# What We Know About Climate Change

Kerry Emanuel

**Lorenz Center**

Department of Earth, Atmospheric, and Planetary Sciences, MIT

# This Evening's Program

- Overview of climate and climate change
- Solutions

# Important Points about Climate and Climate Science

- Earth's climate is not terribly stable
- Climate science has a long and illustrious history
- Human activities can and do have a strong effect on climate
- The idea that we are altering climate is based on much more than complex global models
- Anthropogenic climate change is not controversial among climate scientists

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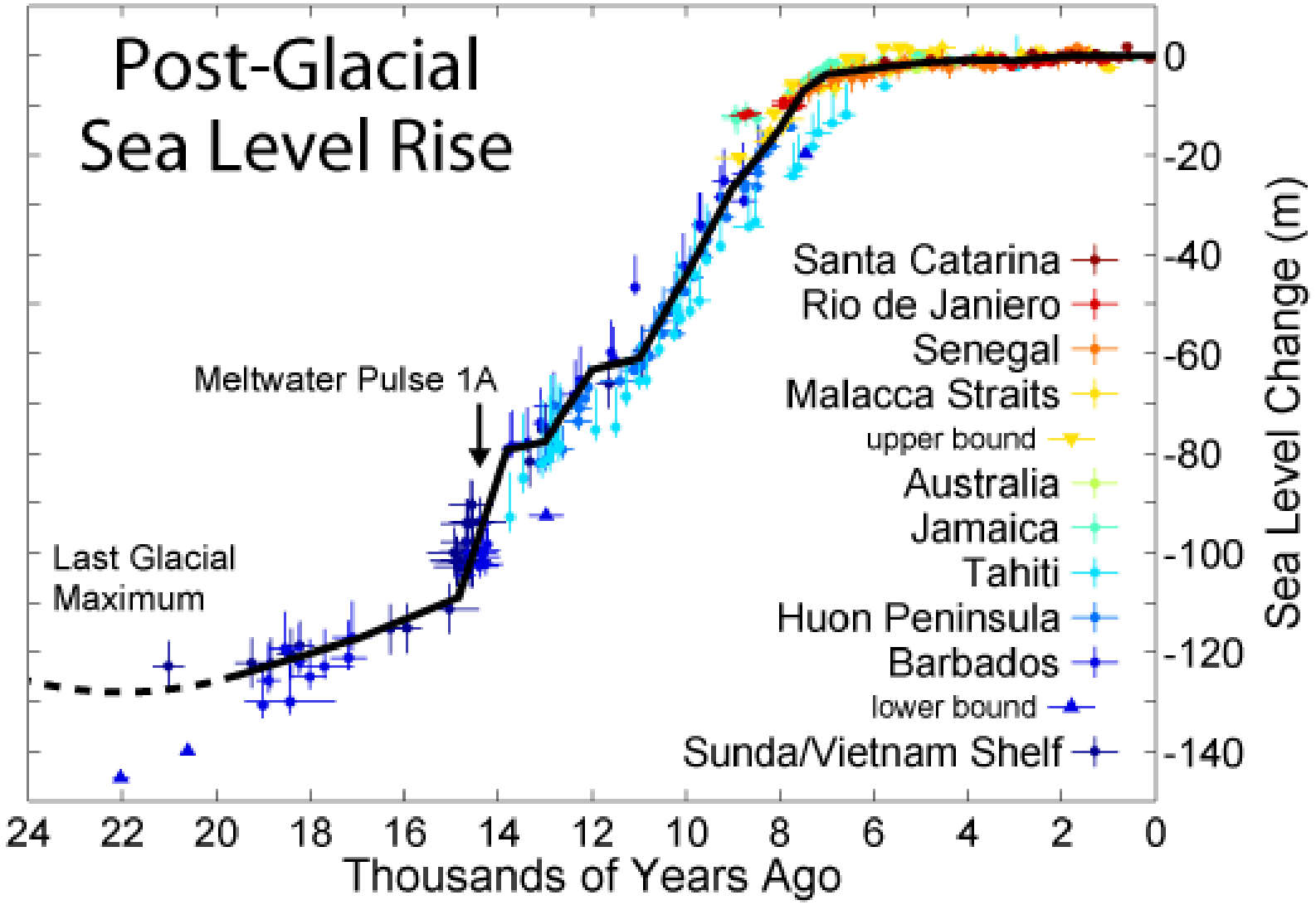
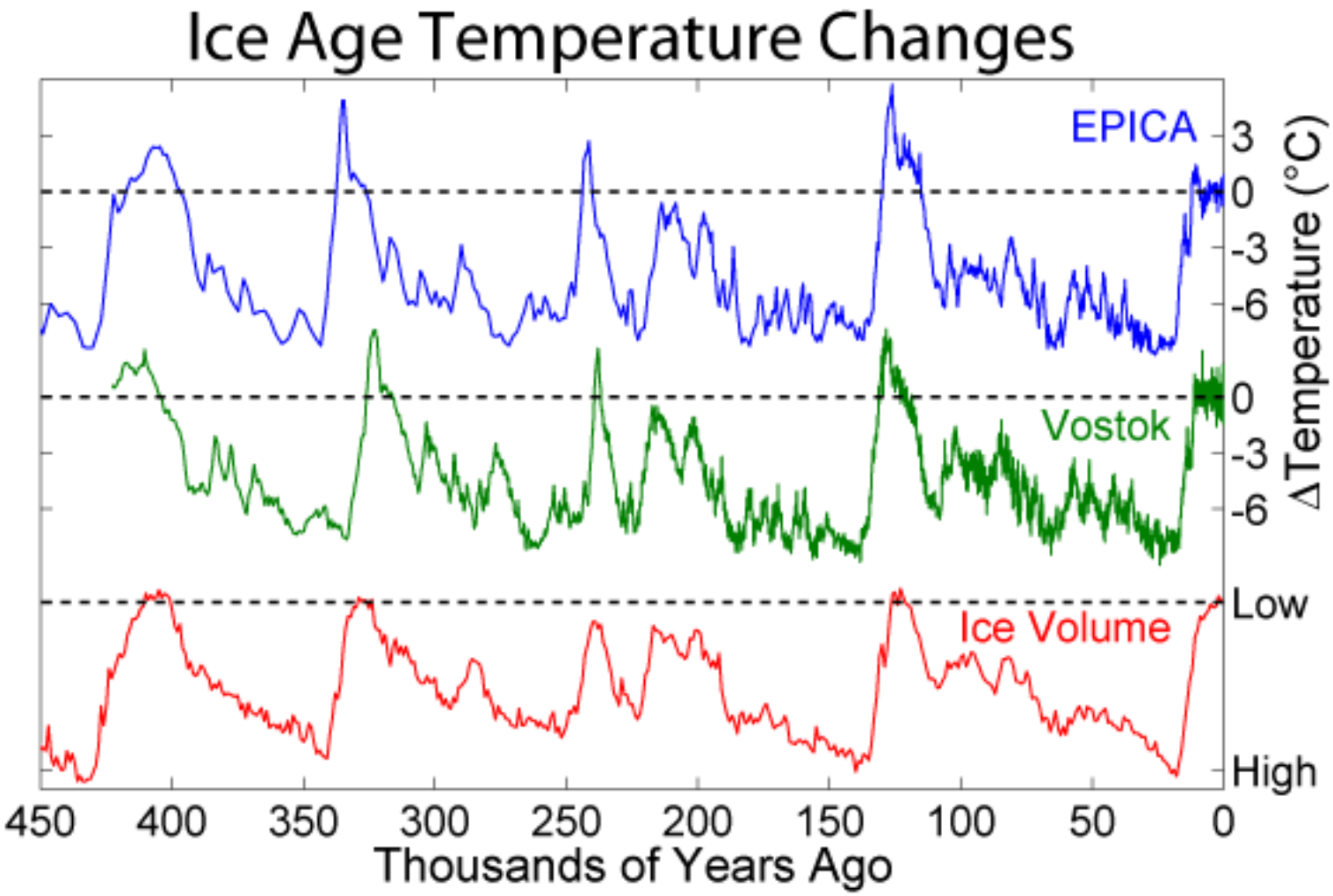
~ 20,000 years before present

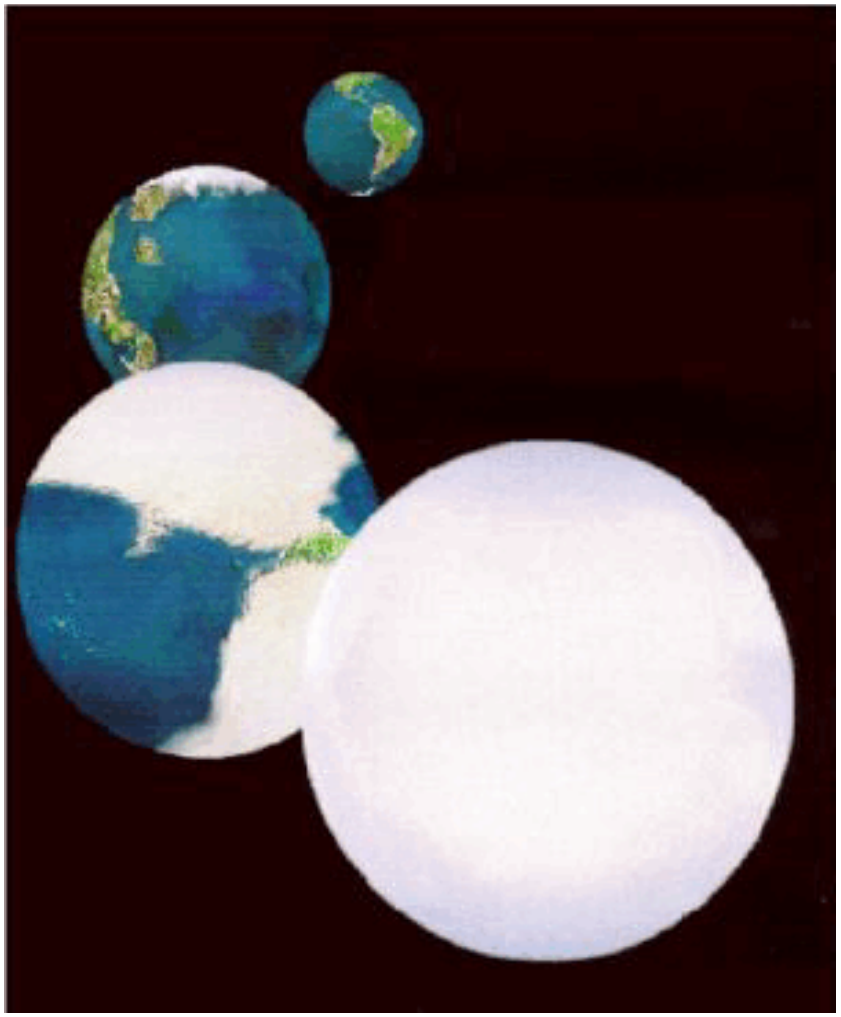



- Polar radiative forcing: 10 W/m$^2$ (4 W/m$^2$ for 2 x $CO_2$)
- Global mean temperature fluctuation: ~5 C

# Last 450 Thousand Years



# The Snowball Earth, 650-750 mya



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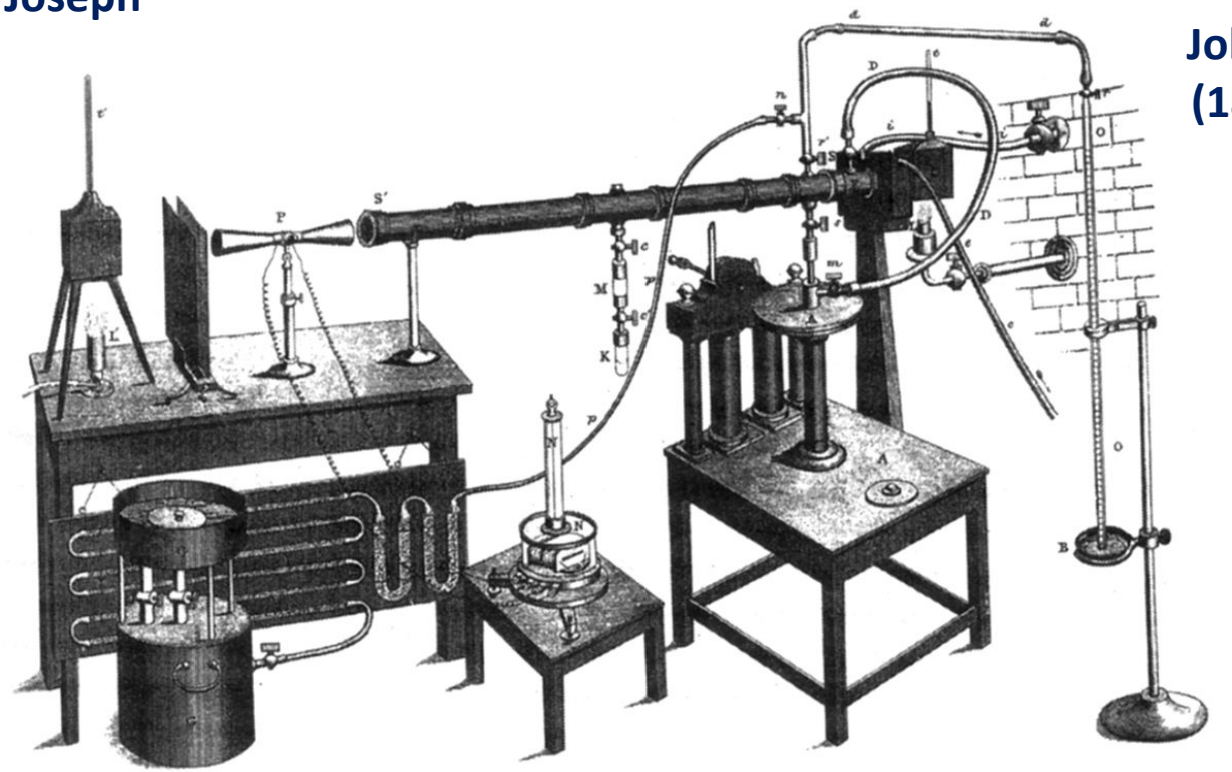
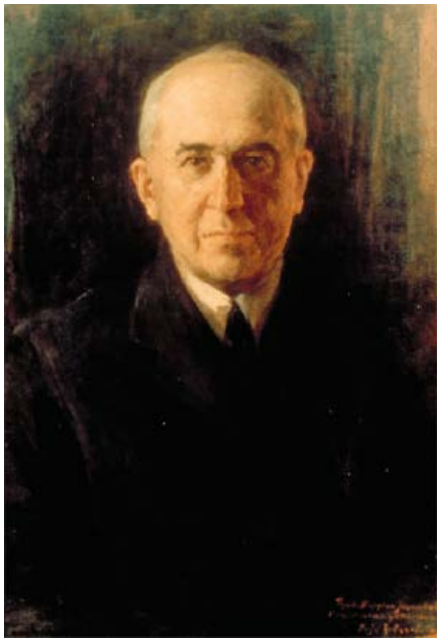
Jean Baptiste Joseph Fourier (1768-1830)

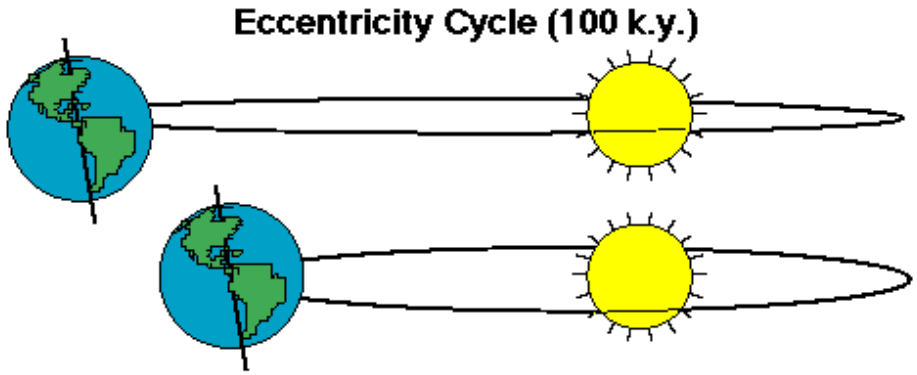
John Tyndall (1820-1893)

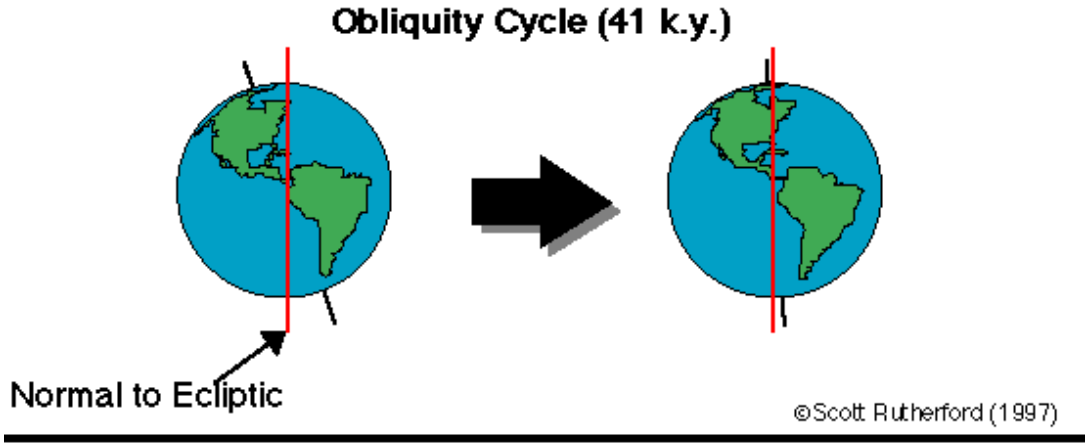


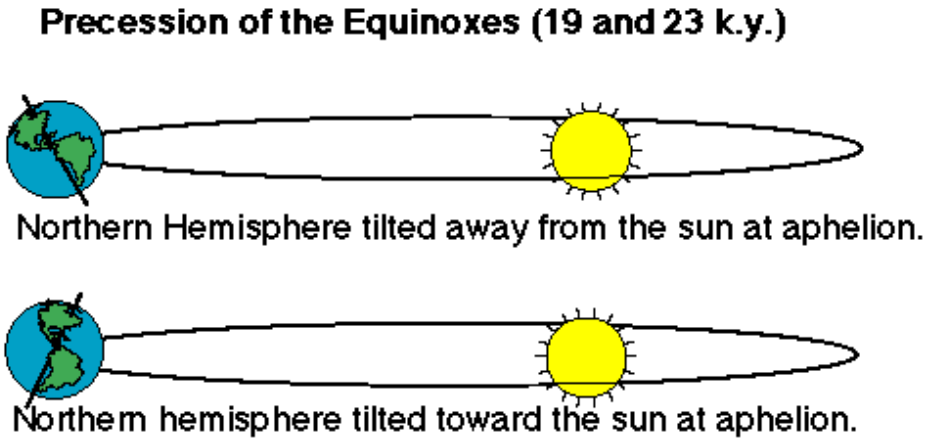
# Climate Forcing by Orbital Variations (1912)



**Milutin Milanković, 1879-1958**



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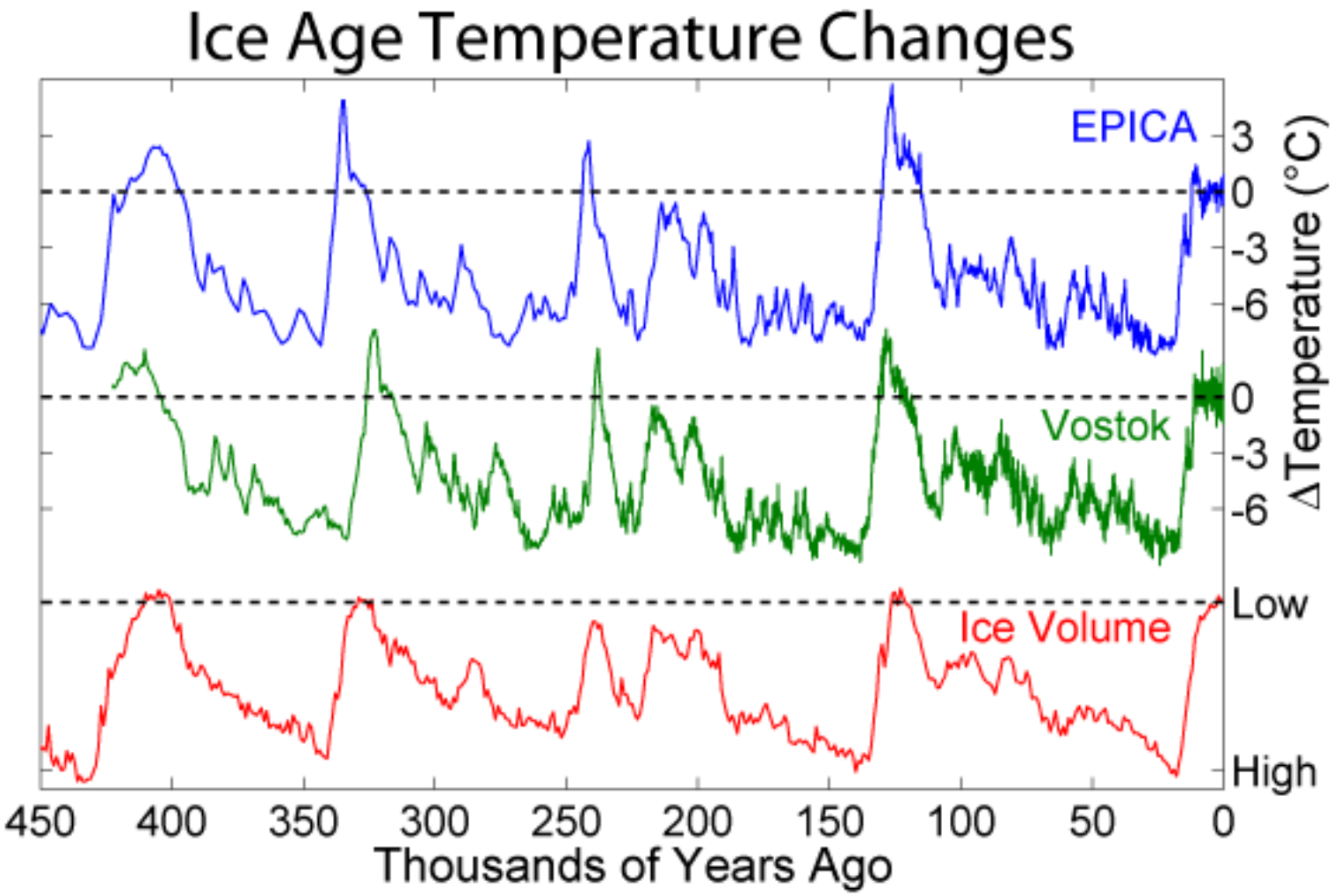
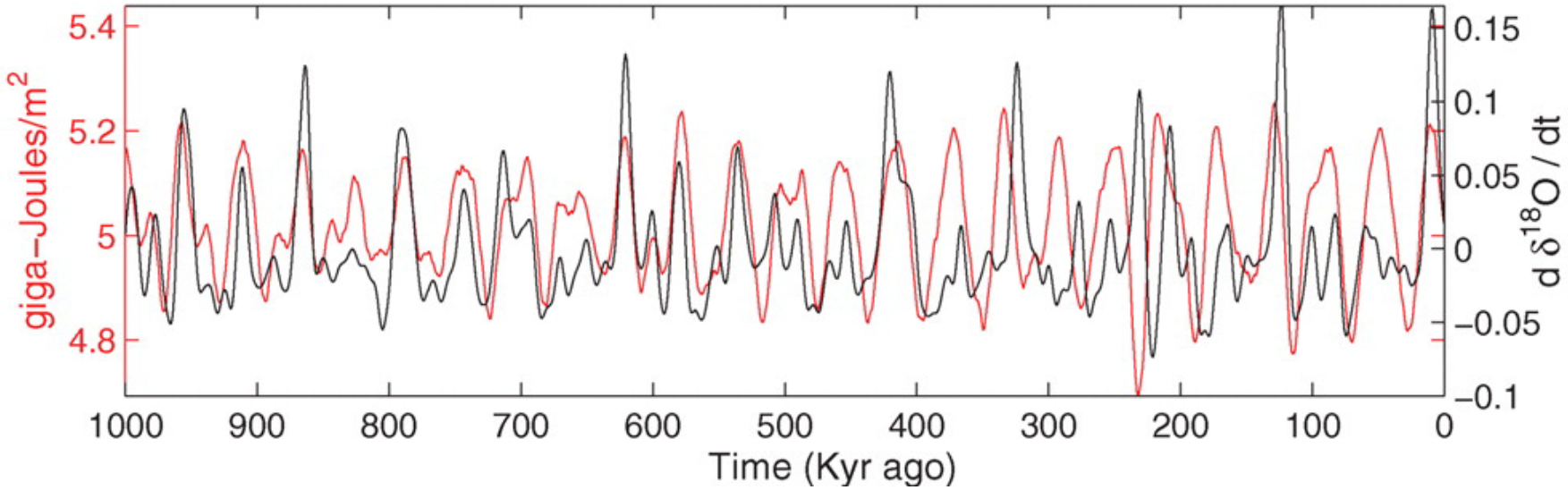


# Strong Correlation between High Latitude Summer Insolation and Ice Volume




Black: Time rate of change of ice volume

Red: Summer high latitude sunlight

P. Huybers, *Science*, 2006

# Svante Arrhenius, 1859-1927

# Guy Stewart Callendar (1898 - 1964)

## THE ARTIFICIAL PRODUCTION OF CARBON DIOXIDE AND ITS INFLUENCE ON TEMPERATURE

By G. S. CALLENDAR

(Steam technologist to the British Electrical and Allied Industries Research Association.)

(Communicated by Dr. G. M. B. Dobson, F.R.S.)

[Manuscript received May 19, 1937—read February 16, 1938.]

# Carbon Dioxide and Climate: A Scientific Assessment

## Report to the National Academy of Sciences
## Jule G. Charney and co-authors
## 1979

*When it is assumed that the CO2 content of the atmosphere is doubled and statistical thermal equilibrium is achieved, the more realistic of the modeling efforts predict a global surface warming of between 2°C and 3.5 °C, with greater increases at high latitudes.*

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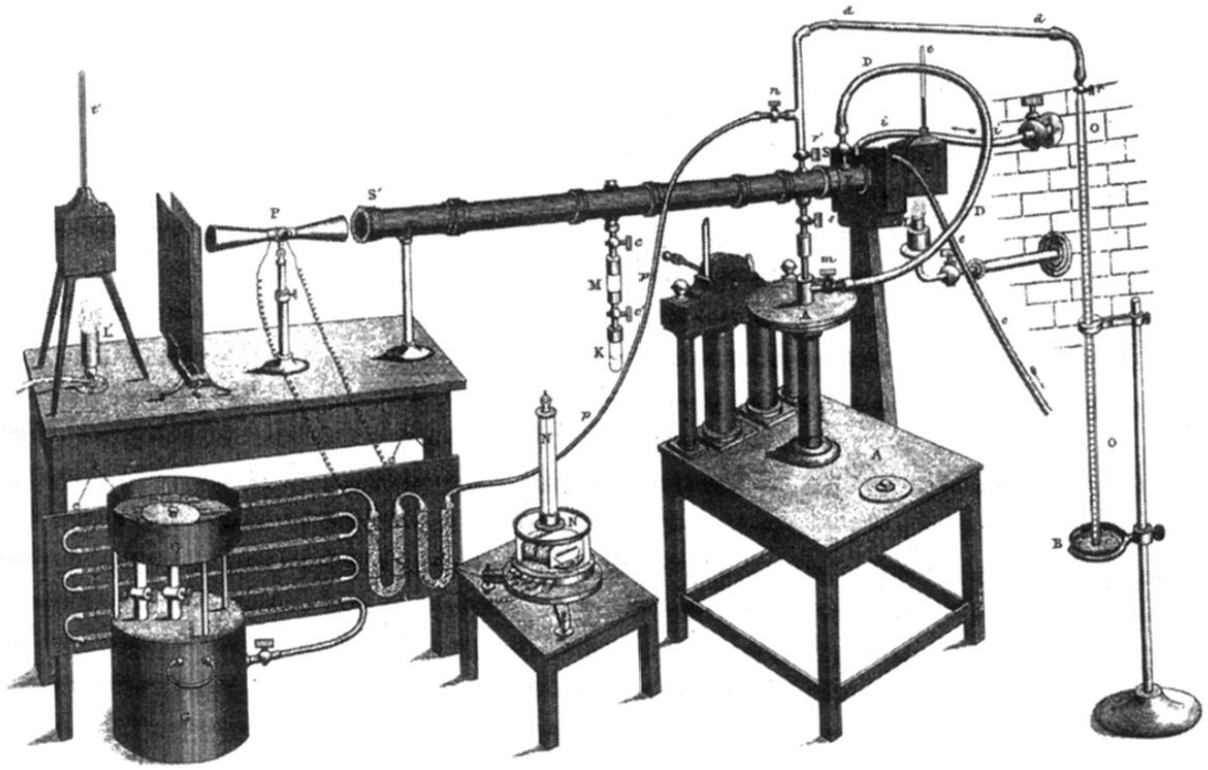


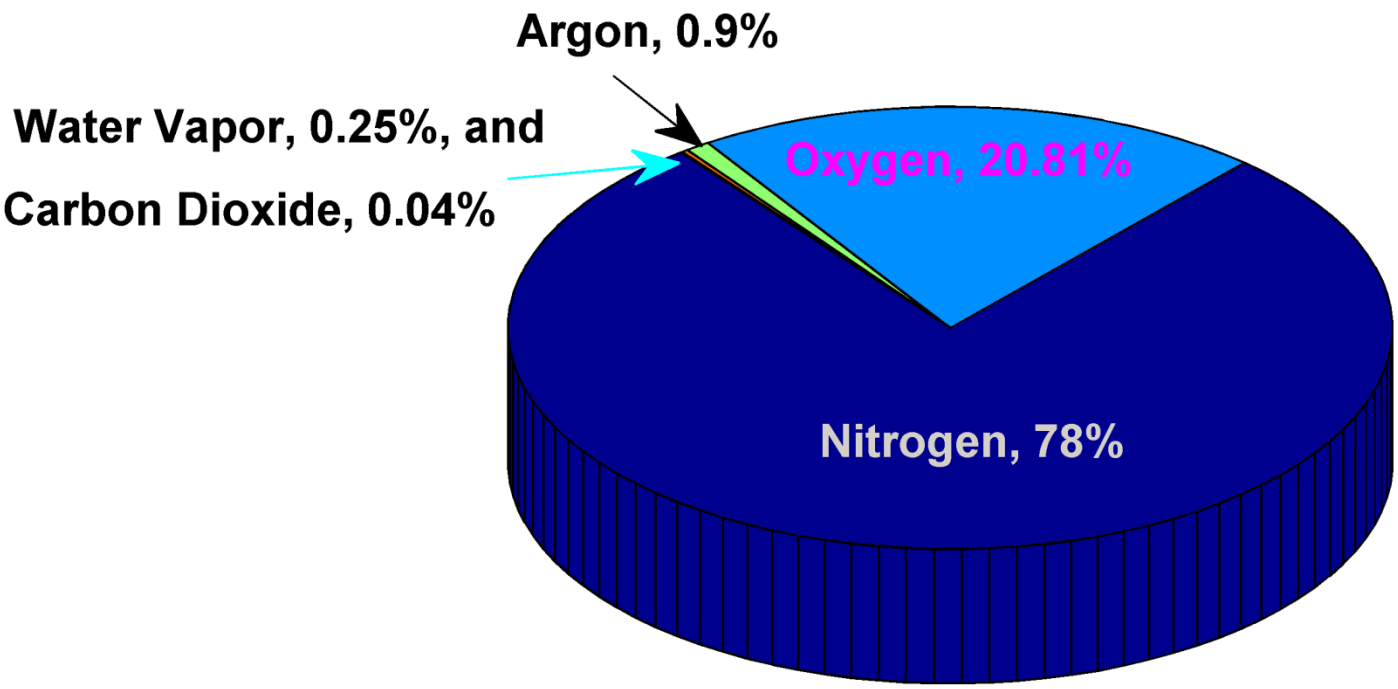
**John Tyndall**
**(1820-1893)**

# Tyndall's Essential Results:

- **Oxygen ($O_2$ ), nitrogen ($N_2$), and argon (Ar), though they make up ~99% of the atmosphere, are almost entirely transparent to solar and terrestrial radiation**

- **Water vapor ($H_2O$), carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), and a handful of other trace gases make the lower atmosphere nearly opaque to infrared radiation, though still largely transparent to solar radiation (but clouds have strong effects on radiation at all wavelengths). Together they increase the Earth's surface temperature from about 0°F to around 60°F.**

# Atmospheric Composition



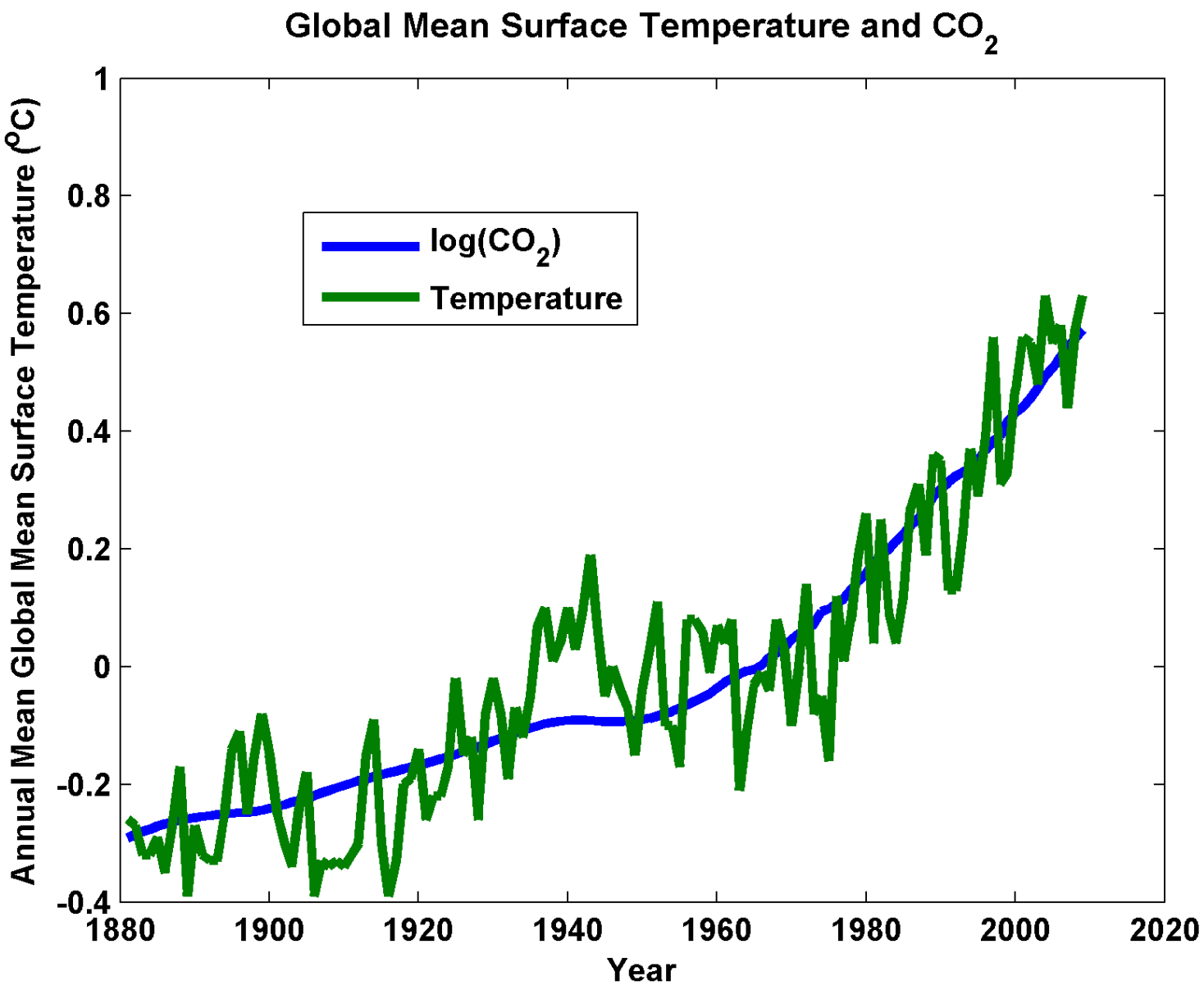

The orange sliver (can you see it?) makes the difference between a mean surface temperature of 0$^{o}$F and of 60$^{o}$F.

- Water Vapor ($H_2O$), about 0.25% of the mass of the atmosphere, is the most important greenhouse gas, but responds to atmospheric temperature change on a time scale of about 2 weeks

- Climate is therefore strongly influenced by long-lived greenhouse gases (e.g. $CO_2$, $CH_4$, $N_2O$) that together comprise about **0.04%** of the mass of the atmosphere. Concentration of $CO_2$ has increased by 43% since the dawn of the industrial revolution

# Svante Arrhenius, 1859-1927

*"Any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4°; and if the carbon dioxide were increased fourfold, the temperature would rise by 8°."* – *Världarnas utveckling (*Worlds in the Making), 1906


Global Mean Surface Temperature and CO2
Annual Mean Global Mean Surface Temperature (°C)
Year
log(CO2)
Temperature
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
1880
1900
1920
1940
1960
1980
2000
2020

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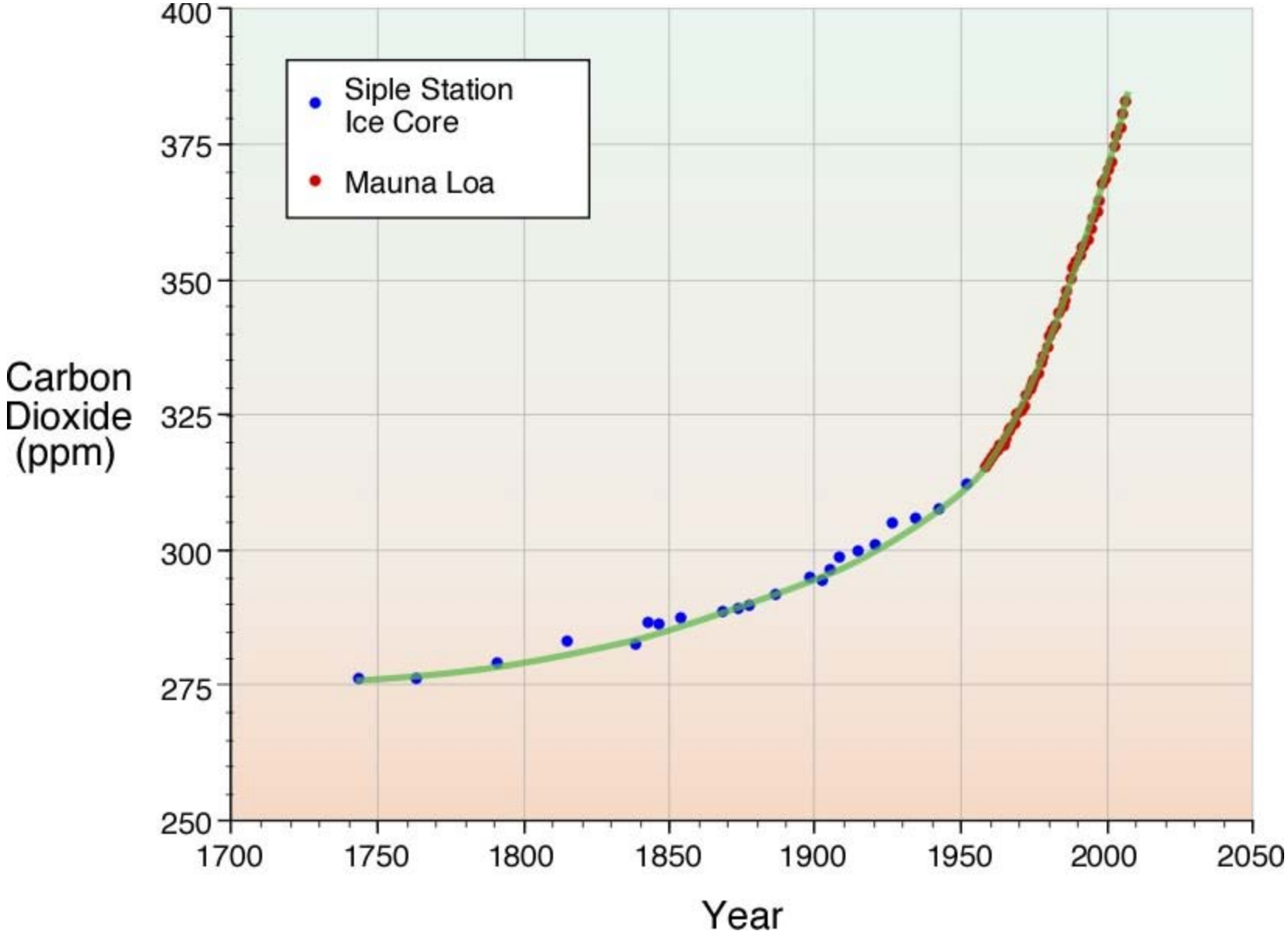
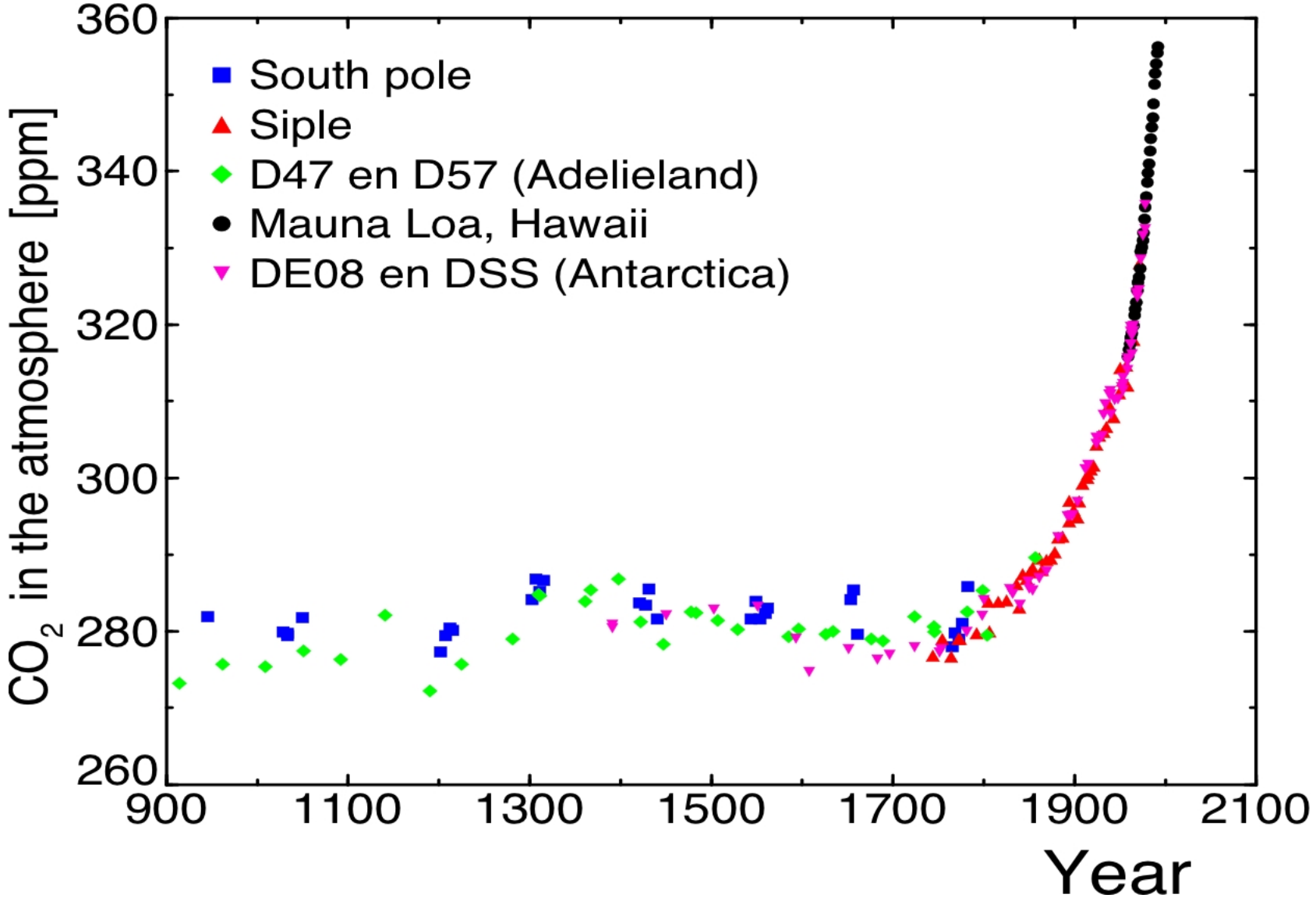
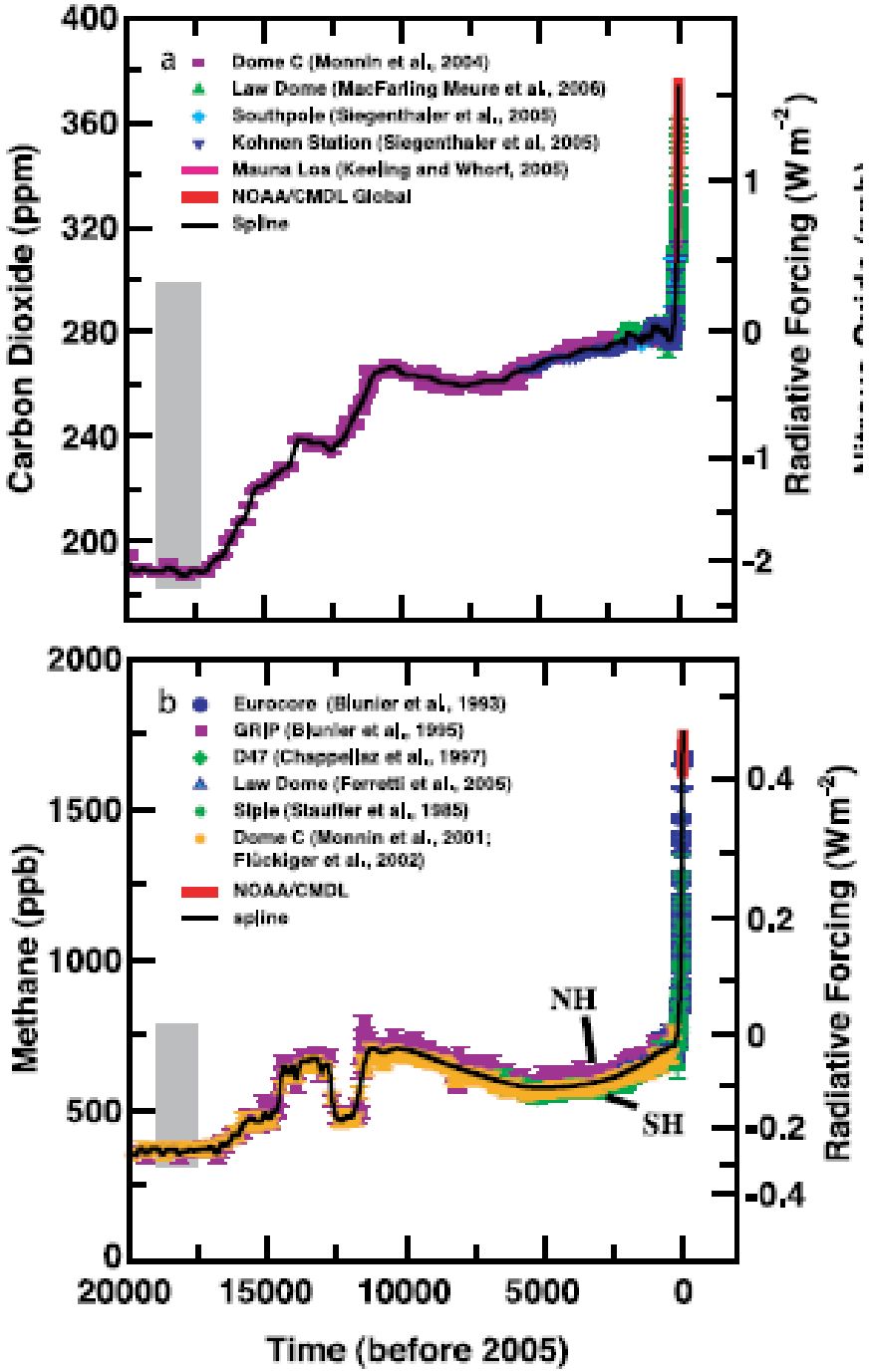
# Paleoclimate

# Carbon Dioxide from Ice Cores and Direct Measurements

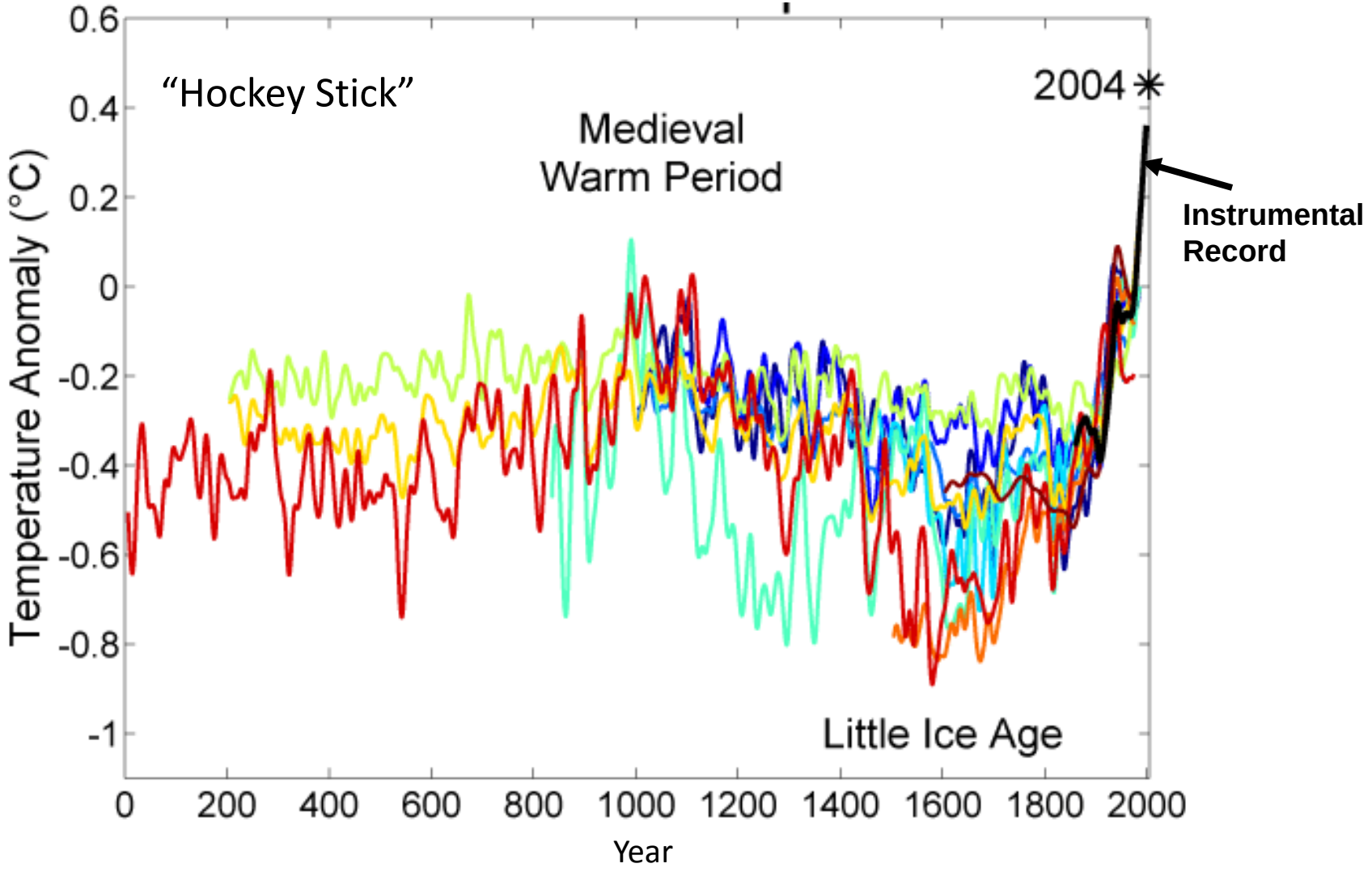



South pole
Siple
D47 en D57 (Adelieland)
Mauna Loa, Hawaii
DE08 en DSS (Antarctica)
$CO_2$ in the atmosphere [ppm]
360
340
320
300
280
260
900
1100
1300
1500
1700
1900
2100
Year

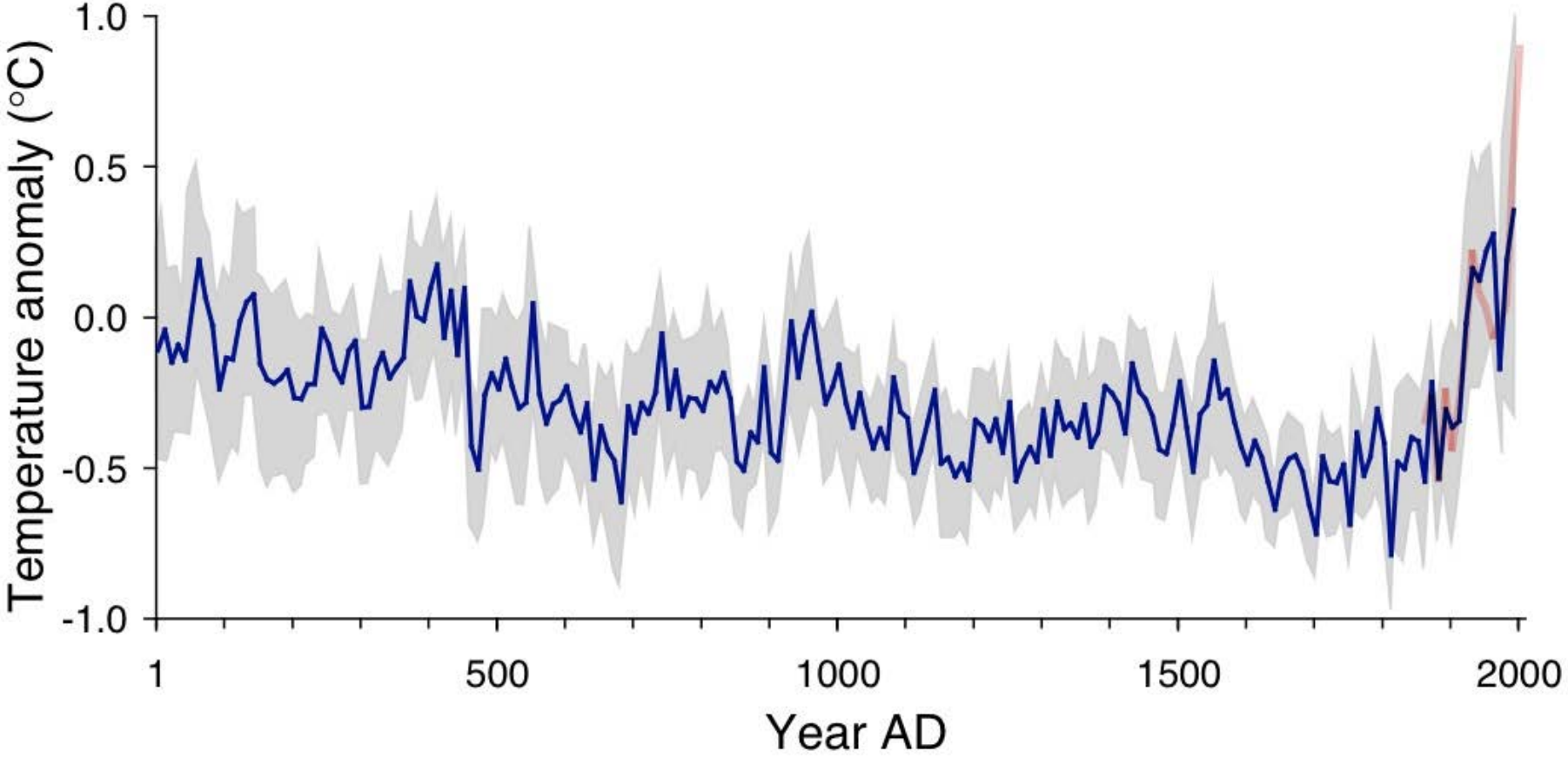



**Variation in carbon dioxide and methane over the past 20,000 years, based on ice core and other records**

# Paleo reconstructions of temperature change over the last 2000 years

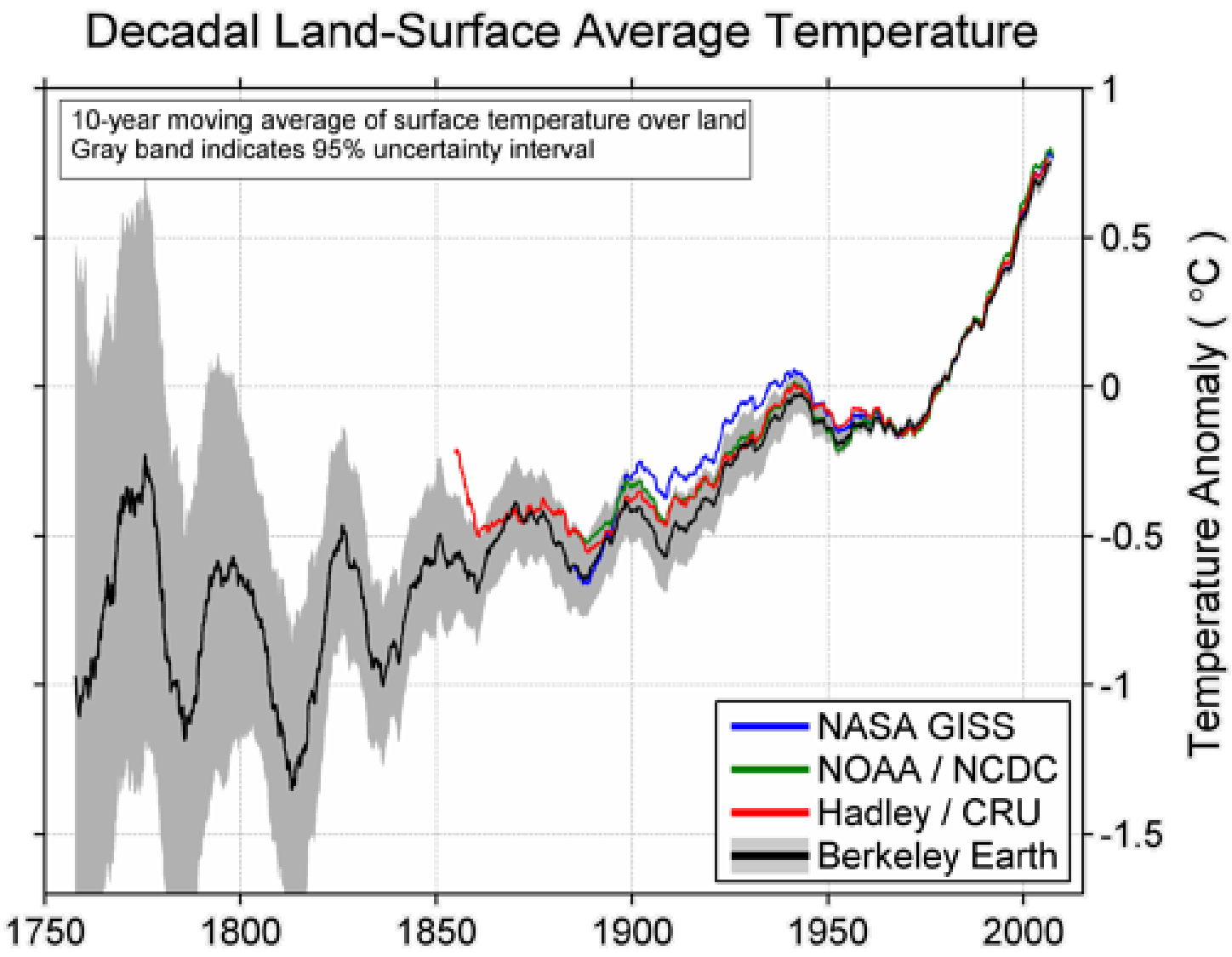


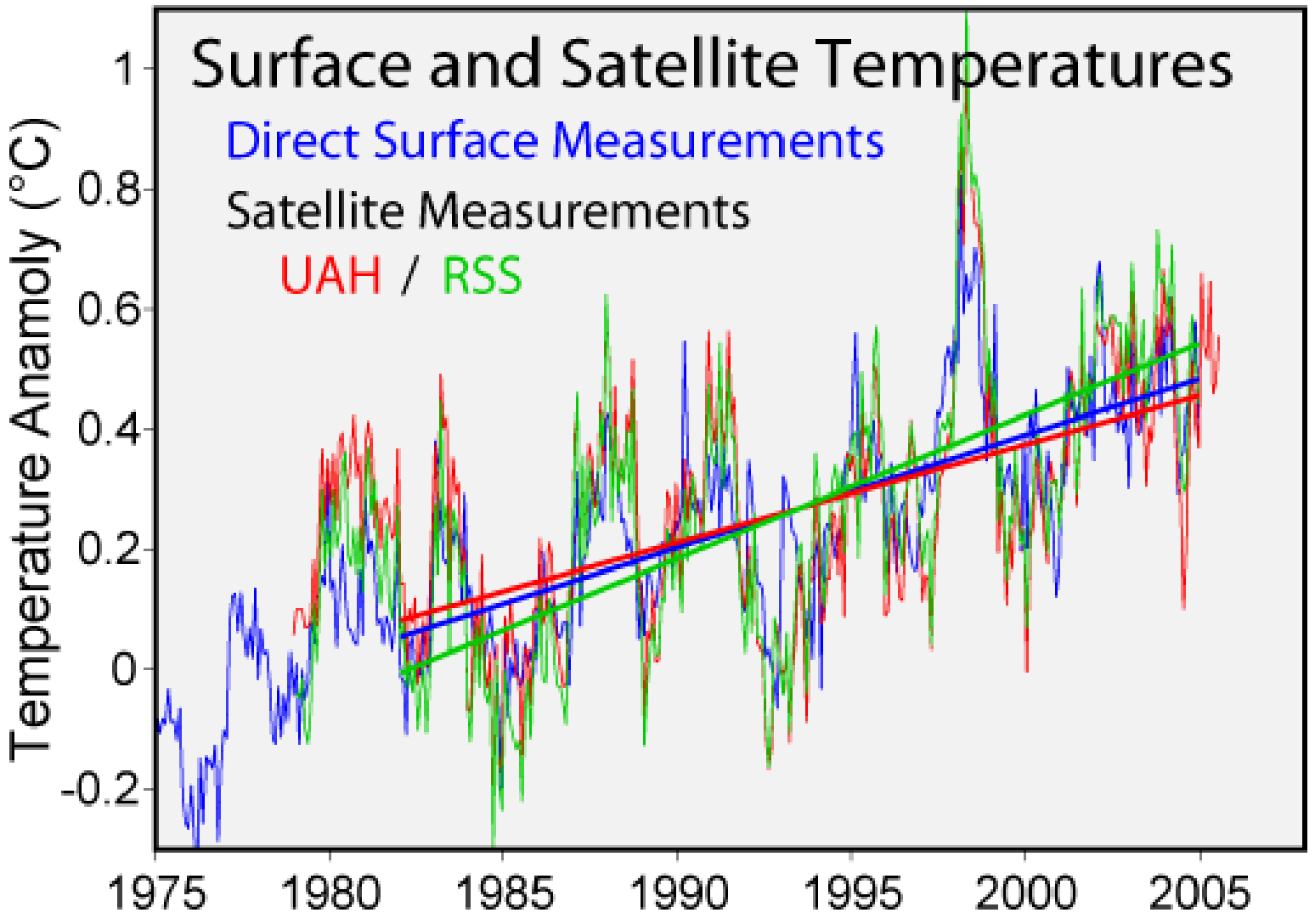
# Arctic air temperature change reconstructed (blue), observed (red)



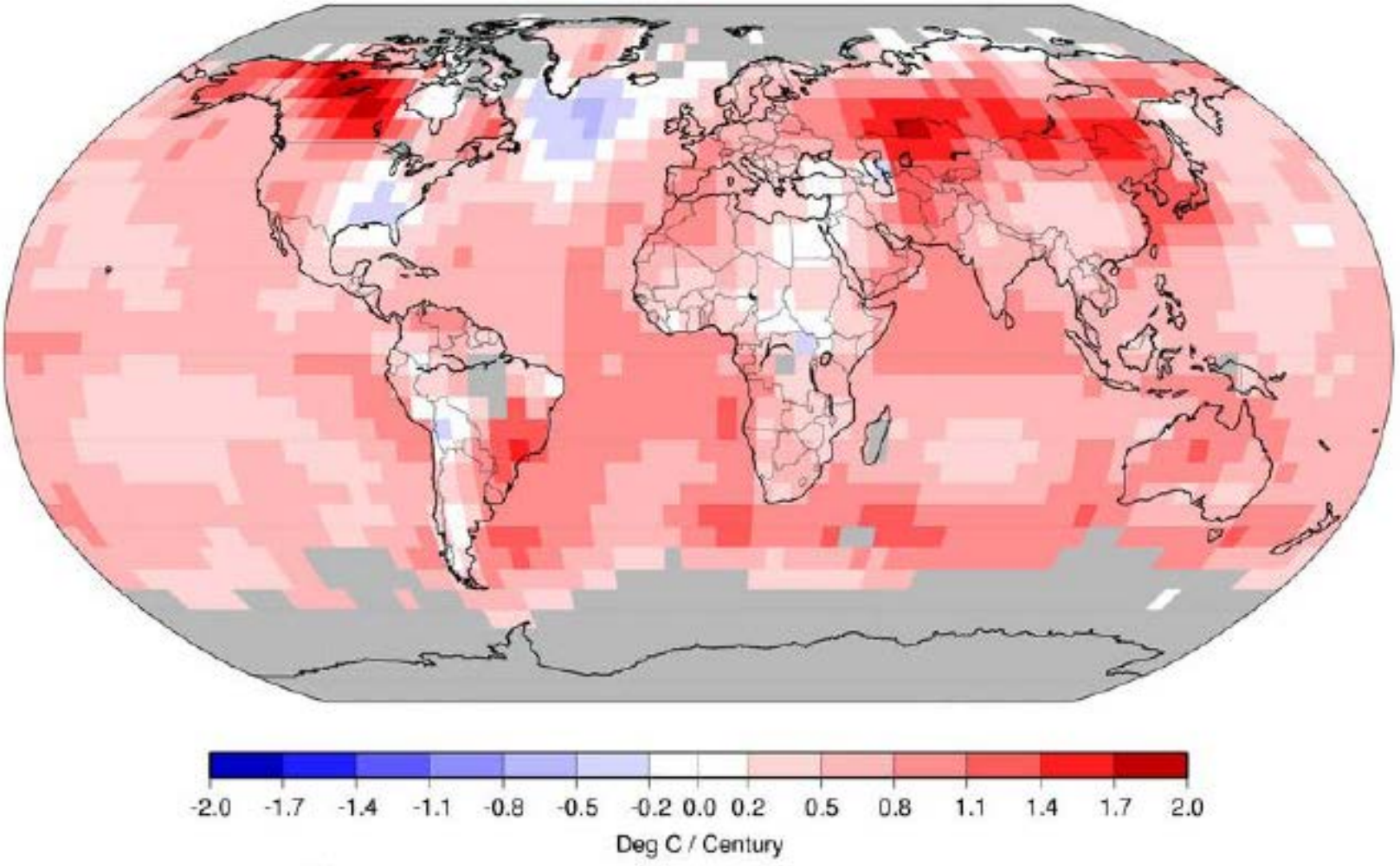

The long-term cooling trend in the Arctic was reversed during recent decades. The blue line shows the estimated Arctic average summer temperature over the last 2000 years, based on proxy records from lake sediments, ice cores, and tree rings. The shaded area represents variability among the 23 sites use for the reconstruction. The red line shows the recent warming based on instrumental temperatures. From Kaufman et al. (2009).

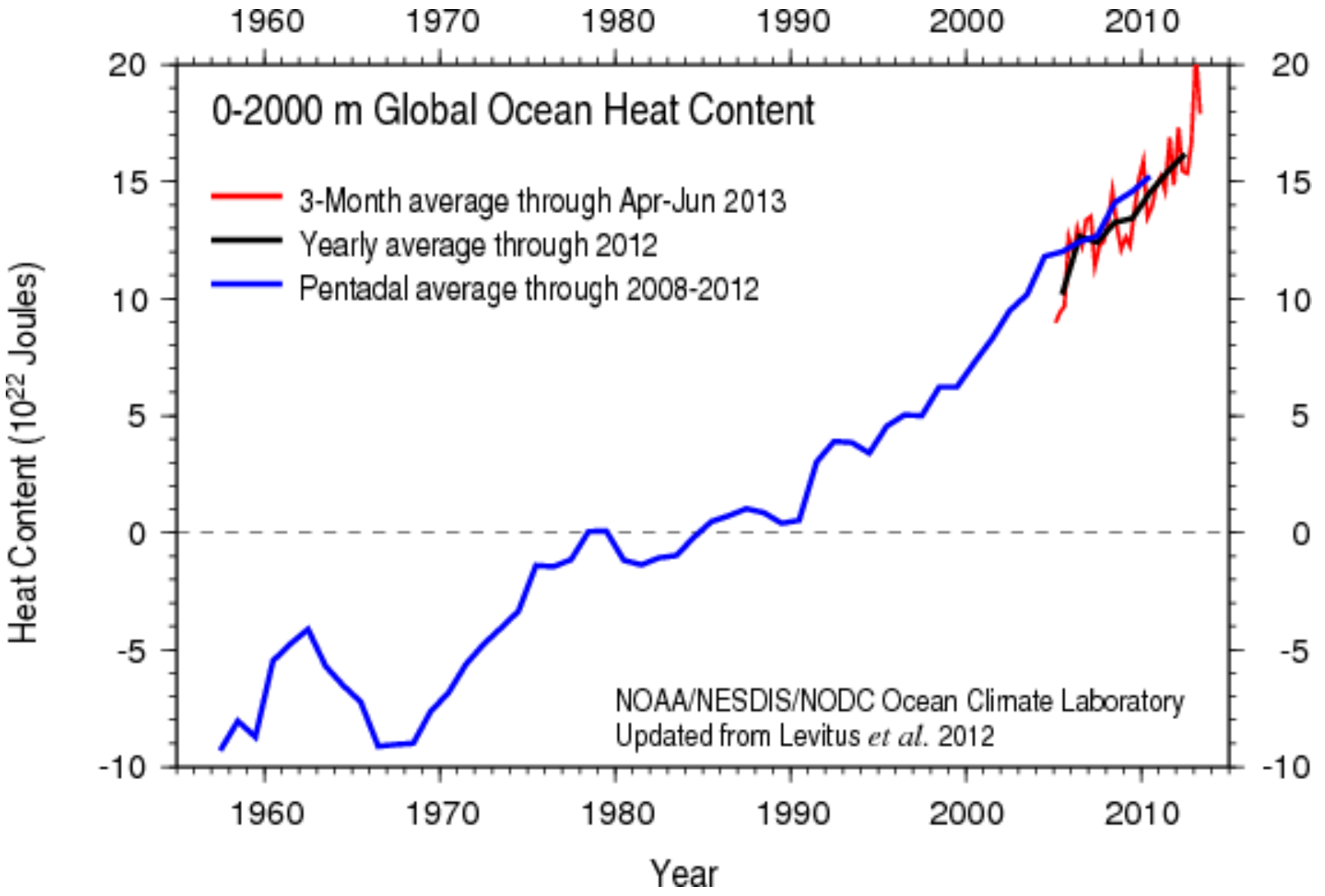
# Instrumental Record


Decadal Land-Surface Average Temperature
10-year moving average of surface temperature over land
Gray band indicates 95% uncertainty interval
NASA GISS
NOAA / NCDC
Hadley / CRU
Berkeley Earth
1
0.5
0
-0.5
-1
-1.5
Temperature Anomaly ( °C )
1750
1800
1850
1900
1950
2000


Surface and Satellite Temperatures
Direct Surface Measurements
Satellite Measurements
UAH / RSS
Temperature Anamoly (°C)
1
0.8
0.6
0.4
0.2
0
-0.2
1975
1980
1985
1990
1995
2000
2005

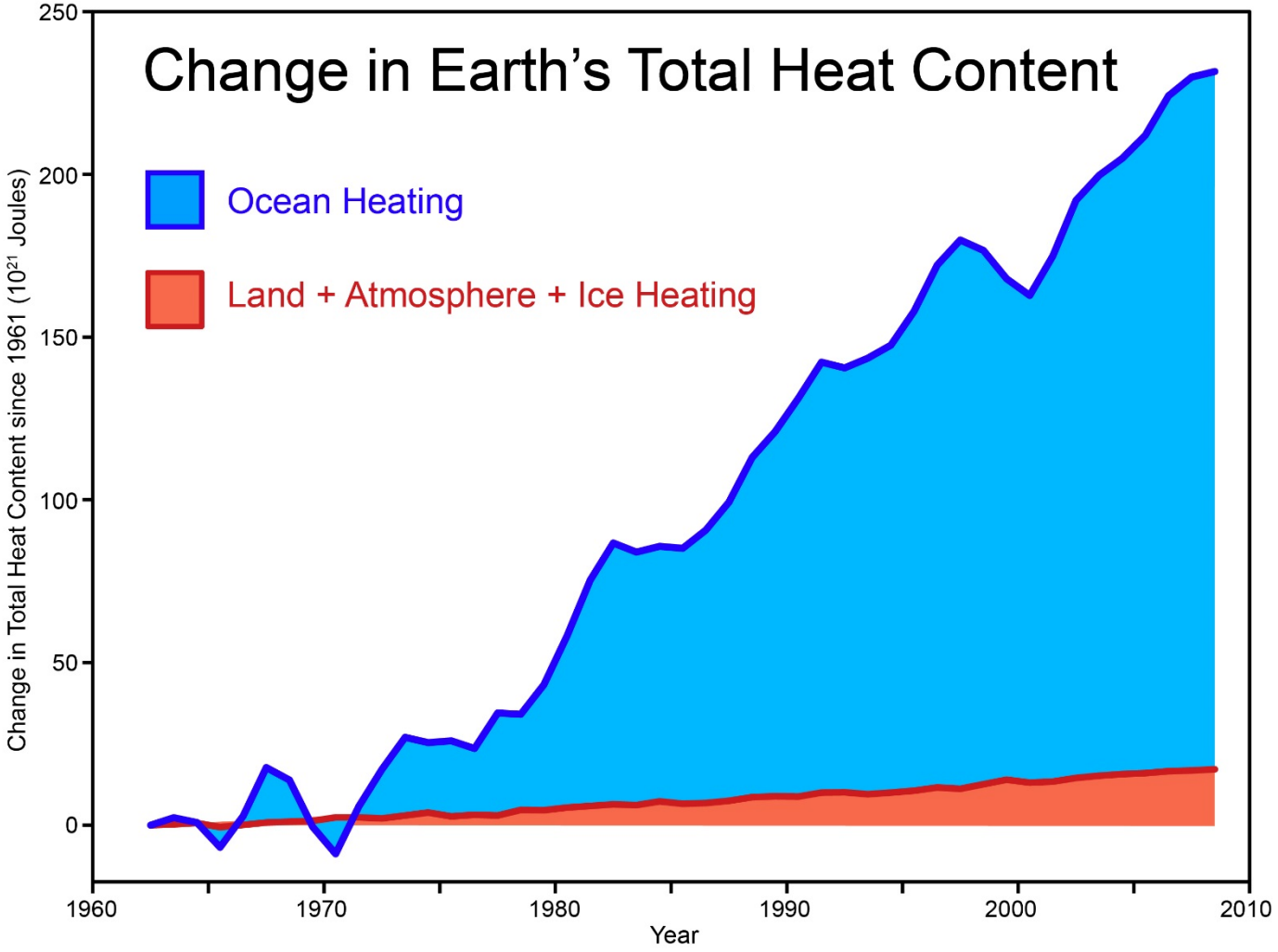
# Distribution of temperature change, 1901-2005



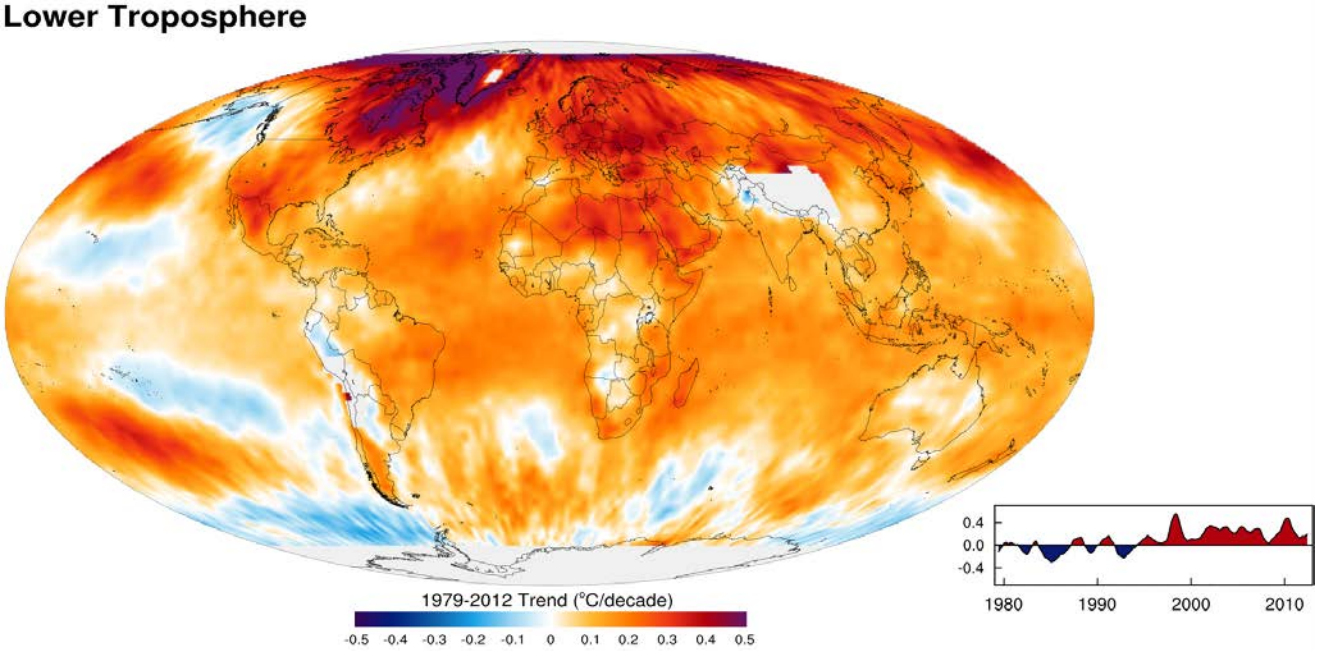



Based on bathythermograph and ARGO (post-2004) data

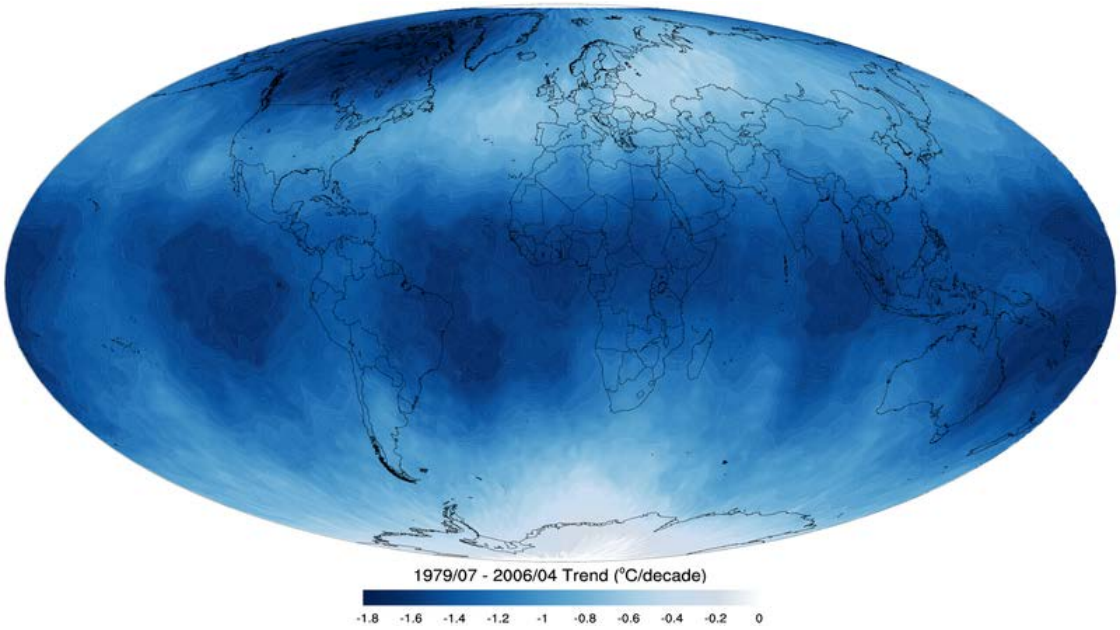
Image credit: *NOAA*




Total amount of heat from global warming that has accumulated in Earth's climate system since 1961, from Church et al. (2011) (many thanks to Neil White from the CSIRO for sharing their data).

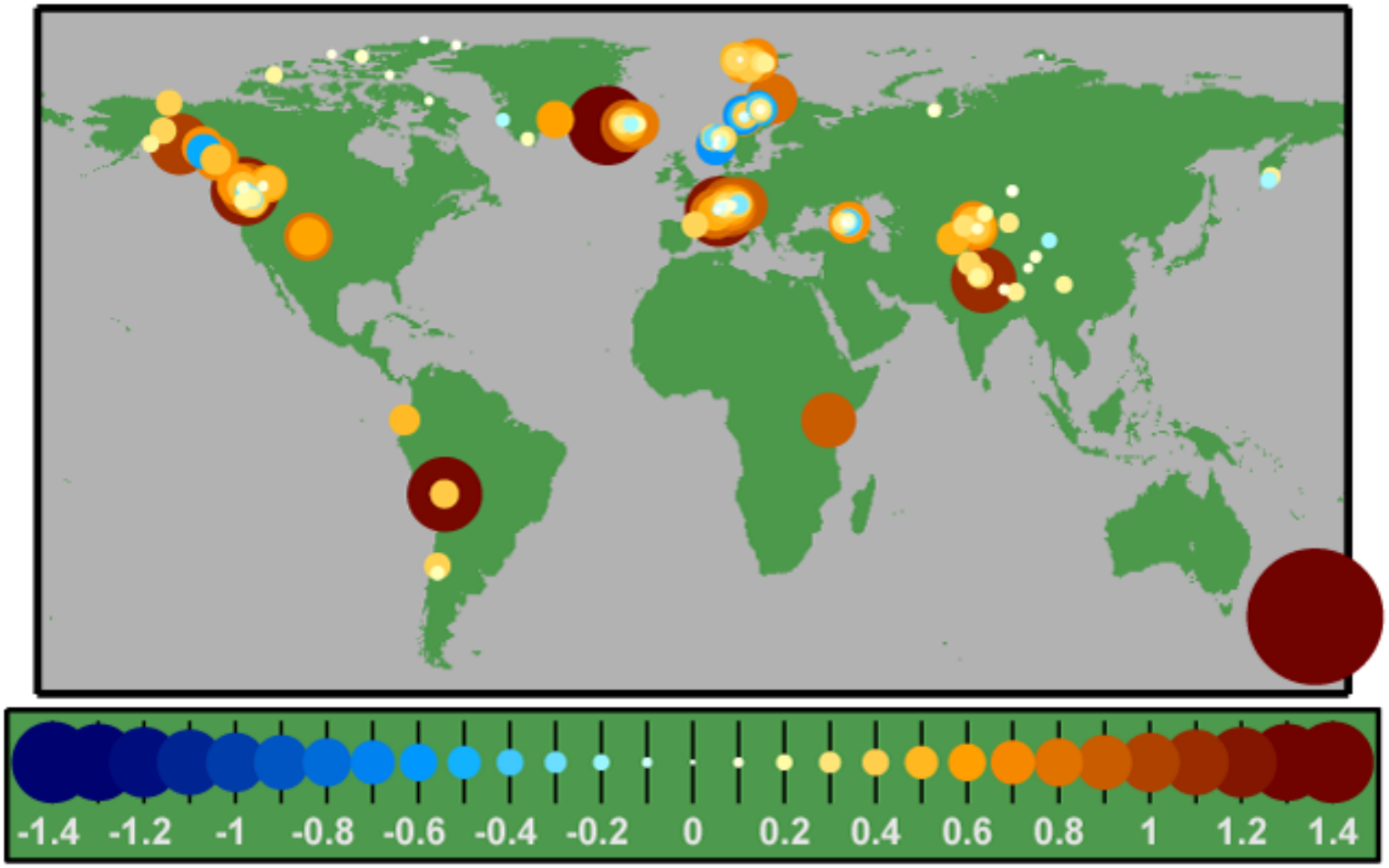



**Tropospheric temperature trend from 1979-2012 based on satellite measurements (RSS)**



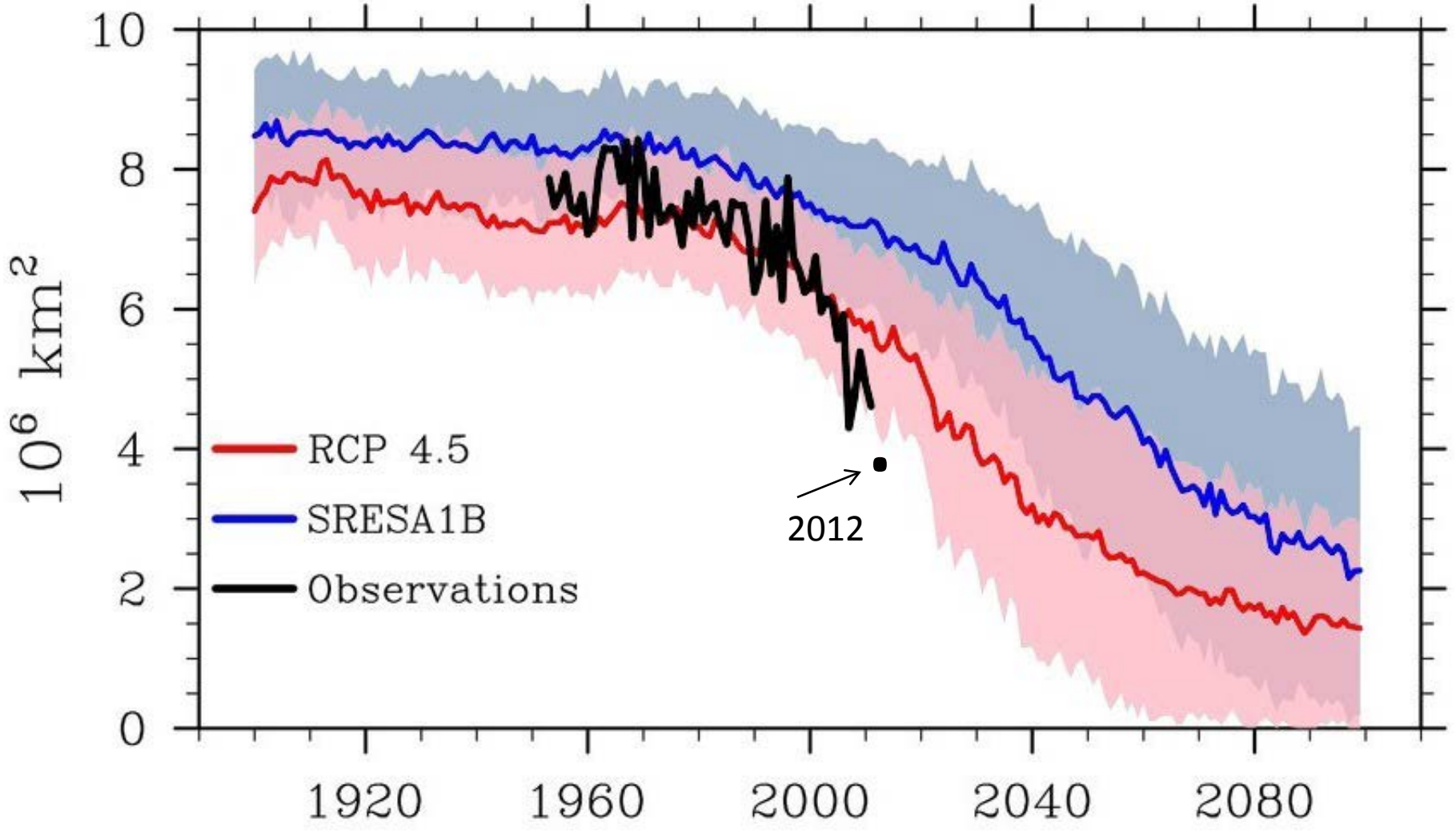

**Top of the stratosphere (TTS) 1979-2006 temperature trend.**

# Mountain Glacier Changes Since 1970

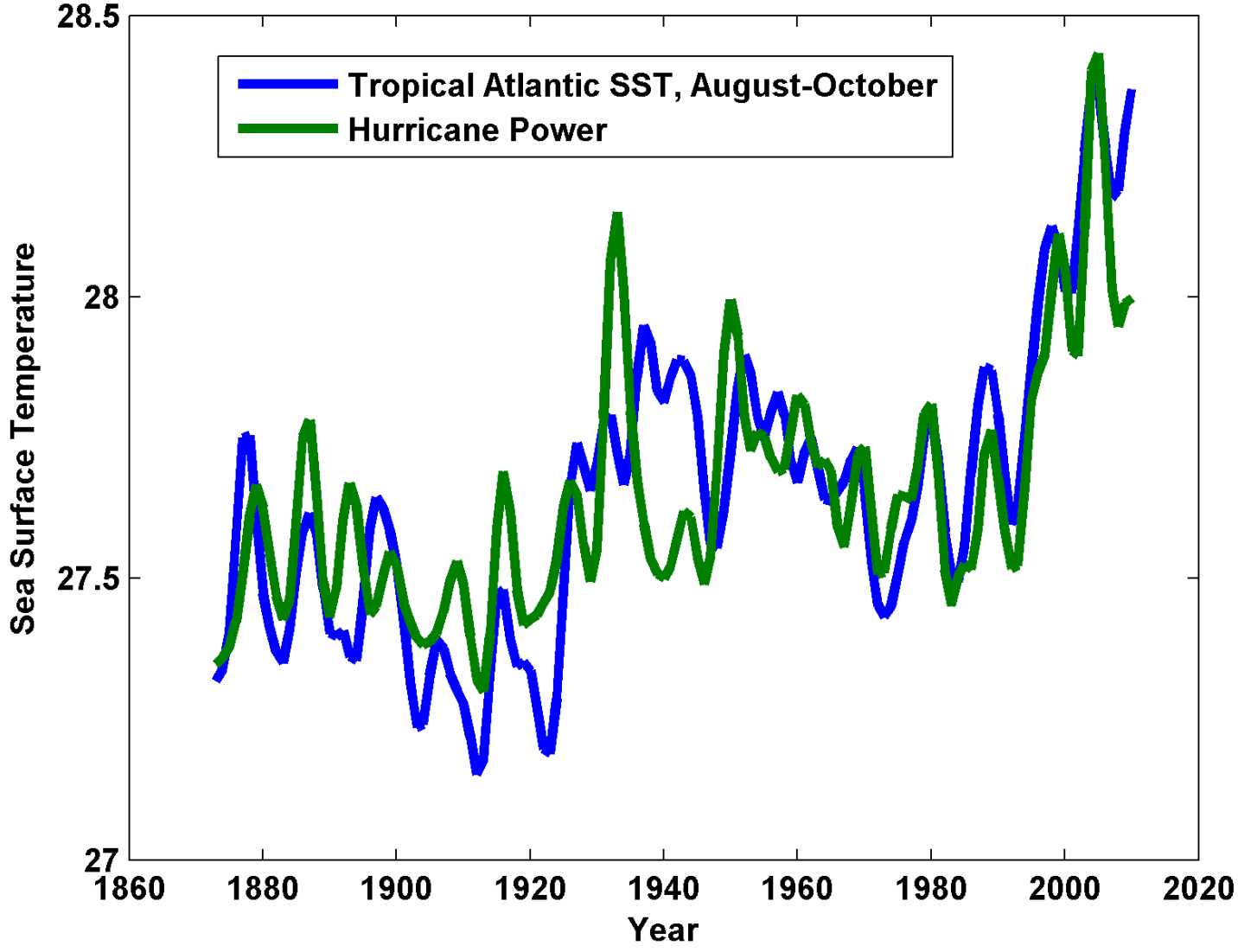


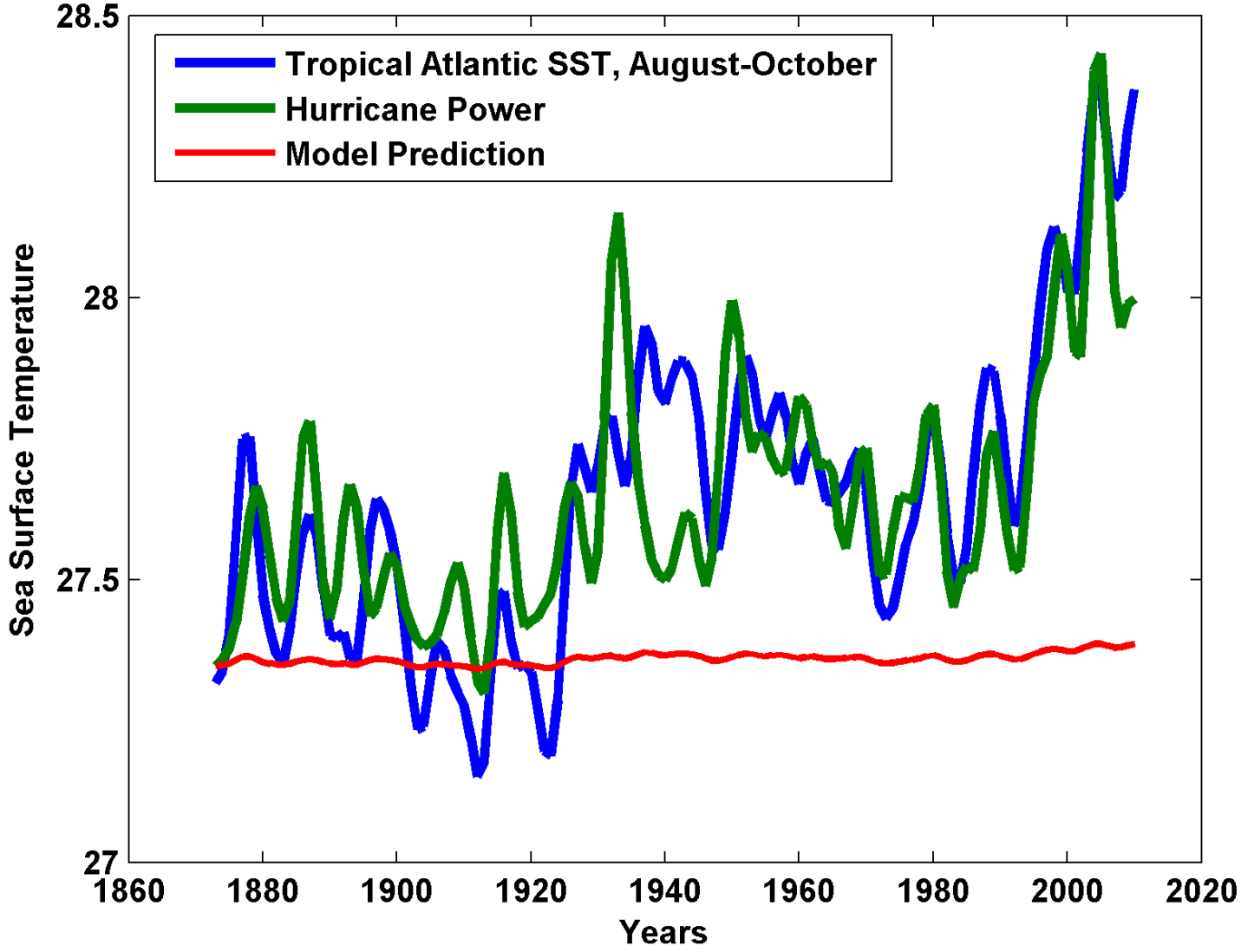

Effective Glacier Thinning (m / yr)

# September Arctic Sea Ice Extent

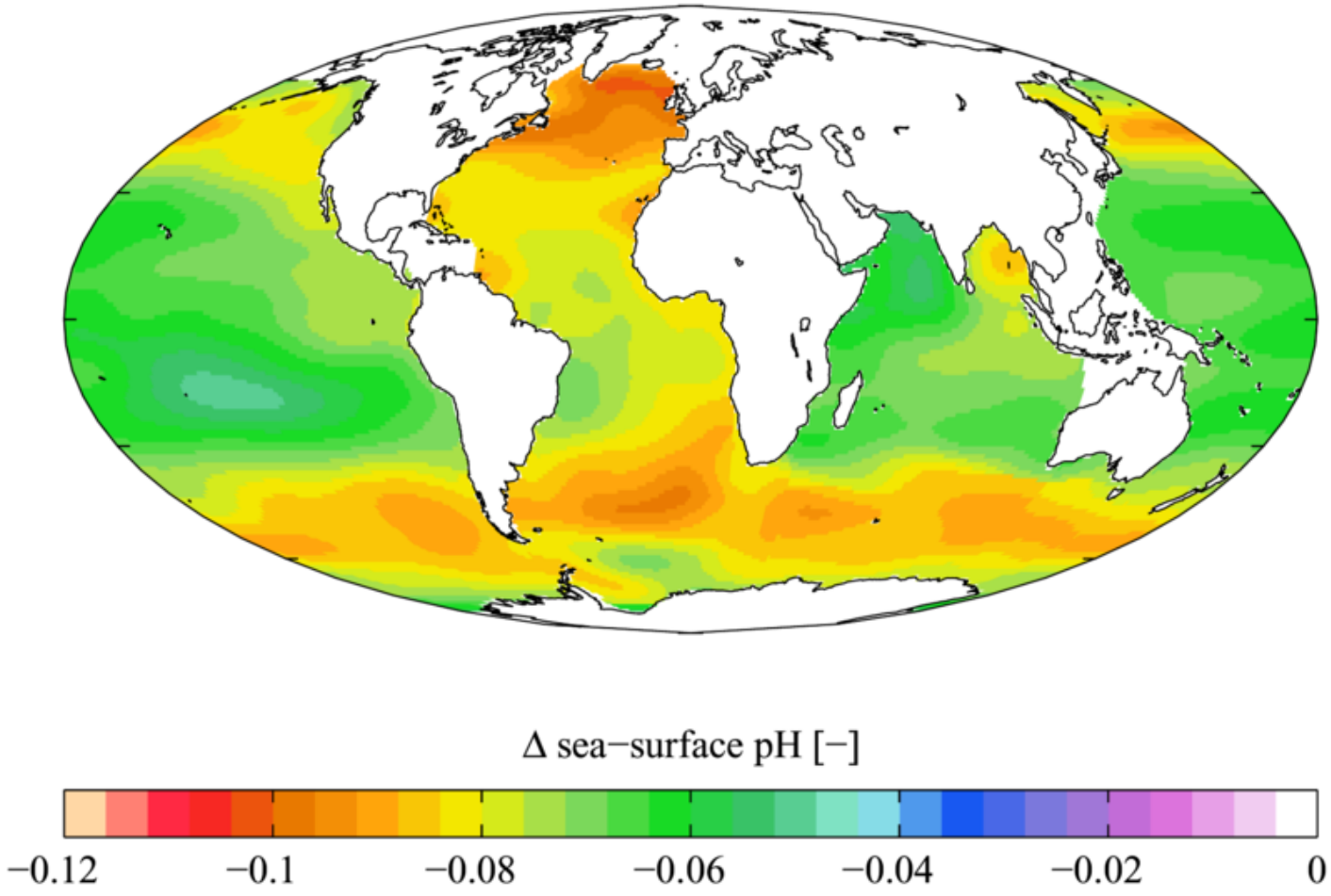



**Credit: National Snow and Ice Data Center courtesy Stroeve et al. 2012**


Tropical Atlantic SST, August-October
Hurricane Power
Sea Surface Temperature
28.5
28
27.5
27
1860
1880
1900
1920
1940
1960
1980
2000
2020
Year

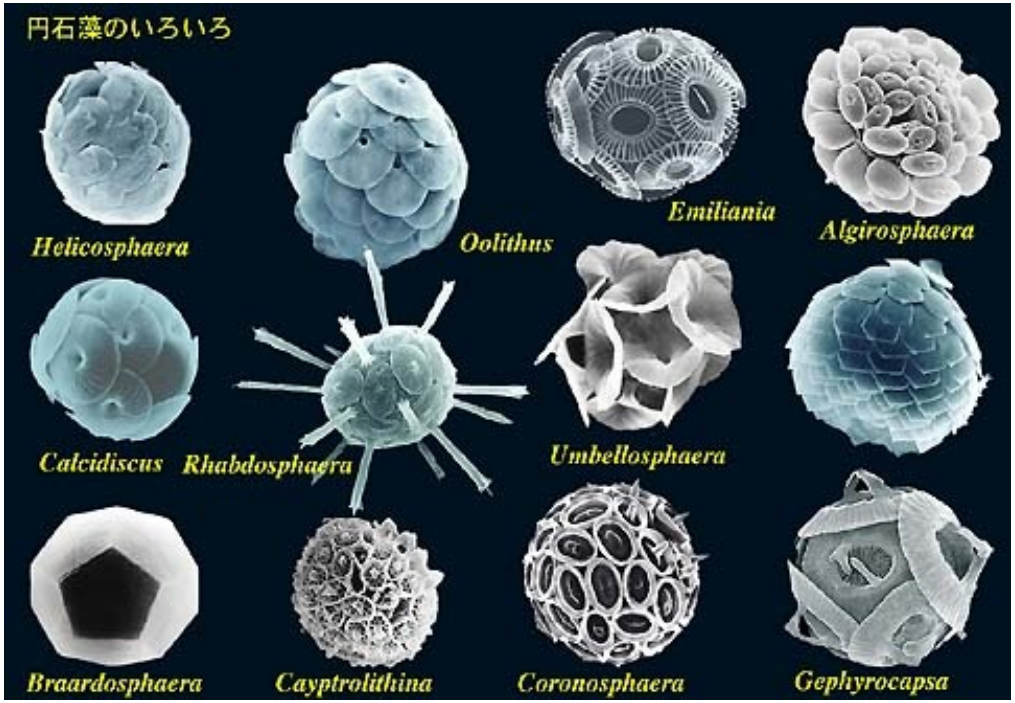

Tropical Atlantic SST, August-October
Hurricane Power
Model Prediction
Sea Surface Temperature
28.5
28
27.5
27
1860
1880
1900
1920
1940
1960
1980
2000
2020
Years

# The Oceans Are Becoming More Acidic



- Acidification through $CO_2$ threatens marine life

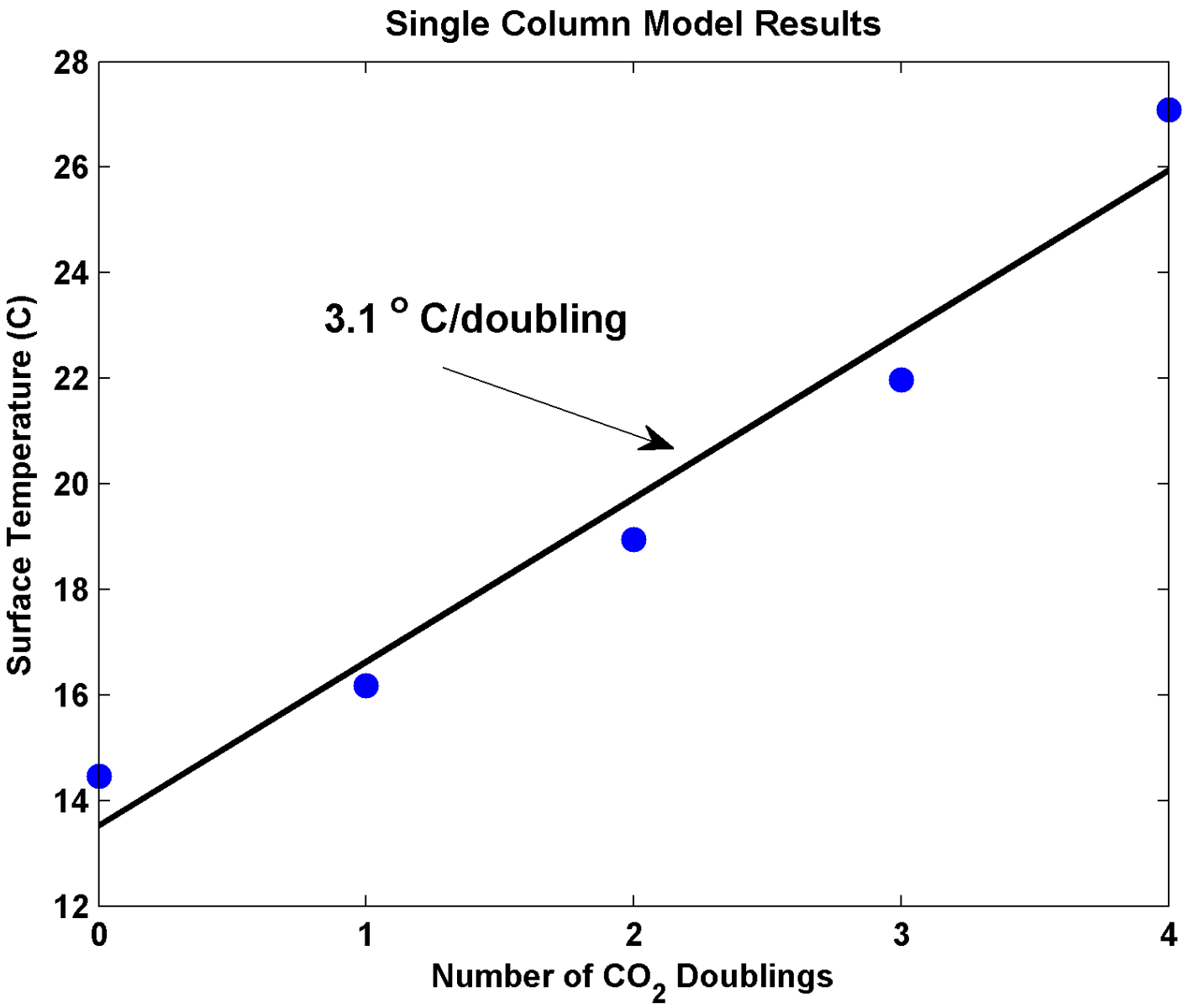
Plankton




Coral Reefs

# Simple Models

# MIT Single Column Model




IPCC Estimate: 2-4.5 °C

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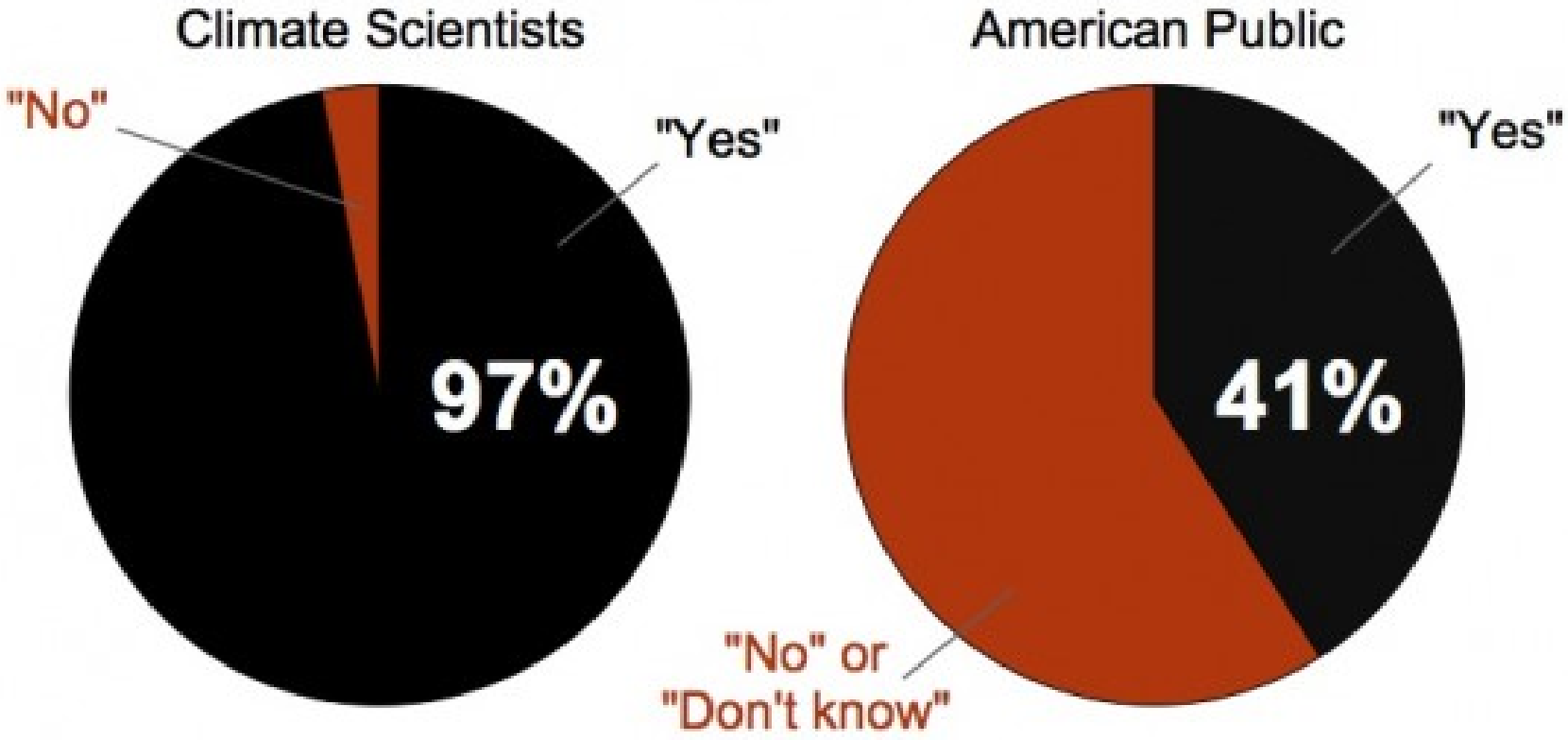
## Say Climate Change is Happening and Human Caused




*Left*: Proportion of peer-reviewed research papers that stated a position on the reality of human-caused global warming and said that it is happening and human caused (Cook et al. 2013). *Right*: Proportion of the American public that says climate change is happening and human caused (Leiserowitz et al. 2013).

# Known Risks

- Increasing sea level
- Increasing hydrological events… droughts and floods
- Increasing incidence of high category hurricanes and associated storm surges and freshwater flooding
- More heat stress

*"Climate change could have significant geopolitical impacts around the world, contributing to poverty, environmental degradation, and the further weakening of fragile governments. Climate change will contribute to food and water scarcity, will increase the spread of disease, and may spur or exacerbate mass migration."*

-- Quadrennial Defense Review, U.S. Department of Defense, February, 2010

# The Future

# Estimate of how much global climate will warm as a result of doubling $CO_2$: a probability distribution

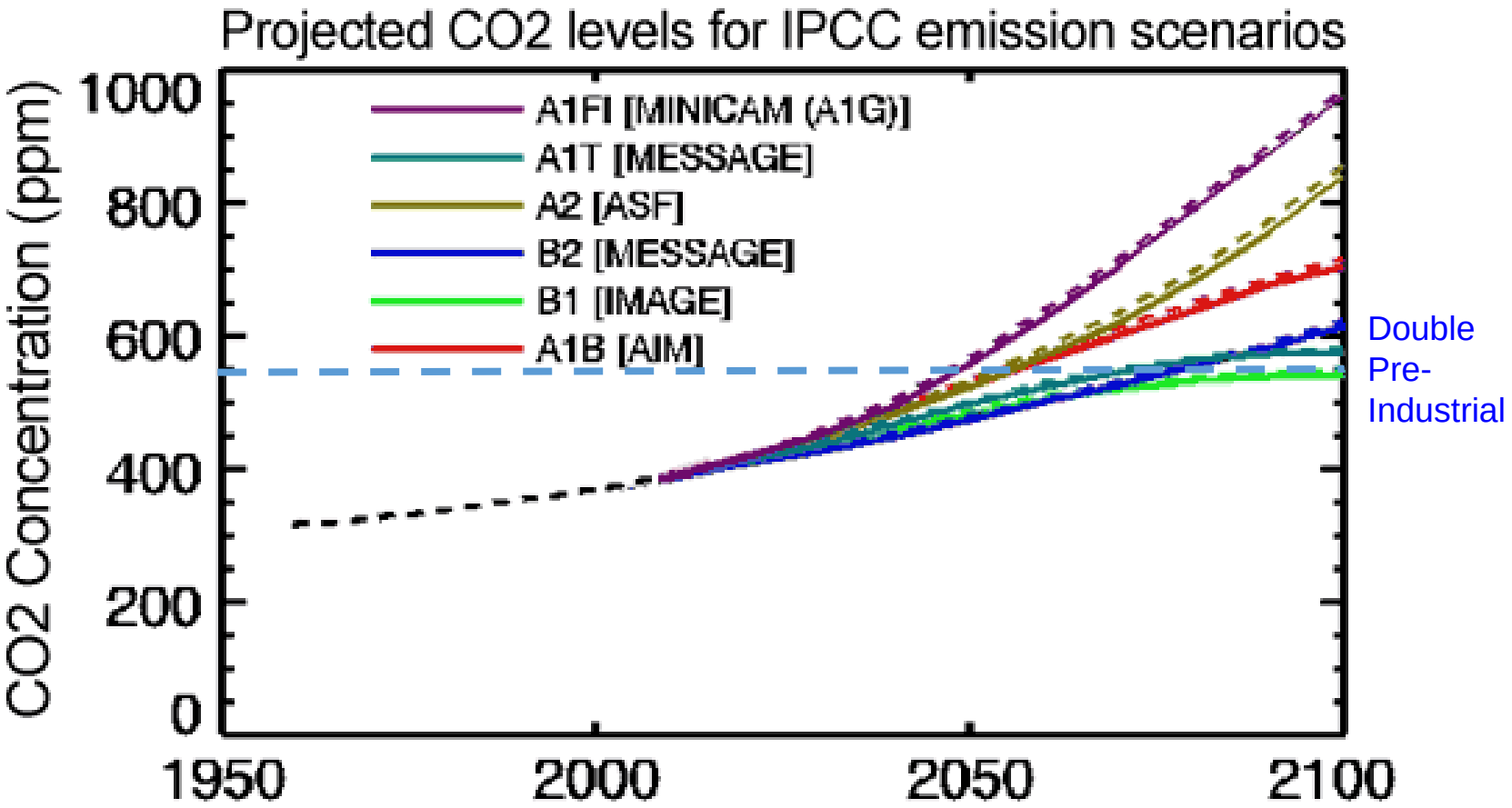

*Source: 100000 PAGE09 runs*

SEI

ClimateCost

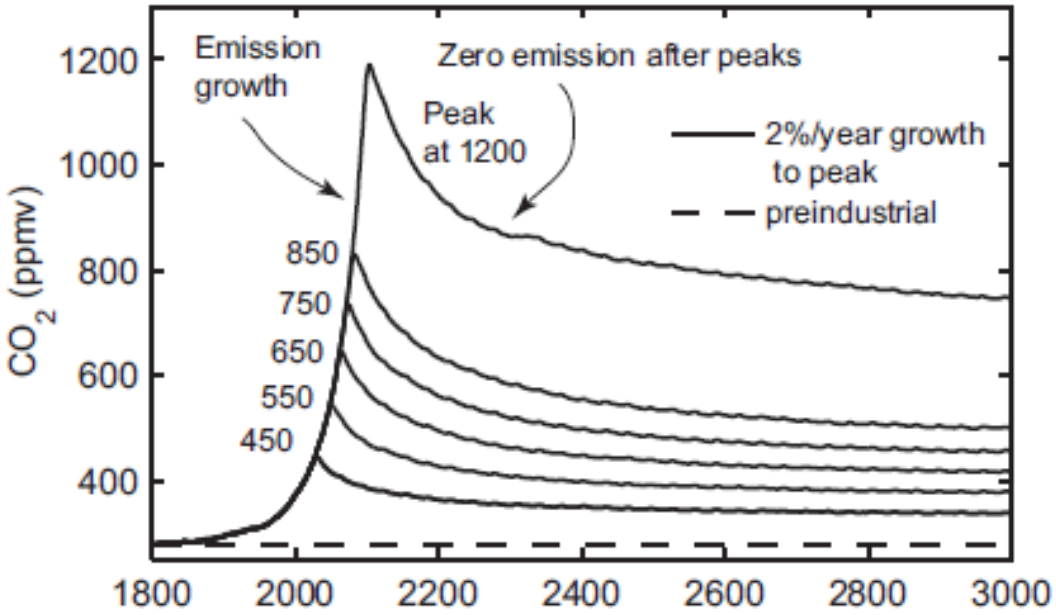
Chris Hope, U. Cambridge
courtesy Tim Palmer

# $CO_2$ Will Go Well Beyond Doubling

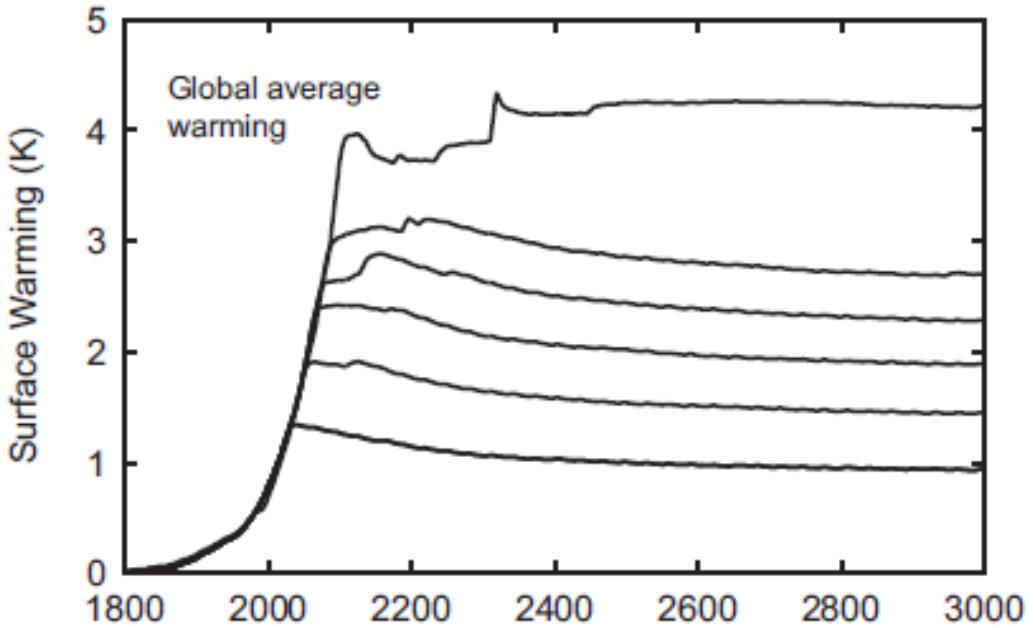


IPCC 2007: Doubling $CO_2$ will lead to an increase in mean global surface temperature of 2 to 4.5 $^oC$.

Atmospheric $CO_2$ assuming that emissions stop altogether after peak concentrations




Global mean surface temperature corresponding to atmospheric $CO_2$ above

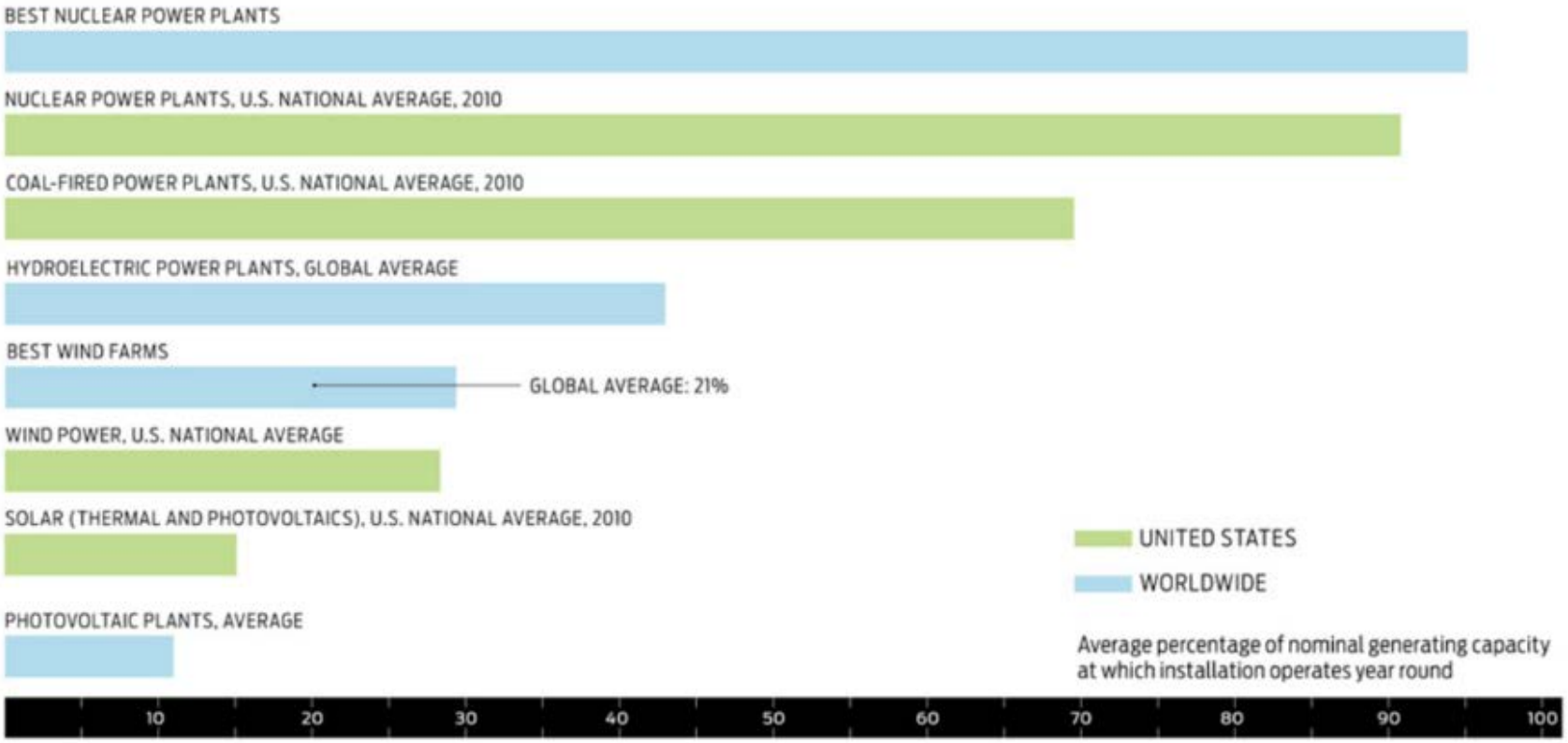



Courtesy Susan Solomon

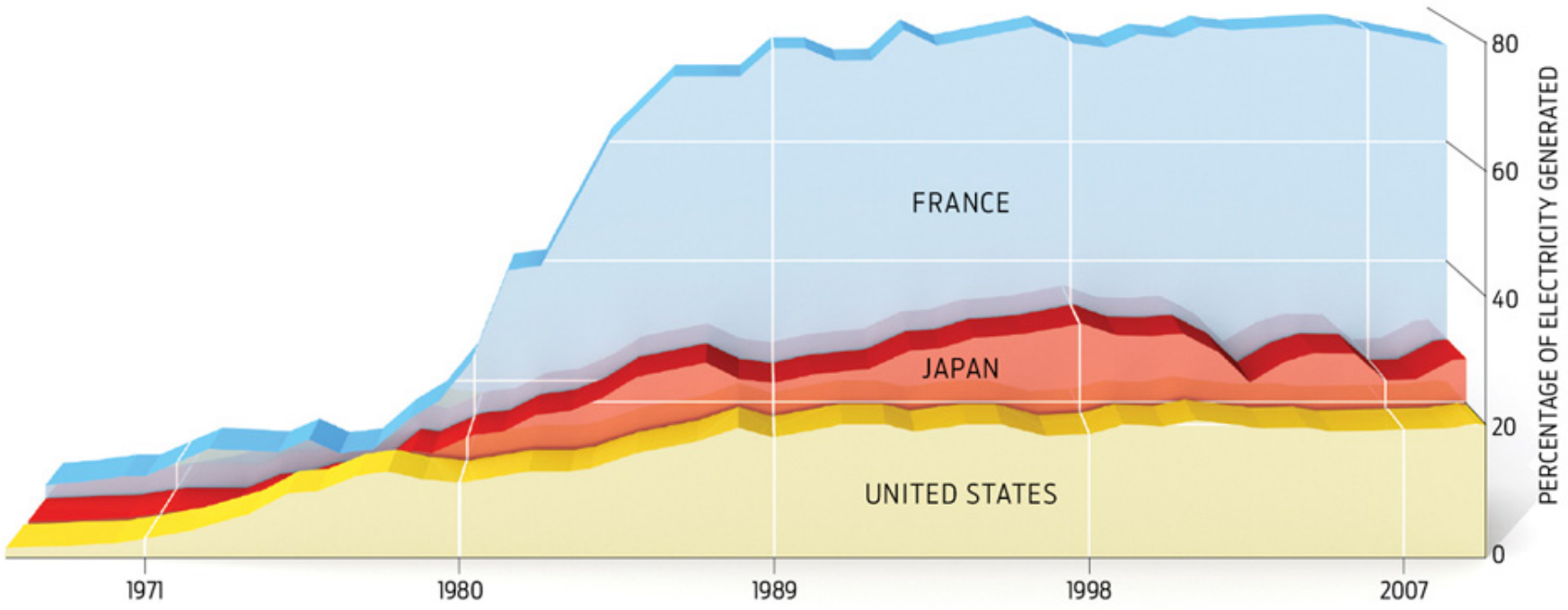
# Realistic Solutions

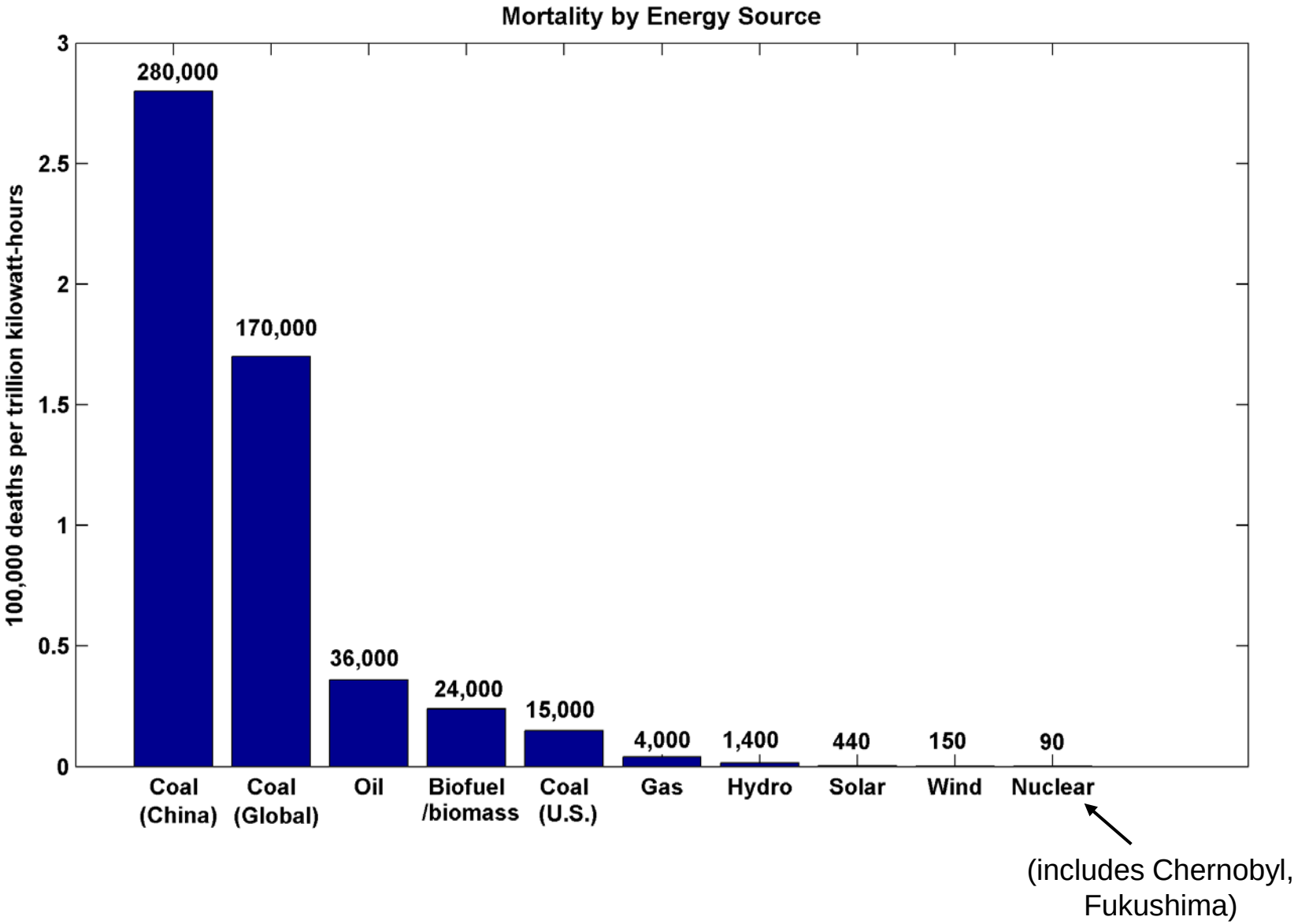
- Carbon Capture and Sequestration
  - Currently would add ~$200/ton to energy costs
  - Reasonable prospects for reducing this to ~$100/ton
  - Currently little incentive to develop this
- Nuclear Energy

# Renewables Require Baseload



# Can be deployed on 15-25 year time scale




Mortality by Energy Source
100,000 deaths per trillion kilowatt-hours
3
2.5
2
1.5
1
0.5
0
280,000
170,000
36,000
24,000
15,000
4,000
1,400
440
150
90
Coal (China)
Coal (Global)
Oil
Biofuel /biomass
Coal (U.S.)
Gas
Hydro
Solar
Wind
Nuclear
(includes Chernobyl, Fukushima)

# Summary of Main Points

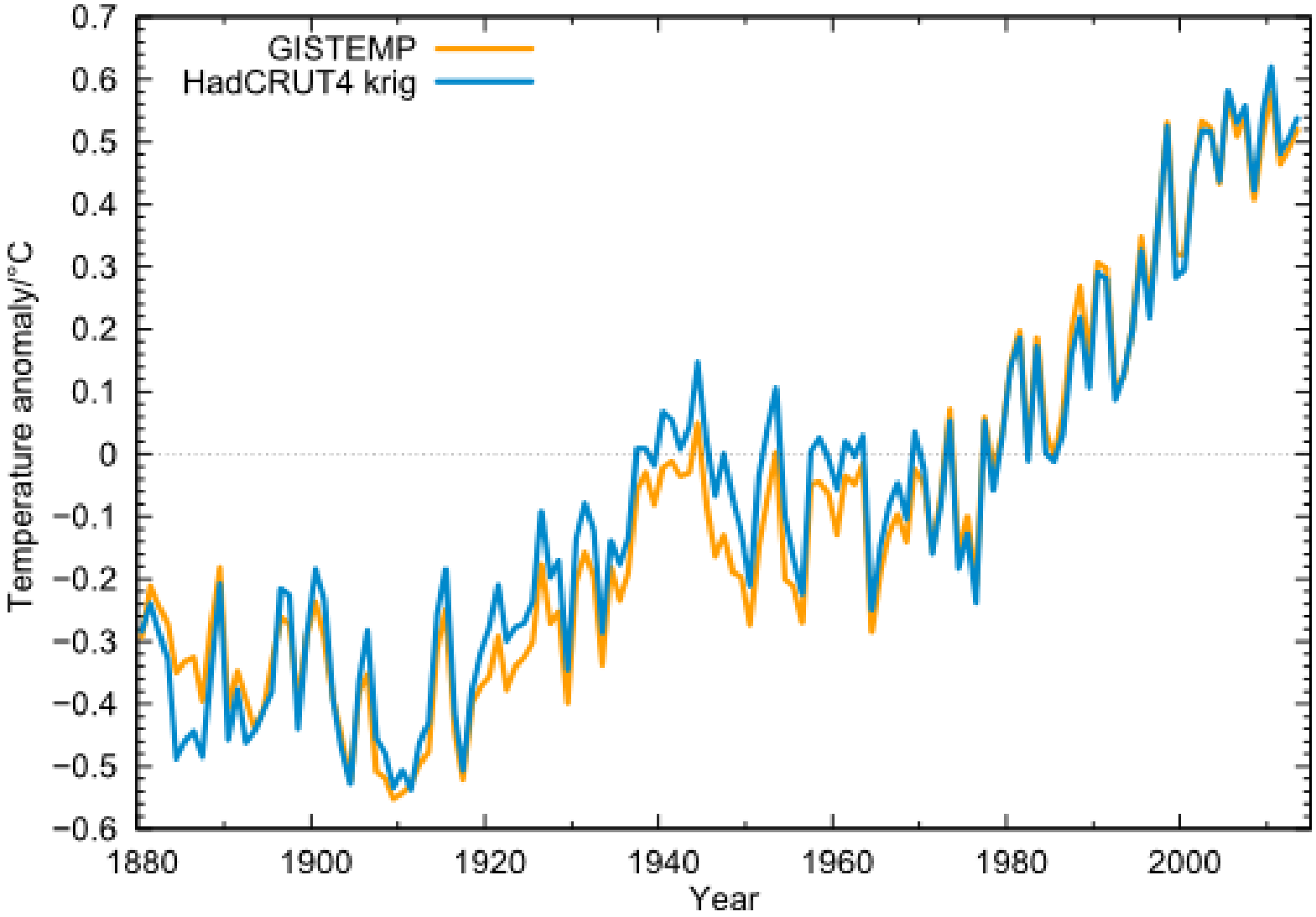
- Several aspects of climate science are well established
- Projections entail uncertainty, particularly at the regional scale
- Ill effects felt mostly through sea level rise, weather extremes and through indirect fallout, such as global armed conflict

# Summary of Main Points

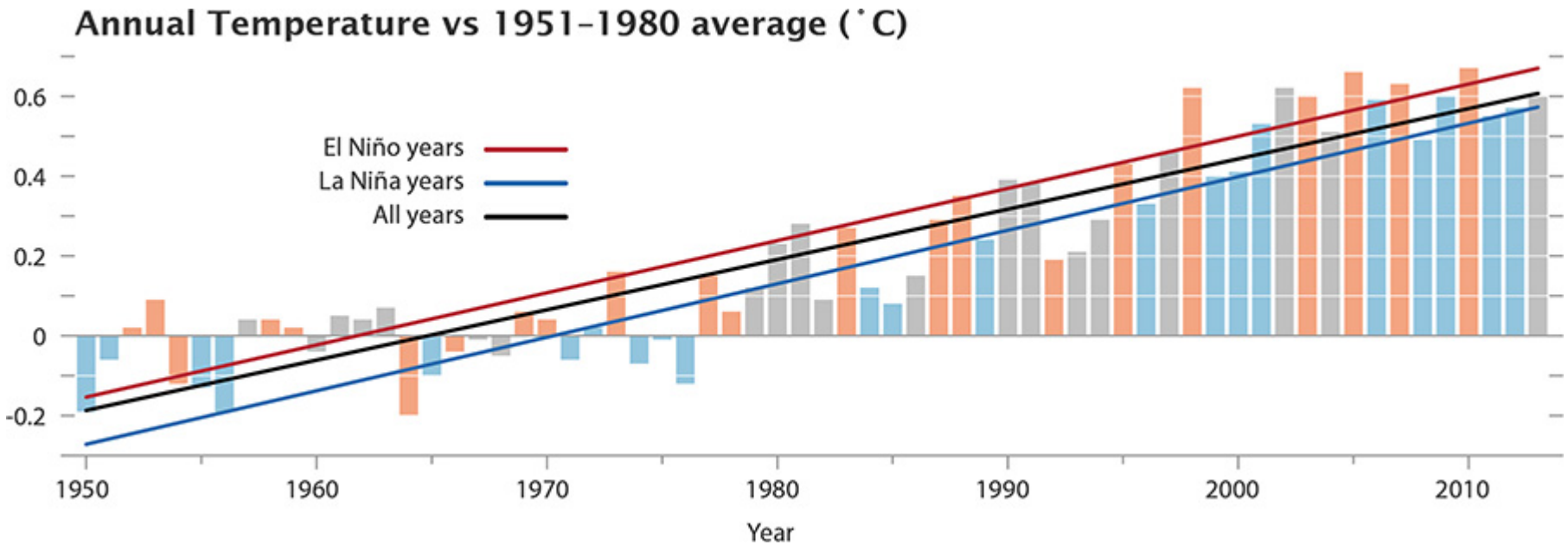
- Highly asymmetric risk function
- Rational response to risk impeded by well-funded and highly effective marketing campaign by fossil fuel interests
- Rational measures possible when many begin to notice tangible climate change

# Spare Slides

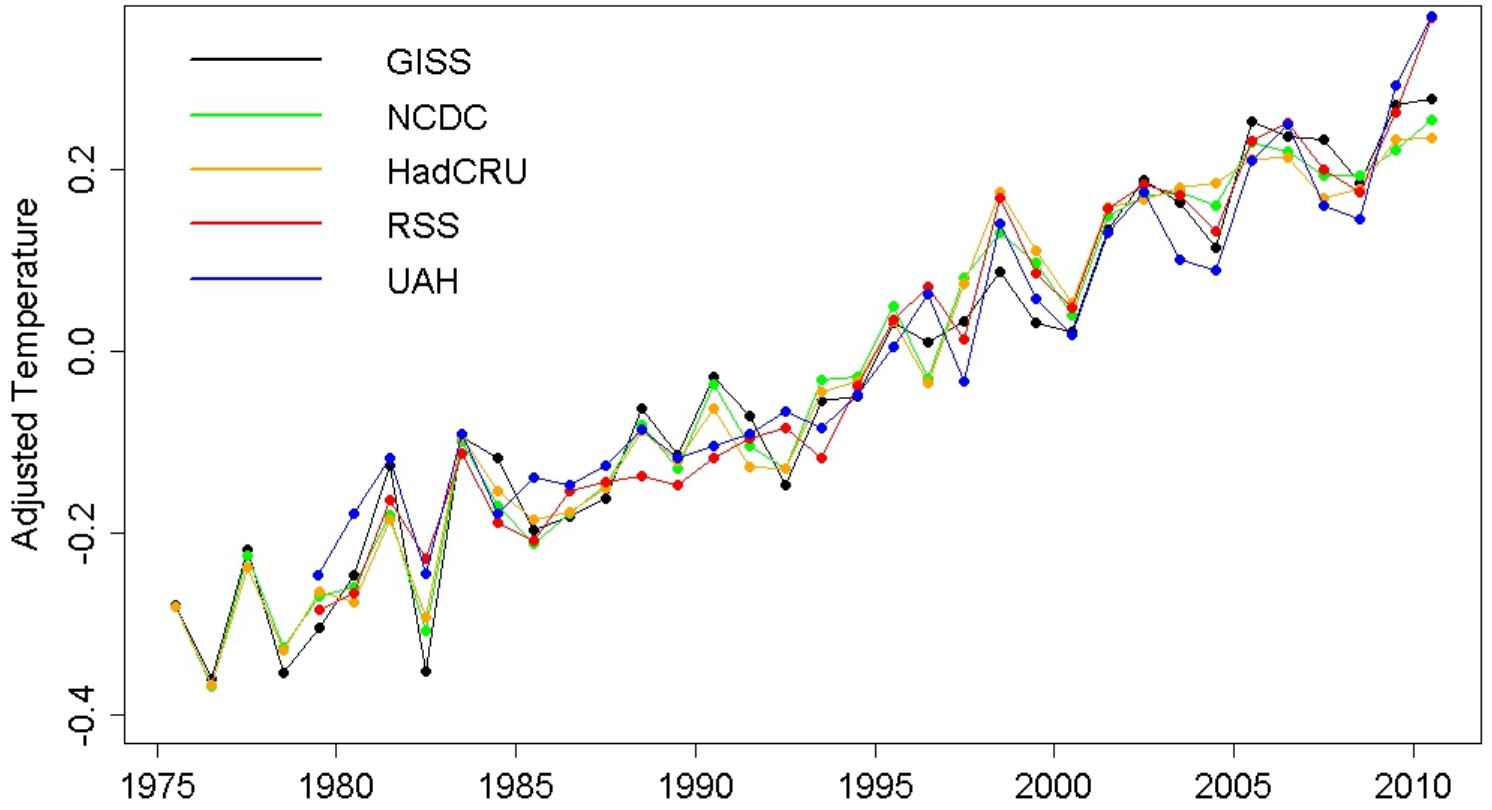
| **Energy Source** | **Mortality Rate (deaths/trillionkWhr)** | |
|---|---|---|
| Coal – global average | 170,000 | (50% global electricity) |
| Coal – China | 280,000 | (75% China's electricity) |
| Coal – U.S. | 15,000 | (44% U.S. electricity) |
| Oil (electricity) | 36,000 | (36% of energy, 8% of Natural |
| Gas | 4,000 | (20% global electricity) |
| Biofuel/Biomass | 24,000 | (21% global energy) |
| Solar (rooftop) | 440 | (< 1% global electricity) |
| Wind | 150 | (~ 1% global electricity) |
| Hydro – global average | 1,400 | (15% global electricity) |
| Nuclear – global average | 90 | (17% global electricity w/Chern&Fukush) |




Global temperature (annual values) in the data from NASA GISS (orange) and from Cowtan & Way (blue), i.e. HadCRUT4 with interpolated data gaps.




The GISS data, with El Niño and La Niña conditions highlighted. Neutral years like 2013 are gray.




Adjusted annual average temperature data with the estimated impact of El Niño, volcanic eruptions, solar variation, and the residual annual cycle removed.

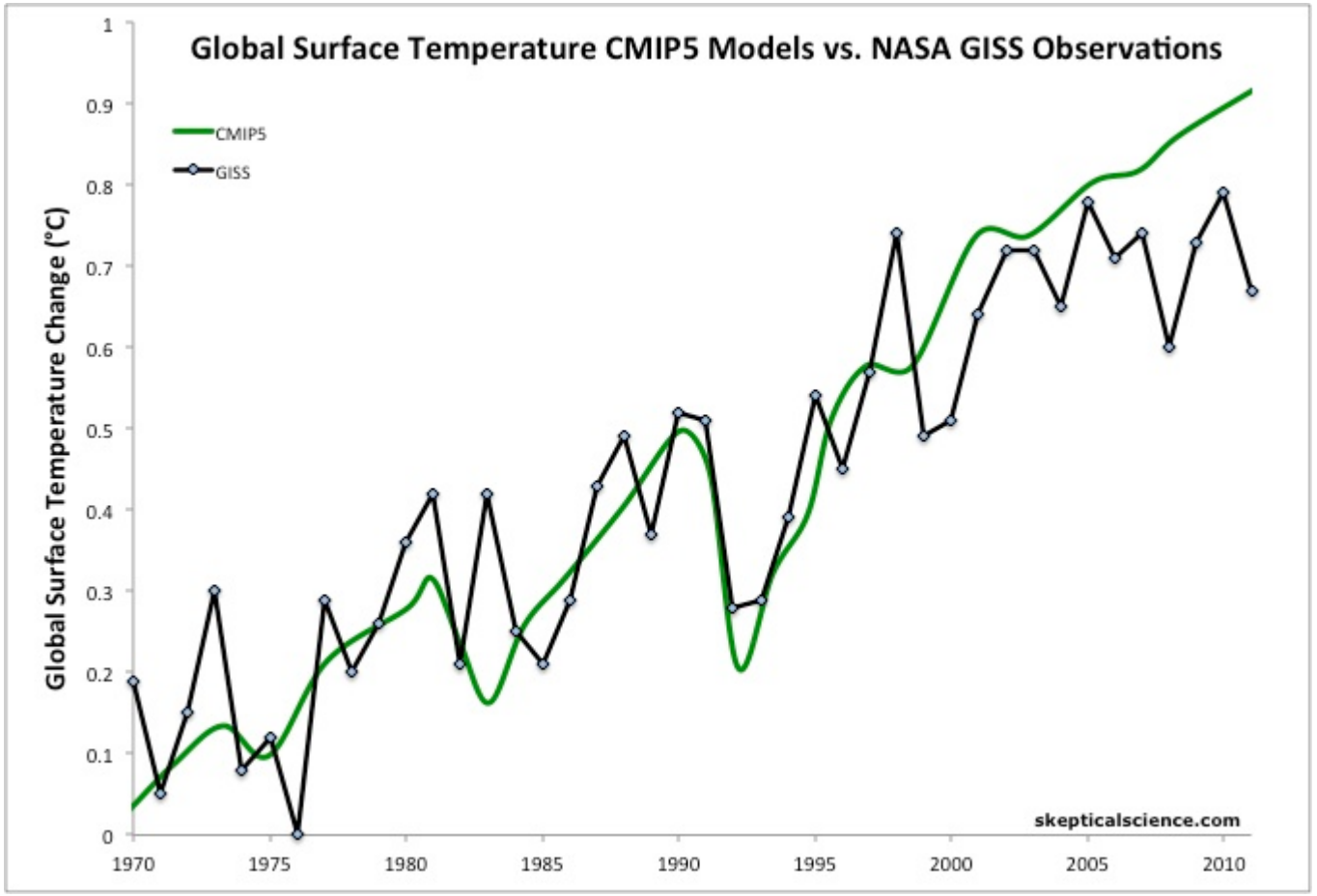



Figure 1: Average global temperature surface anomaly multi-model mean from CMIP5 (green) and as measured by the NASA Goddard Institute for Space Studies (GISS black). Most of this figure is a hindcast of models fitting past temperature data.

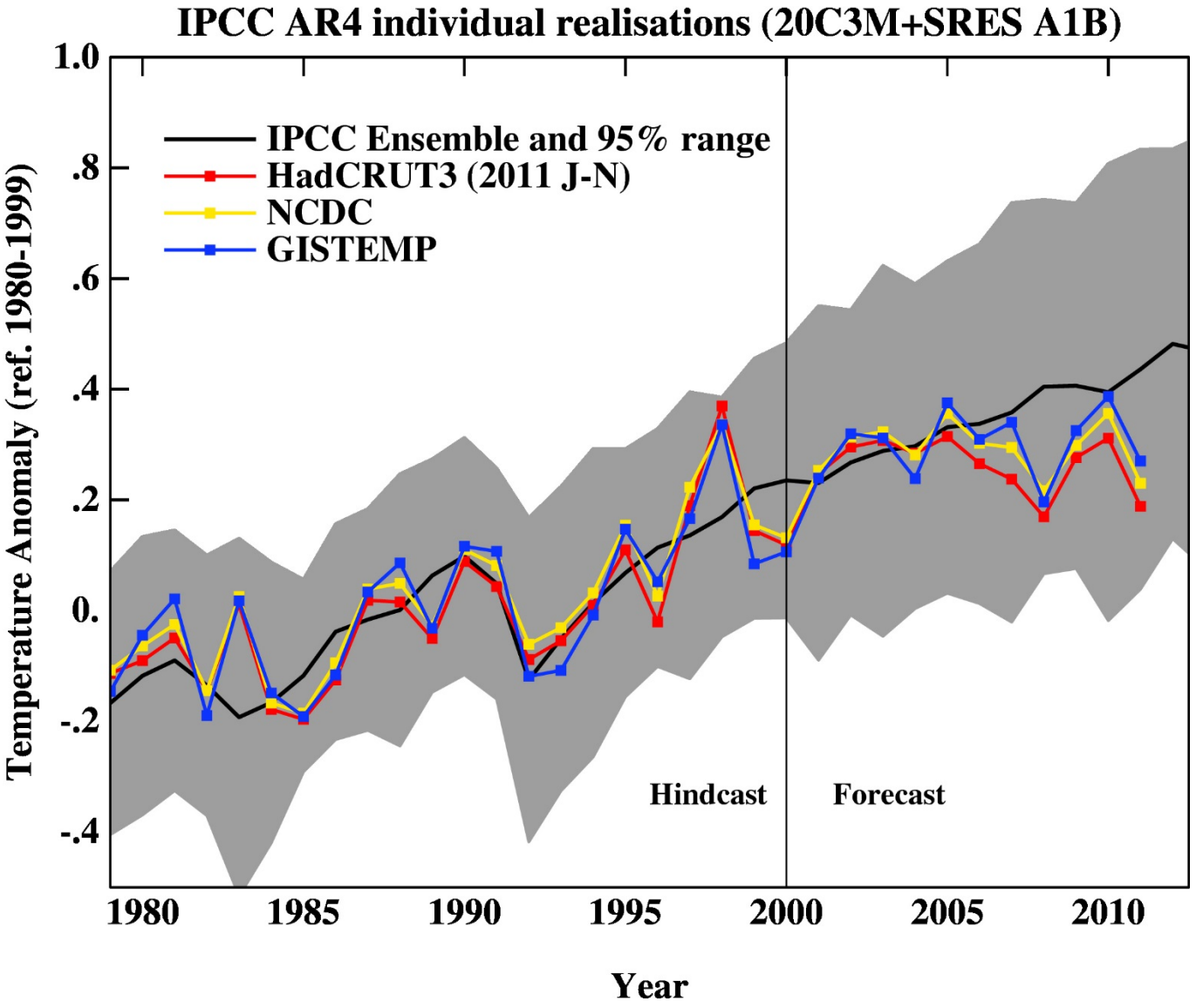



Figure 2: 2007 IPCC report model ensemble mean (black) and 95% individual model run envelope (grey) vs. surface temperature anomaly from GISS (blue), NOAA (yellow), and HadCRUT3 (red).

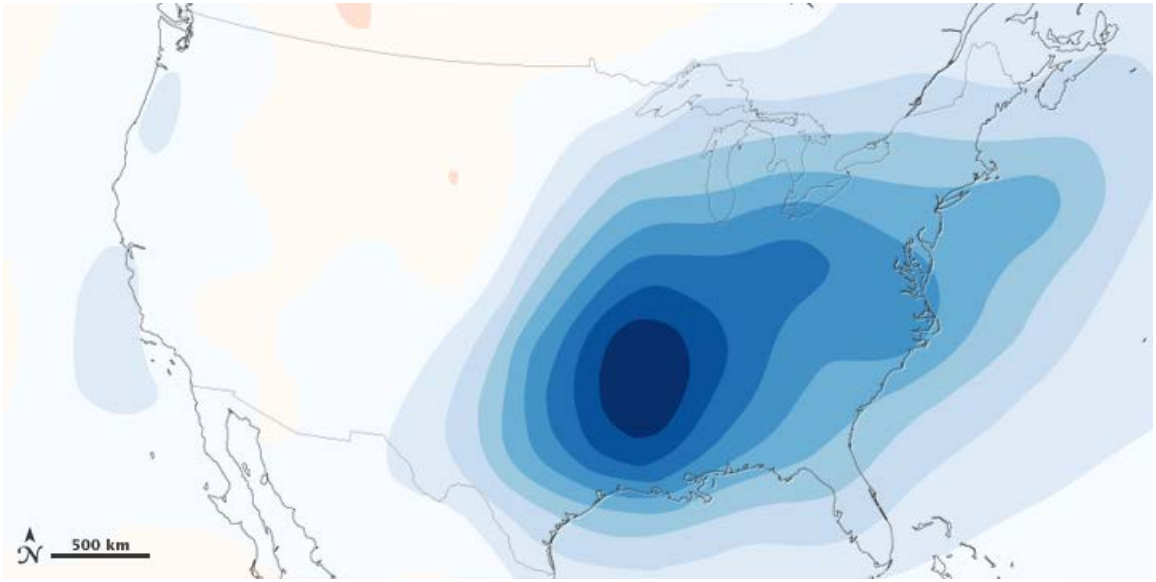



Figure 5: 1970-1990 aerosol loading of the atmosphere over the lower 48 United States and estimated associated surface air temperature change.

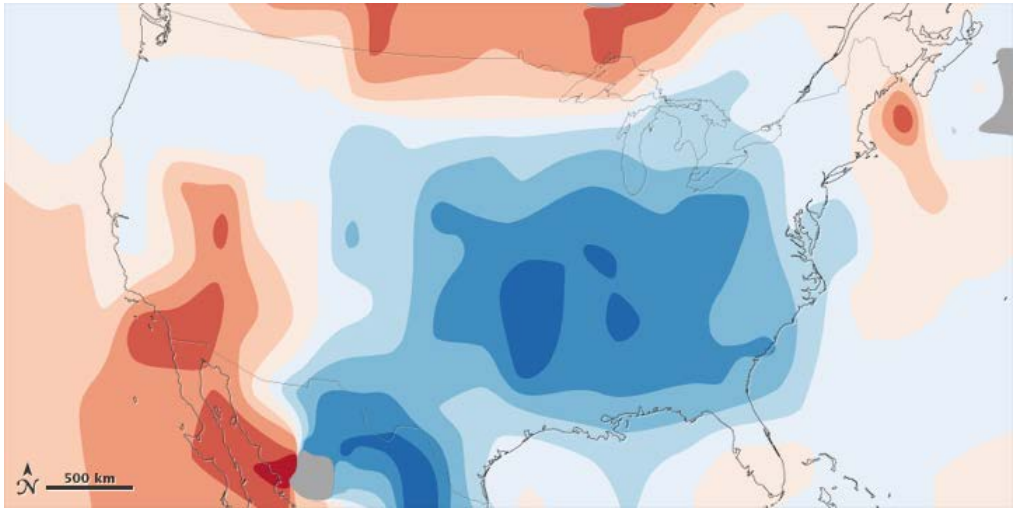
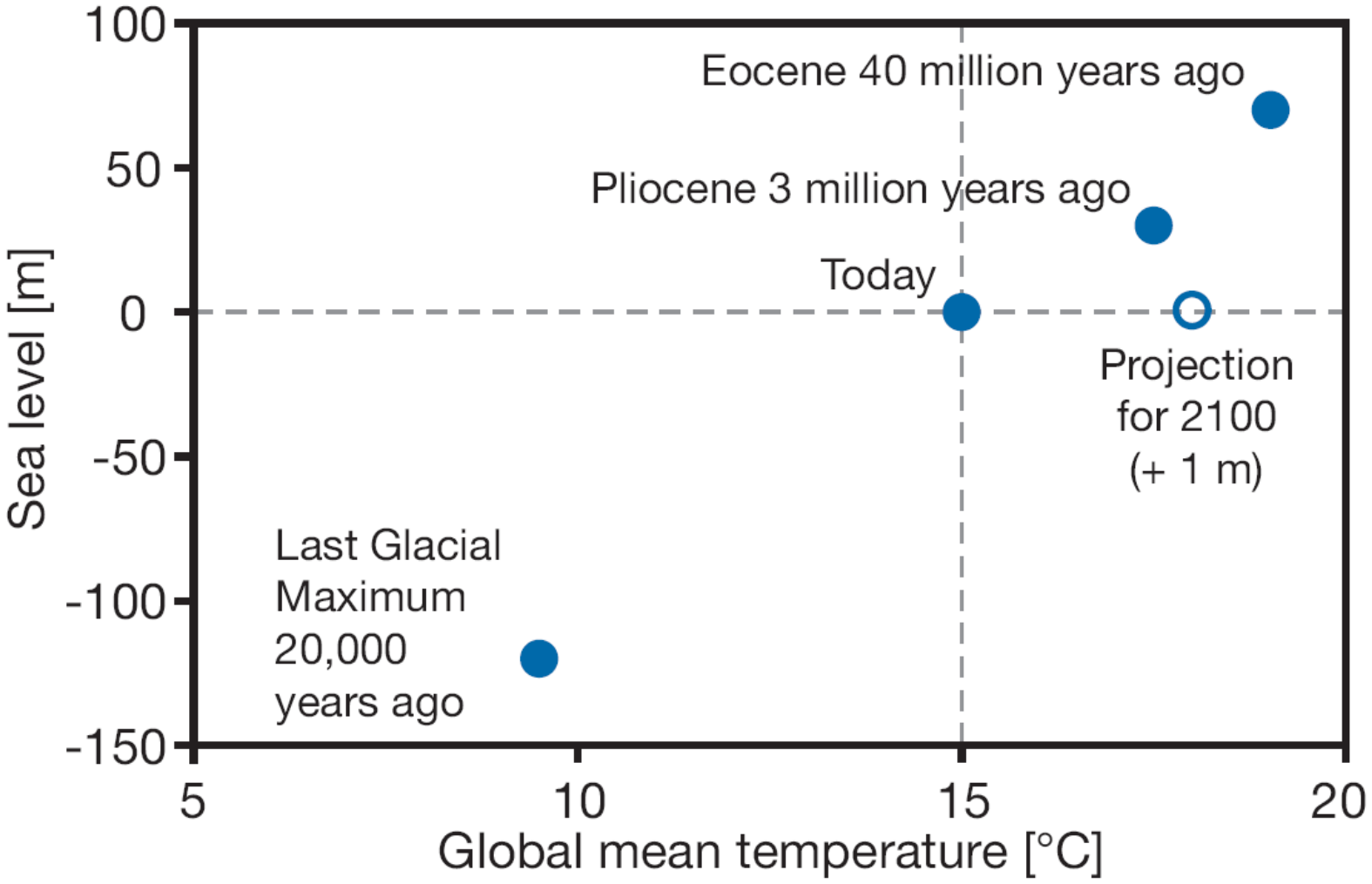



Figure 6: Observed total surface temperature change over the lower 48 United States from 1930 to 1990.

# Past and Projected Sea Level vs. Temperature




(Source: WBGU after David Archer 2006)