

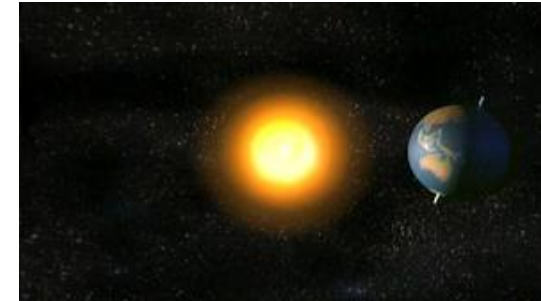
# Main causes of climate change

When the net outgoing thermal energy is equal to the net incoming solar radiation the Earth is in **radiative equilibrium**

Deviations from equilibrium imply a **radiative forcing**

Forcings may be **external**:

1. Changes in solar output
2. Changes in Earth's orbit



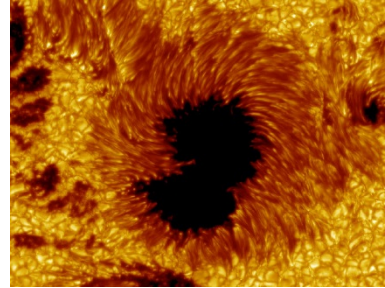
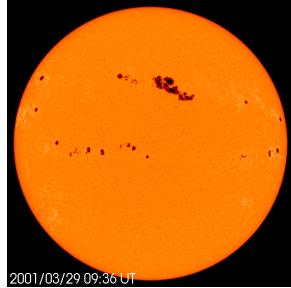
or **internal**:

3. Changes in surface energy balance
4. Changes in circulation
5. Changes in atmospheric composition

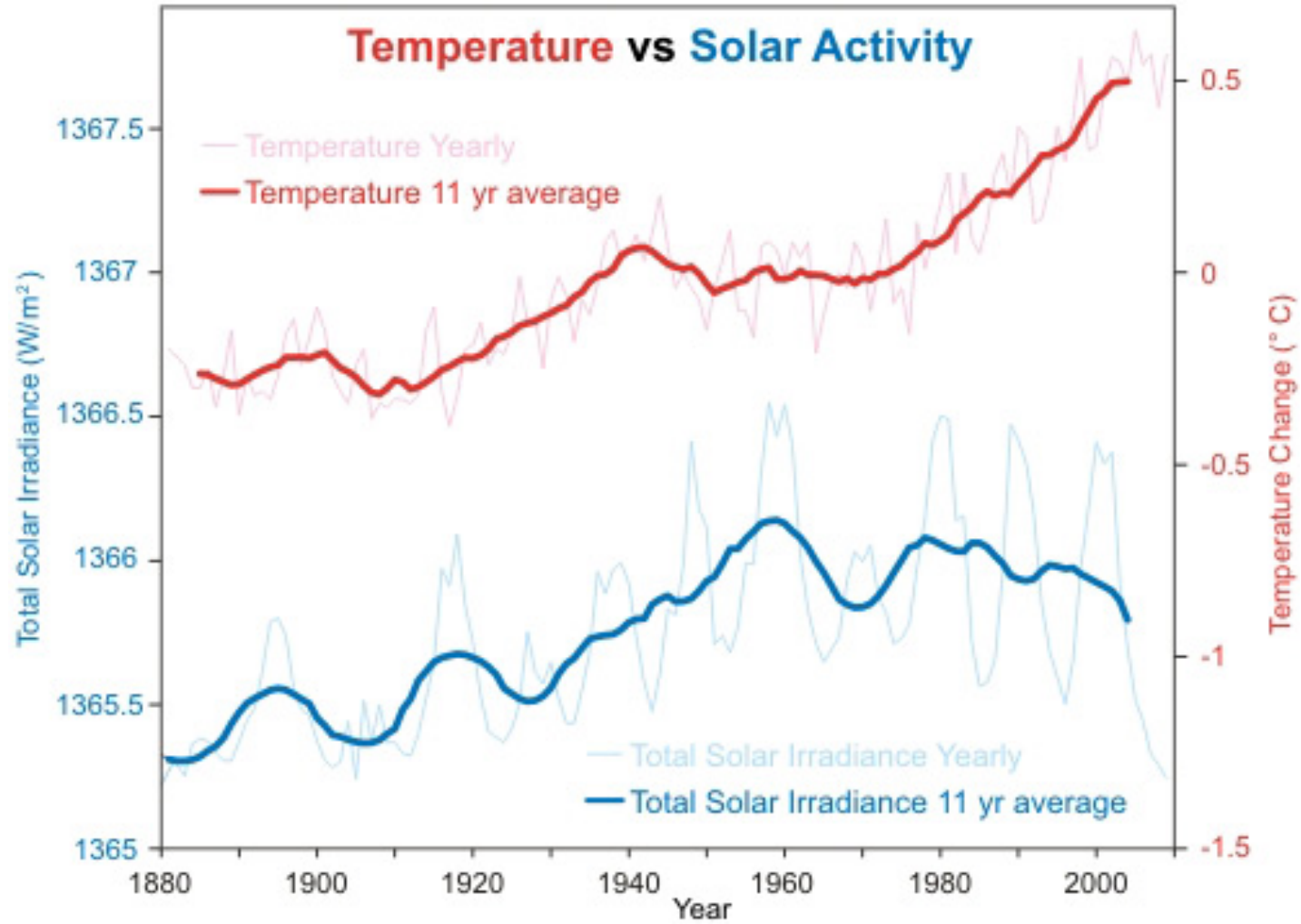


**All act all the time but at varying strengths and time scales**

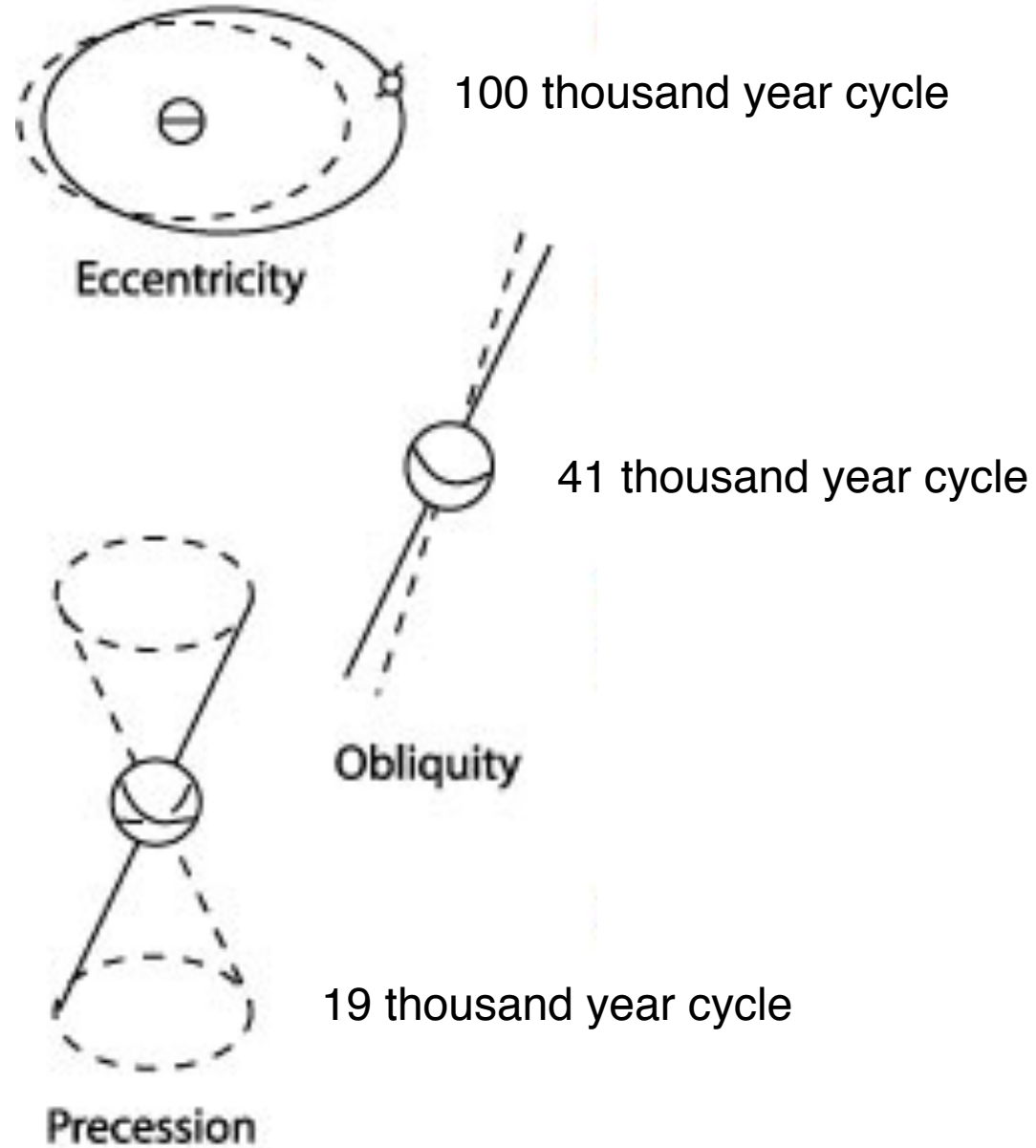
# 1. Changes in Solar Output



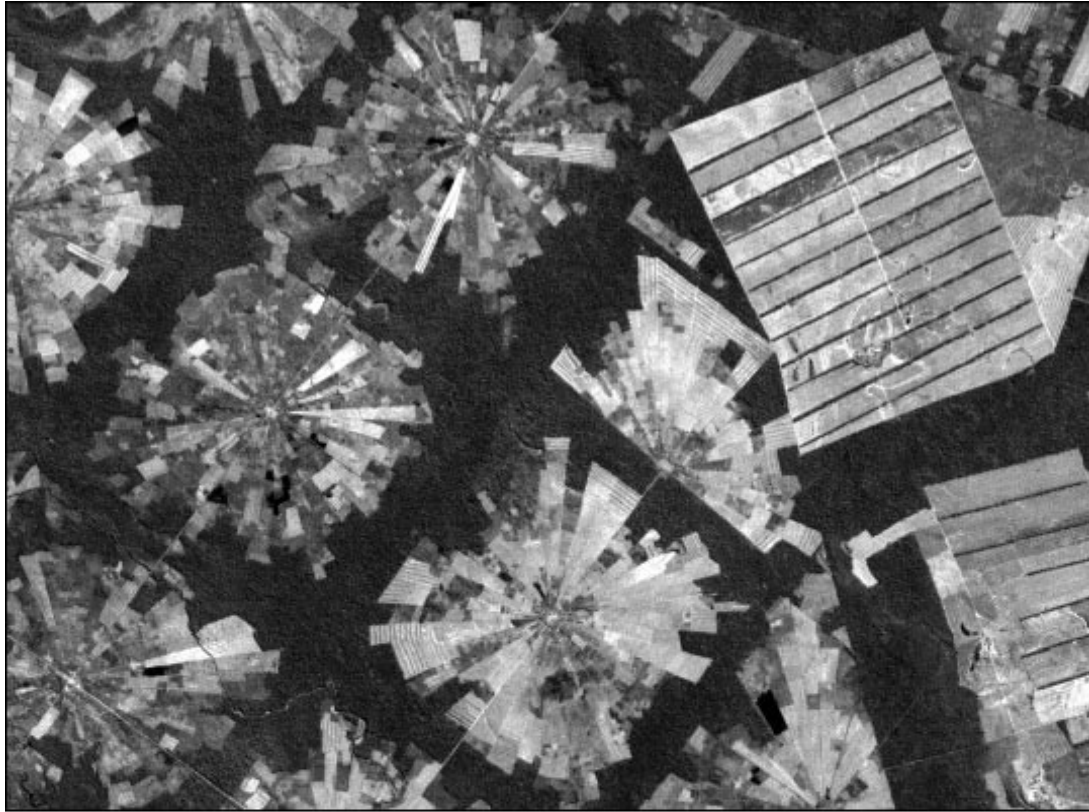
Sunspots have an 11-year cycle



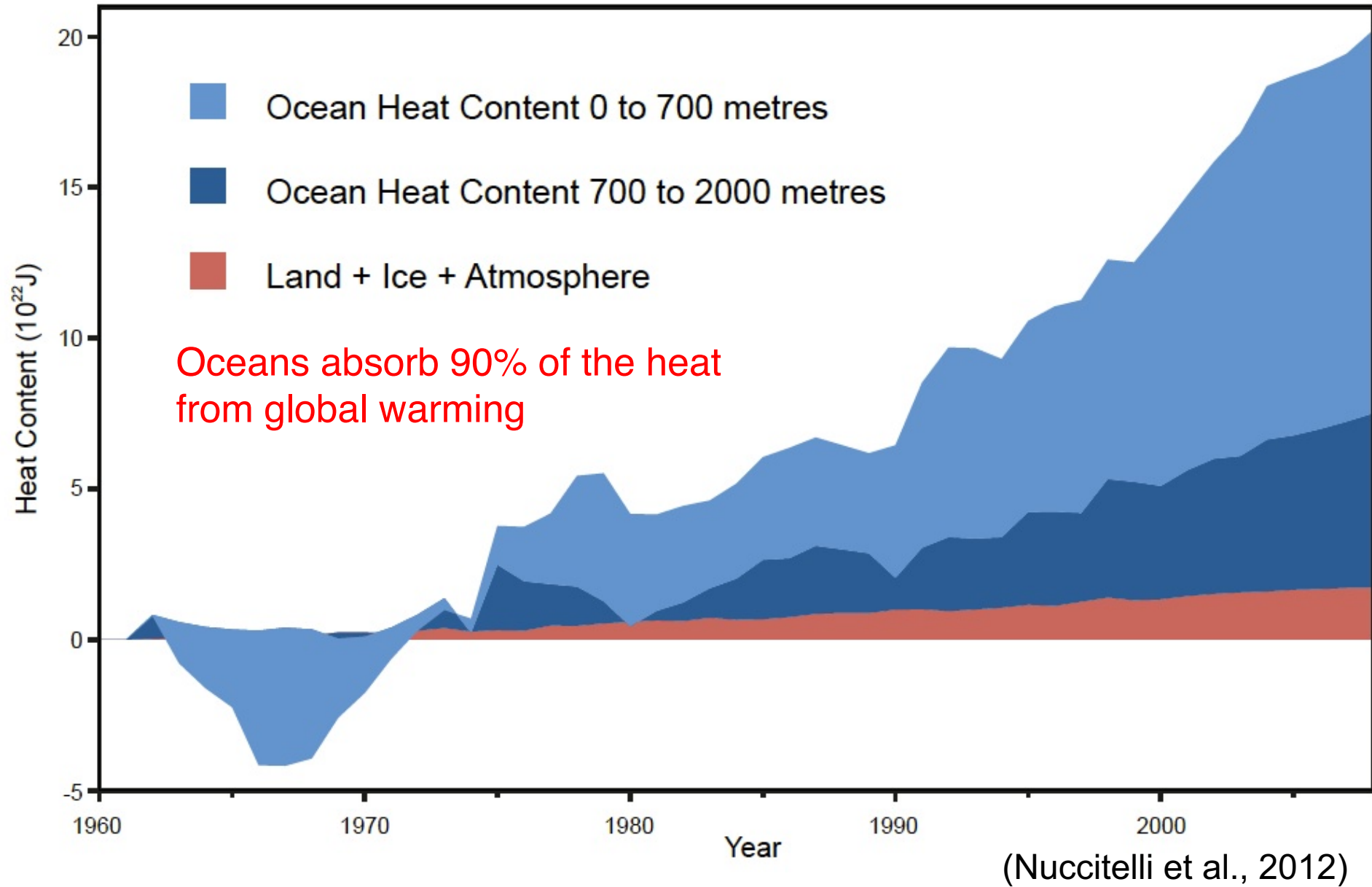
## 2. Changes in Earth's Orbit



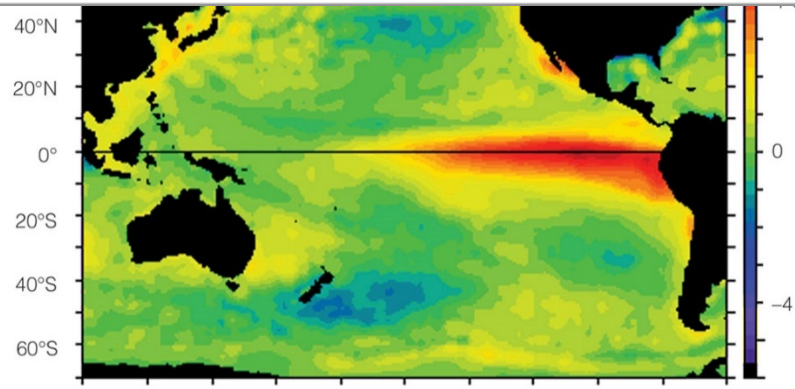
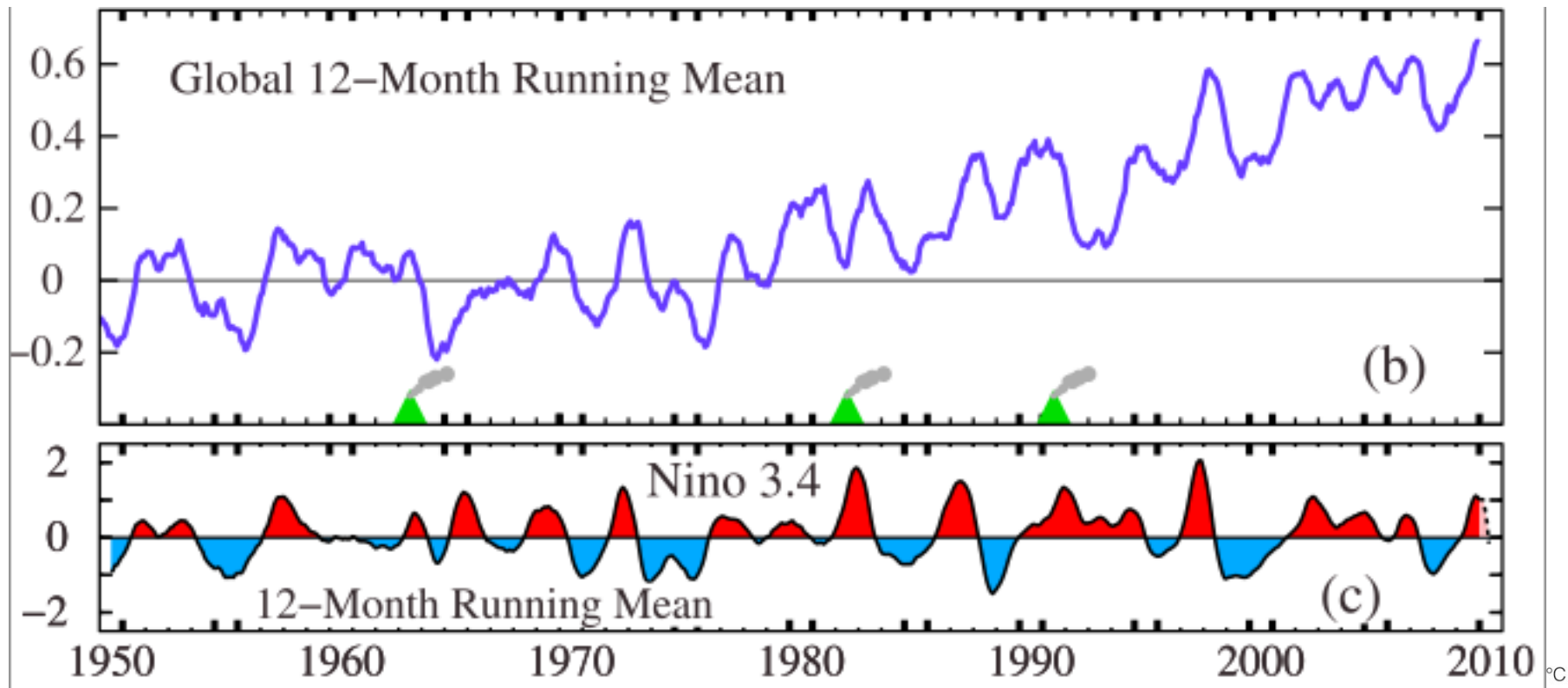
### 3. Changes in Surface Energy Balance



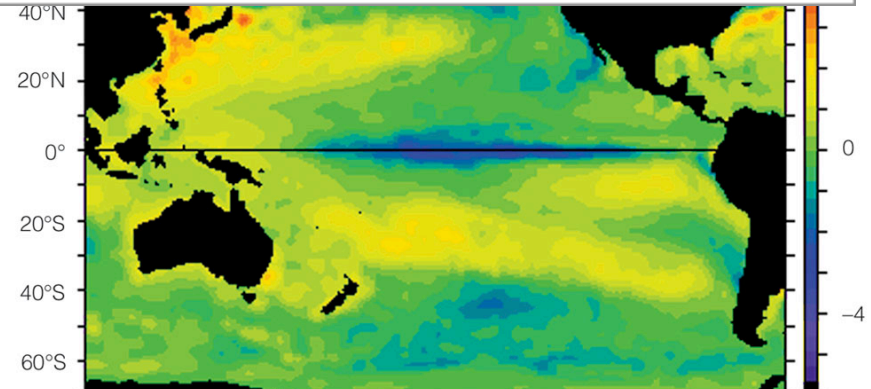
### 3. Changes in Surface Energy Balance



# 4. Changes in Circulation



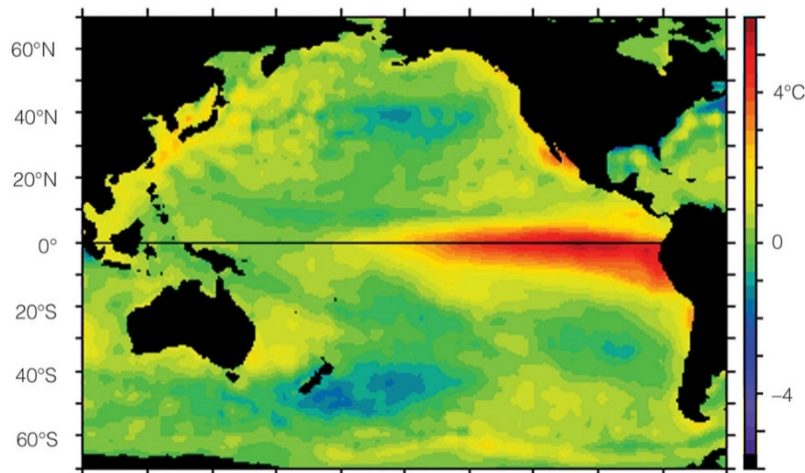
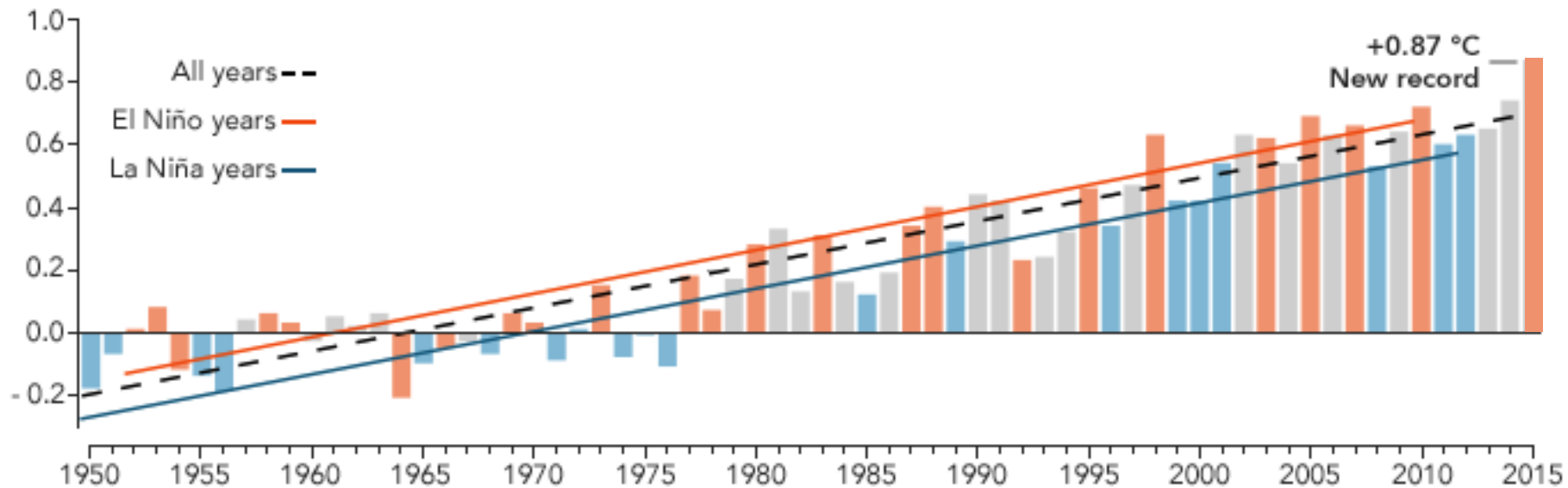
El Niño



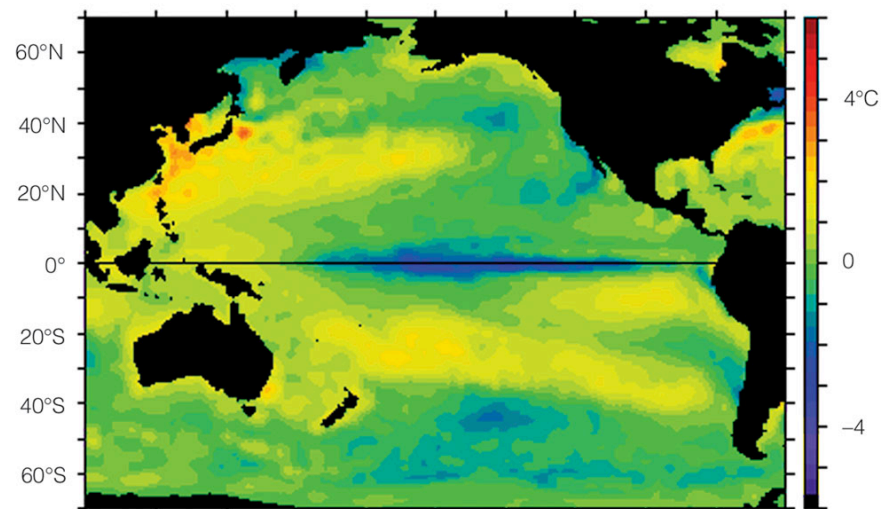
La Niña

# 4. Changes in Circulation

Annual Temperature vs 1951-1980 Average (°C)



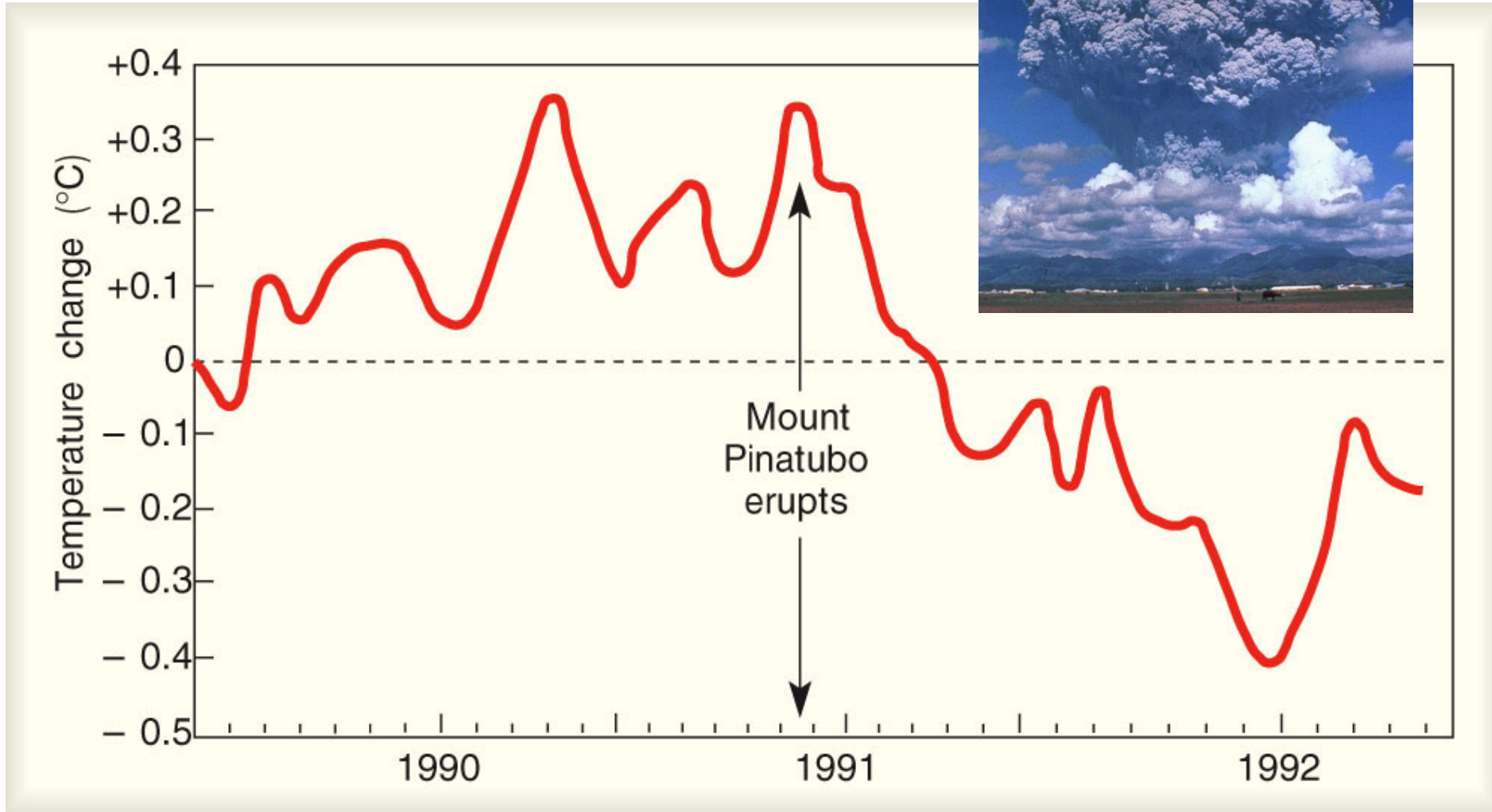
El Niño



La Niña

# 5. Changes in Atmospheric Composition

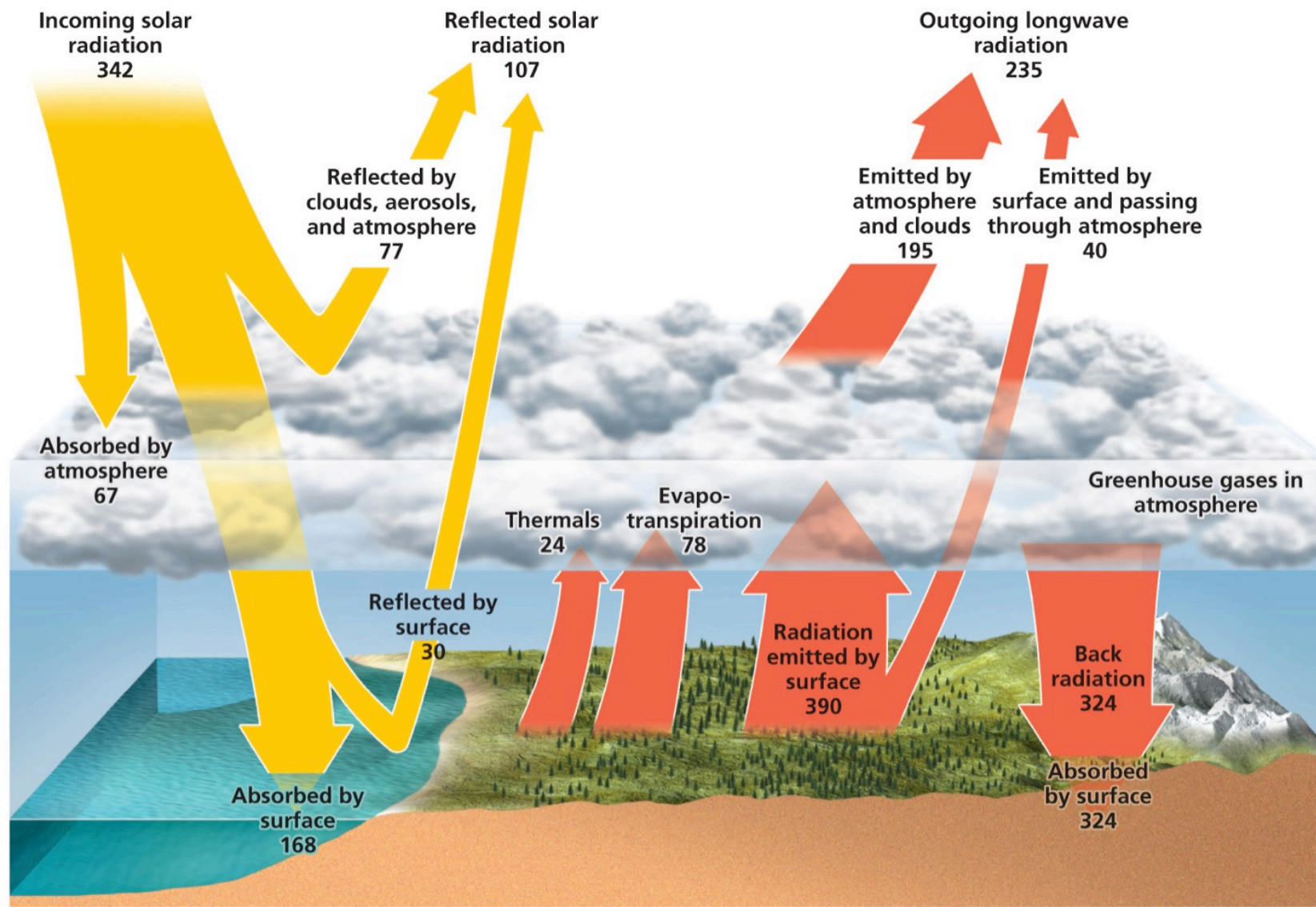
**Aerosols:** scatter incoming solar radiation



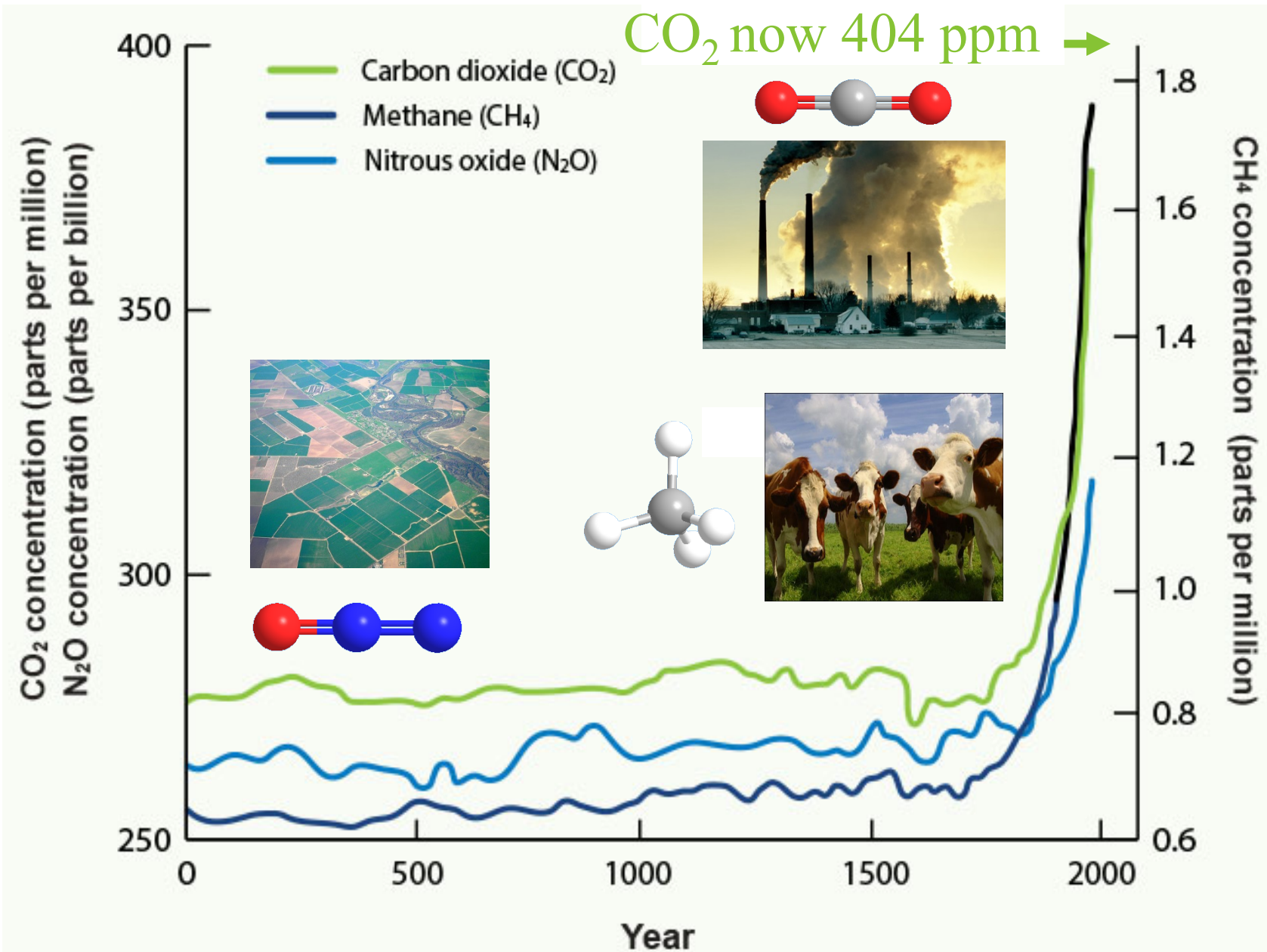


# 5. Changes in Atmospheric Composition

Greenhouse Gases: trap thermal energy from Earth

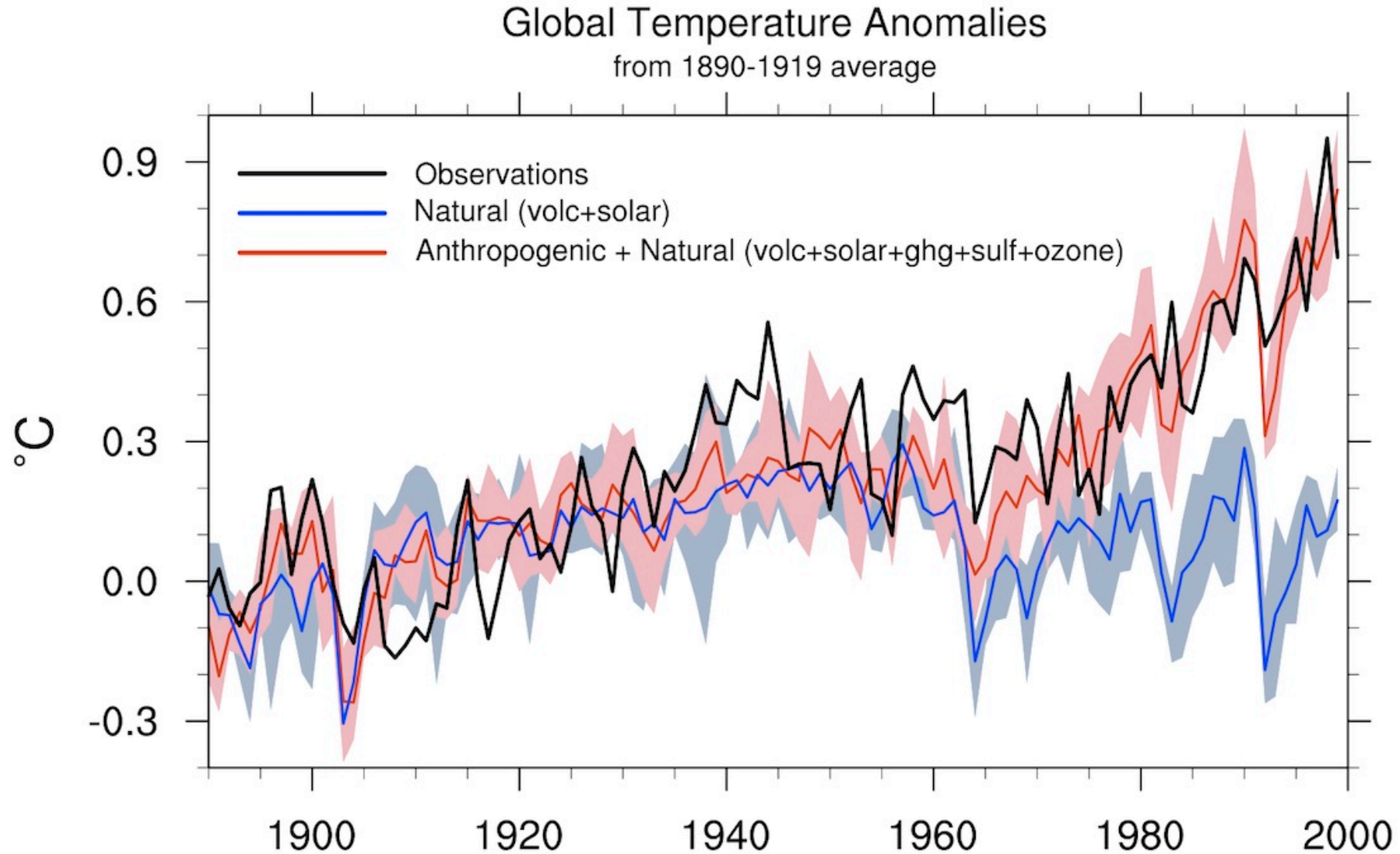


# 5. Changes in Atmospheric Composition



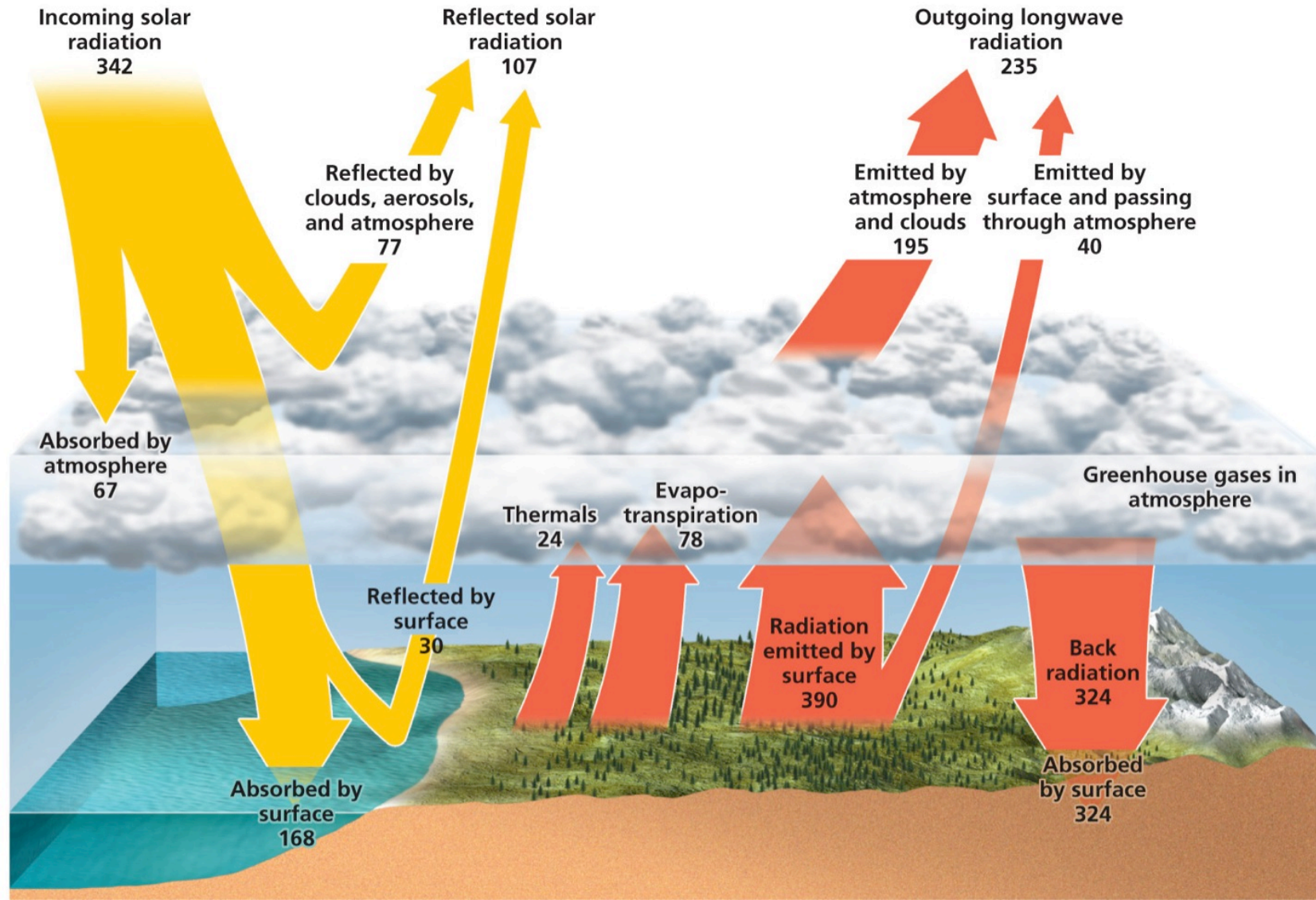
# Main causes of climate change

Global Average Temperature: With and without human influence



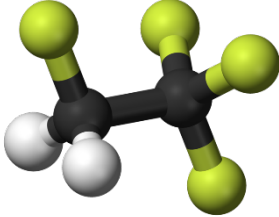

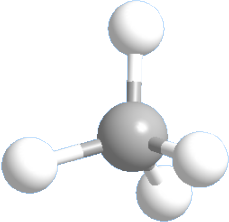

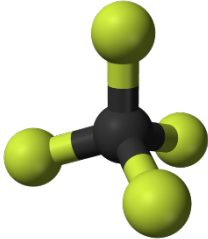



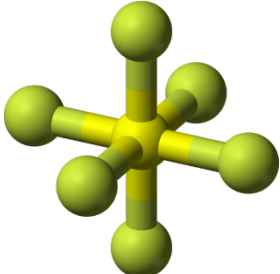



# Changes in Atmospheric Composition

**Greenhouse Gases:** trap thermal energy in the atmosphere



# 100 Year Global Warming Potentials

<u>Greenhouse Gas</u>	<u>GWP</u>	<u>Greenhouse Gas</u>	<u>GWP</u>
<b>Carbon Dioxide – CO<sub>2</sub></b>  	1	<b>HFC-134a – CH<sub>2</sub>FCF<sub>3</sub></b>  	1,300
<b>Methane – CH<sub>4</sub></b>  	28	<b>Tetrafluoromethane – CF<sub>4</sub></b>  	6,630
<b>Nitrous Oxide – N<sub>2</sub>O</b>  	265	<b>Sulfur hexafluoride – SF<sub>6</sub></b>  	23,900

# Main driving forces of climate change

When the net outgoing thermal energy is equal to the net incoming solar radiation the Earth is in **radiative equilibrium**

Deviations from equilibrium imply a **radiative forcing**

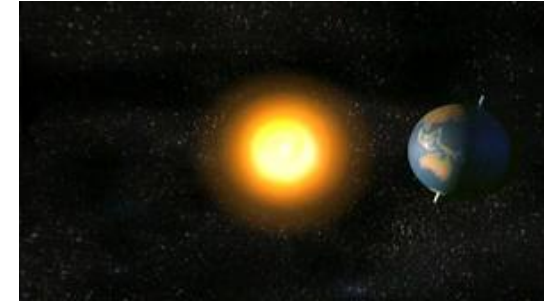
**Forcings may be external:**

1. Changes in solar output
2. Changes in orbital parameters

**or internal:**

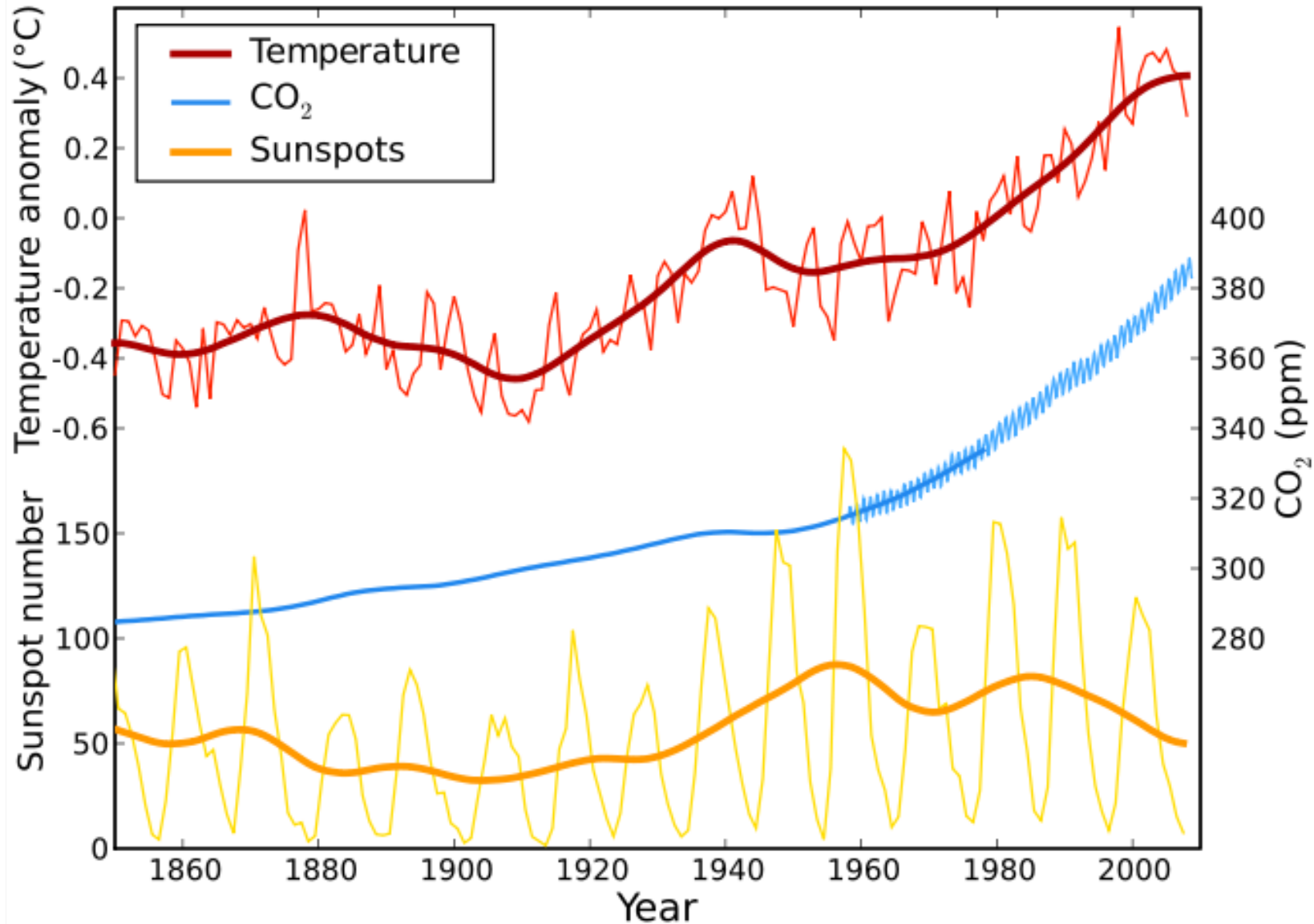
3. Changes in surface energy balance
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All act all the time but at varying strengths and time scales

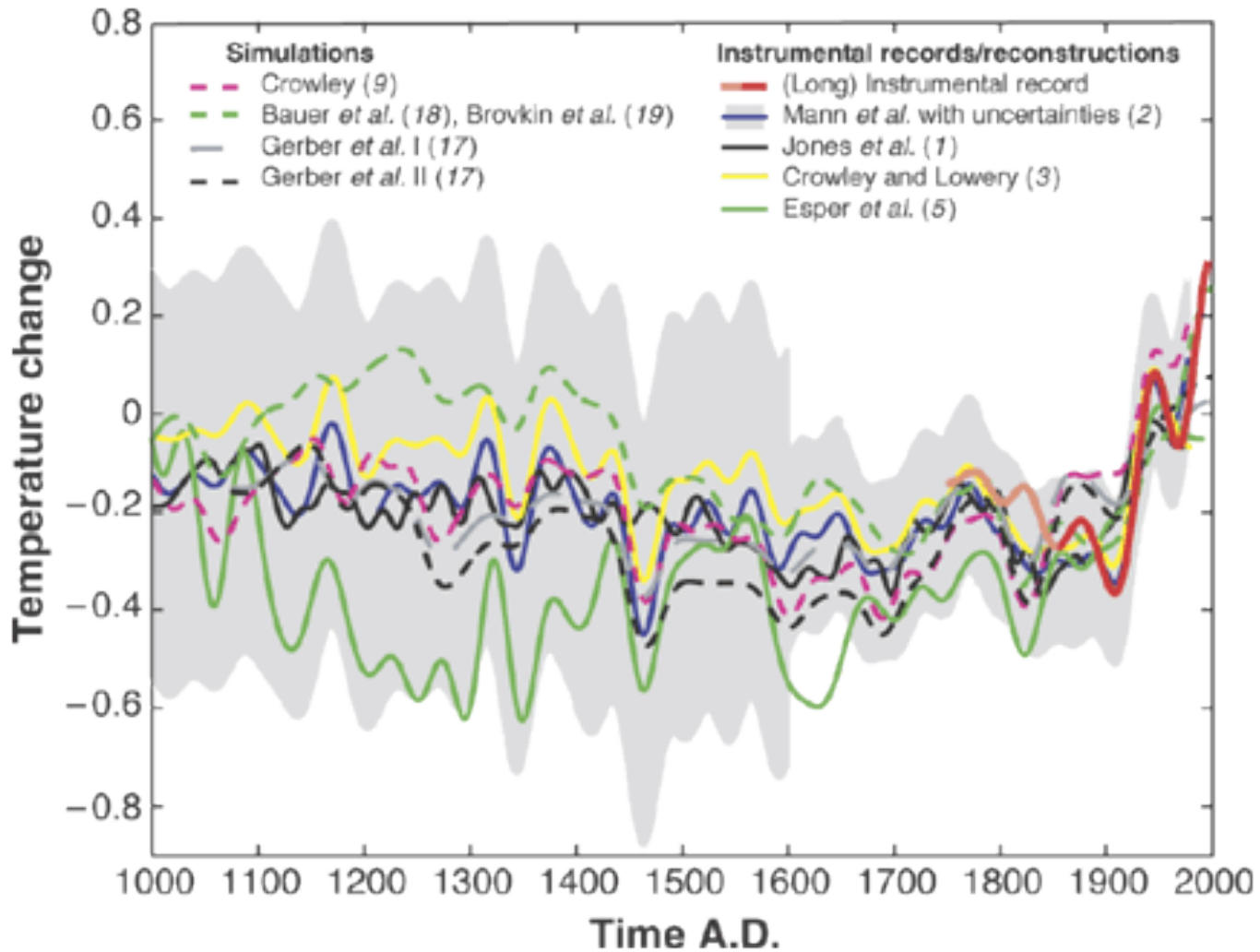


# Main driving forces of climate change

## Temperature, CO<sub>2</sub>, and Sunspots



# Thousand Year Atmospheric Temperature 'Hockey Stick' Record



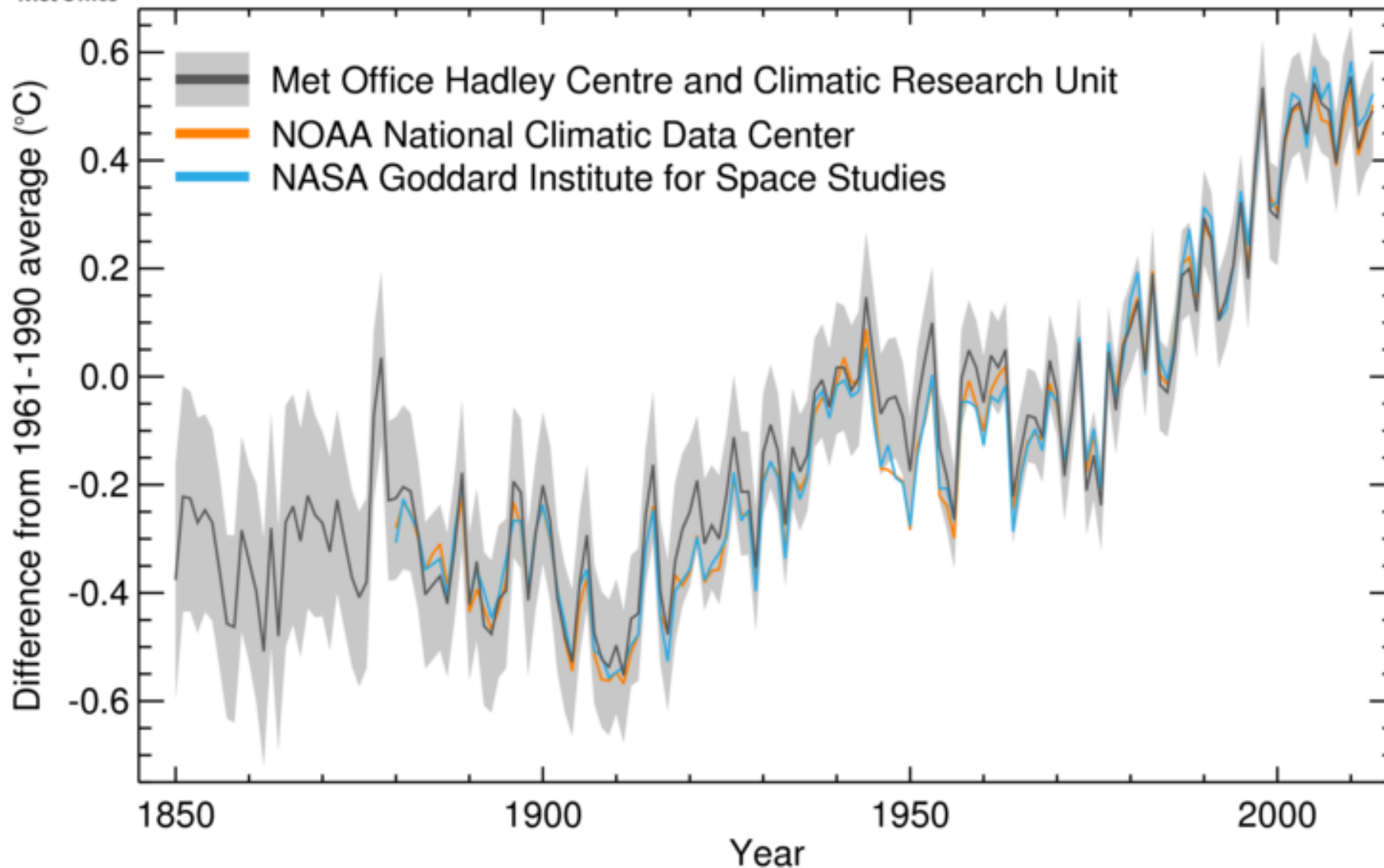


# Global Temperature Increase

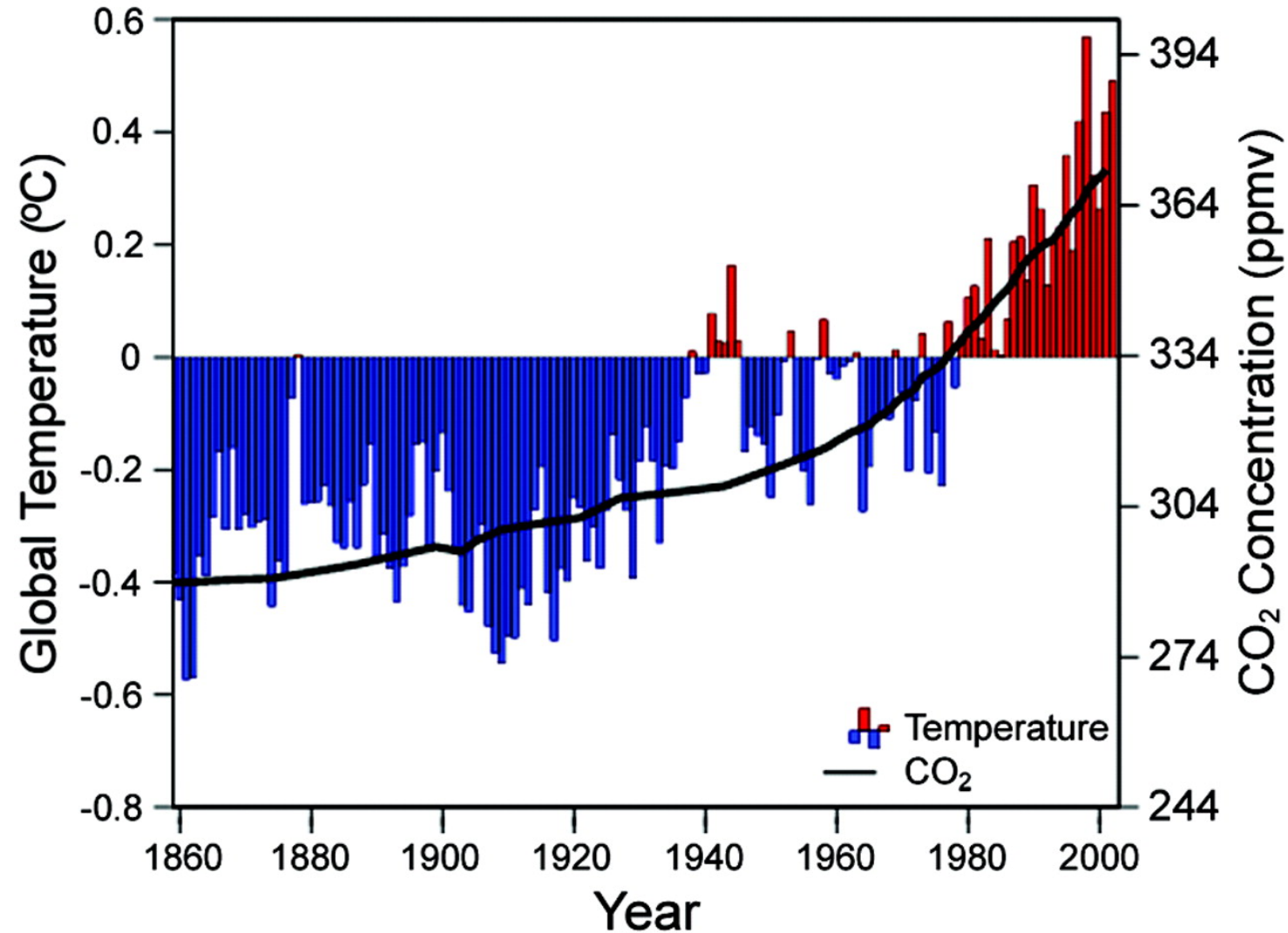


Met Office

Global average temperature anomaly (1850-2013)

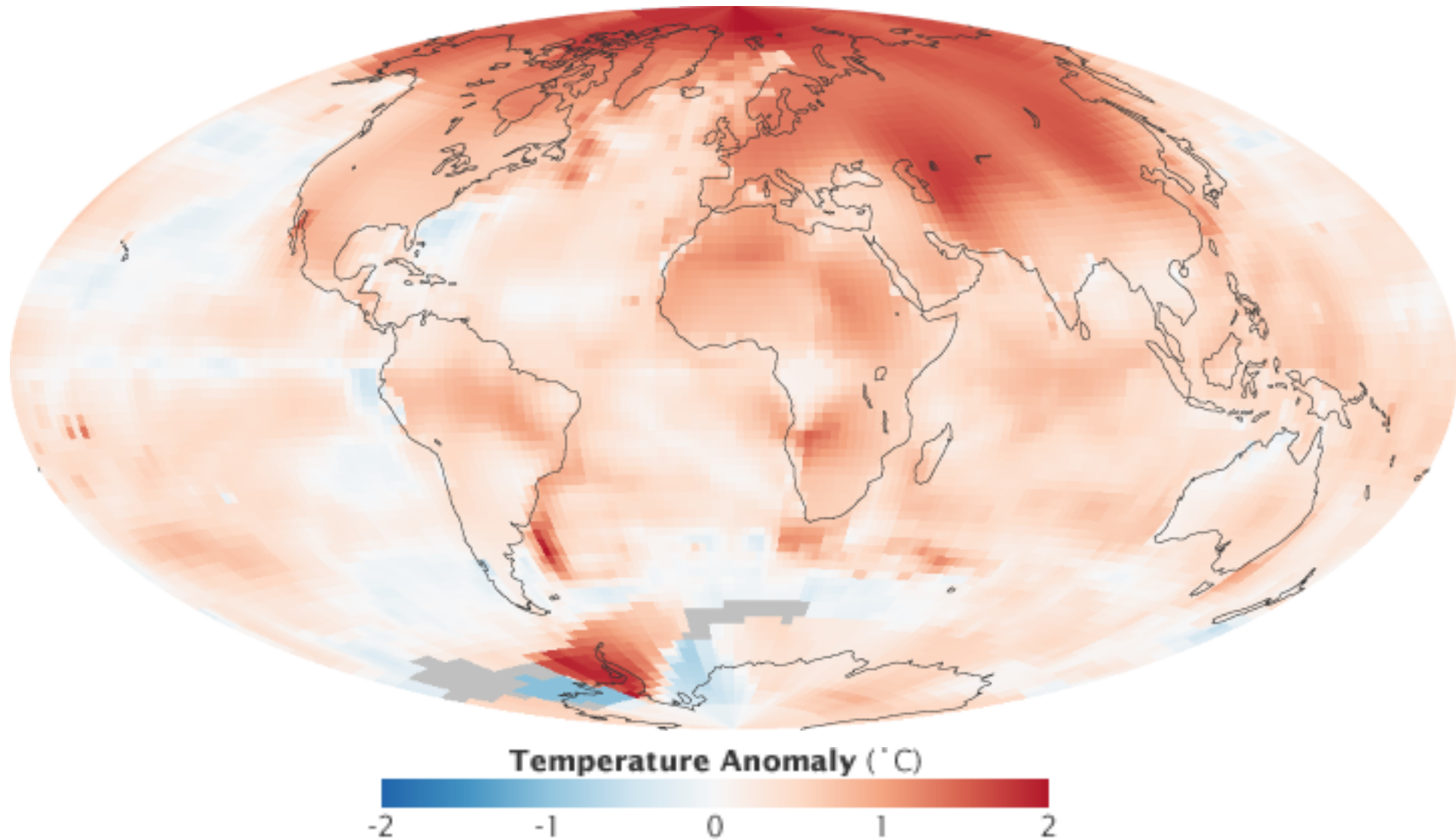


# Correlation between Recent Temperature Anomalies and Carbon Dioxide

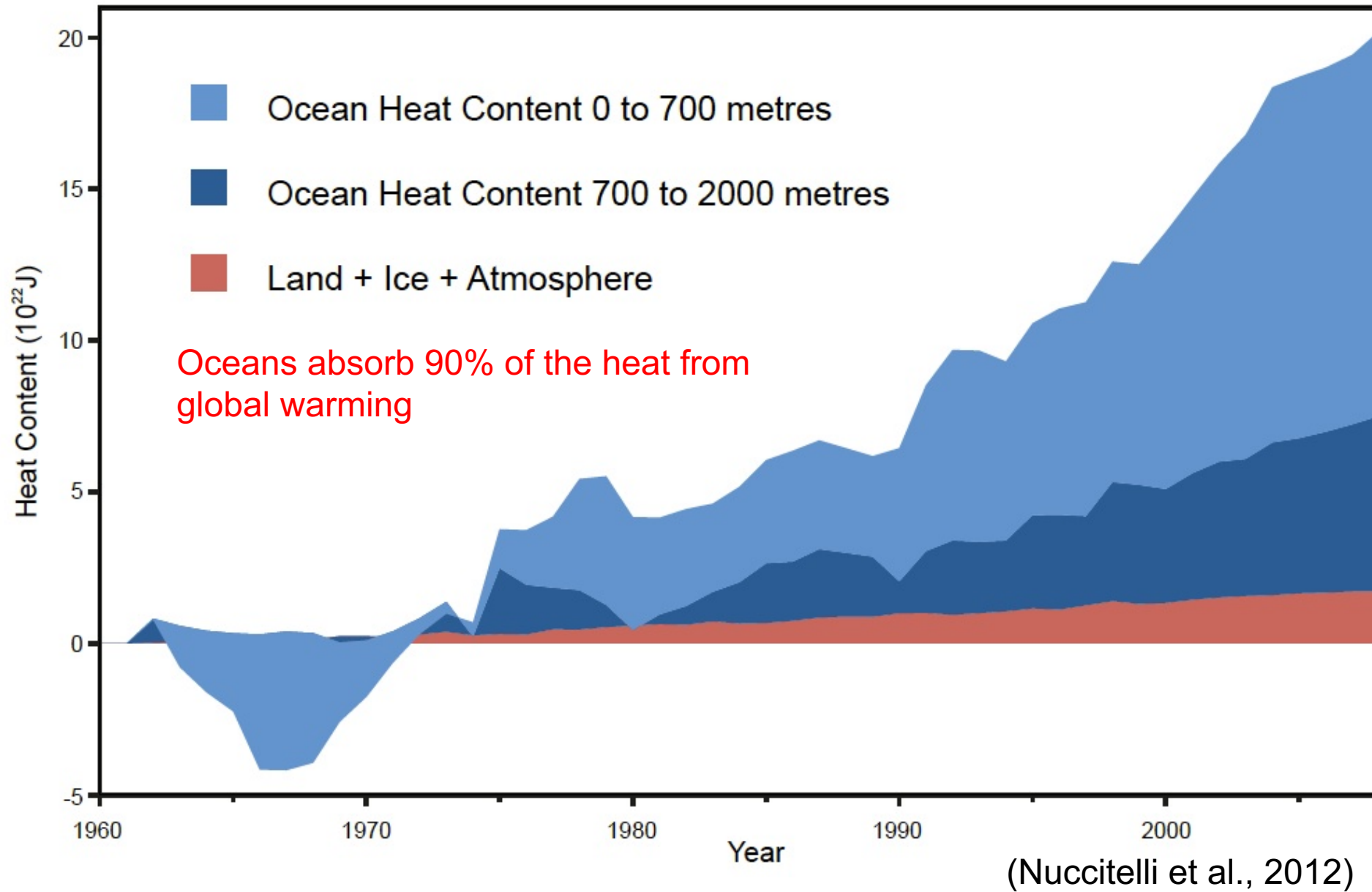


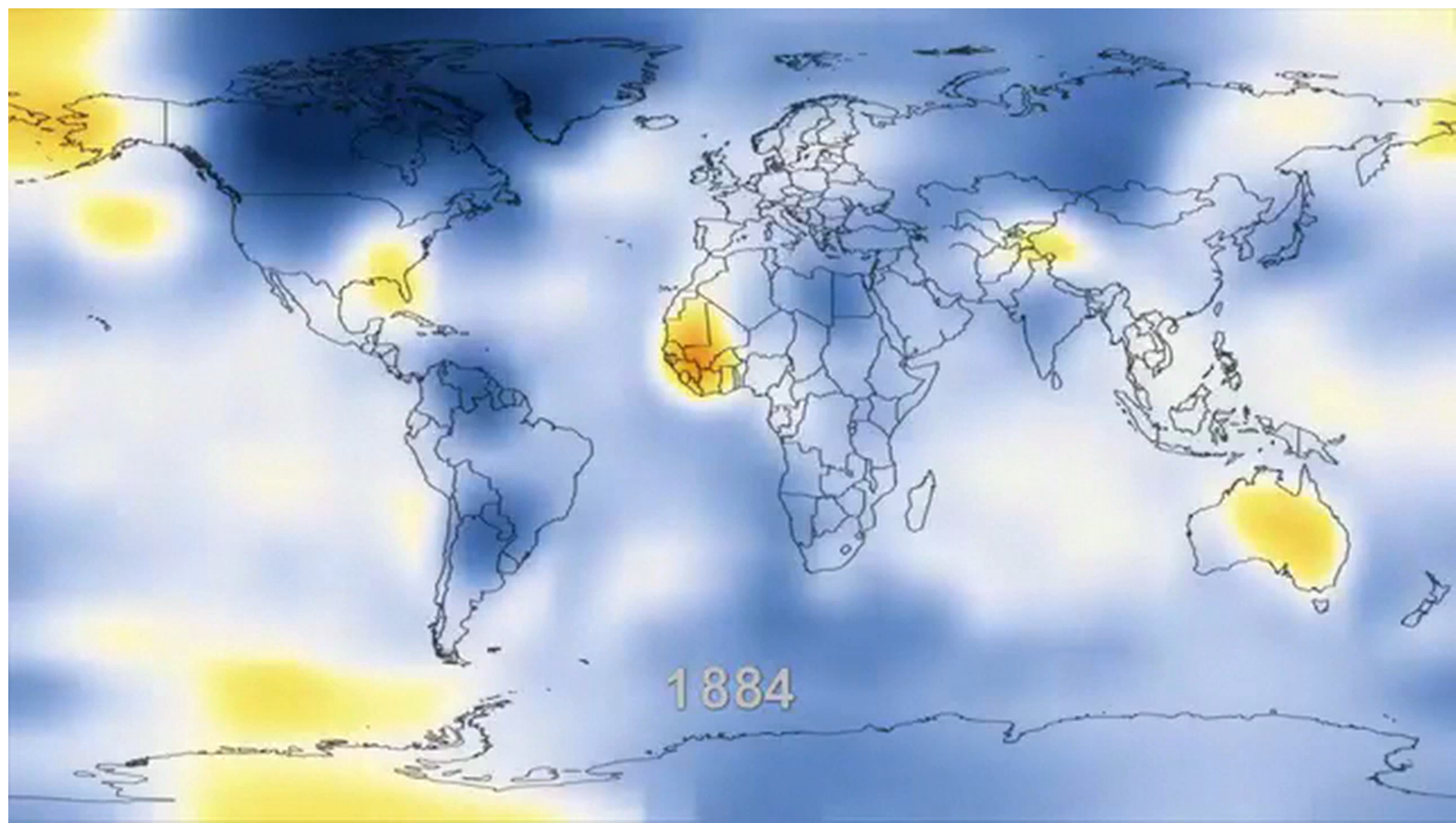
# Global Temperature Increase

**2000-2009** compared to the average of 1951-1980



# Global Temperature Increase





# Detection vs Attribution

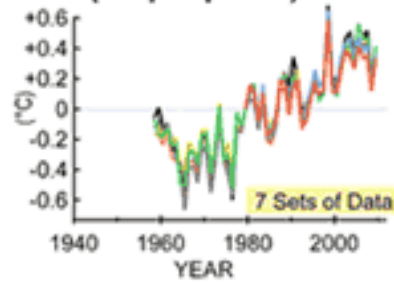
(Cause & Effect)

- *Detection* requires demonstrating that an observed change is statistically significant
  
- *Attribution* requires demonstrating that observed change is:
  - unlikely to be due entirely to internal variability;
  - consistent with the estimated response to combination of anthropogenic and natural forcing;
  - not consistent with alternative, physically plausible explanations of recent climate change.

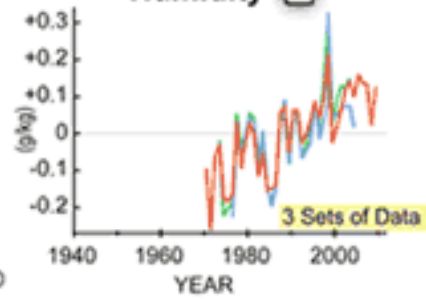
# Basic Scientific Principles

- Reproducible independent observation  
(i.e., recent increase in atmospheric gas concentrations, direct temperature measures and temperature proxies)
- Underlying fundamental principles  
(i.e., Earth emits IR, certain gases absorb IR, the absorption of IR increases temperature)
- Inherently Skeptical (must stand up to scientific scrutiny and peer-review)

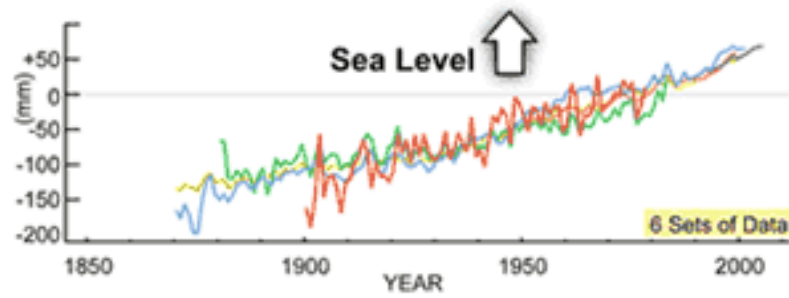
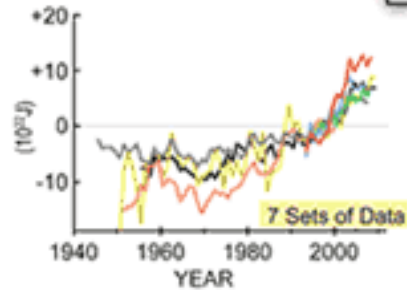
**Air Temperature Near Surface (Troposphere)** ↑



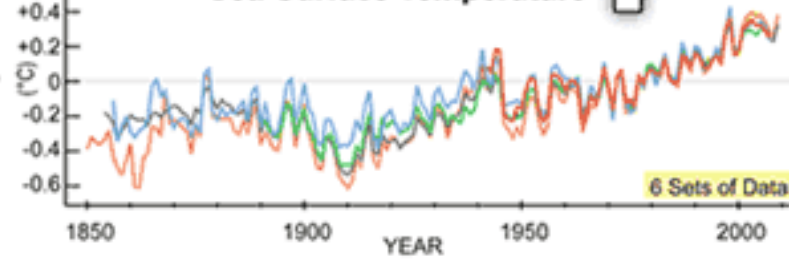
**Specific Humidity** ↑



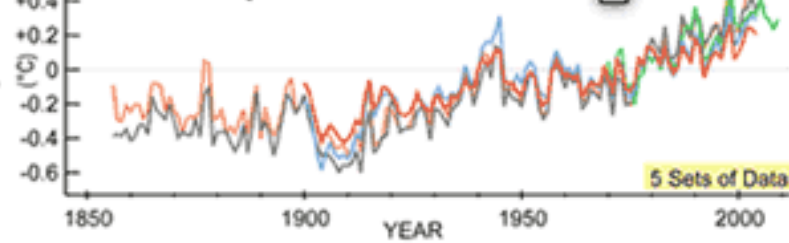
**Ocean Heat Content** ↑



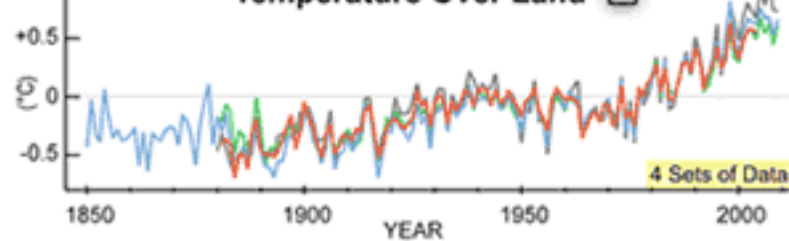
**Sea-Surface Temperature** ↑



**Temperature Over Oceans** ↑



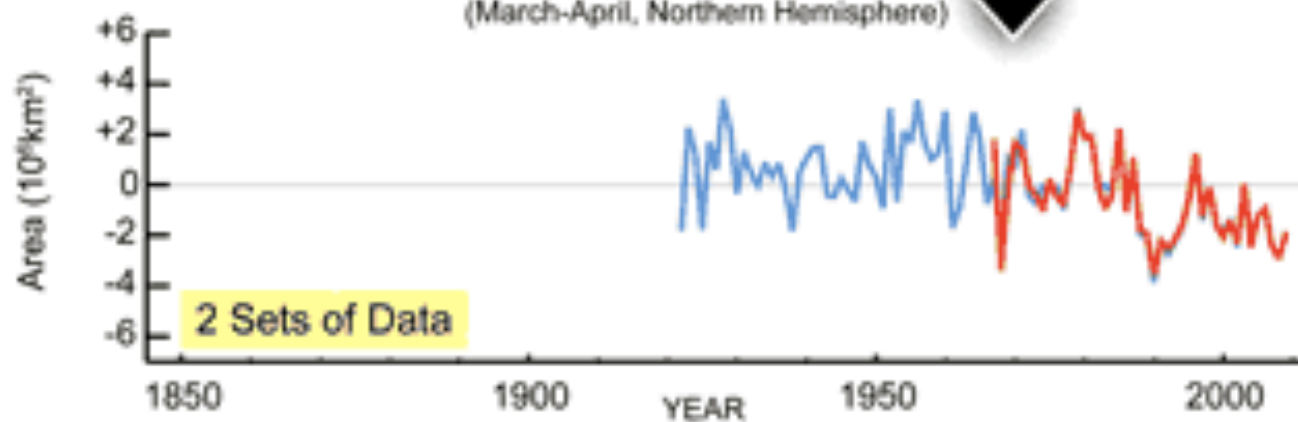
**Land Surface Air Temperature Over Land** ↑





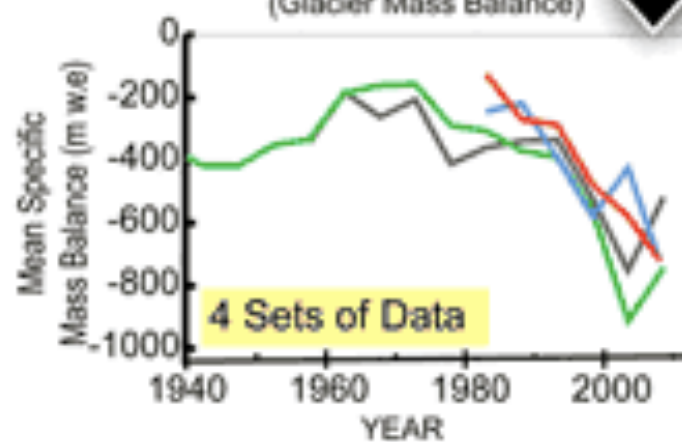
## Snow Cover

(March-April, Northern Hemisphere)



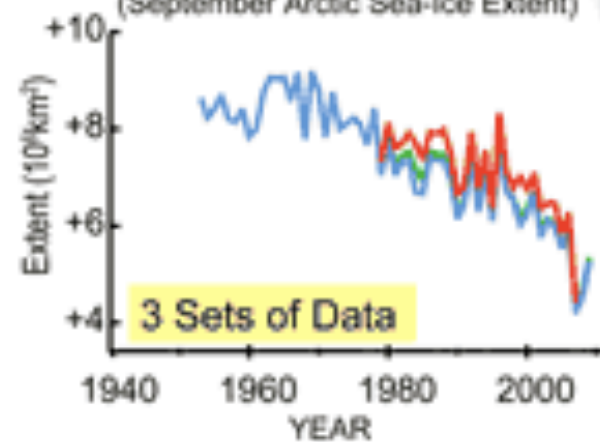
## Glaciers

(Glacier Mass Balance)

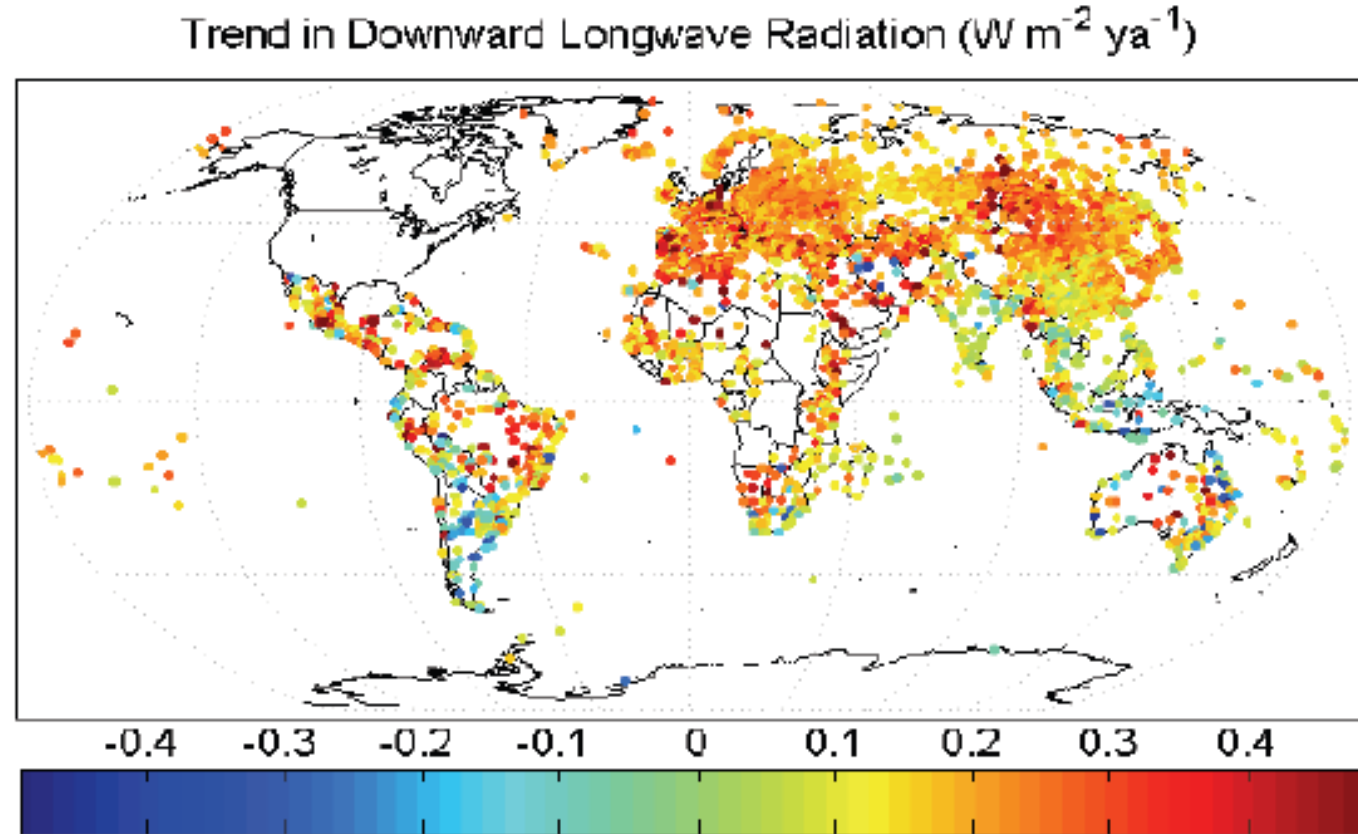


## Sea-Ice

(September Arctic Sea-Ice Extent)



# More heat energy is coming back to the surface

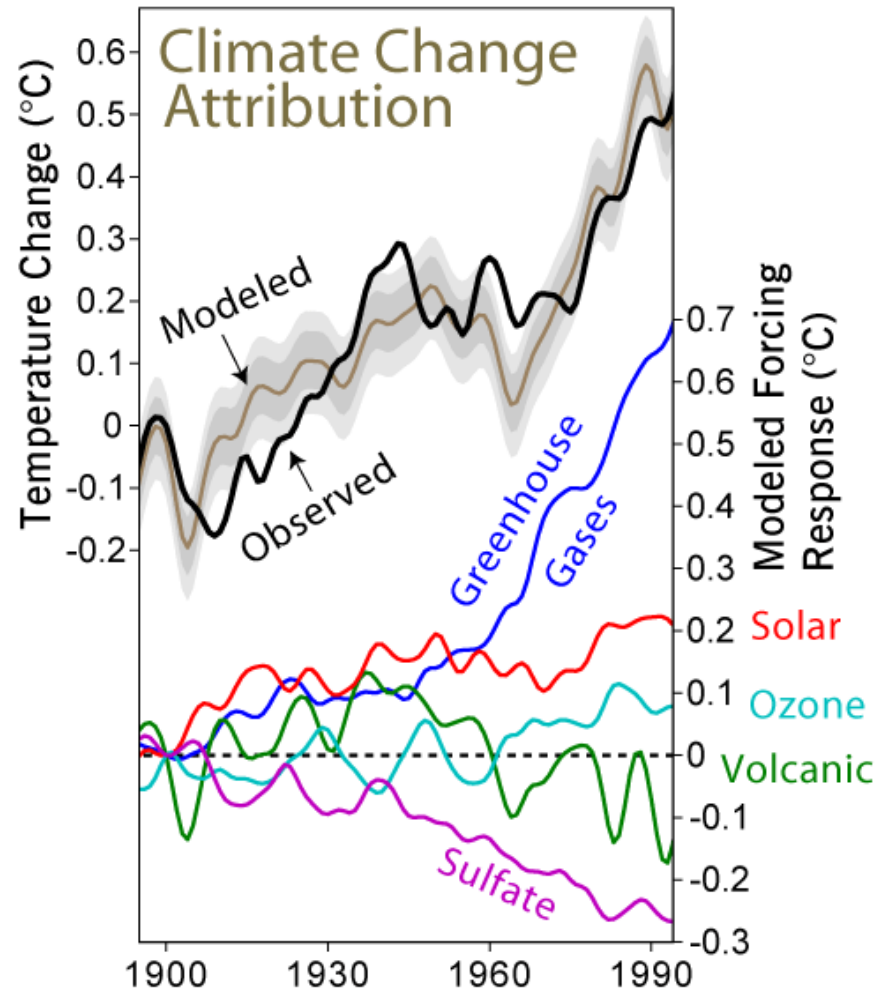


Linear trend of daily ( $L_d$ ) over 3200 global weather stations where data are available for at least 300 months (25 years) during the period of 1973-2008.

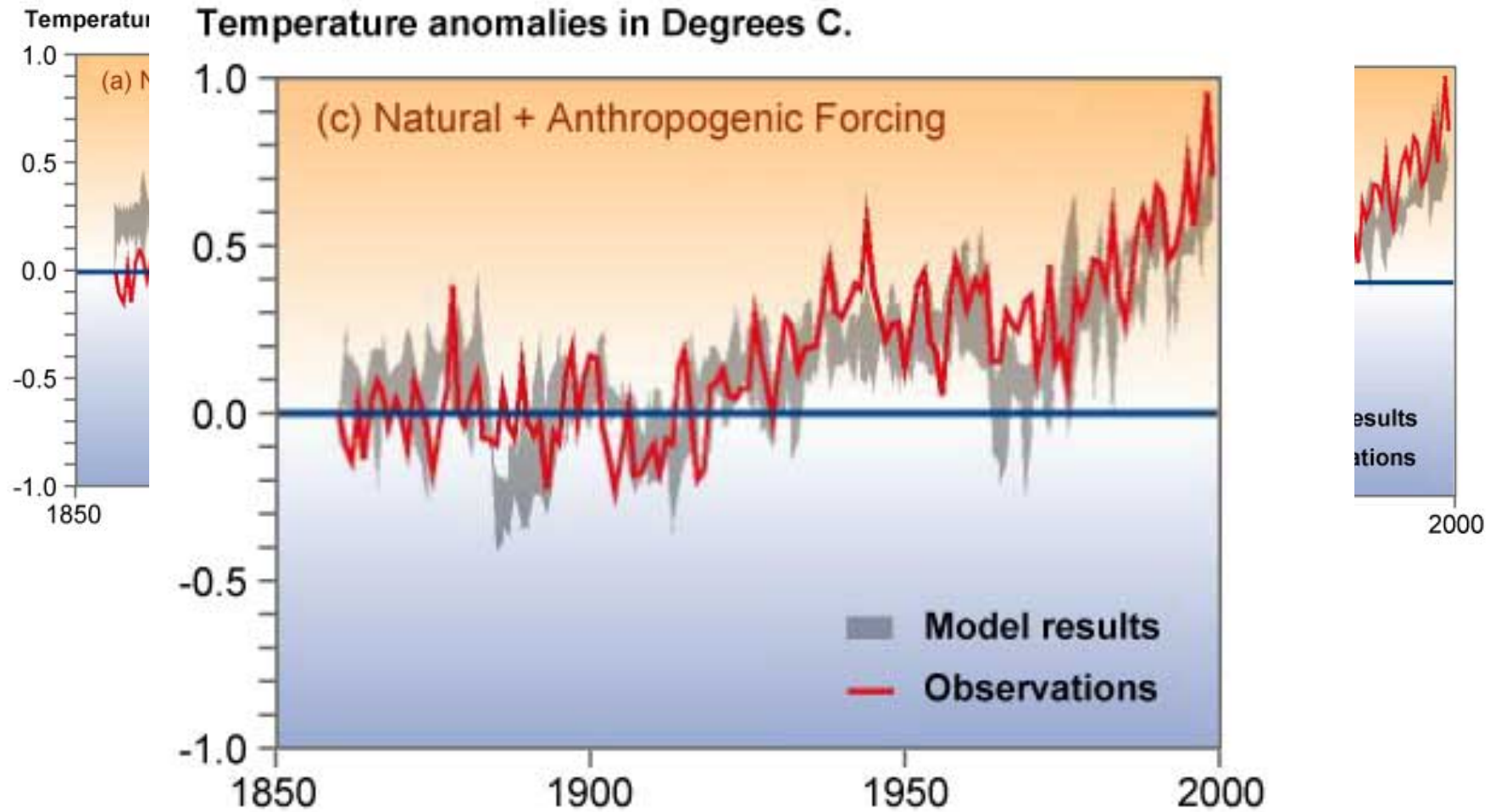
Wang, K., and S. Liang, (2009), Global atmospheric downward longwave radiation under all-sky conditions from 1973 to 2008, *Journal of Geophysical Research*, 114, D19101, doi:10.1029/2009JD011800



# Modeled Contributions to Global Average Temperature Changes

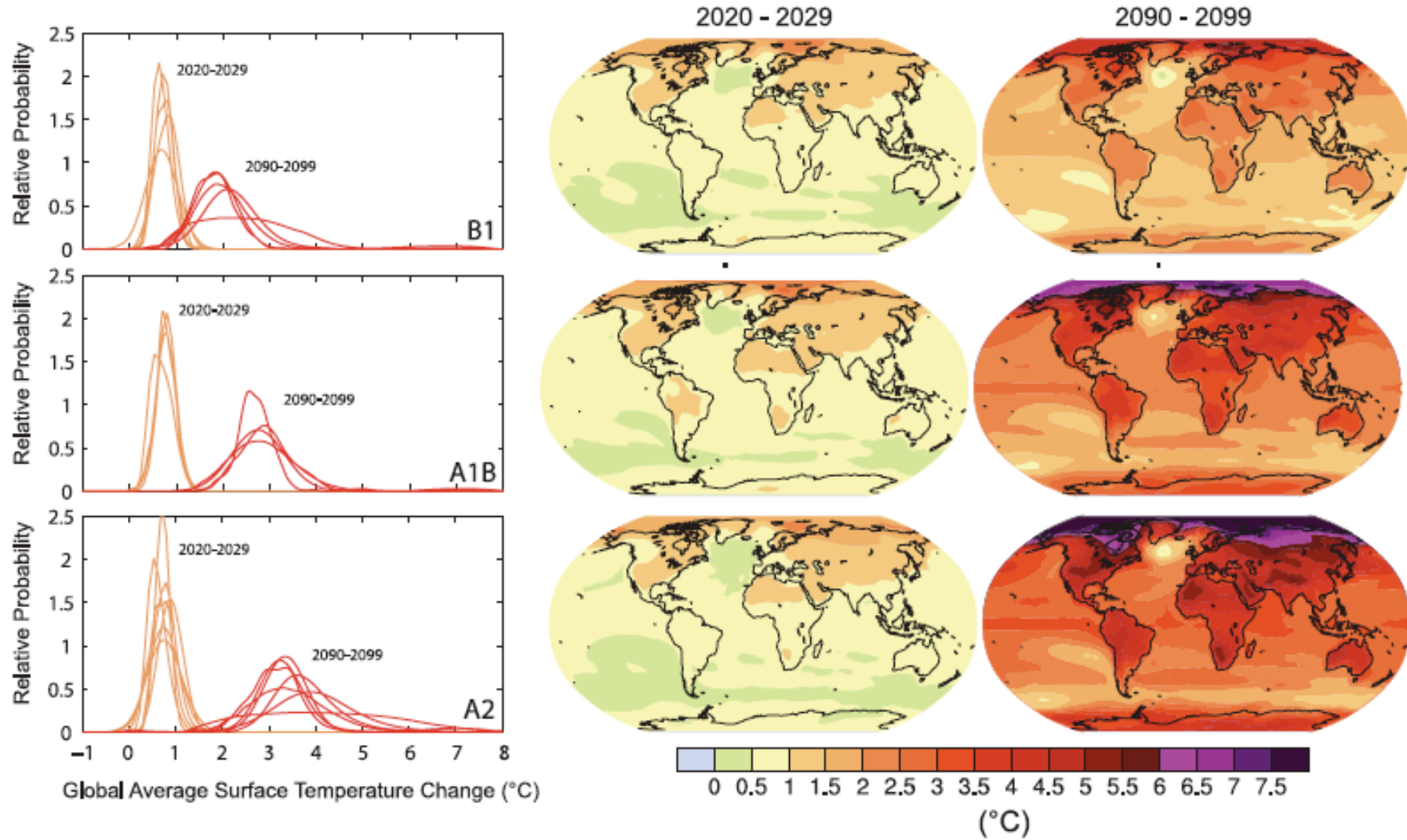


# Modern Global Temperature Models

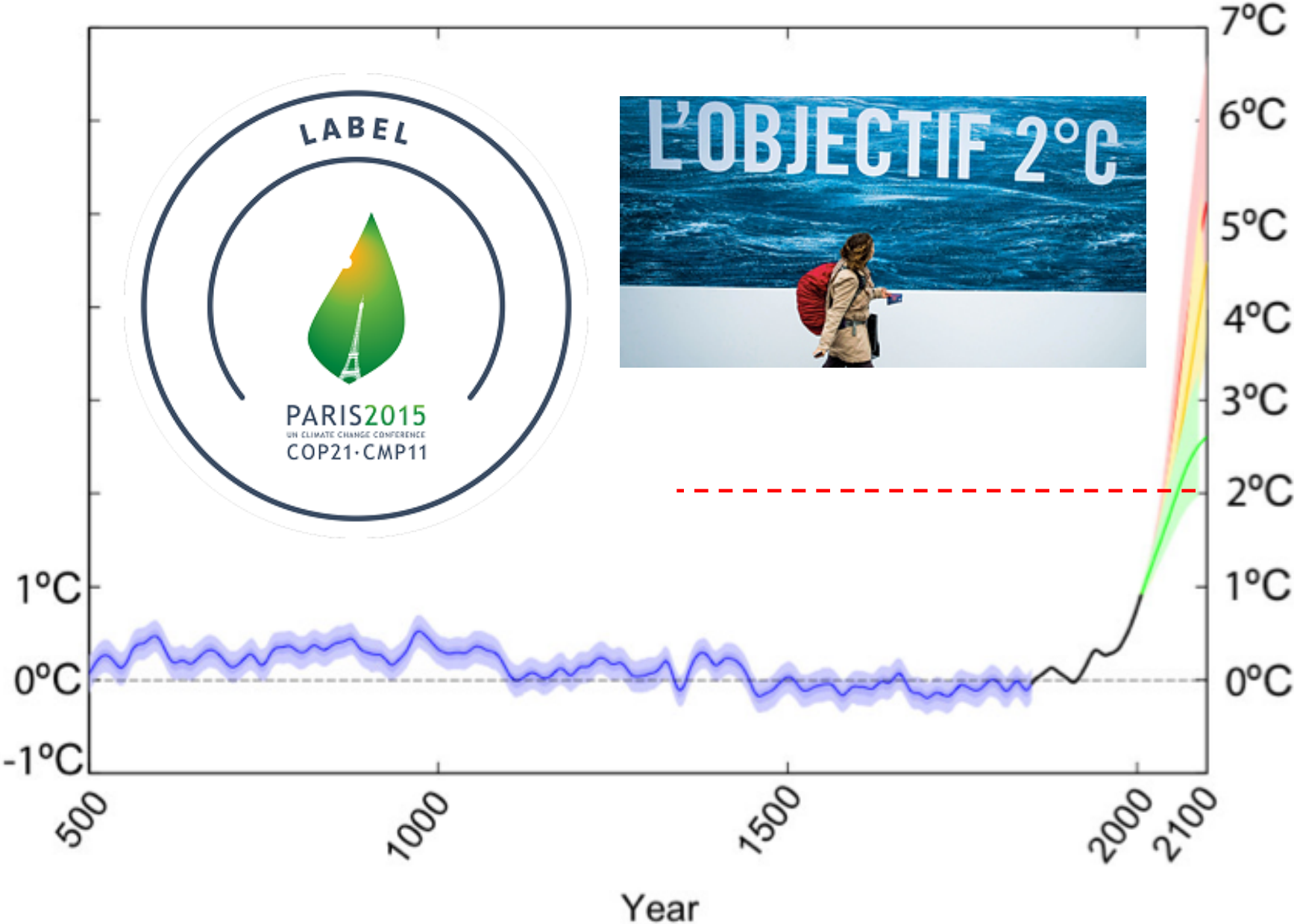


# It is going to get warmer

## PROJECTIONS OF SURFACE TEMPERATURES



# How much warmer?



**National Science Academies** stress that the scientific understanding of climate change is sufficiently clear to justify nations taking prompt action.

Canada, US, UK, China, India, France, Germany, Italy, Japan, Russia, Brazil



“We recognize the rising environmental, social, economic, and security risks posed by climate change, and that delaying action will result in greater risks and costs,”

**“We stand ready to work with governments and our civil society partners to deliver and implement a sensible and effective global climate agreement in Paris.” Oct. 2015**

The statement was endorsed by Alcoa, Alstom, BHP Billiton, **BP**, Calpine, HP, Intel, LafargeHolcim, National Grid, PG&E, Rio Tinto, Schneider Electric, **Shell**, and Siemens Corporation. The companies have combined revenues of \$1.1 trillion and more than 1.5 million employees.

# 2014 CLIMATE CHANGE ADAPTATION ROADMAP



- The U.S. military refers to climate change as a **“threat multiplier”**
- “Among the future trends that will impact our national security is climate change.”
- “Rising global temperatures, changing precipitation patterns, climbing sea levels, and more extreme weather events will intensify the challenges of global instability, hunger, poverty, and conflict.”



Da



ndler

“To a patient scientist, the unfolding greenhouse [story] is far more exciting than the plot of the best mystery novel. But it is slow reading, with new clues sometimes not appearing for several years.”

“Impatience increases when one realizes that it is not the fate of some fictional character, but of our planet and species, which hangs in the balance...”

# Impacts of Global Warming

- **Rising Surface and Air temperatures** (non-uniform around globe)
- **Loss of Polar Ice** (albedo)
- **Loss of High Altitude Ice** (summer water storage)
- **Sea-Level Increase** (depends on Greenland ice cap)
- **Ocean Acidification** (phytoplankton and coral loss)
- **Increasing Extreme Events** (heat waves and floods)

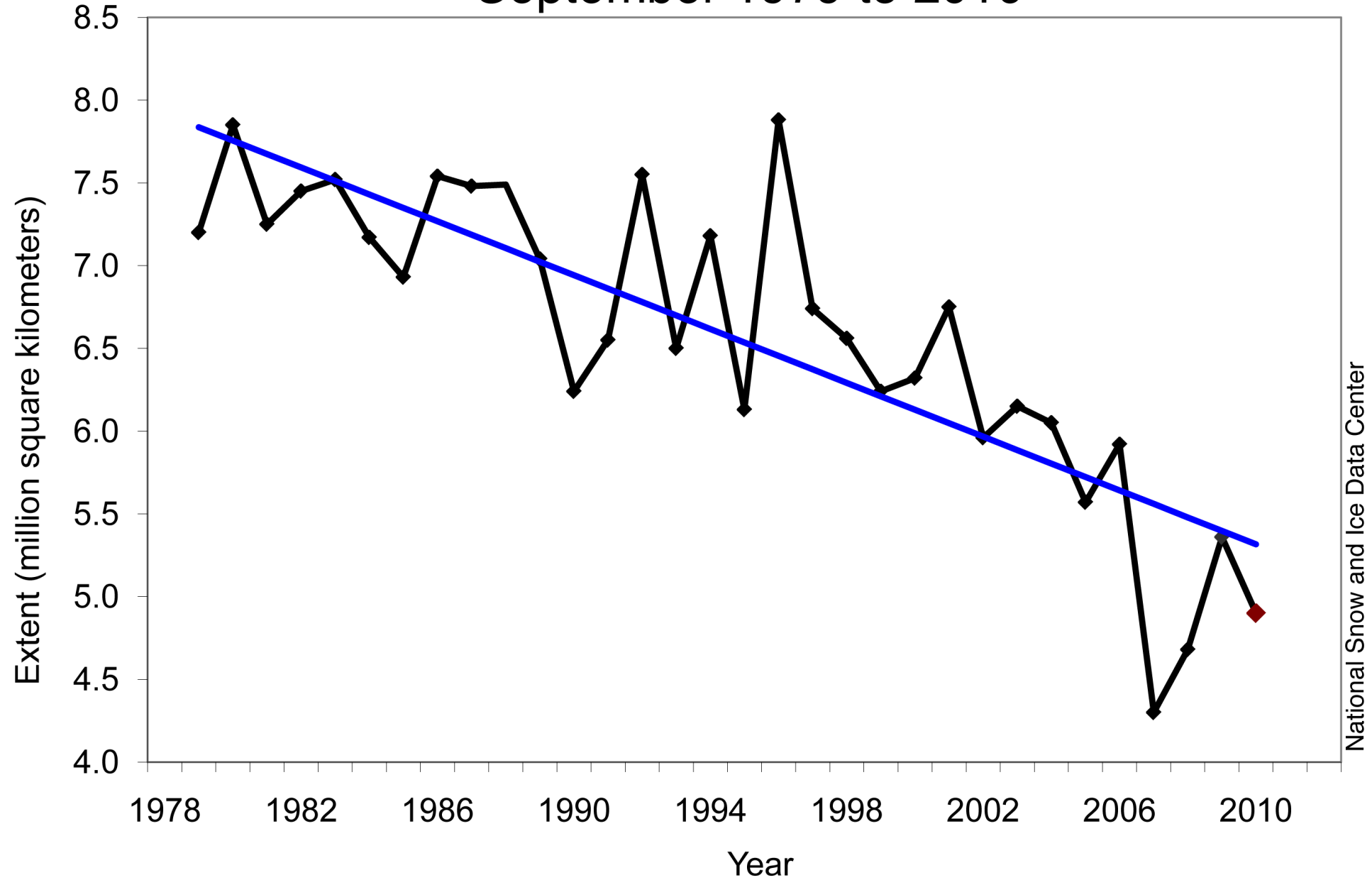
Non-Linear and Irreversible Effects

# North Polar Ice Cap



Summer Minimums

# Average Monthly Arctic Sea Ice Extent September 1979 to 2010

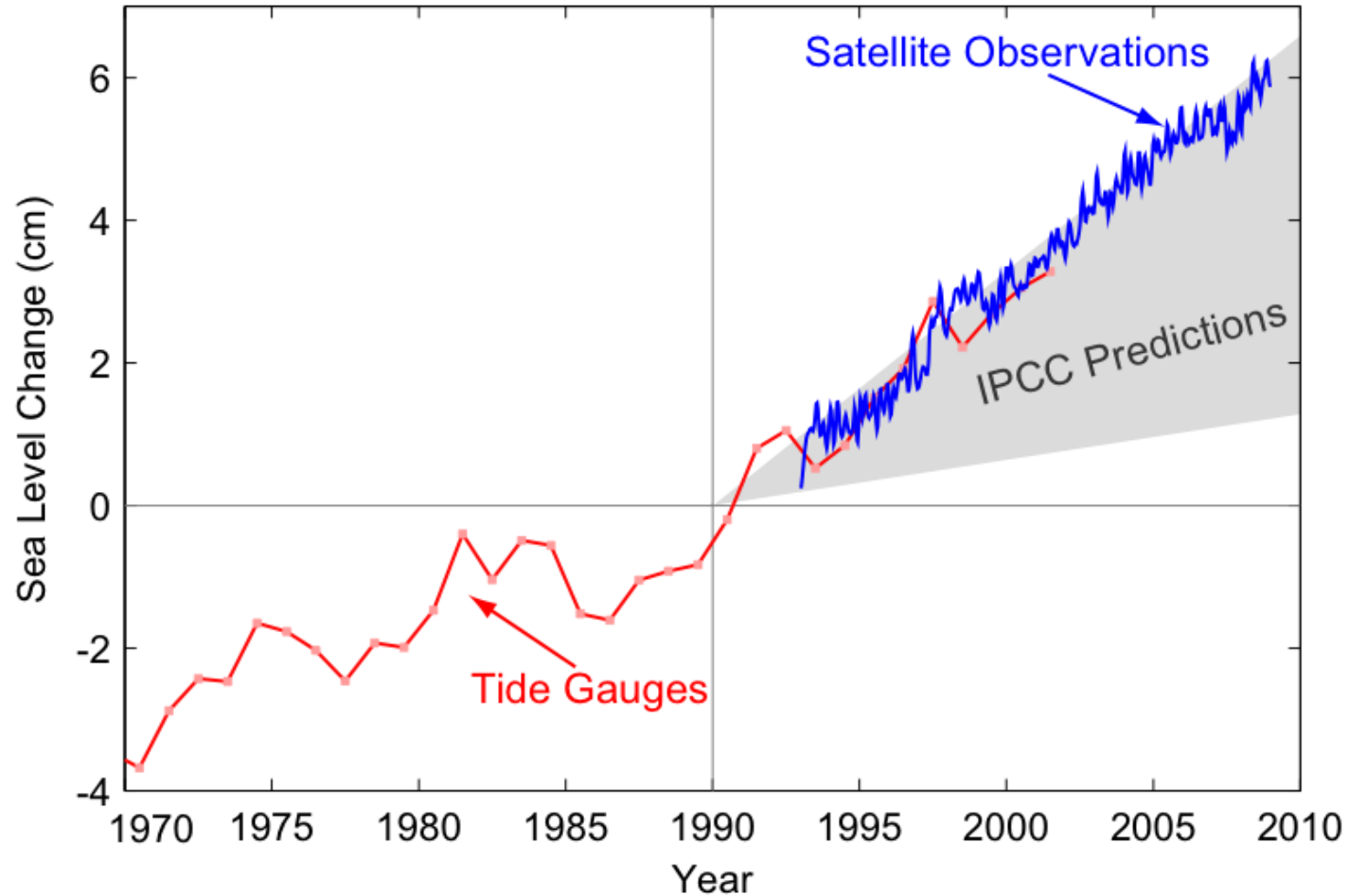


National Snow and Ice Data Center

# Retreating Alpine Ice



# Sea-Level Change 1970-2010





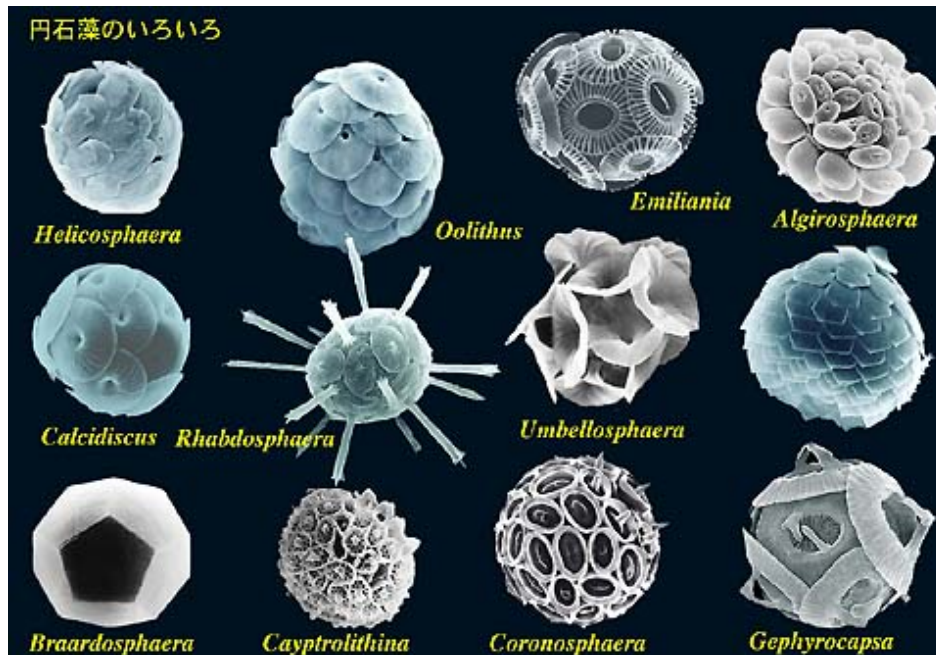
# Ocean Acidification



$K_H$

$K_{a1}$

$K_{sp}$



Certain plankton (Calcite)

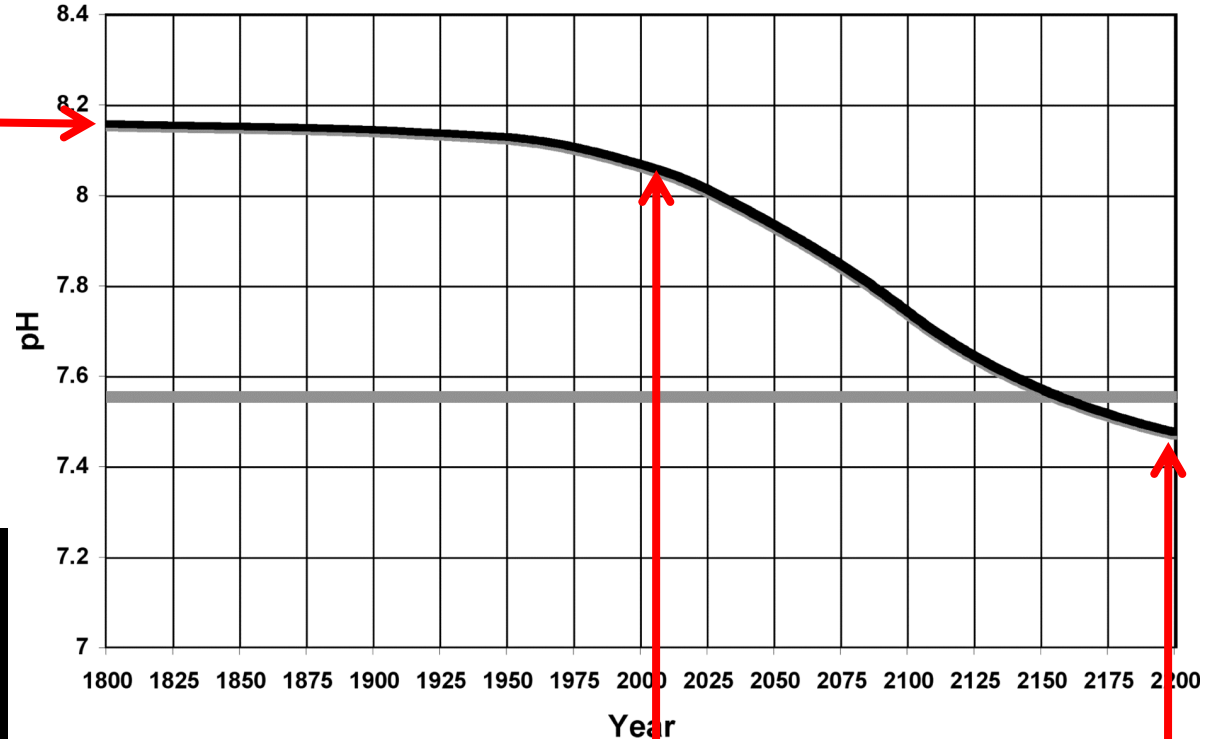


Corals (Aragonite)

# Projected Ocean Acidification

Acidity of Surface Waters

pH of preindustrial surface ocean

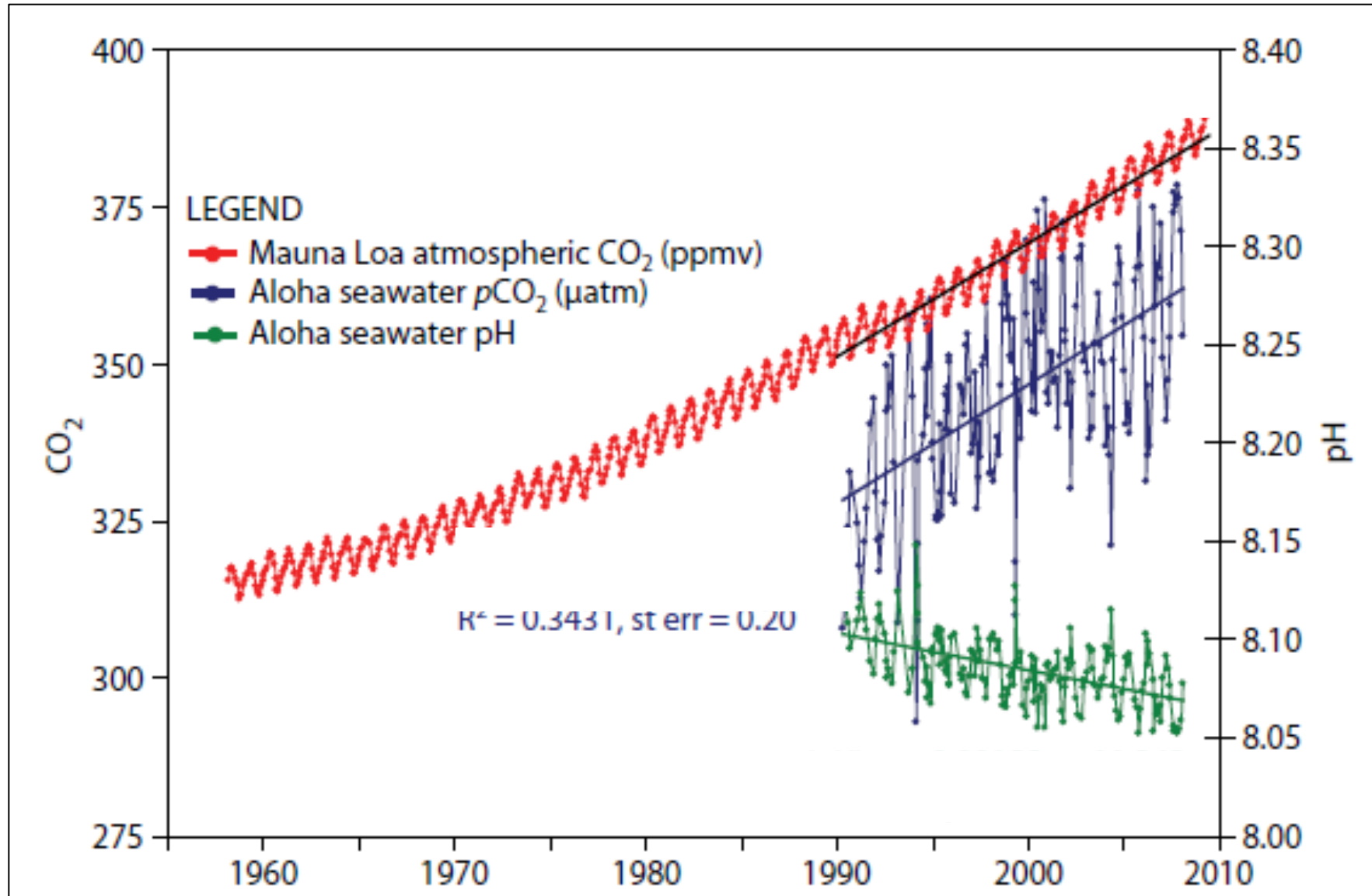


“There is no evidence of pH values more than 0.6 units below the pre-industrial pH during the past 300 million years ”  
IPCC AR4, 2007

pH drop of 0.1 since preindustrial times

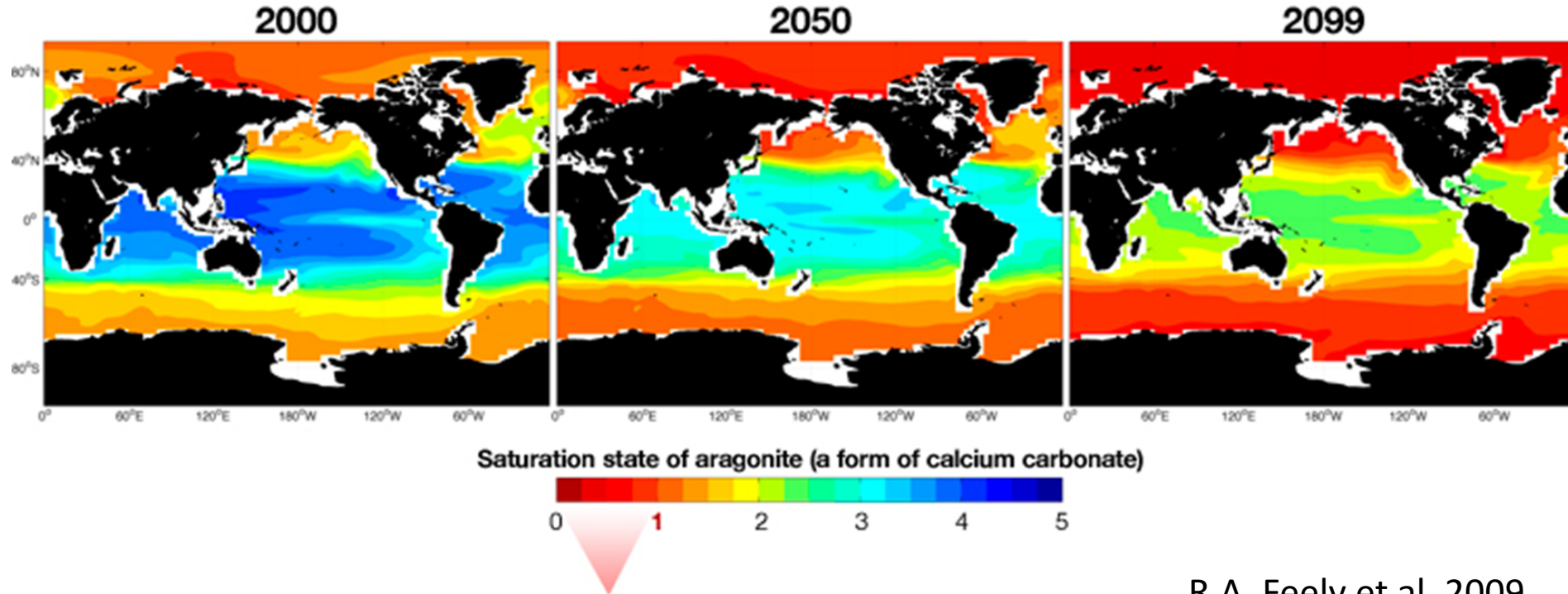
pH drop of 0.7 by year 2200

# Ocean Acidification (measured)



# Ocean Acidification

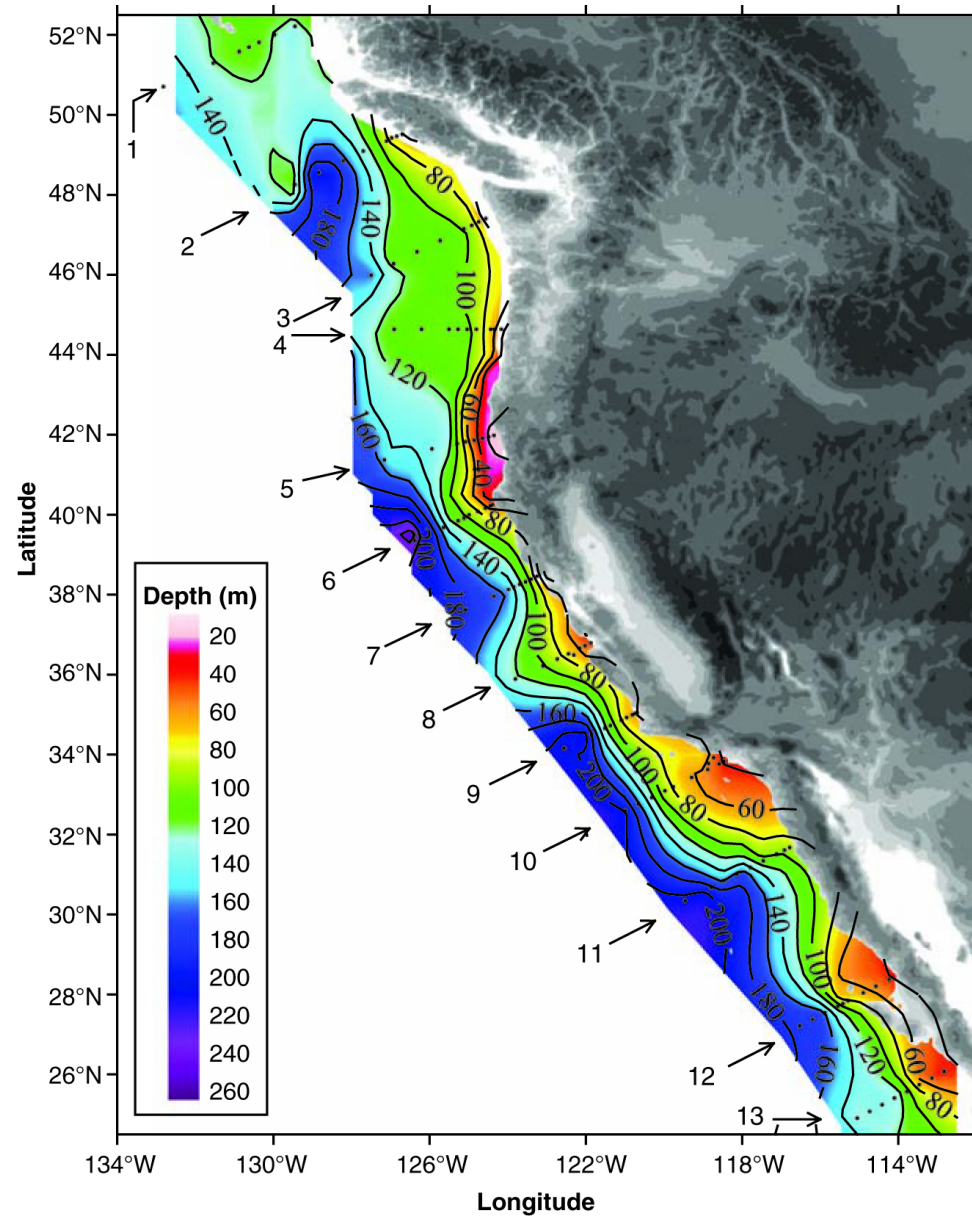
Carbonate levels predicted to drop as ocean acidifies



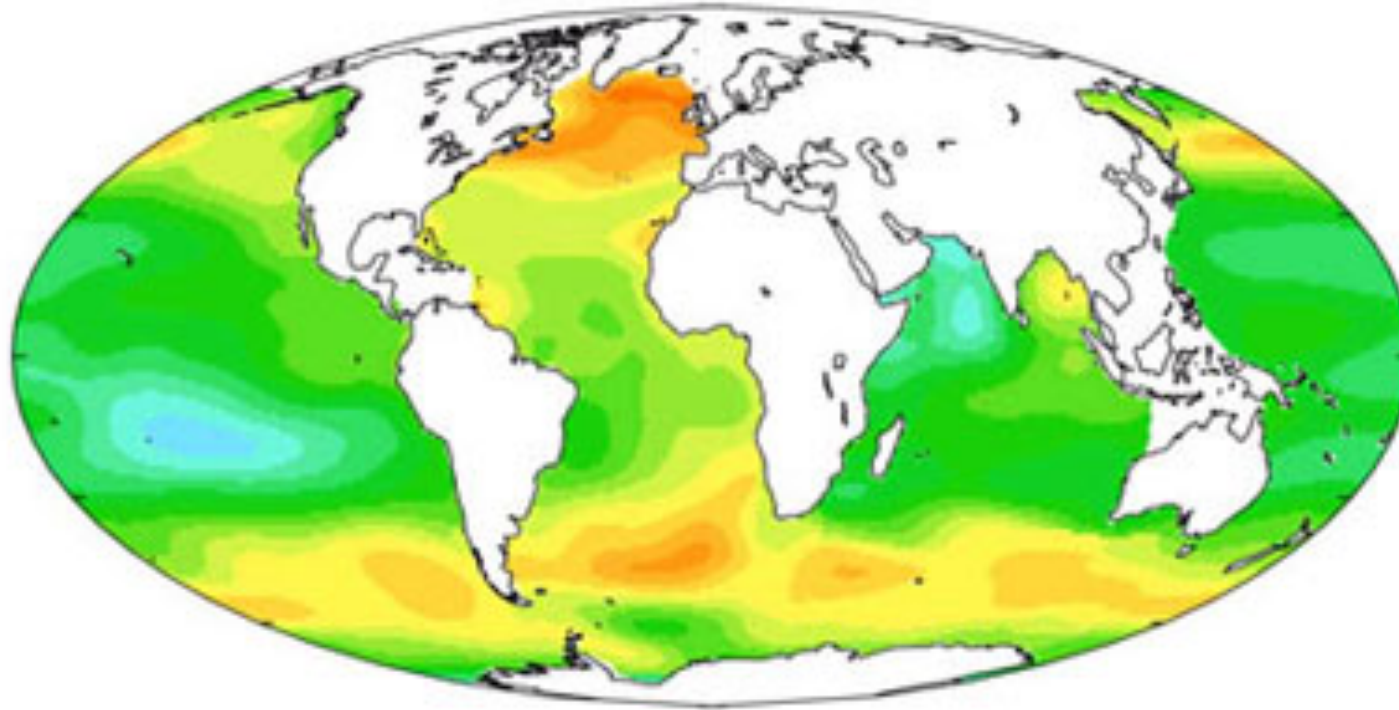
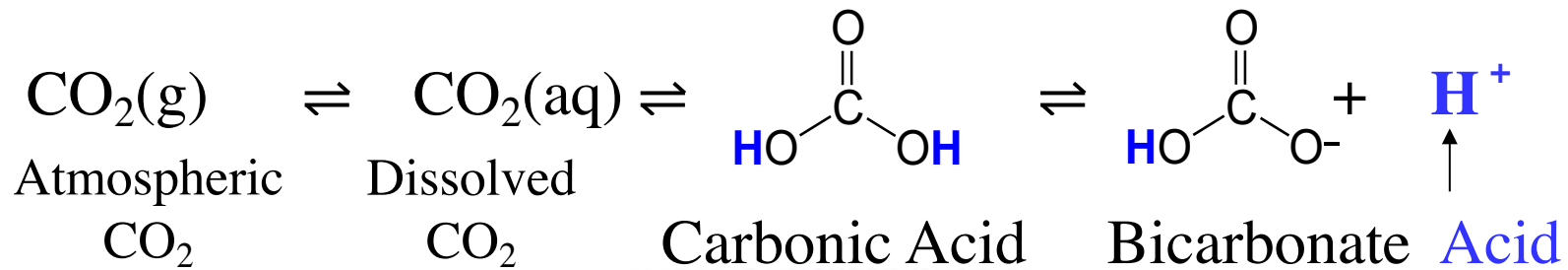
R.A. Feely et al. 2009,  
*Oceanography* 22:36-47

$$\text{Saturation Index } \Omega = Q_{\text{sp}}/K_{\text{sp}} \text{ for } \text{CaCO}_3$$

# Local Ocean Acidification

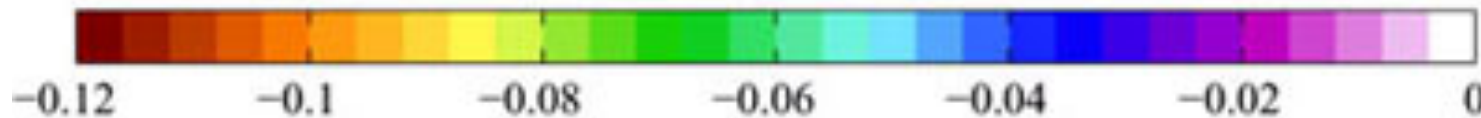


# Increasing Atmospheric CO<sub>2</sub> Makes the Oceans More Acidic



Changes in Sea-Surface pH  
(pre-industrial to 1990s)

Δ sea-surface pH [-]



# Examples of Marine Life Threatened by Ocean Acidification

Most threatened are cold-water calcifying organisms, including sea urchins, cold-water corals, coralline algae, and plankton known as pteropods (winged snails)



Coralline algae



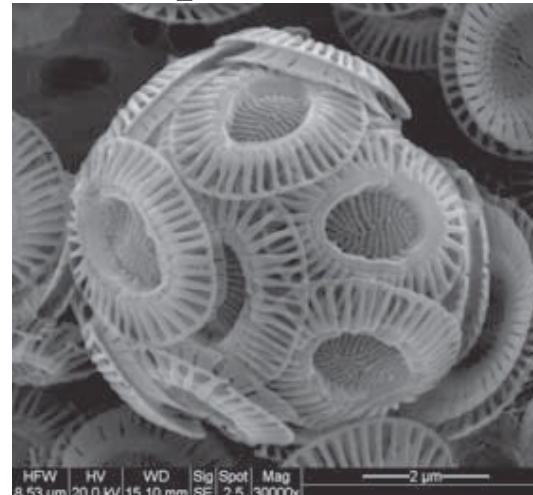
Deep-water coral



Echinoderm (brittle star)



Crustacean (lobster)



Coccolithophore



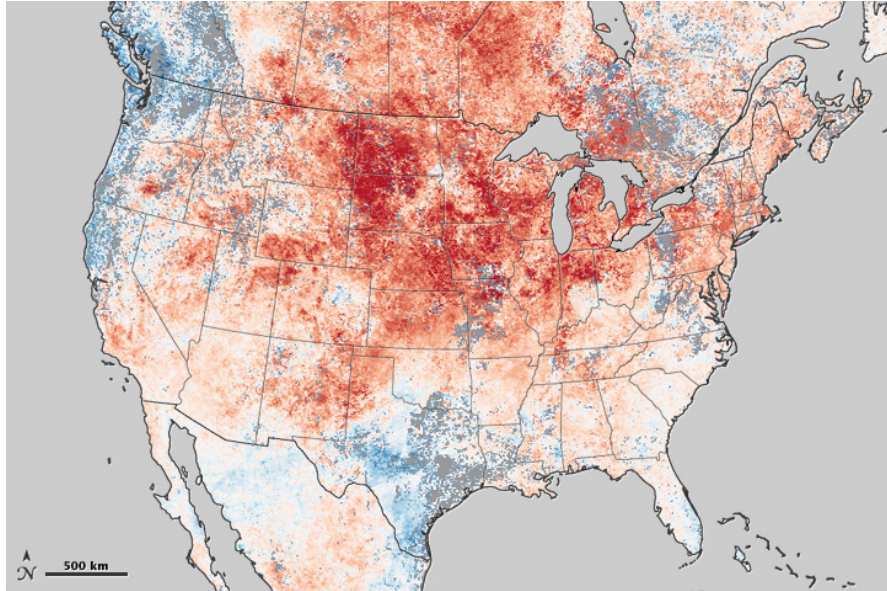
Eutecosomatous pteropod

Photos from:

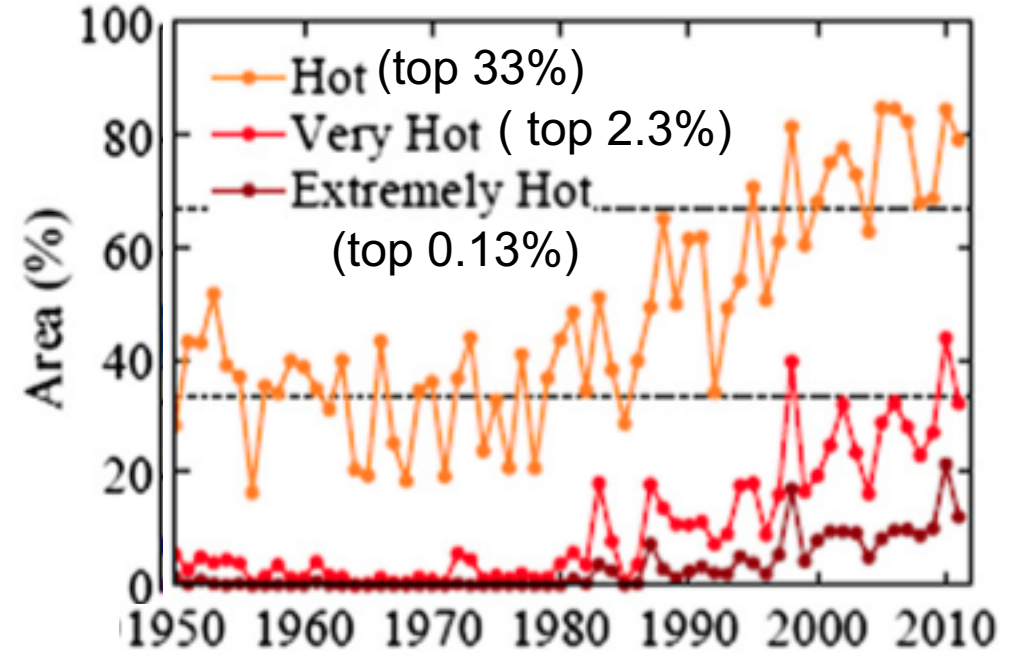
Kleypas, J.A., R.A. Feely, V.J. Fabry, C. Langdon, C.L. Sabine, and L.L. Robbins, 2006. *Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers* Workshop held April 2005, St. Petersburg, FL, sponsored by NSF, NOAA, and the U.S. Geological Survey

# Increasing Extreme Events

## Summer temperature anomalies



## Hot Areas



(Hansen et al., 2012)

- Instead of asking “Was this event caused by climate change”
- Ask “What is the chance that this event would occur without climate change?”
- Extreme temperature events are 10 times more common



# Stratospheric Cooling (Predicted)

Stratosphere

Troposphere

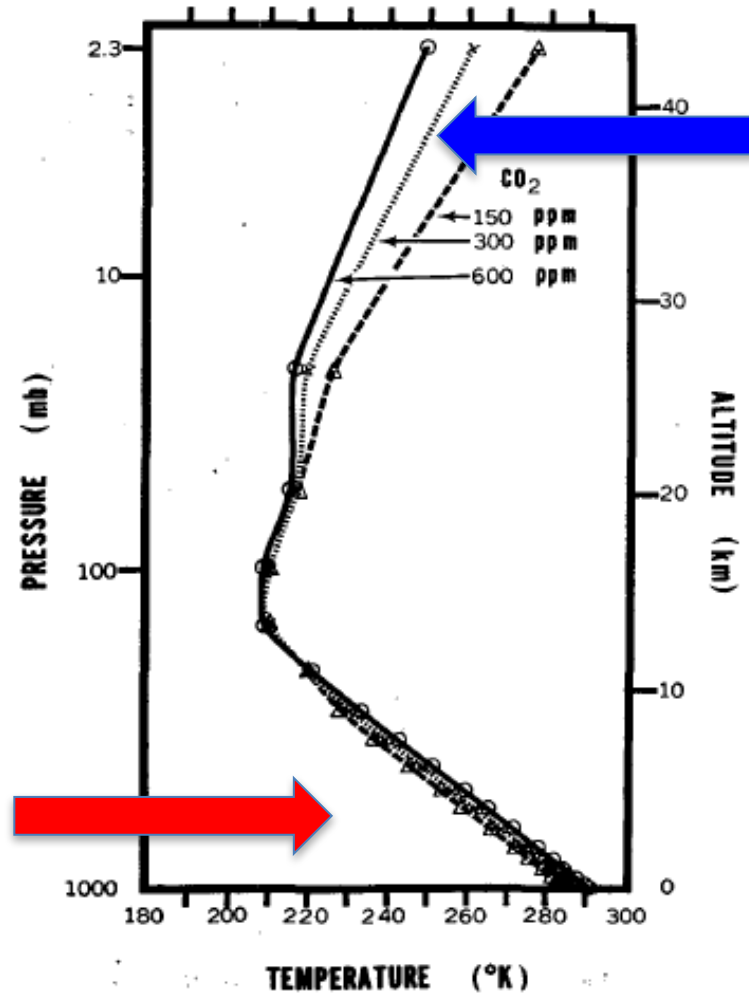


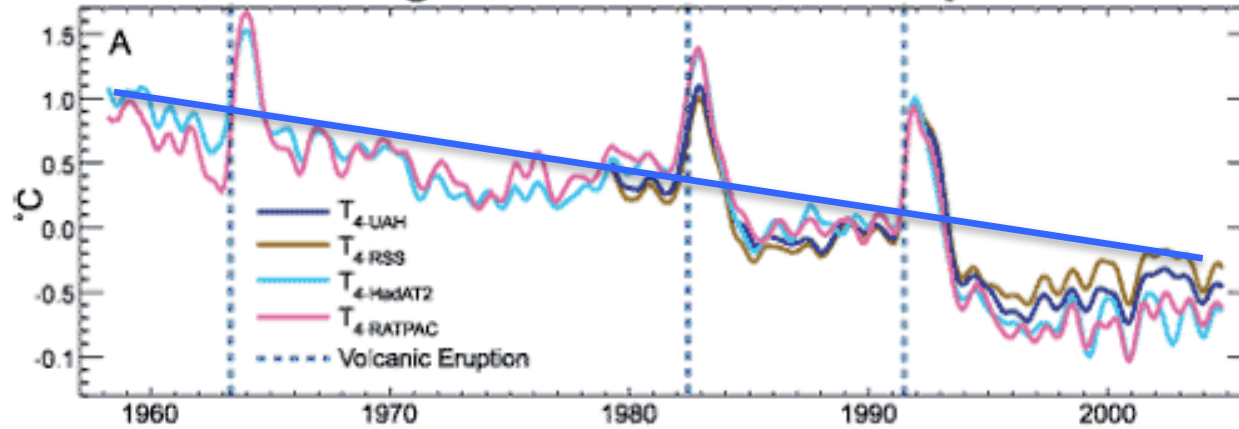
FIG. 16. Vertical distributions of temperature in radiative convective equilibrium for various values of CO<sub>2</sub> content.

Atmos. Sci., 24, 241-259, 1967

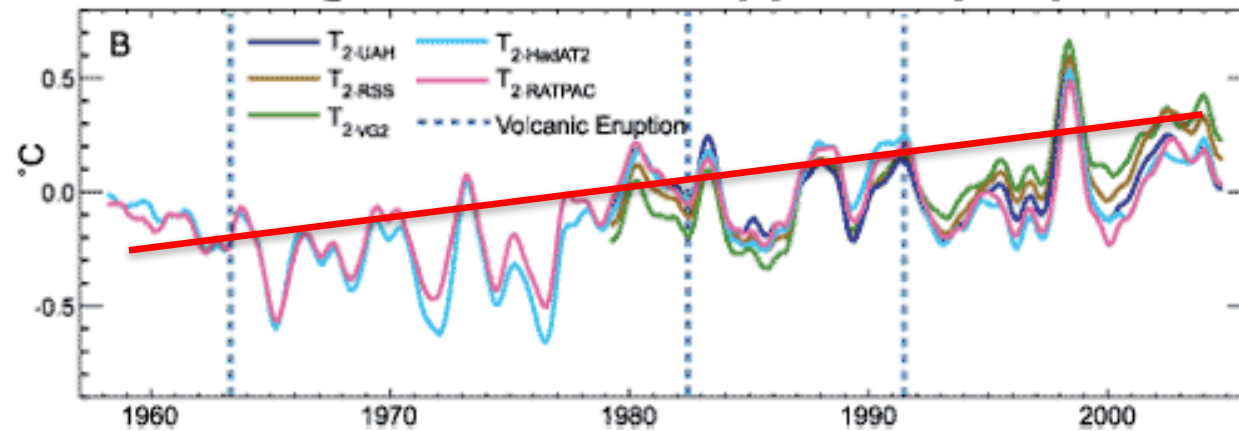
# Stratospheric Cooling

(Measured)

## Cooling in the lower stratosphere

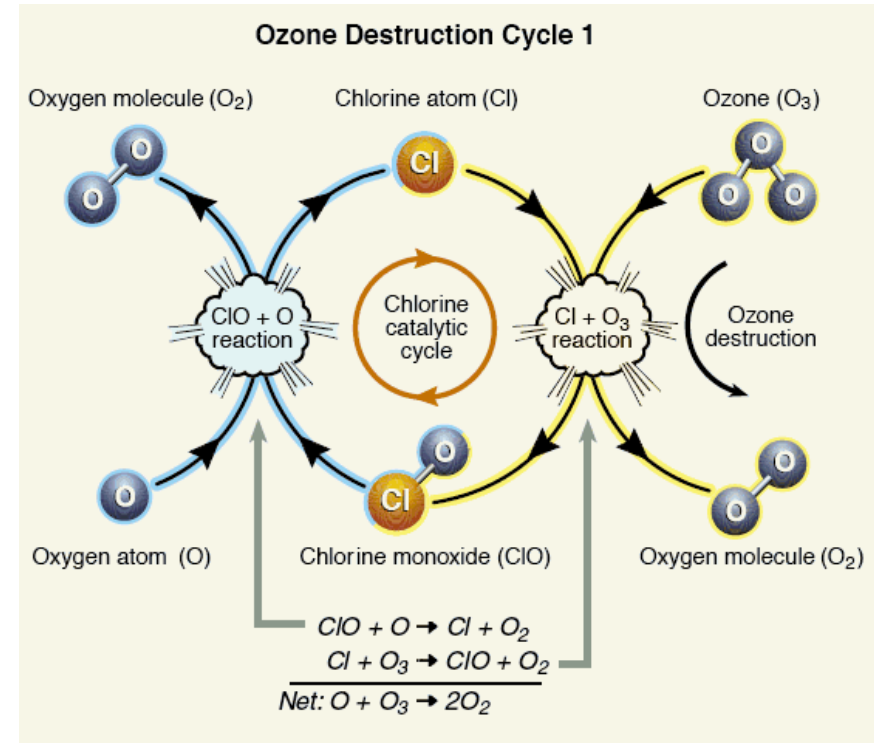
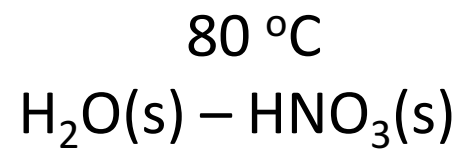


## Warming in the Mid to Upper Troposphere

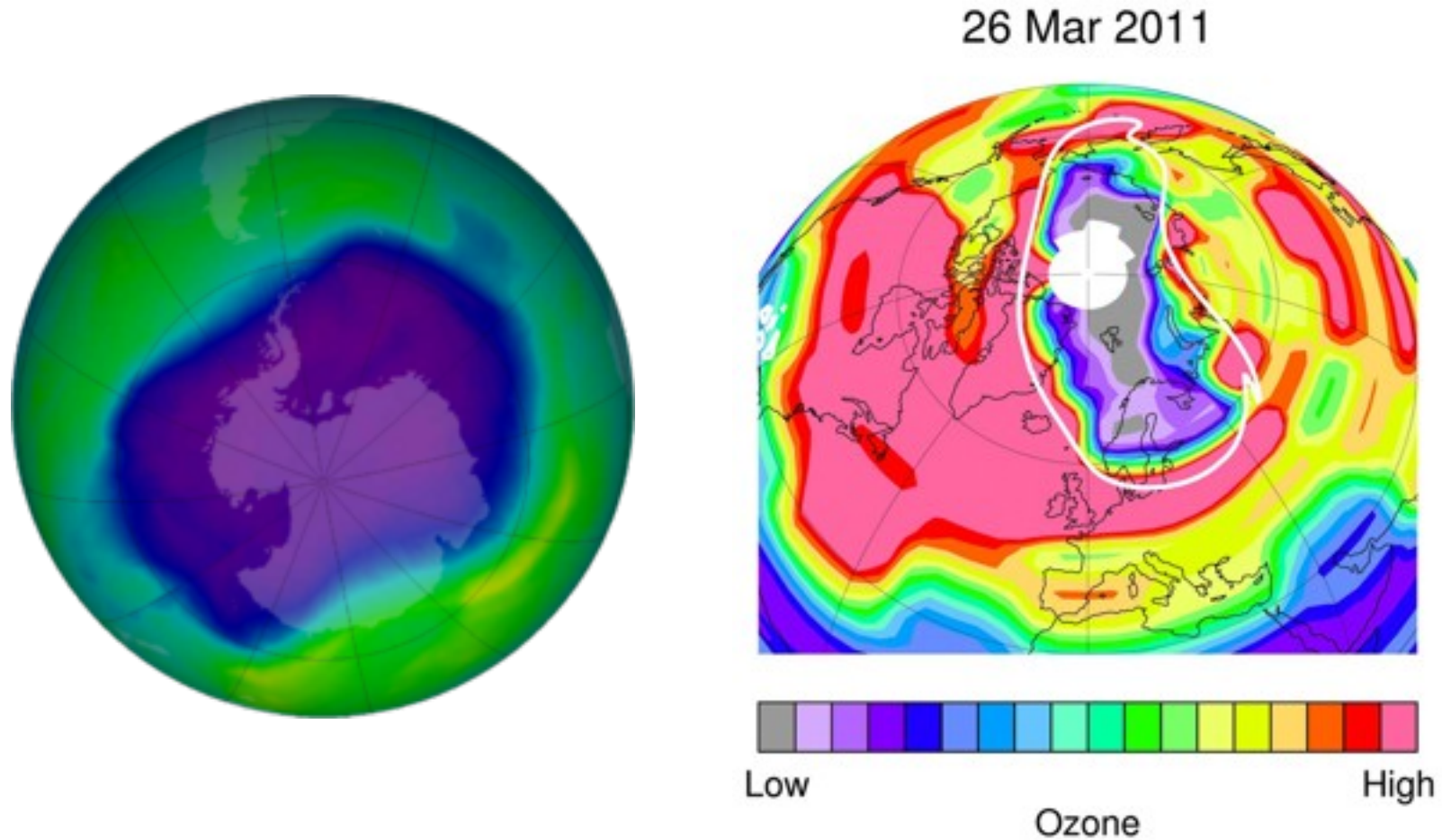


# Polar Stratospheric Clouds

## Catalyze Ozone Destruction



# Arctic Stratospheric Ozone Loss





"IPCC gets an A+ for scientific assessment, but a gentleman's C for communication."  
—Richard Somerville, Scripps Institution of Oceanography

# Pushing the Scary Side Of Global Warming

Greenhouse warming might be more disastrous than the recent international assessment managed to convey, scientists are realizing. But how can they get the word out without seeming alarmist?

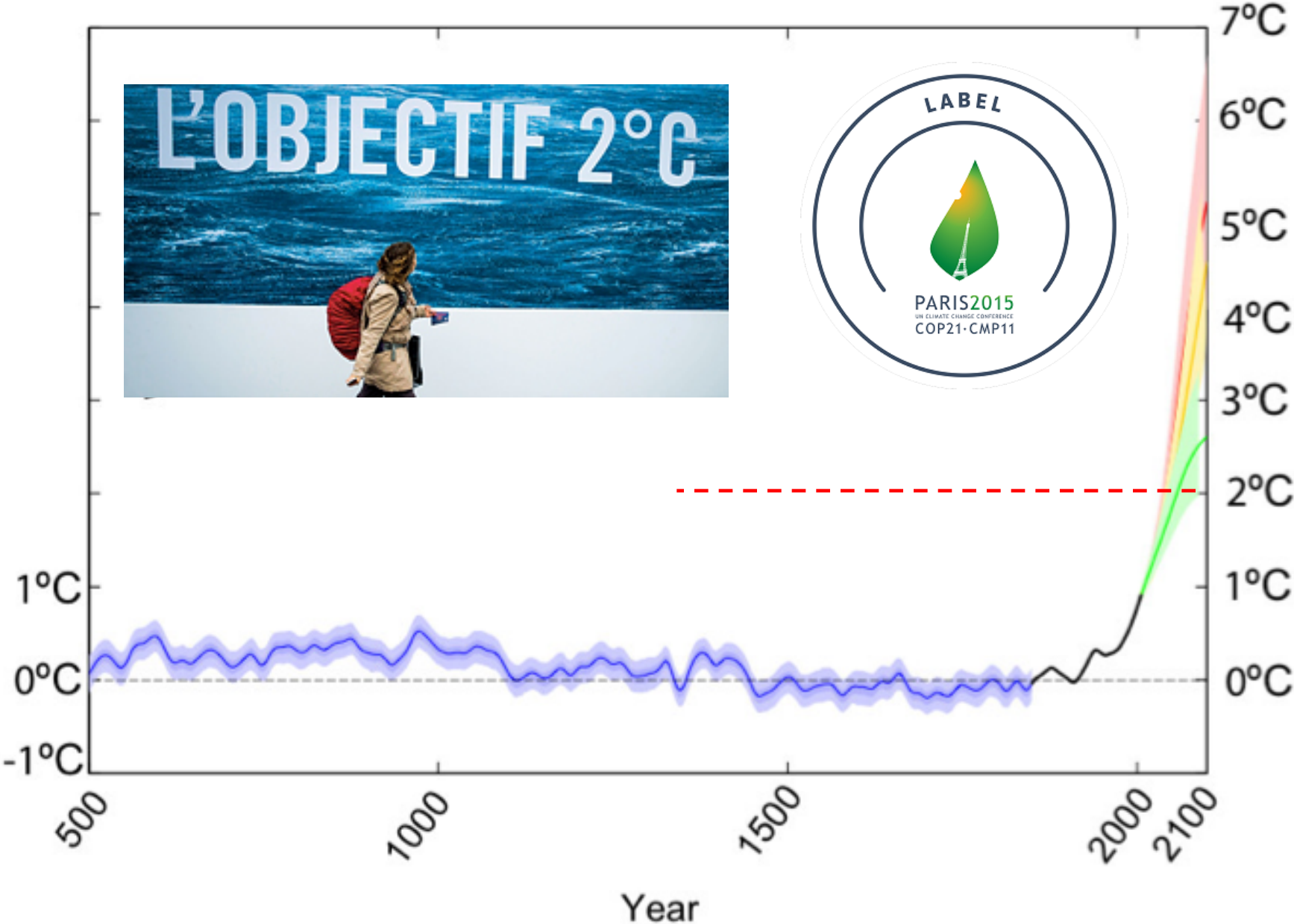
**CLIMATE MODELER JAMES HANSEN** knows all about sounding the alarm. In the summer of 1988, drought wracked the country, fire was consuming Yellowstone National Park, and the nation's capital sweltered. Even the Senate hearing room where Hansen was testifying was warm and stuffy—the Democrats had

and policymakers. This time he worries that sea level could rise several disastrous meters by the end of the century, as the warming he heralded sends the great ice sheets rumbling toward the sea. If nothing is done to rein in greenhouse gas emissions, he says, "I just can't imagine that you could keep sea-level

end of the century. "The IPCC has been overly cautious in not wanting to give any large number to [future] sea-level rise," says climate researcher Stefan Rahmstorf of the Potsdam Institute for Climate Impact Research in Germany.

Scientists are still trying to strike a bal-

# How much warmer?



# Progression of Scientific Consensus Statements

**Intergovernmental Panel on Climate Change (IPCC)** [www.ipcc.ch](http://www.ipcc.ch)

“the **balance of evidence suggests** that there is a discernible human influence on global climate.” IPCC SAR, **1995**

“..most of the observed warming over the last 50 years is **likely to have** been due to the increase in greenhouse gas concentrations.” IPCC, TAR, **2001**

"it is ***extremely likely*** that human activities have exerted a substantial net warming influence on climate since 1750," where "***extremely likely***" indicates a probability greater than 95%. IPCC, FAR, **2007**

# Overwhelming Burden of Evidence

**Intergovernmental Panel on Climate Change (IPCC)** [www.ipcc.ch](http://www.ipcc.ch)

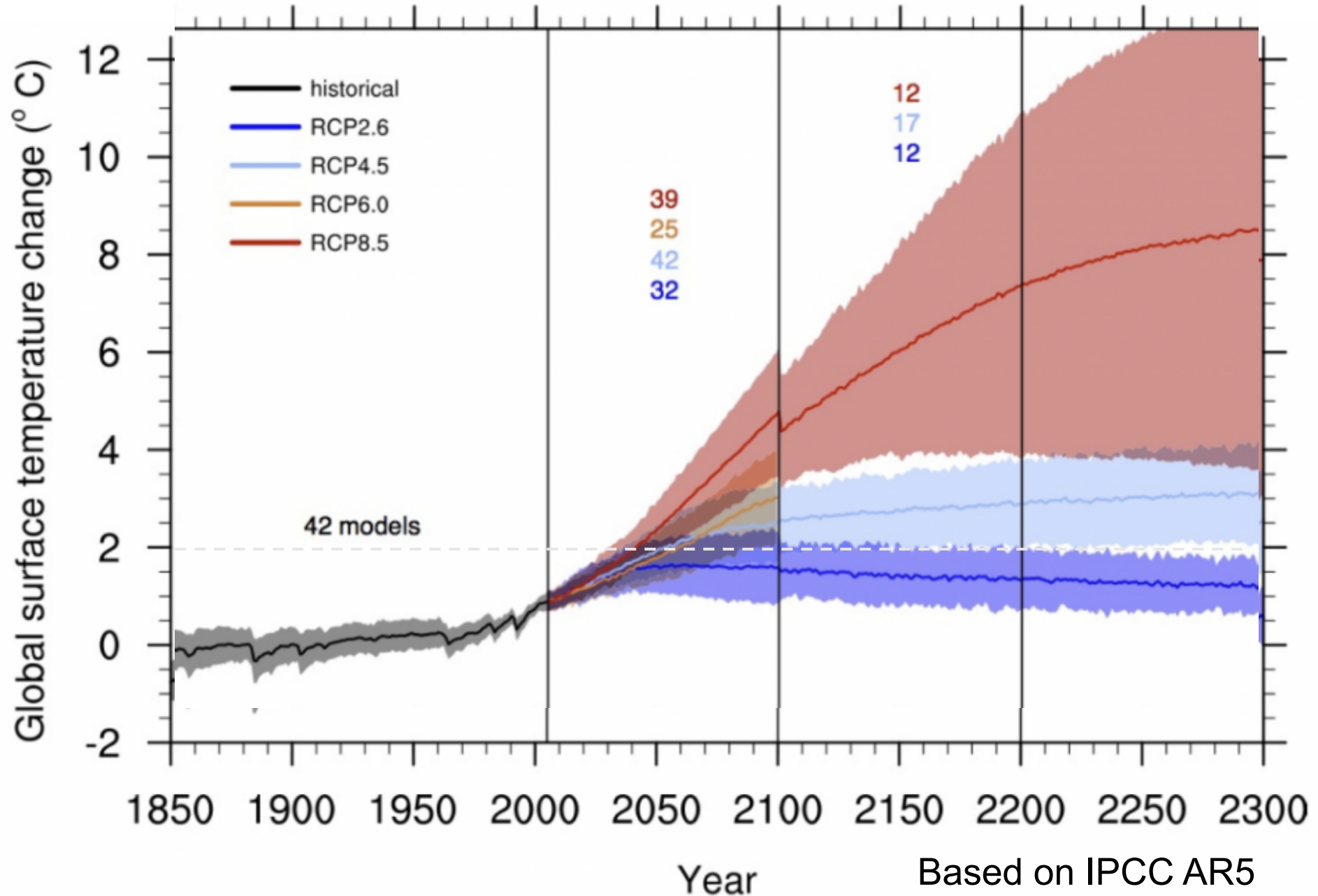
**2014:** “It is extremely likely [**>95%**] that human influence has been the dominant cause of observed warming since the mid-20th century”

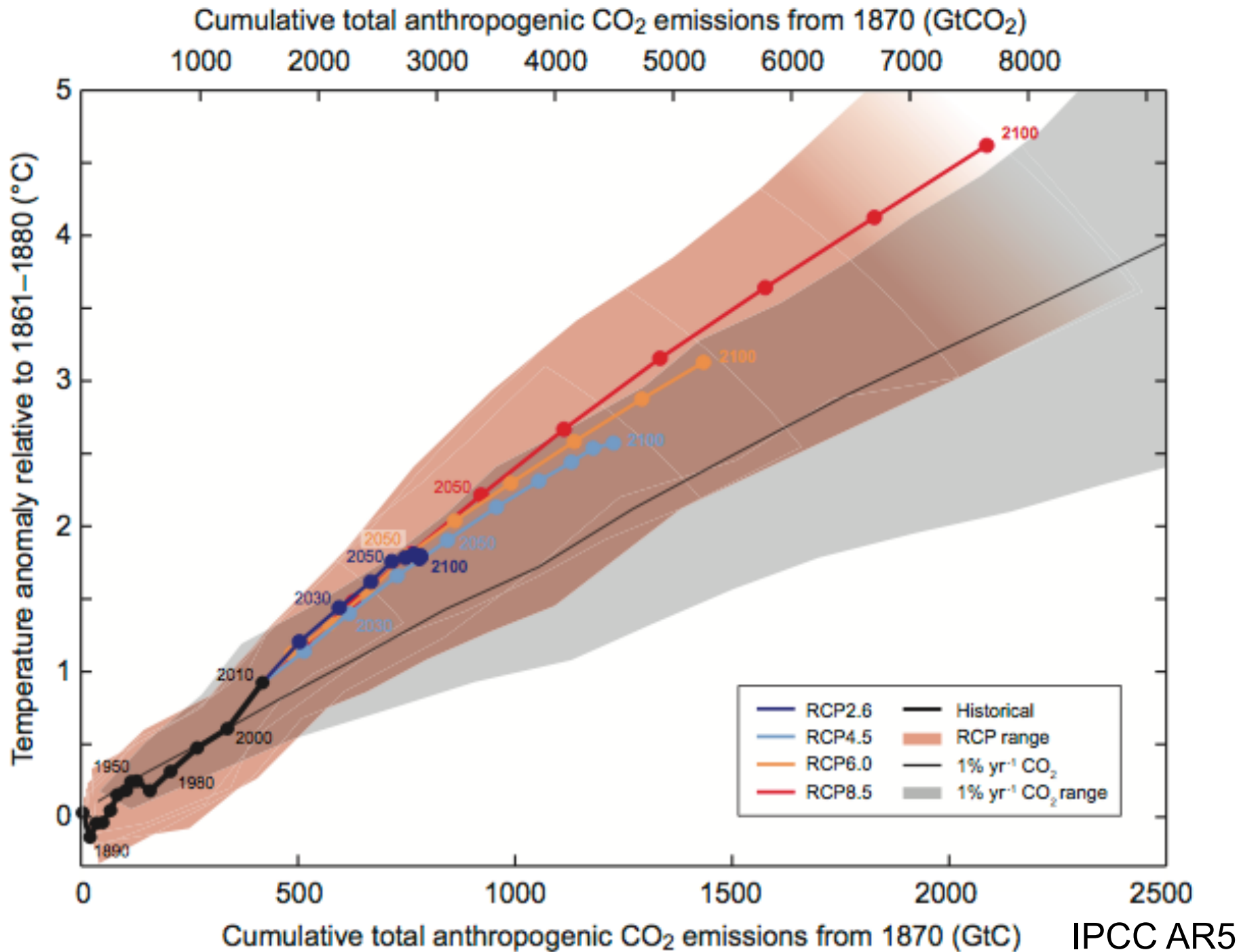
## **5<sup>th</sup> Assessment Report (AR5) Summary**

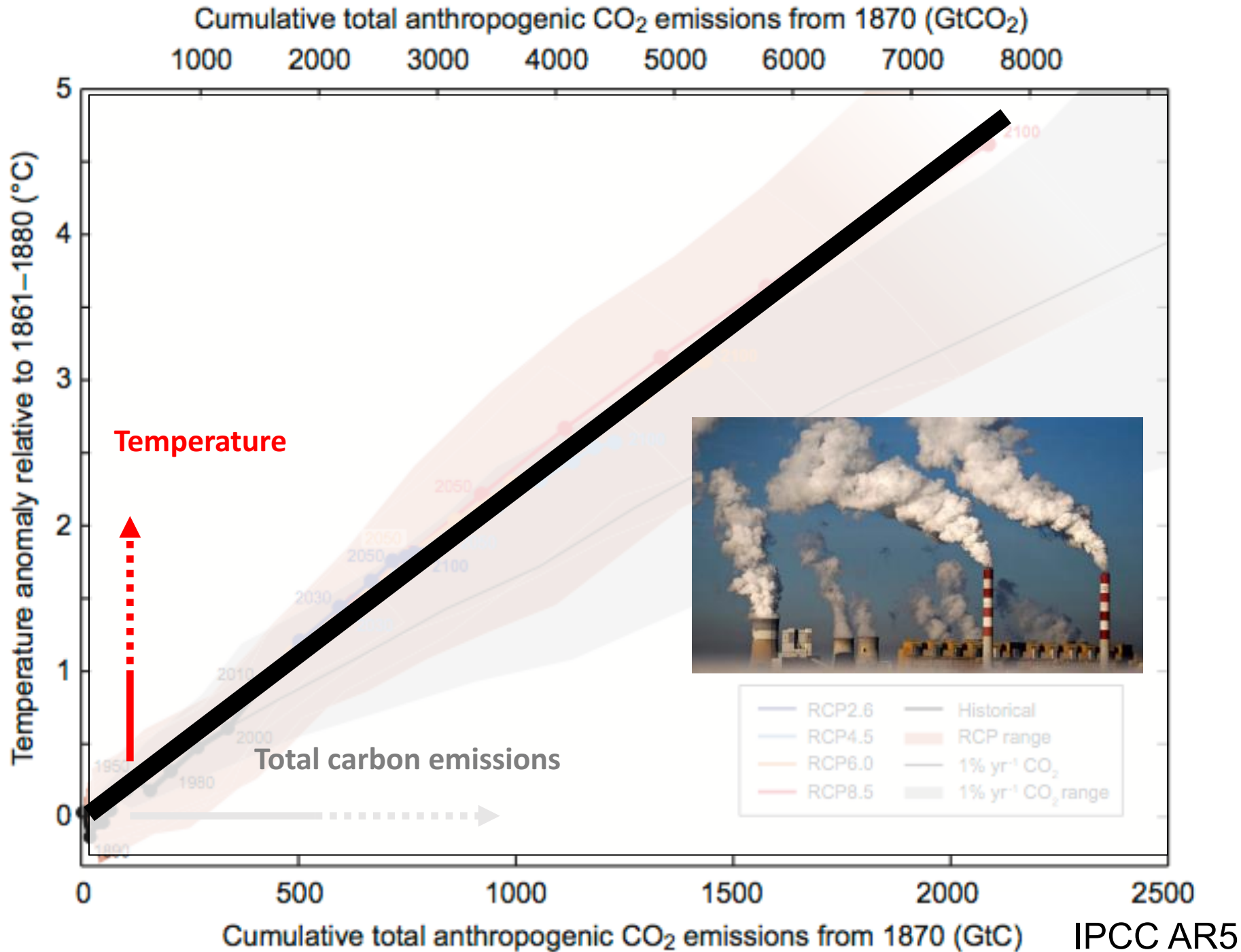
- Humans have caused the majority of present day climate change
- The warming is largely irreversible
- Most of the heat is going into the oceans
- Current rates of ocean acidification are unprecedented
- To stay below 2° C of warming, most fossil fuels must stay buried in the ground

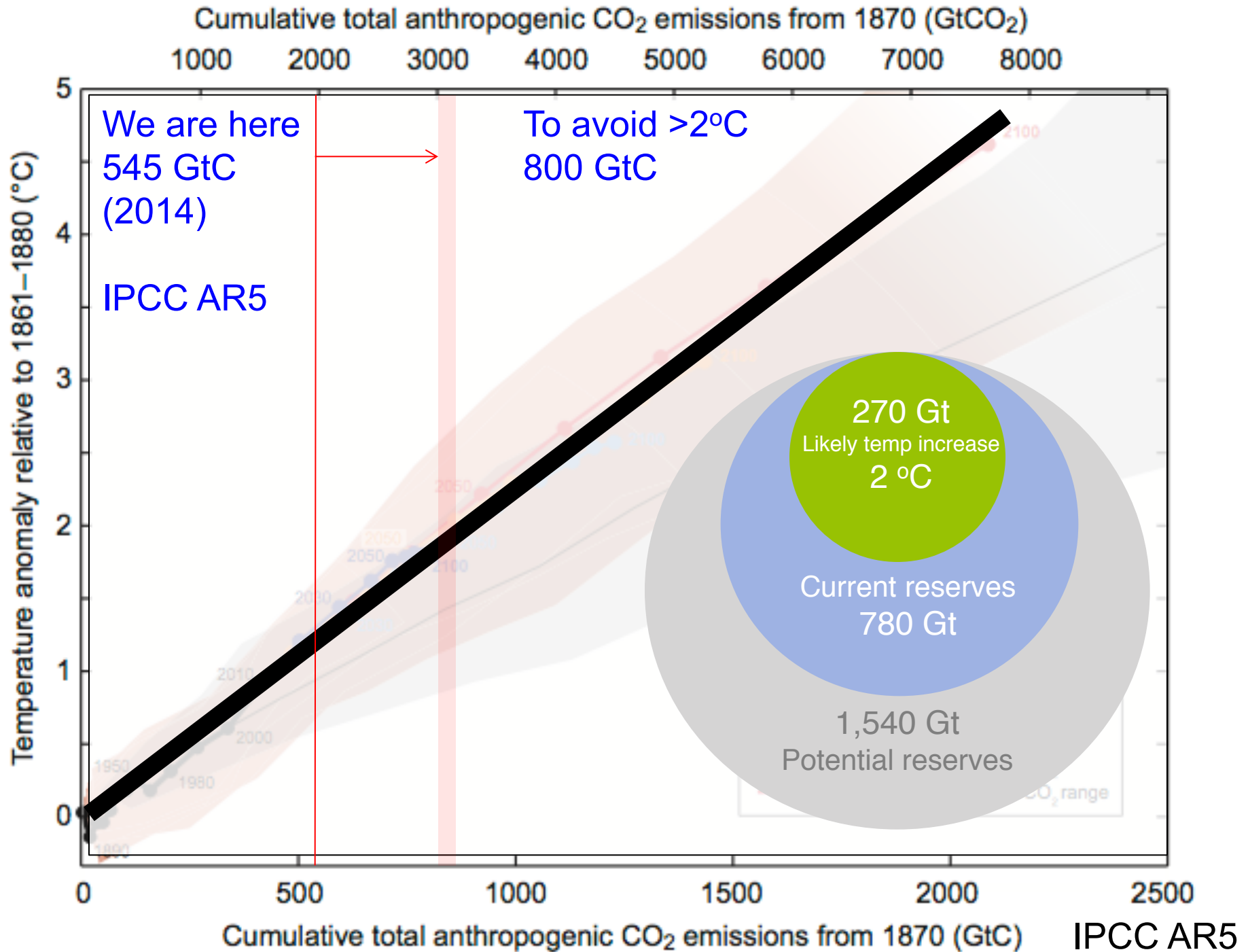


# Avoiding more extreme climate change









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## The oil and gas we have already tapped will take us past 1.5 °C

