

The Rock-Solid Scientific Evidence for Anthropogenic Global Warming*

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Abstract

Atmospheric CO₂ concentrations have increased from 280 ppmv (parts per million by volume) prior to 1800 AD to almost 410 ppmv today, an increase of some 46%. Virtually all this increase has been caused by human activities. In the early 19th century, the main cause of the increase was deforestation, primarily in North America. Since then, the main driver has been consumption of fossil fuels. In the millennium prior to 1800, atmospheric CO₂ oscillated between ~200 ppmv and 280 ppmv as part of the Pleistocene glacial-interglacial cycles. These data were obtained from polar ice cores. The last time CO₂ levels exceeded 400 ppmv was probably during the mid-Pliocene, more than 3 m.y. ago, based on indirect proxy data.

Global surface temperatures have also risen by about 0.8° C (1.5° F) since 1880; although the database is sparse before this time, as thermometers had just recently been invented. About 2/3 of this increase has occurred since 1975. Some, or all, of the initial increase in surface temperature may have been a result of natural climate cycles, but the increase over the last four decades is almost certainly anthropogenic. Climate models that do not include the anthropogenic CO₂ increase during this time interval do not reproduce the observed surface warming. Climate theory and observations are now in good agreement.

What will happen to atmospheric CO₂ and climate during the next century depends largely on how much fossil fuel we consume. The 2018 CO₂ emission rate from fossil fuel burning was over 10 Gt(C)/yr, a new record. By comparison, volcanoes emit about 0.1 Gt(C)/yr, or 1% of the fossil fuel burning rate. The terrestrial biosphere emits about 60 Gt(C)/yr from respiration and decay, but this emission is almost completely balanced by CO₂ uptake during photosynthesis. The pre-industrial atmosphere contained about 600 Gt(C); the living biosphere (mostly trees) holds roughly this same amount. If we could substantially increase the amount of vegetation on Earth, we could postpone global warming temporarily; however, if we continue to deforest the globe, the global warming problem is simply exacerbated. The total economically recoverable fossil fuel reservoir is at least 5000 Gt(C). If we burn this all up over the next few centuries, atmospheric CO₂ concentrations could rise to almost 2000 ppmv, just under 8 times the pre-industrial level. Surface temperatures are predicted to increase by (3±1.5)° C per CO₂

doubling, so three such doublings could produce a warming of $\sim 9^{\circ}\text{C}$, or 16°F . This is not an acceptable outcome, as it would make much of the world uninhabitable by humans who do not have access to air conditioning.

Reports written by the Intergovernmental Panel on Climate Change (IPCC) are a definitive source of information on past changes in CO_2 and climate, and they represent consensus views about how these variables might change in the future. The IPCC reports typically make projections through the year 2100. The 2013 report presents several future CO_2 emission scenarios. The most pessimistic ('business as usual') scenario, RCP8.5, envisions emissions climbing to 25 Gt(C)/yr by 2100, with atmospheric CO_2 concentrations reaching 950 ppm. The associated increase in global mean surface temperature is $(4\pm 1)^{\circ}\text{C}$, or roughly 7°F . Predicted sea level rise is $\sim 0.7\text{ m}$; however, this estimate does not include possible contributions from melting of the West Antarctic ice sheet and could be too low by a factor of several (private communication, R. Alley). Of the many possible adverse effects of climate warming, sea level rise and increased human heat stress are likely the two most consequential (personal opinion).

In summary, human activities are currently warming the climate, with potential effects that are serious on the 50-100 year time scale and devastating on longer time scales. The largest contributor to global warming, by far, is the burning of fossil fuels. How exactly to deal with this problem is a topic for continued debate. To make progress in this debate, however, we must first acknowledge that the problem itself is real.

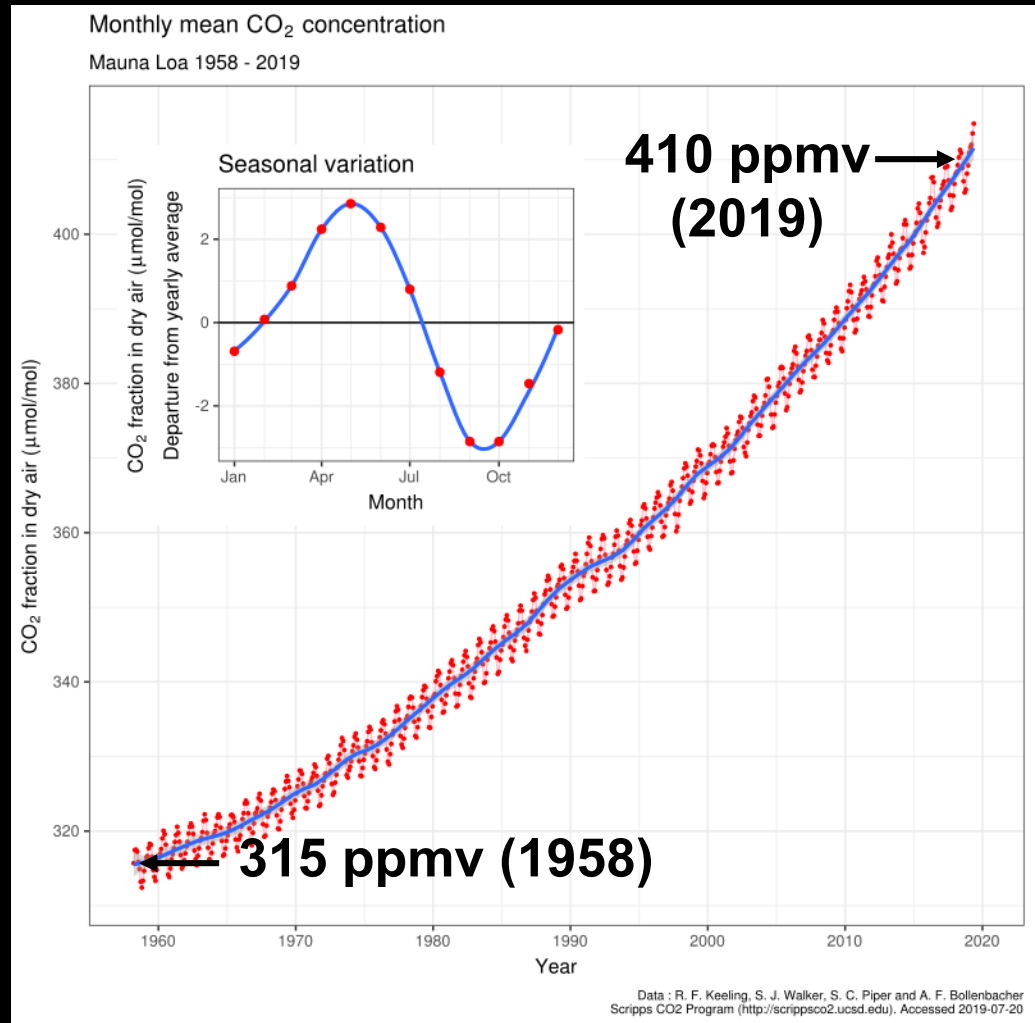
ESAAPG meeting
Columbus, OH
Oct. 15, 2019

The Rock-Solid Evidence for Anthropogenic Global Warming

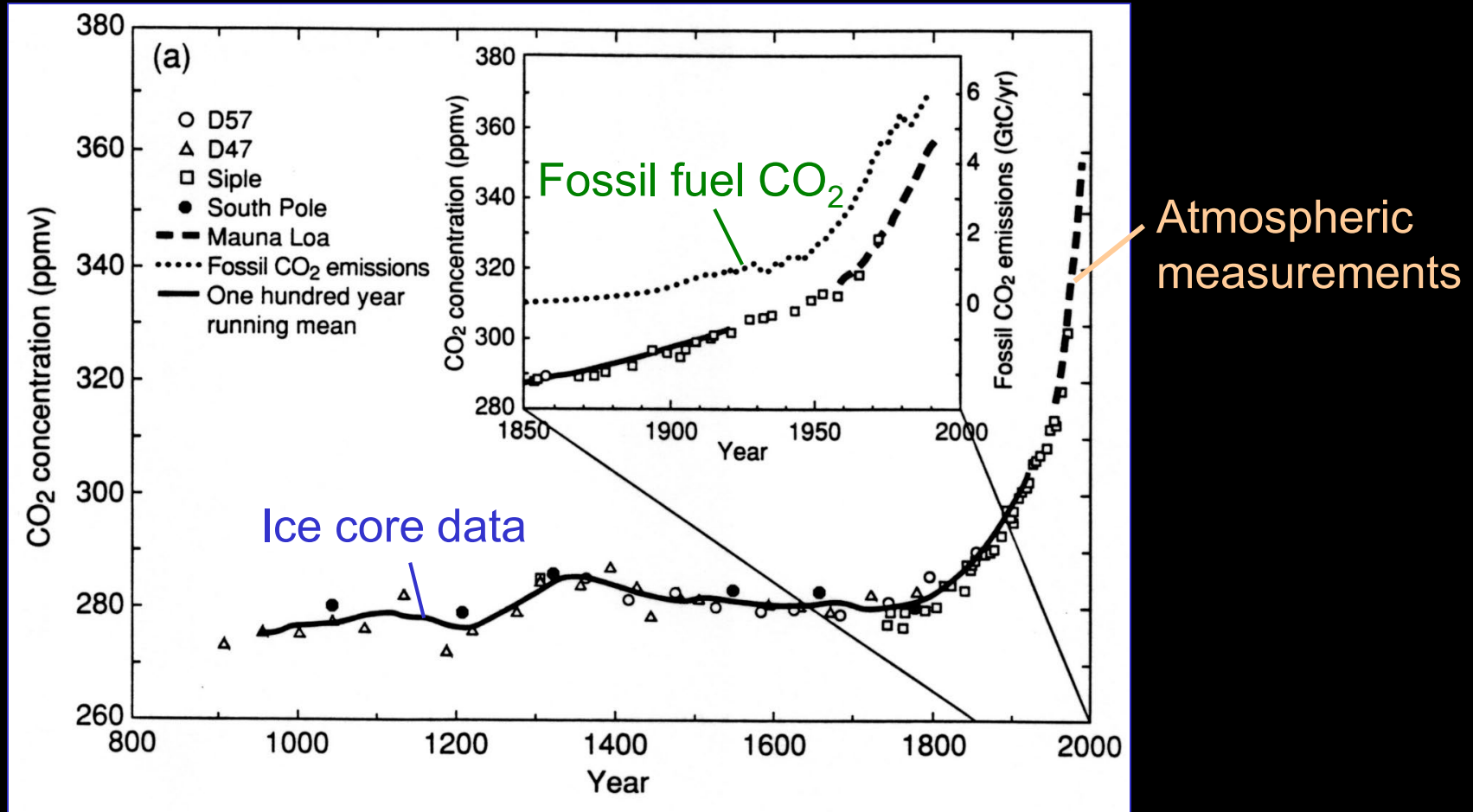
James Kasting
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Penn State University

Atmospheric CO₂ observations from Mauna Loa: The Keeling curve

- CO₂ has been measured monthly on top of Mauna Loa for the past 61 years
- The average rate of change has been **1.6 ppmv/yr**
- The average rate of change over the past 10 years is **2.4 ppmv/yr**, so the rate of CO₂ increase is accelerating with time



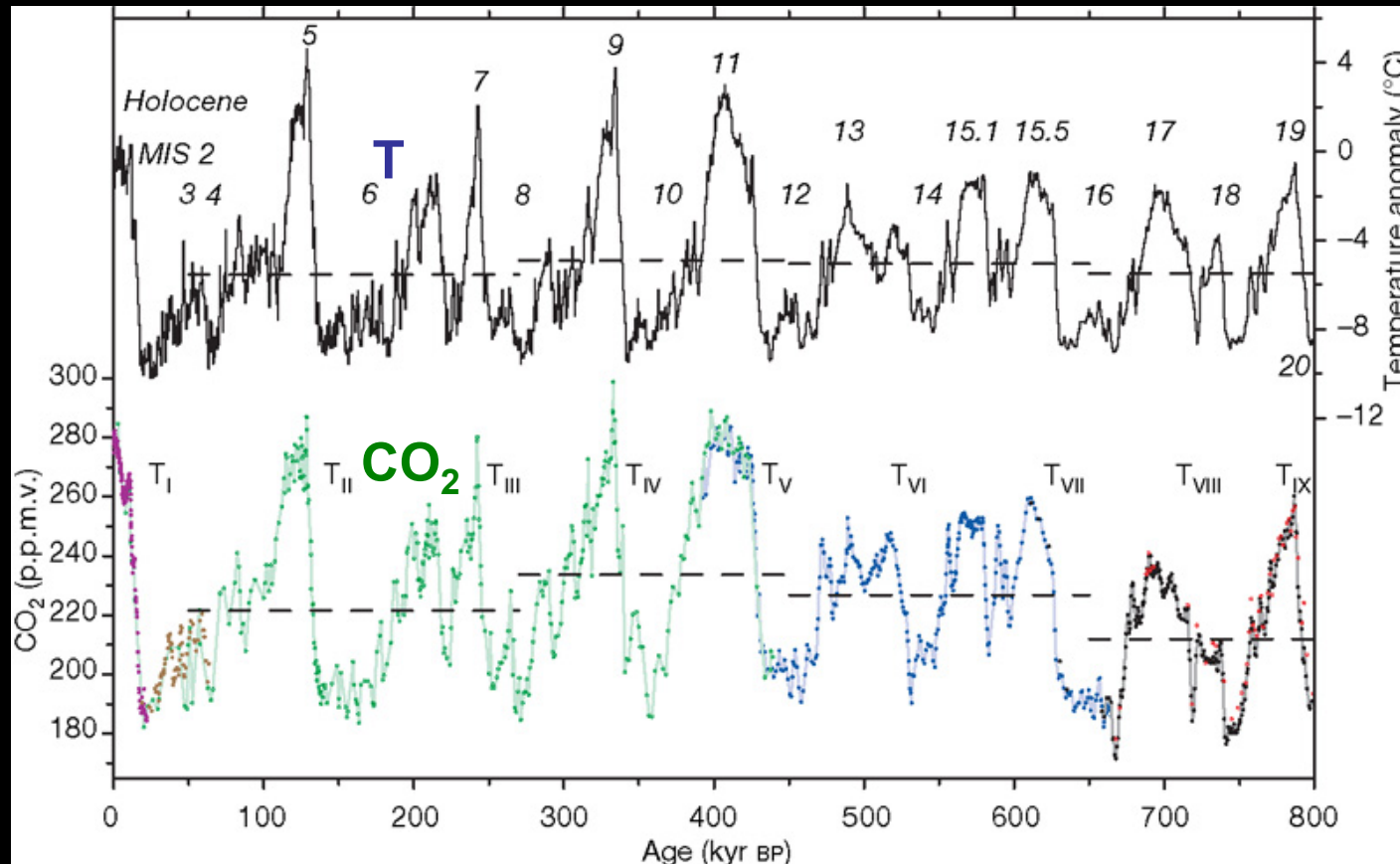
Ice core CO₂/Keeling curve



- 280 ppmv is the preindustrial atmospheric CO₂ level

Source: *Climate Change 1994* (IPCC)

Dome C record--Antarctica

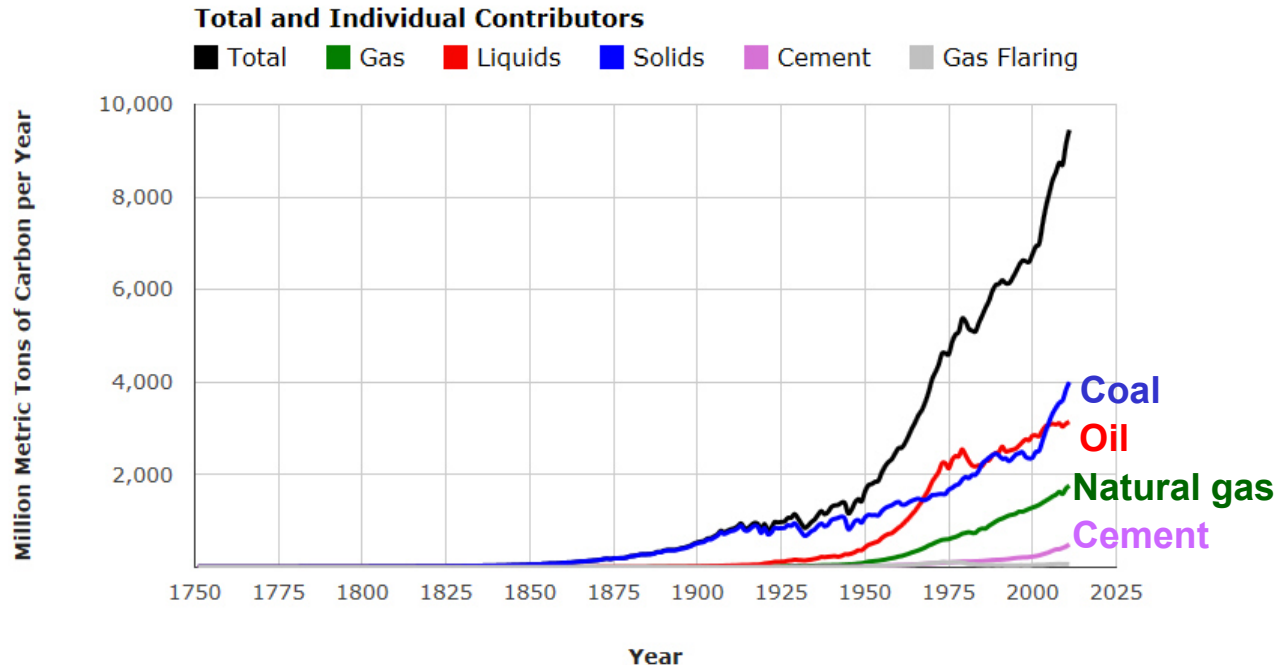


- Atmospheric CO₂ has fluctuated between ~180 ppmv and ~280 ppmv for the last 800,000 years, based on records from polar ice cores

http://www.nature.com/nature/journal/v453/n7193/fig_tab/nature06949_F2.html

- We know very well what is causing the current atmospheric CO₂ increase ⇒

Global CO₂ emissions thru 2014



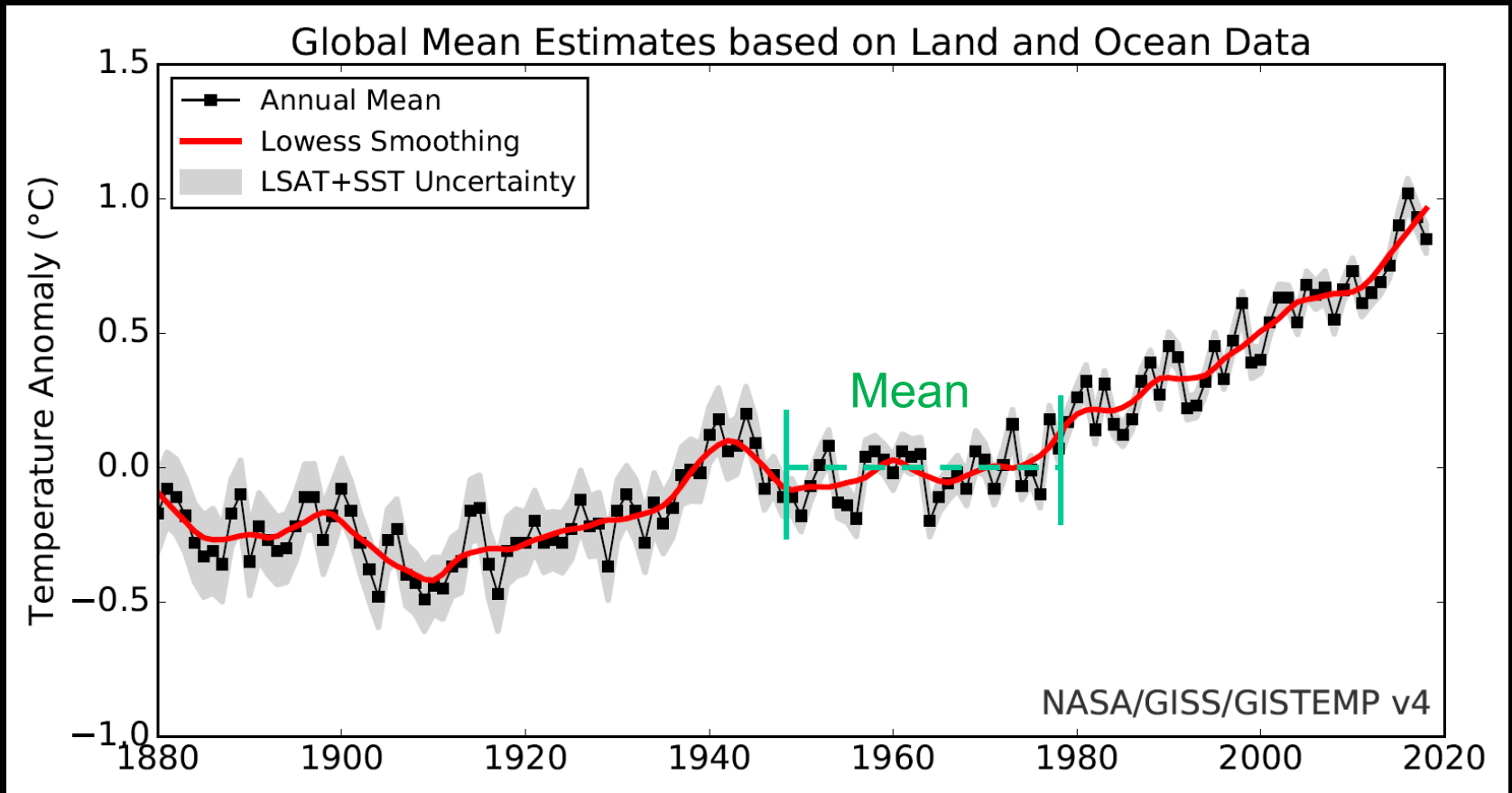
Source: Boden, T.A., G. Marland, and R. J. Andres. 2015. Global, Regional, and National Fossil-Fuel CO₂ Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi: 10.3334/CDIAC/00001_V2015.

- Total anthropogenic CO₂ emissions $\cong 9.9 \text{ Gt(C)/yr}$ in 2014
- By comparison, the volcanic CO₂ flux is $\sim 0.1 \text{ Gt(C)/yr}$
- Photosynthesis (land + ocean) is $\sim 100 \text{ Gt(C)/yr}$, but this flux is mostly balanced by respiration and decay

Source: https://cdiac.ess-dive.lbl.gov/trends/emis/glo_2014.html

- Global surface temperatures have been increasing, as well \Rightarrow

Global surface temperature anomaly

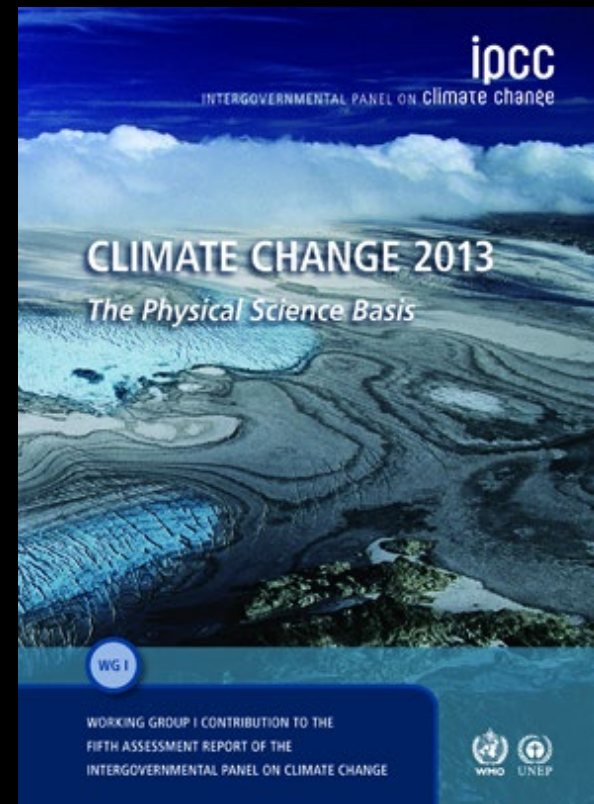


- Zero is the 1951-1980 mean
- Average surface temperatures have risen by $\sim 1^{\circ}\text{C}$ (1.8°F) since that time

Source: NASA GISS

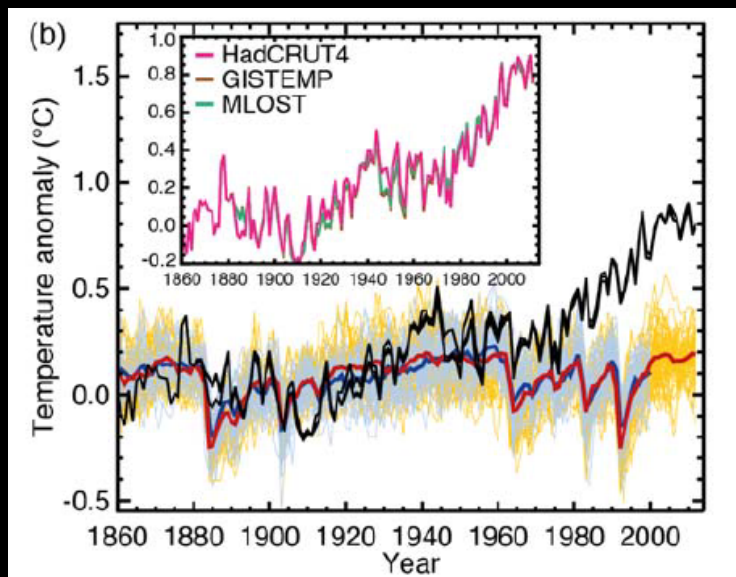
Intergovernmental Panel on Climate Change (IPCC)

- The climate change problem has been studied by researchers from around the world, including the IPCC
- The IPCC issues reports on climate change every 6-7 years
- The 2013 report is the 5th such assessment

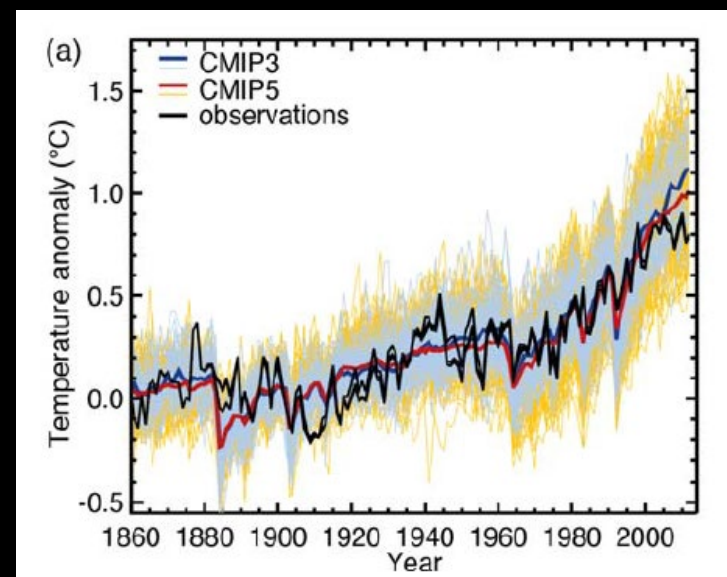


<http://www.ipcc.ch/report/ar5/wg1/>

Climate projections with and without anthropogenic forcing



Without



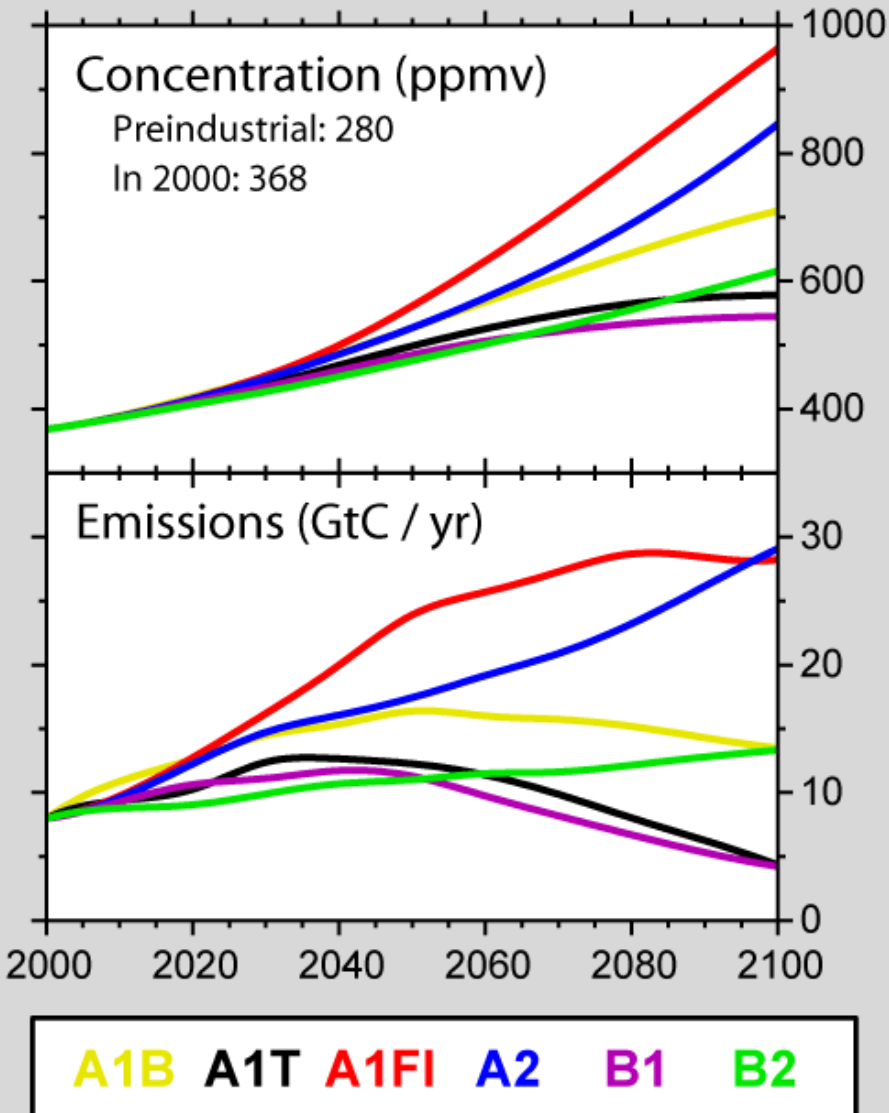
With

This is the key figure from the 2013 IPCC report

Result: Only by including anthropogenic forcing (*i.e.*, greenhouse gas emissions) can the models reproduce the warming observed over the last 50 years

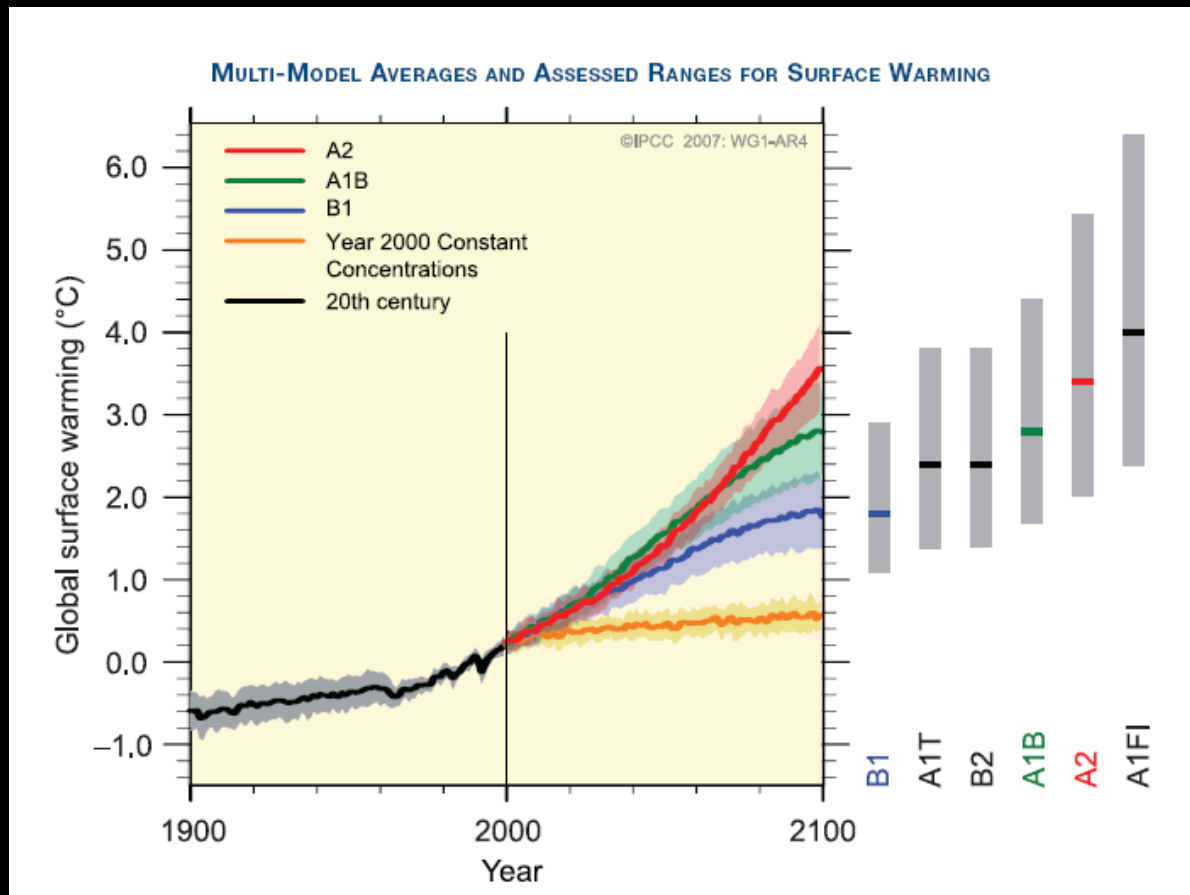
IPCC Emissions Scenarios: Carbon Dioxide

Possible Scenarios for Future Fossil Fuel Use and Resulting Atmospheric CO₂ Levels (2007 IPCC Report)



- The future is hard to predict, but we can examine the effects of different CO₂ emission scenarios

Predicted surface temperature change over the next century



Global mean surface temperature is predicted to increase by $\sim 3.6^{\circ}\text{C}$ (6.5°F) by 2100 in the 'business as usual' A2 scenario

Possible adverse effects of global warming

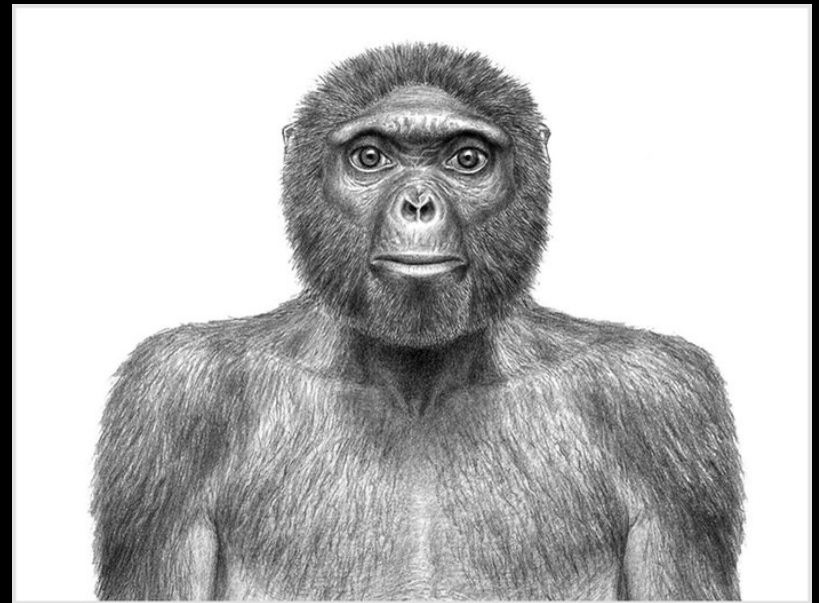
- Global warming could have many possible adverse consequences. I will mention just two:
 1. Sea level rise
 2. Human heat stress

Possible adverse effects of global warming

- Global warming could have many possible adverse consequences. I will mention just two and focus on just one:
 1. Sea level rise
 2. Human heat stress

Heat stress and human evolution

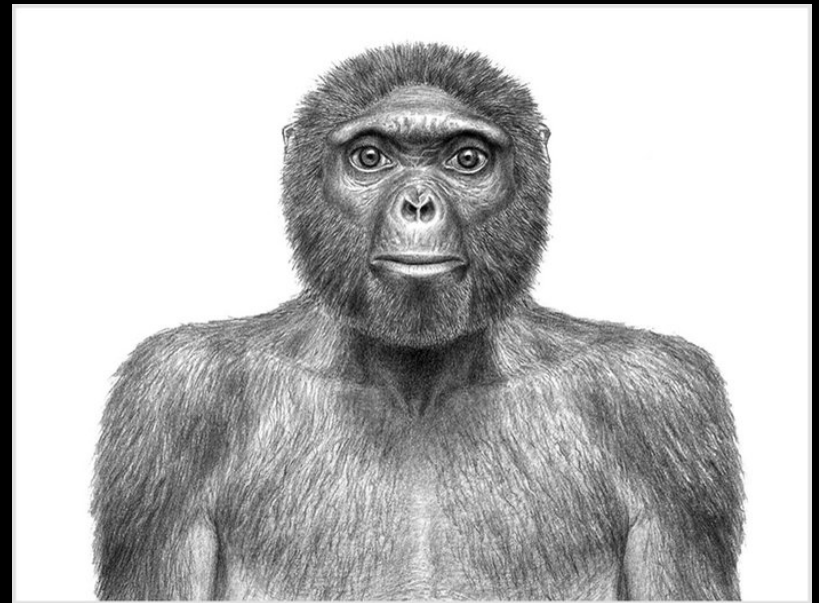
- Humans evolved over the last 2 m.y. from hairy, ape-like ancestors
 - According to Nina Jablonski, we lost our hair at least partly because we became more active (hunting hooved animals) and needed to cool ourselves



<http://www.npr.org/2009/10/01/113387960/move-over-lucy-ardi-may-be-oldest-human-ancestor>

Heat stress and human evolution

- Humans evolved over the last 2 m.y. from hairy, ape-like ancestors
 - We had evolved during the Ice Ages to have as low an internal body temperature as possible, so that we would not waste metabolic energy
 - This positioned us close to our heat stress limit



<http://www.npr.org/2009/10/01/113387960/move-over-lucy-ardi-may-be-oldest-human-ancestor>

An adaptability limit to climate change due to heat stress

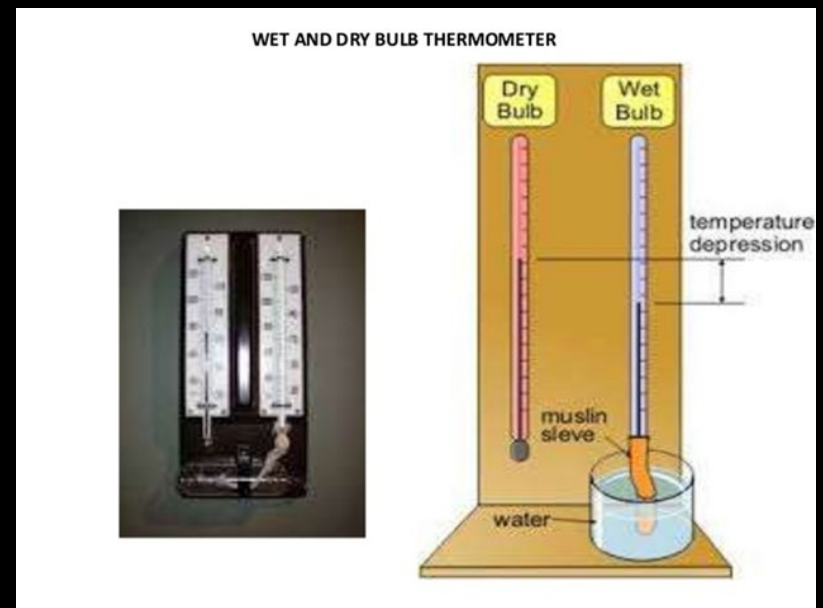
Steven C. Sherwood^{a,1} and Matthew Huber^b

Proc. Nat. Acad. Sci. (2010)

- Humans (and many other mammals) are fairly close to their upper limits on temperature in parts of the world today
 - Human body temperature: 37°C (98.6°F)
 - Required skin temperature: $\leq 35^{\circ}\text{C}$
- If the *wet bulb* temperature is $>35^{\circ}\text{C}$, you can't lose heat by sweating and evaporation

Different measurements of temperature

- **Dry bulb** temperature—the temperature measured by a standard thermometer
- **Dewpoint**—the temperature at which water vapor condenses when an air parcel is cooled
- **Wet bulb** temperature—the temperature that a thermometer registers when enclosed in a wet sleeve, or sock



Future temperature in southwest Asia projected to exceed a threshold for human adaptability

Jeremy S. Pal^{1,2} and Elfatih A. B. Eltahir^{2*}

Nature Geoscience, 2016

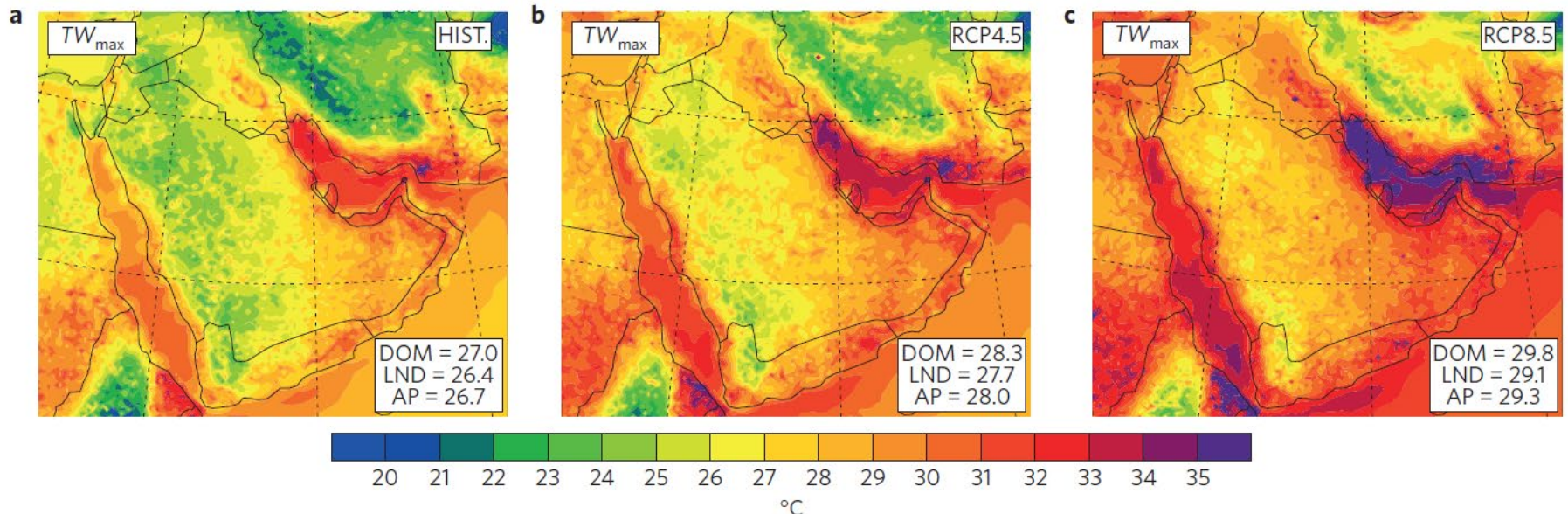
Maximum wet bulb temperatures:

2070 - 2100

Today

Medium emissions

High emissions

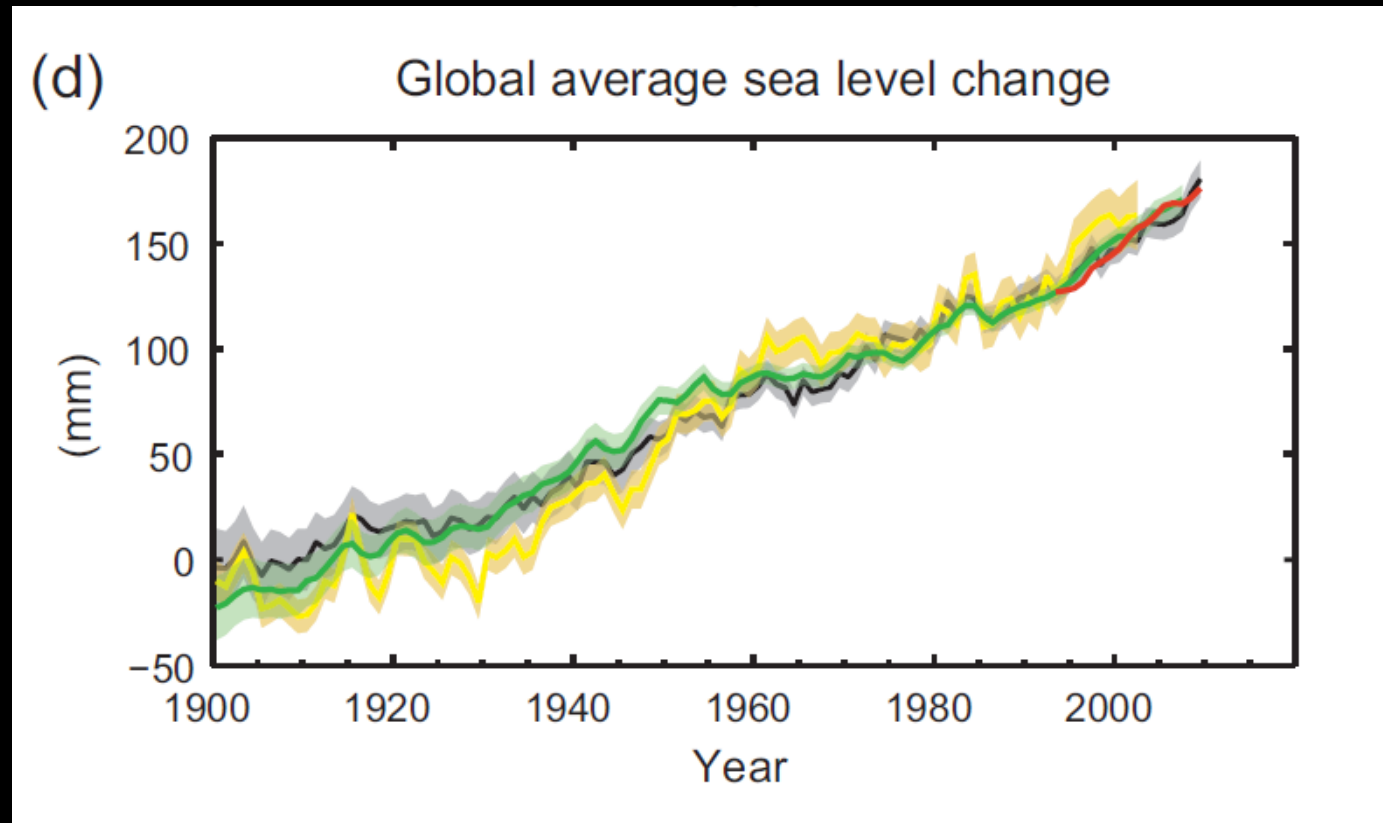


Conclusions

1. Atmospheric CO₂ is increasing rapidly
2. Global surface temperatures are increasing, as well, in agreement with model predictions. The effects of this increase on humans are potentially costly and dangerous
3. Consequently, we should quit arguing about the basic science of global warming, which is mostly settled, and focus our attention on how best to deal with it

- Backup slides

Historical sea level change

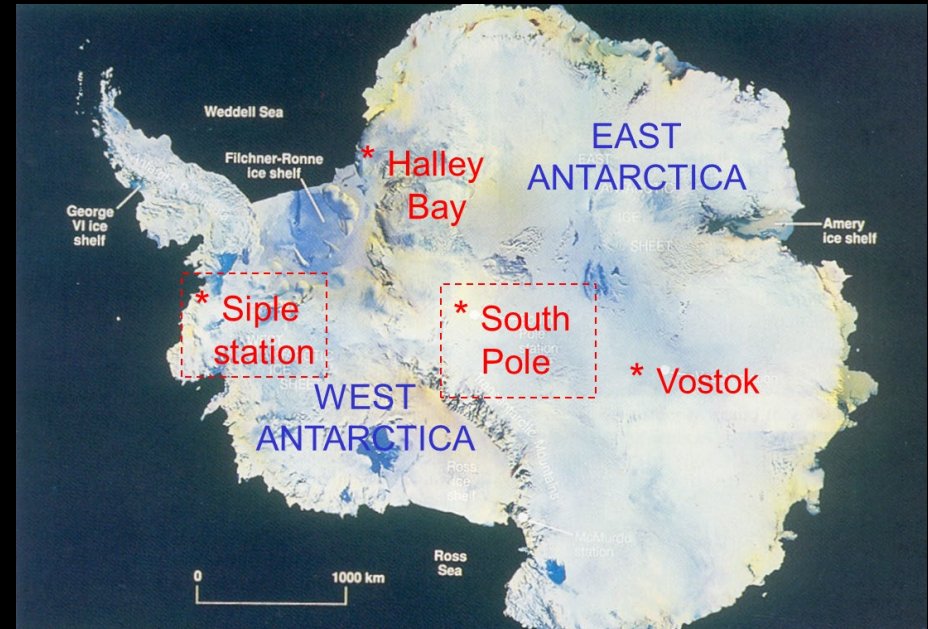


- Sea level has increased by about 20 cm over the past 120 years
- Most of this increase has been caused by thermal expansion of the surface ocean and melting of mountain glaciers

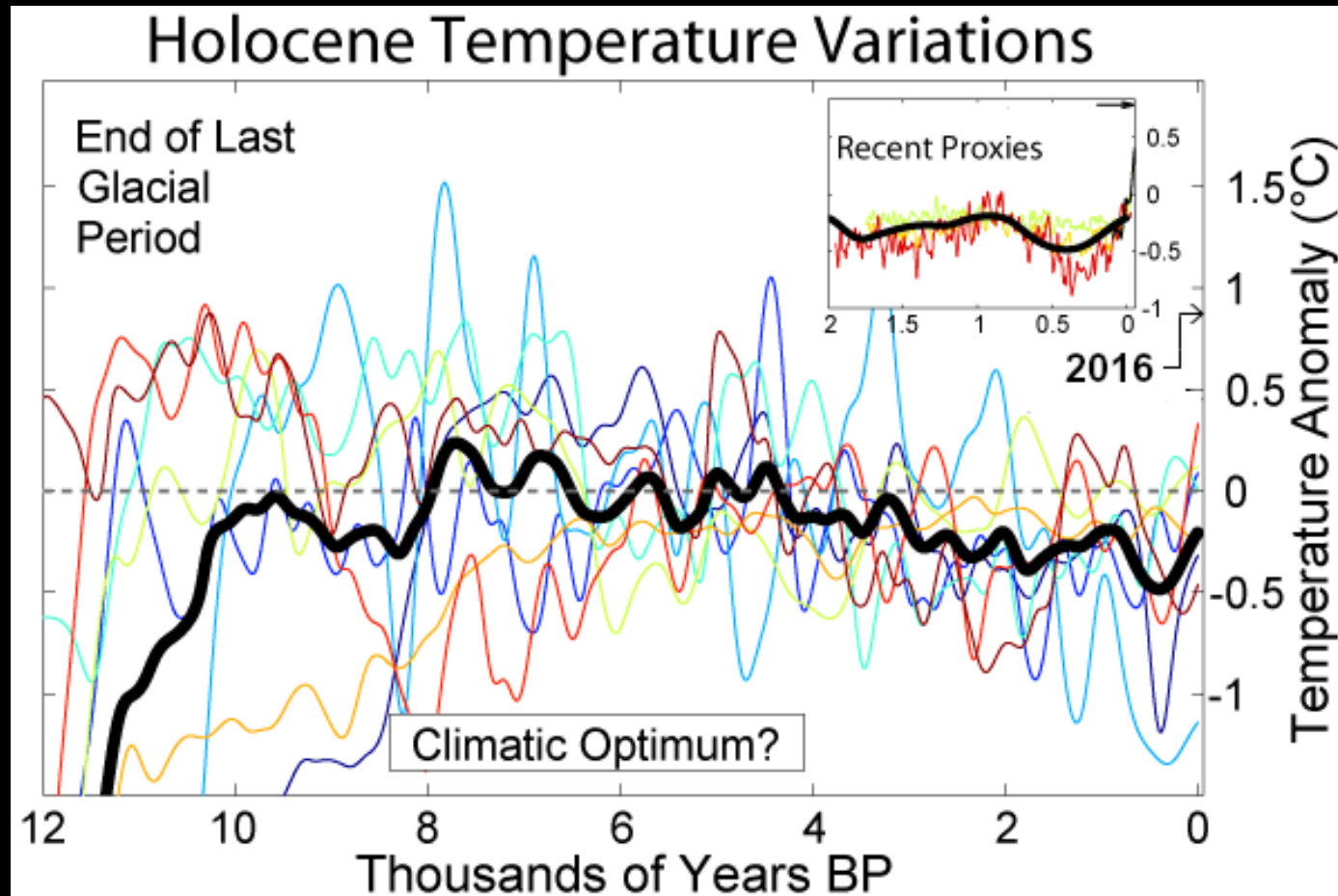
Source: 2013 IPCC report

Future sea level increases

- But sea level could increase by much more than this (several meters?) over the next century from melting of the polar ice caps
 - West Antarctica contains 6-7 m of equivalent sea level (as ice)
 - Greenland contains another 6 m
 - East Antarctica contains 60 m but is unlikely to melt anytime soon



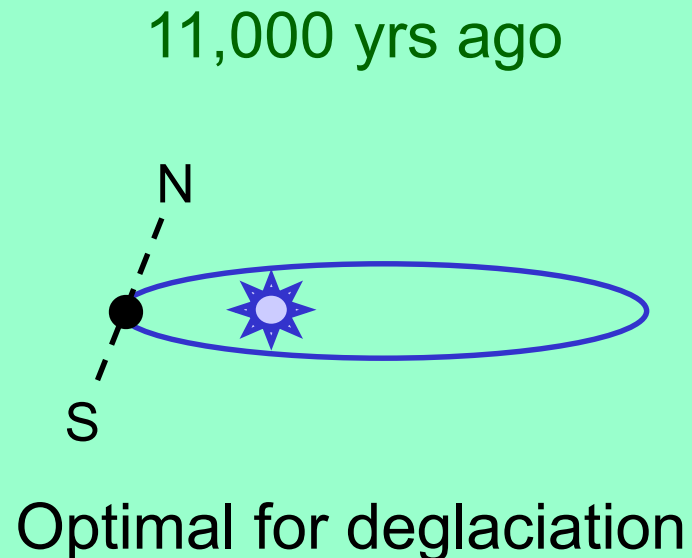
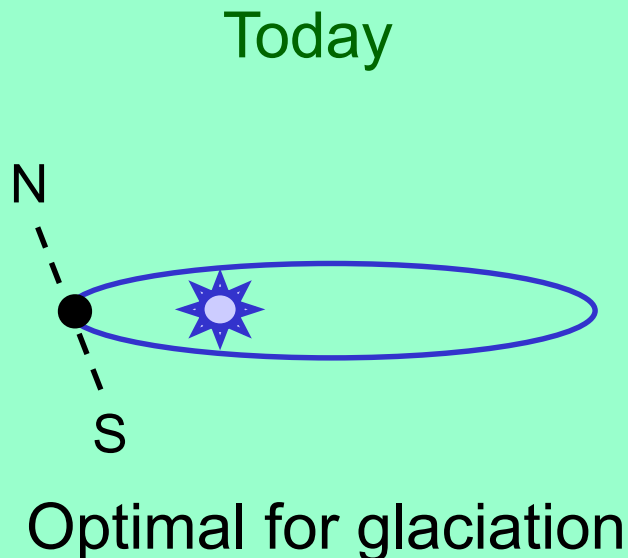
Holocene mean surface temperatures

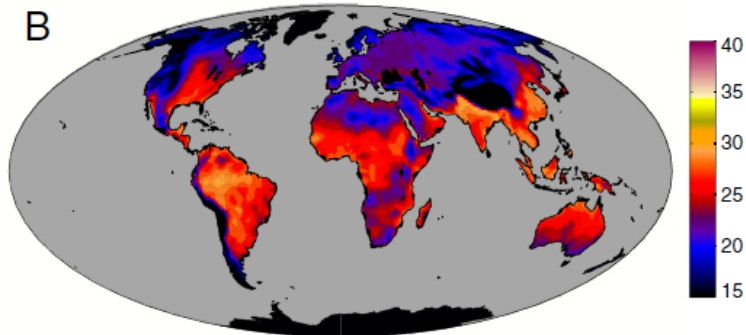
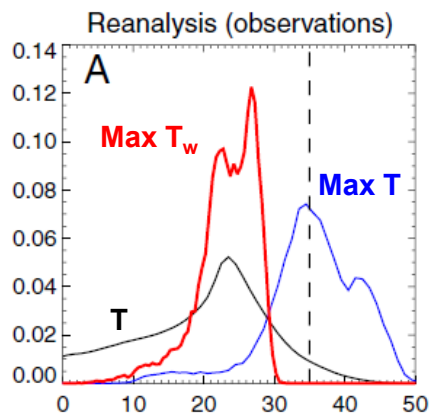


https://en.wikipedia.org/wiki/Holocene_climatic_optimum

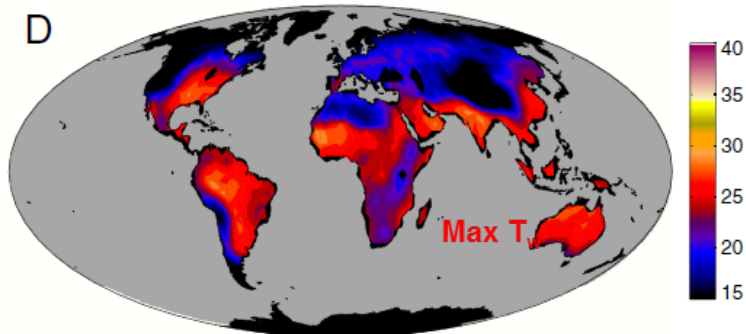
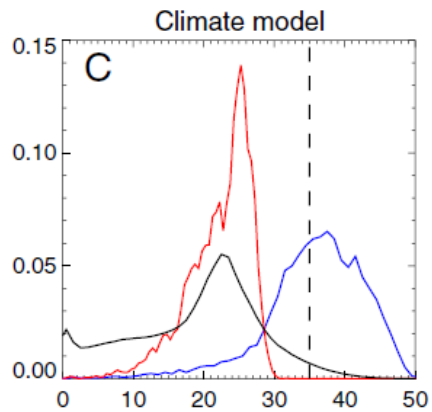
Optimal Conditions for Deglaciation:

1. High obliquity (high seasonal contrast)
2. High eccentricity and **NH summers during perihelion** (hot summers in the north)

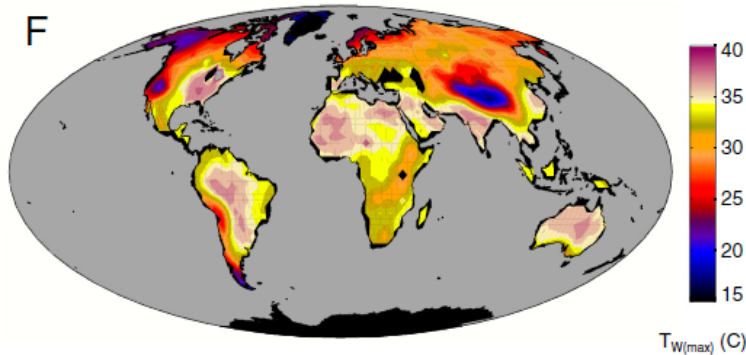
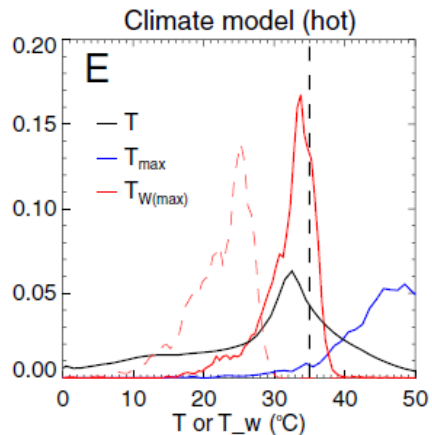




← Measurements today



← Climate model today



← Climate model for 10°C global warming