Ask-a-Scientist, January 5, 2014:

The Science of Climate Change

Dr. Erik Ramberg, Fermilab

- Solar irradiation and the Greenhouse Effect
- What forces are at work to change the Earth's temperature?
- What caused the Ice Ages?
- What is the latest data on temperature?
- How are the planet's ice sheets and oceans changing?
- Predictions for the future

The extinction optical thickness of aerosols from a free running 10-km GEOS-5 satellite, including: **dust (red)** **sea salt (blue)**, **black and organic carbon (green)** **and** **sulphate (white)**.

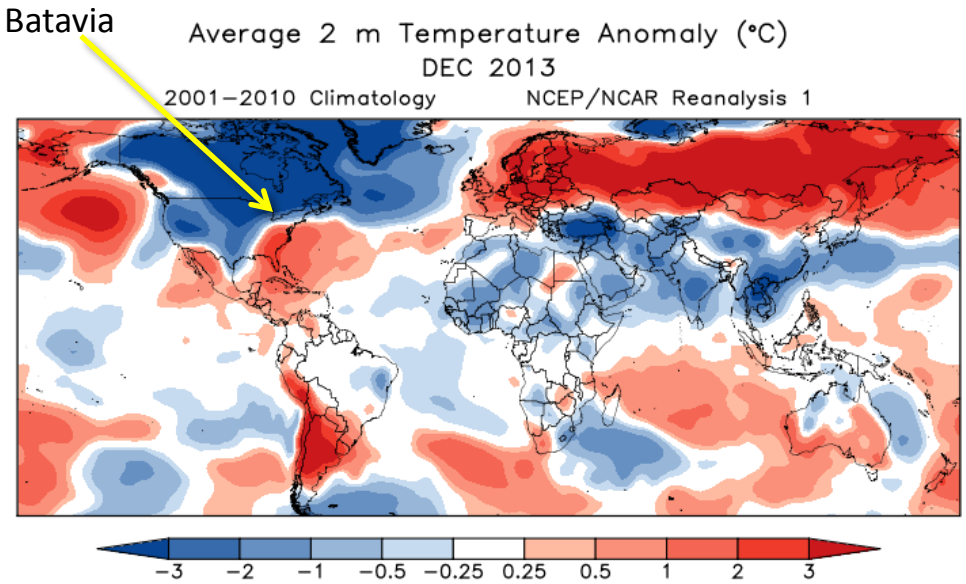
Three Key Concepts to Walk Away With:

- The Earth's climate is predictable
- The two biggest knobs that control climate on Earth are:
  - The planet's reflectivity
  - The amount of CO_2 in the atmosphere
- Global temperatures and ice volume indicate global warming has not stopped

Was 2013 a Cold Year for the Planet?

NO !

2013 was one of the hottest years in the history of mankind



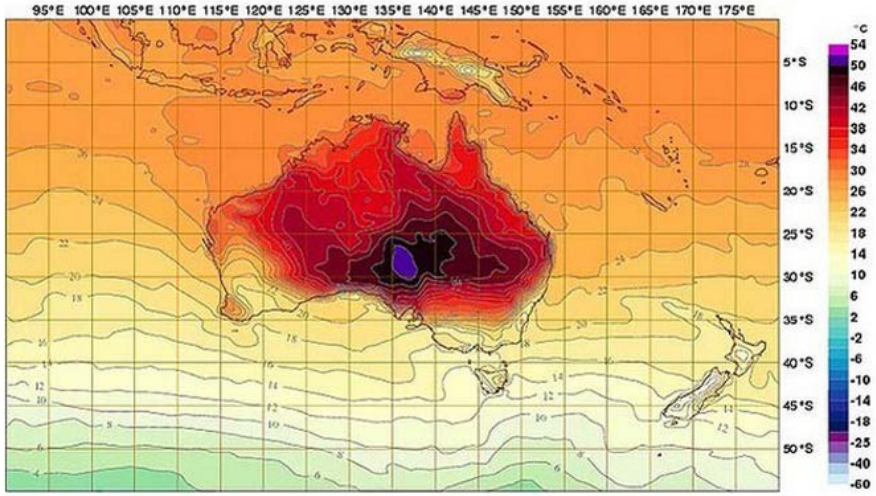
Global average temperature (Departures from 30-year norm, °C)

Rank	Year	Temp.
1	1998	0.419
2	2010	0.398
3	2005	0.260
4	**2013**	**0.236**
5	2002	0.21
6	2009	0.209
7	2007	0.204
8	2003	0.187
9	2006	0.186
10	2012	0.170

(Christy, et.al. 2014)

Australia has been particularly hellish this past year

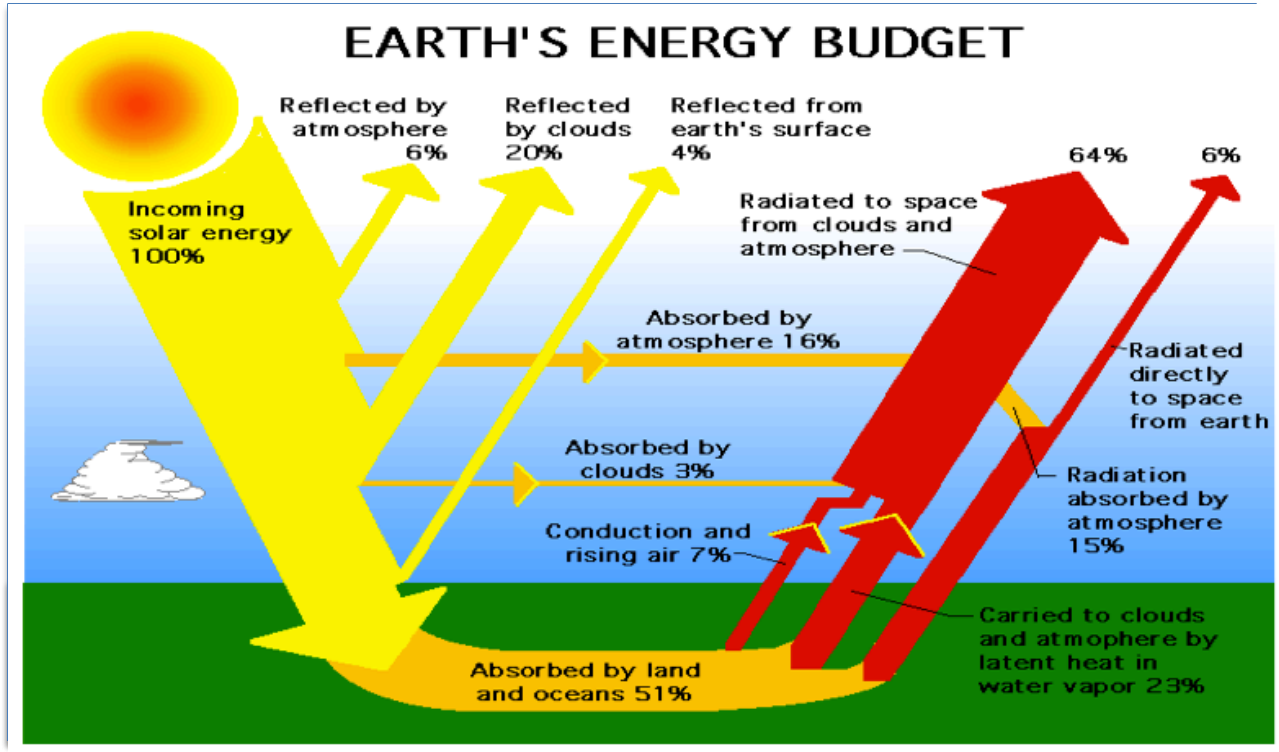
- Massive firestorms
- Lions fed frozen blood to keep them cool,
- New color added to temperature map: purple is > 120° F
- Australian Open player hallucinates an image of Snoopy



Be careful wishing for a warmer climate!

Thermal Energy on Earth

Energy flow in the Earth system



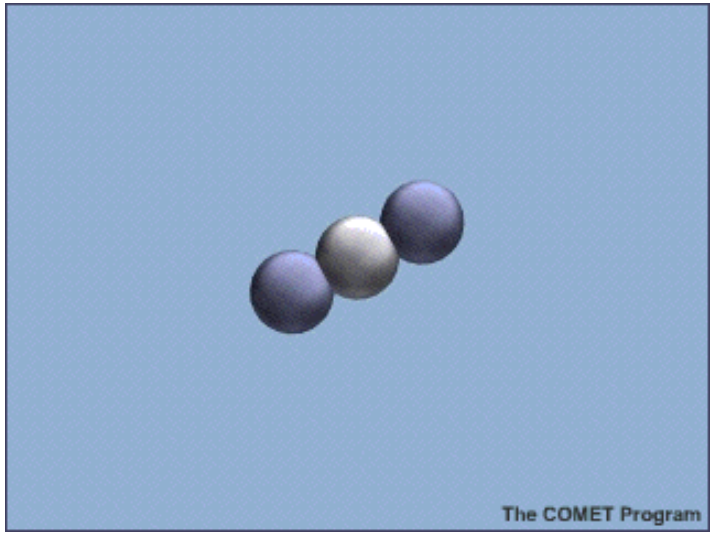
Without greenhouse gases in our atmosphere, the Earth's surface would be at -**18 degrees C. (0 degrees F)**

With greenhouse gases in our atmosphere, the Earth's surface is at a balmy **17° C (60° F).**

The [illegible] before it hits the surface.

CO_2 absorbs infrared light by bending and stretching its chemical bonds and then re-emits it in all directions.

Discovered by John Tyndall in 1865



Water vapor (H_2O) and methane (CH_4) act this way also, and have much stronger absorption than CO_2:

All 3 gases cause trapping of some of the infrared heat coming from the surface of the Earth: the **Greenhouse Effect** !

Greenhouse Effect 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° ..."

Guess what? His predictions still hold up today, 118 years later!

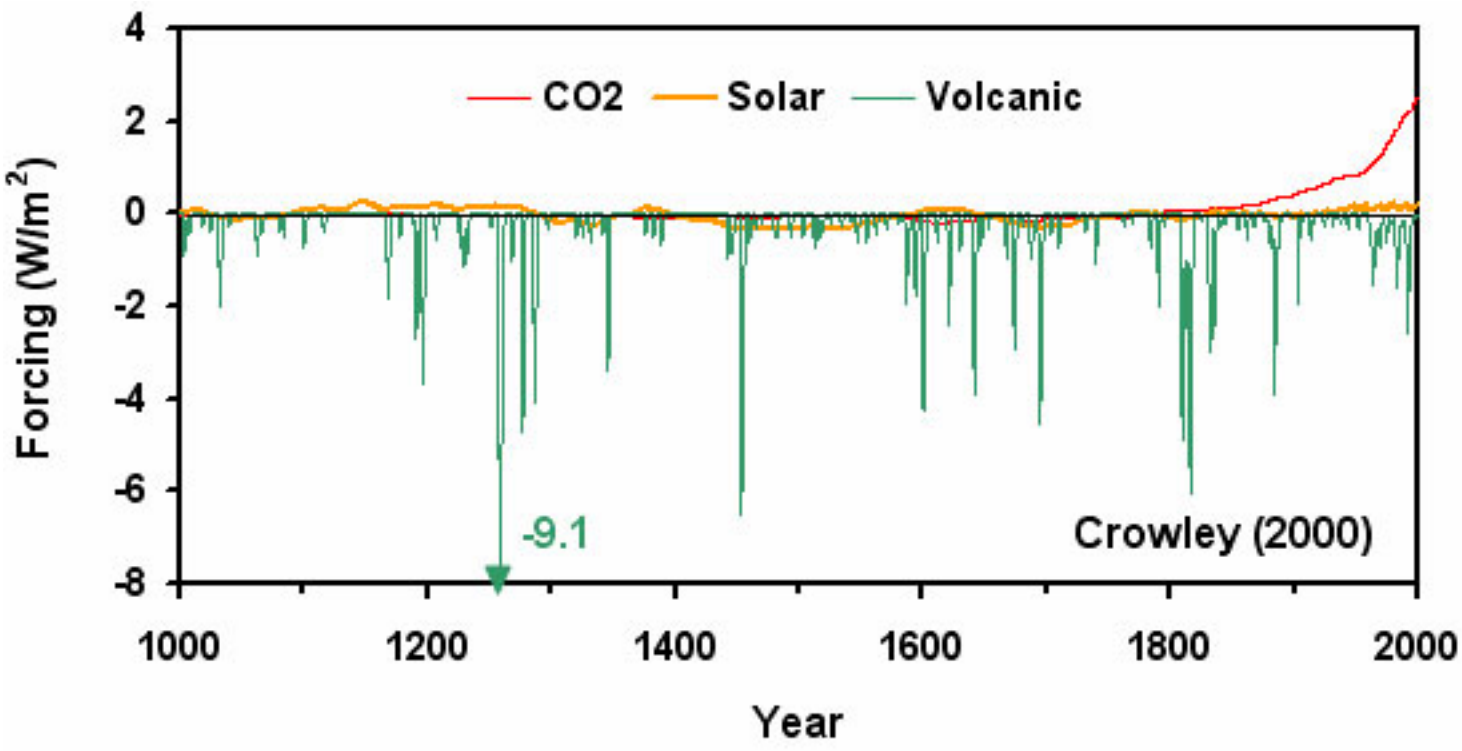
Doubling of CO_2 is expected to raise temperatures between 2.5-4 degrees

If water vapor is a stronger greenhouse gas than carbon dioxide, then why do we have a CO_2 problem, not an H_2O problem ?

The lifetime of water in the atmosphere is about a week, while the lifetime of CO_2 in the atmosphere is on the order of 100 to 1000 years.

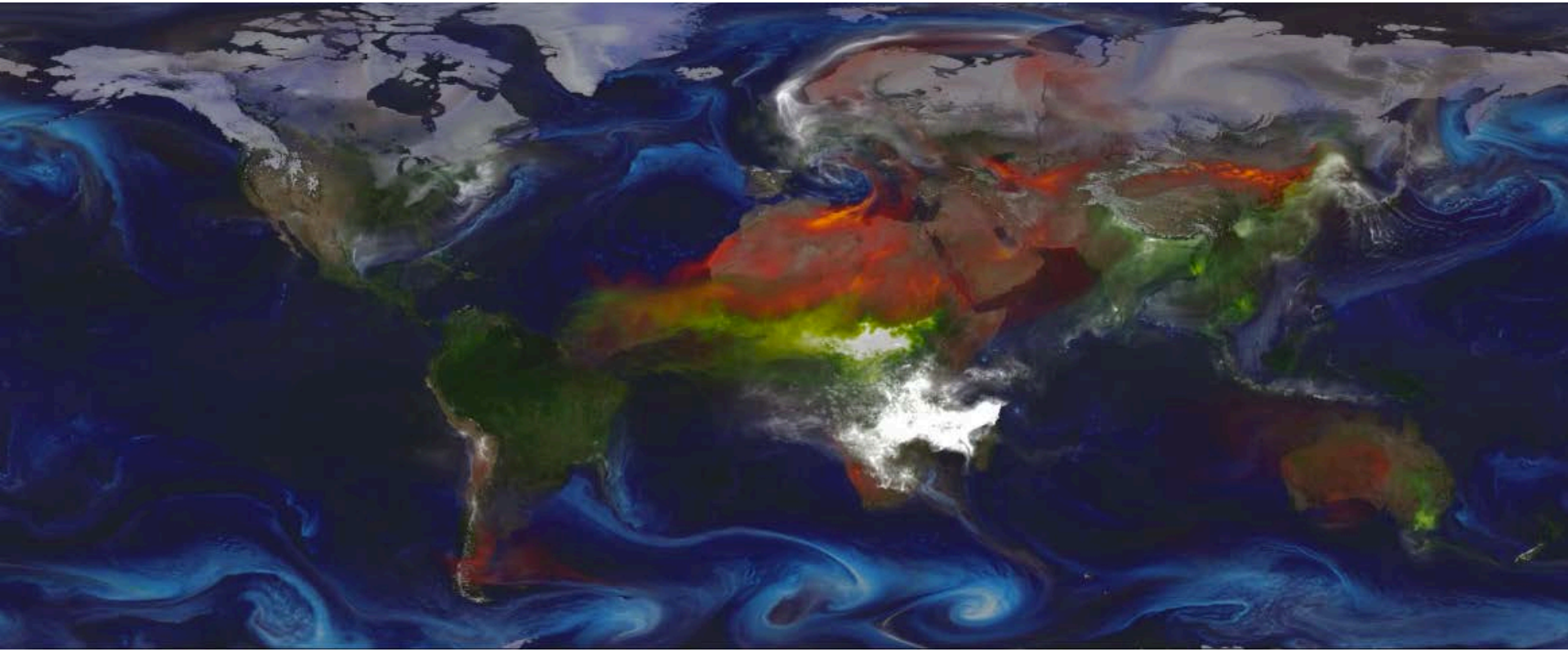
Forcings

Forces acting on the climate

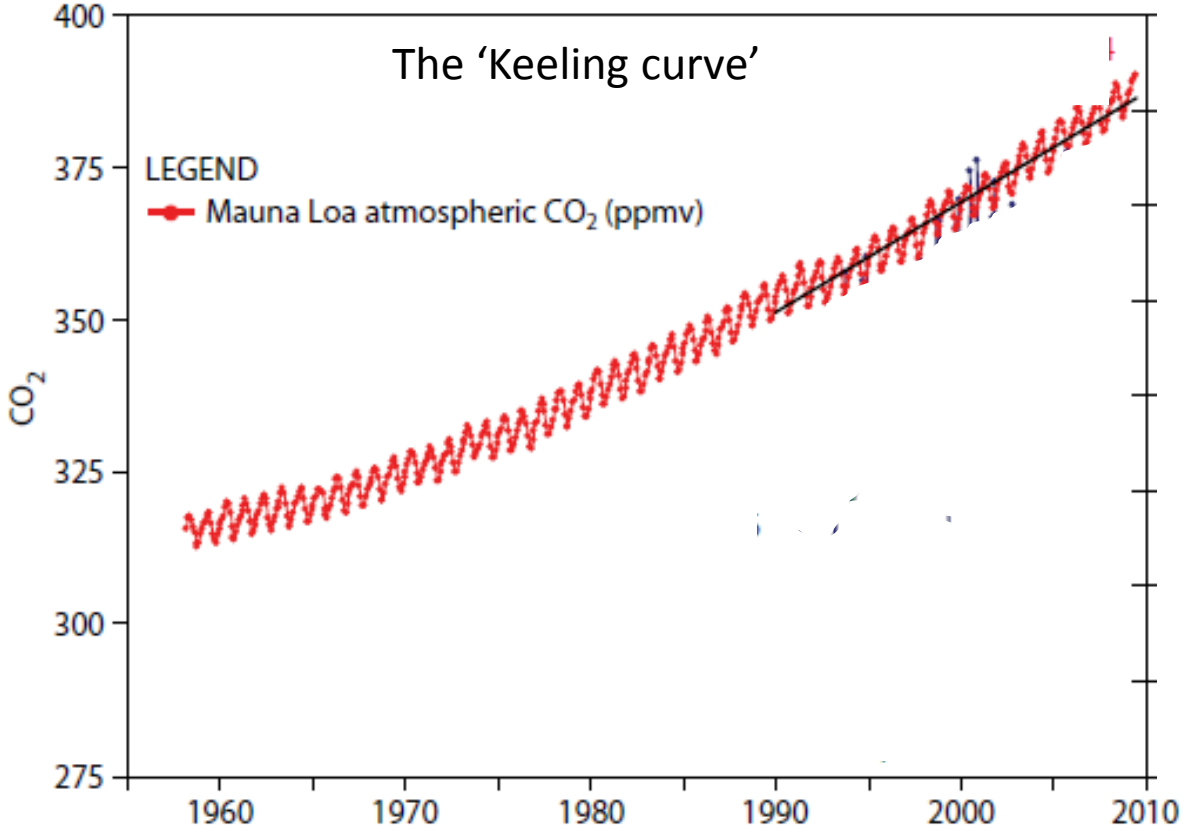


- Volcanic dust (an 'aerosol') increases the reflectivity of the Earth and thus has a cooling effect on climate.
- But, like water, the aerosol falls out of the atmosphere (in about 2 years) and the reflectivity and climate return to their normal value.
- The average effect of volcanic aerosols on climate is smaller than the steady increase in heat trapping CO_2
- The Sun doesn't have a major effect on climate on the 1000 year time scale.

Volcano Exploding in Madagascar

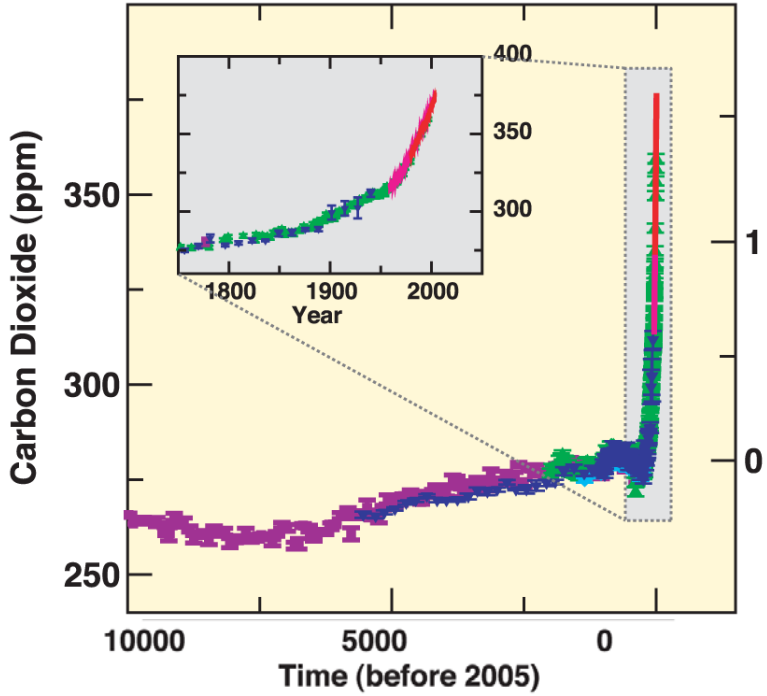


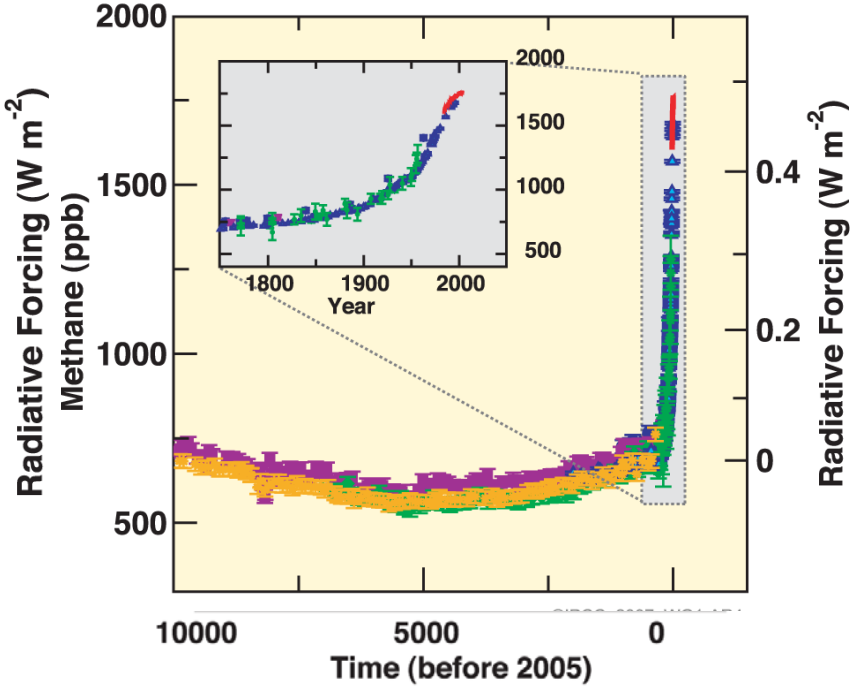
CO_2 in the Ocean Atmosphere



- The 'missing' CO_2 is going into the ocean
- The 'missing' CO_2 is so fuel is causing the CO_2 concentration in the atmosphere to rise significantly. Isotopes show this is fossil based CO_2.
- The ocean is getting significantly more acidic as a consequence.
- This is actually less than what we predict from industrial processes. Where is the rest of the CO_2?

CO_2 and other Green House Gases (GHG) are now the dominant elements of climate forcing, and this situation has been instantaneous on geological time scales





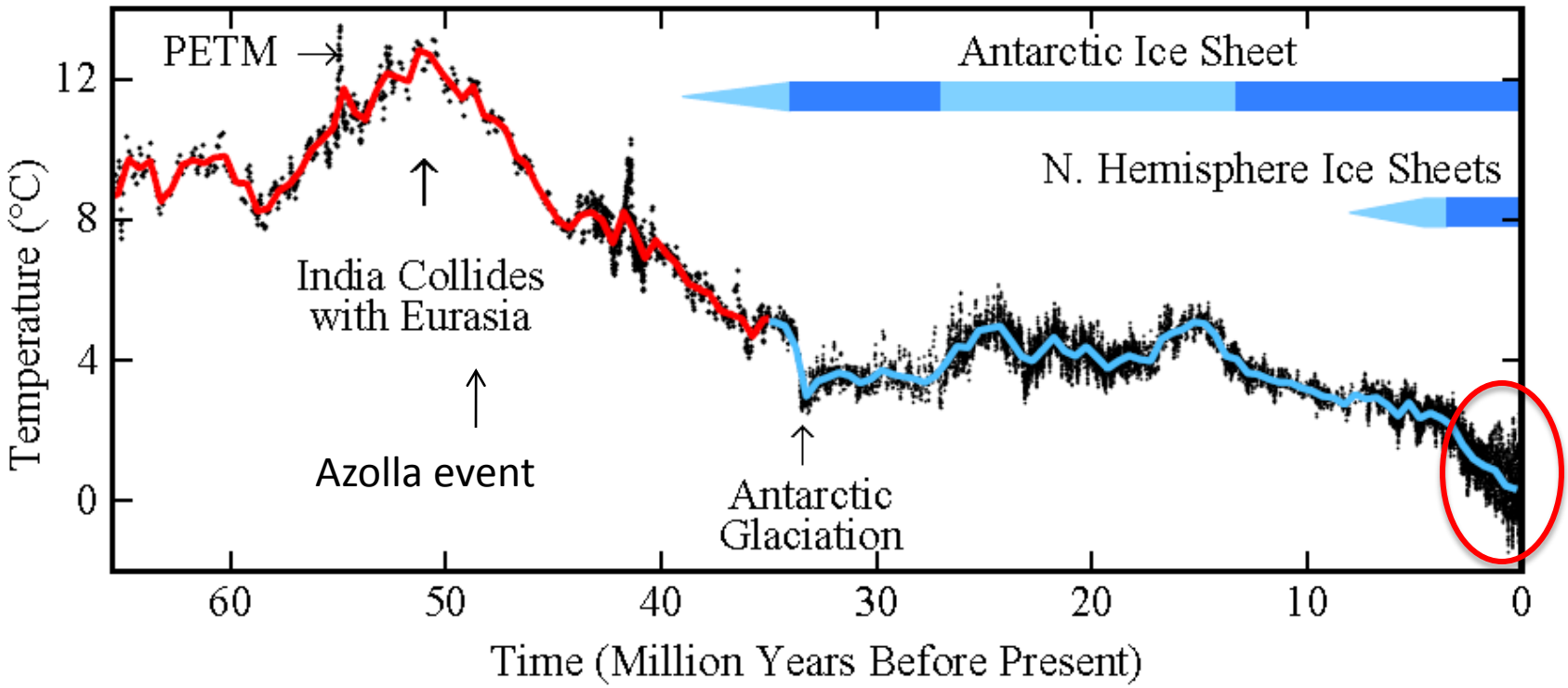
CO_2

Methane

Source: IPCC AR4

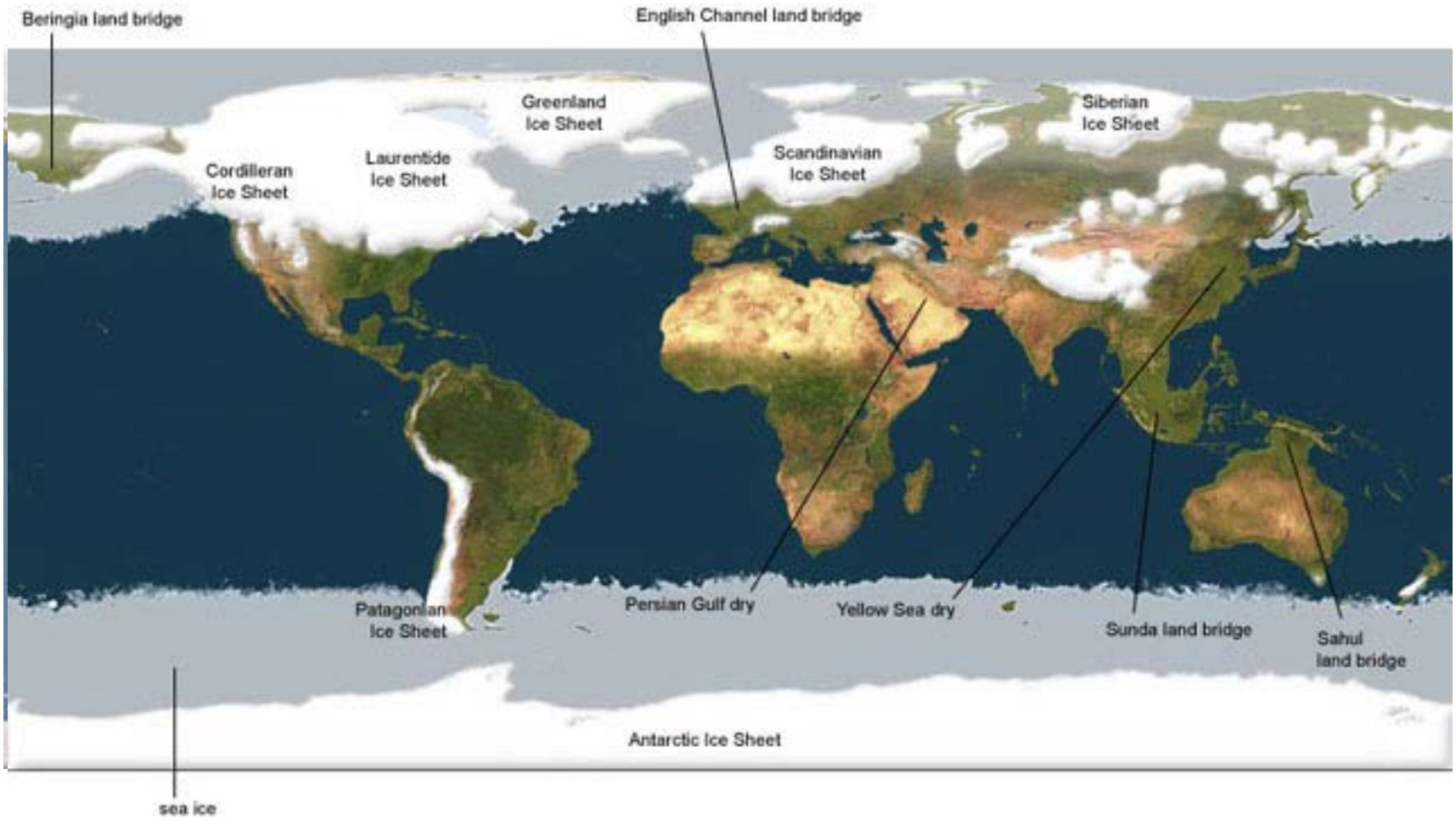
The Ice Ages

The Slooow 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

Ice Sheets During Last Ice Age



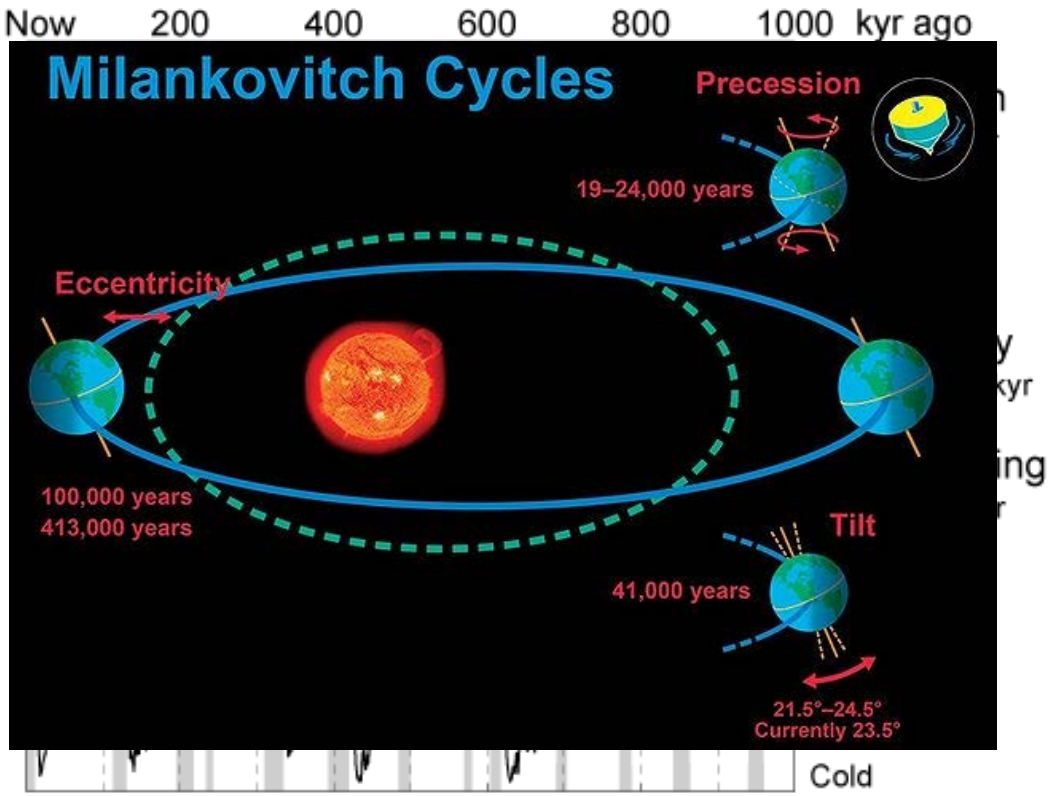
Two important changes that accelerate the freezing:

1) High reflectivity from the new ice

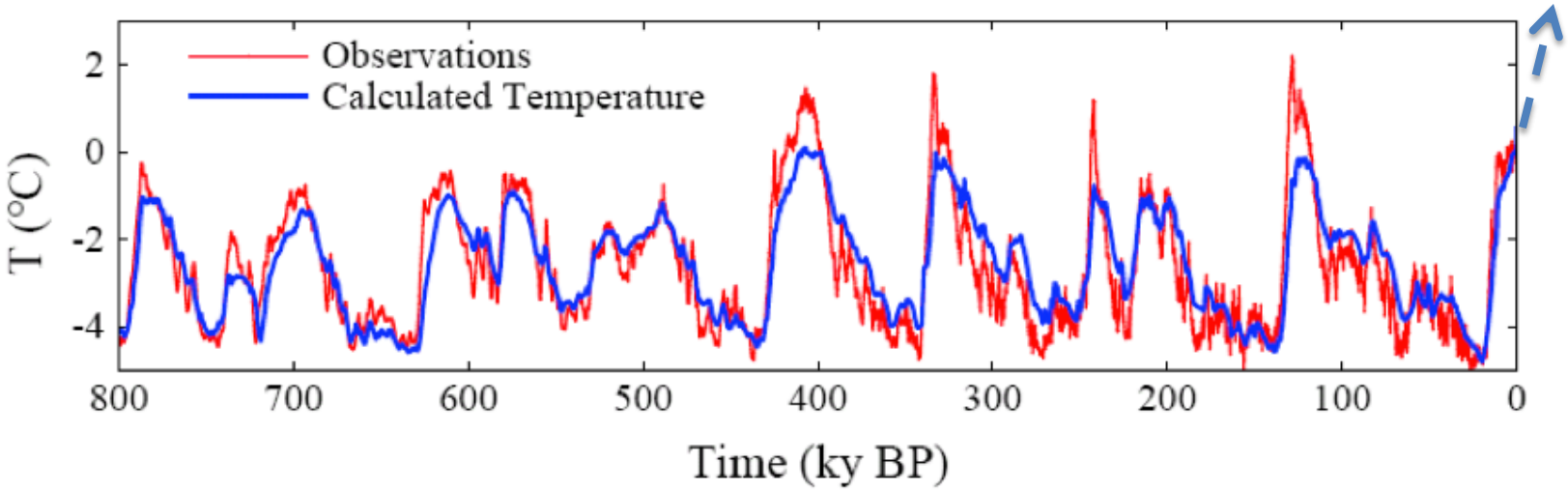
2) The cooling ocean absorbs CO_2

Milankovitch Cycles

- These cycles occur because of the various wobblings of the Earth's orbit
- They happen over a period of tens of thousands of years.
- This affects the average sunlight hitting the Northern Hemisphere
- The Ice Ages are then caused by the two main amplification mechanisms: ice sheet albedo and CO_2 uptake into the cooling ocean.



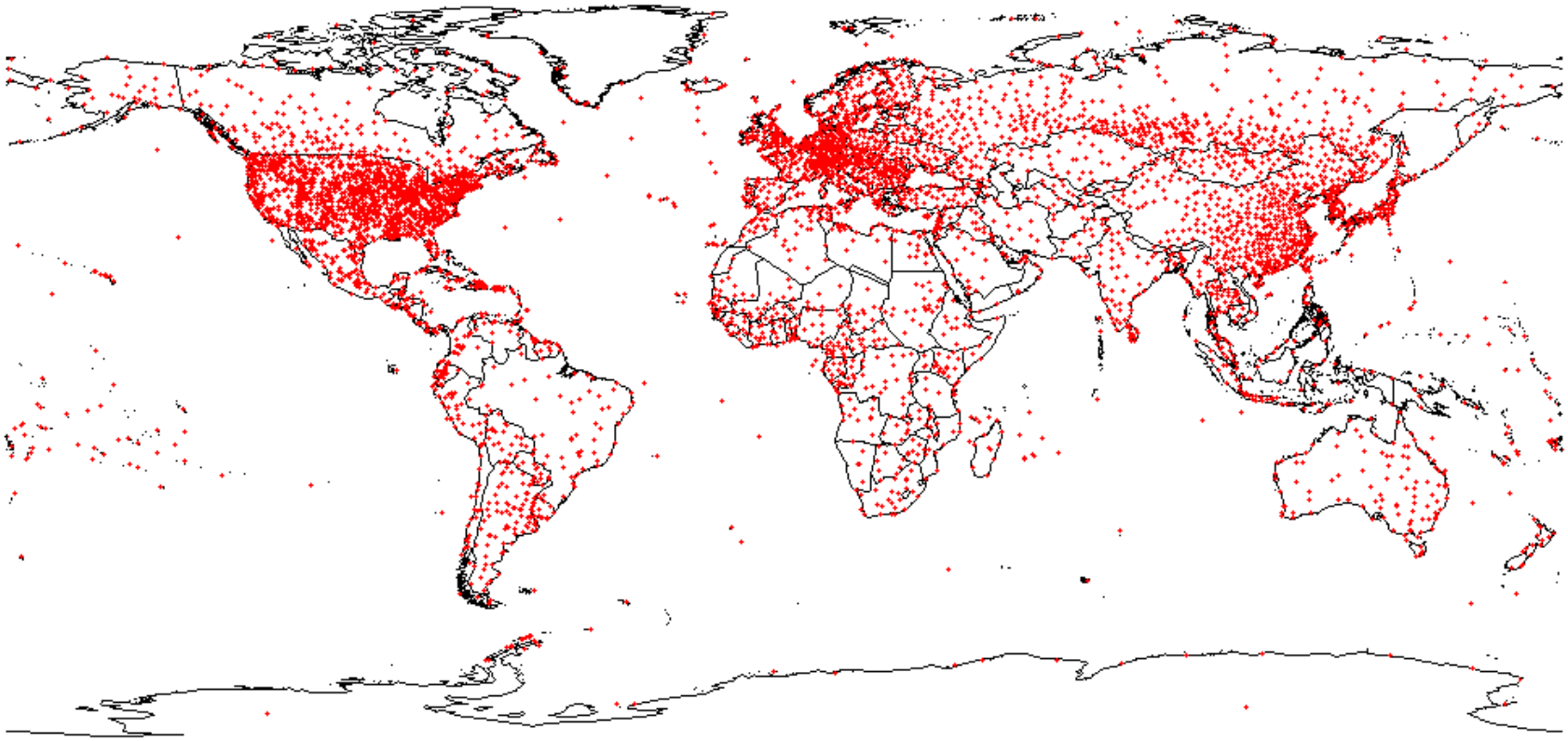
The Ice Age Climate is Predictable



- We understand all the cycles and bumps of the last 800,000 years.
- From this data, we now know that we will be increasing the temperature of the Earth 3° C – and we will shut off the Ice Ages forever. (Yay!)
- Unfortunately, we may not stop there. We will likely start climbing up the temperature curve back into the Eocene Era. (Boo!)

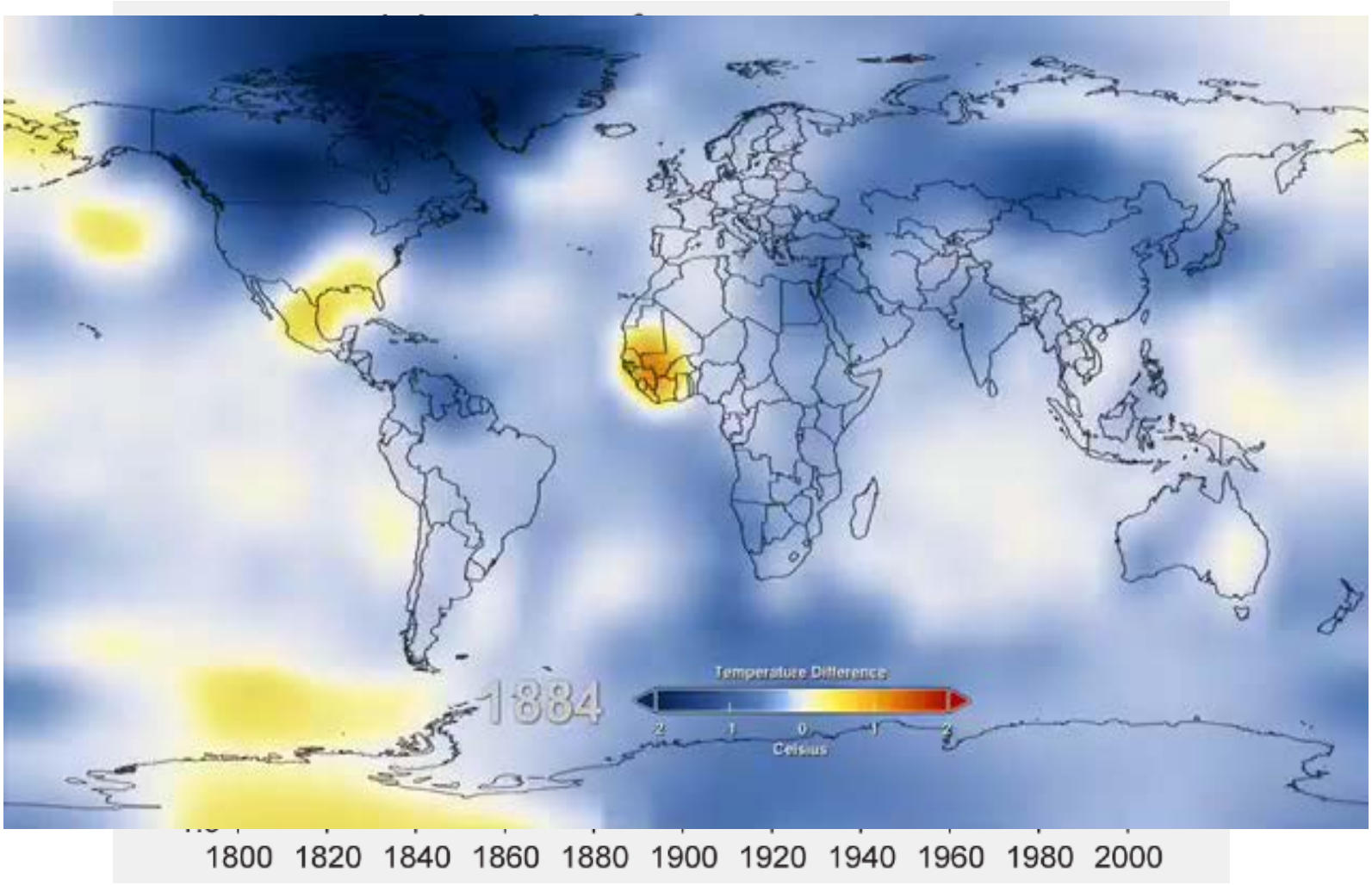
Measurement of Earth's Surface Temperature

GHCN Version 1 Temperature Stations



Only 200 temperature stations, equally spaced, would give enough information to calculate the mean temperature of the Earth

Gridded Mean Surface Temperatures Over 125 years



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

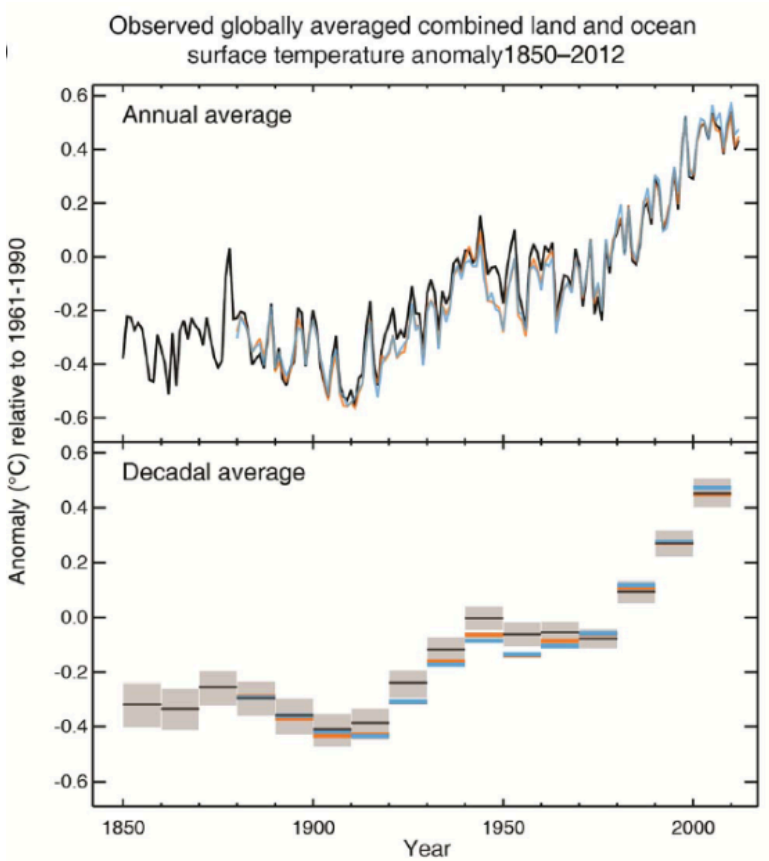
every second

Has Global Warming ‘Stopped’ ?

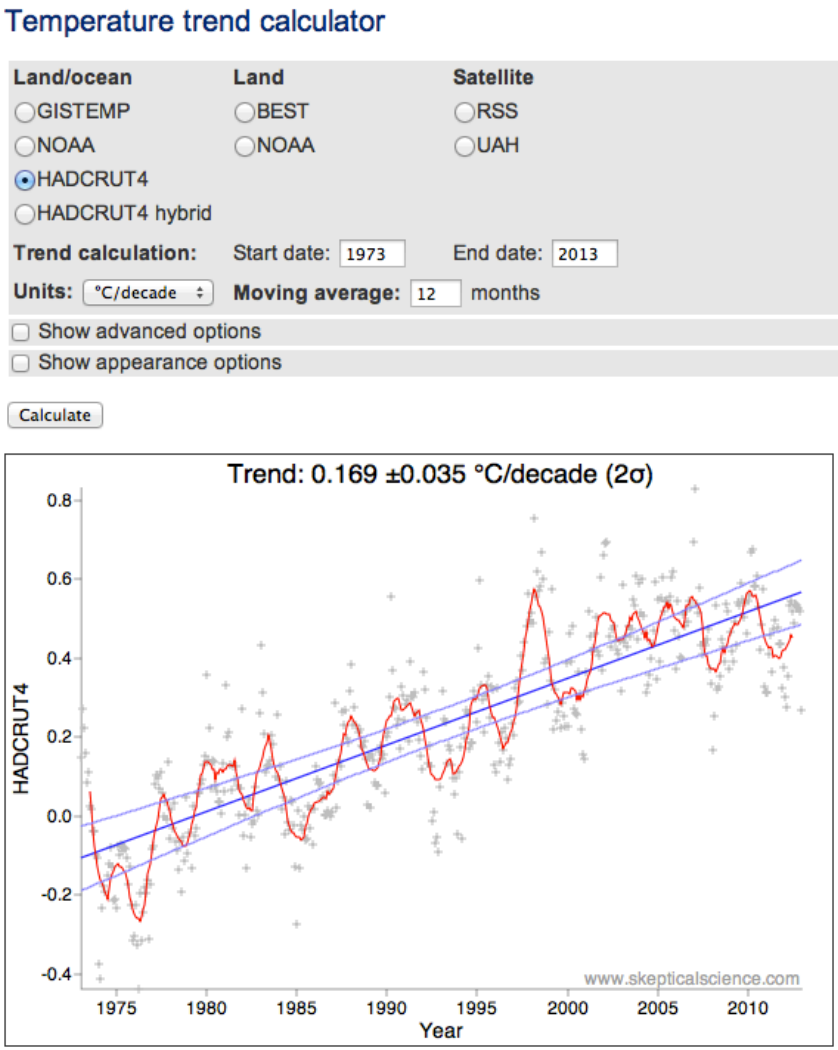
- Here is the NASA yearly mean global temperature data. The 10-year average indicates that the Earth is steadily warming up

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	0.43
1998	0.62	
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	0.59
2008	0.49	
2009	0.60	
2010	0.67	
2011	0.55	
2012	0.57	
2013	*	

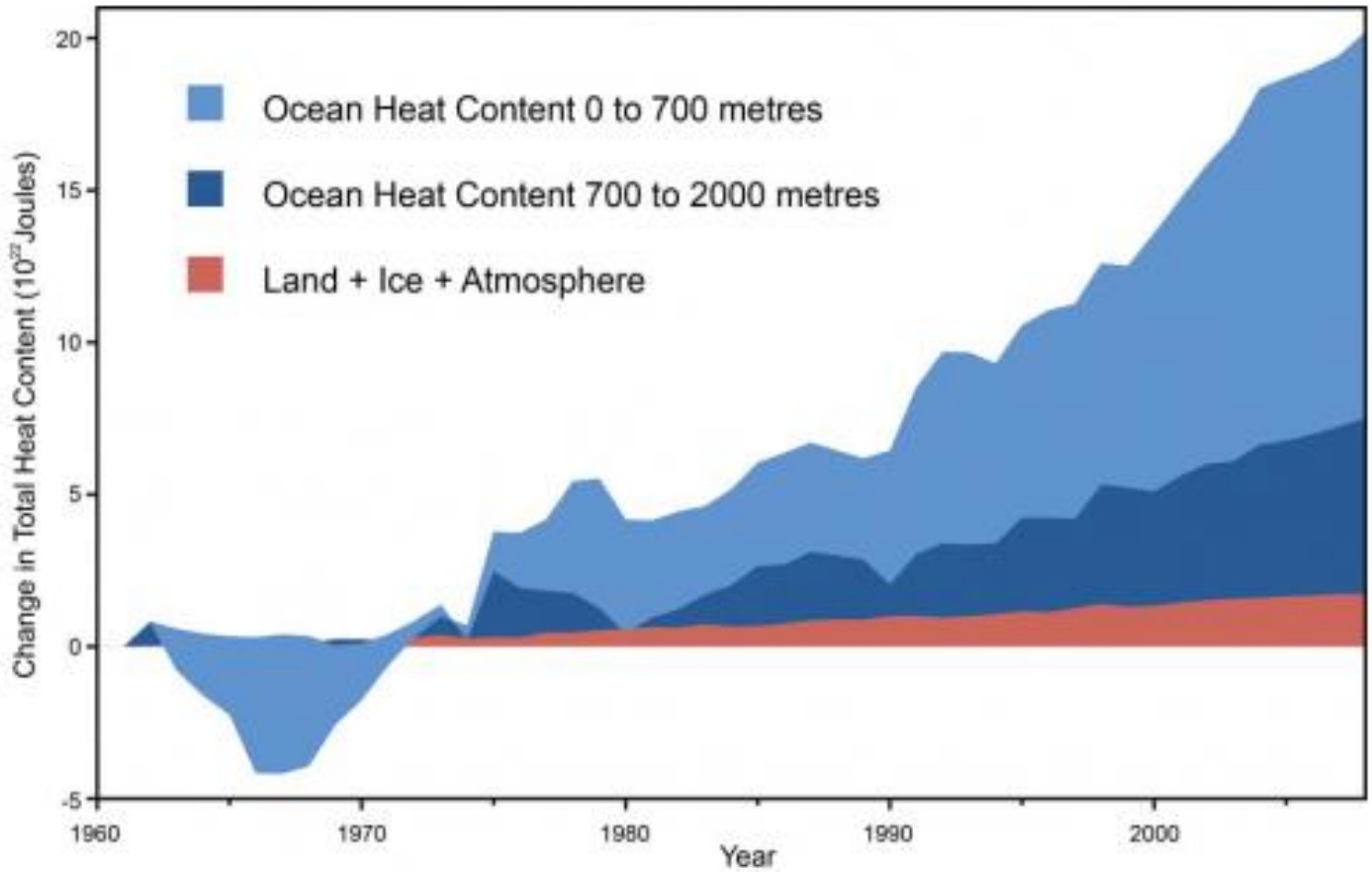


An excellent trend calculator (skepticalscience.com)



Water and Ice

Nuccitelli et al 2012 Total Heat Content

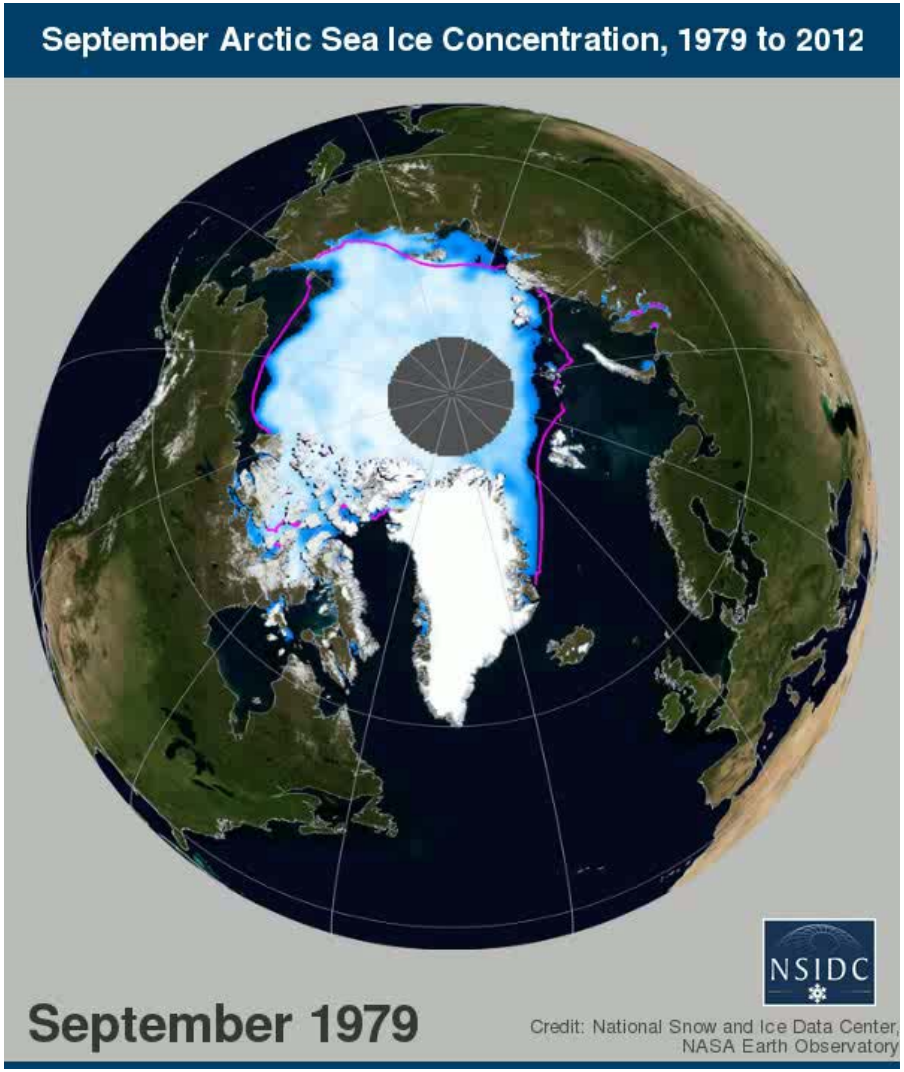


Most of the added heat is absorbed in the ocean.

Will it be able to provide this buffer in the future?

What is it doing to deep sea ecology?

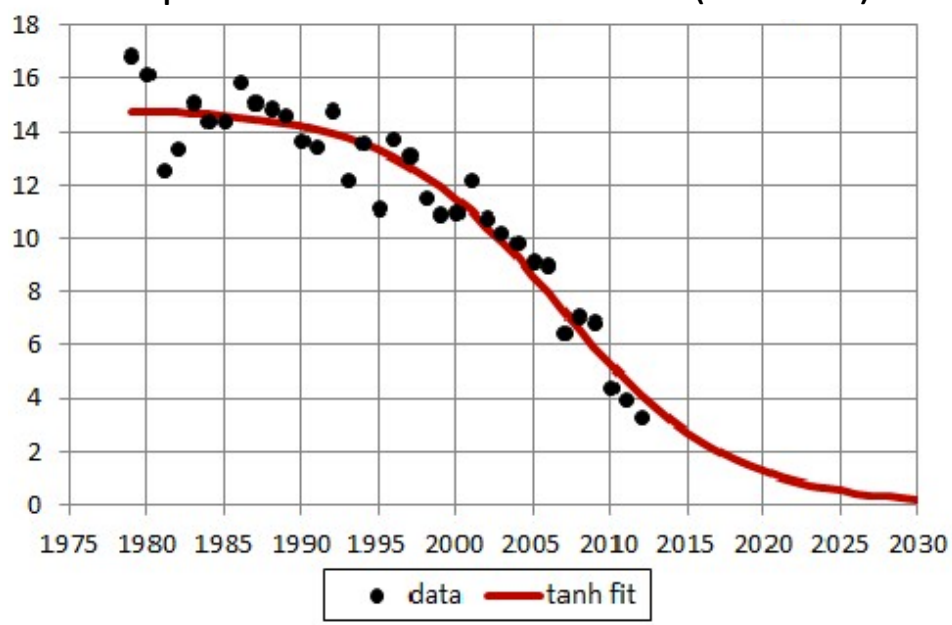
A Consequence of this Enormous Ocean Heat - Melting Ice !



Pay attention to ice volume, not area. Most of the melting is due to thinning of ice.

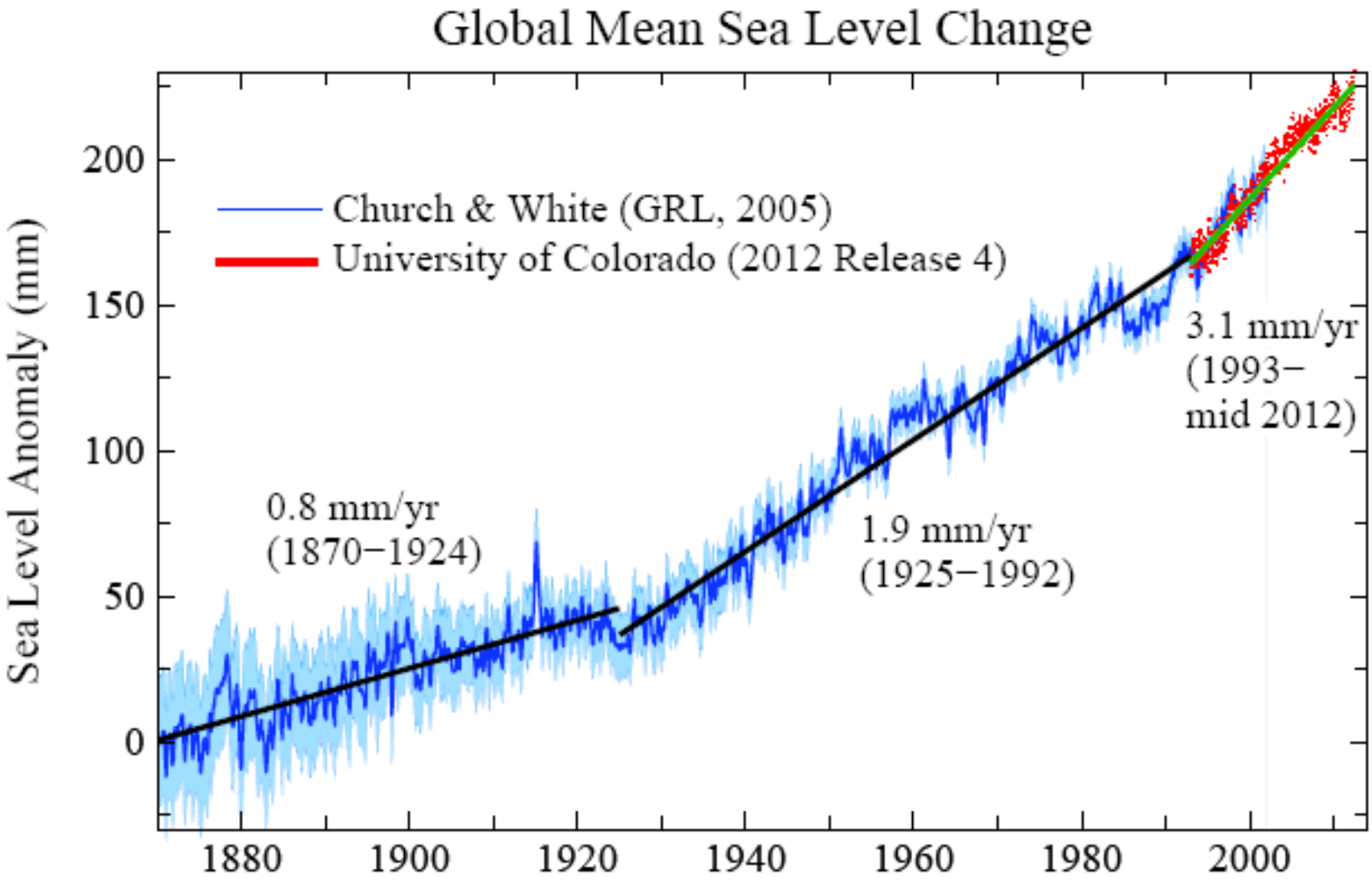
These maps show that we are rapidly transitioning to a world without permanent Arctic Ice

September Arctic Ice Volume (10^3 km^3)



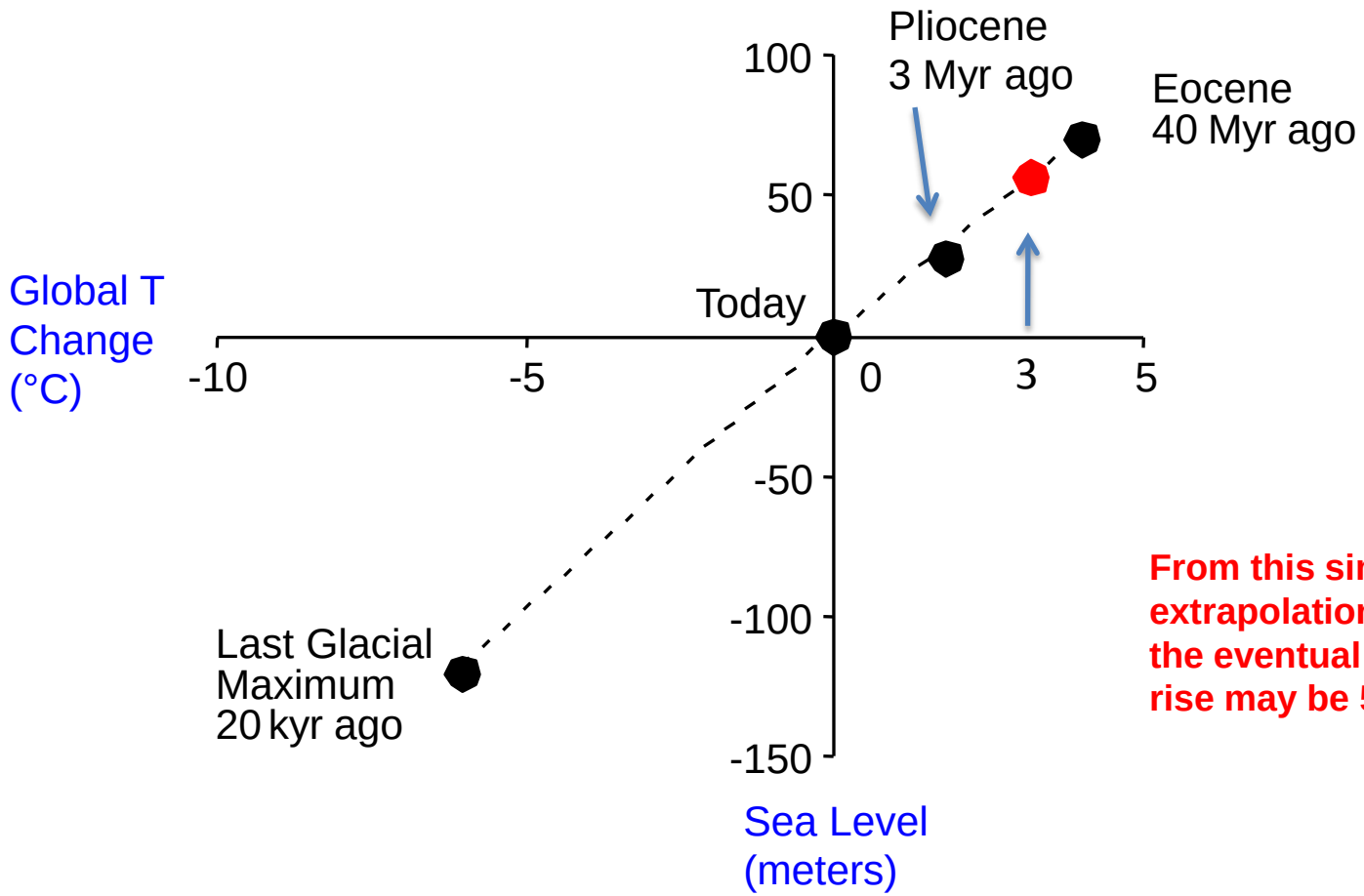
Results from the GRACE satellites

Loss of mass in all three of the Earth's major ice sheets is of the same order and is accelerating.



Most of the sea level rise is due to the warming of the ocean.
Melting ice sheets will continue to contribute to sea level rise.

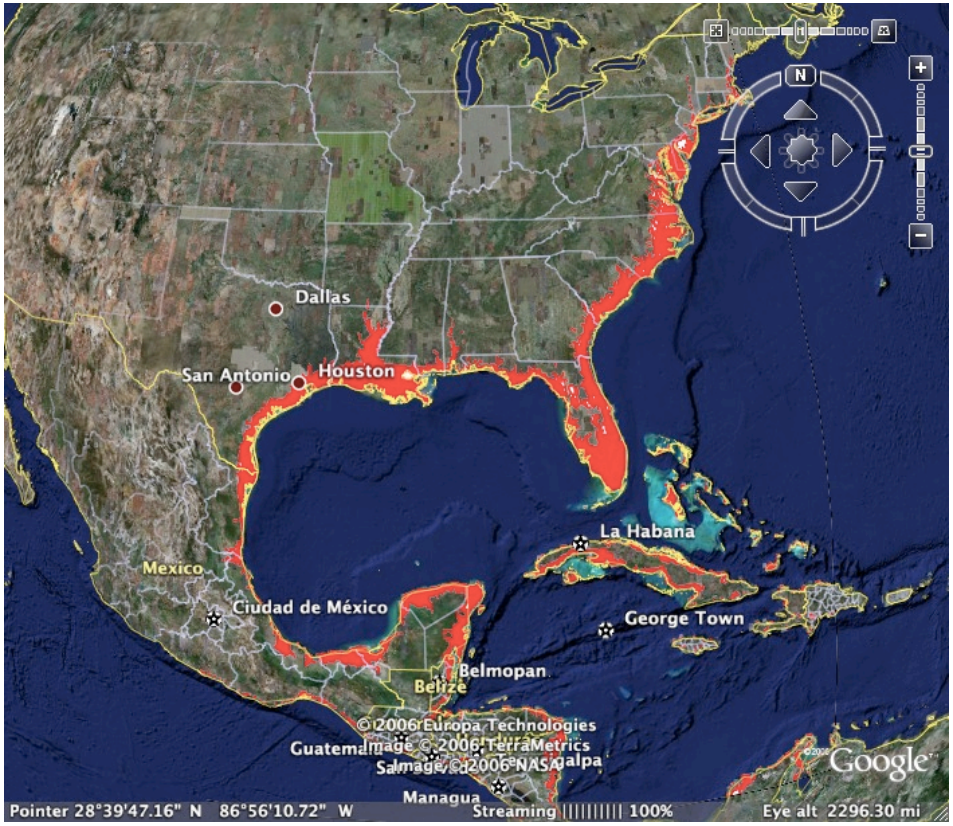
Simple Sea Level Extrapolation, Using Historical Data, Not Models



From this simple extrapolation of data, the eventual sea level rise may be 50 meters!

Source: David Archer, U.C.

Map of 20 meter Rise of Sea Level



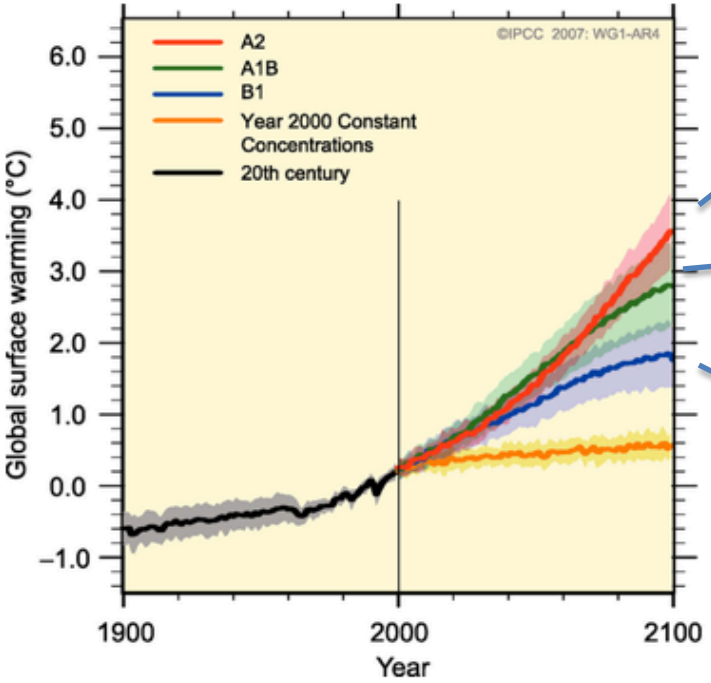
Note: this will not happen in your lifetime.
We can talk about it without a sense of panic.
However, it very likely WILL happen

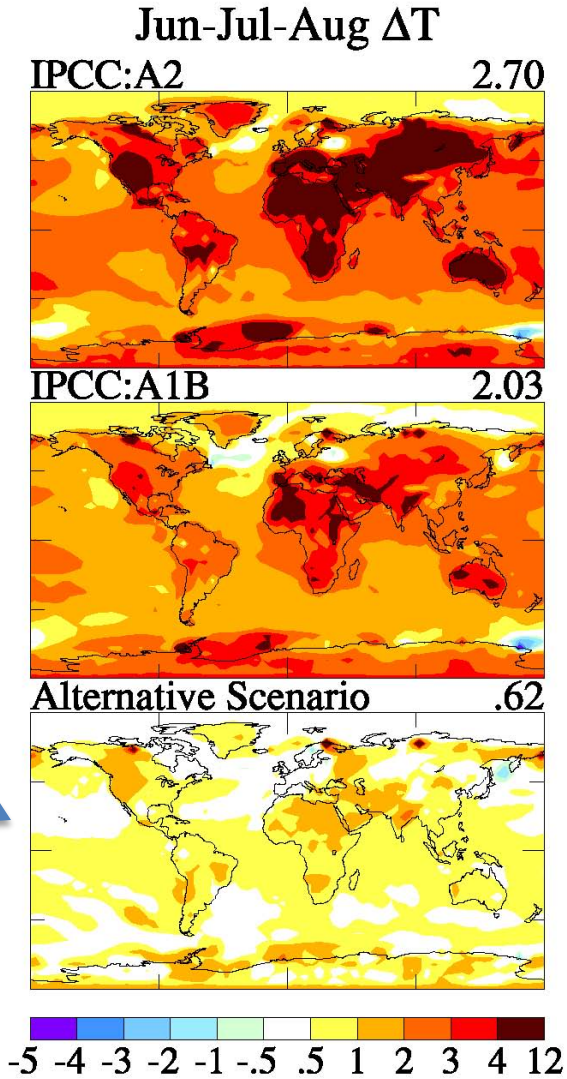
How long will it take? 500 Years? 200 Years? 100 Years? Nobody really knows.

Facing the Future

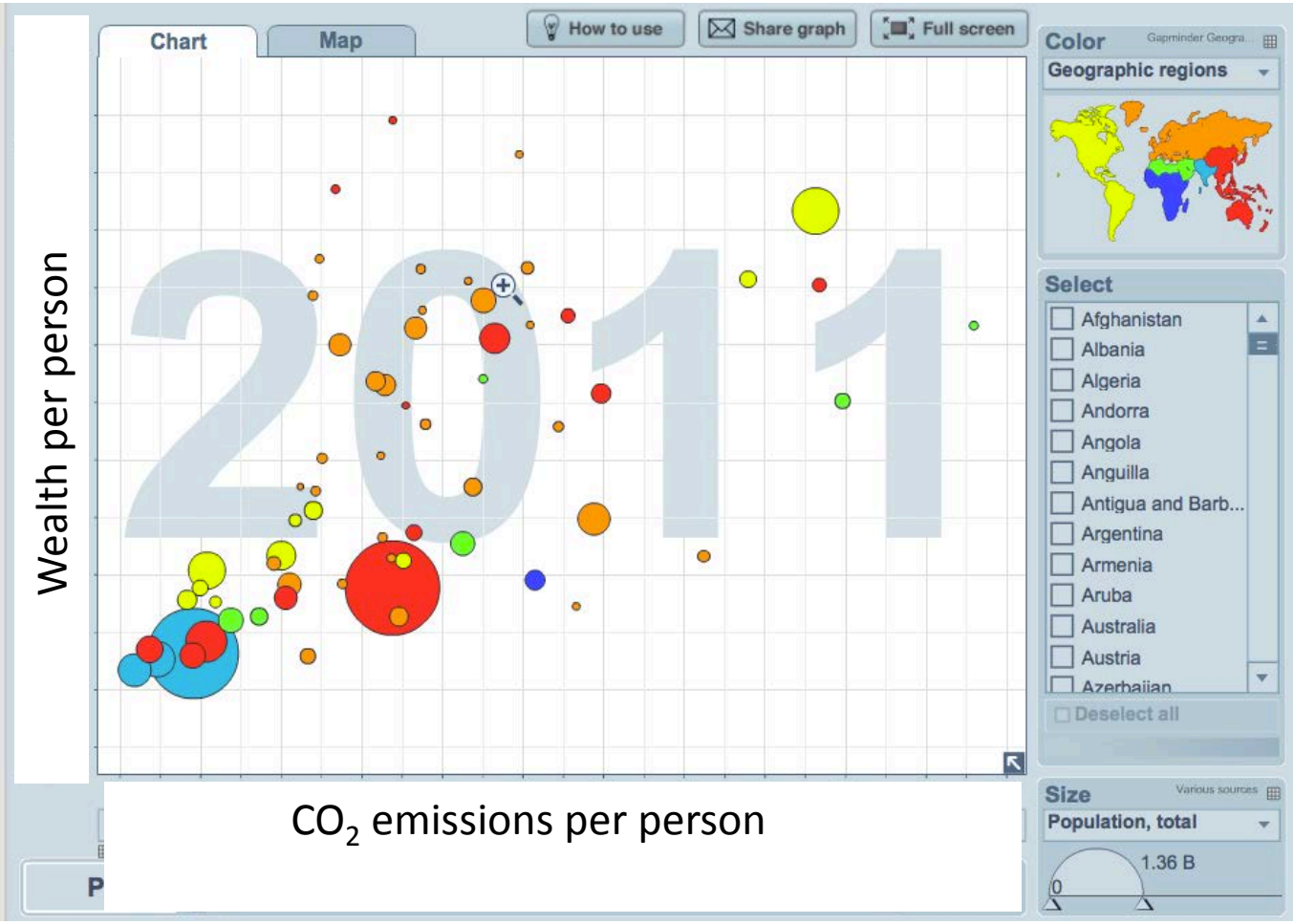
Predicted 2000-2100 Temperature Change

We don't know how hot it is going to get, since we don't know how fast carbon emissions will rise.





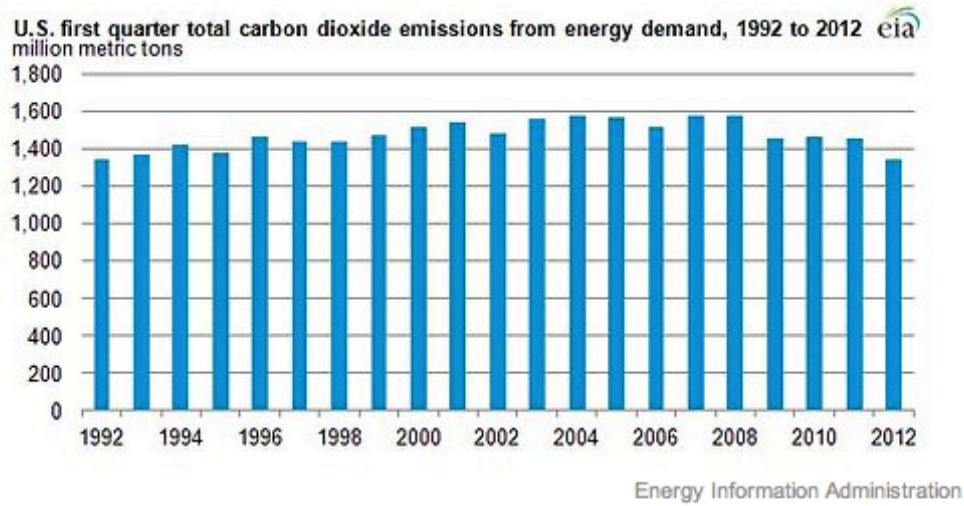
The Economic Imperative for Burning Carbon



Gapminder.org

A 20-Year Low in U.S. Carbon Emissions

By RACHEL NUWER



In the first three months of this year, energy-related carbon dioxide emissions were lower than in any first quarter in 20 years.

Business

Energy-related carbon dioxide emissions in the United States from January through March were the lowest of any recorded for the first quarter of the year since 1992, the federal Energy Information Administration reports.

The agency attributed the decline to a combination of three factors: a mild winter, reduced demand for gasoline and, most significant, a drop in coal-fired electricity generation because of historically low natural gas prices. Whether emissions will continue to drop or begin to rise again, however, remains to be seen, experts said Friday.

Natural Gas:	1100 lbs C/MWh
Oil:	1600 lbs C/MWh
Coal:	2200 lbs C/MWh

→ Natural gas is very much more efficient than coal. If we wish to reduce CO_2 emission, switching generation plants to natural gas can be a good start.

Summary

- Climate on Earth is predictable
- The two main 'knobs' that control our climate are:
  - CO_2 in the atmosphere
  - Reflectivity ('albedo') of the planet
- Water vapor in the atmosphere follows these changes
- Man made CO_2 emission from fossil fuels is the dominant climate force now and is predicted to lead to a 5° F rise in temperature compared to pre-industrial times.
- Temperature measurements are very clear that the global temperature has risen already about 2.7^o F and that the greenhouse effect has not stopped.
- All major ice sheets are dramatically decreasing in mass.
- Change is possible.

Here is what change looks like!

James Hansen was the head of the climate branch of the NASA Goddard Institute for Space Studies.

Since the 1980's he has been giving a clarion call for action.

He recently quit NASA to devote full time to environmental advocacy.

"Every major national science academy in the world has reported that global warming is real, caused mostly by humans, and requires urgent action. The cost of acting goes far higher the longer we wait — we can't wait any longer to avoid the worst and be judged immoral by coming generations."

James Hansen, New York Times, May 9, 2012

What kind of courageous change can you engender? That's easy: Vote!

Climate Science is for everyone

Any time you want to talk about climate related issues, just email me at RAMBERG@FNAL.GOV

For further information, please contact the real experts at:

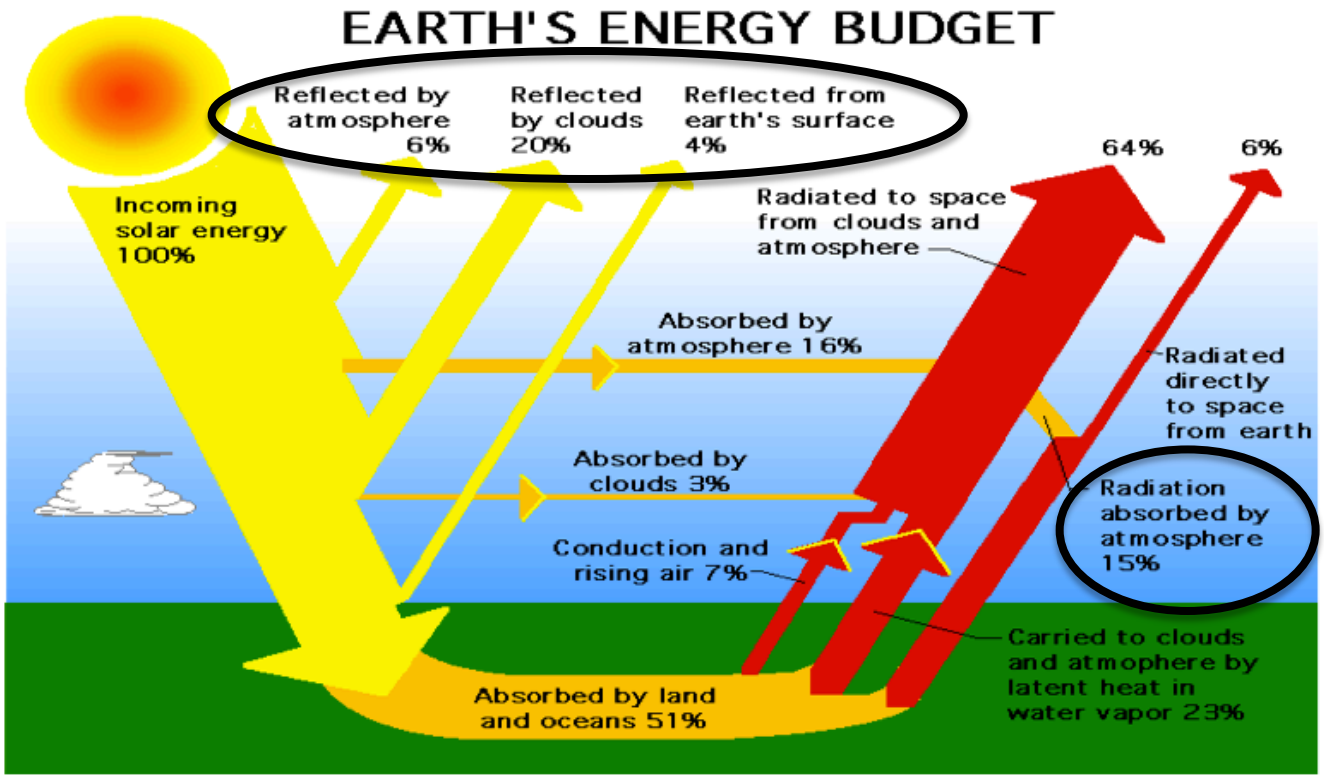
NOAA – National Oceanic and Atmospheric Administration
NASA – National Aeronautics and Space Administration
AGU – American Geophysical Union
EPA – Environmental Protection Agency
APS – American Physical Society
NAS – National Academy of Sciences

Thank you so much
for your kind attention !

Any more questions?

A Bunch of Extra Slides !

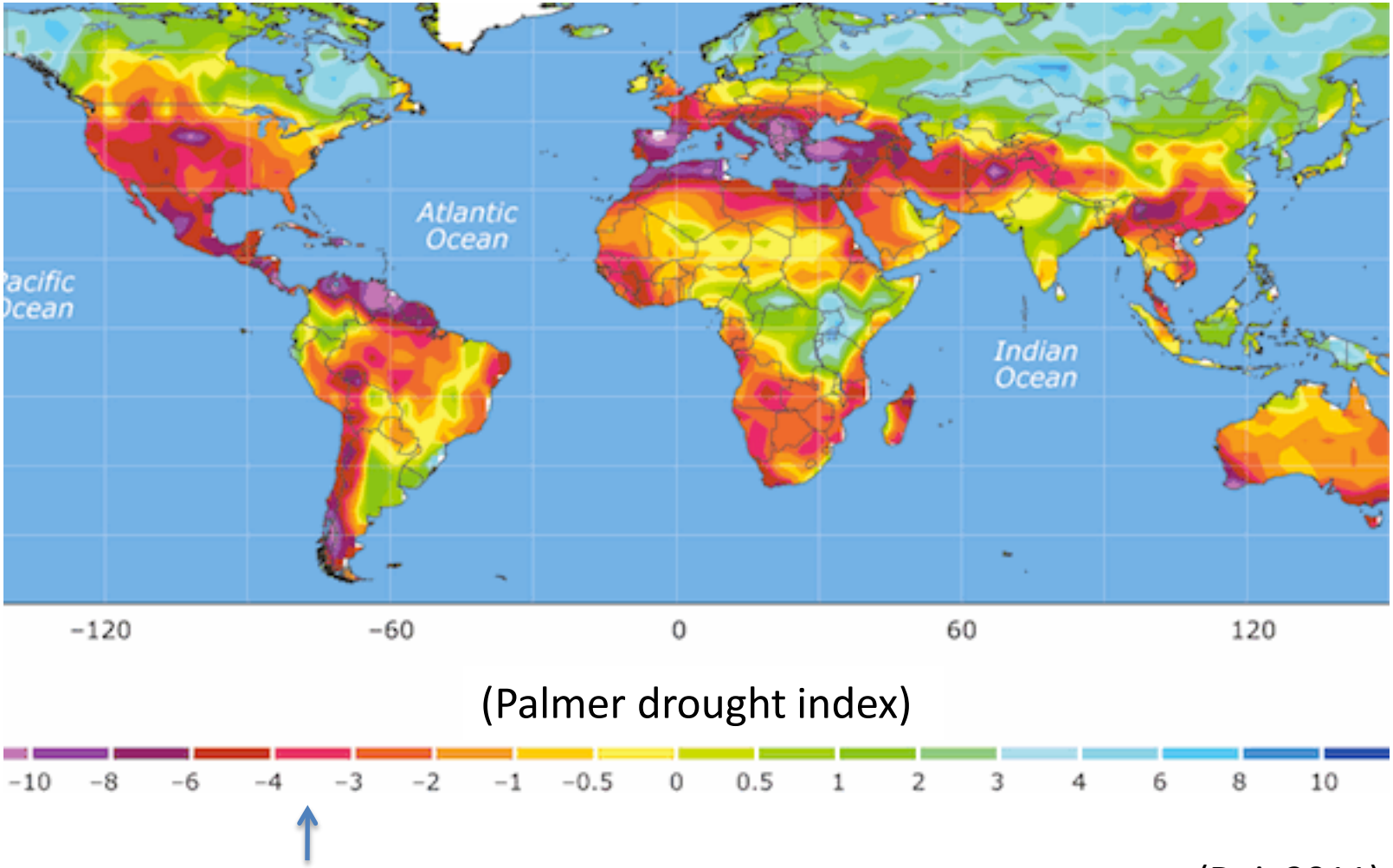
Energy flow in the Earth system



This is what changes when you increase or decrease the albedo.

This is what changes when you add greenhouse gases, like CO_2.

Much of the land surface may experience semi-permanent drought



(Palmer drought index)

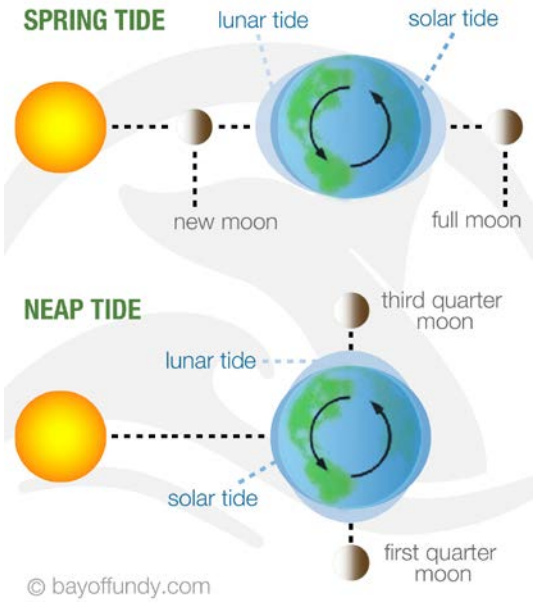
U.S. 'Dust Bowl' condition (1930)

(Dai, 2011)

An Analogy about Predicting Climate:

Nobody can predict what the height of any given wave will be at the seashore:

But the timing and magnitude of the tides (the 'average height') is quite predictable:

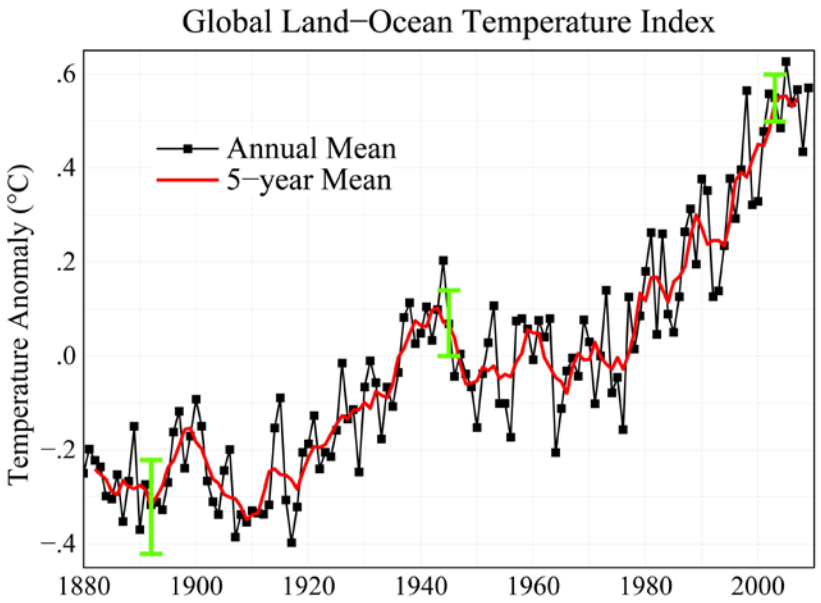


Similarly, it is hard to predict the Earth's temperature for any given year, but the slow, steady change of its' climate is quite predictable

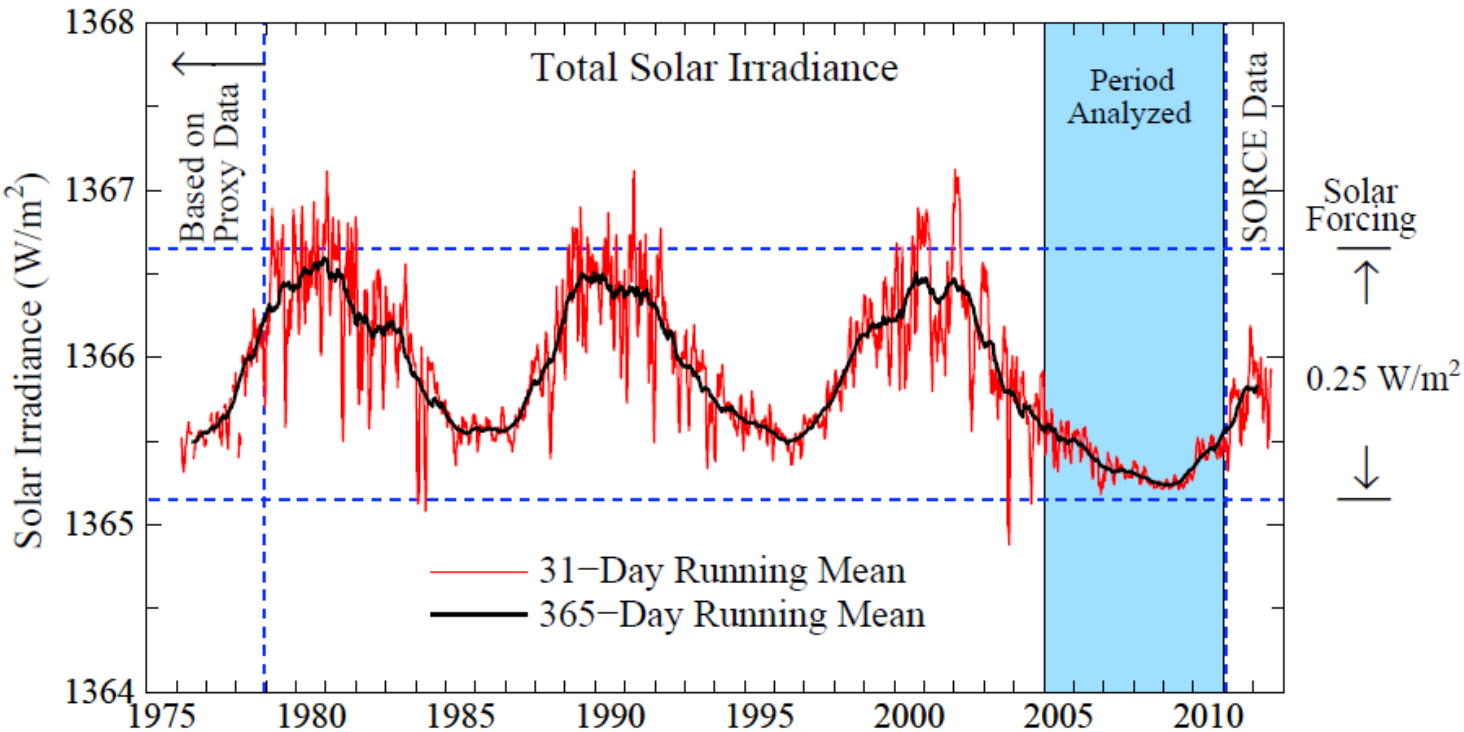
An Analogy about Predicting Climate:

- Likewise, nobody can predict the weather that crashes on us in any one year:

- But the slow changes in global temperature ('Climate') are understood:



Variations in Solar Output on the Short Time Scale are Irrelevant



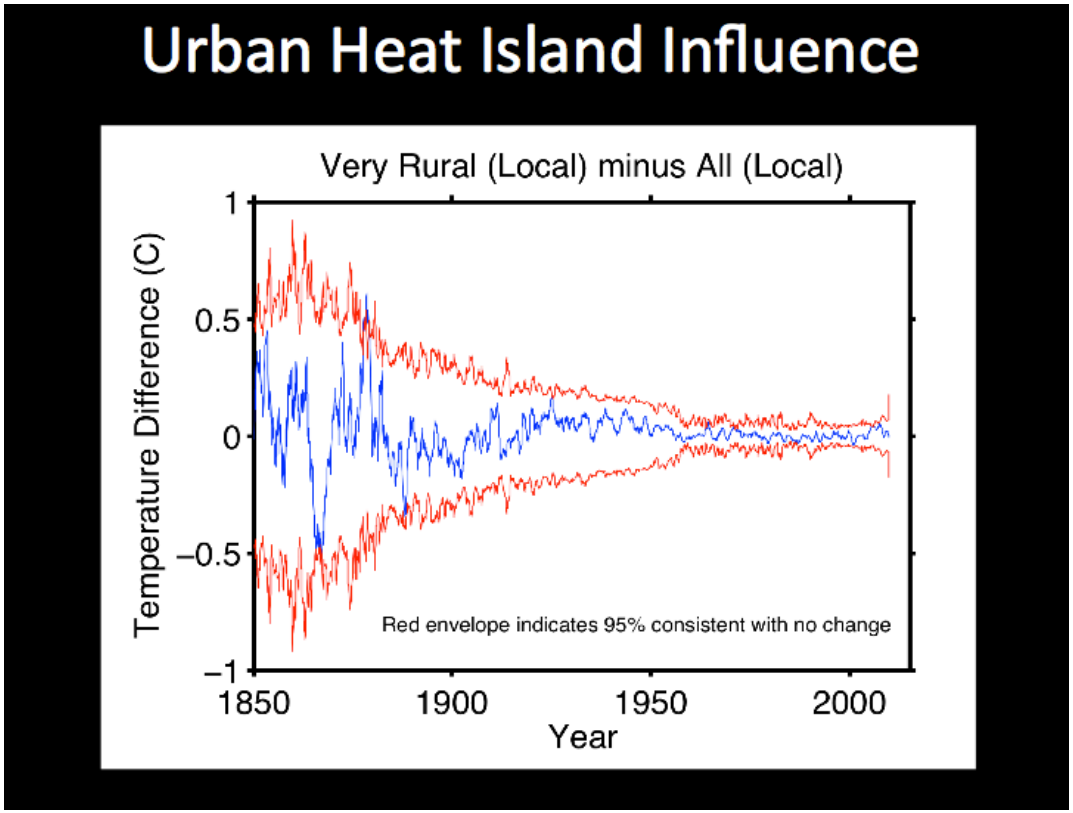
Surface Averaged Solar Forcing

Reference: Fröhlich, C. and J. Lean, *Astron. Astrophys. Rev.*, **12**, pp. 273--320, 2004.
http://www.pmodwrc.ch/pmod.php?topic=tsi/composite/SolarConstant

No urban vs rural systematic effect exists

Rural sited meteorological station

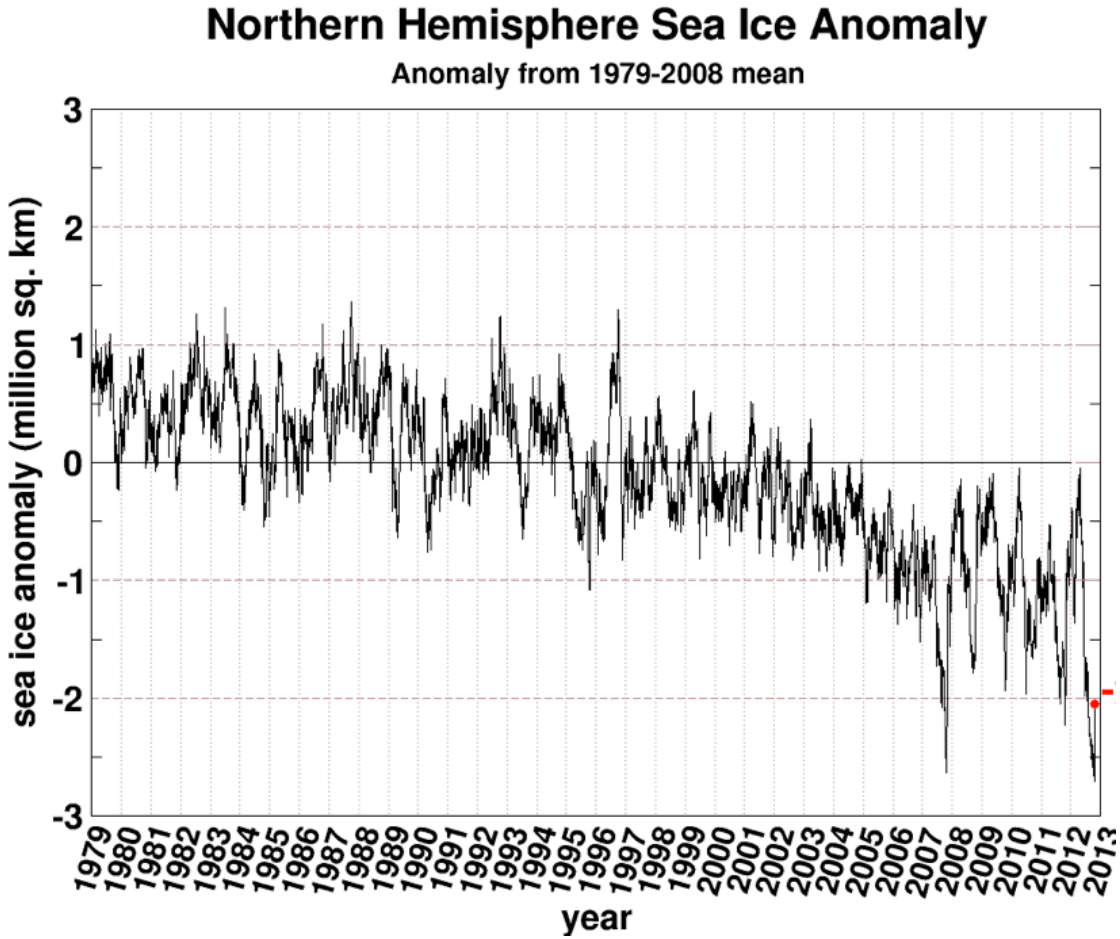
Urban sited meteorological station



Blue curve is difference between good stations and bad stations –

There is no difference !

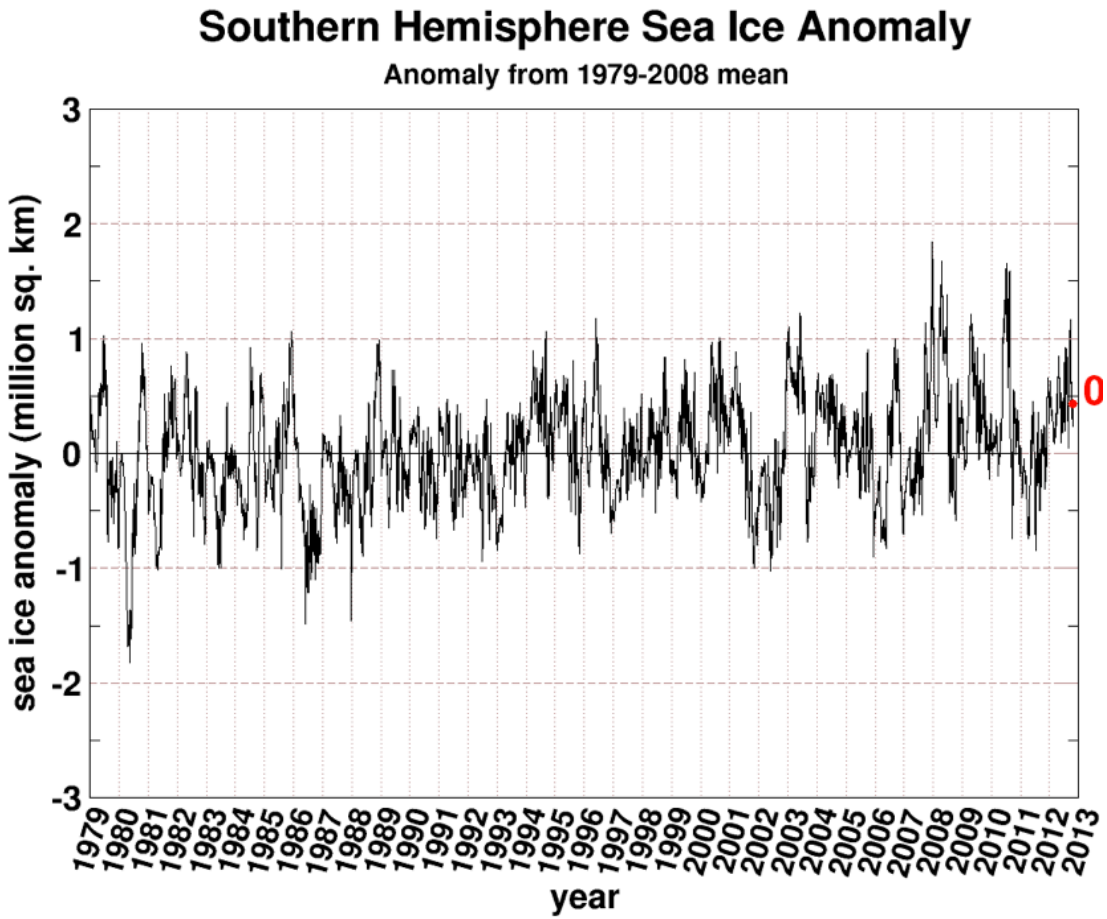
Arctic Sea Ice Area



Sea ice area reached a new summer minimum in 2012

Re: Cryosphere Today

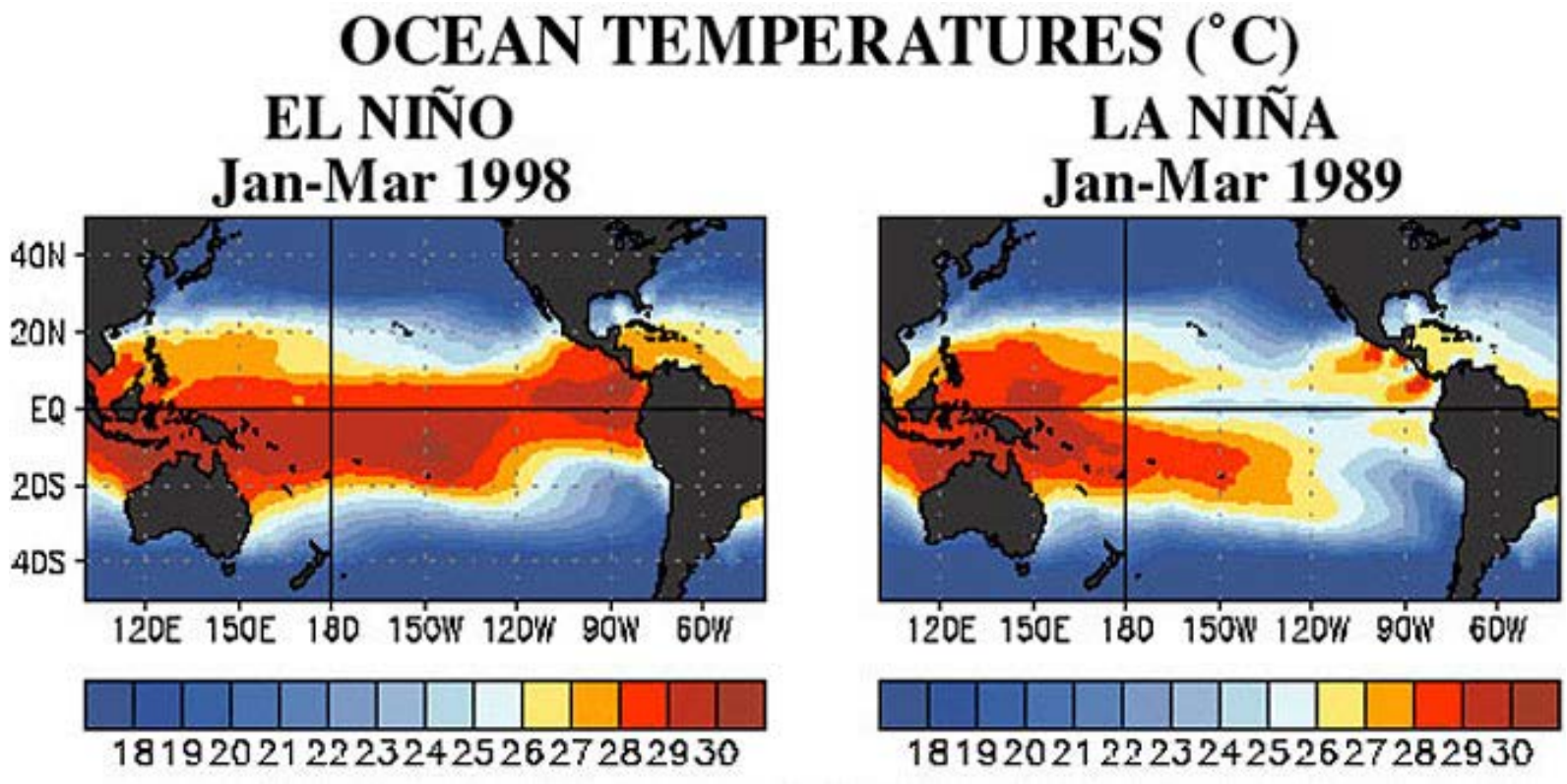
Antarctic Ice Area



- Antarctica is buffered by an extremely large land ice mass
- There is a modest increase in sea ice area, but this does not match Arctic losses

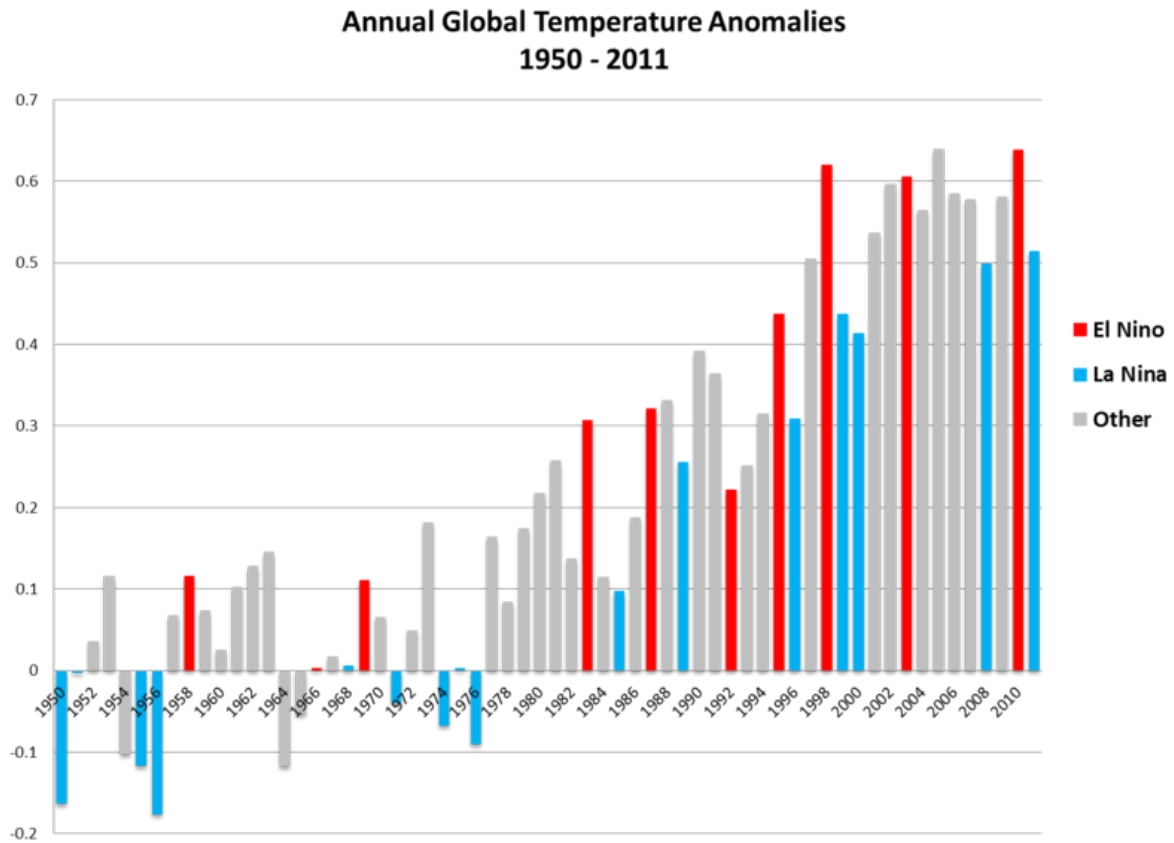
Re: Cryosphere Today

El Nino (& La Nina) – Southern Oscillation (ENSO)



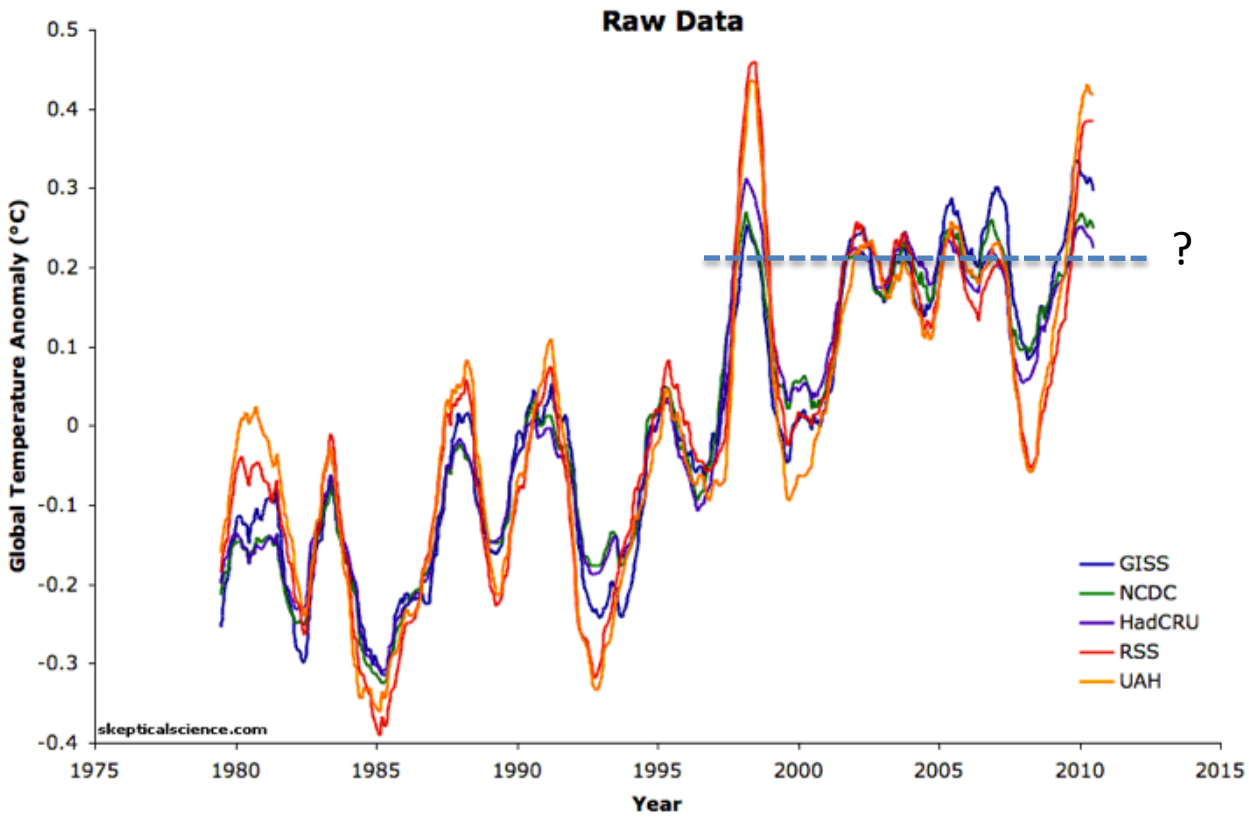
El Nino: High atmospheric pressure in the western Pacific causes heat flow eastward. La Nina is the reverse.

El Nino (& La Nina) – Southern Oscillation (ENSO)

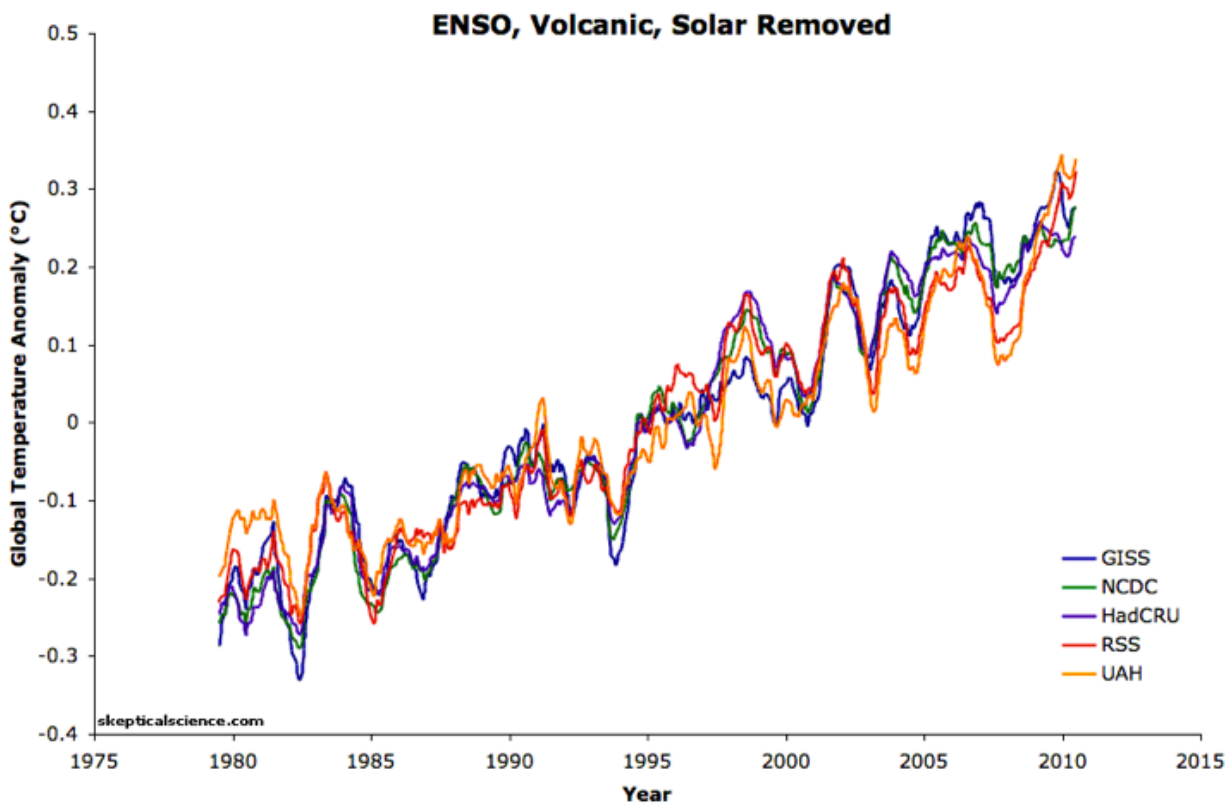


These episodes are correlated to global temperatures at the 0.2^{o} C level and can be corrected for in global averages.

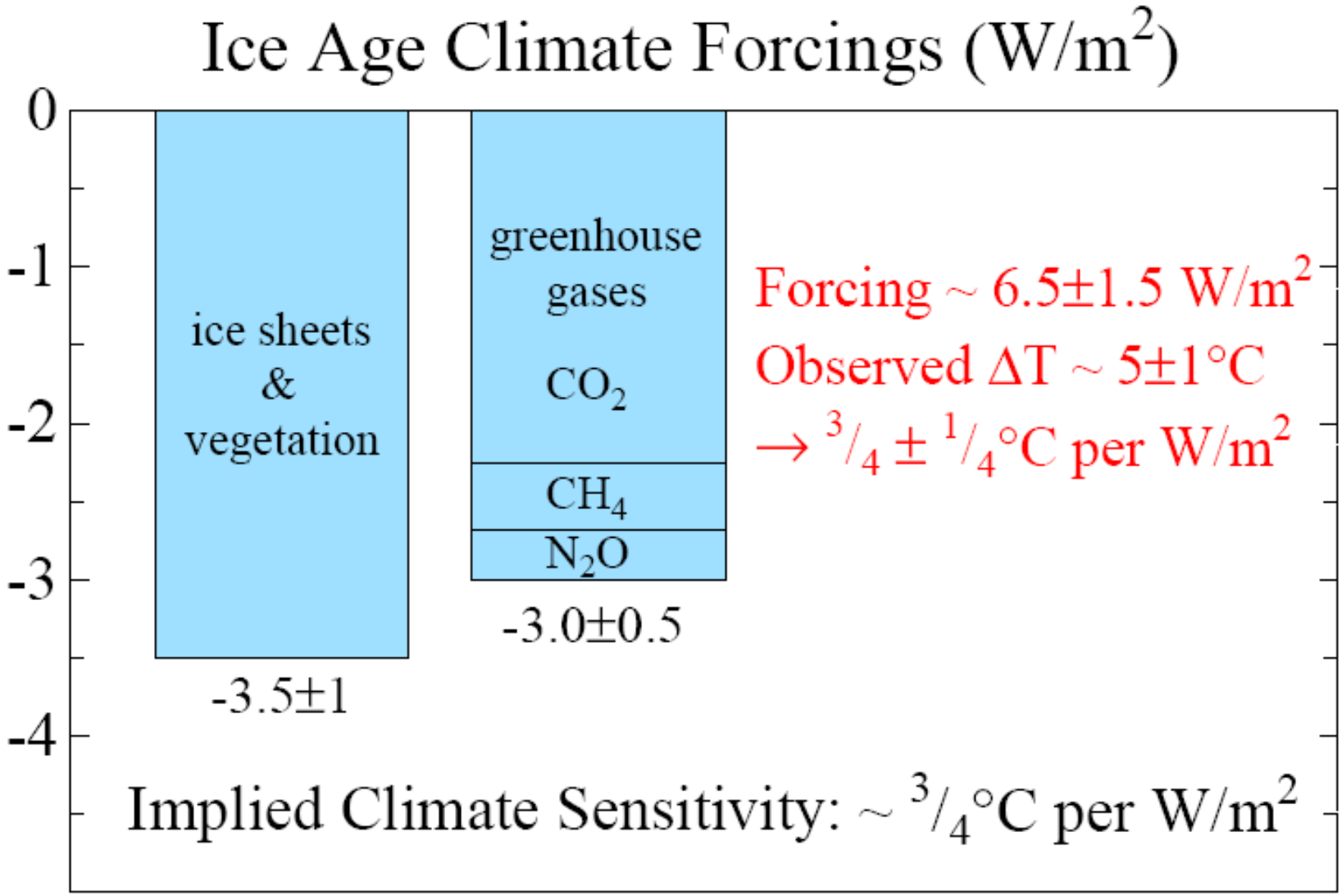
Has Global Warming Stopped in the last 15 years?

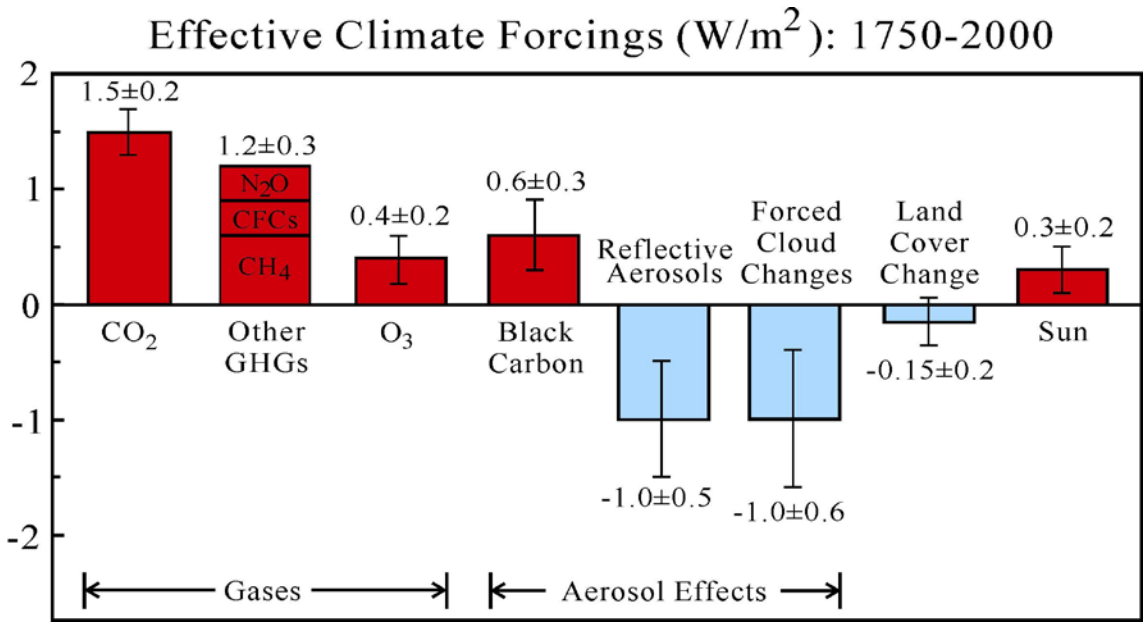


No. Anthropogenic Global Warming is Continuing at a Steady Pace



Important observation: The El Nino fluctuation and slightly lower solar power in the last few years have given slower temperature rises. But make no mistake about it: the underlying trend will overpower any such noise sources


Ice Age Climate Forcings (W/m2)
0
-1
-2
-3
-4
ice sheets & vegetation
-3.5±1
greenhouse gases
CO2
CH4
N2O
-3.0±0.5
Forcing ~ 6.5±1.5 W/m2
Observed ΔT ~ 5±1°C
→ 3/4 ± 1/4°C per W/m2
Implied Climate Sensitivity: ~ 3/4°C per W/m2



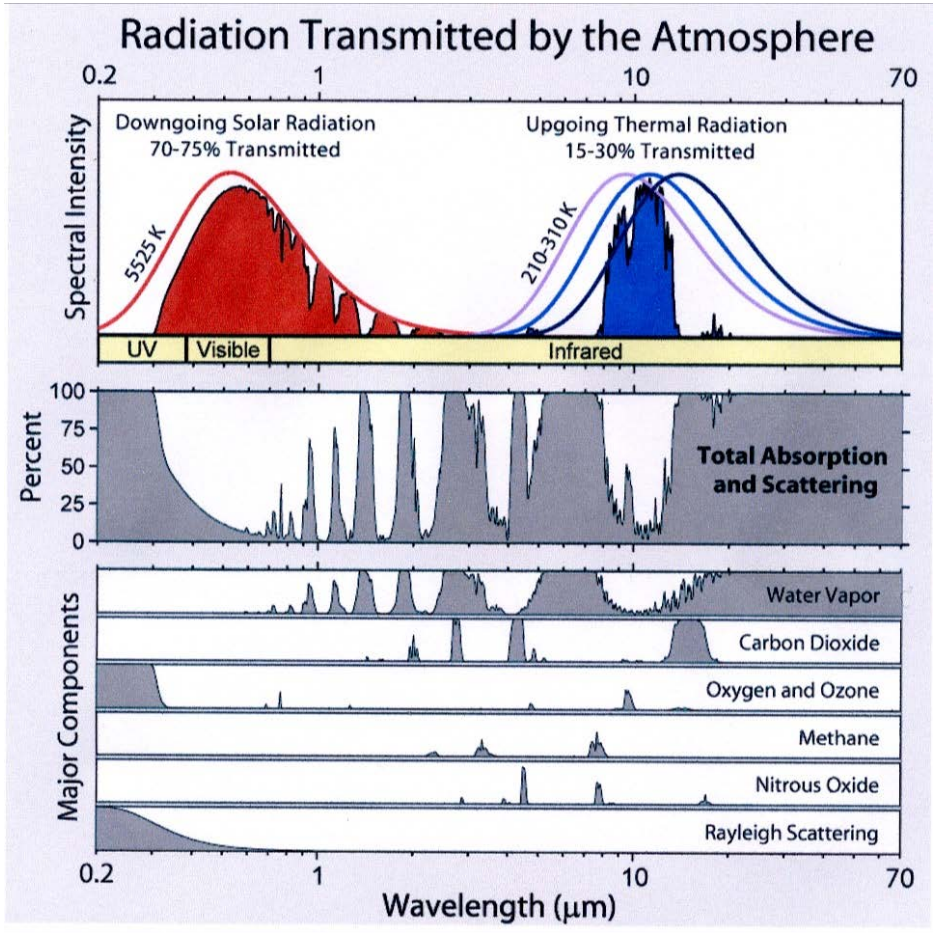
Climate forcing agents in the industrial era.

Source: Hansen et al., JGR, **110**, D18104, 2005.

Forcing during the Industrial era has been about 1.8 W/m^2. For a sensitivity of 3/4° C per W/m^2, as just shown from Ice Age data, we expect a 1.4^o C rise in temperature – which is what we have experienced.

Expected total forcing from doubled CO_2 concentration is 3.7 W/m^2. We can expect a total of at least 2.5^o C rise in global temperature compared to pre-industrial times. Other feedbacks may start up (CH_4 clathrates?)

Absorption and Emission of Radiation on Earth



CO_2 and water absorb in the infrared region of 5-50 micron wavelength, where the Earth is trying to radiate its heat away.

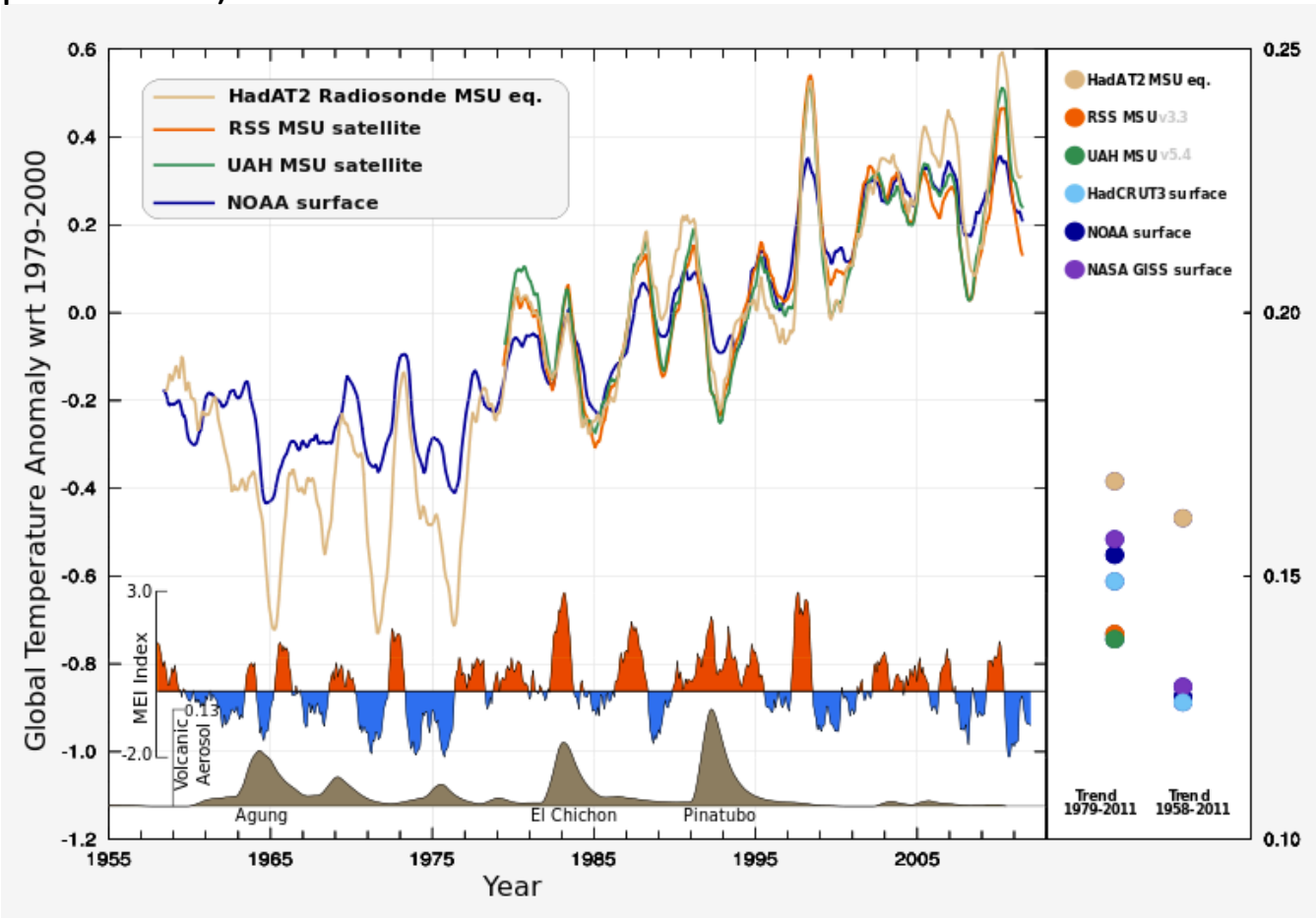
If you increase the concentration of CO2 or H2O, these 'absorption' bands get broader and trap more heat before it can escape.

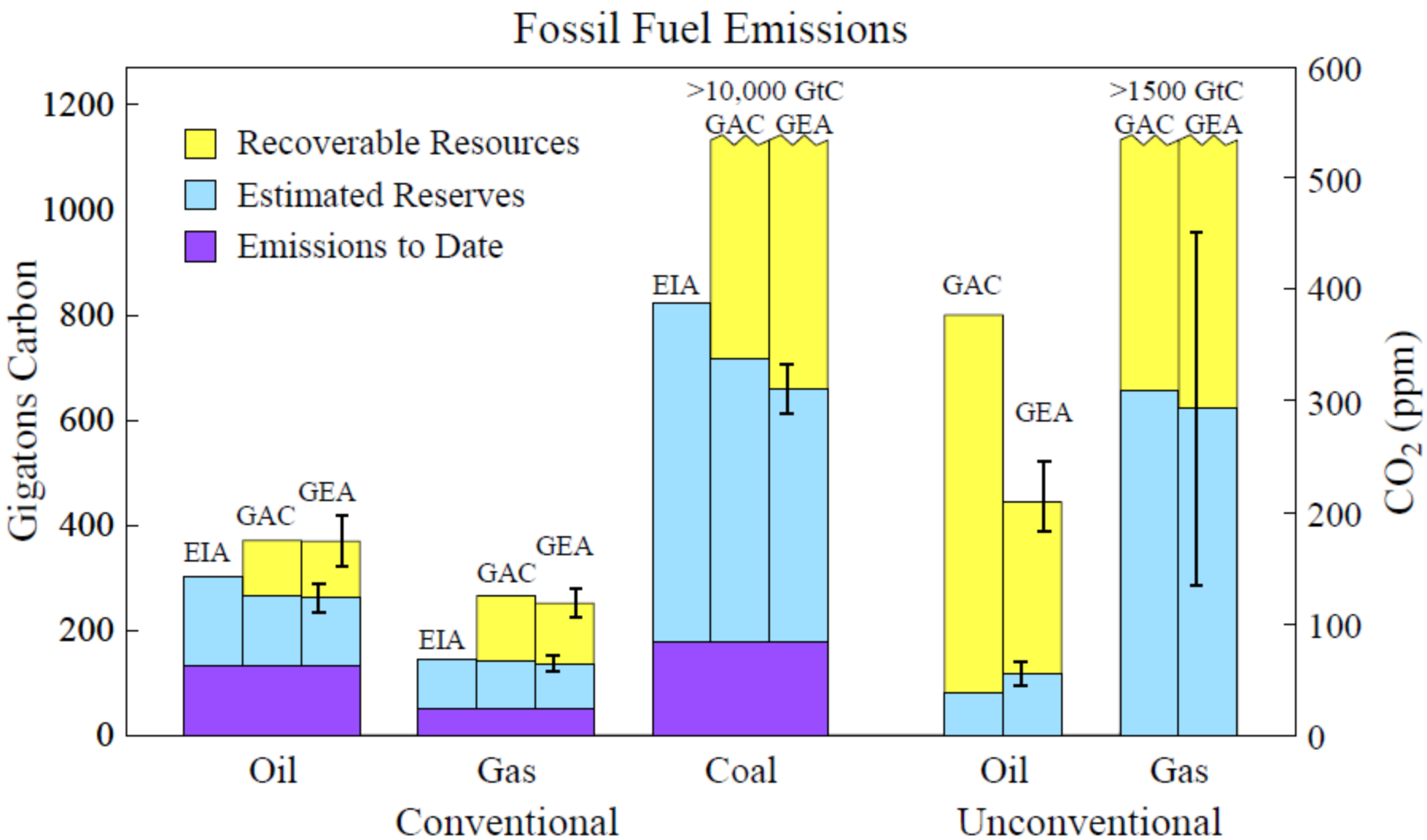
This is the 'Greenhouse effect', which has been understood for more than 100 years.

Note how powerful water is as a greenhouse gas.

Satellite measurements

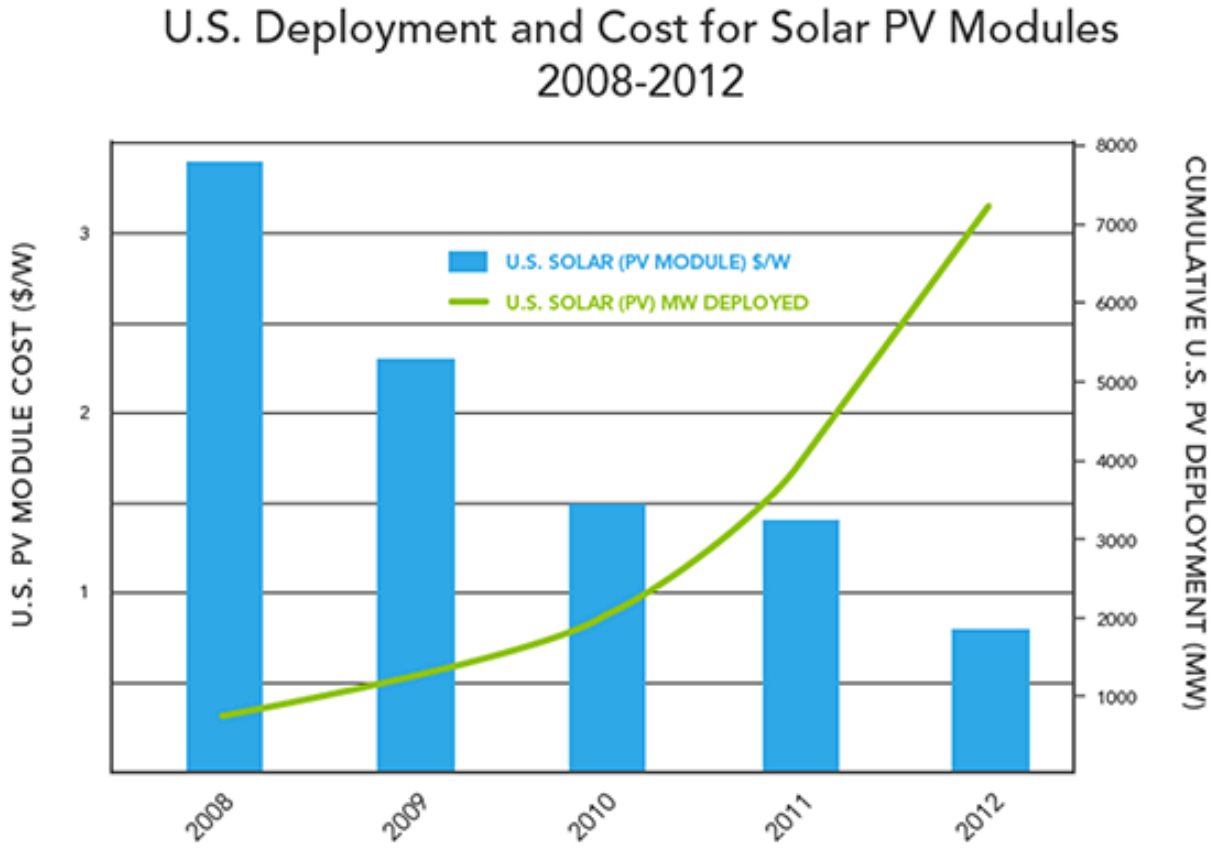
- University of Alabama in Huntsville (UAH) and Michigan State U (MSU) have made extensive analyses of the temperature of the surface of the Earth from an ever changing array of satellite measurements of the radian
- These satellite measurements confirm the surface station average (0.15 degree C per decade)





CO_2 emissions by fossil fuels
(500 GtC ~ 250 ppm CO_2 ~ 2° C.)

‘60 Minutes’ says that clean energy technology is ‘dead’. It looks like they did not take into account the facts:



As prices of solar panels have dropped, Americans are installing them at record levels.

Chart by Levi Tillemann-Dick/US Department of Energy

Making the 'BEST' Measurement of the Earth's Surface Temperature – By a 'Skeptic' !

- Many insist that as cities and their 'urban heat islands' have grown in size, any local temperature sensors will record an artificial increase.
- There are many temperature sensor locations that are obviously flawed (near air conditioning exhausts, parking lots, etc.), but most aren't.
- A self-described 'skeptic' Berkeley professor – Richard Muller – embarked on a complete reanalysis of the temperature record, independent of NASA:

'BEST' = 'Berkeley Earth Surface Temperature project'

Dataset	Berkeley Earth	GHCN-M v3
Number of Stations	39,028	7,280
Monthly Observations	14,786,160	5,150,496
Median Record Length	25.8 Years	58.5 Years

Carbon cycle in the Earth/Atmosphere

- Note that the carbon resident in fossil fuels outweighs combined mass of carbon in atmosphere + soil + biomass + upper ocean
- Our impact on the atmosphere is about 0.7% per year, and rising

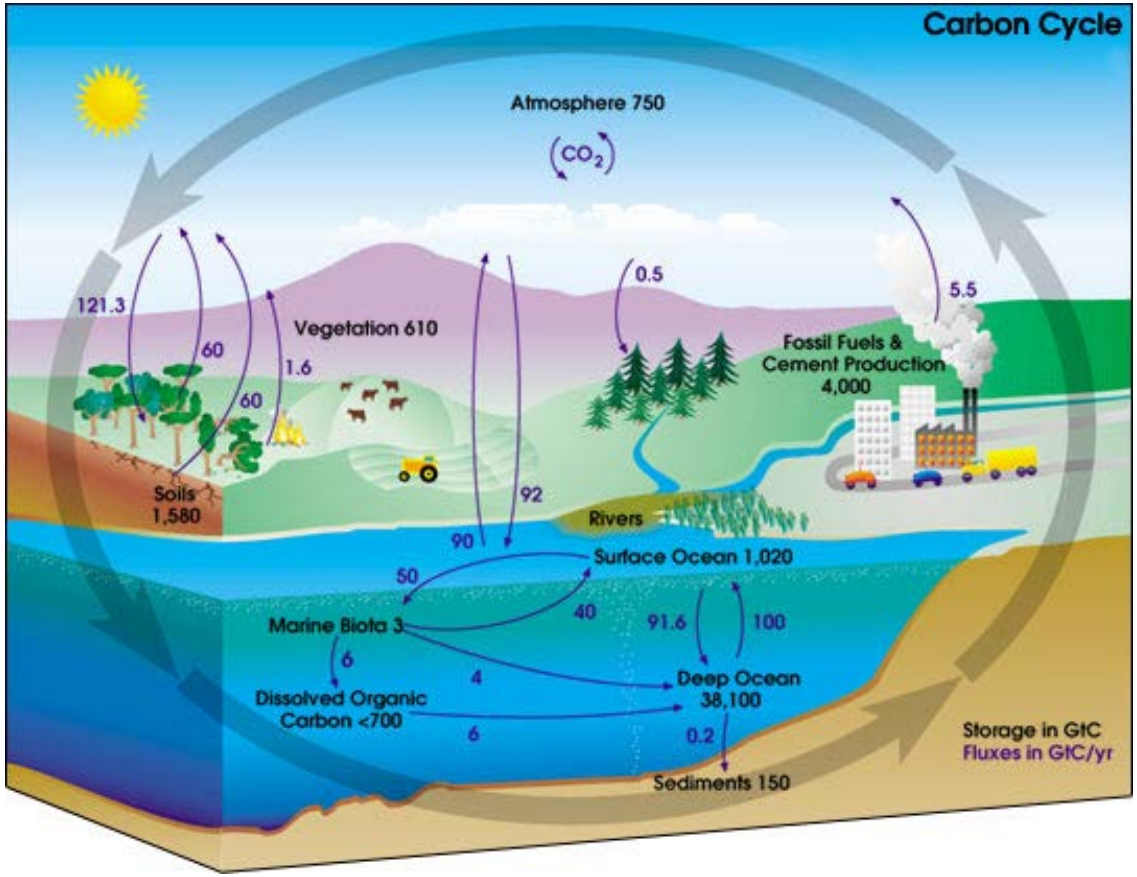
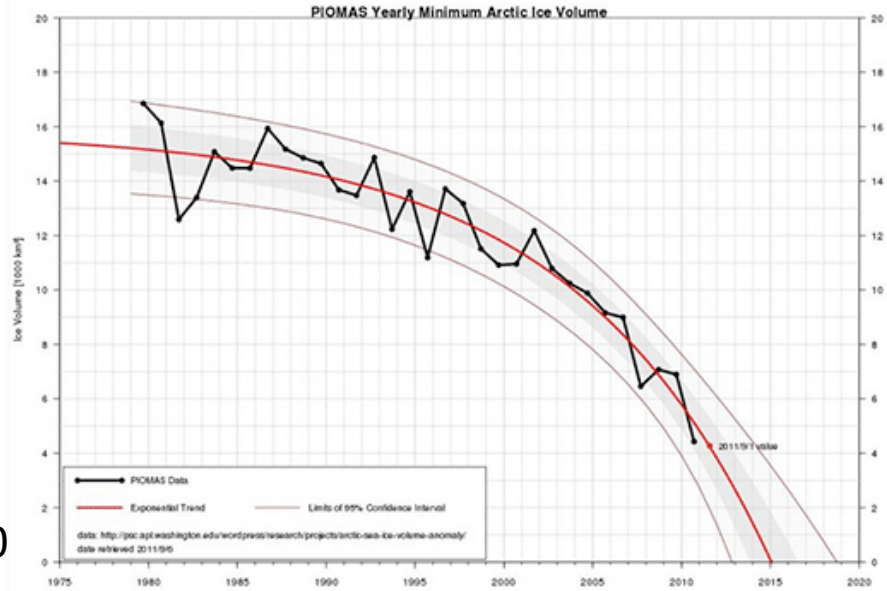


Illustration courtesy NASA Earth Science Enterprise.

To understand the drastic nature of what is happening in the Arctic regions, it's Important to Concentrate on Volume, not Area

PIOMAS (Pan-Arctic Ice Ocean Modeling and Assimilation System – U. Washington) is a model that uses estimates for sea ice thickness and then calculates ice volume

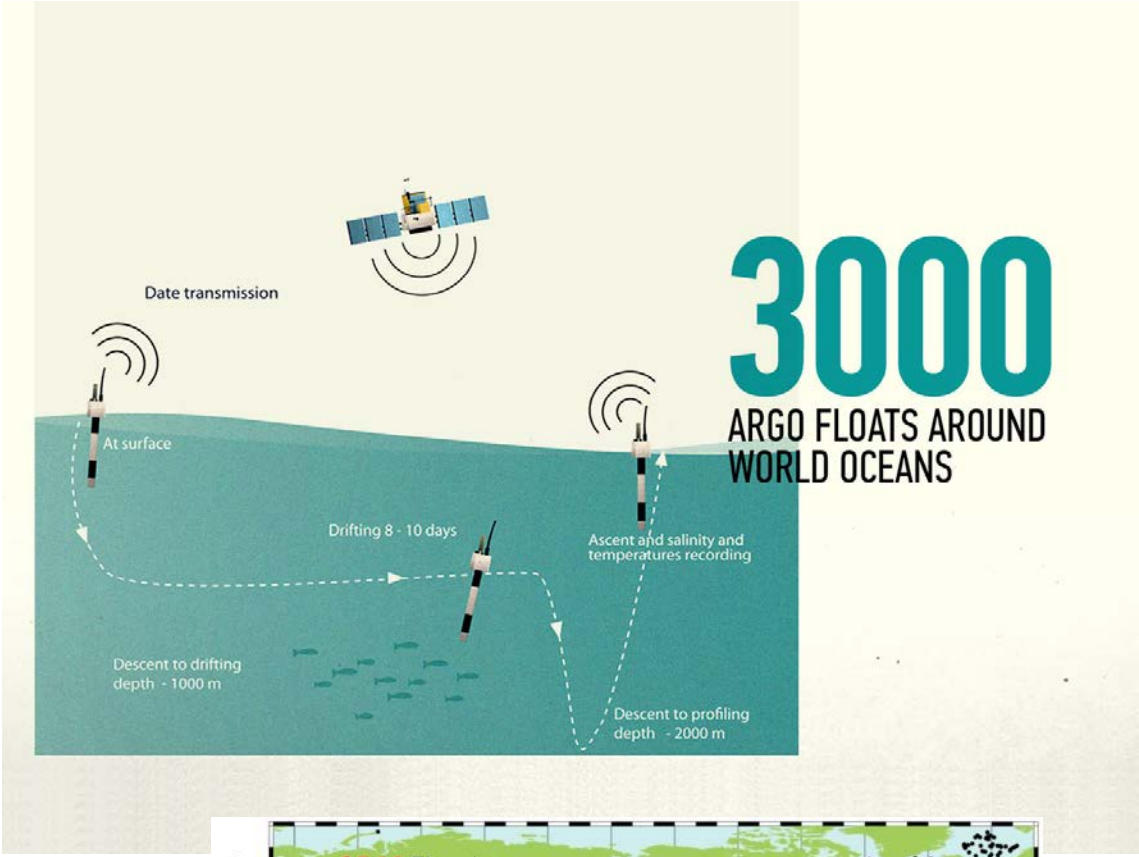
20,000 km^3

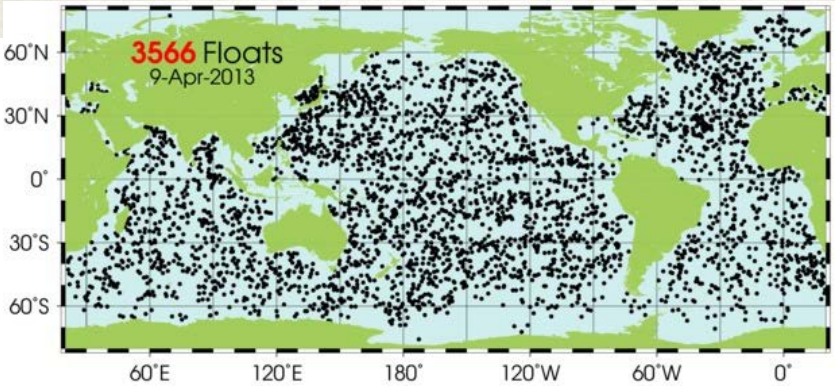


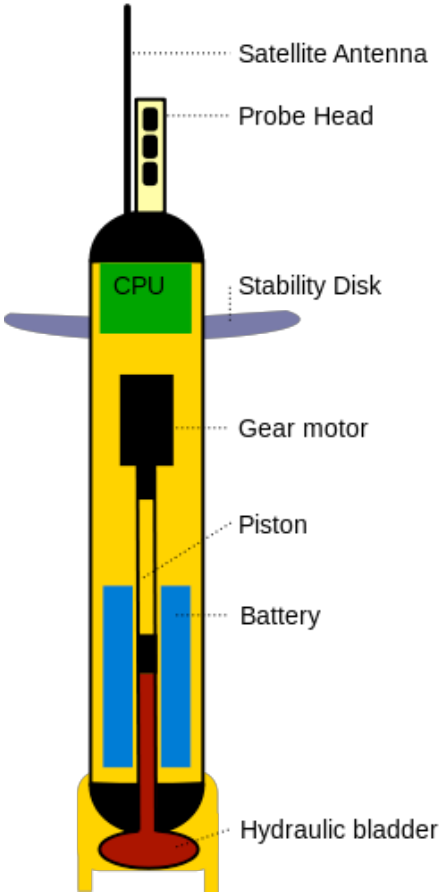
1980

2015

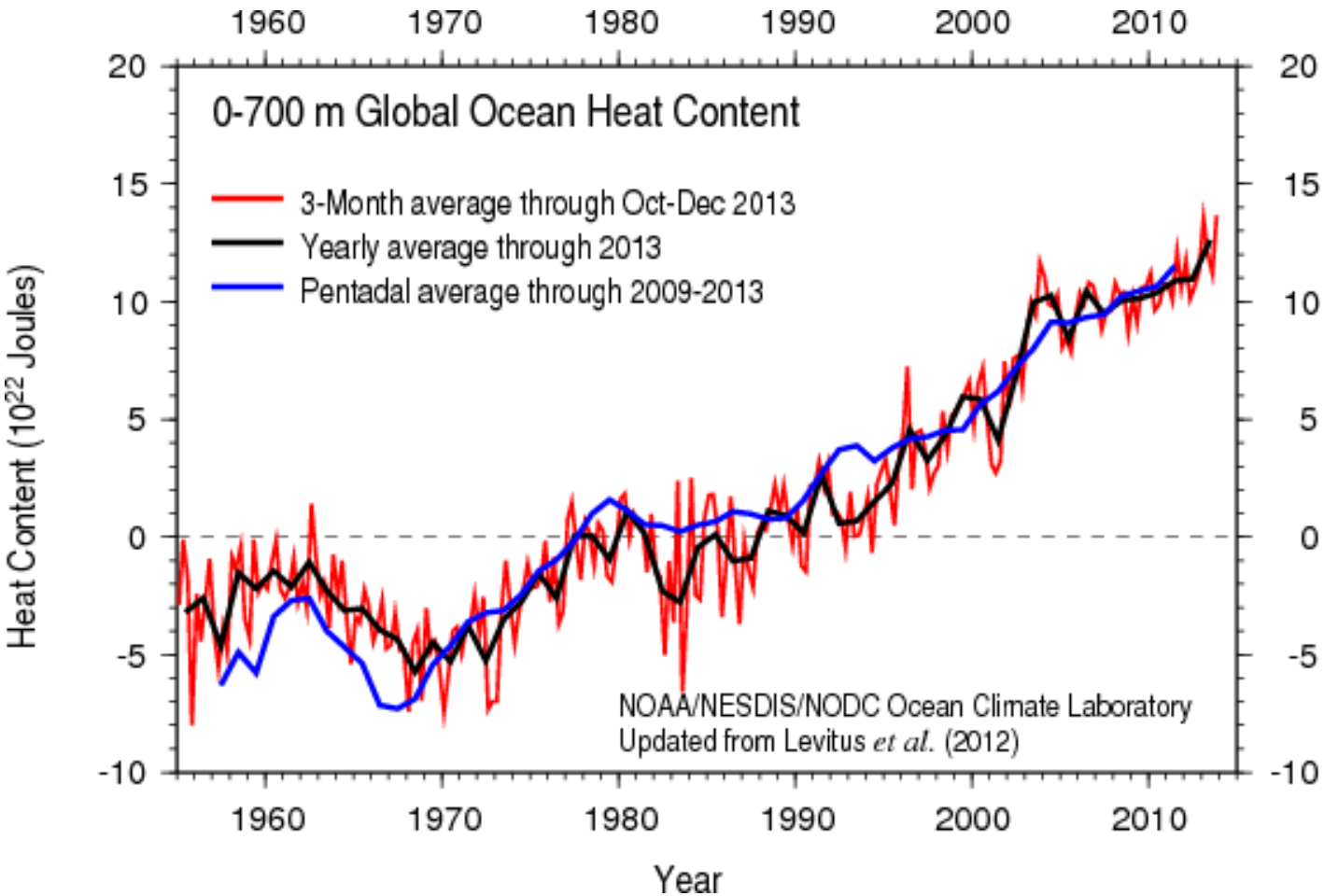
ARGO buoy's measurement of ocean's energy imbalance







Results on Upper 700 meters heat content



The heat energy flowing into the oceans is equivalent to exploding 4 Hiroshima atomic bombs every second, 24 hours a day, 365 days per year.

Geothermal Forcing is Irrelevant

This heat source does not affect climate since it is too weak (.1 W/m^2) and is very, very constant

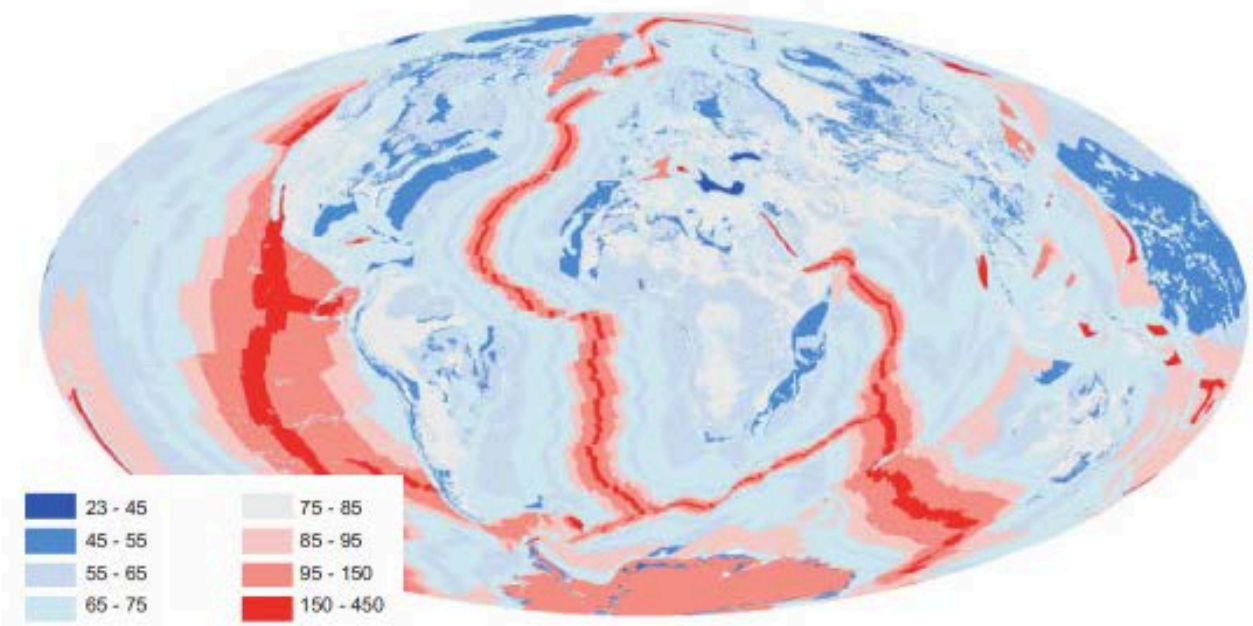
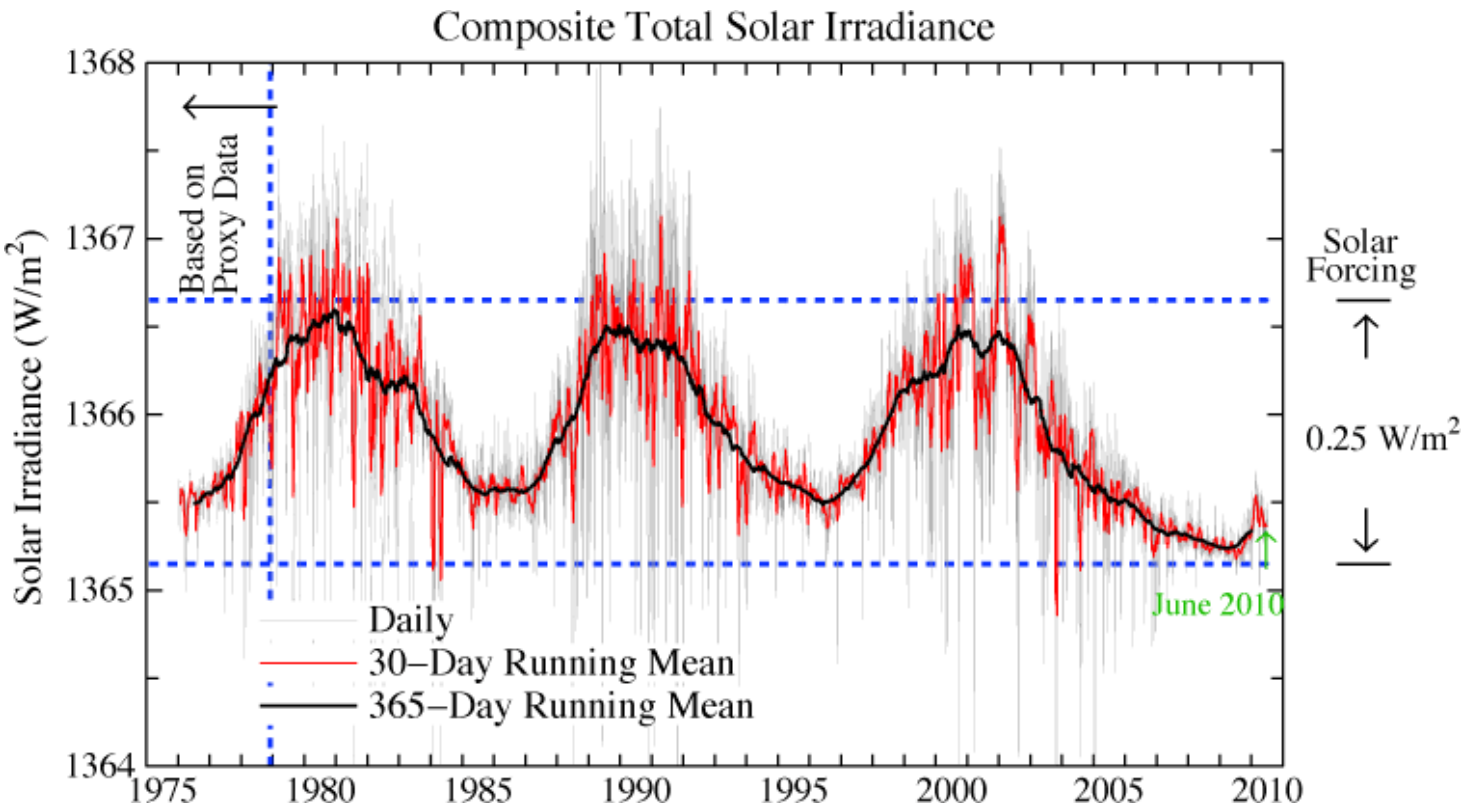


Figure 3: Heat flow at the surface of the earth, from Davies and Davies (2010). Heat flow units are in mW Note how the areas of highest heat flow follow the mid-ocean ridges. The largest areas of measure uncertainty are along the very crests of the ridges and under the Greenland and Antarctic ice caps. The tota flow for the planet is 47 TW +/- 2TW, which is equivalent to 0.09Wm^{-2} (90mWm^{-2}).

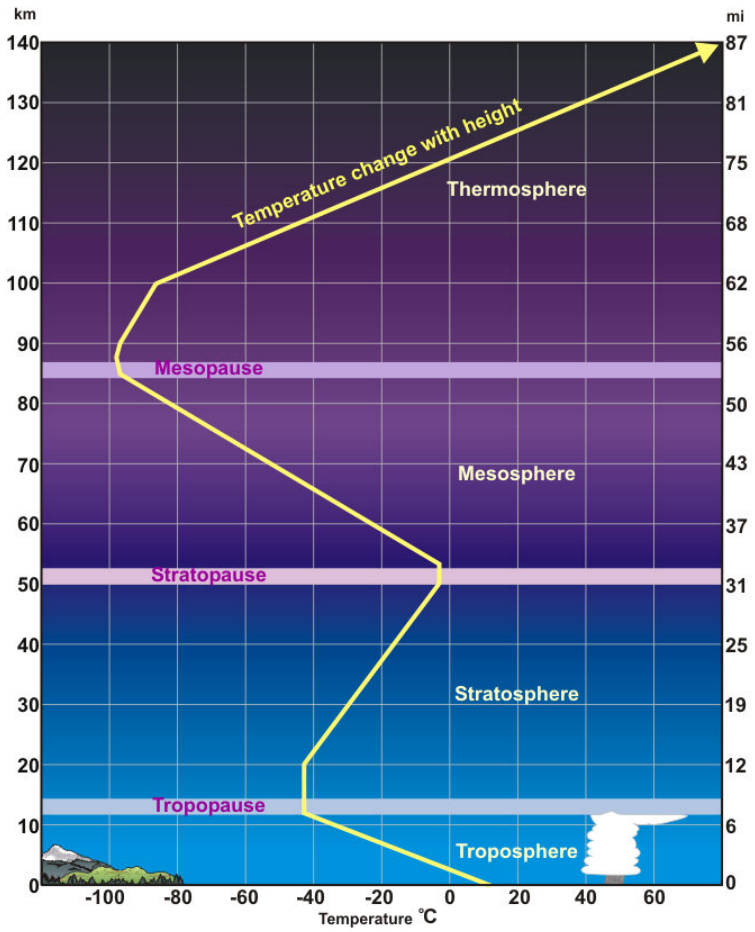
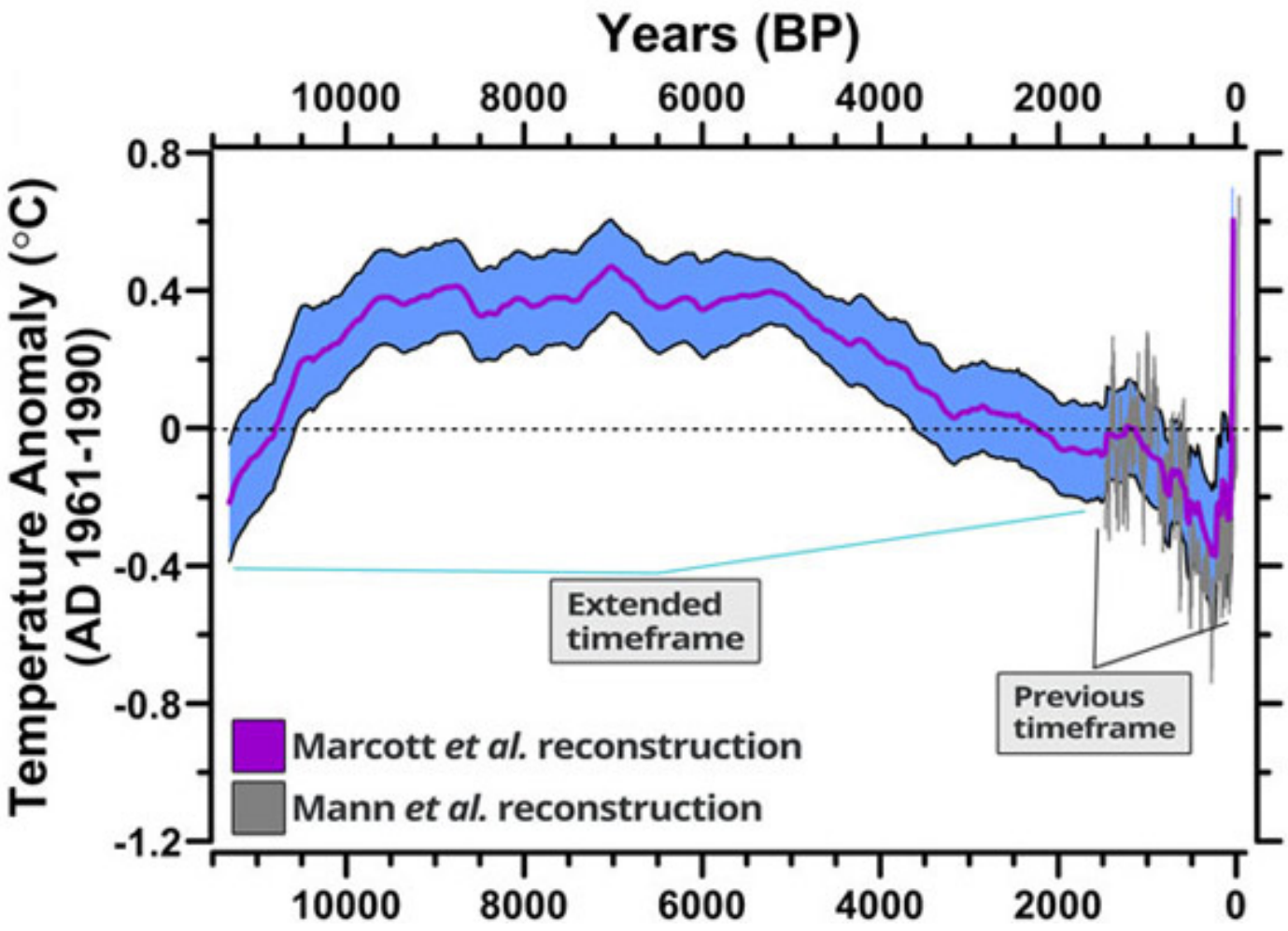
Variations in Solar Output are Small



Surface Averaged Solar Forcing

Pick a Temperature !

- The temperature of the Earth changes as you go up or down in the atmosphere – by 100 degrees C!
- The temperature depends critically on the composition of the gases in its atmosphere, their spectral properties and their distribution.
- Let's talk about the average temperature on the surface, where we live.



Mean Surface Temperatures Over 11,000 years