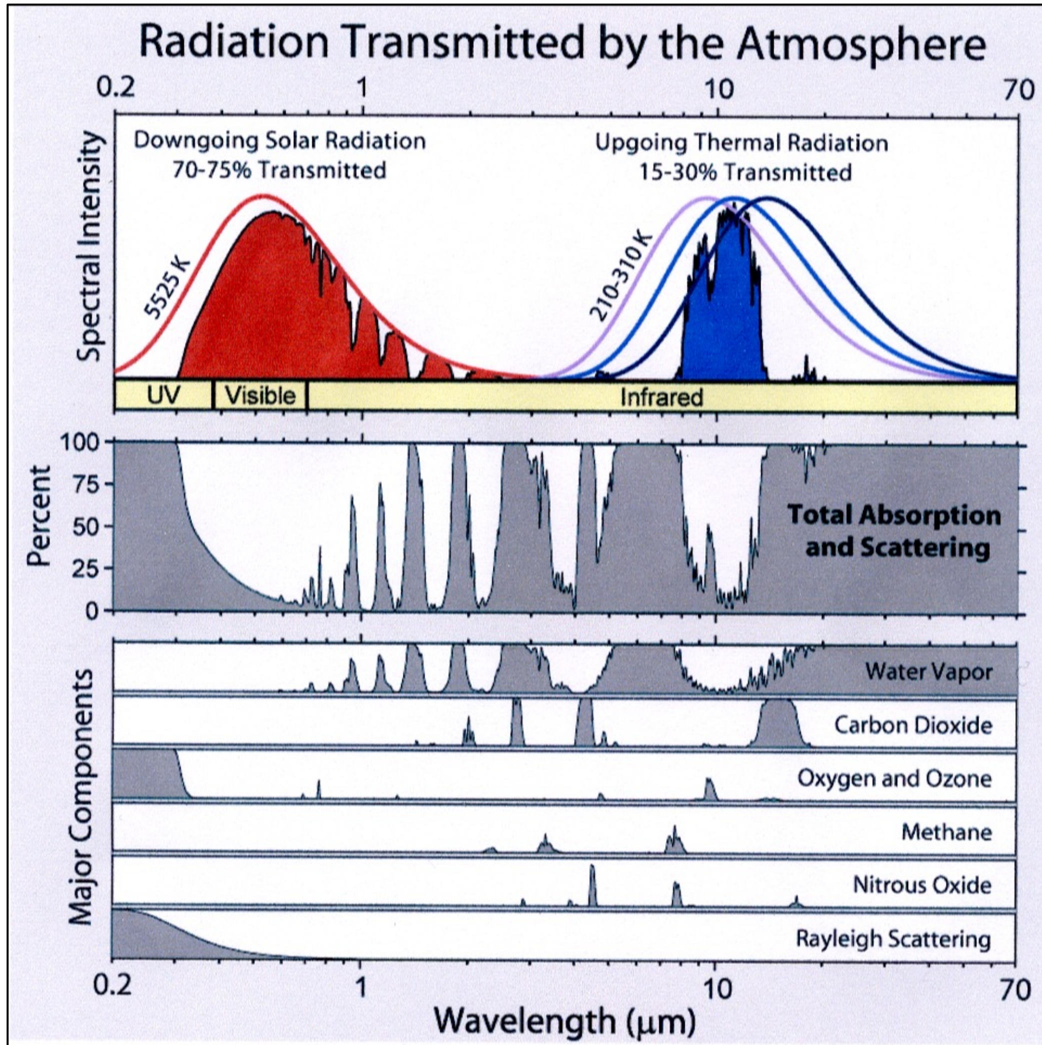
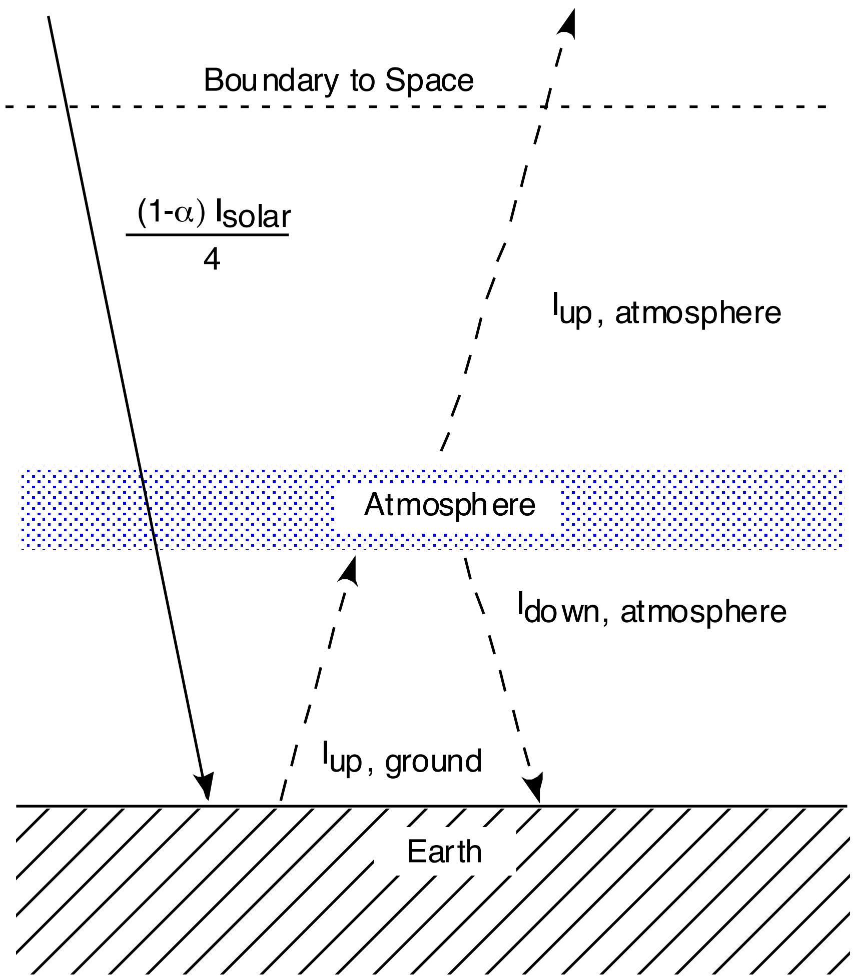


Question: Why don't we usually discuss H_2O as a greenhouse gas?

The Greenhouse Effect



- The Greenhouse Effect was first described in 1827 by Joseph Fourier
- In 1859, John Tyndall discovered that CO_2, H_2O, O_3 and CH_4 are important greenhouse gases, while O_2 and N_2 are not
- Clouds, dust, convection (winds) and stratified temperatures all complicate the real atmosphere, but this is the basic picture

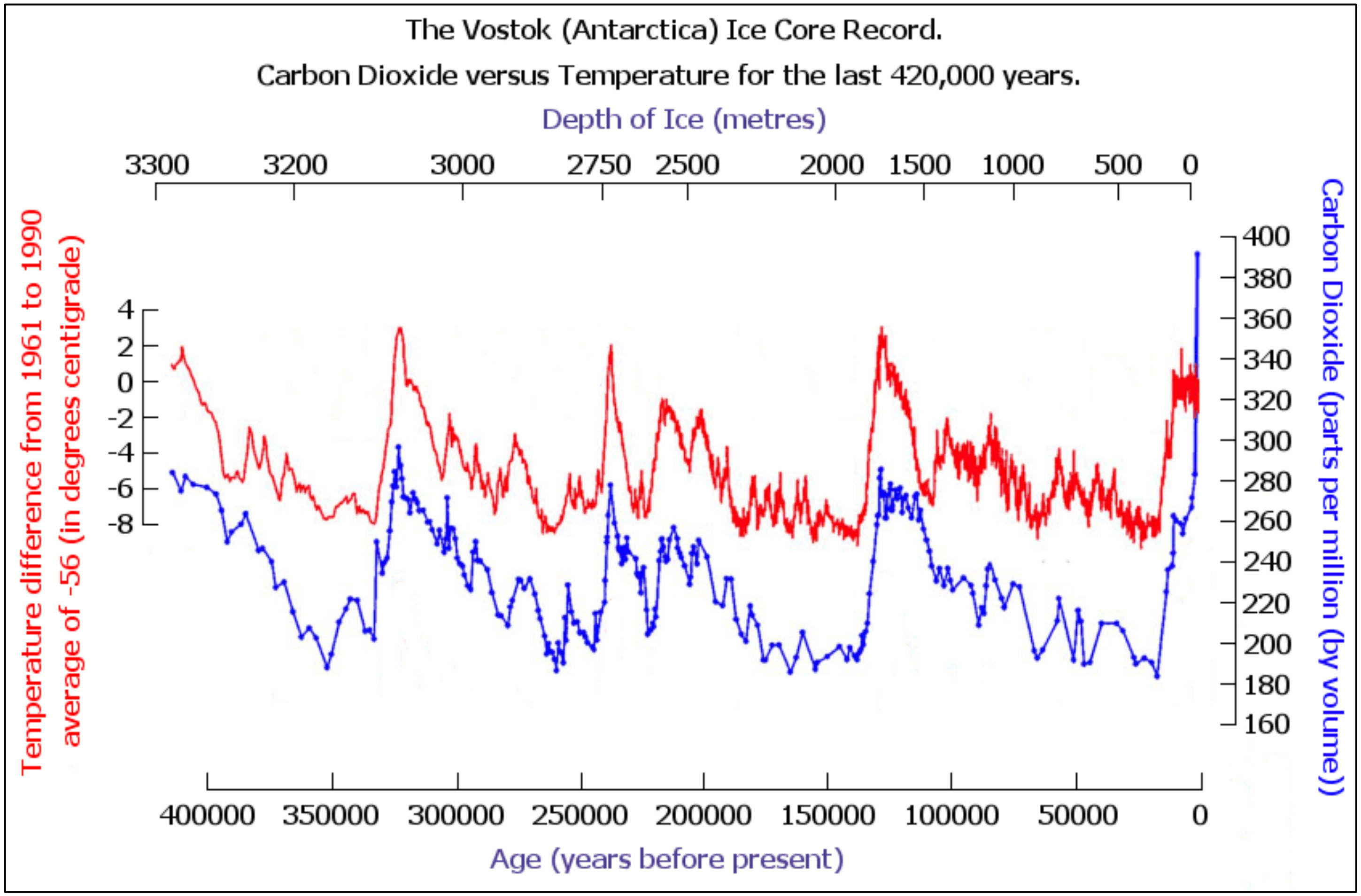
The Connection Between The Earth's Atmosphere and Climate Is Not A New Idea

(predicted in 1896 by Nobel prize winner Svante Arrhenius)

".. any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4° …"

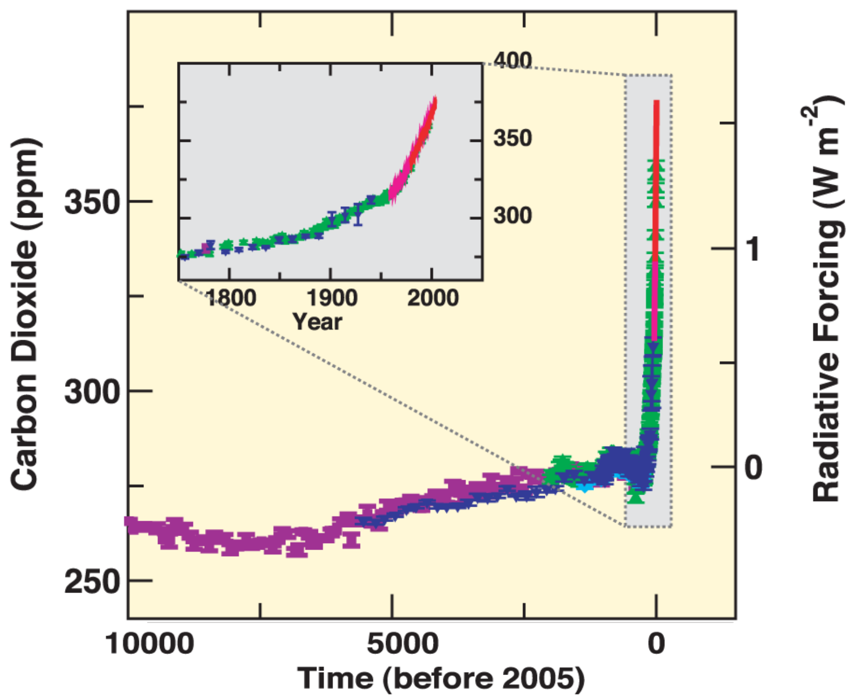
(His predictions are approximately valid today: Doubling of CO_2 is expected to raise temperatures by between 2.5 and 4 degrees)

The Data Show a Clear Connection Between CO_2 and Global Temperature

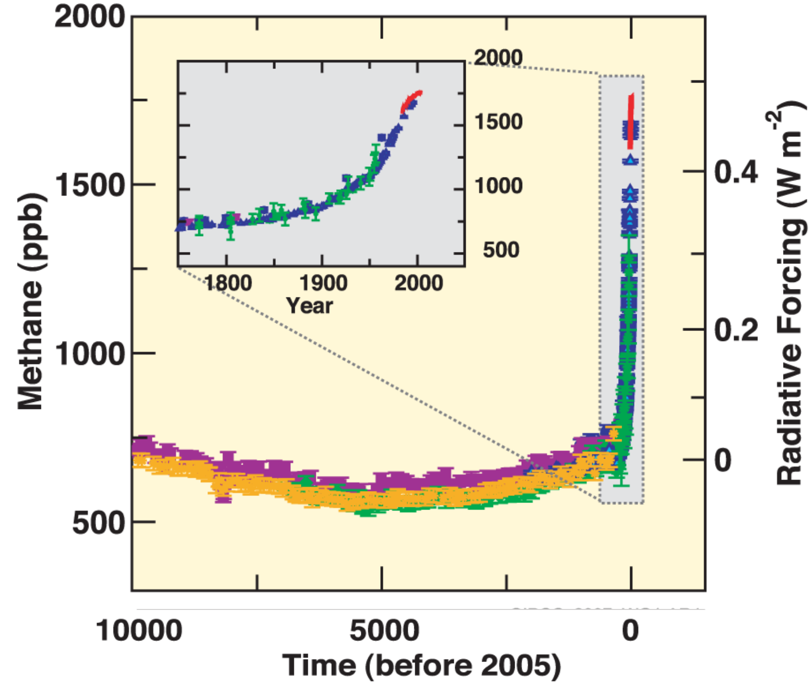


Temperature derived from an O^{18}/O^{16} Isotope ratio proxy

Recent Changes In Atmospheric CO_2 Levels



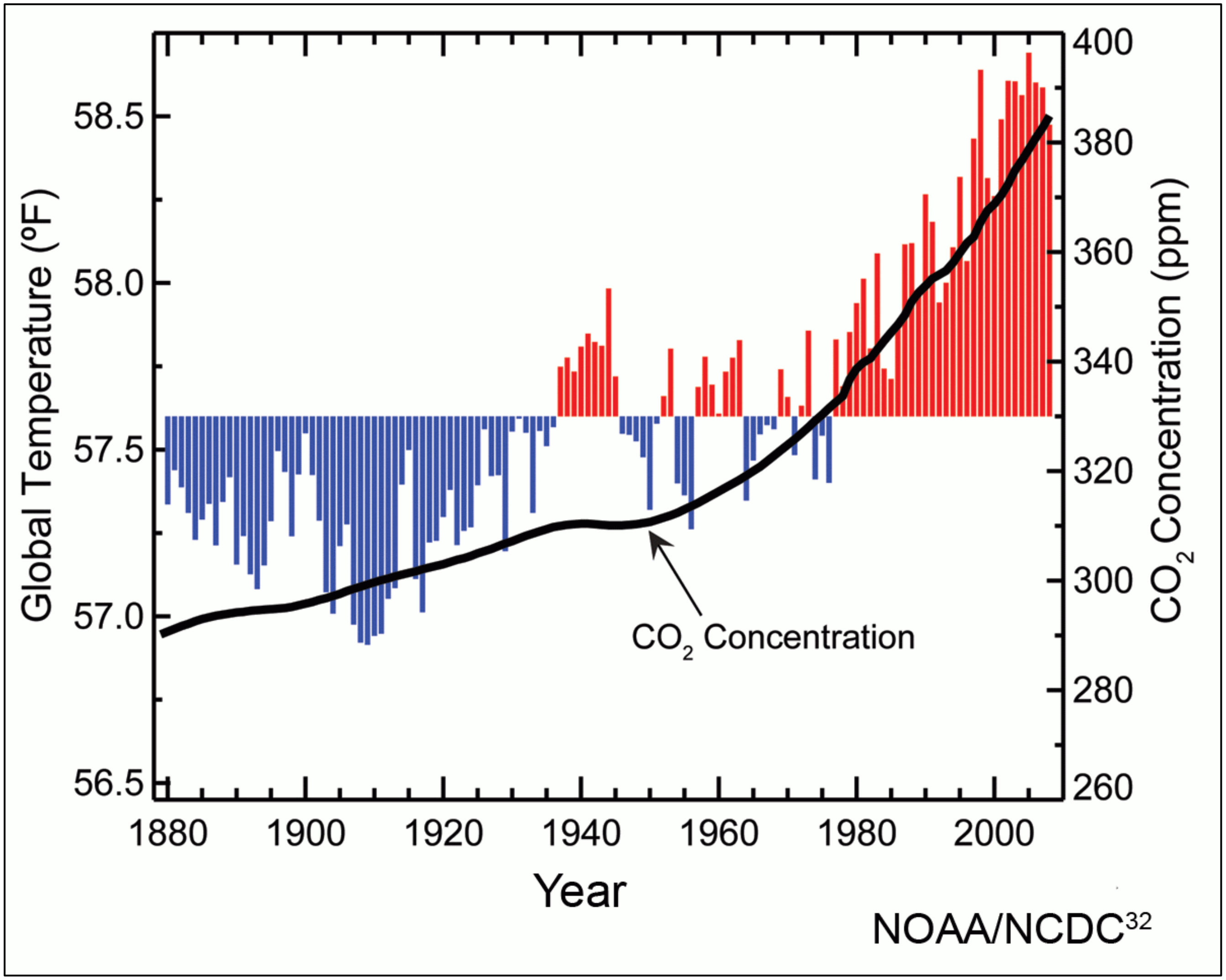
CO_2



CH_4

Source: IPCC AR4

Recent Temperatures Reflect This Change



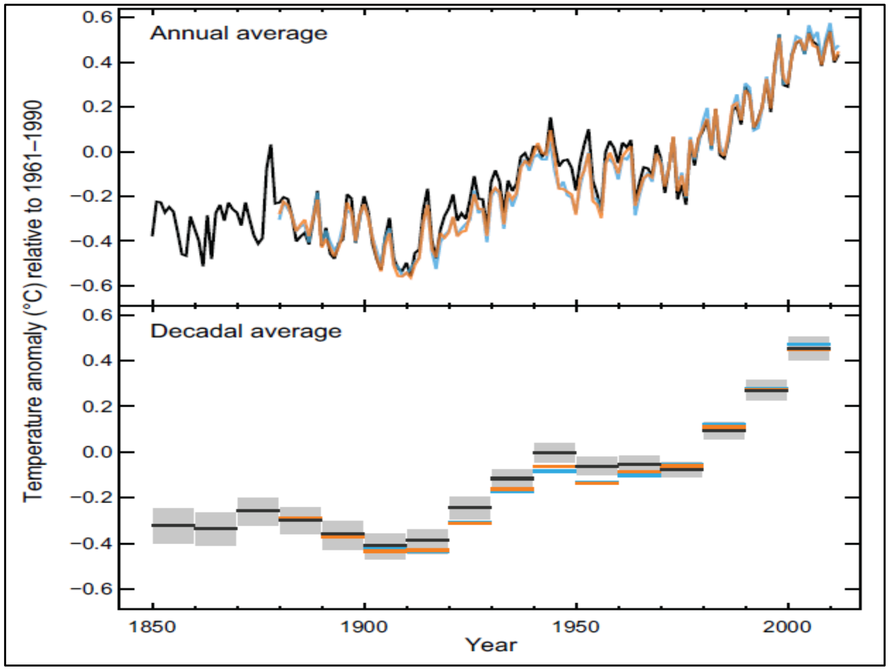
Impacts of a Warming Planet

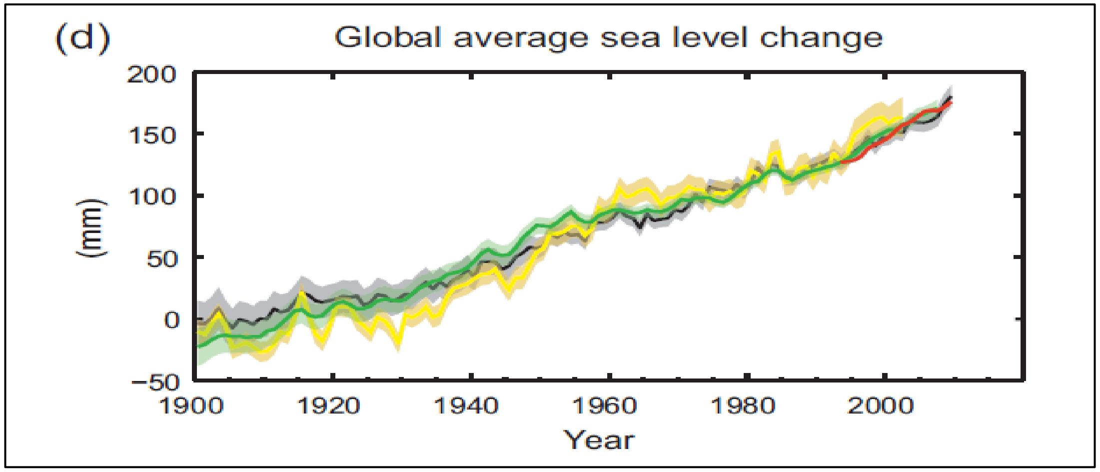
- Rising sea levels
- Melting of Arctic/Antarctic ice
- Glaciers retreating
- Increasing rate of severe droughts, floods, fires
- Plant and animal habitats are changing

Changing Sea Levels

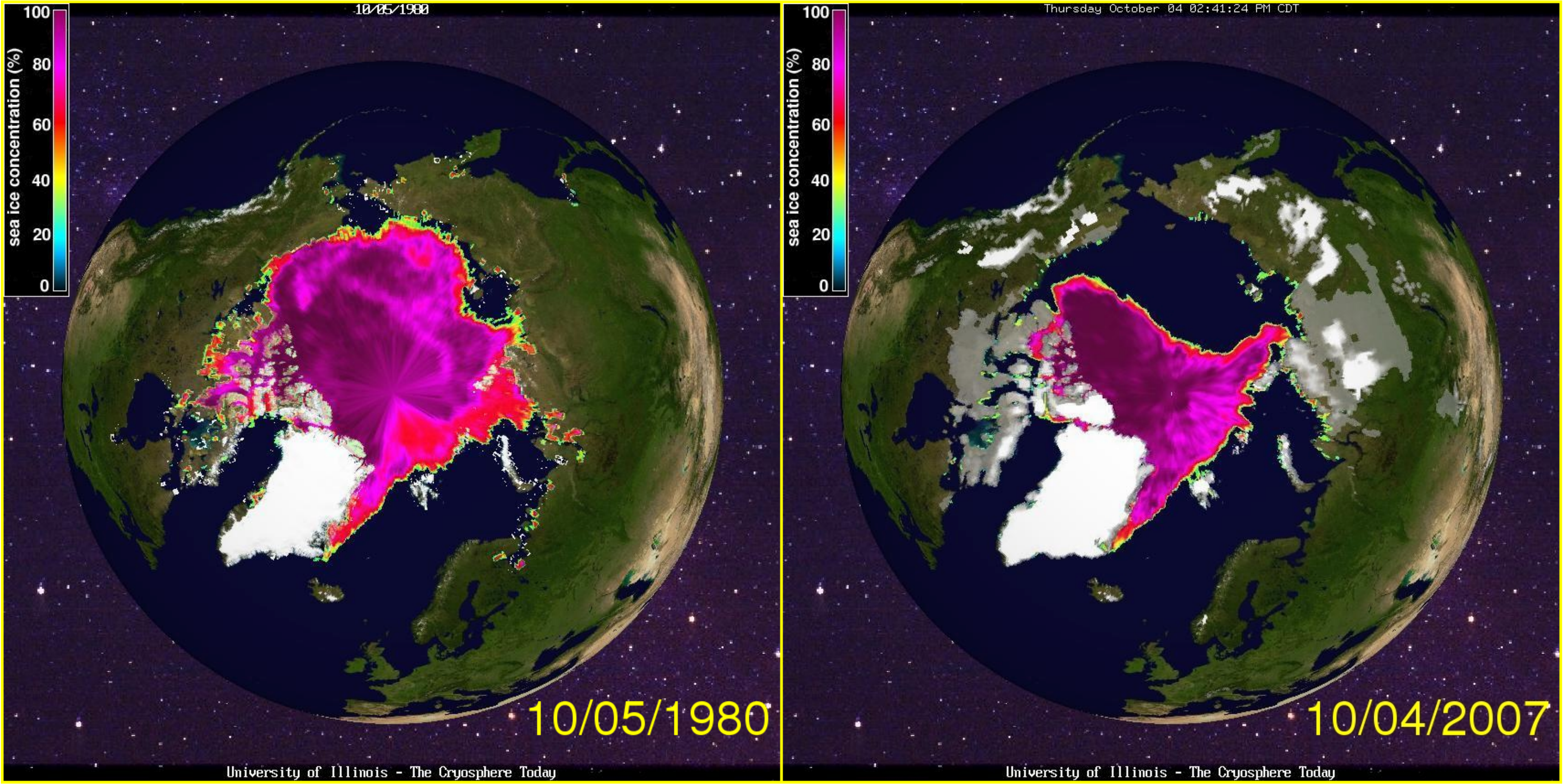
- Since industrialization, the average temperature of the Earth's oceans has increased by about ~1^{0}C
- Heating water causes it to expand (about 1.5x10^{-4} per ^{0}C at 15 ^{0}C)
- As a simple estimate, we should expect sea levels to have risen: (1x10^3 m) x (1.5x10^{-4}) ~ 0.15 m

(sidenote: below 1000 m, oceans are much colder, and thermal expansion is negligible)





Melting Arctic Ice (satellite view)

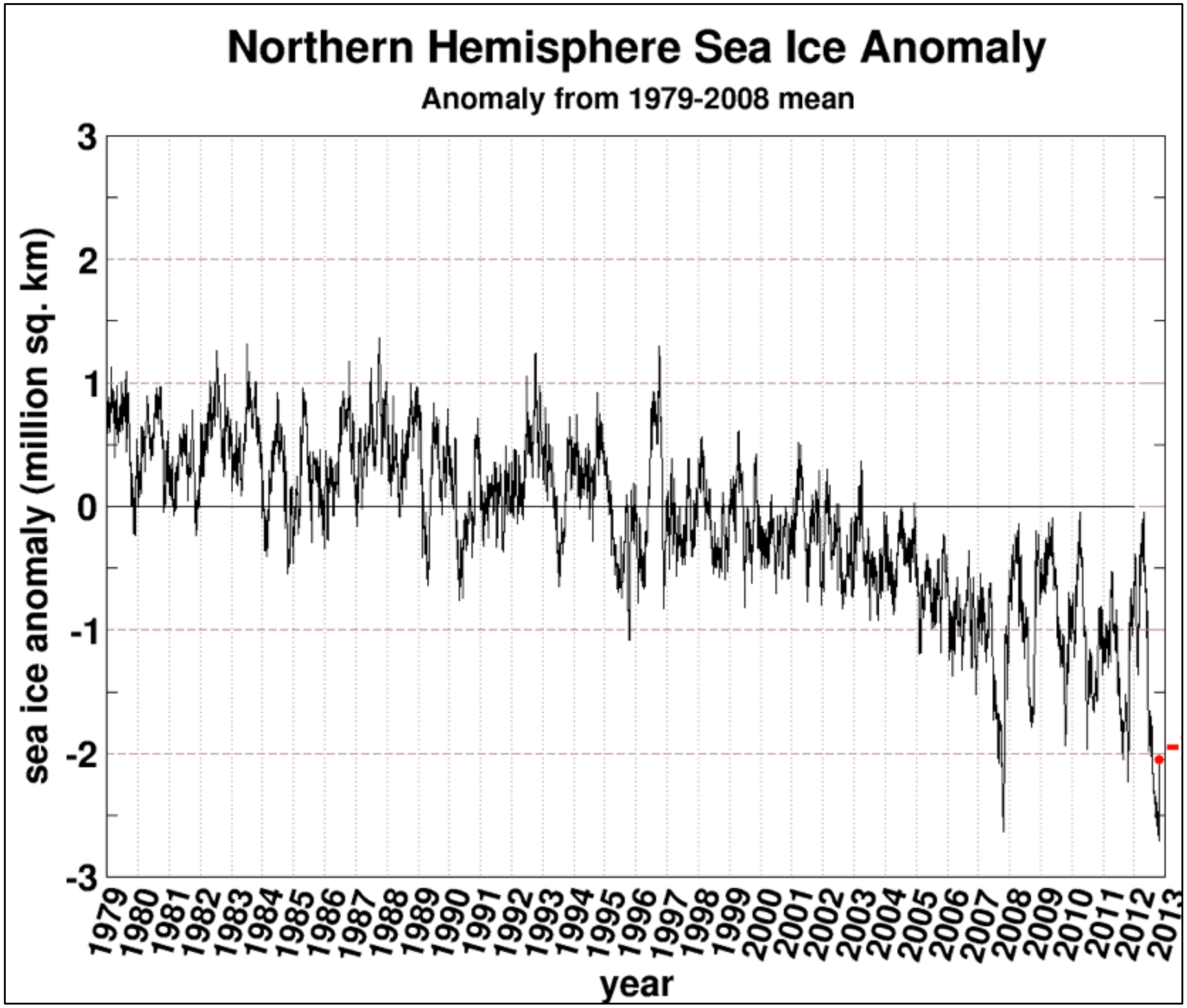


We are rapidly transitioning to a permanent state without arctic ice

And while most of the sea level rise is due to the warming of the ocean, melting ice sheets also contribute

Melting ice also changes the Earth's albedo, further exacerbating climate change

Melting Arctic Ice



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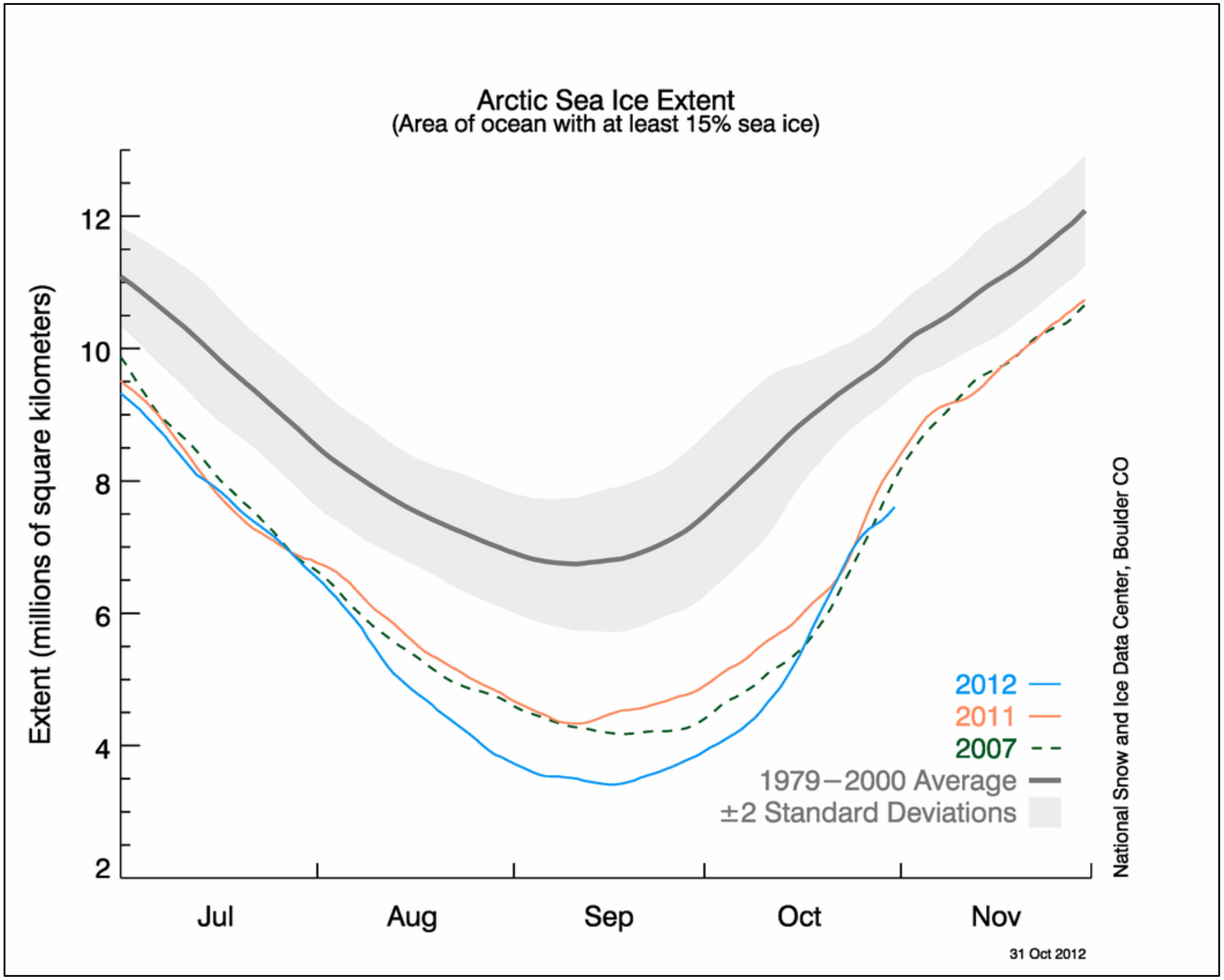
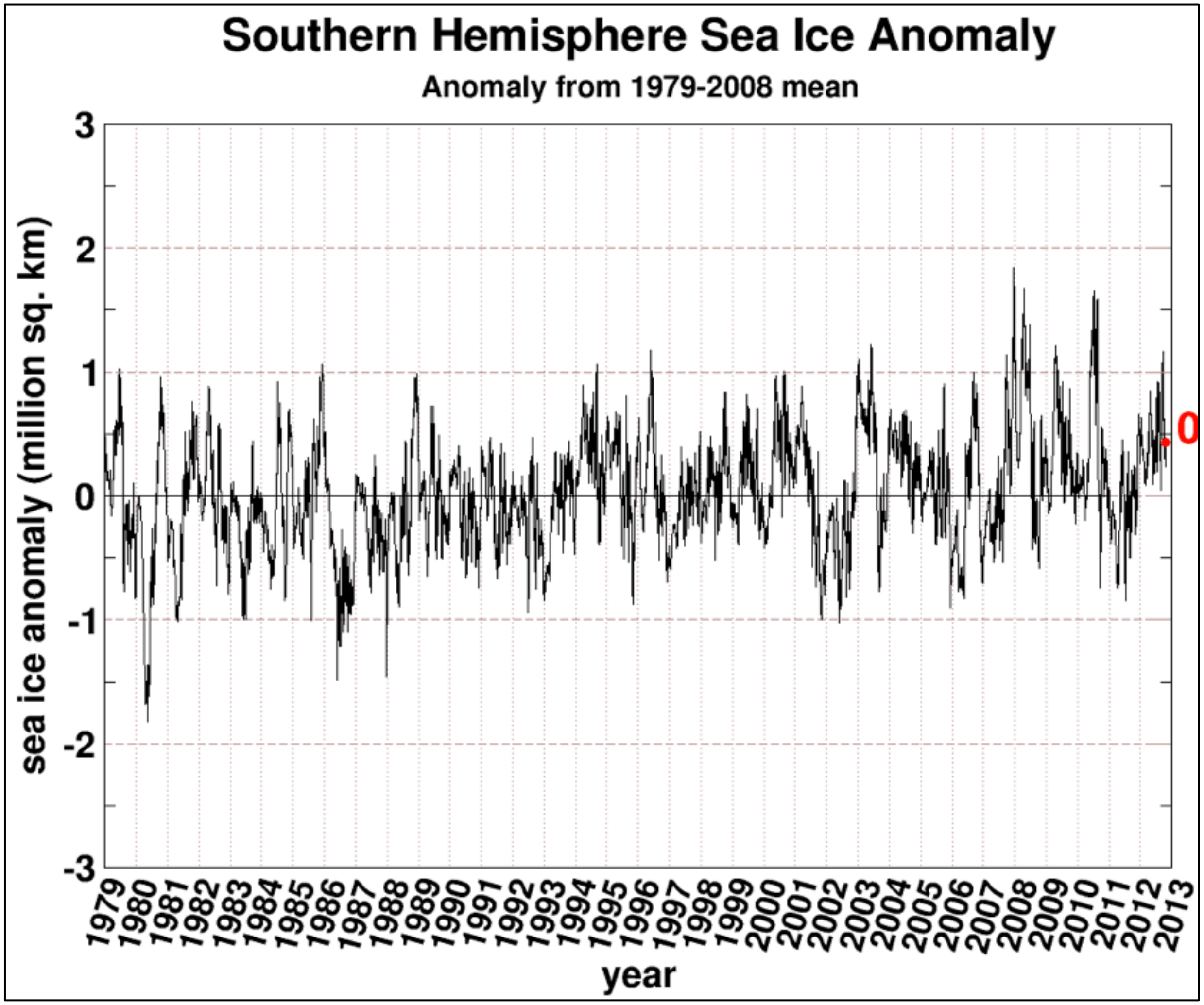
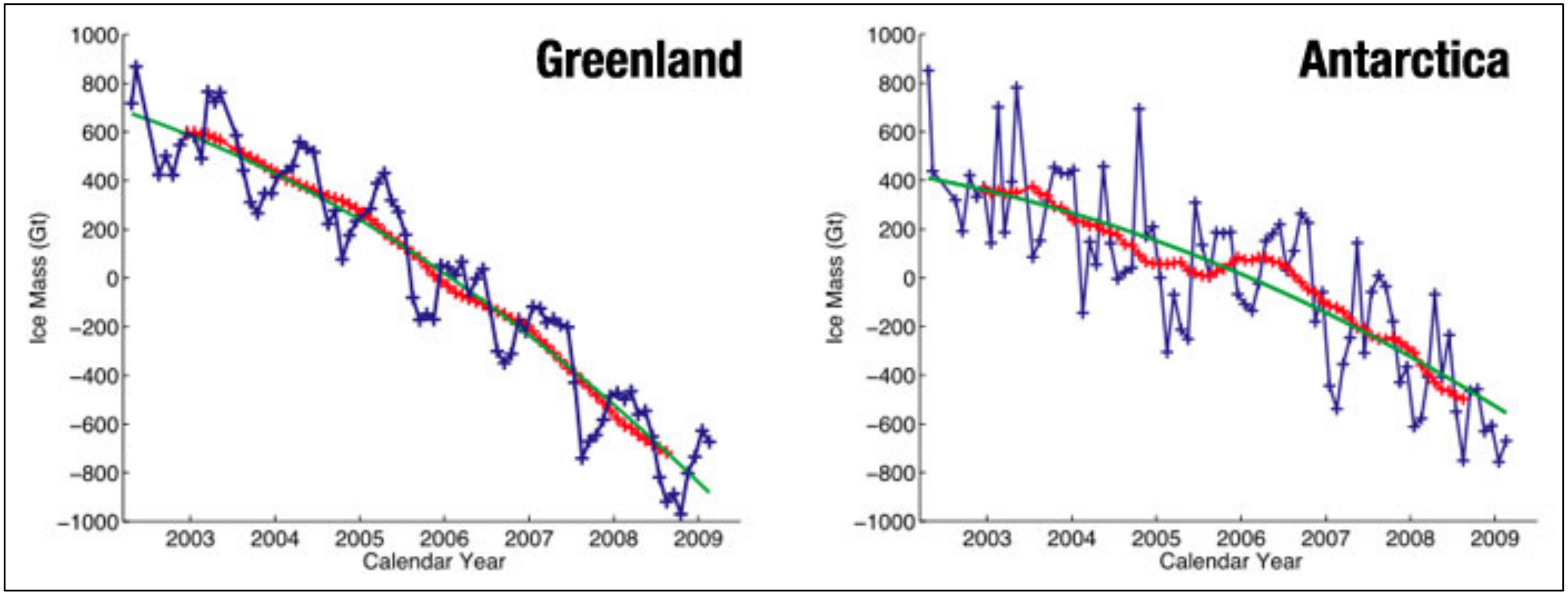


What About Antarctic Ice?



What About Antarctic Ice?

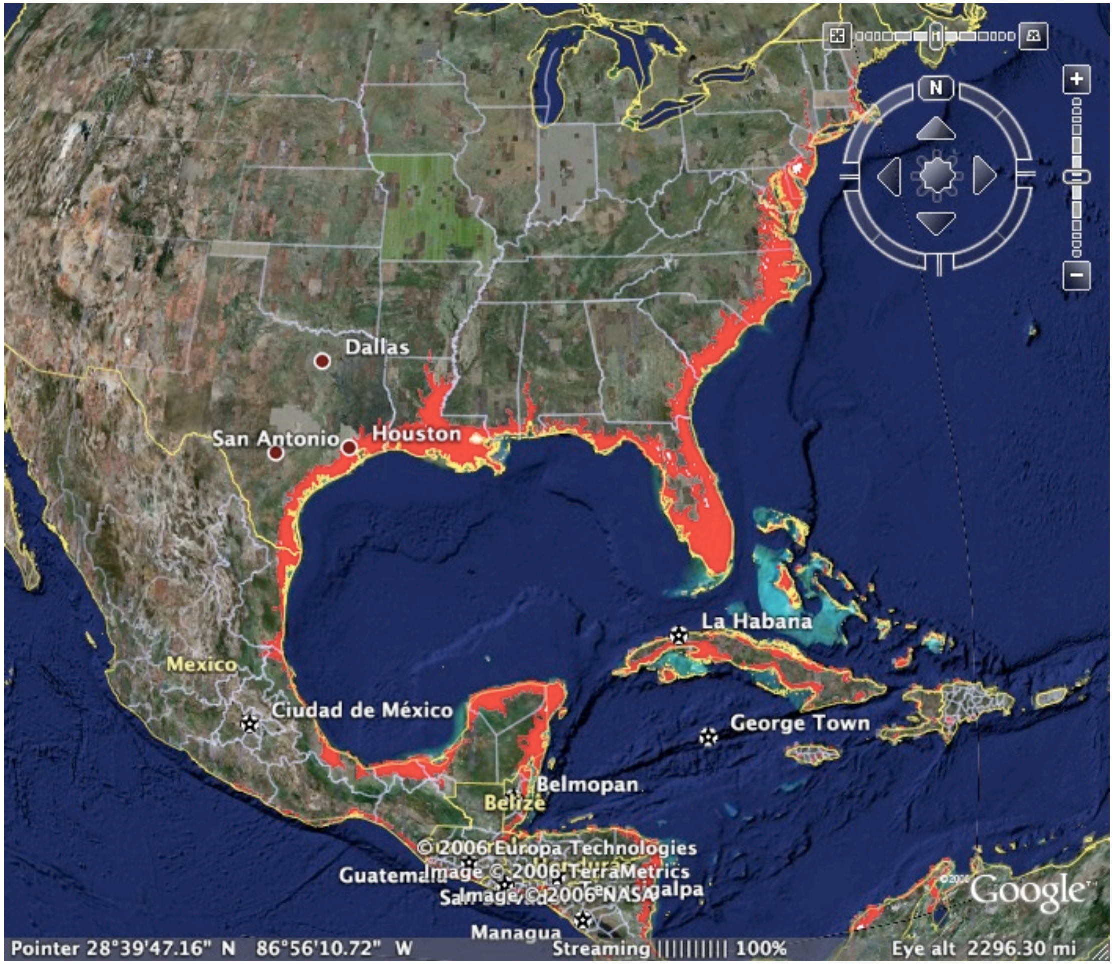
- When considering ice melt, its important to consider not only surface area, but also volume:



- The rate of mass loss is similar for all three of Earth's major ice sheets

(data from GRACE, a pair of polar orbiting satellites)

Map After 20 Meters of Sea Level Rise



Recall that sea levels are currently rising at about 3 mm/yr
20 meters will take a long time (6000 Years at present rate)

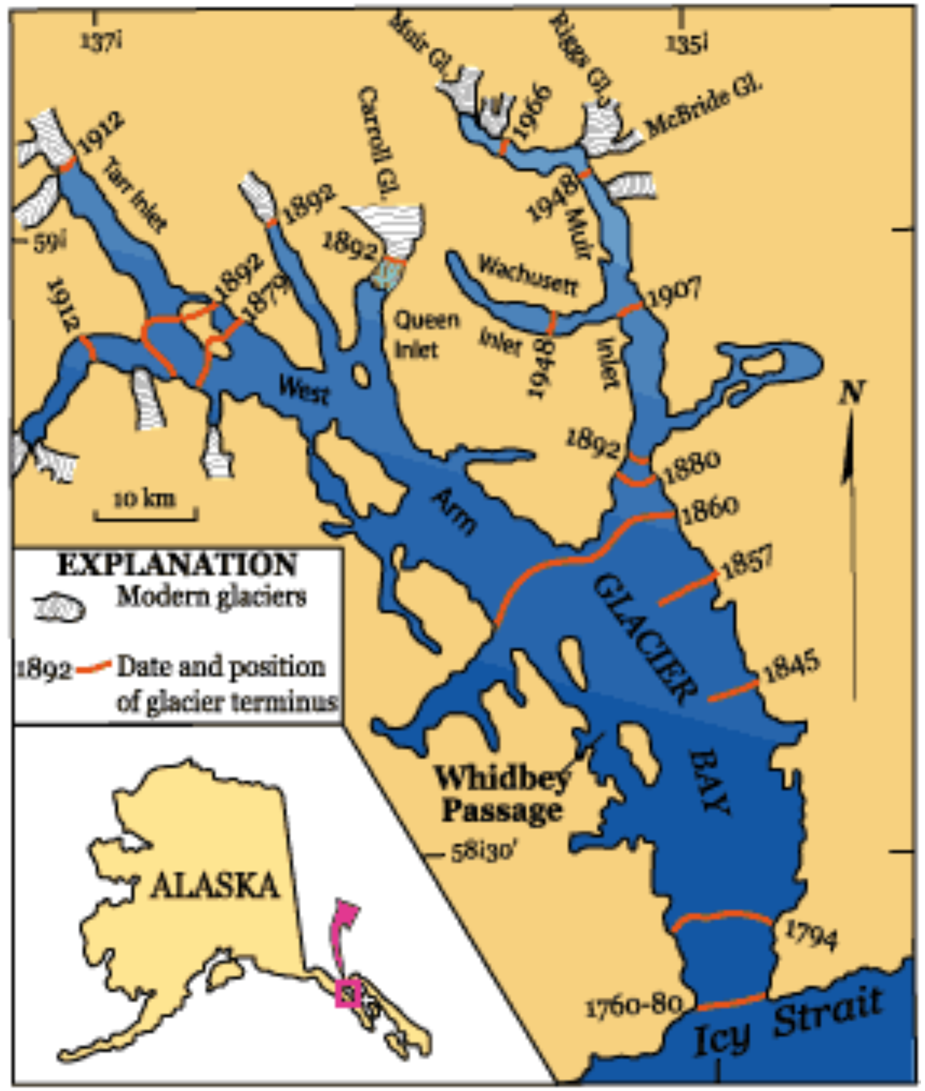
Retreating Glaciers

- View of the Whitechuck Glacier in Glacier Peak Wilderness (North Cascades, Washington State)

- Retreated by ~2 km

Retreating Glaciers

- Glacier Bay, Alaska
- The fastest retreating glacier observed directly by humans



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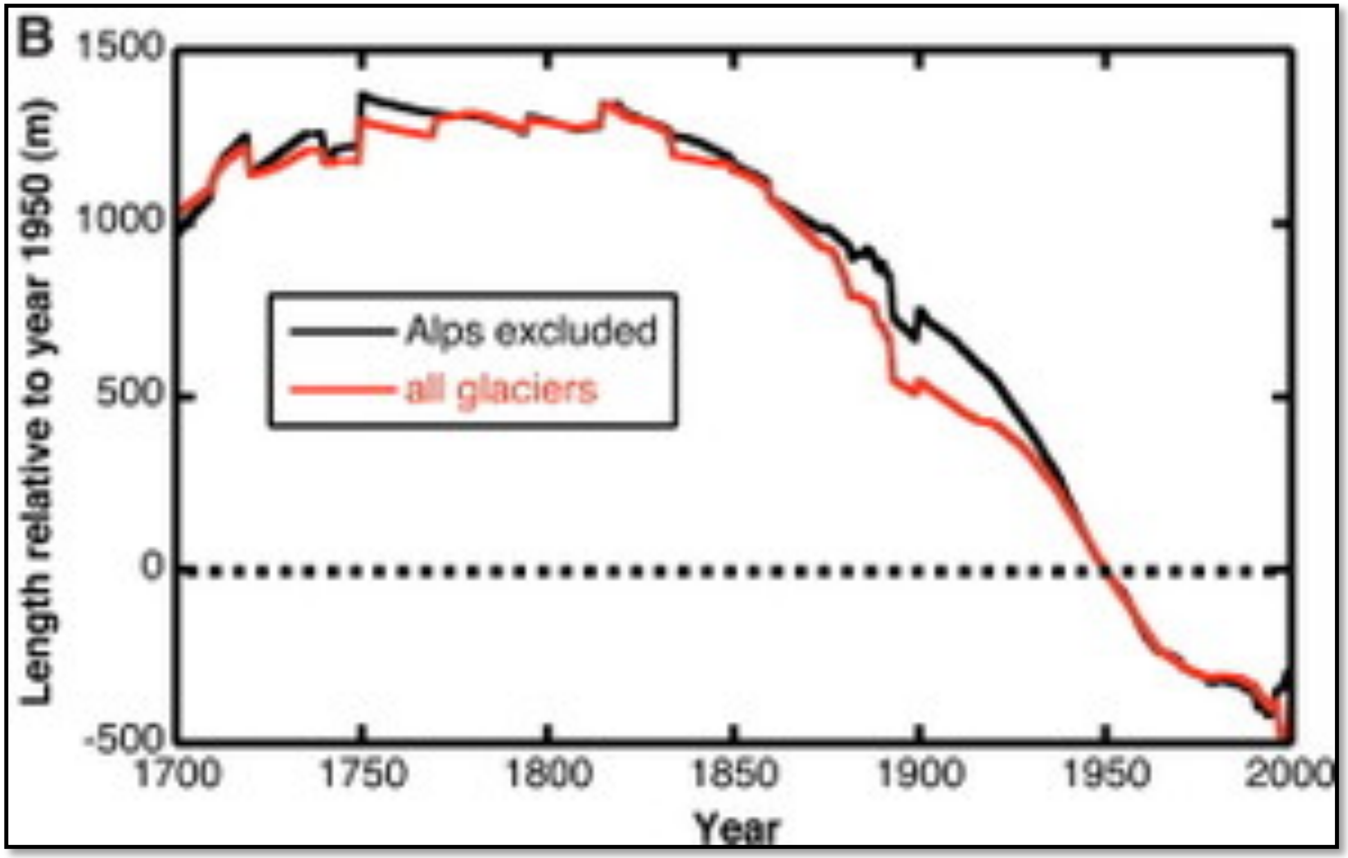
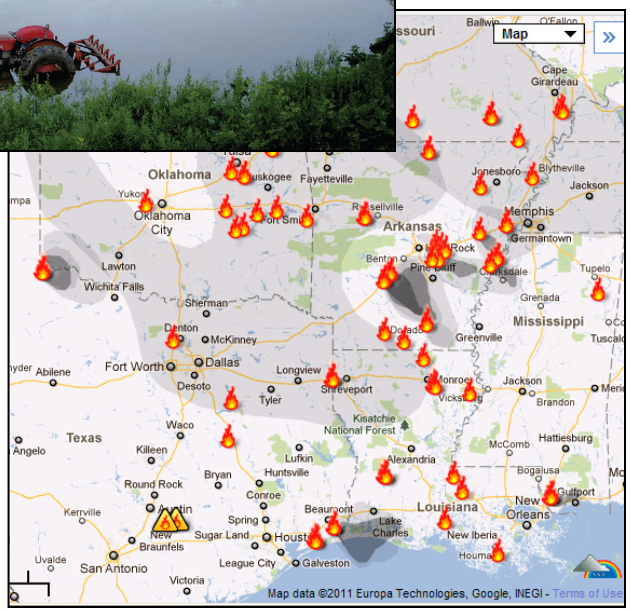


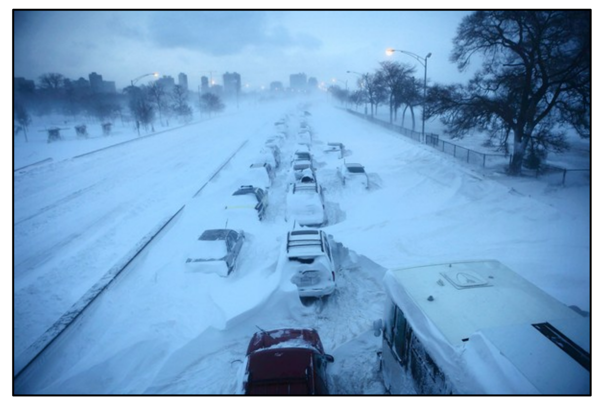
Rate and Severity of Storms, Droughts, Fires, etc.

Record floods in the Midwest



Record temperatures/droughts: 1,554 homes destroyed in Texas wildfires (2011)

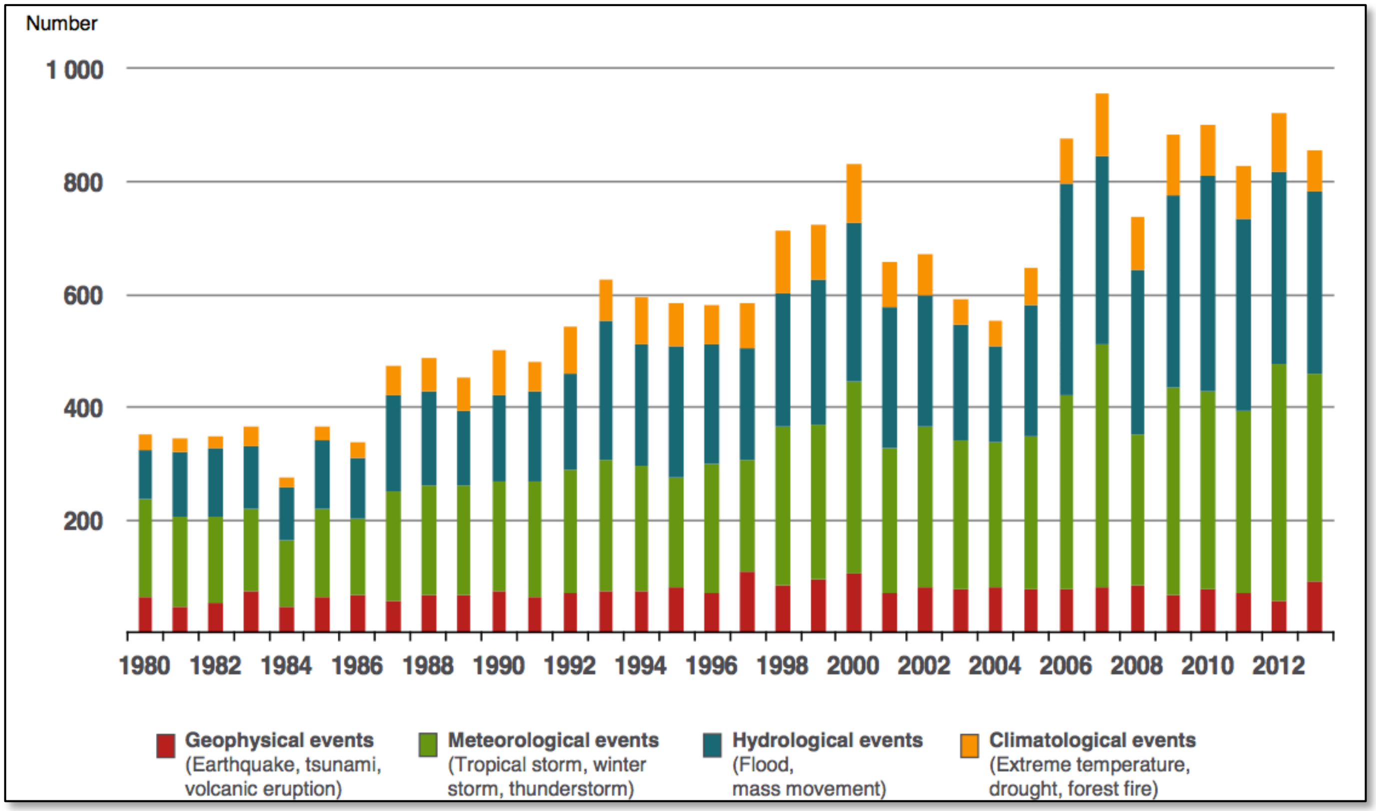
Record-breaking river flooding swamps New Jersey



Record snowstorms in the east (and Lakeshore Drive!)

Rate and Severity of Storms, Droughts, Fires, etc.

- On a case-by-case basis, it is difficult to associate severe weather events with long-term climate change
- That being said, modern climate models generally predict that the number of extreme weather events will increase as a result of climate change



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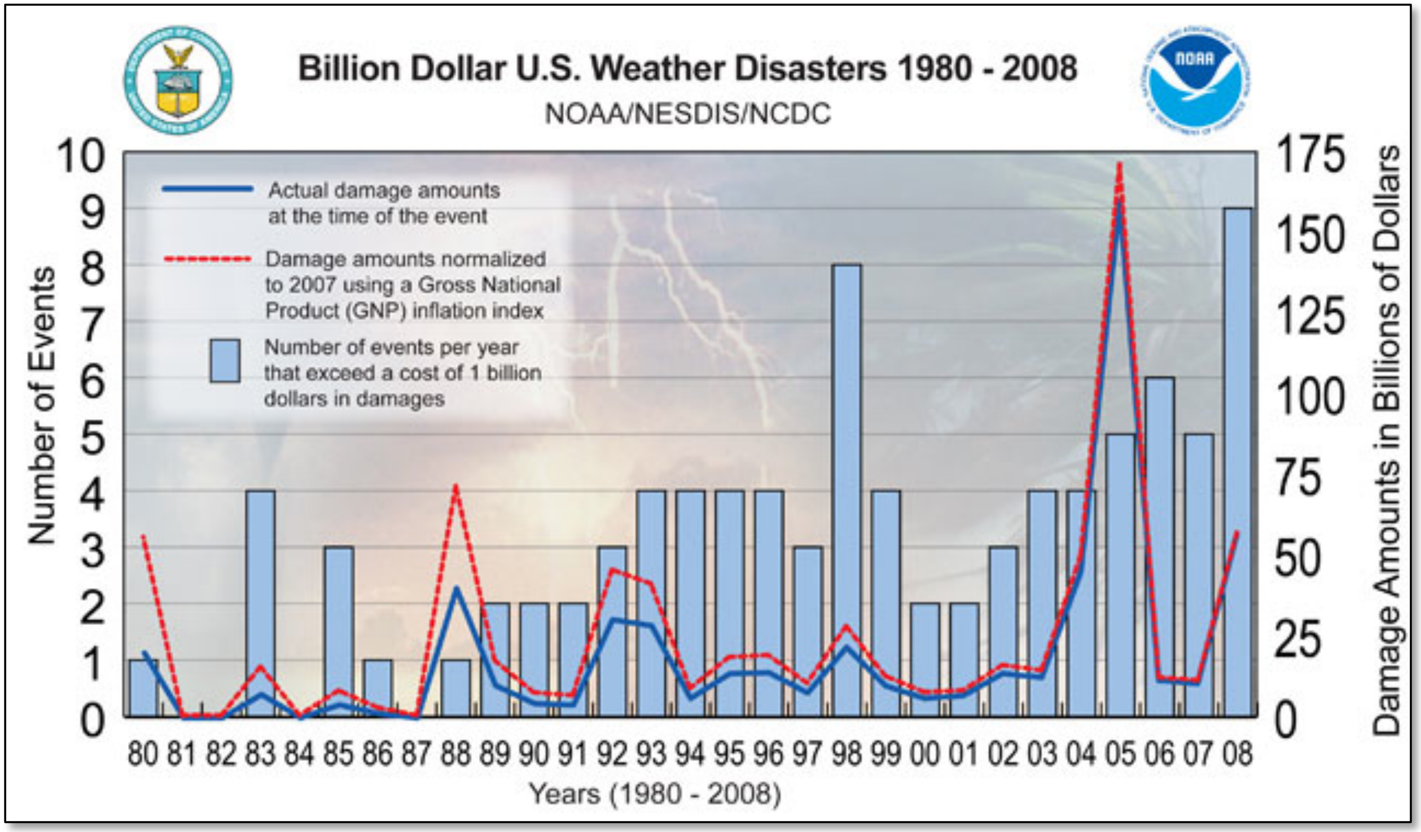
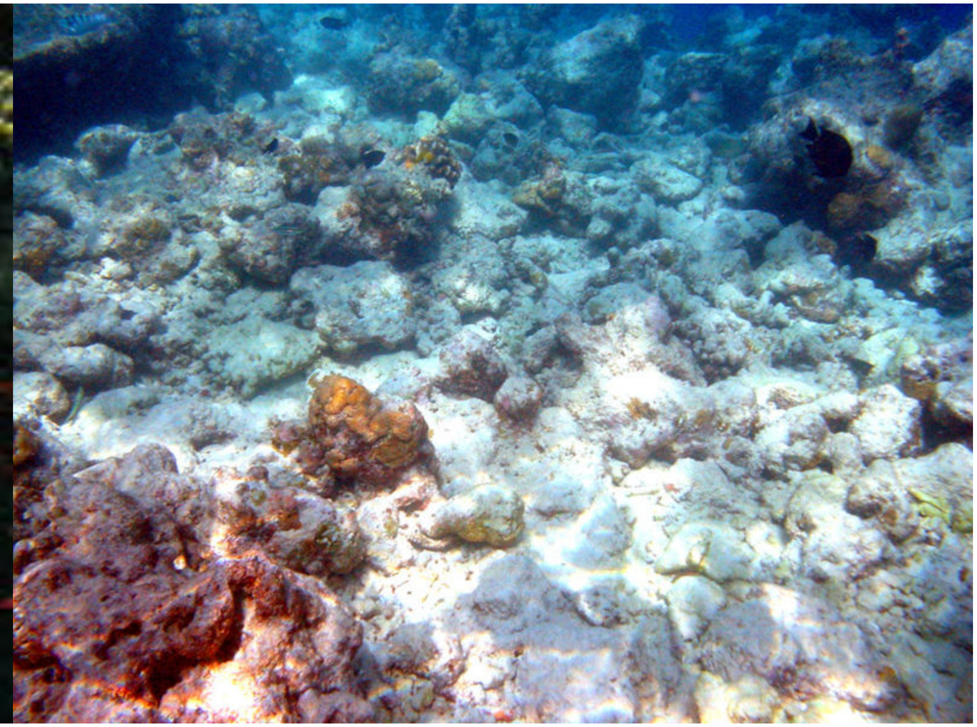


Changing Habitat: Coral Reefs

Healthy corals



Bleached corals

Australia experienced its warmest year on record in 2005. High sea temperatures caused massive coral bleaching in the Great Barrier Reef.

The IPCC 2007 report predicts (with 80% probability): the Great Barrier Reef is at grave risk and will be "functionally extinct" by 2030,

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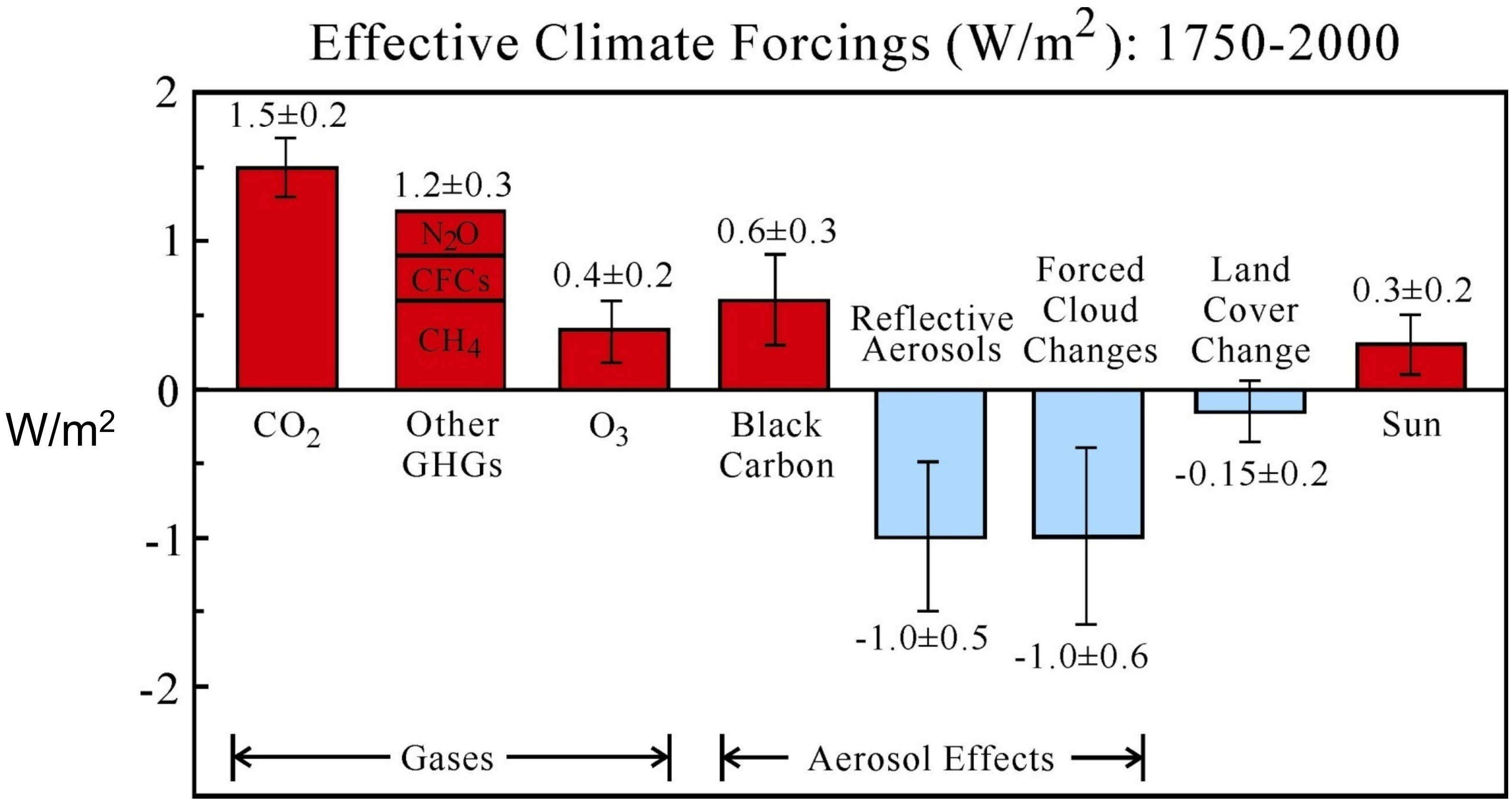


Total = 1.85+/-1.0 W/m²

Much more work is needed to reduce the +/-1.0 error bars!

(Note: Average sunlight intensity is 340 W/m²)

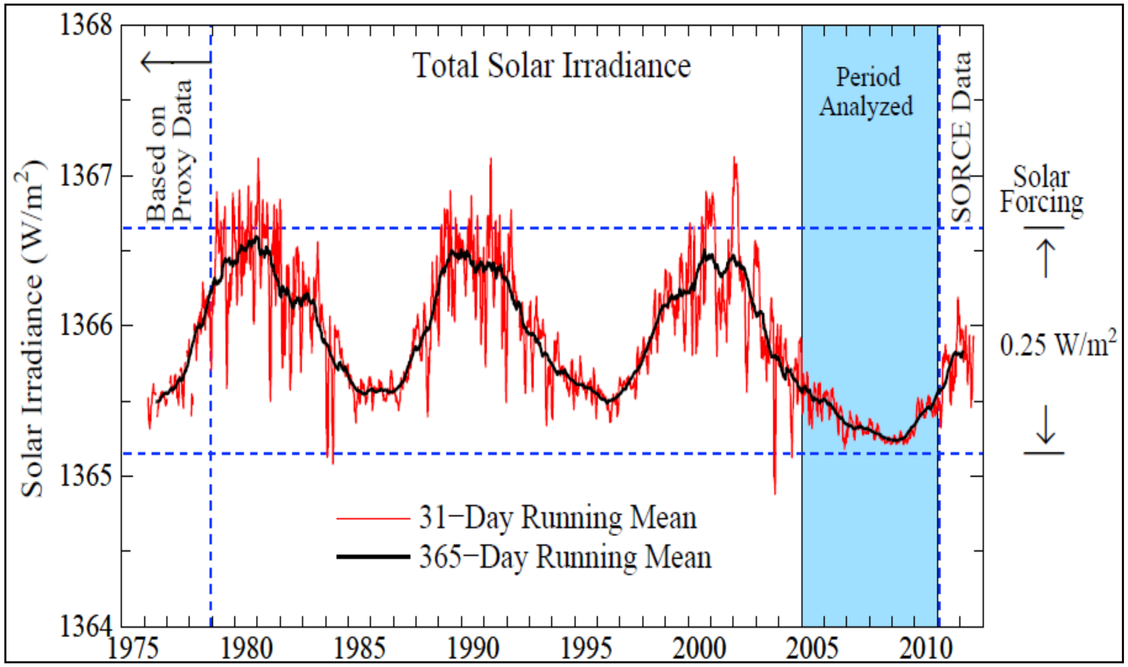
Are Greenhouse Gases the Only Thing That Can Change The Earth's Climate?

1) Variations in Solar Intensity

-Sunspots and other factors lead to variations in the intensity of sunlight

-These variations are small (~0.25 W/m^2, or about 10% of that from GHGs)

-They take place over timescales of a few years, and average out over many decades



Are Greenhouse Gases the Only Thing That Can Change The Earth's Climate?

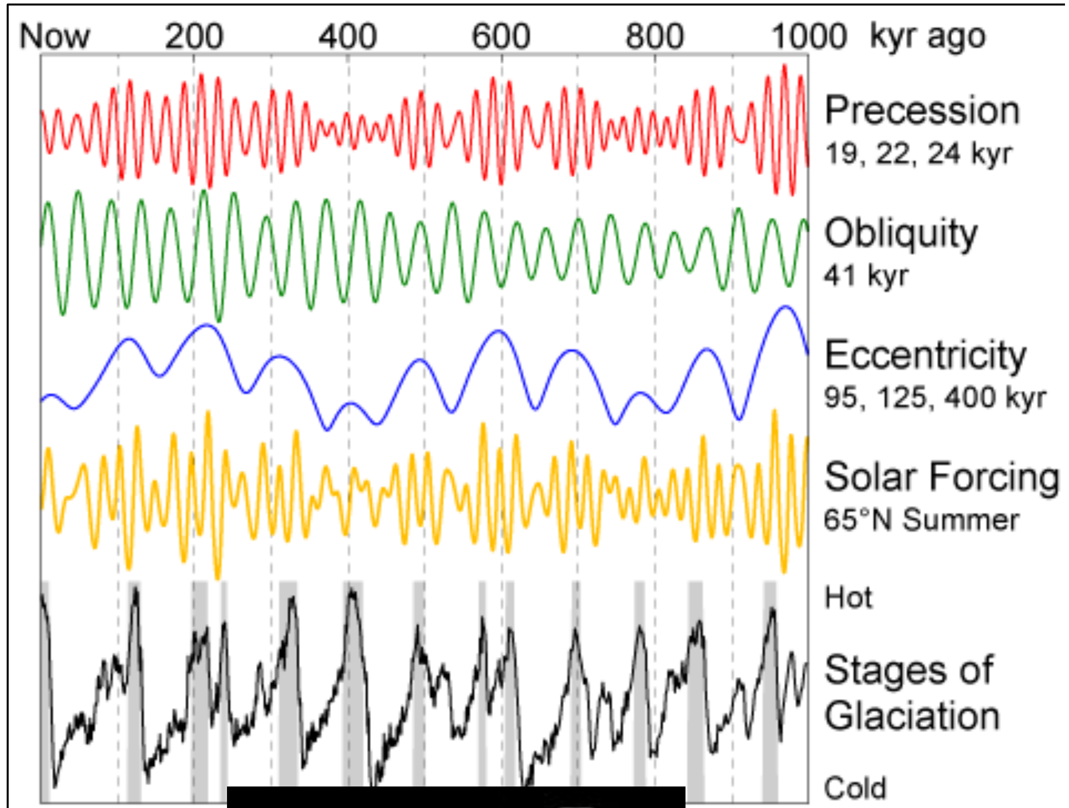
2) Milankovitch Cycles

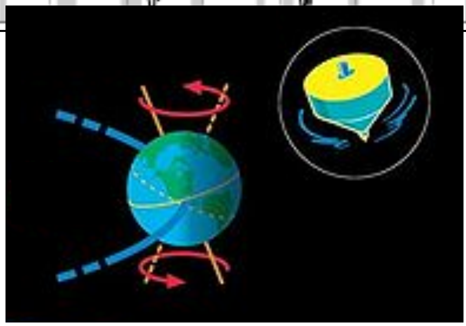
-The axis of Earth's orbit precesses (like a top) over a period of 20,000 years or so

-This affects the average intensity of sunlight hitting the Northern Hemisphere

-Variation of about 15 W/m^2, corresponding to about 2° C

-This is further amplified by the resulting change in Earth's albedo (more ice) and the increased absorption of CO_2 into the cooling oceans → periodic ice ages



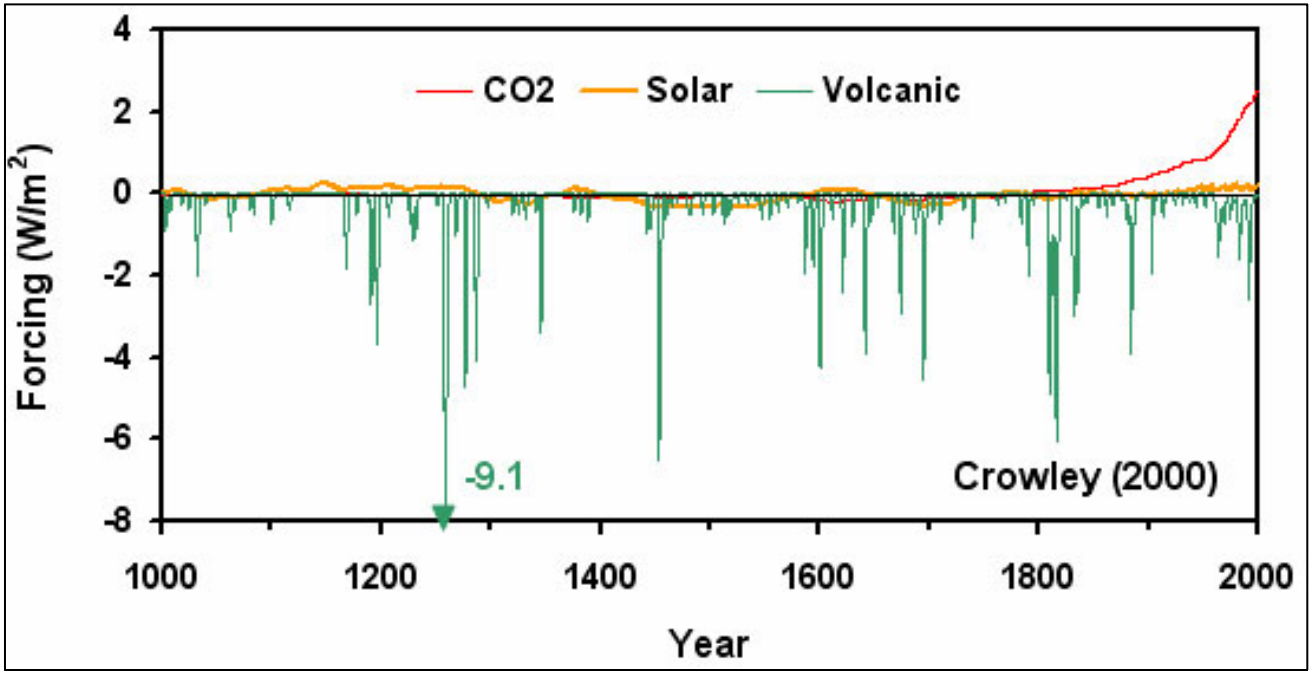


Are Greenhouse Gases the Only Thing That Can Change The Earth's Climate?

3) Volcanic Activity

-Volcanic dust is an "aerosol", and can have a powerful cooling effect if present in Earth's atmosphere

-Such effects are very short term, however, as aerosols fall out of the atmosphere within ~1-2 years

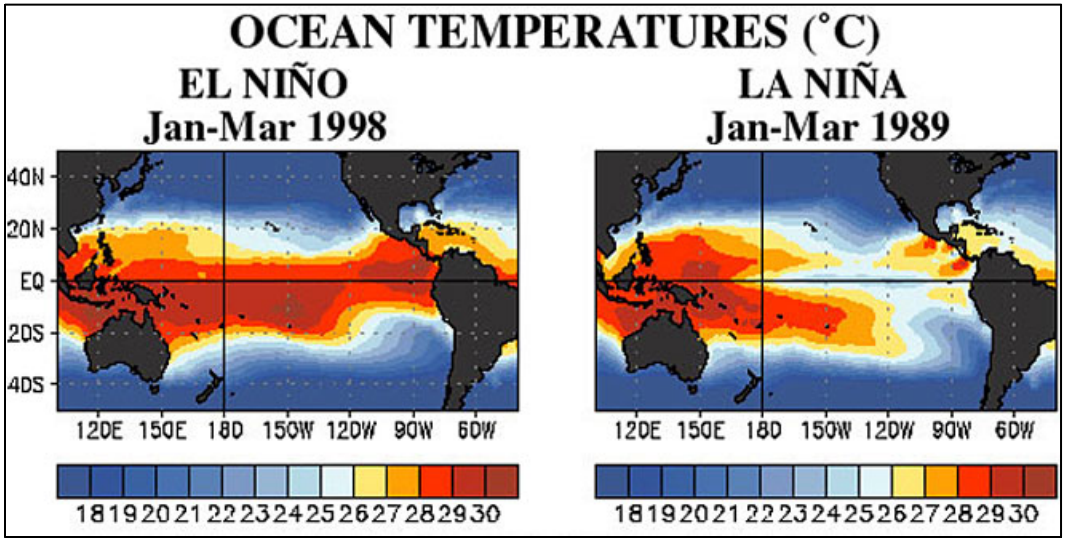


Are Greenhouse Gases the Only Thing That Can Change The Earth's Climate?

4) El Nino/La Nina

-High atmospheric pressure in the western Pacific causes heat flow eastward (La Nina is the reverse)

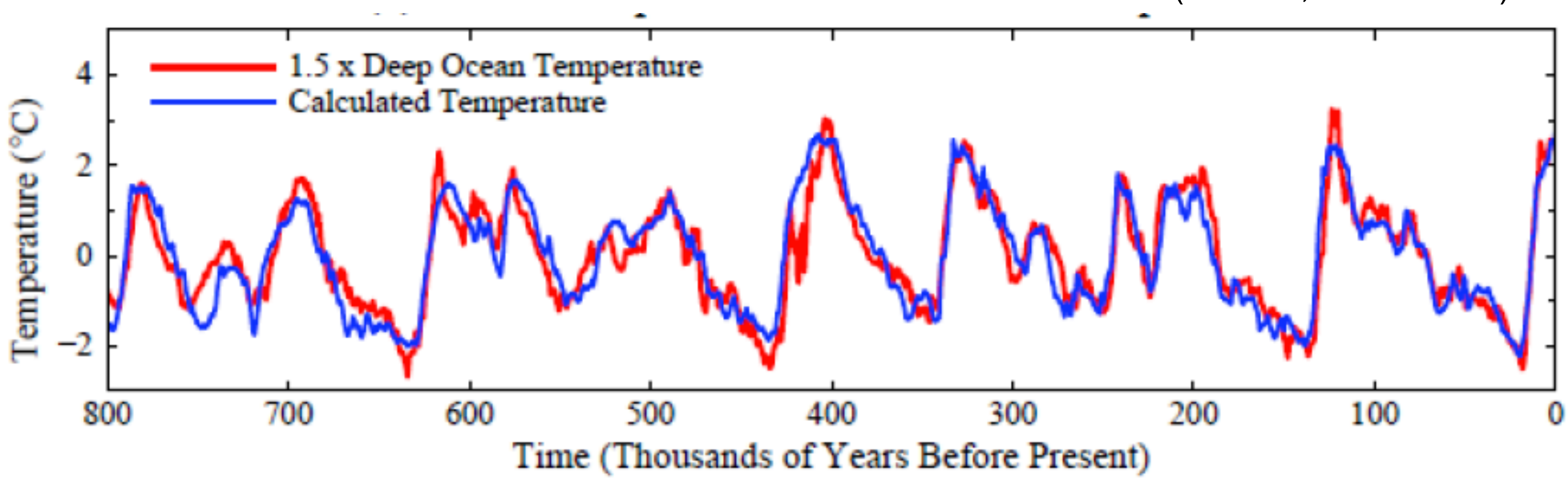
-Moves heat around, no net change in average global temperatures



Are Greenhouse Gases the Only Thing That Can Change The Earth's Climate?

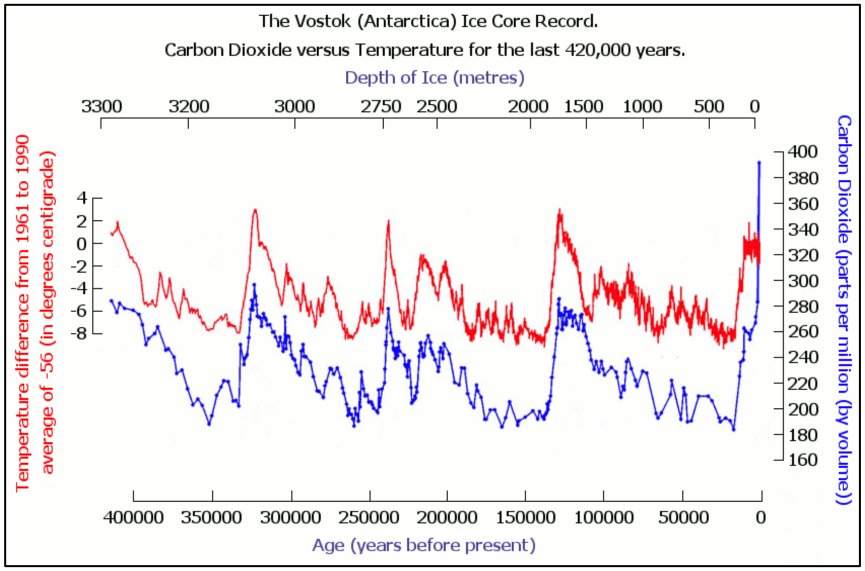
- Modern climate calculations and simulations take all of these effects (and others) into account
- These models agree very well with past data, are have been successful at predicting our changing climate in recent years

(Hansen, Sato – 2011)



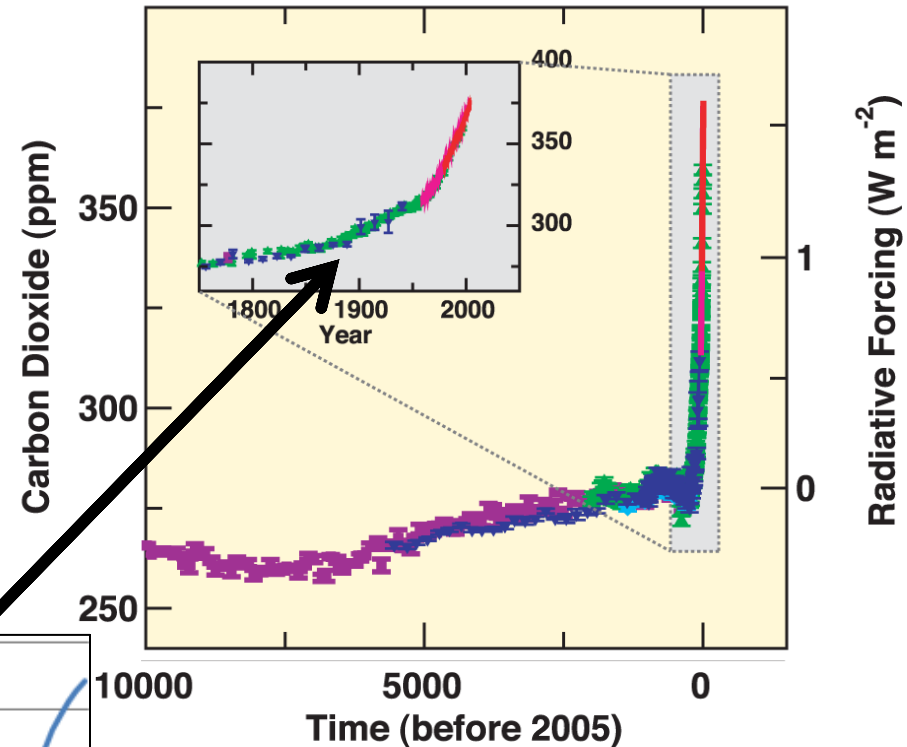
The Connection Between Climate and Human Activity

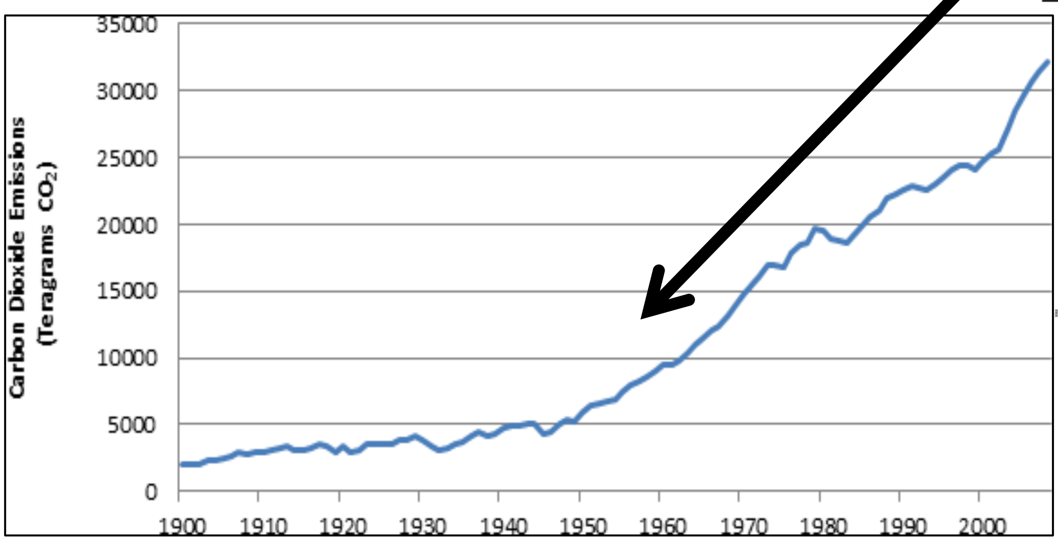
- The correlation between global temperatures and atmospheric greenhouse gases is overwhelming – the Earth's temperature has increased in large part because of increases in carbon dioxide and methane in its atmosphere
- This fact is not in dispute (among scientists)



The Connection Between Climate and Human Activity

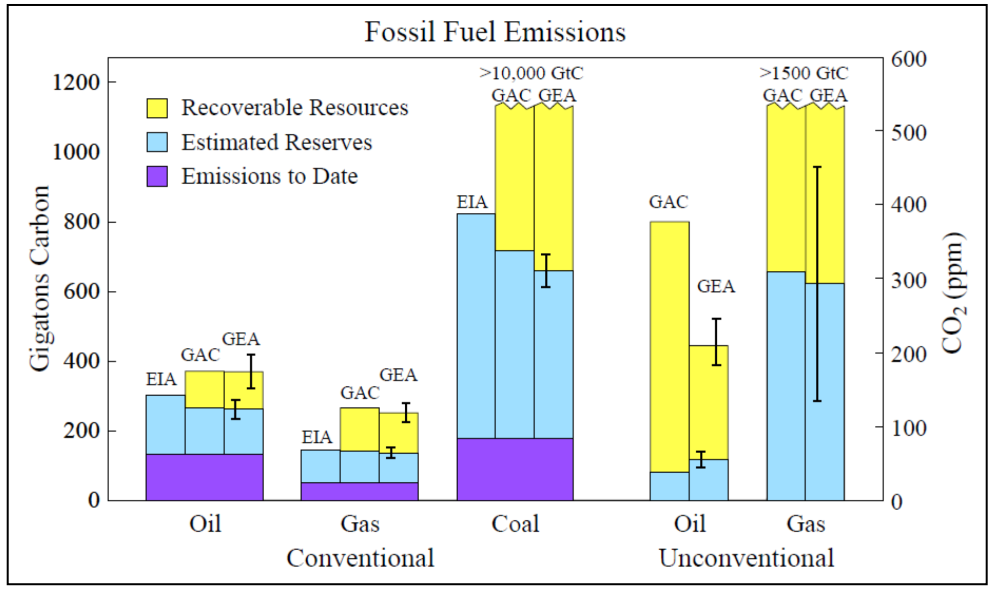
- The increase in CO_2 and other greenhouse gases is a recent phenomena, coincident with the explosion fossil fuel use and population growth





The Connection Between Climate and Human Activity

- The increase in CO_2 and other greenhouse gases is a recent phenomena, coincident with the explosion fossil fuel use and population growth
- Furthermore, the amount of CO_2 we've emitted in the past century is about the right amount to account for the measured temperature rise
- If this quantity of greenhouse gases had been emitted without a corresponding increase in the global temperature of ~1° C, it would be very hard to understand why



Carbon emissions by fossil fuel type

~300 Gigatons ➔ 125 ppm CO_2 ➔ ~1° C

The Current Scientific Consensus

The Intergovernmental Panel on Climate Change

- Established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO)
- Formed to provide a consensus scientific view on the current state of climate change science, and on the potential environmental and socio-economic consequences
- More than 1000 climate experts, from over 100 countries
- From the (most recent) October 2013 Report:

"Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased."

"Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, in global mean sea level rise, and in changes in some climate extremes. The human influence has grown since 2007. It is ***extremely likely**** *that human influence has been the dominant cause of the observed warming since the mid-20th century."*

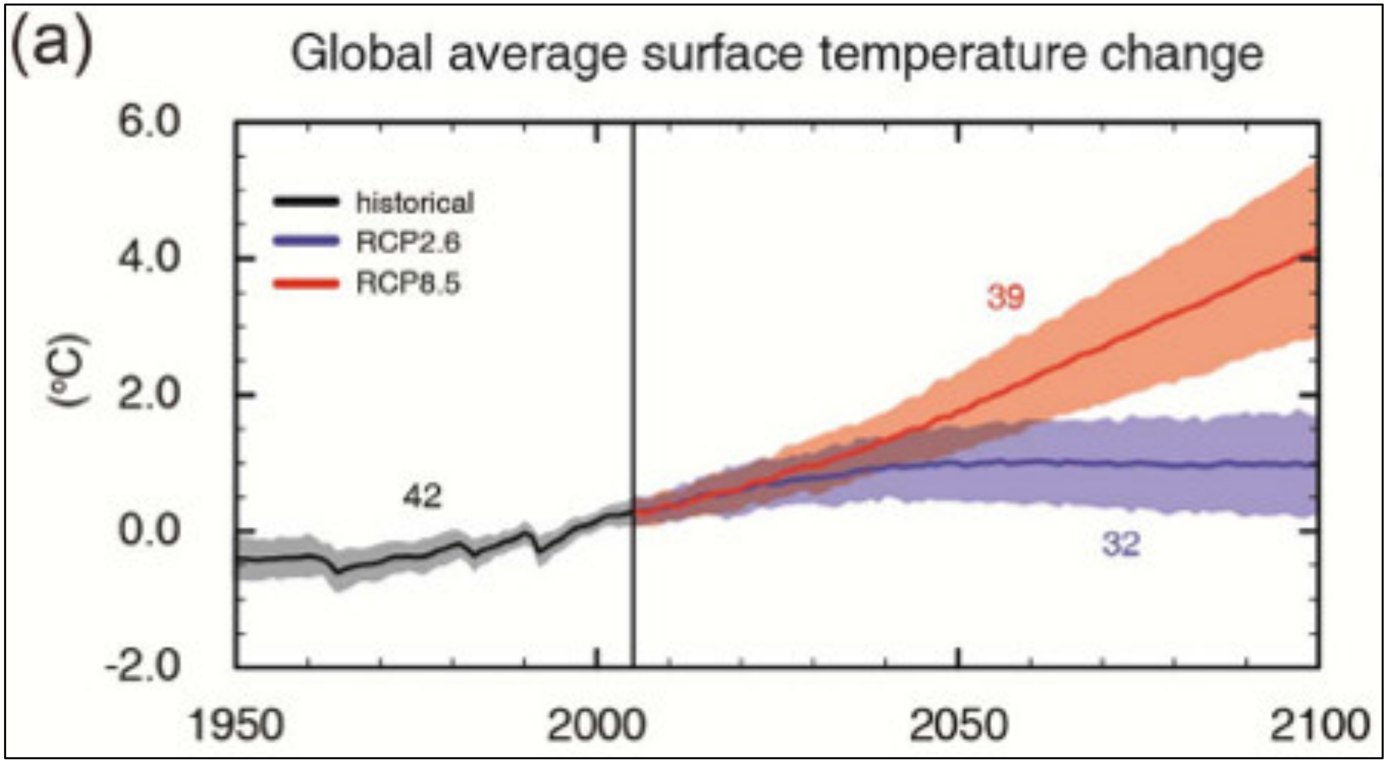
* Defined as a likelihood higher than 95%

FUTURE PROJECTIONS

- The future of the Earth's climate will depend largely on how much we continue to burn fossil fuels, depositing CO_2 and other greenhouse gases into the atmosphere
- There are also uncertainties related to our ability to model and forecast climate, but these are comparatively modest

TEMPERATURE PROJECTIONS

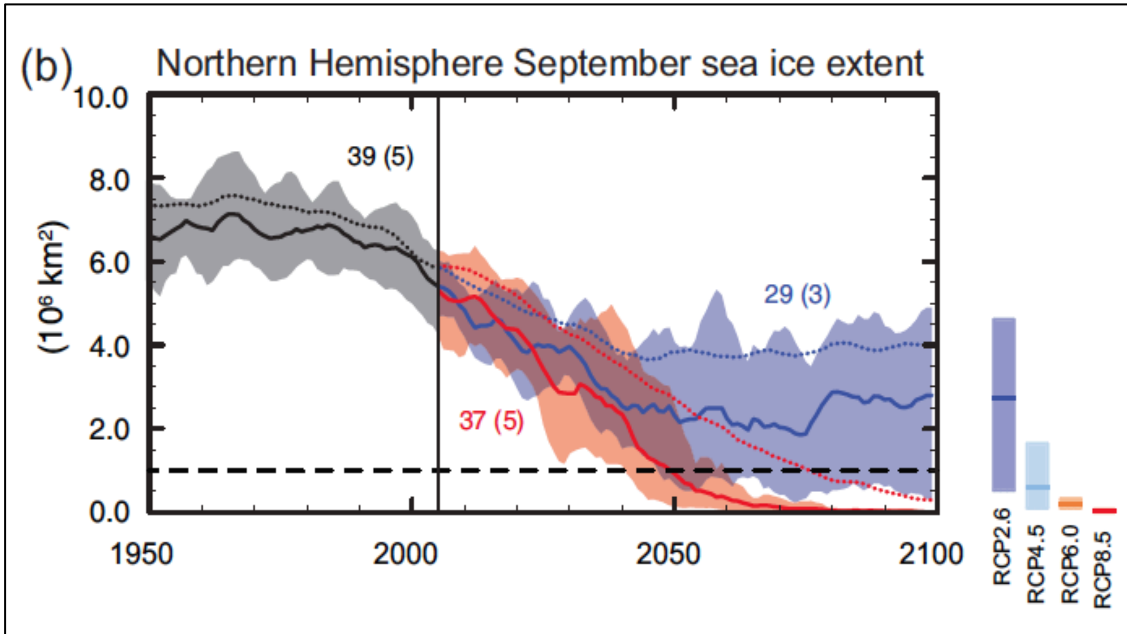
(From IPCC 2013 Summary for Policymakers)

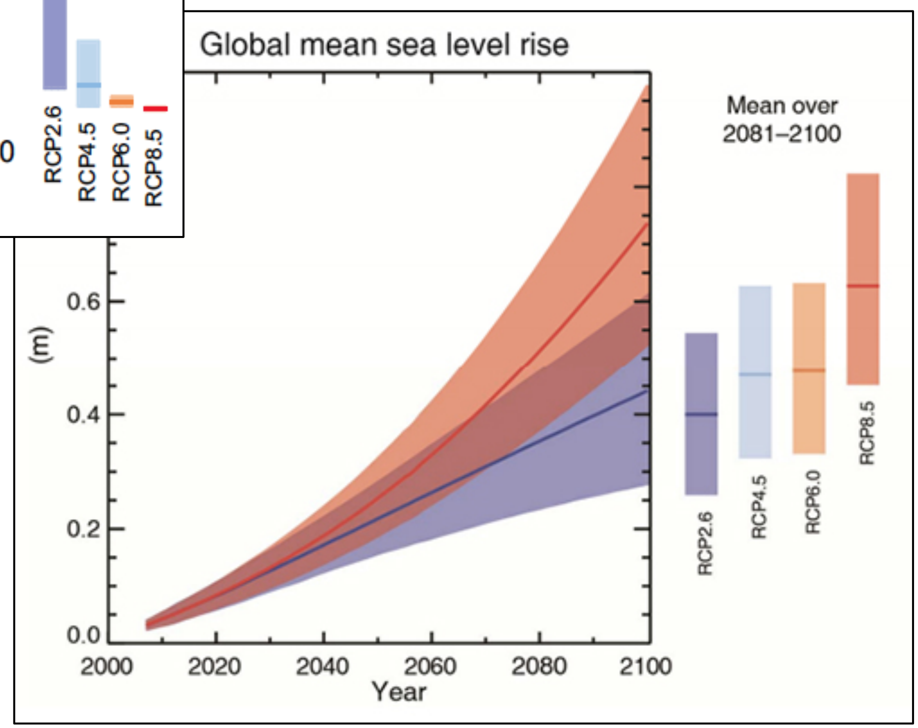


RCP8.5 (somewhat pessimistic)
1685 gigatons of carbon emitted between 2012 and 2100 – corresponds to a modest deceleration in the rate of increasing fossil fuel use

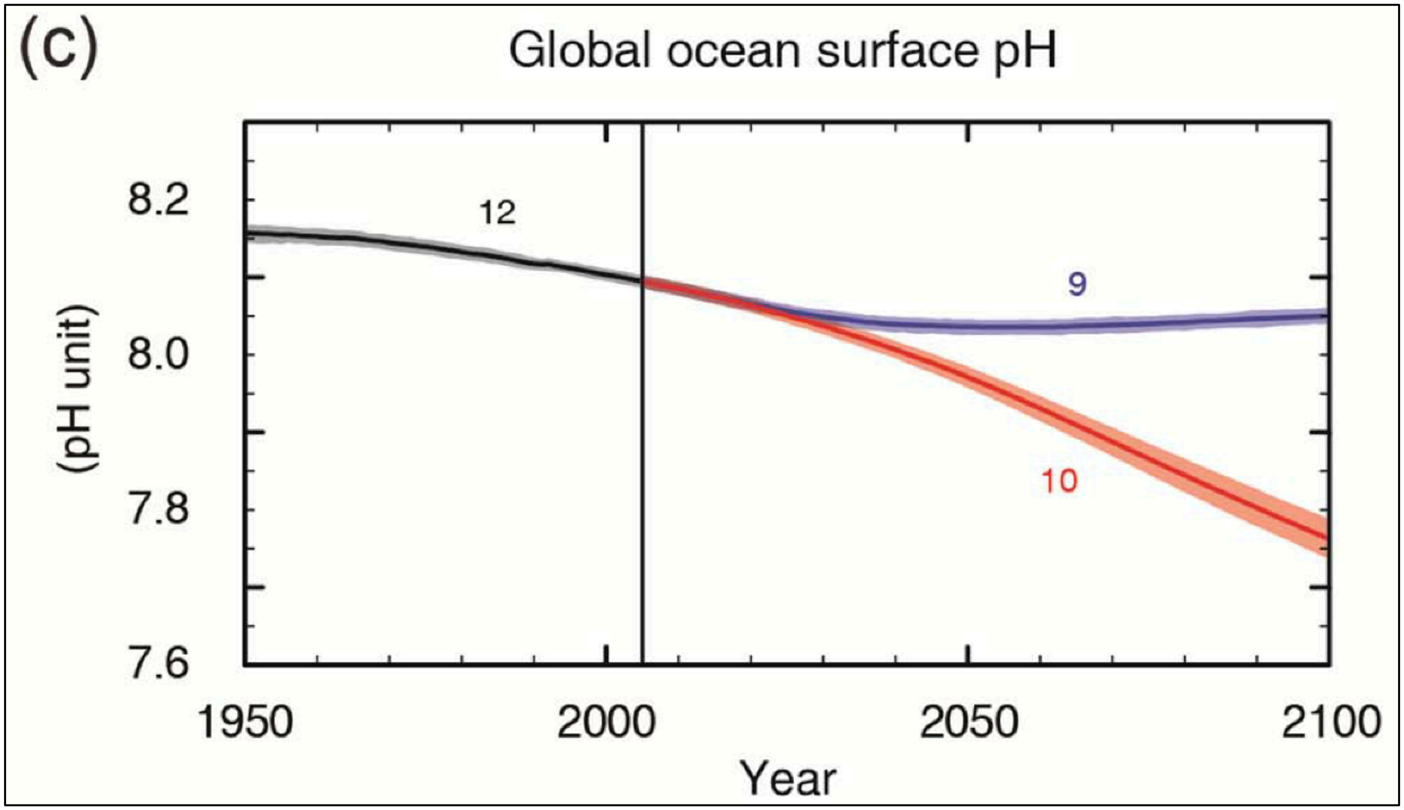
RCP2.6 (most optimistic)
270 gigatons of carbon emitted between 2012 and 2100 – very aggressive reduction in rate of fossil fuel use

ICE EXTENT AND SEA LEVEL PROJECTIONS
(From IPCC 2013 Summary for Policymakers)





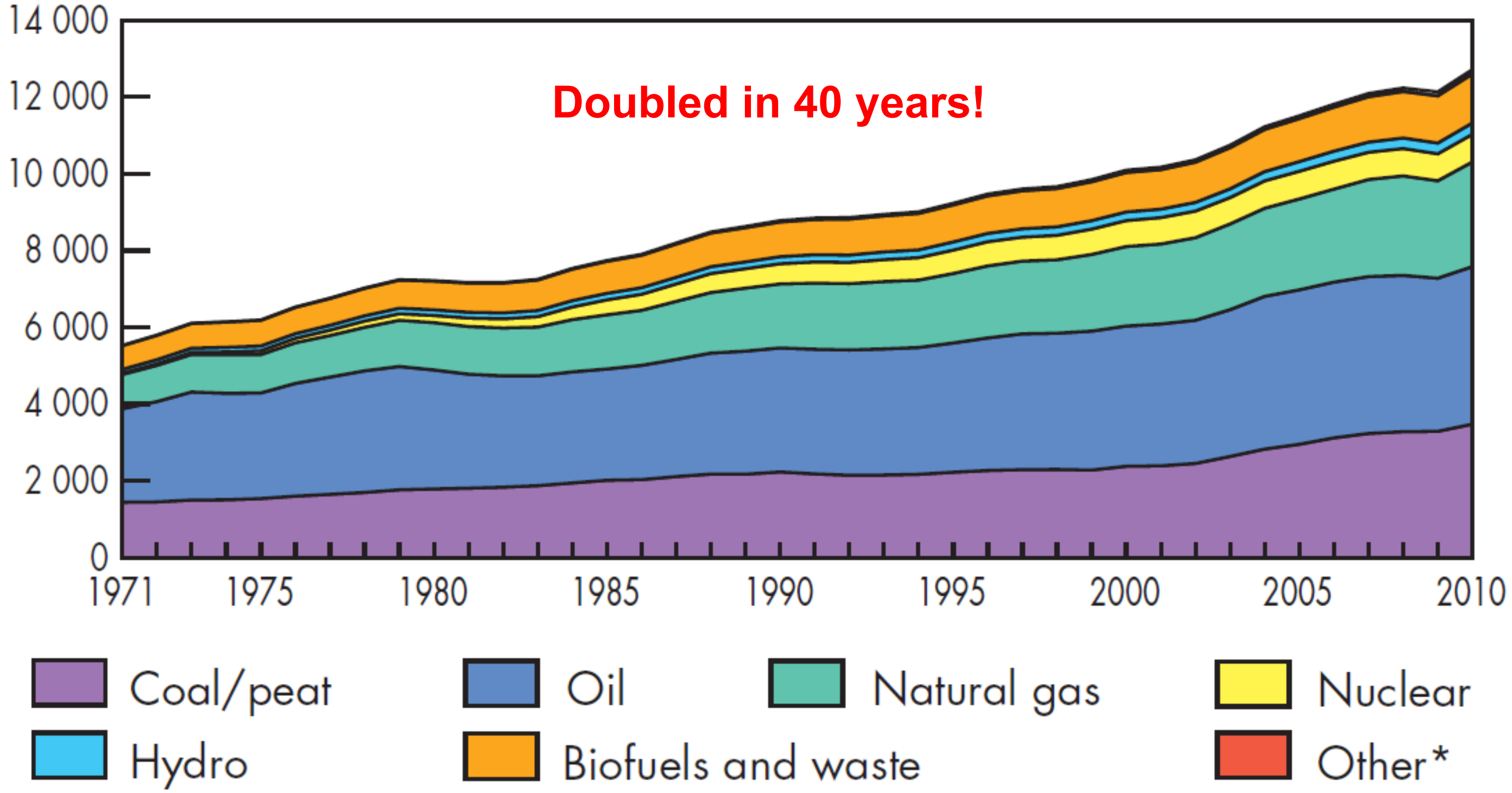
ACIDITY OF OCEANS
(From IPCC 2013 Summary for Policymakers)



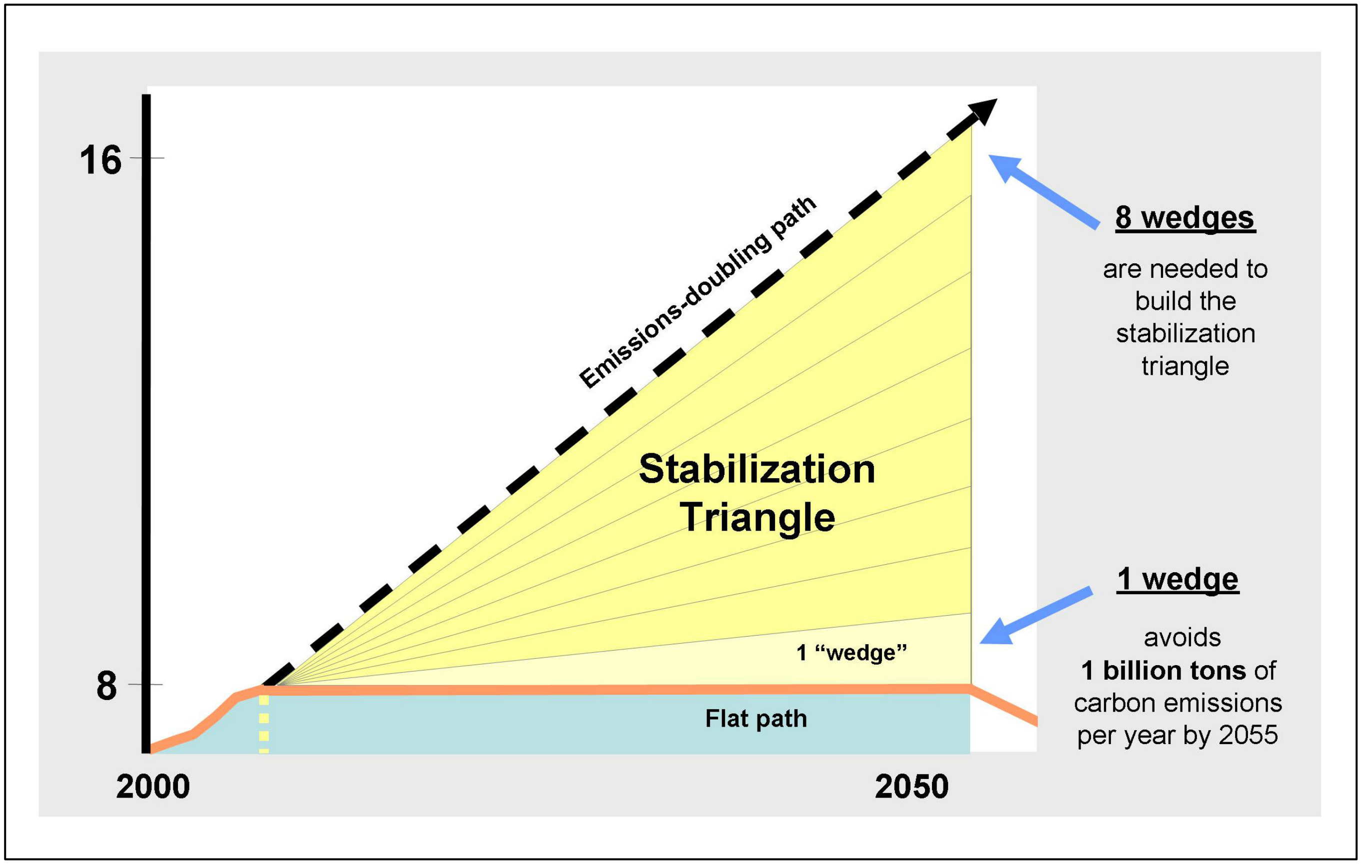
RCP8.5: 1685 gigatons of carbon emitted between 2012 and 2100 – requires a modest deceleration in the rate of increasing fossil fuel use

RCP2.6: 270 gigatons of carbon emitted between 2012 and 2100 – very aggressive reduction in rate of fossil fuel use

World total primary energy supply from 1971 to 2010 by fuel (Mtoe)



MITIGATING CLIMATE CHANGE

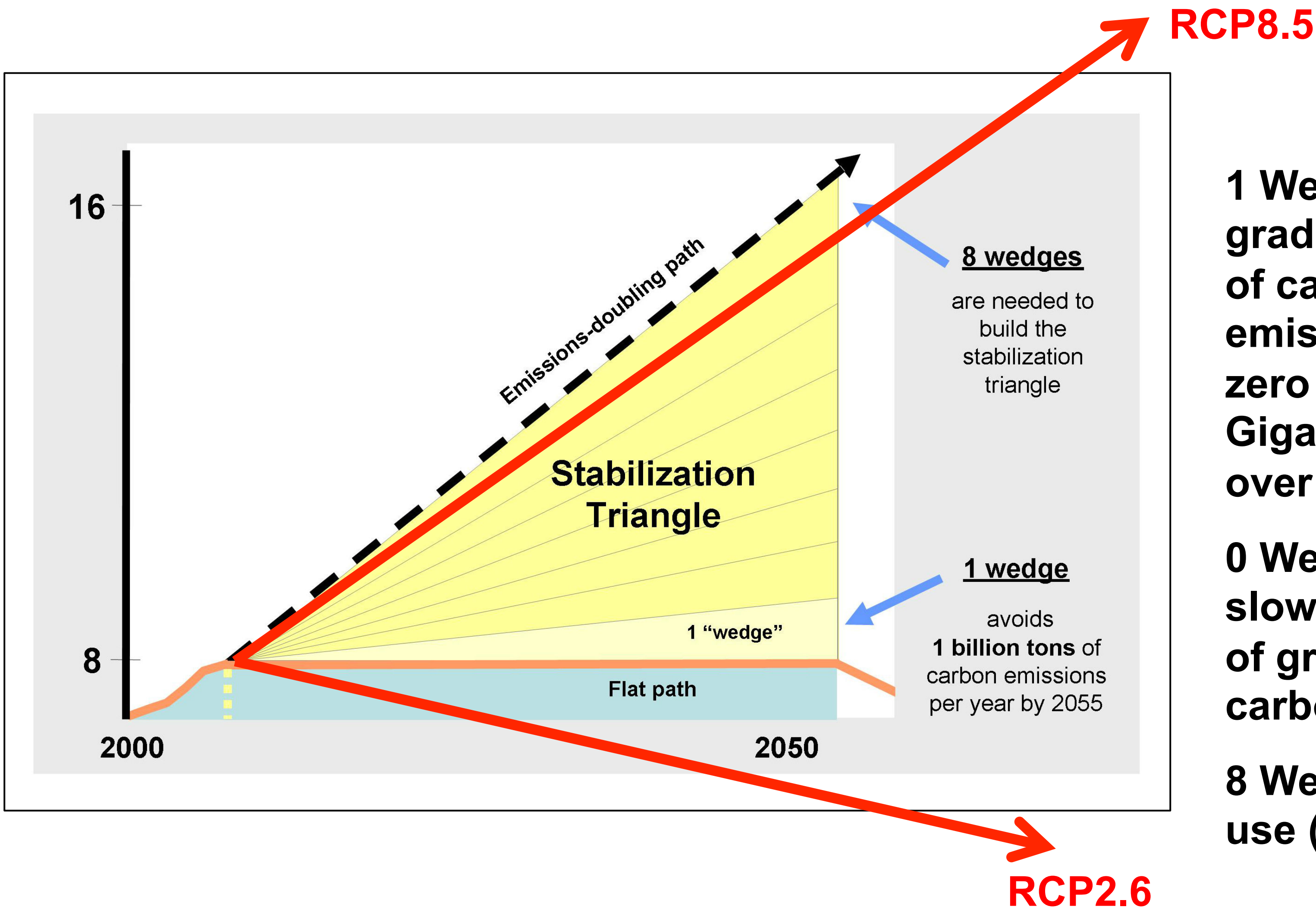


1 Wedge=the gradual reduction of carbon emissions from zero to 1.0 Gigatons per year, over 50 years

0 Wedges=no slowing of the rate of growth in carbon emissions

8 Wedges= flat use (no increase)

MITIGATING CLIMATE CHANGE



1 Wedge=the gradual reduction of carbon emissions from zero to 1.0 Gigatons per year, over 50 years

0 Wedges=no slowing of the rate of growth in carbon emissions

8 Wedges= flat use (no increase)

Worldwide possible 1.0 GtC/yr Wedges
(over the next 50 years)

Energy efficiency and conservation

1 **Increase** Vehicle Efficiency - 2 billion cars from 30 to 60 MPG

2 **Decrease** Vehicle Mileage - 2 billion cars from 10,000 to 5,000 Miles per Year

3 **Increase** Building Efficiency - by 33% in all new buildings and appliances

4 **Increase** Coal Plant Efficiency – increase coal plant efficiency by 50%

Fuel Shift

5 **Replace** 1400 Coal Power Plants with Natural Gas

CO_2 Capture and Storage

6 **Capture** the CO_2 at 800 Coal Plants

7 **Capture** CO_2 at coal-to-synfuels plant

8 **Store** CO_2 geologically

Alternate Fuels

9 **Double** the number of nuclear plants

10 **Add** 1 million (2TW) windmills

11 **Add** 2 TW of photovoltaic power

12 **Generate** H_2 with 4 million windmills and use in fuel-cell cars

13 **Produce** 50 times more biomass ethanol (but not from Corn!)

Forests and Soils

14 **Decrease** deforestation to zero

15 **Conservation** tillage 10 times current usage

ENERGY BASICS

- What is energy?

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- Ways to store energy:

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  2) Elastic potential energy
  3) Chemical potential energy
  4) Nuclear potential energy

  Etc.

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  Etc.

- What is the energy content of

  1) A gram of chocolate?

  2) A gram of steak?

  3) A gram of coal?

  4) A gram of gasoline?

  5) A gram of uranium?

  6) A gram of antimatter?

ENERGY BASICS

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- Ways to store energy:

  1) Gravitational potential energy
  2) Elastic potential energy
  3) Chemical potential energy
  4) Nuclear potential energy

  Etc.

- What is the energy content of
  1) A gram of chocolate?
  2) A gram of steak?
  3) A gram of coal?
  4) A gram of gasoline? 50 kJ
  5) A gram of uranium?
  6) A gram of antimatter?

ENERGY BASICS

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- Ways to store energy:

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2) Elastic potential energy
3) Chemical potential energy
4) Nuclear potential energy
Etc.

- What is the energy content of

1) A gram of chocolate? 15-20 kJ
2) A gram of steak? 15-20 kJ
3) A gram of coal? 40 kJ
4) A gram of gasoline? 50 kJ
5) A gram of uranium? 10^8 kJ
6) A gram of antimatter? 10^{11} kJ

ENERGY BASICS

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  6) A gram of antimatter? 10^{11} kJ

(Items 1–4:) Examples of Chemical Potential Energy (each about 10-50 kJ/g)

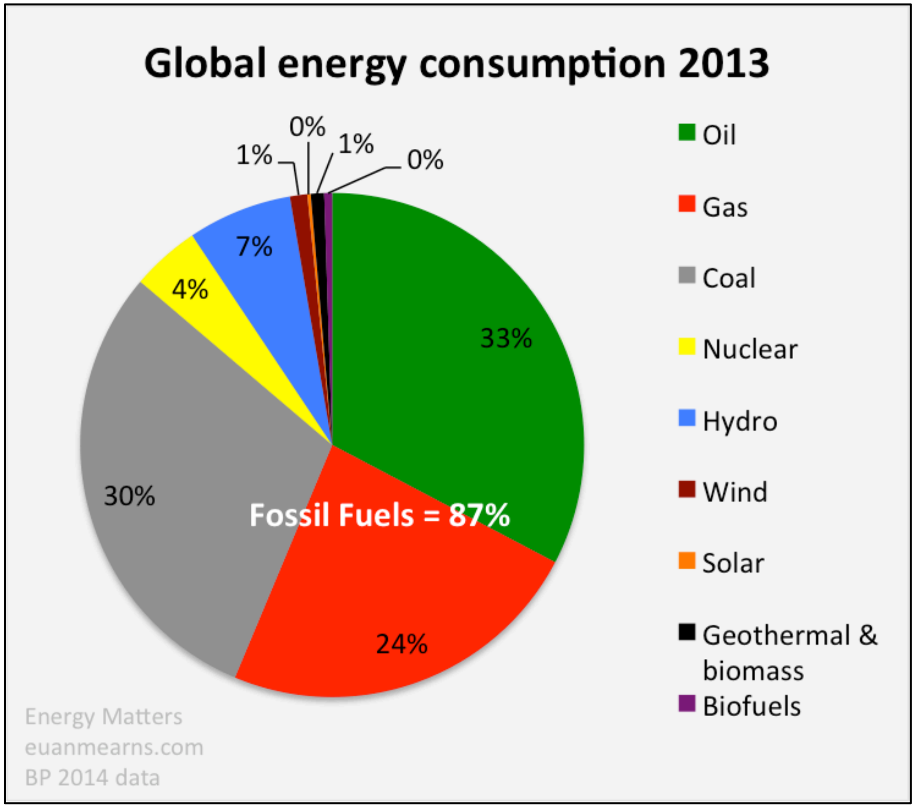
Question: why can't we we solve our energy needs with chocolate and steak?

ENERGY

- At present, most of our energy production comes from the burning of fossil fuels (including oil, coal and natural gas)
- Greenhouse gases are a bi-product of this process

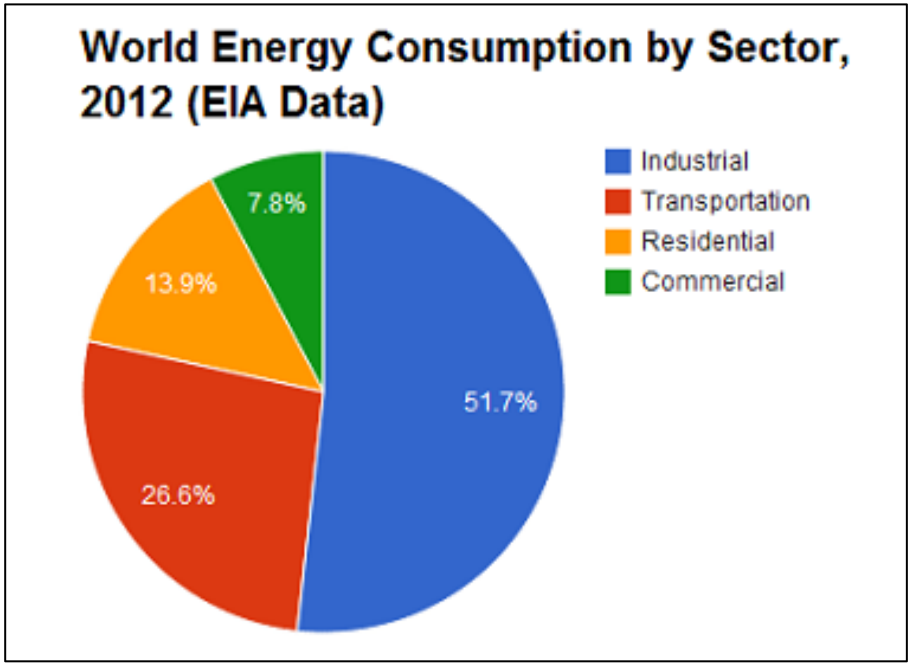
Example: coal is made up mostly of carbon and water (along with some hydrogen, oxygen, nitrogen, etc.)

The energy in coal is released in reactions of the type: $C + O_2 \rightarrow CO_2$



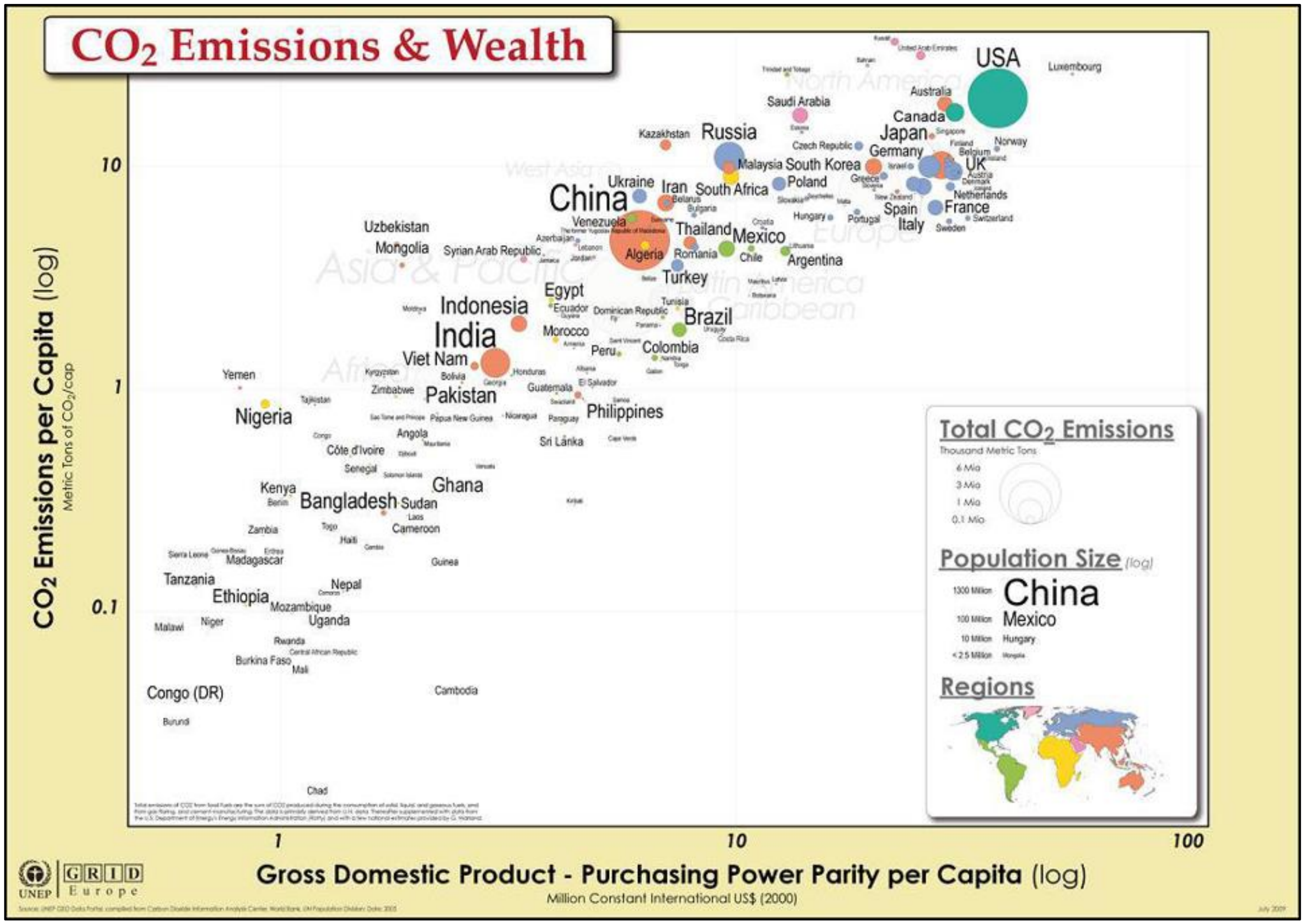
ENERGY

- This energy is used not only (or even primarily) by cars/vehicles, but mostly in manufacturing and heating/cooling



ENERGY

- This energy makes it possible for us to live very comfortably
- Wealth (GDP/capita) is highly correlated to greenhouse gas emissions



ENERGY

- Climate change resulting from greenhouse gas emissions are beginning to impose significant costs and these costs will almost certainly increase over the coming decades
- The question we face now is how do we limit climate altering carbon emissions as much as possible while minimizing the impact on the global economy and on the quality of our lives – this is a question of economics and politics, as well as science

WAYS TO REDUCE CARBON EMISSIONS

1) We could use less energy

	1 Stabilization Wedge
▪ Higher efficiency vehicles	2 billion cars from 30 to 60 MPG
▪ Less vehicle usage	2 billion cars from 10,000 to 5,000 miles/yr
▪ Higher building efficiency	By 33% in all new buildings and appliances

WAYS TO REDUCE CARBON EMISSIONS

2) We could burn fossil fuels more efficiently

	<u>1 Stabilization Wedge</u>
▪ Use more natural gas, less coal	Replace 1400 coal plants with natural gas
▪ CO_2 capture (and storage)	Implemented in 800 coal plants
▪ Increase coal plant efficiency	By 50% overall

WAYS TO REDUCE CARBON EMISSIONS

3) We could burn less fossil fuels and use more alternative energy

	1 Stabilization Wedge
▪ Generate more nuclear power	Double the number of nuclear plants
▪ Generate more wind power	Add 1 million (2TW) windmills
▪ Generate more solar power	Add 2 TW
▪ Produce more biomass ethanol (sugarcane, switchgrass, not corn!)	Increase by factor of 50

THE COSTS OF ENERGY

Price per kiloWatt-hour (approximate)

	not including plant/delivery	including plant/delivery
▪ Coal	0.6¢ ($60 per ton)	4¢
▪ Natural Gas		
▪ Gasoline		
▪ Car Battery		
▪ Computer Battery		
▪ Flashlight battery		
▪ Hydropower		
▪ Nuclear		
▪ Wind (offshore)		
▪ Solar		

THE COSTS OF ENERGY

Price per kiloWatt-hour (approximate)

	not including plant/delivery	including plant/delivery
Coal	0.6¢ ($60 per ton)	4¢
Natural Gas	3.4¢ ($10 per million cubic ft.)	5¢
Gasoline		11¢ ($3.70 per gallon)
Car Battery		21¢ ($50 per battery)
Computer Battery		$4 ($100 per battery)
Flashlight battery		$1,000 ($1.50 per AAA)
Hydropower		7¢
Nuclear	0.6¢	6¢
Wind (offshore)		~20¢
Solar		~10-30¢

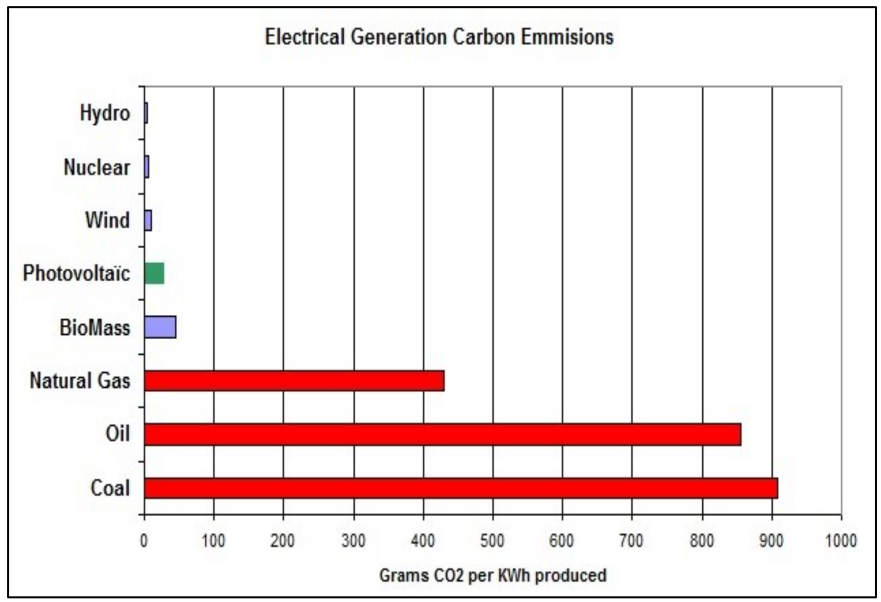
Why This Is Such A Hard Problem

- Imagine that we decided to replace all of the coal consumption in the world with solar power (increasing from 4¢/kWh to ~20¢/kWh)
- For the ~50 trillion kWh of electricity we get from coal each year, this would cost an additional $7 trillion/year (about 10% of global GDP)
- This would constitute about 2-3 stabilization wedges – a good start, but not enough to strongly mitigate the effects of climate change
- This doesn't solve the problem of energy storage (we need energy at night)
- The politics of coordinating the world's governments in such a project seem challenging, to say the least

- The bright side: as the efficiency of solar and wind power increases, they will become much more economically viable

Burning Fossil Fuels With Less CO_2 Emissions

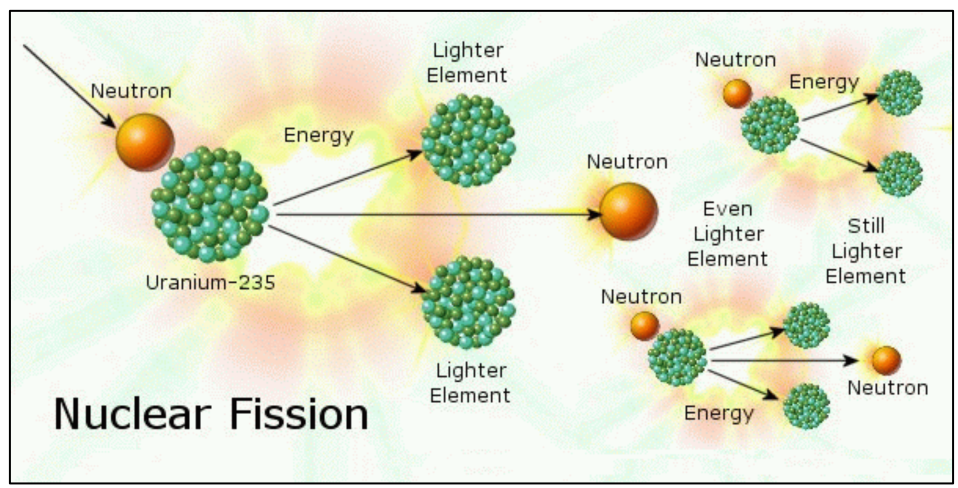
- Existing plants are relatively inefficient – technology exists that makes it possible to get more energy per unit coal, gas, etc.
- Electricity from natural gas is only modestly more expensive than from coal, but generates about half the CO_2
- Clean Coal?
  - Some environmentalist call this an oxymoron
  - Modern coal plants (Geneva, Batavia, Rochelle) are much more efficient than older plants
  - CO_2 sequestration is a goal, but technology is not yet demonstrated



Nuclear Power (Fission)

- Nuclear plants currently generate about 20% of the power in the US
- Nuclear plants do not (directly) generate greenhouse gases
- Currently much cheaper than wind or solar power
  (slightly more expensive than coal, natural gas)
- Unlike solar and wind power, uranium is not a renewable energy
  (although current reserves will likely last for hundreds of years)
- Nuclear waste requires care to safely dispose
- The public is generally skeptical regarding the safety of nuclear power

Should they be?



The Relative Safety of Nuclear Power

- To date, there have been three accidents at nuclear power plants:

  Three Mile Island (1979) No deaths

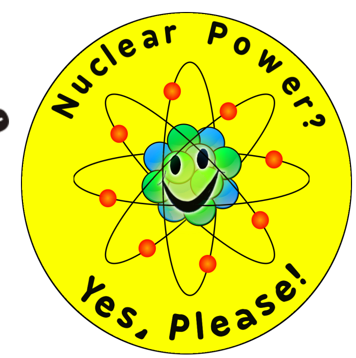
  Cherobyl (1986) ~9000 deaths (mostly from cancer), according to IAEA/WHO/UN forum

  Fukushima (2011) No deaths so far (although many thousand died as a result of the Earthquake and Tsunami); estimates for the number of eventual cancer deaths vary, ranging from ~0 to ~130

- Lets compare this to coal mining-related deaths:

  ~30 deaths/year in the US

  ~6000 deaths/year in China



- This doesn't even count the rate of deaths from pollution (~7500/year in the US alone)
- The worst year for nuclear power (Cherobyl, 1986) is better than the average year for coal

Climate Engineering

- The deliberate large scale intervention in the Earth's climate system, aim to reduce the effects of global warming/climate change
- Possibilities generally fall into two categories:

1) Solar radiation management (increase the albedo of Earth's atmosphere)
   - -Using pale-colored roofing and paving materials
   - -Tropospheric cloud whitening
   - -Depositing reflective aerosols into the upper atmosphere
2) Atmospheric CO_2 removal
   - -Large scale tree planting
   - -Ocean iron fertilization
   - -Carbon sequestration

The most potentially effective of these strategies are also potentially very hazardous; difficult to predict outcomes and difficult to manage the global politics

My view: it would be foolish to assume that climate engineering will solve our climate problems, but research should be pursued

Summary

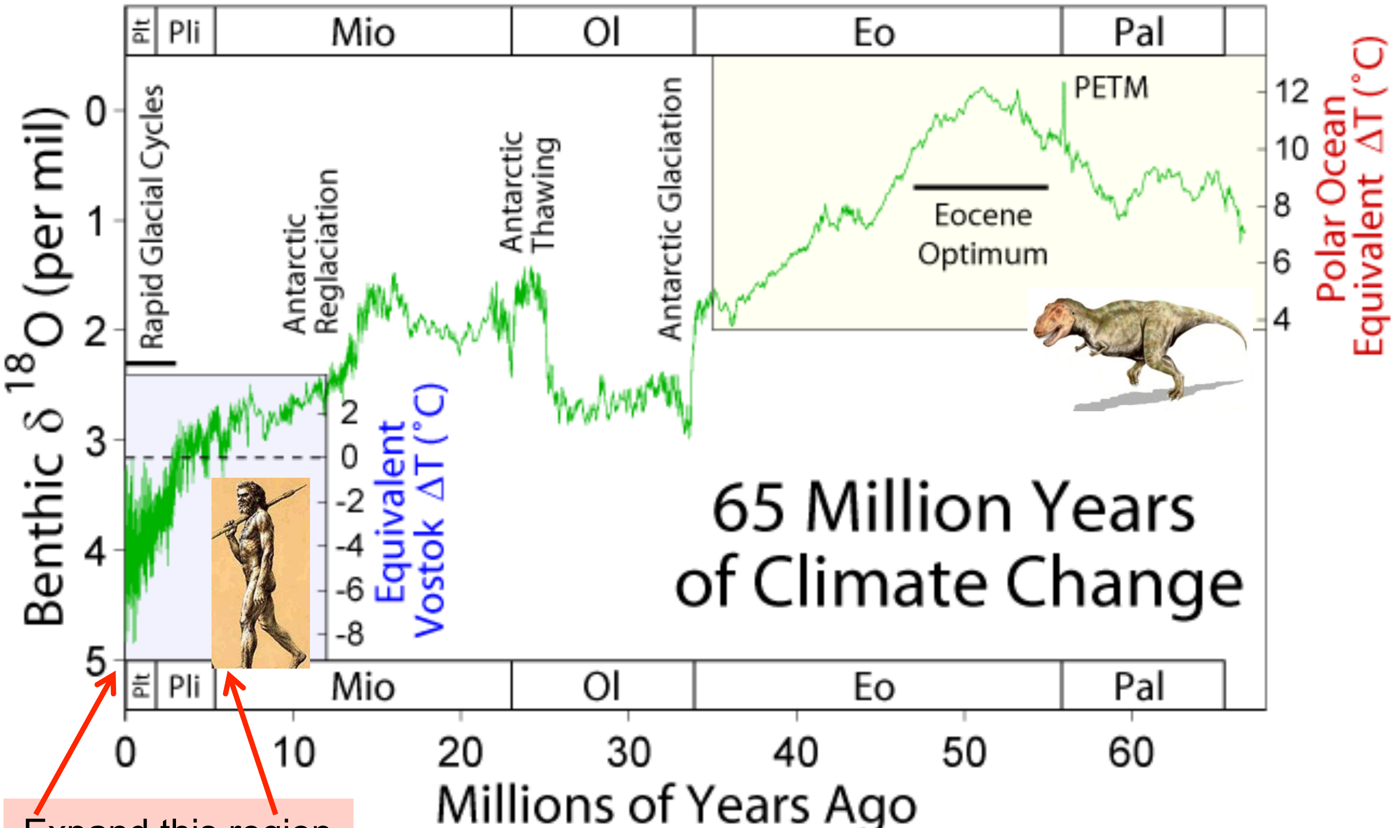
- The Earth's climate is significantly impacted by the chemistry of its atmosphere; these effects are quite well understood
- As human beings have increased the quantity of greenhouse gases in the atmosphere (by burning fossil fuels), global temperatures have predictably increased
- If we continue on the current trajectory of fossil fuel use, Earth's temperature is likely to increase by another ~3-5° C by the end of the century

Some Predictions (subjective!)

- Global emission of CO_2 will not slow down significantly over the next decade
- The melting of the summer Arctic polar ice cap, and increasing storms and drought, will help to awaken global public opinion on the reality of global warming
- Canada and Russia will gain economically from global warming
- Southern Europe will swelter
- The US will have winning regions and losing regions.
- Acidification and warming of the oceans will cause significant changes in plankton, fisheries, corals, etc.
- Life and civilization will endure, but we will be living in a increasingly warmer and stormier world, with fewer species

A Long History of Earth's Temperature

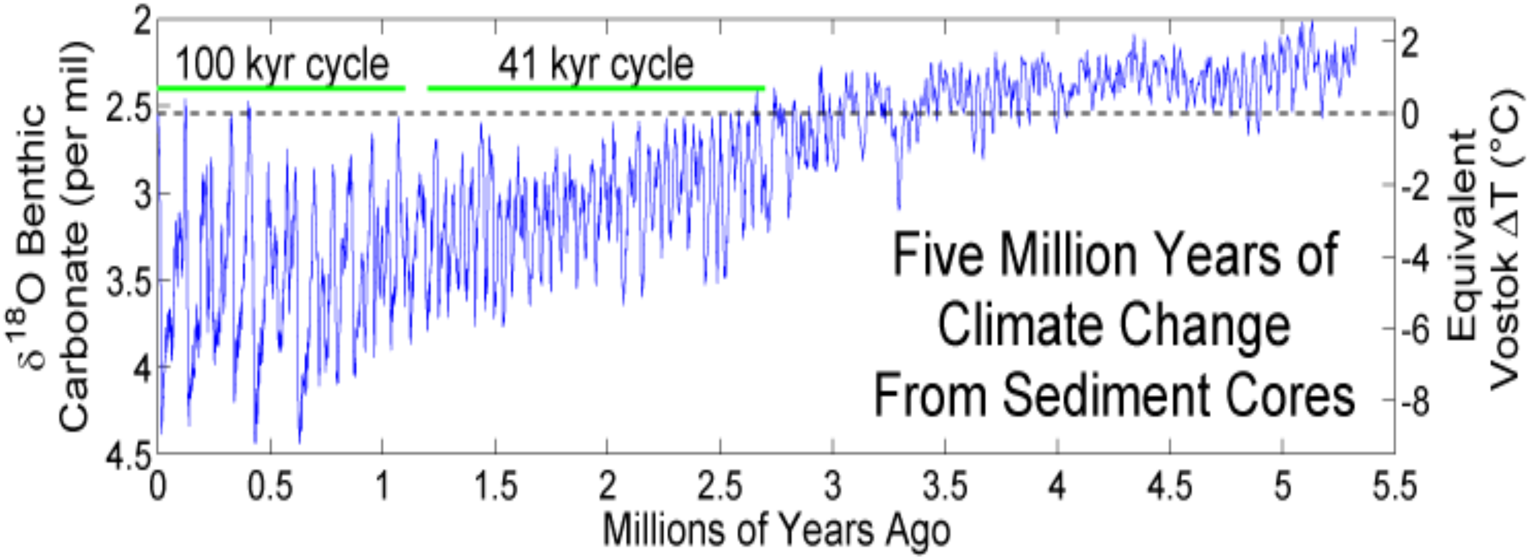
O^{18}/O^{16} Isotope ratio proxy for temperature



Expand this region

- The Earth has very long and slow temperature changes
- It has been steadily cooling for the last 50 million years.
- Recently, 5 deg C instabilities associated with glaciations have appeared?

The last 5 million years, the Ice Ages

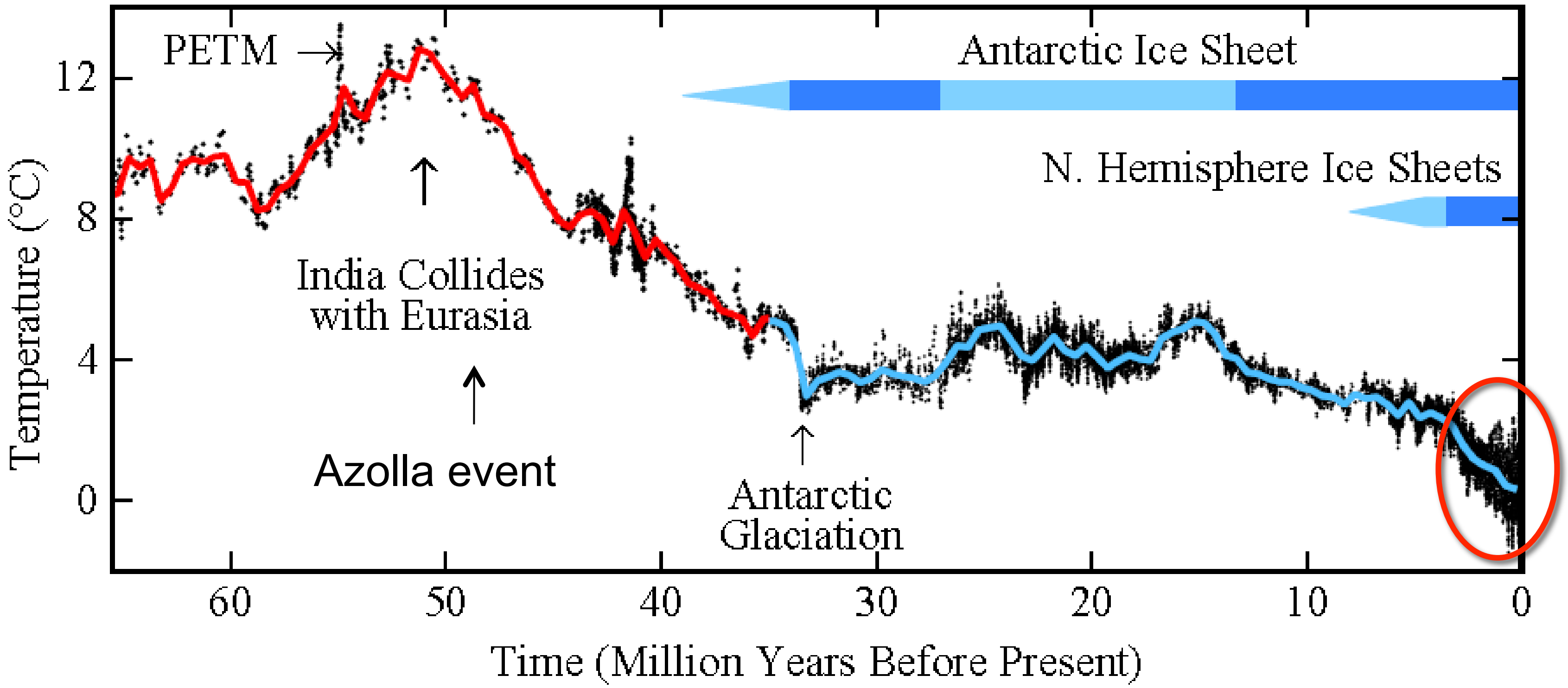


Oscillatory behavior has increased in the last 2-3 million years.

Is this a typical behavior for Earth's climate?

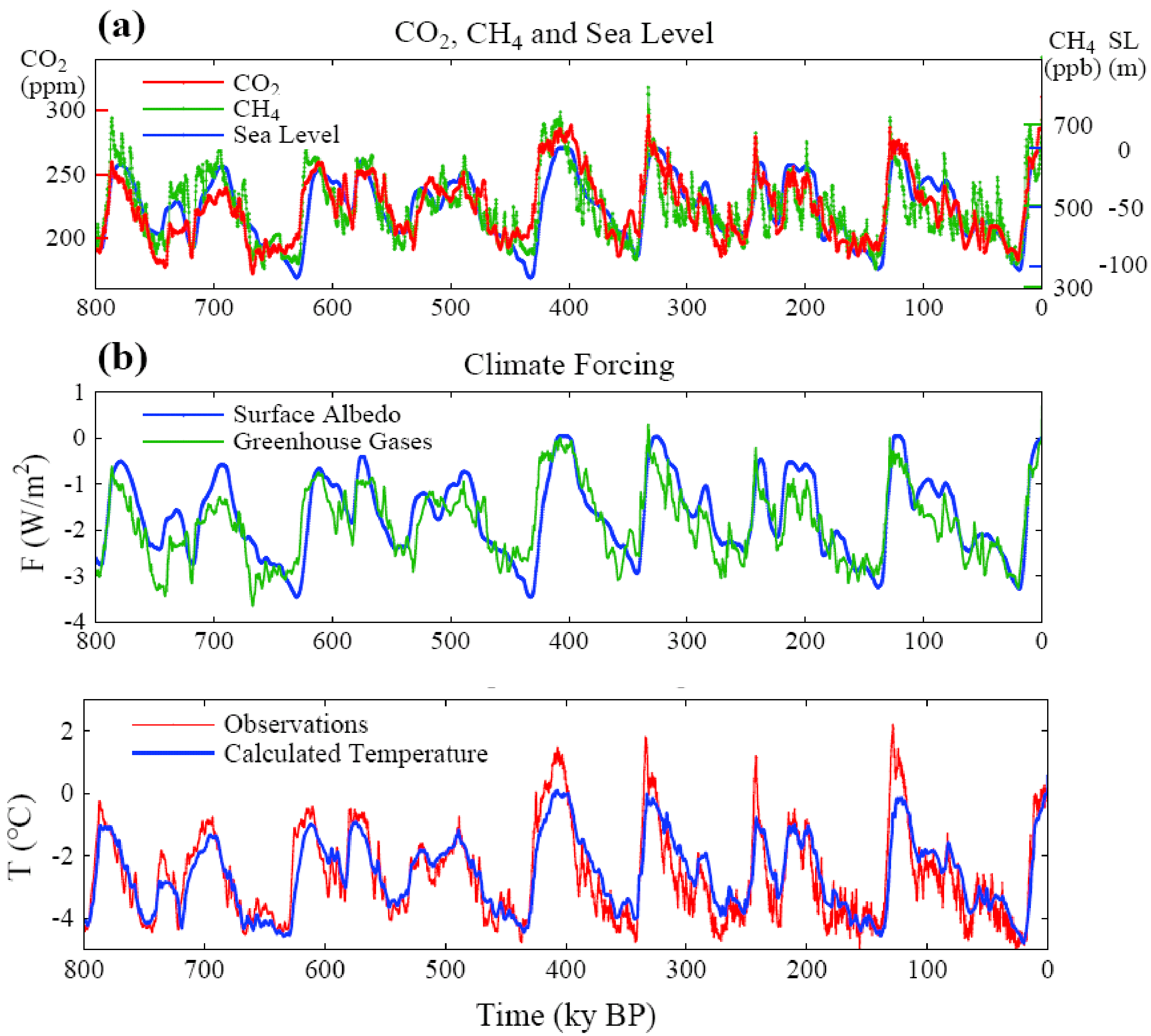
Is this rather due to a very special set of circumstances?

The Sloooow Change in Climate



- 50 million years ago Earth was hot and ice-free (~12 degrees hotter).
- Two events probably caused a drawdown of CO_2:
  - Weathering of new rock faces of Himalayas
  - Giant blooms of algae in the north pole
- The change of CO2 in prehistory was ~1 ppm every 10,000 years
  The change of CO_2 now is ~1 ppm every 8 months

These GHG forcings are in all Climate Models



Data:

CO_2, CH_4 and sea level for past 800 kyears

Convert:

Climate forcings due to changes of GHGs and ice sheet area,

Calculate:

Global temperature change based on above forcings and climate sensitivity ¾°C per W/m^2.

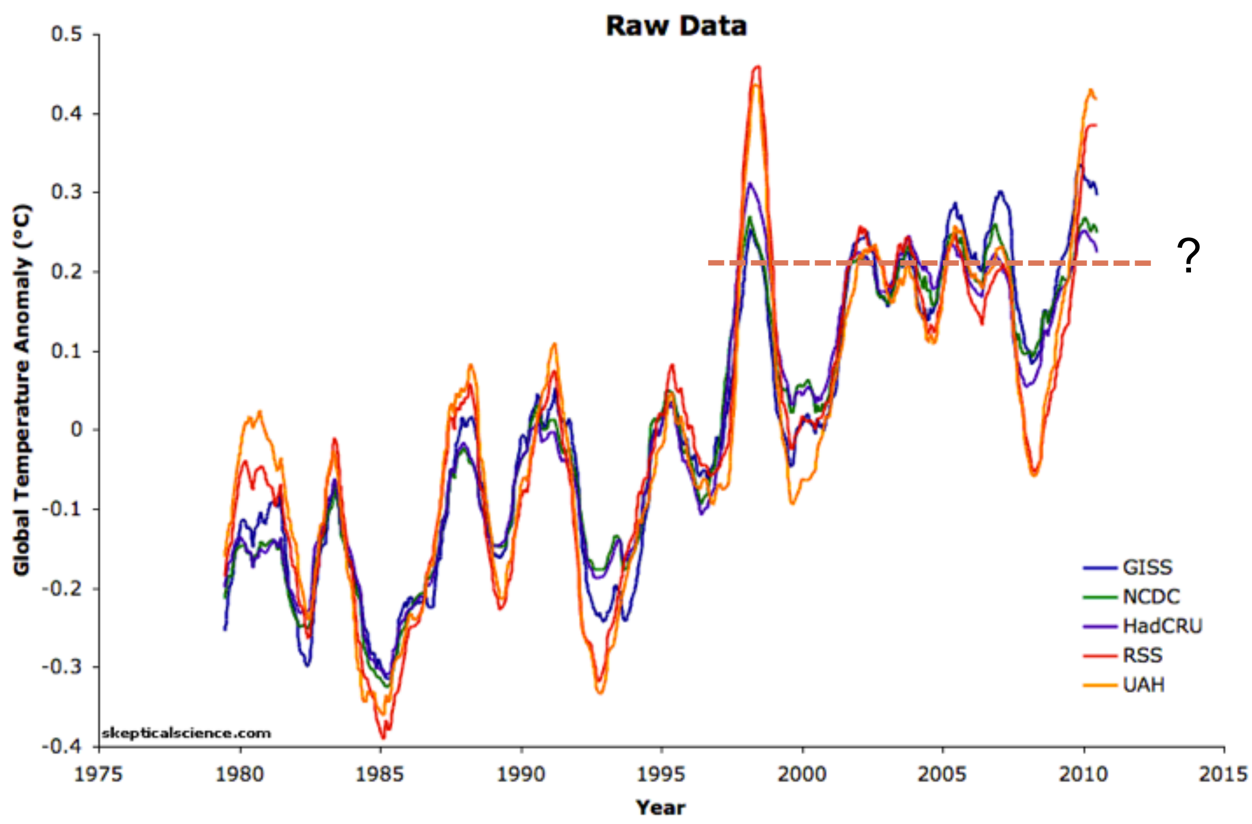
Compare:

O^{18}/O^{16} Temp proxy

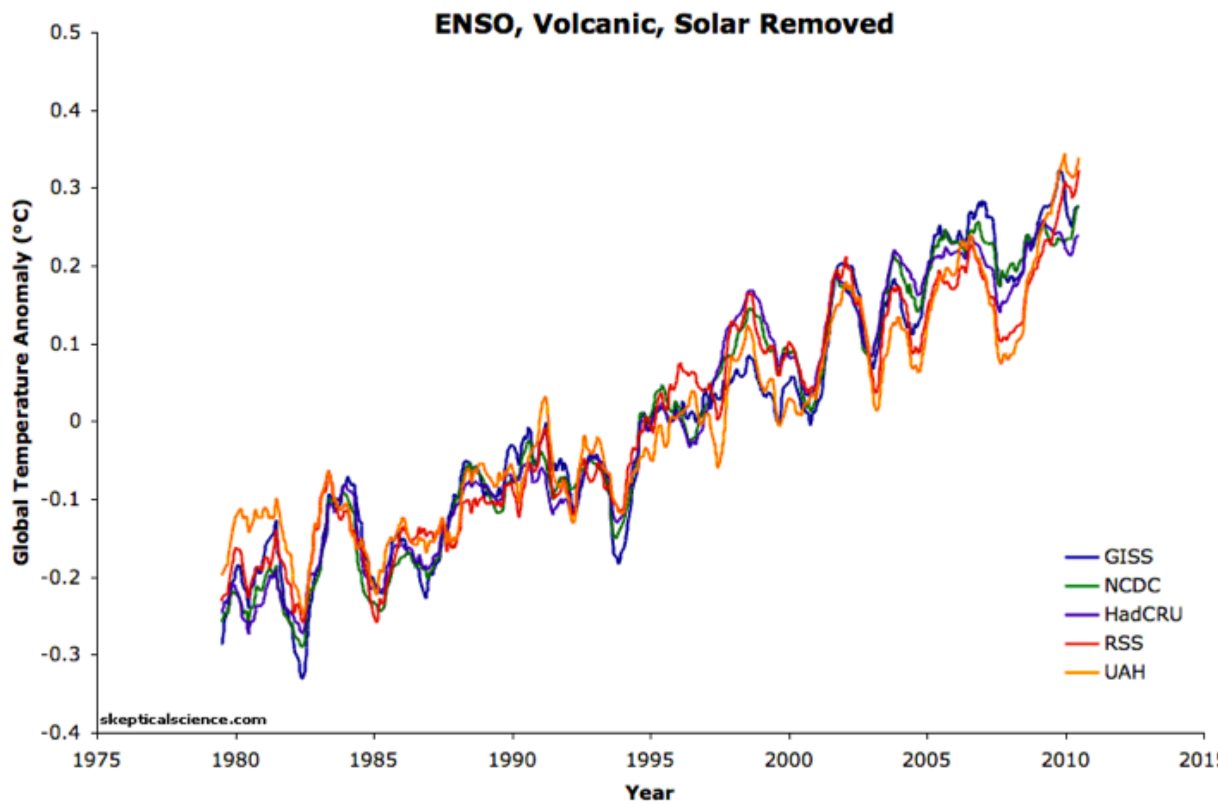
- The increase of heat into the atmosphere, ocean and land (compared to pre-industrial times) is equivalent to 4 Hiroshima size bombs…

every second

Has Global Warming Stopped in the last 15 years?



No. Anthropogenic Global Warming is Continuing at a Steady Pace



(Rahmstorf & Foster, 2012)

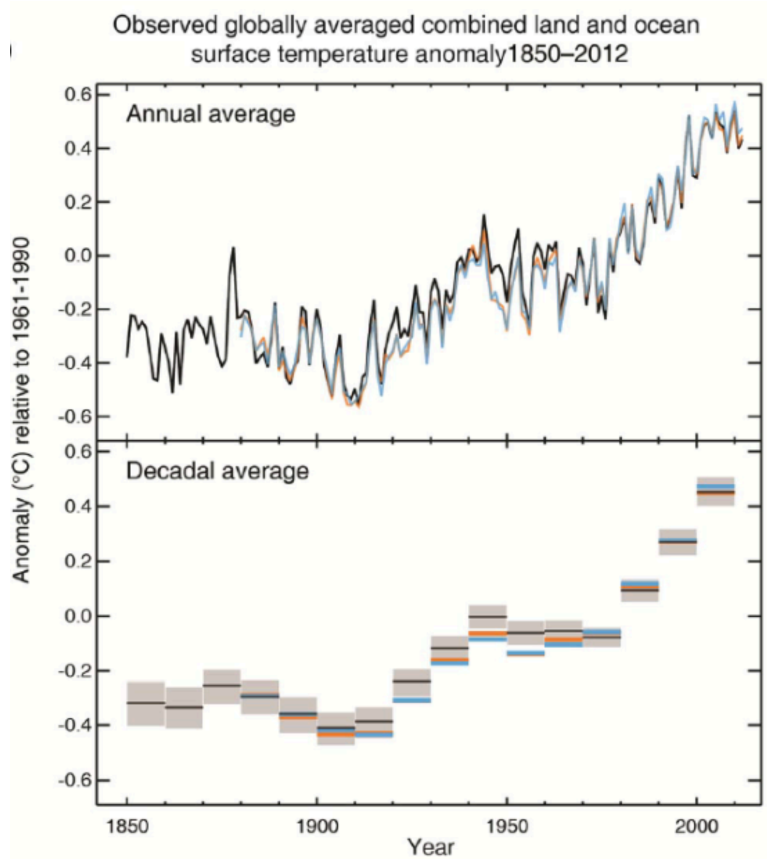
The El Nino fluctuations in the last 15 years have masked the underlying trend . That trend will inevitably overpower the noisy weather.

Has Global Warming ‘Stopped’ ?

- Here is the NASA yearly mean global temperature data. The 10-year average indicates that the Earth is steadily warming up

Global Land-Ocean Temperature Index (C) (Anomaly with Base: 1951-1980)

Year	Annual_Mean	10 year mean
1982	0.09	
1983	0.27	
1984	0.12	
1985	0.08	
1986	0.15	
1987	0.29	
1988	0.35	0.25
1989	0.24	
1990	0.39	
1991	0.38	
1992	0.19	
1993	0.21	
1994	0.29	
1995	0.43	
1996	0.33	
1997	0.46	
1998	0.62	0.43
1999	0.40	
2000	0.41	
2001	0.53	
2002	0.62	
2003	0.60	
2004	0.51	
2005	0.66	
2006	0.59	
2007	0.63	
2008	0.49	0.59
2009	0.60	
2010	0.67	
2011	0.55	
2012	0.57	
2013	*	

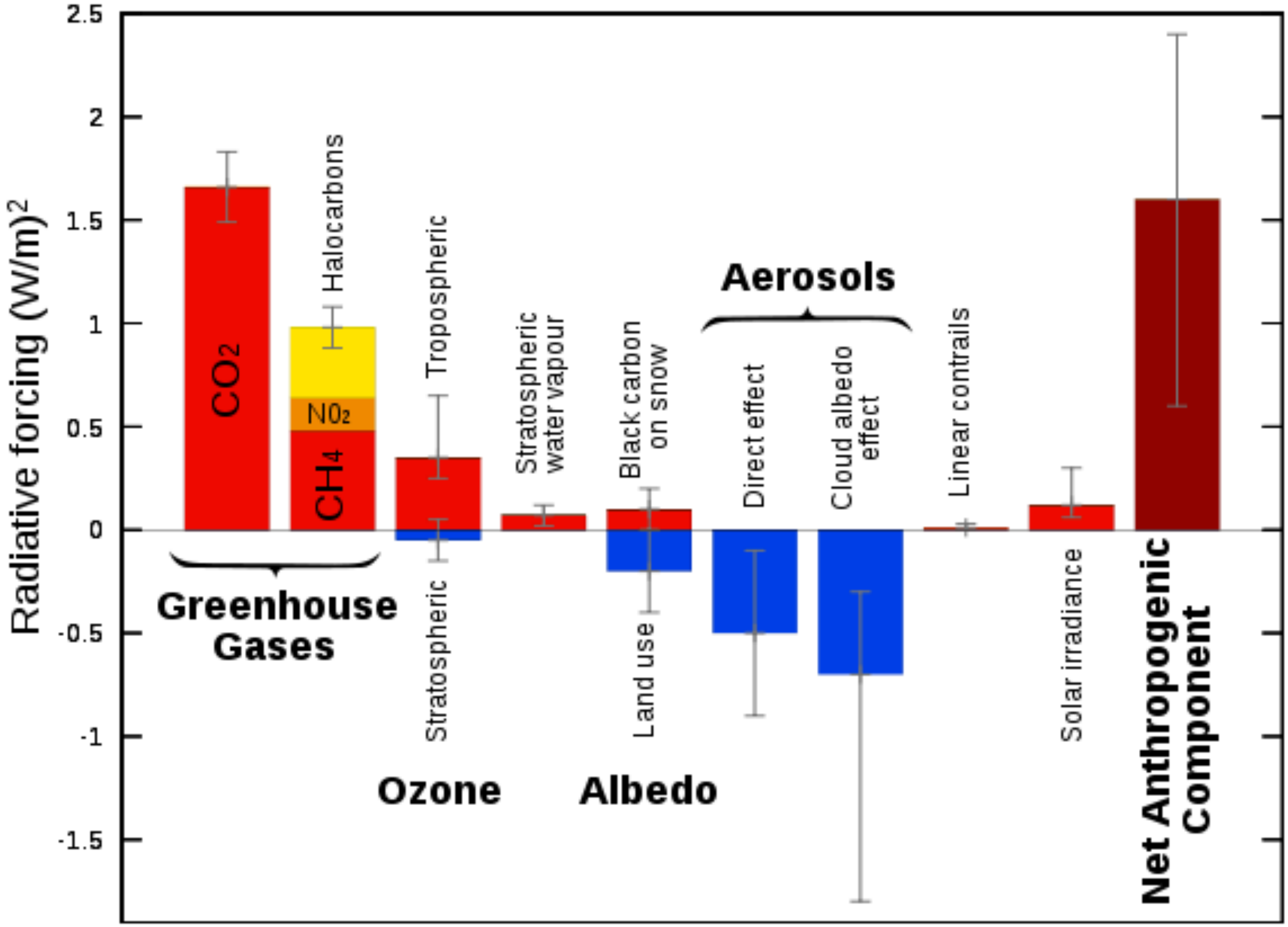


Average US Residential Energy Usage?

(2.7 people, 0.7 dog, 0.7 cat)

- 32% Space Heating
- 13% Water Heater
- 12% Lights
- 11% Air Conditioner
- 8% Refrigerator
- 5% Electronics
- 5% Dryer and Dishwasher
- ?? - Food

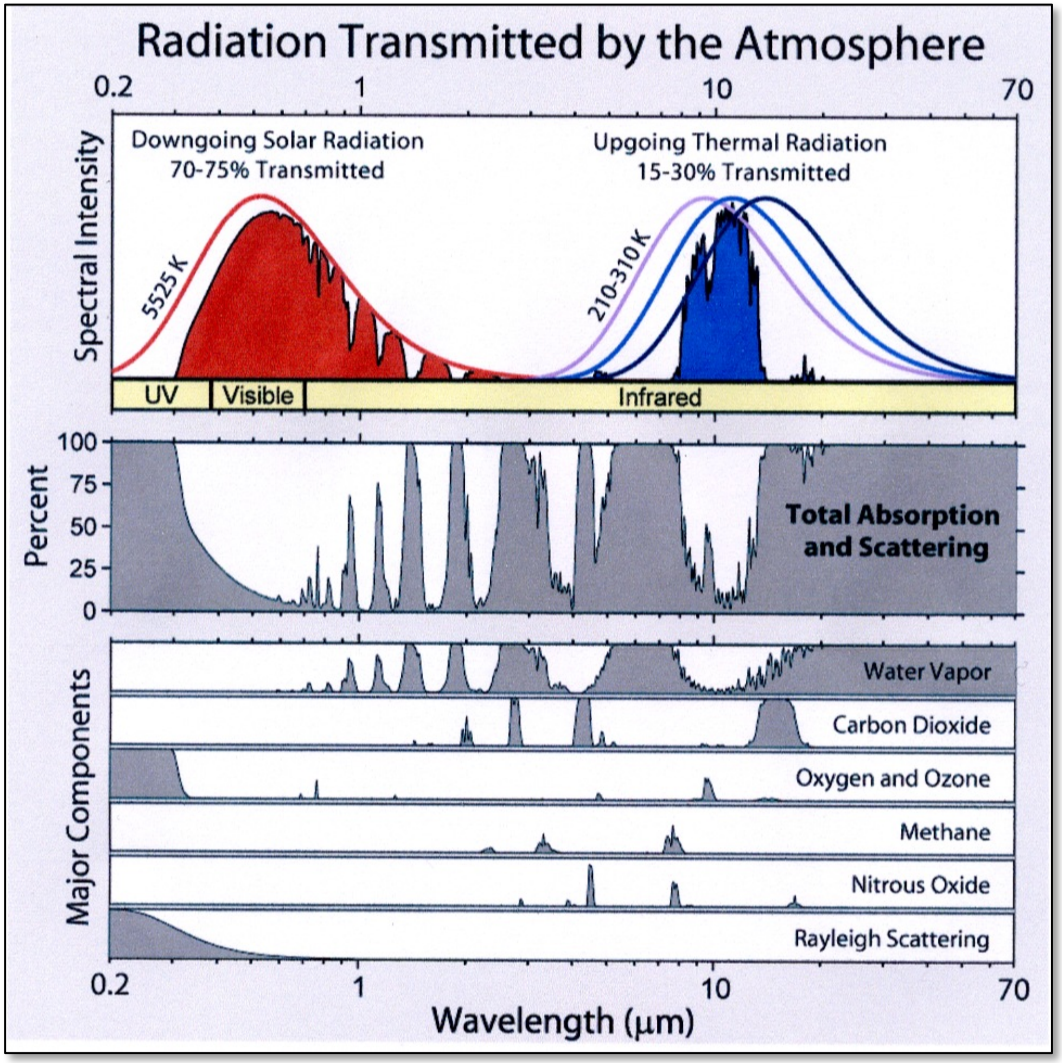
Radiative Forcing Components



Why Do H_2O and CO_2 Absorb Infrared Radiation?

- An individual photon has a quantity of energy related to its wavelength:

  E_γ = 1 eV x (1.24 μm / λ)



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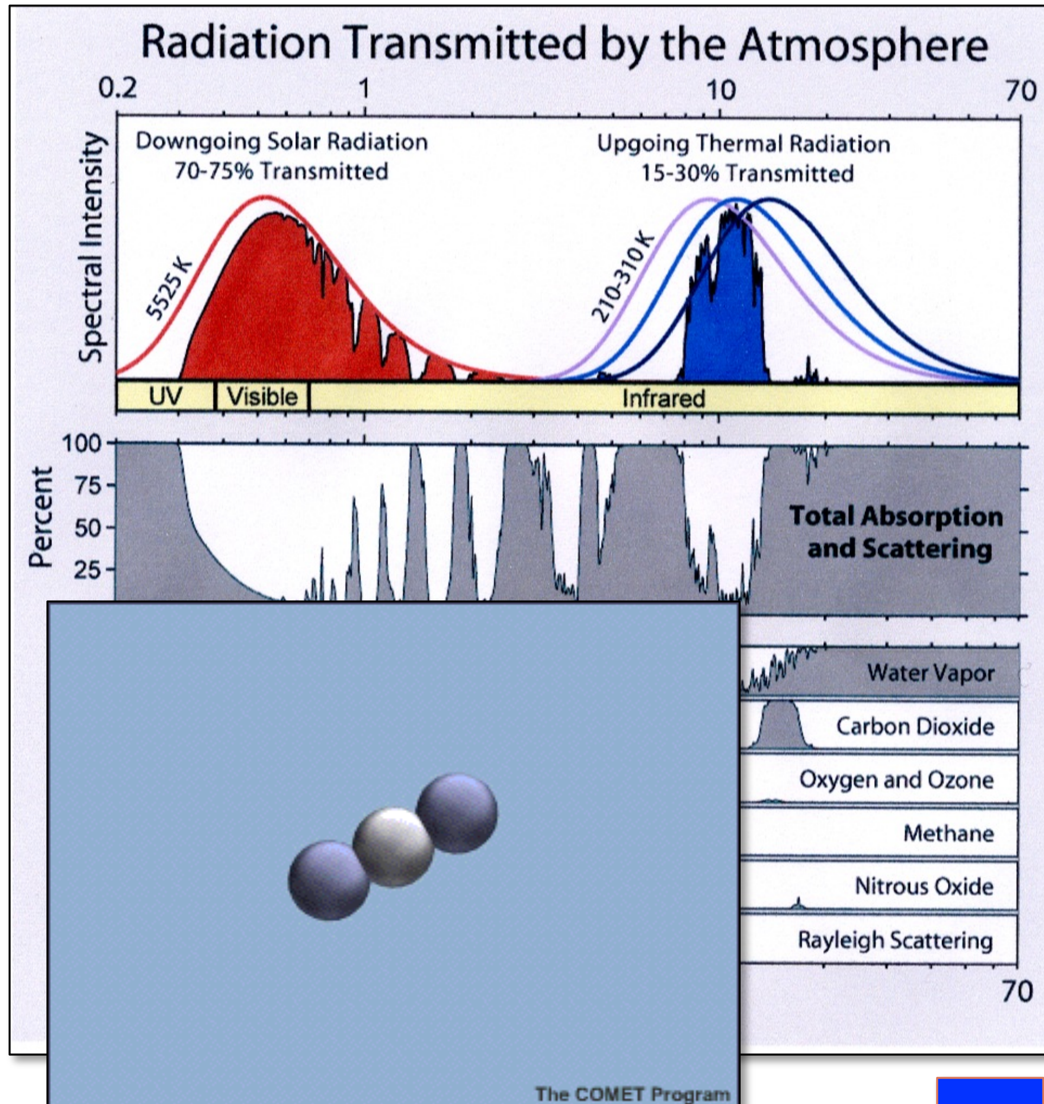
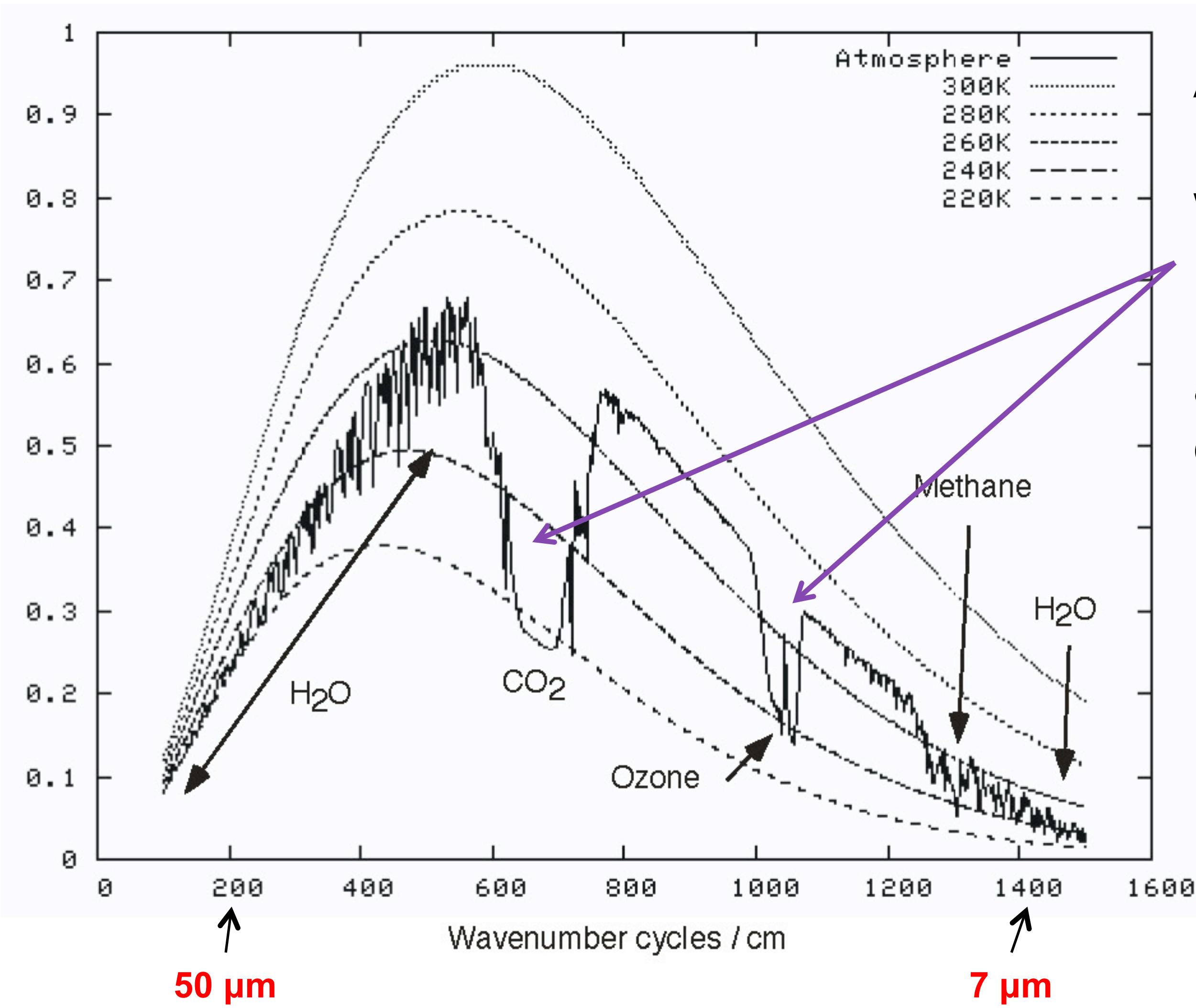
  $$E_\gamma = 1 \text{ eV} \times (1.24\ \mu\text{m} / \lambda)$$

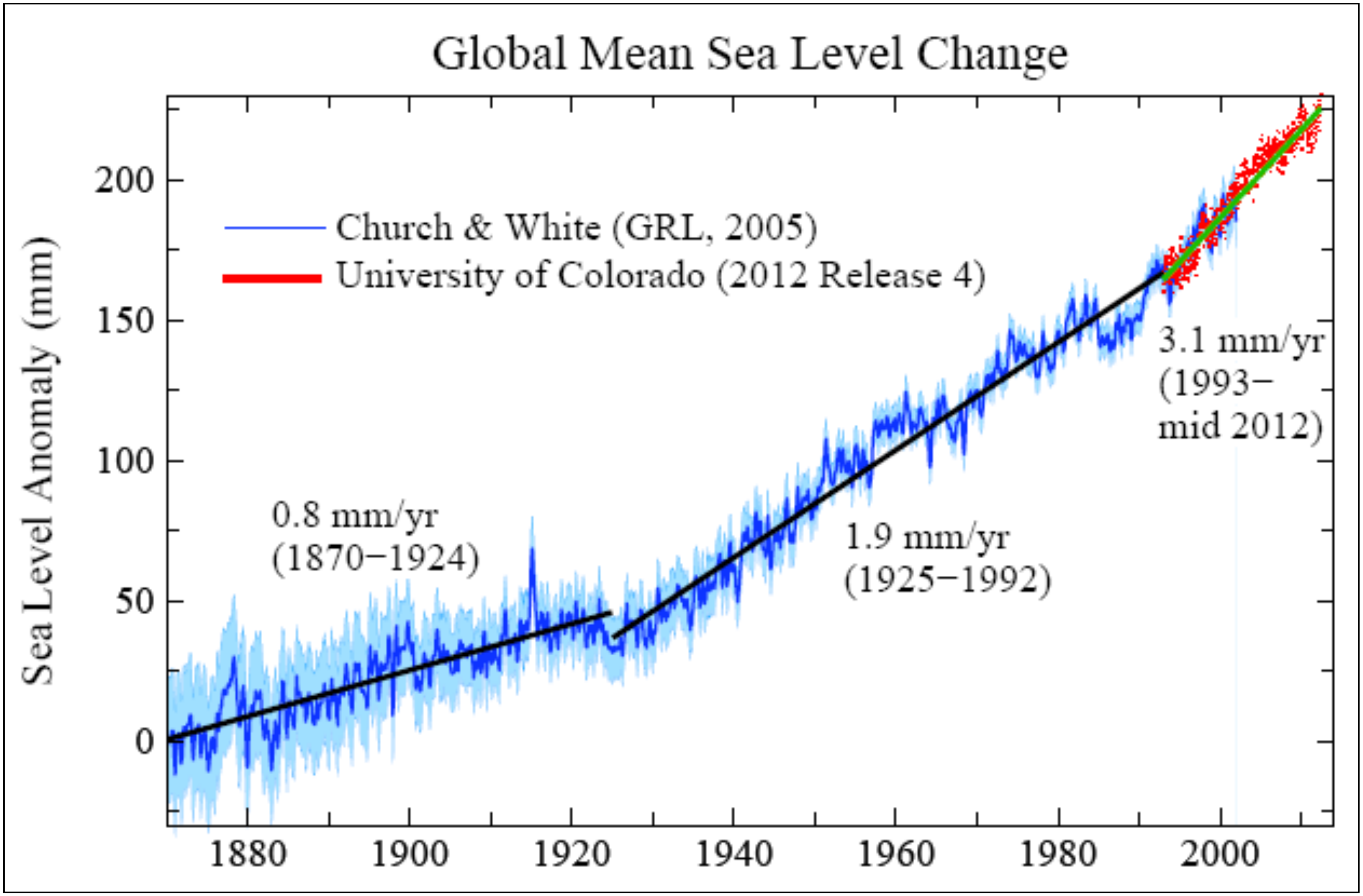
- Carbon dioxide (CO_2) and water vapor (H_2O) are triatomic molecules, which each efficiently vibrate at energies corresponding to IR wavelengths (but not at those of visible light)
- For comparison, most of our atmosphere is made up of diatomic molecules (N_2, O_2), which vibrate efficiently only at $E_\gamma > 5$ eV or $\lambda < 0.25\ \mu$m



Earth's Outgoing Radiation (As Seen From Space)



About half of the radiation at these wavelengths is being absorbed by CO_2 and O_3, and is re-radiated downwards



Most of the sea level rise is due to the warming of the ocean
Melting ice sheets will also contribute to rising sea levels