The Physics of Climate and Climate Change

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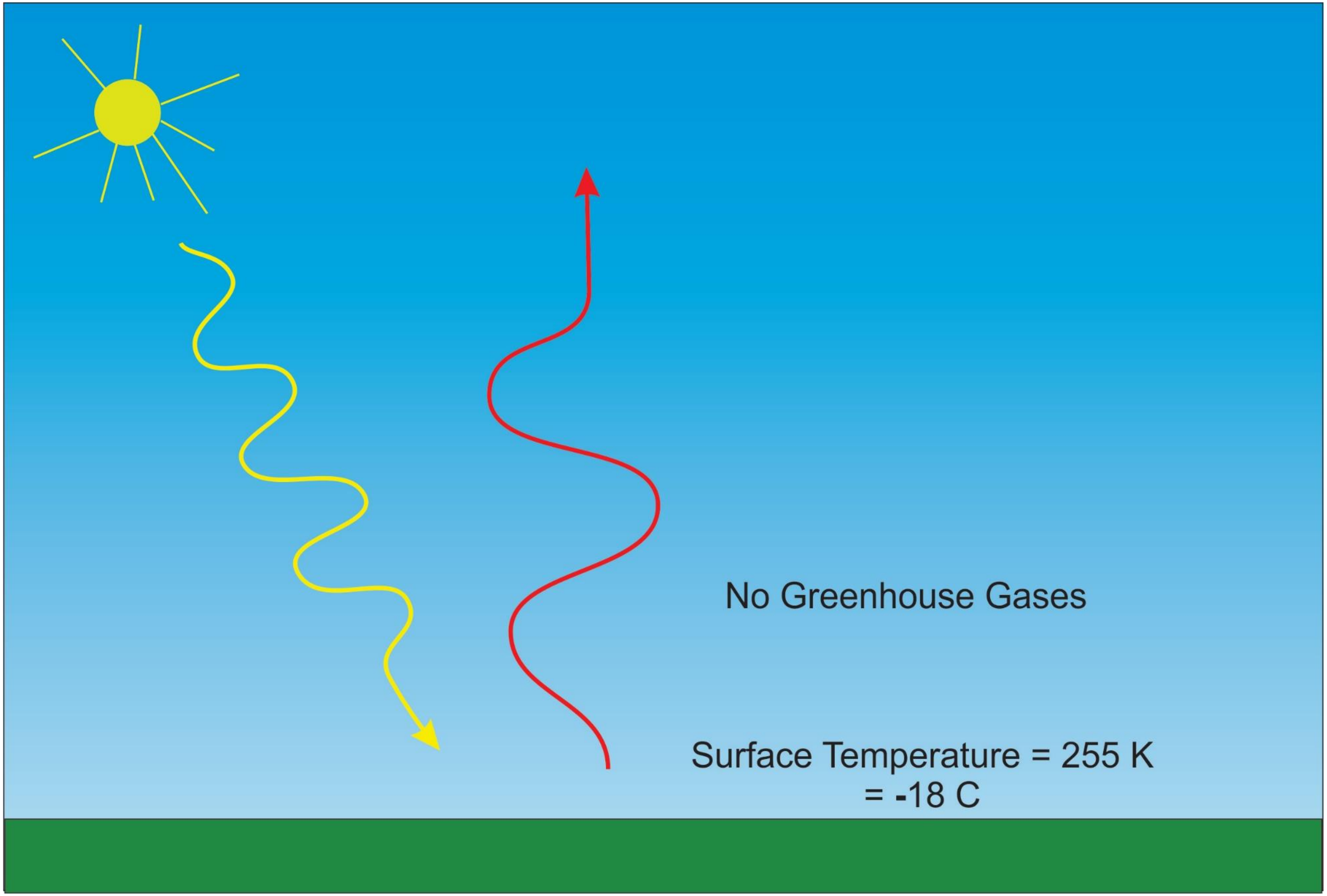
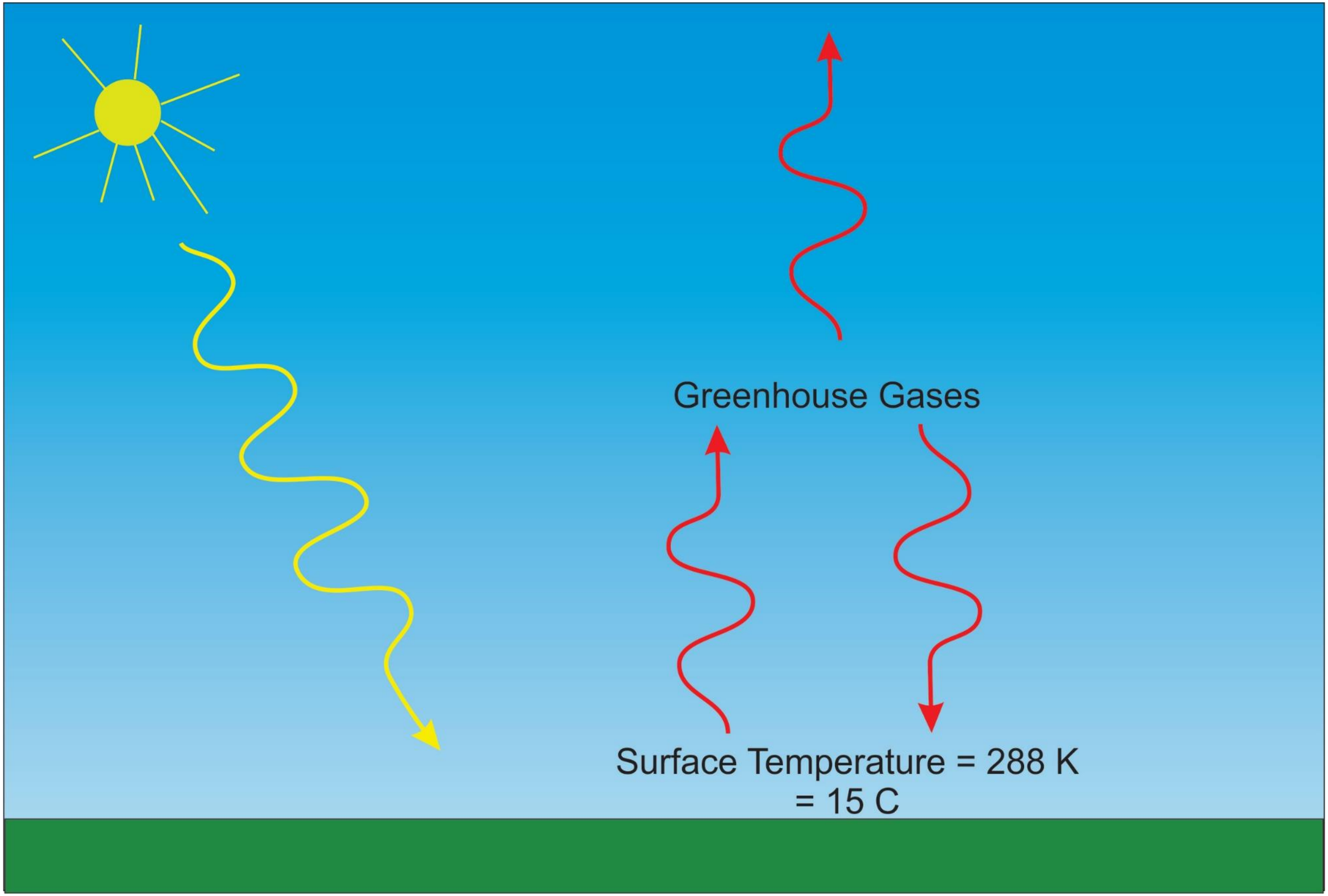
Important Points about Climate and Climate Science

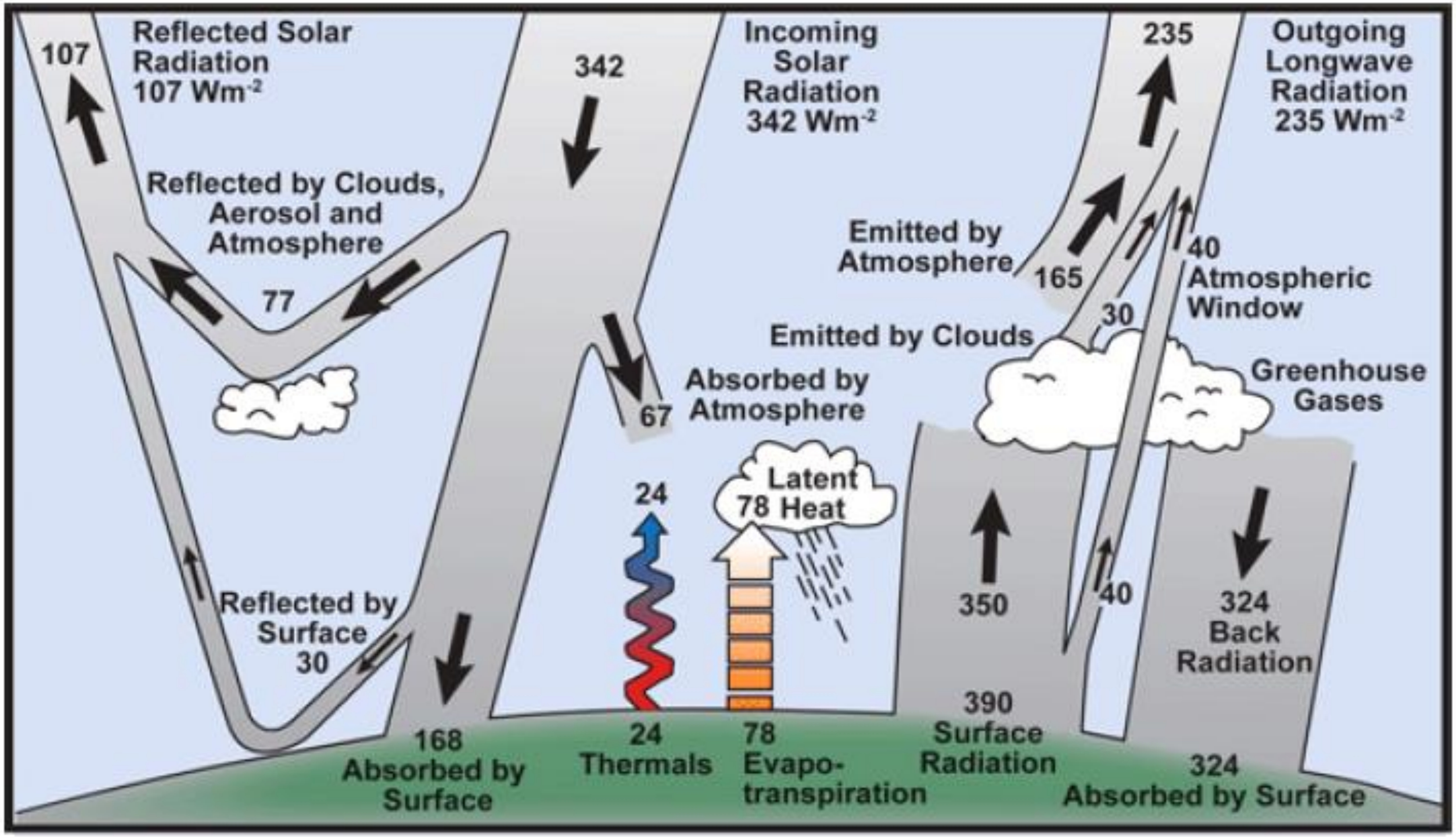
- Earth's climate is stable within certain limits, but sensitive to change in forcing within those limits.
- Climate science has a long and illustrious history
- The idea that we are altering climate is based on simple physics, simple models, and complex models
- Human activities can and do have a strong effect on climate

A Little Physics

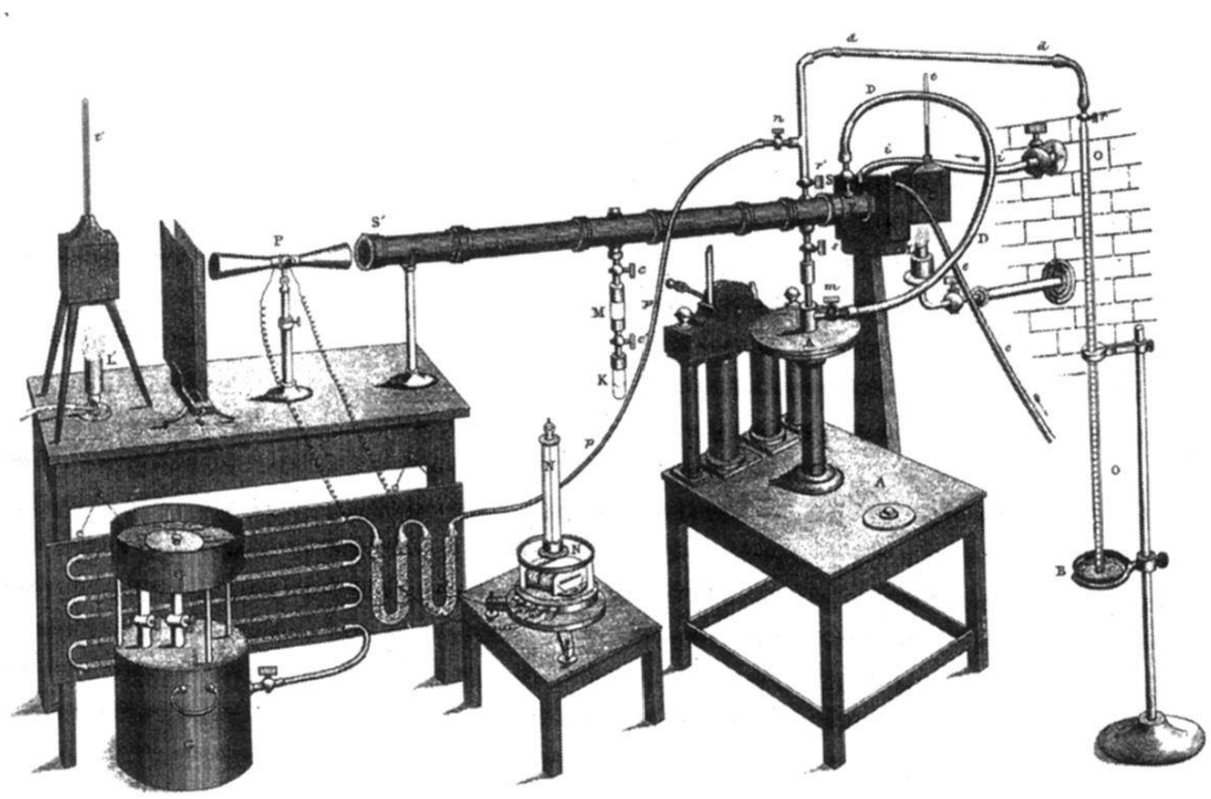

No Greenhouse Gases
Surface Temperature = 255 K
= -18 C


Greenhouse Gases
Surface Temperature = 288 K
= 15 C

Actual Energy Budget



Surface Absorbs Twice as much Radiation from the Atmosphere as Directly from the Sun

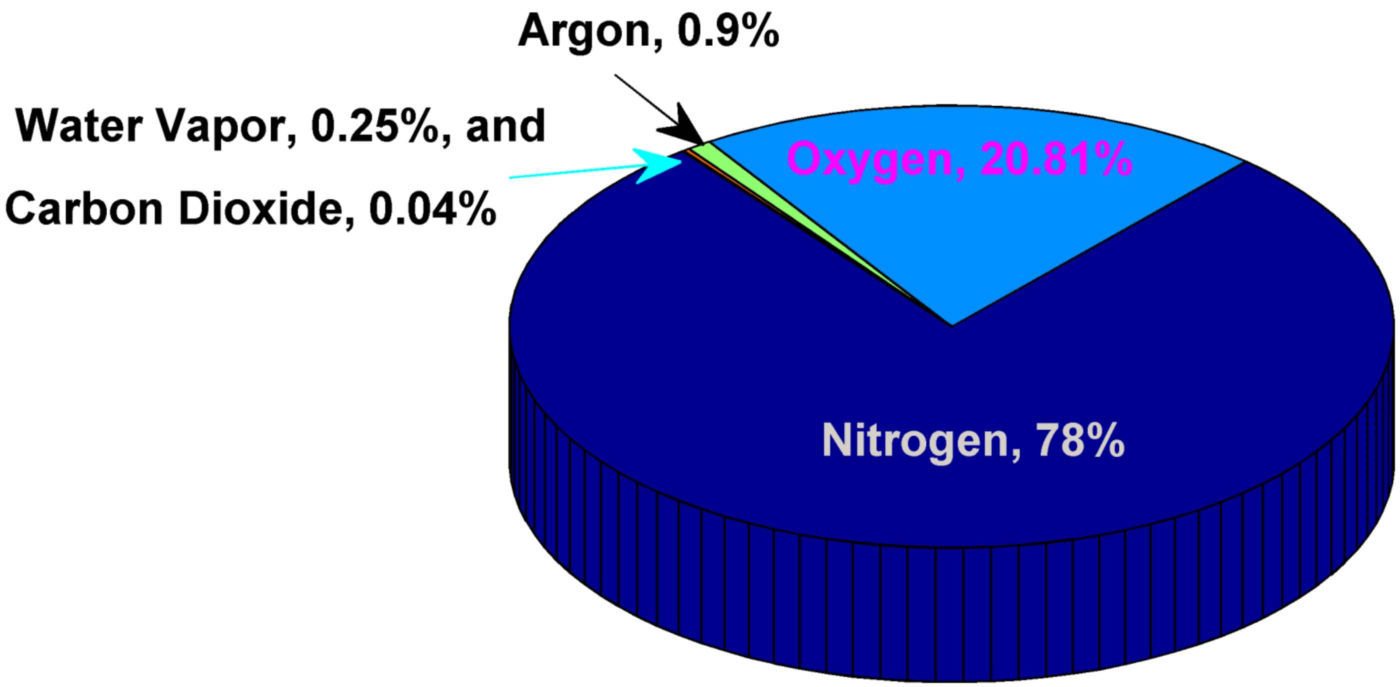


John Tyndall
(1820-1893)

Principal Atmospheric Absorbers

- H_2O: Bent triatomic, with permanent dipole moment and pure rotational bands as well as rotation-vibration transitions
- O_3: Like water, but also involved in photodissociation
- CO_2: No permanent dipole moment, so no pure rotational transitions, but temporary dipole during vibrational transitions
- Other gases: N_2O, CH_4

Atmospheric Composition



The orange sliver makes the difference between a mean surface temperature of 0^{o}F and of 60^{o}F.

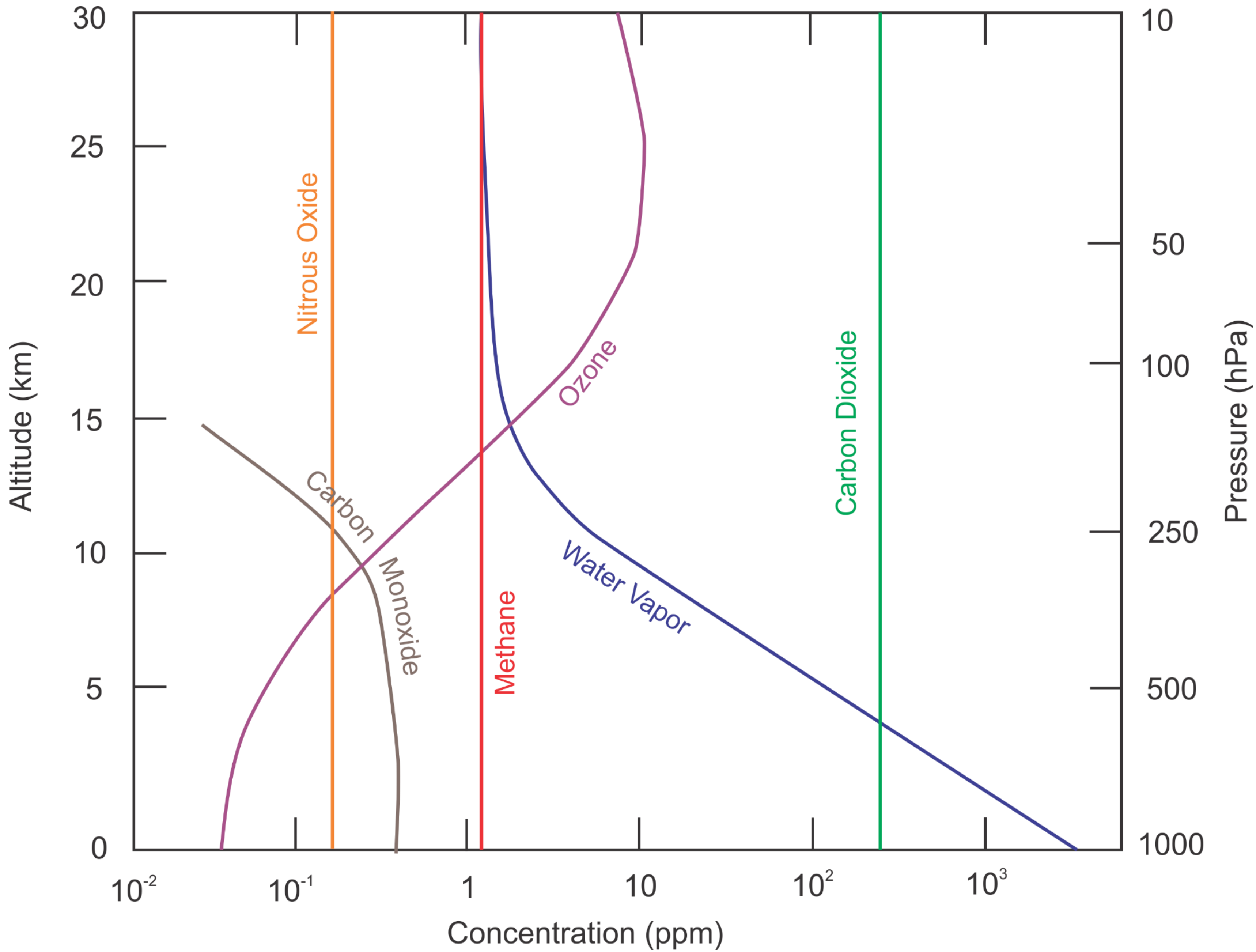
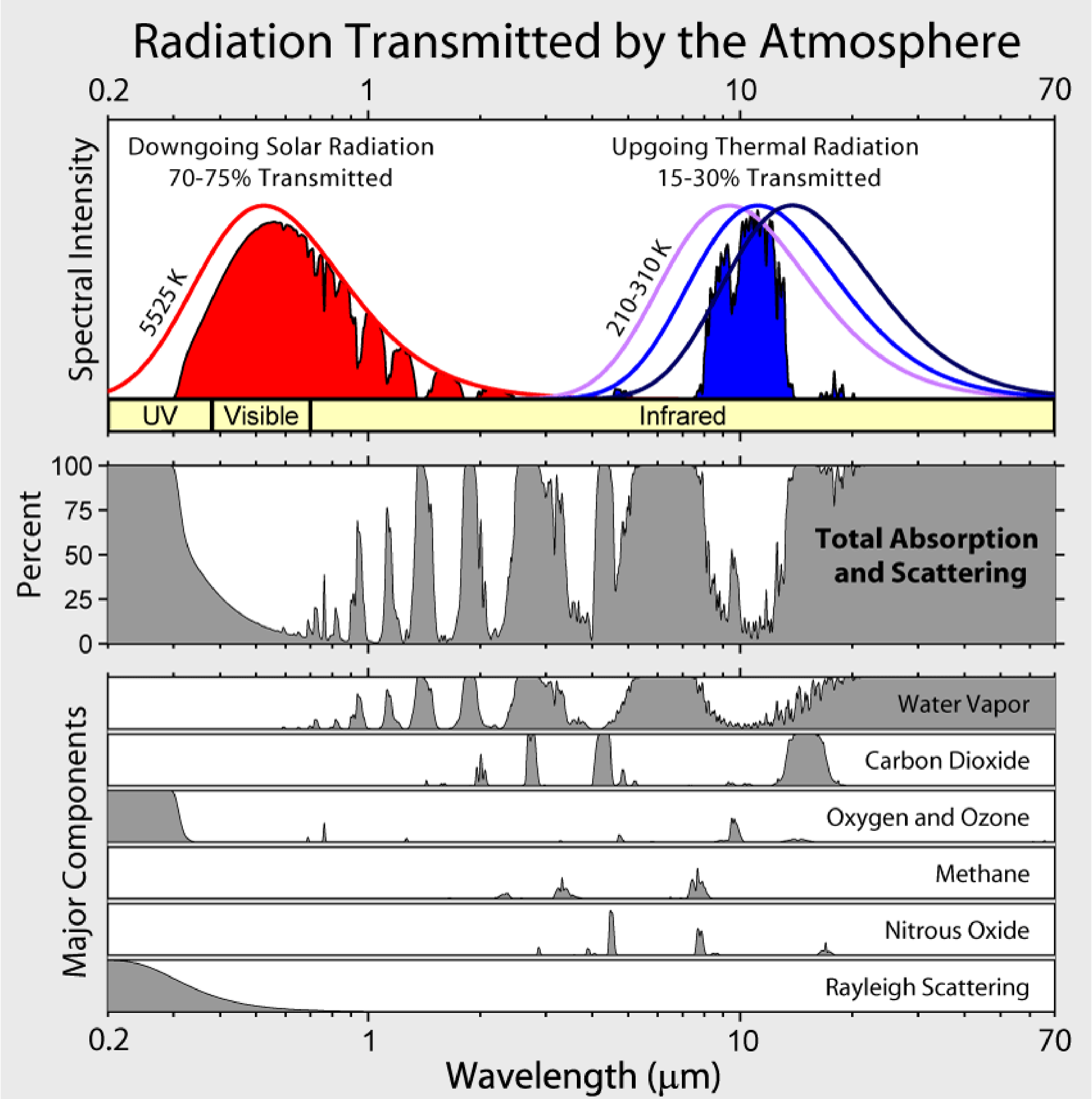


Image credit: *Kerry Emanuel*



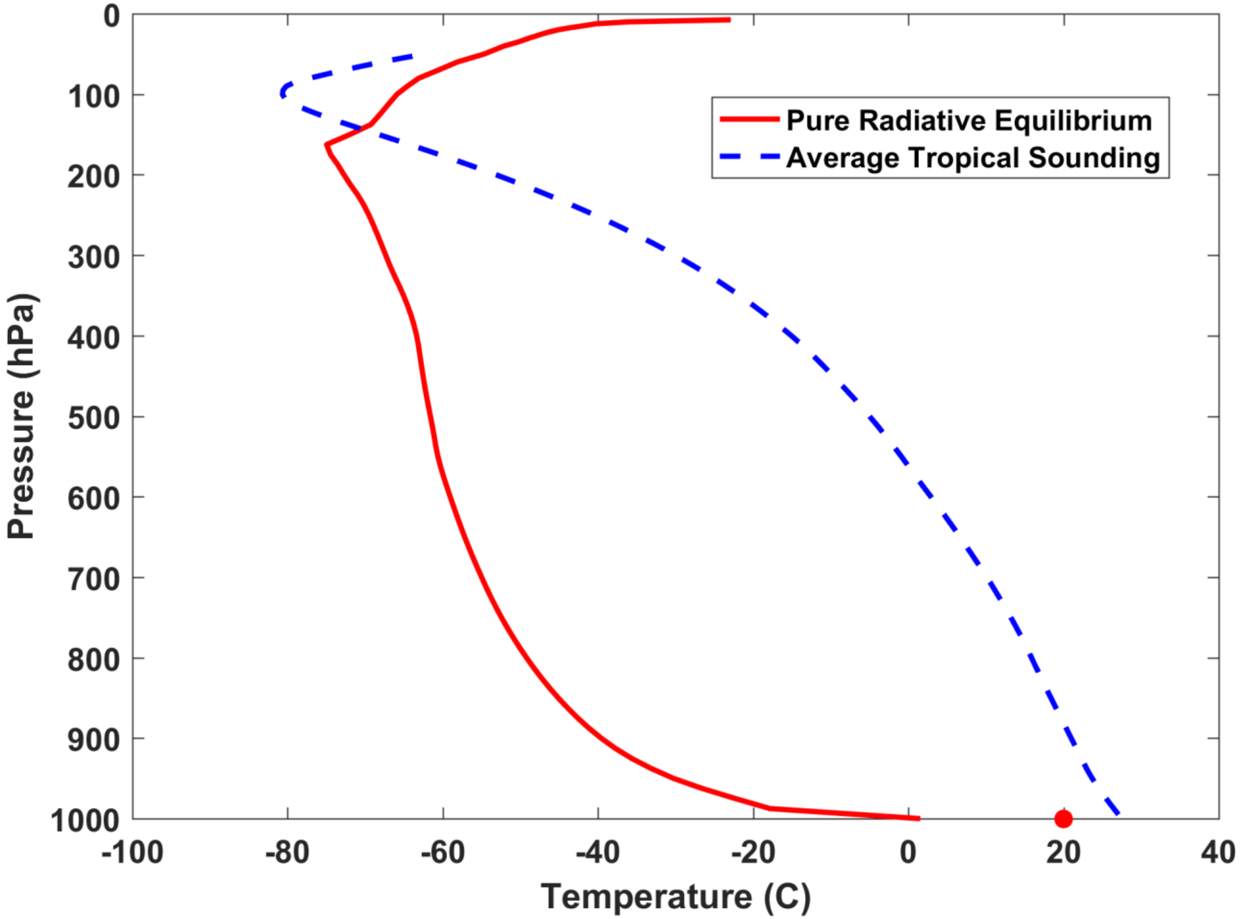
Radiation Transmitted by the Atmosphere
0.2
1
10
70
Downgoing Solar Radiation
70-75% Transmitted
Upgoing Thermal Radiation
15-30% Transmitted
5525 K
210-310 K
Spectral Intensity
UV
Visible
Infrared
100
75
50
25
0
Percent
Total Absorption and Scattering
Major Components
Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering
Wavelength (μm)

Radiative Equilibrium

- Equilibrium state of atmosphere and surface in the absence of non-radiative enthalpy fluxes

- Radiative heating drives actual state toward state of radiative equilibrium

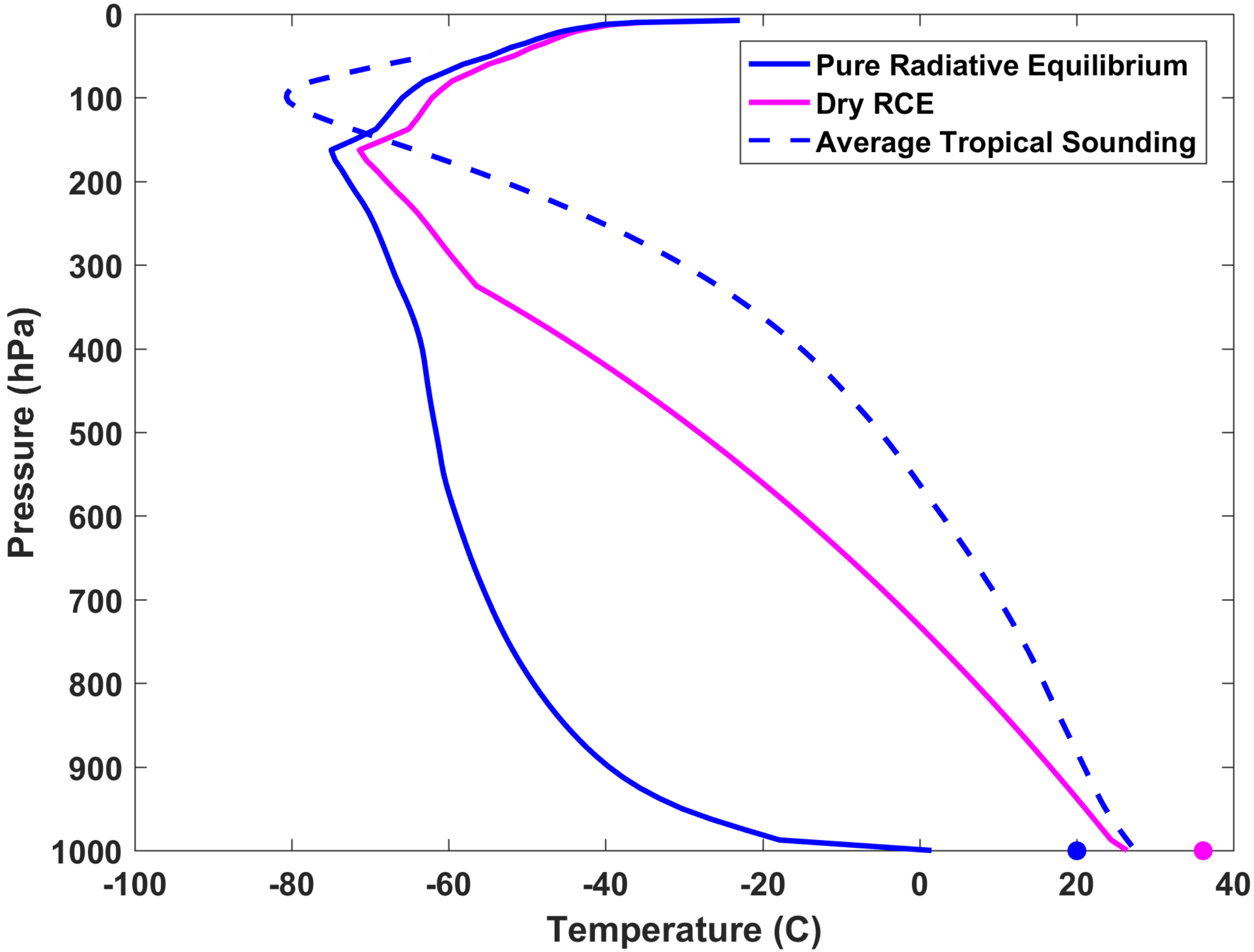
Full calculation of radiative equilibrium:
(no non-radiative fluxes, *fixed relative humidity*)



Radiative-Convective Equilibrium

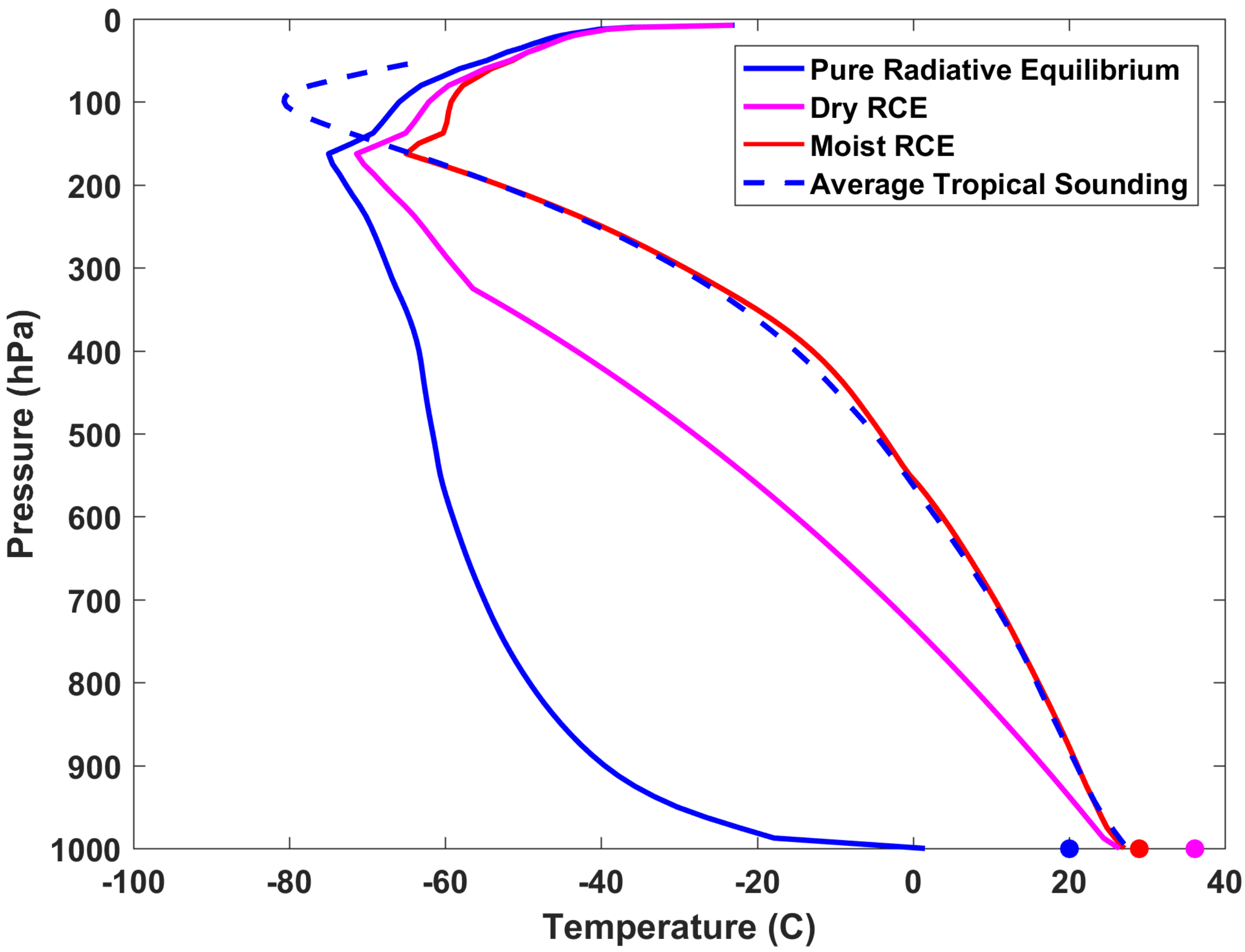
- Radiative equilibrium is unstable to convection
- Atmospheric convection involves phase change of water.. Latent heating (non-dimensionally) large
- Convection is a fast process compared to radiation
- Convection lofts water from its surface source

Full calculation of radiative-dry convective equilibrium
(Surface dry turbulent enthalpy flux, fixed relative humidity)



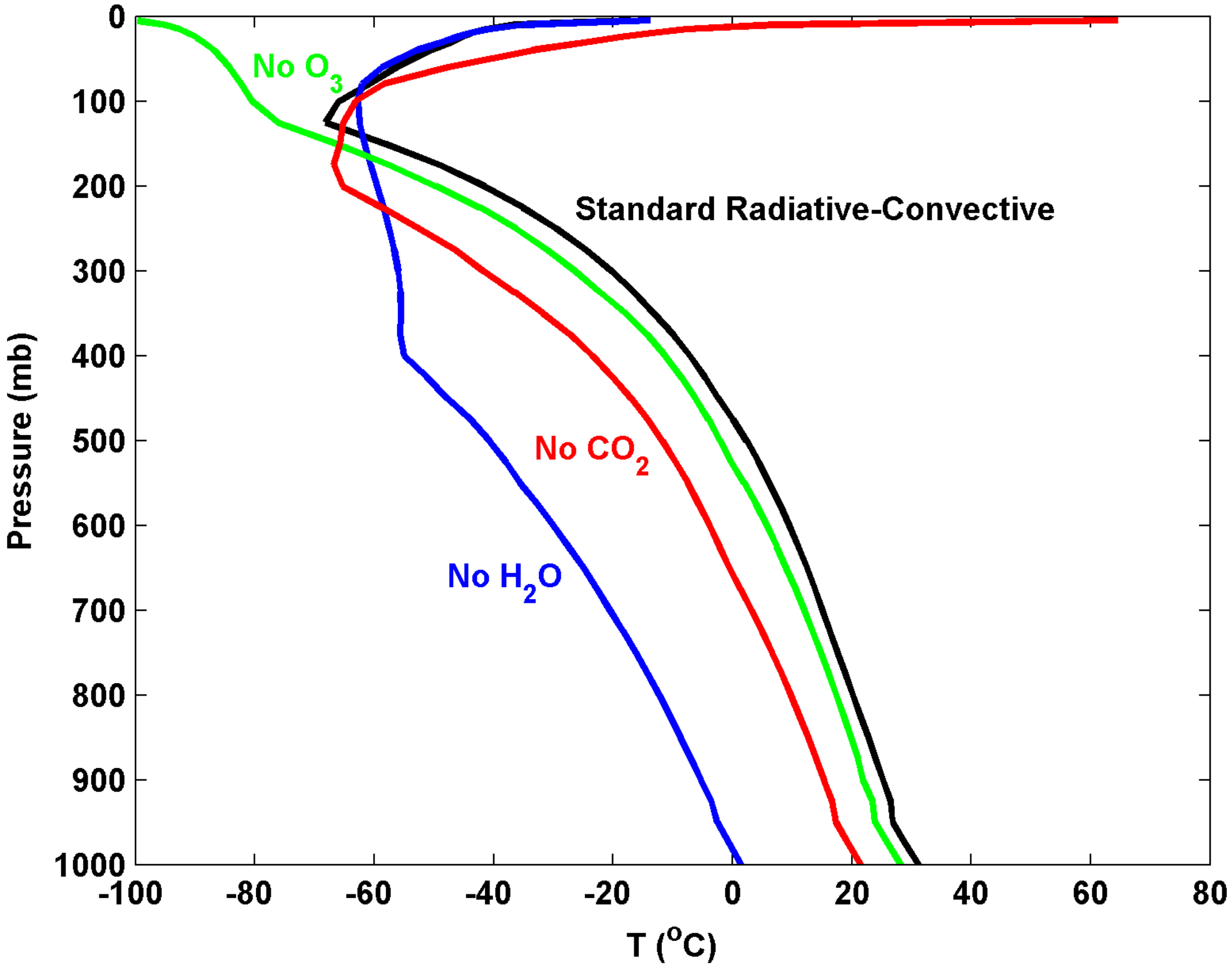
Above a thin boundary layer, convection involves phase change

Spectrum of tropical cumulus clouds photographed from the International Space Station



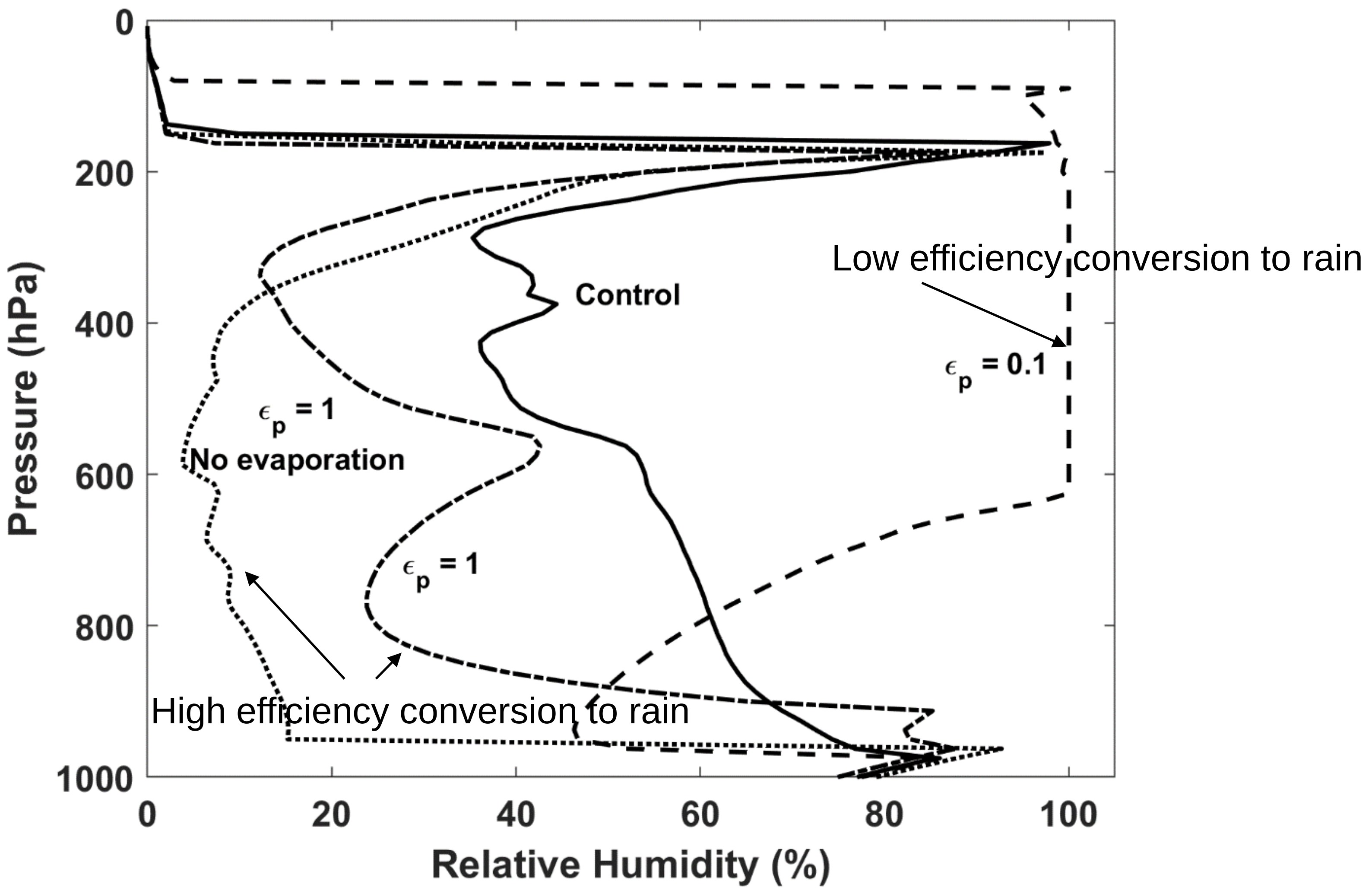
Pure Radiative Equilibrium
Dry RCE
Moist RCE
Average Tropical Sounding
Pressure (hPa)
0
100
200
300
400
500
600
700
800
900
1000
-100
-80
-60
-40
-20
0
20
40
Temperature (C)

Contributions of various absorbers

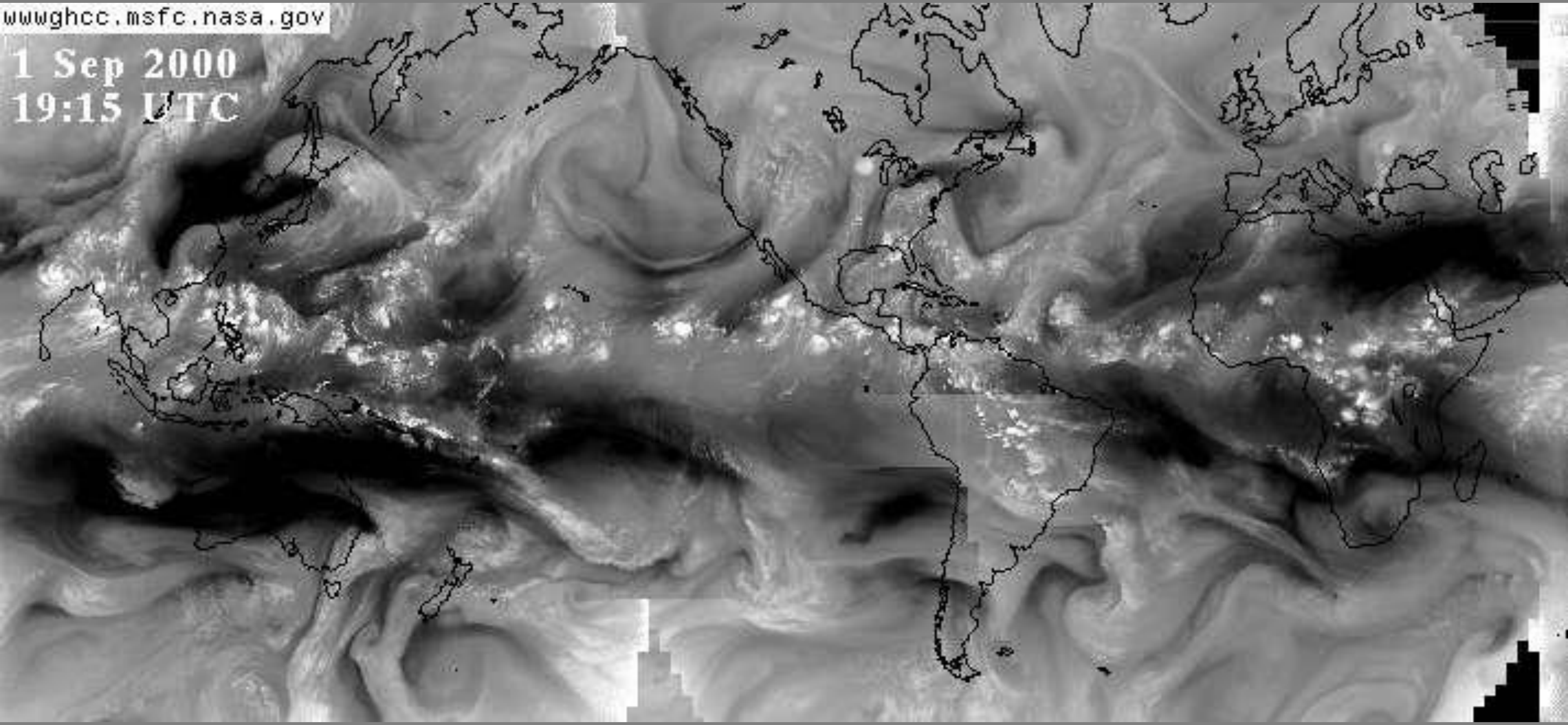


Note: All simulations have variable clouds interacting with radiation

Dependence of Humidity on Cloud Microphysics (Fixed SST experiments)



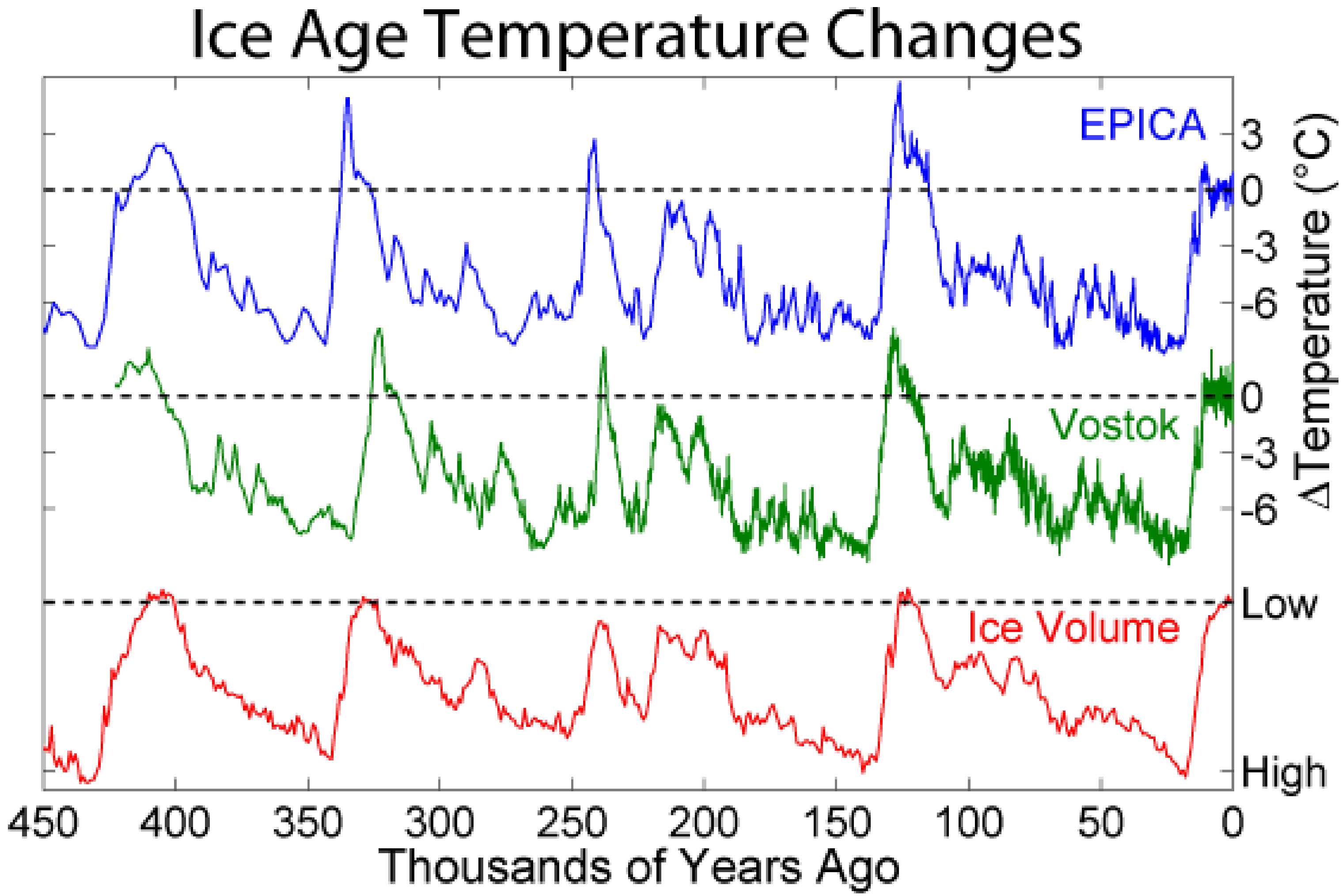
Space-time distributions of the most important greenhouse gas and clouds are extremely inhomogeneous



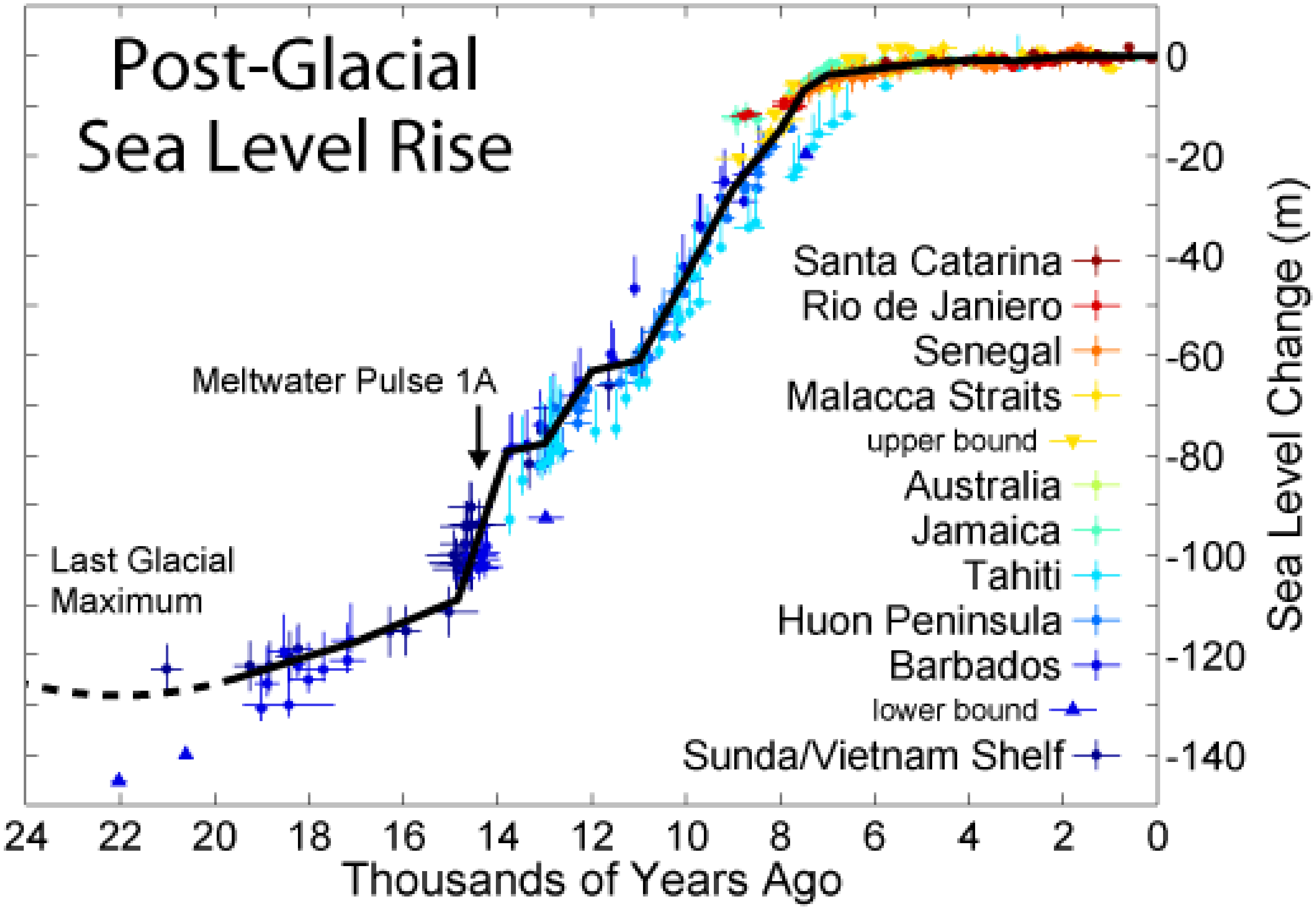
Water in all three of its phases is the greatest source of uncertainty in understanding and modeling climate

What we have learned from paleoclimatology

Last 450 Thousand Years

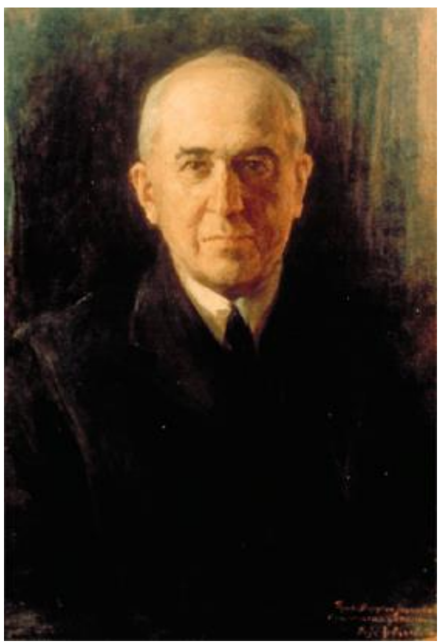


~ 20,000 years before present

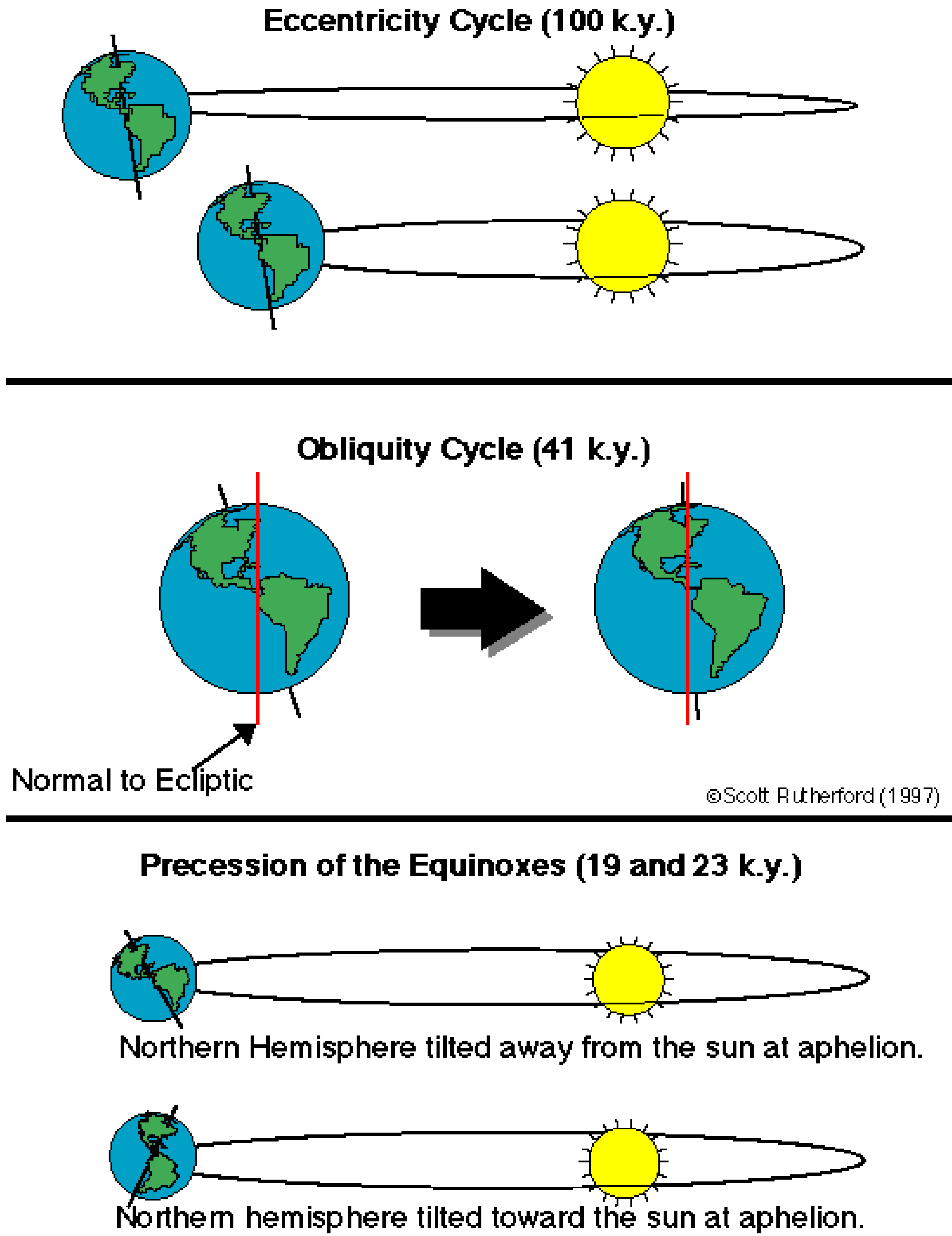


- Polar radiative forcing: 10 W/m^2 (4 W/m^2 for 2 x CO_2)
- Global mean temperature fluctuation: ~5 C

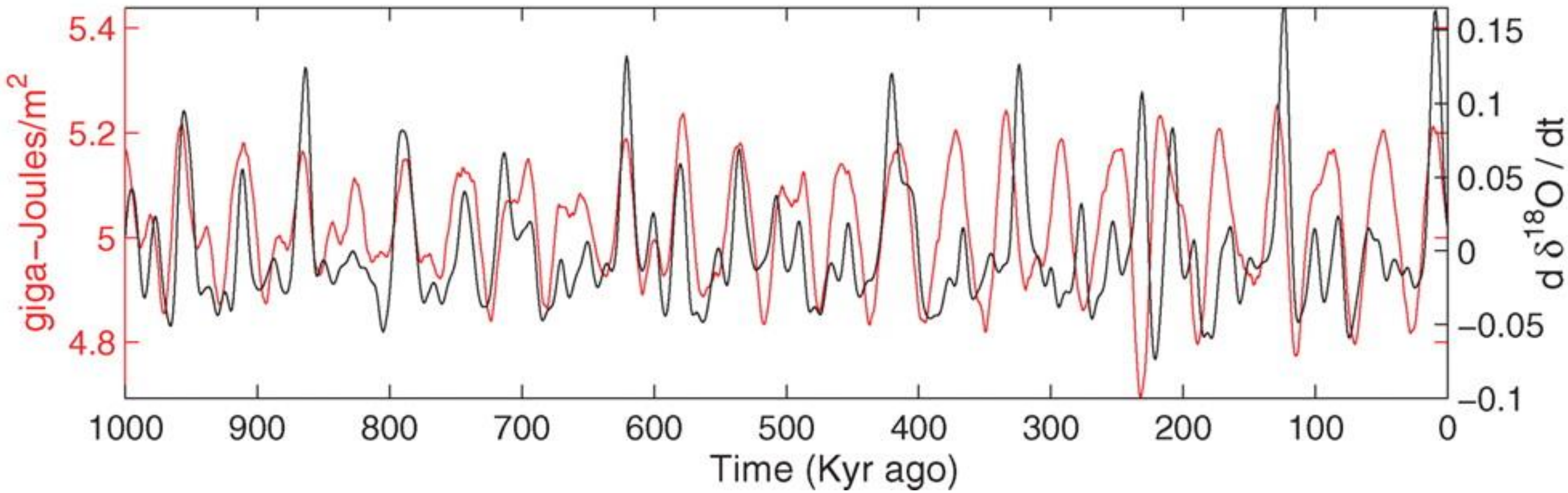
Climate Forcing by Orbital Variations (1912)



Milutin Milanković, 1879-1958



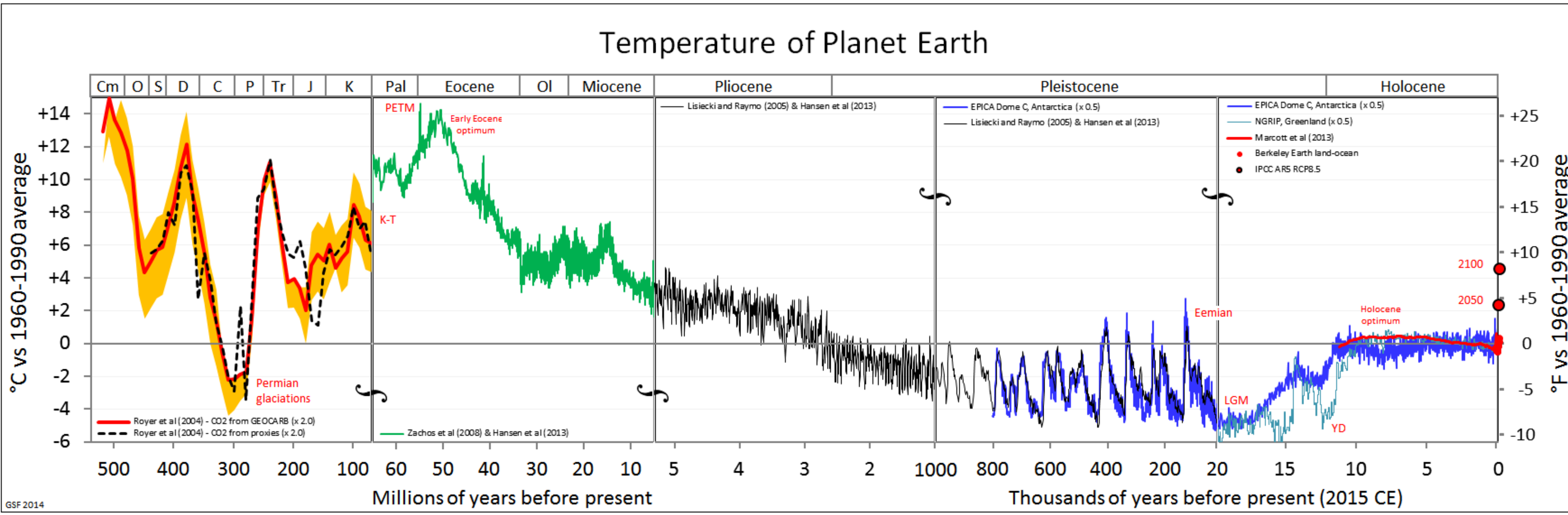
Strong Correlation between High Latitude Summer Insolation and Ice Volume

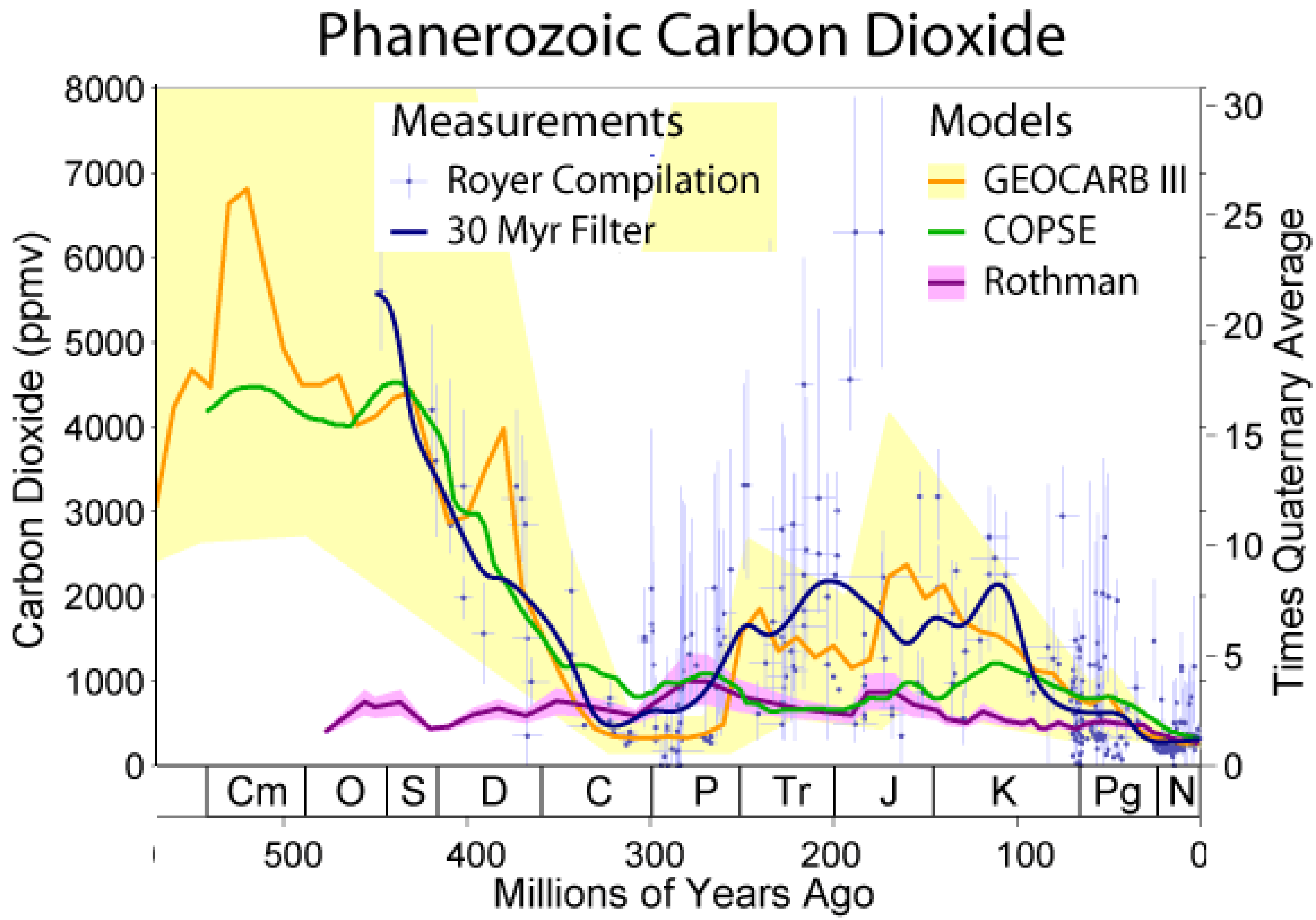


Black: Time rate of change of ice volume

Red: Summer high latitude sunlight

P. Huybers, *Science*, 2006

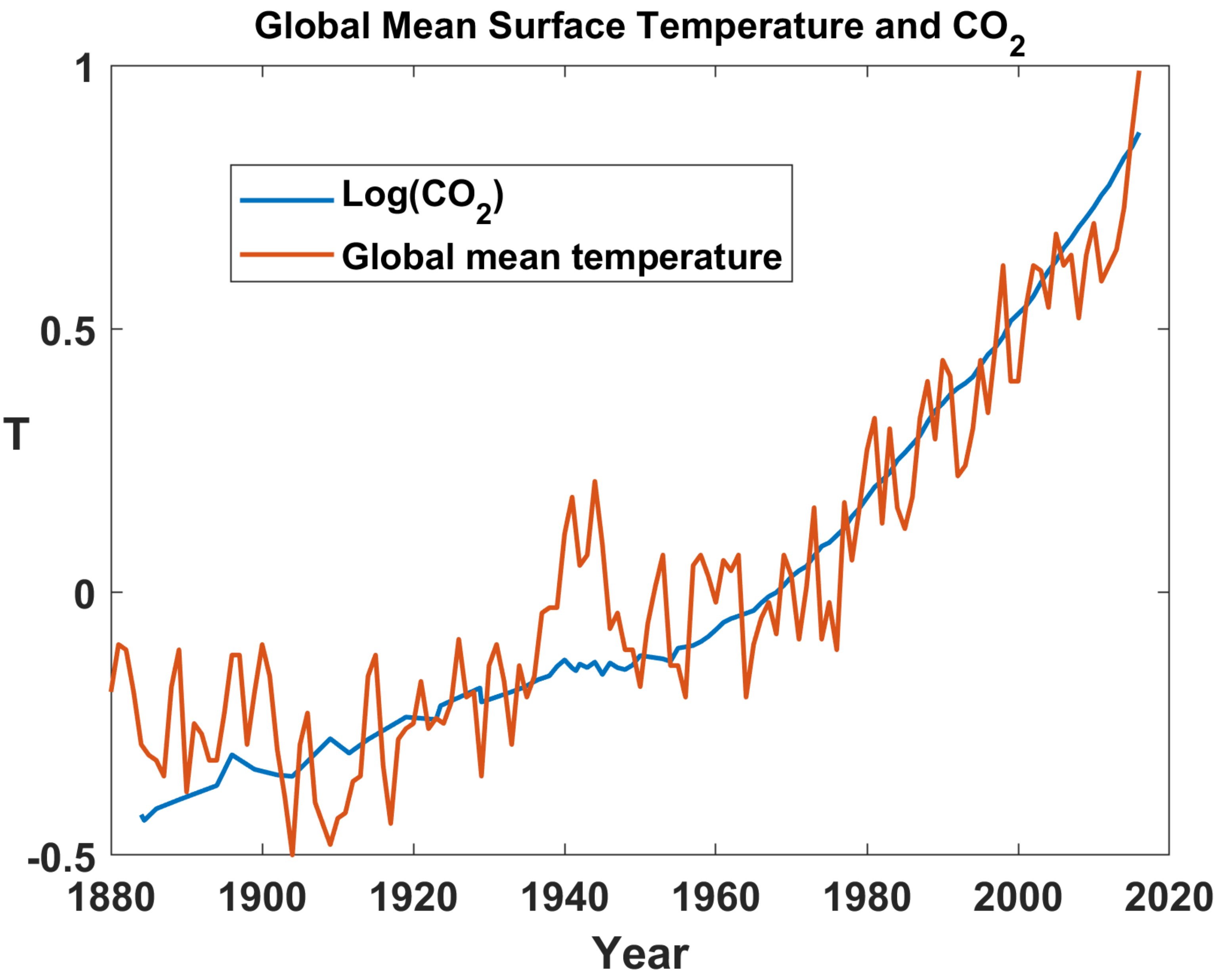

Temperature of Planet Earth
Cm
O
S
D
C
P
Tr
J
K
Pal
Eocene
Ol
Miocene
Pliocene
Pleistocene
Holocene
PETM
Early Eocene optimum
K-T
Permian glaciations
Eemian
LGM
YD
Holocene optimum
2100
2050
Royer et al (2004) - CO2 from GEOCARB (x 2.0)
Royer et al (2004) - CO2 from proxies (x 2.0)
Zachos et al (2008) & Hansen et al (2013)
Lisiecki and Raymo (2005) & Hansen et al (2013)
EPICA Dome C, Antarctica (x 0.5)
NGRIP, Greenland (x 0.5)
Marcott et al (2013)
Berkeley Earth land-ocean
IPCC AR5 RCP8.5
°C vs 1960-1990 average
°F vs 1960-1990 average
Millions of years before present
Thousands of years before present (2015 CE)
GSF 2014


Phanerozoic Carbon Dioxide
Measurements
Royer Compilation
30 Myr Filter
Models
GEOCARB III
COPSE
Rothman
Carbon Dioxide (ppmv)
Times Quaternary Average
8000
7000
6000
5000
4000
3000
2000
1000
0
30
25
20
15
10
5
0
Cm O S D C P Tr J K Pg N
500 400 300 200 100 0
Millions of Years Ago

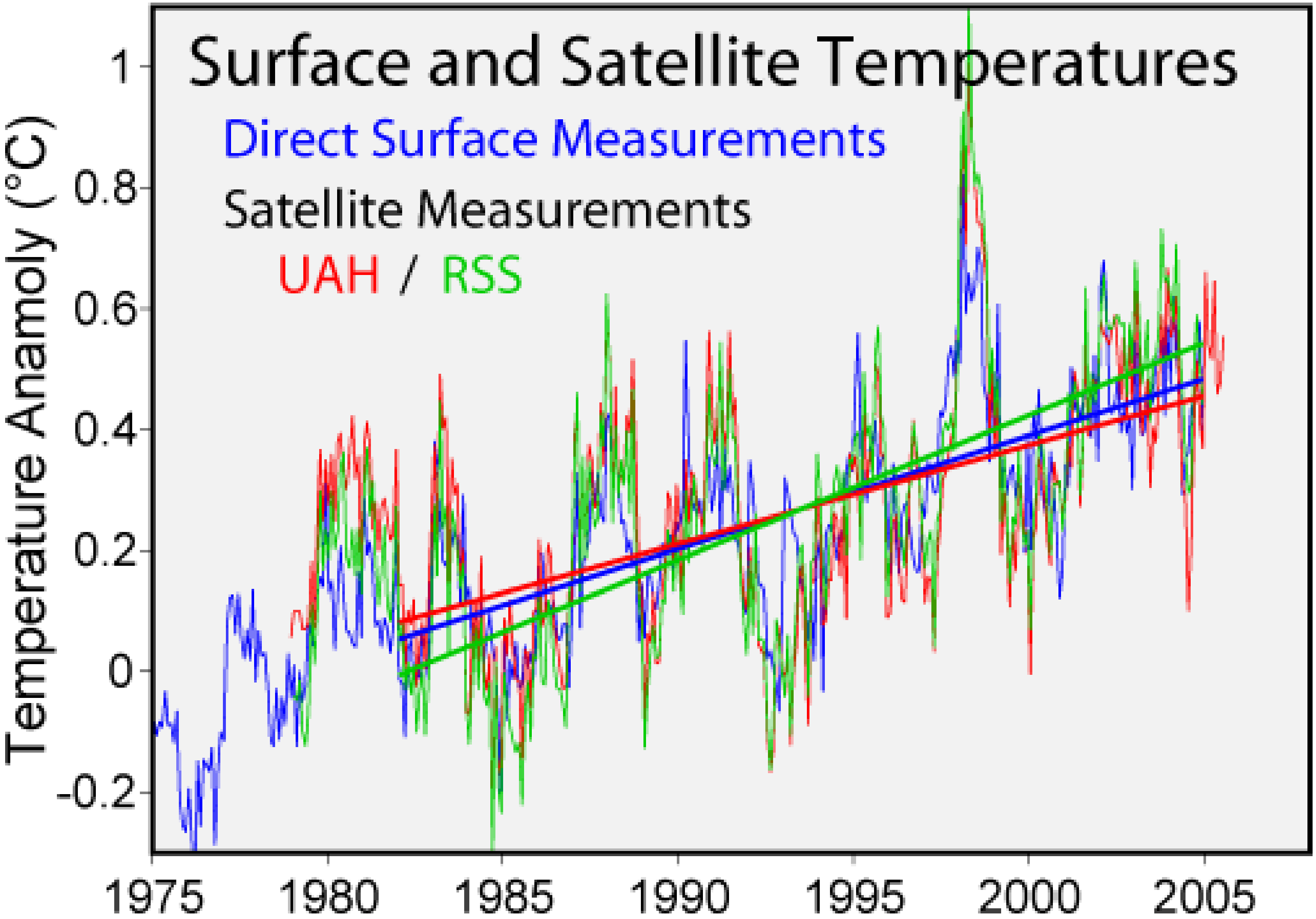
The Human Influence on Climate

Svante Arrhenius, 1859-1927

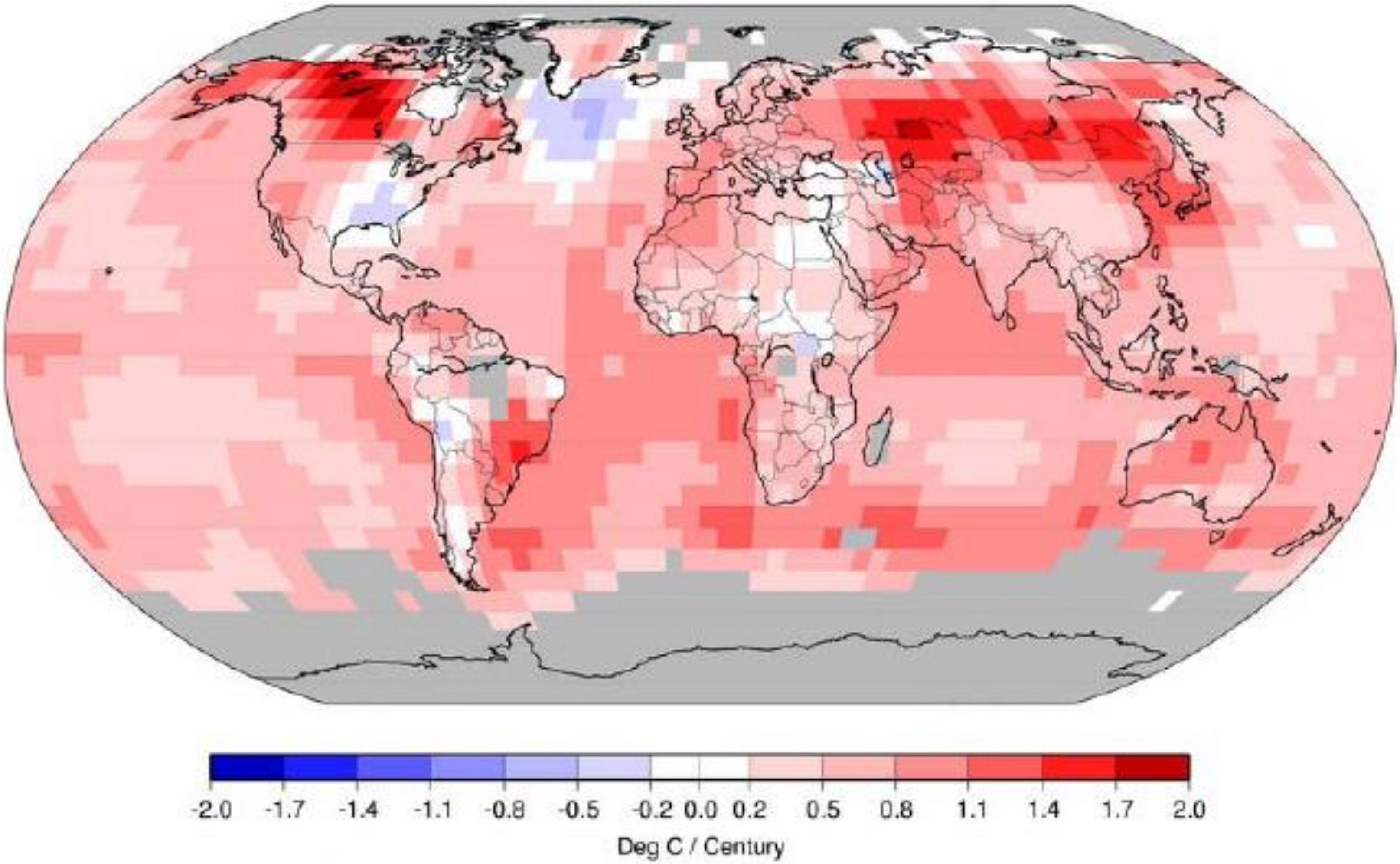
"Any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4°; and if the carbon dioxide were increased fourfold, the temperature would rise by 8°." – *Världarnas utveckling (*Worlds in the Making), 1906

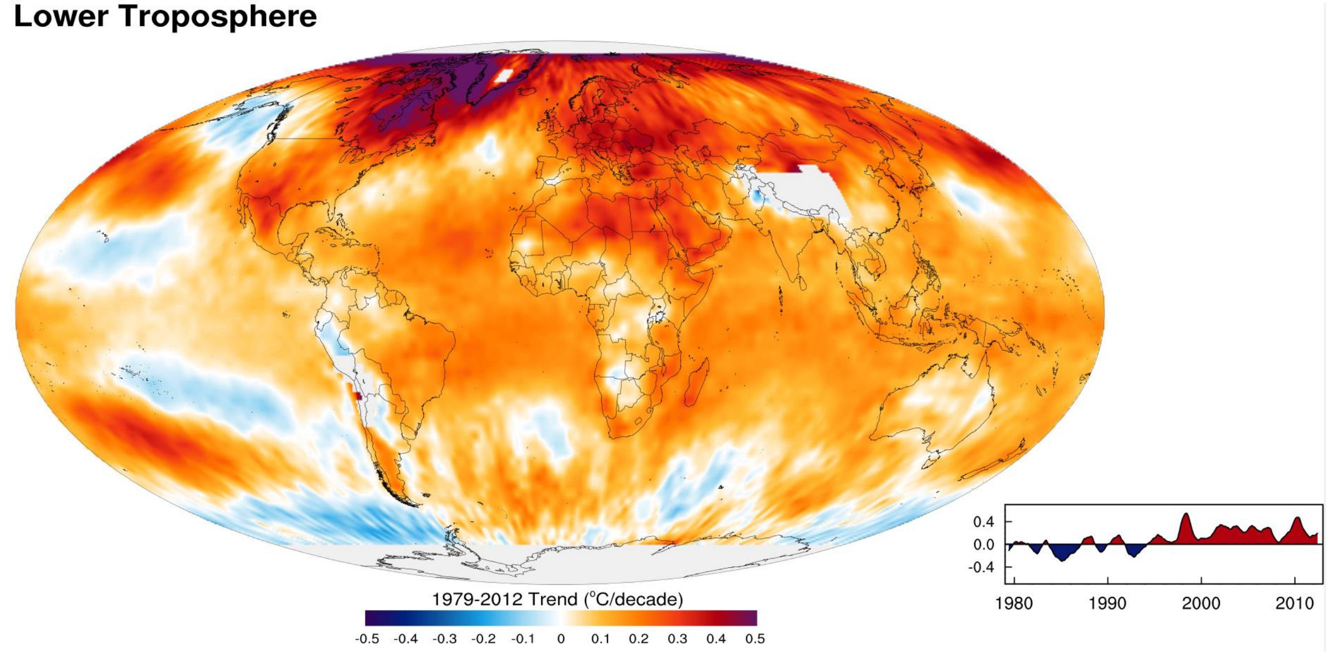


Global Mean Surface Temperature and CO2
Log(CO2)
Global mean temperature
T
1
0.5
0
-0.5
1880
1900
1920
1940
1960
1980
2000
2020
Year

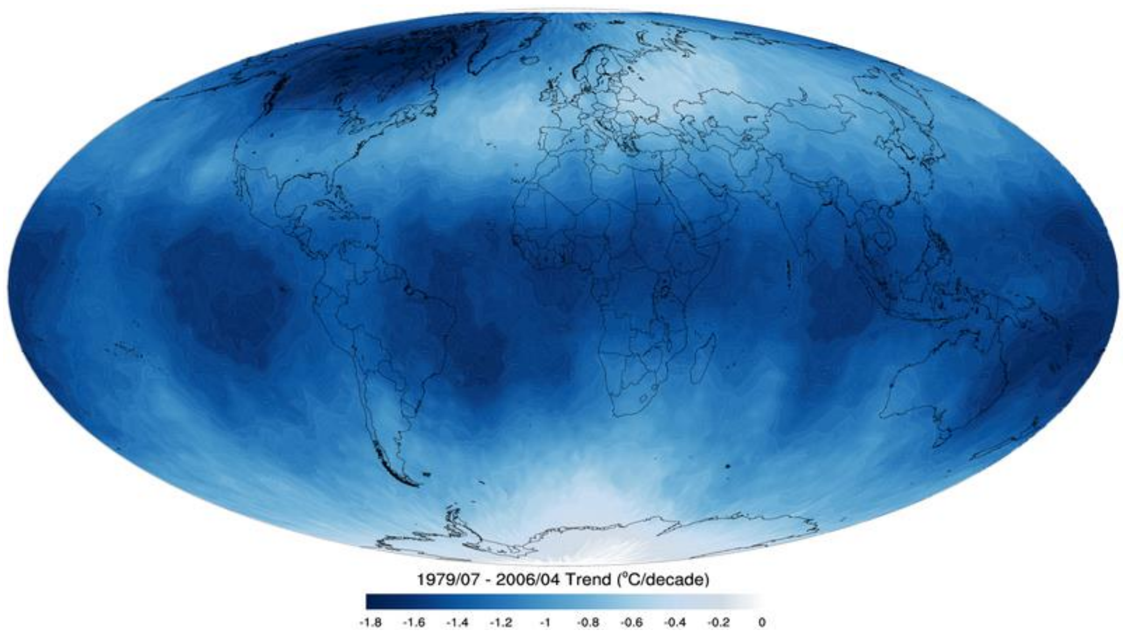

Surface and Satellite Temperatures
Direct Surface Measurements
Satellite Measurements
UAH / RSS
Temperature Anamoly (°C)
1
0.8
0.6
0.4
0.2
0
-0.2
1975
1980
1985
1990
1995
2000
2005

Distribution of temperature change, 1901-2005

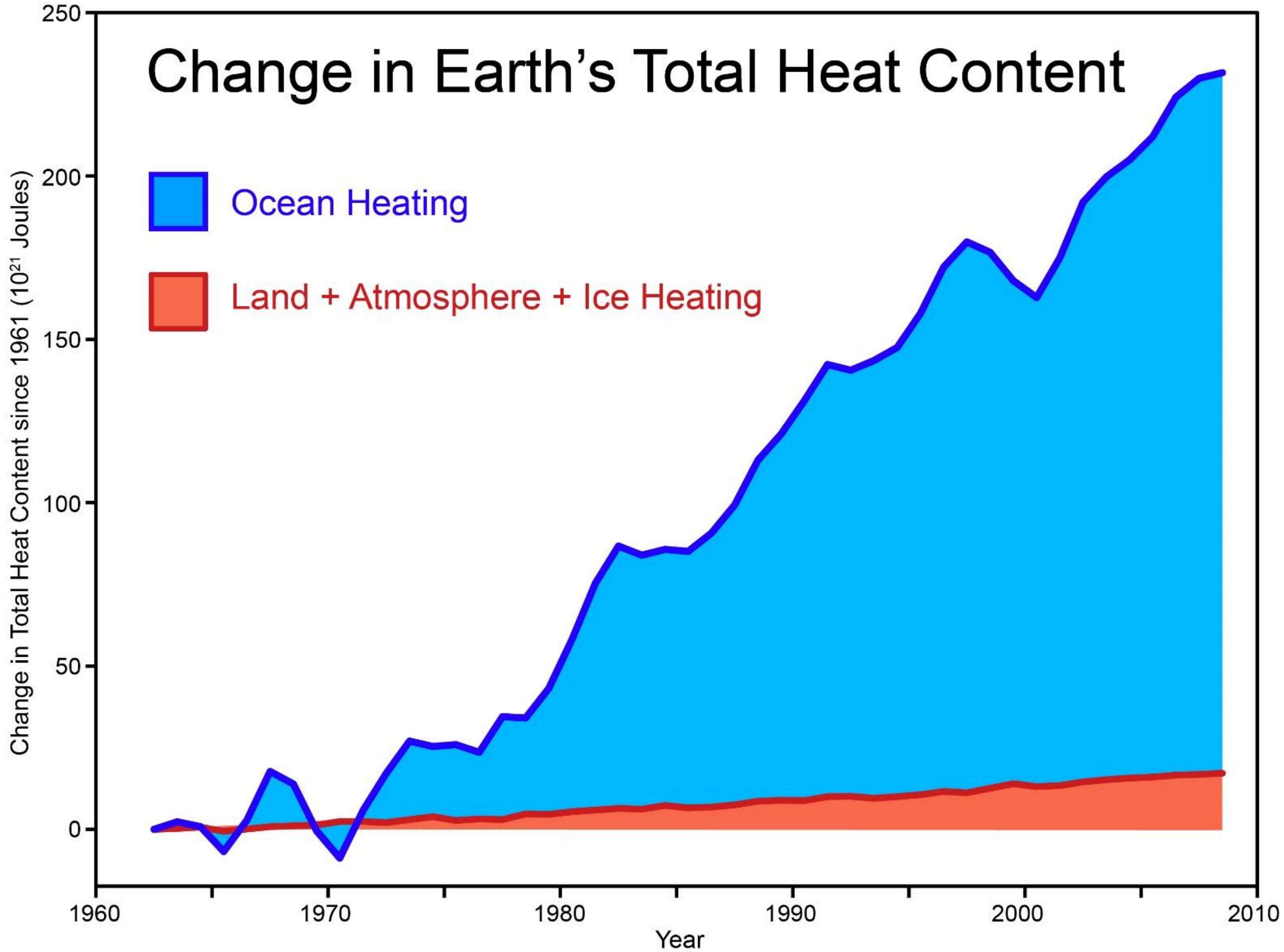




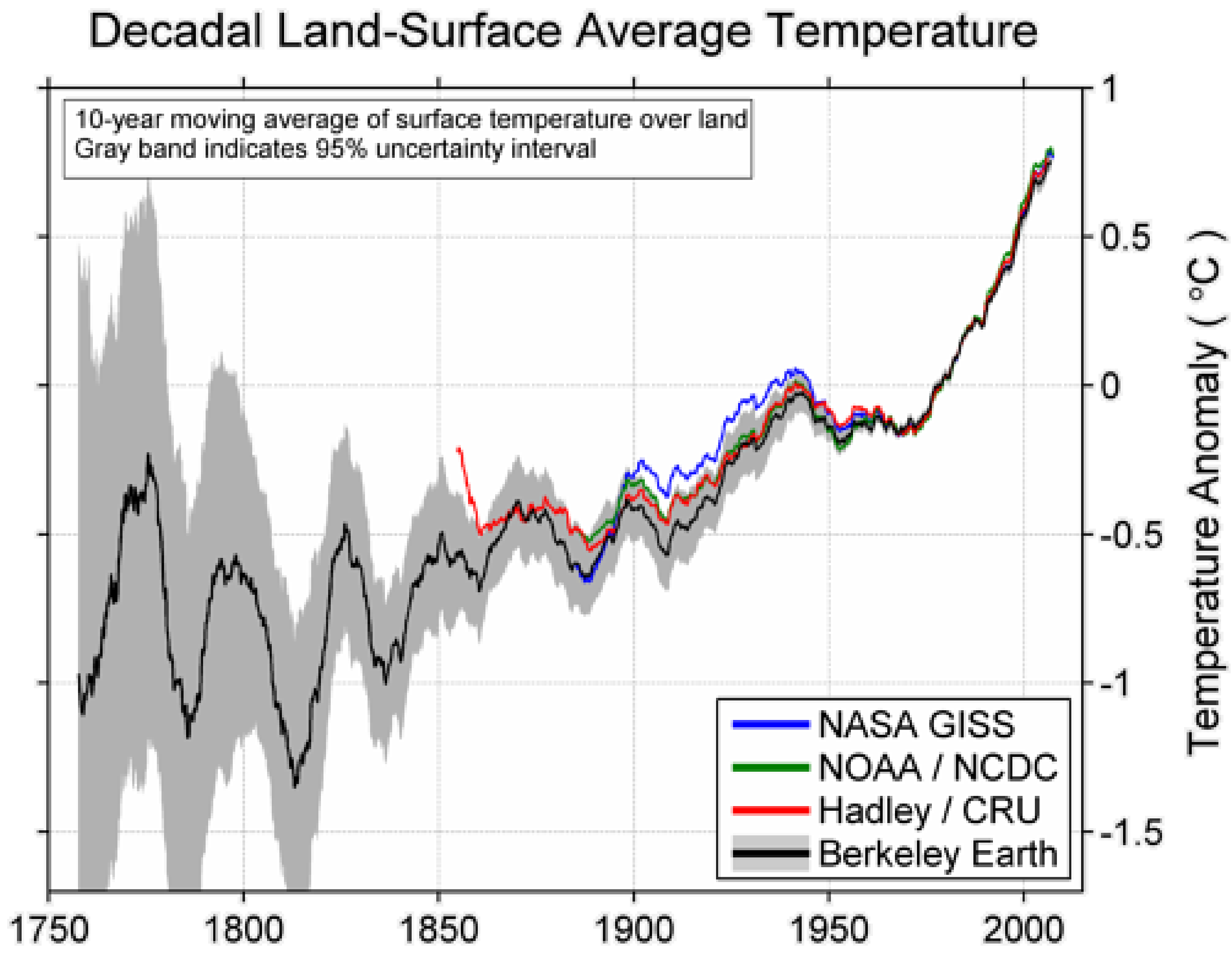
Tropospheric temperature trend from 1979-2012 based on satellite measurements (RSS)



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

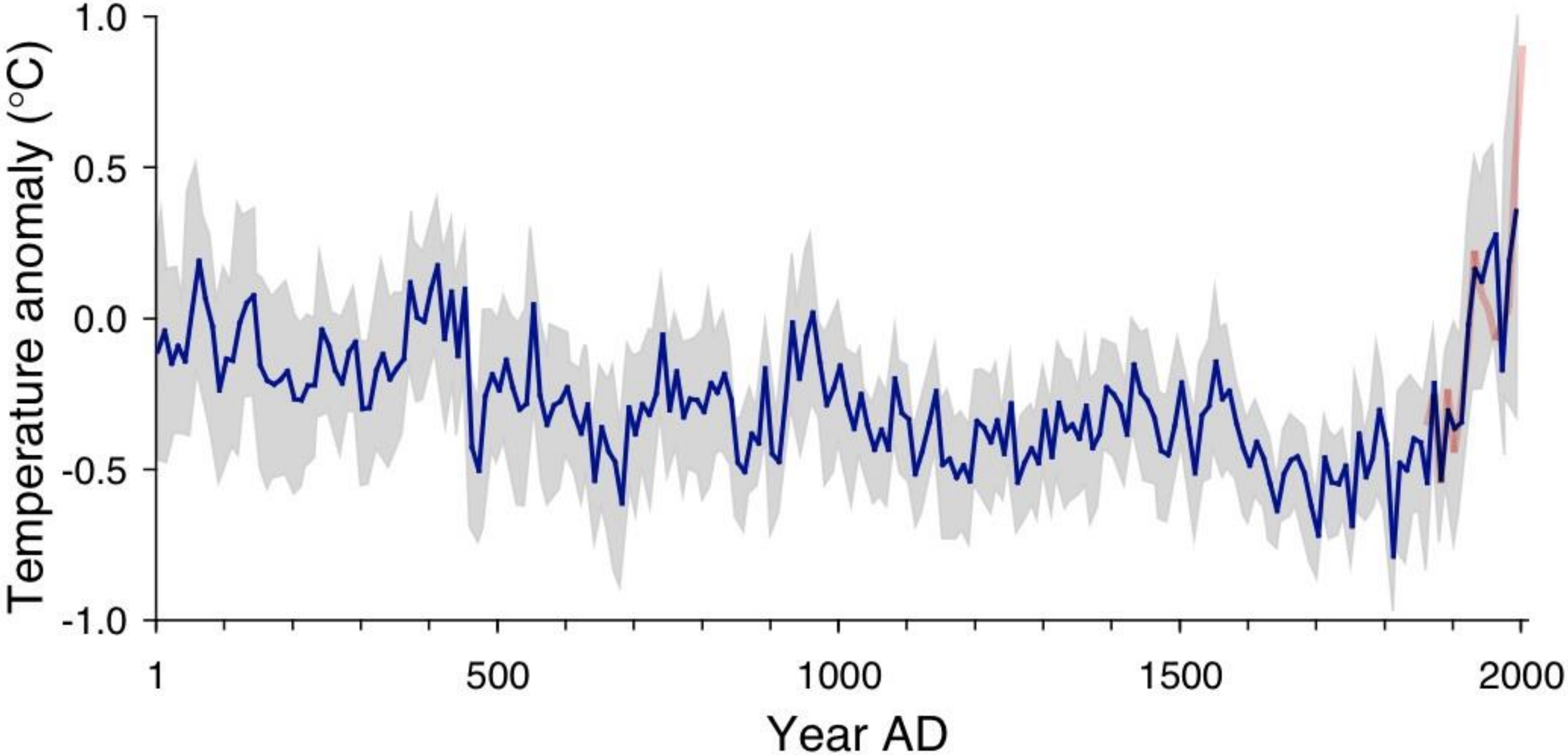


Total amount of heat from global warming that has accumulated in Earth's climate system since 1961, from Church et al. (2011) (many thanks to Neil White from the CSIRO for sharing their data).

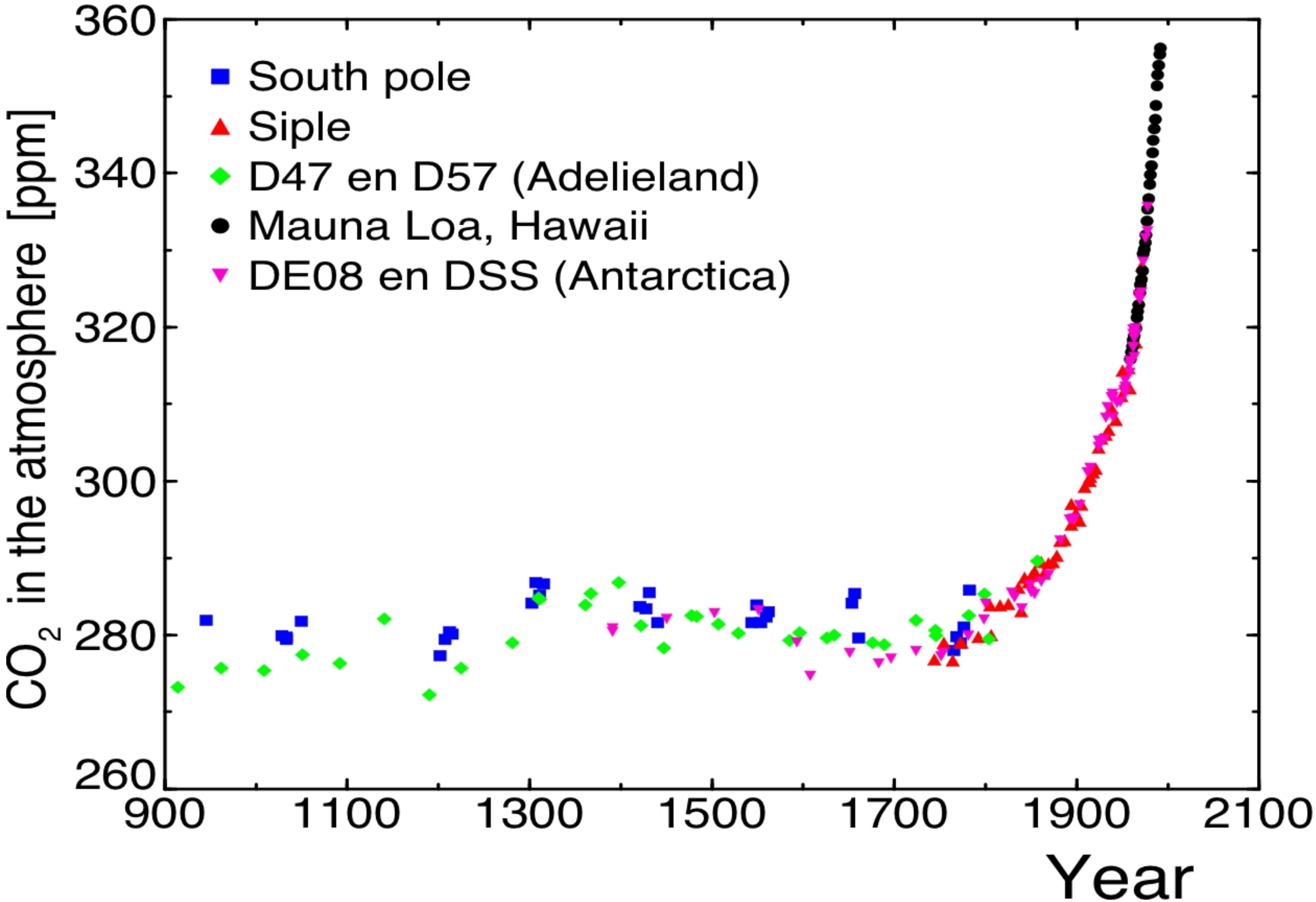


Decadal Land-Surface Average Temperature
10-year moving average of surface temperature over land
Gray band indicates 95% uncertainty interval
Temperature Anomaly (°C)
1
0.5
0
-0.5
-1
-1.5
1750
1800
1850
1900
1950
2000
NASA GISS
NOAA / NCDC
Hadley / CRU
Berkeley Earth

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

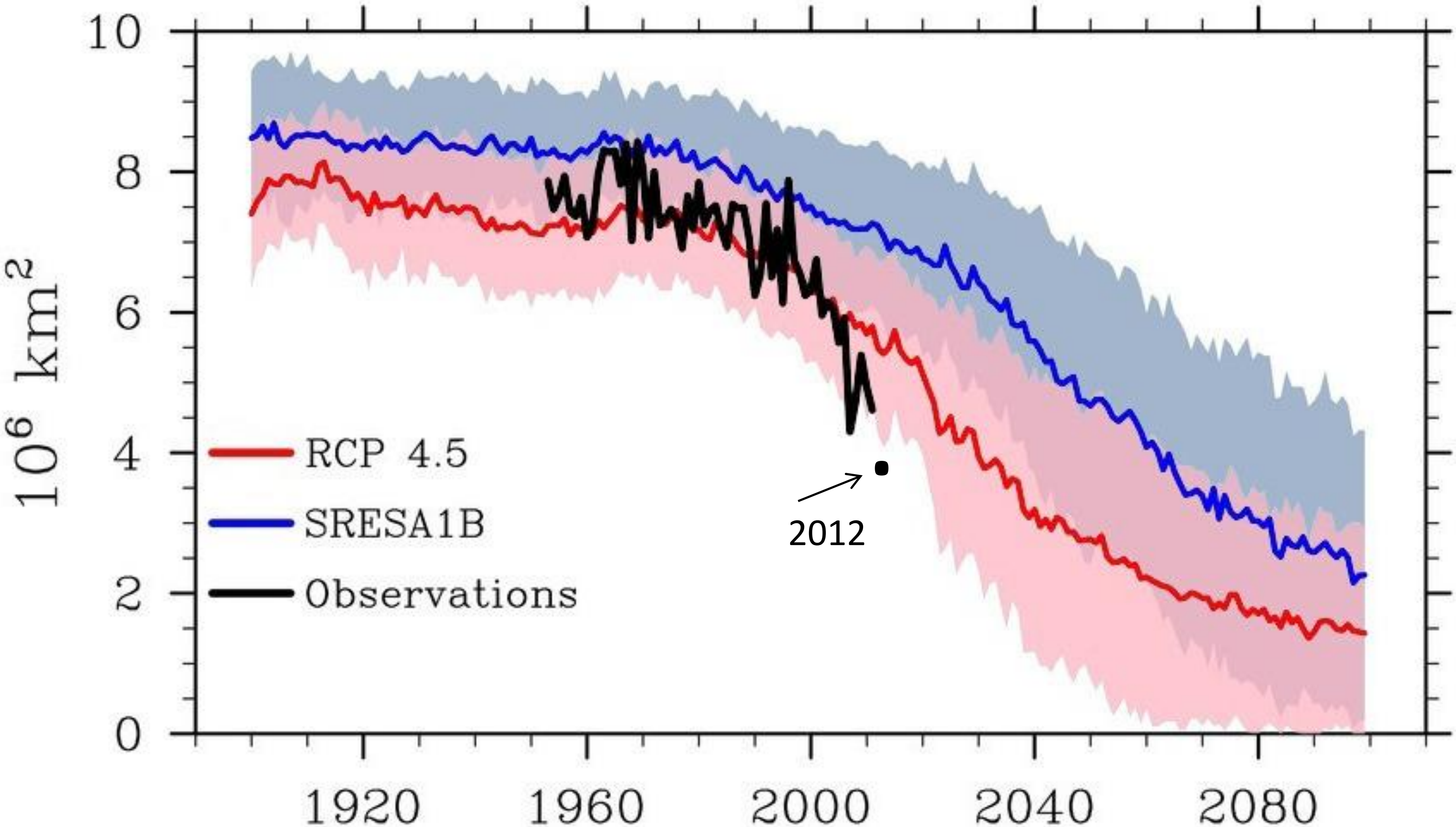


The long-term cooling trend in the Arctic was reversed during recent decades. The blue line shows the estimated Arctic average summer temperature over the last 2000 years, based on proxy records from lake sediments, ice cores, and tree rings. The shaded area represents variability among the 23 sites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


South pole
Siple
D47 en D57 (Adelieland)
Mauna Loa, Hawaii
DE08 en DSS (Antarctica)
CO2 in the atmosphere [ppm]
360
340
320
300
280
260
900
1100
1300
1500
1700
1900
2100
Year

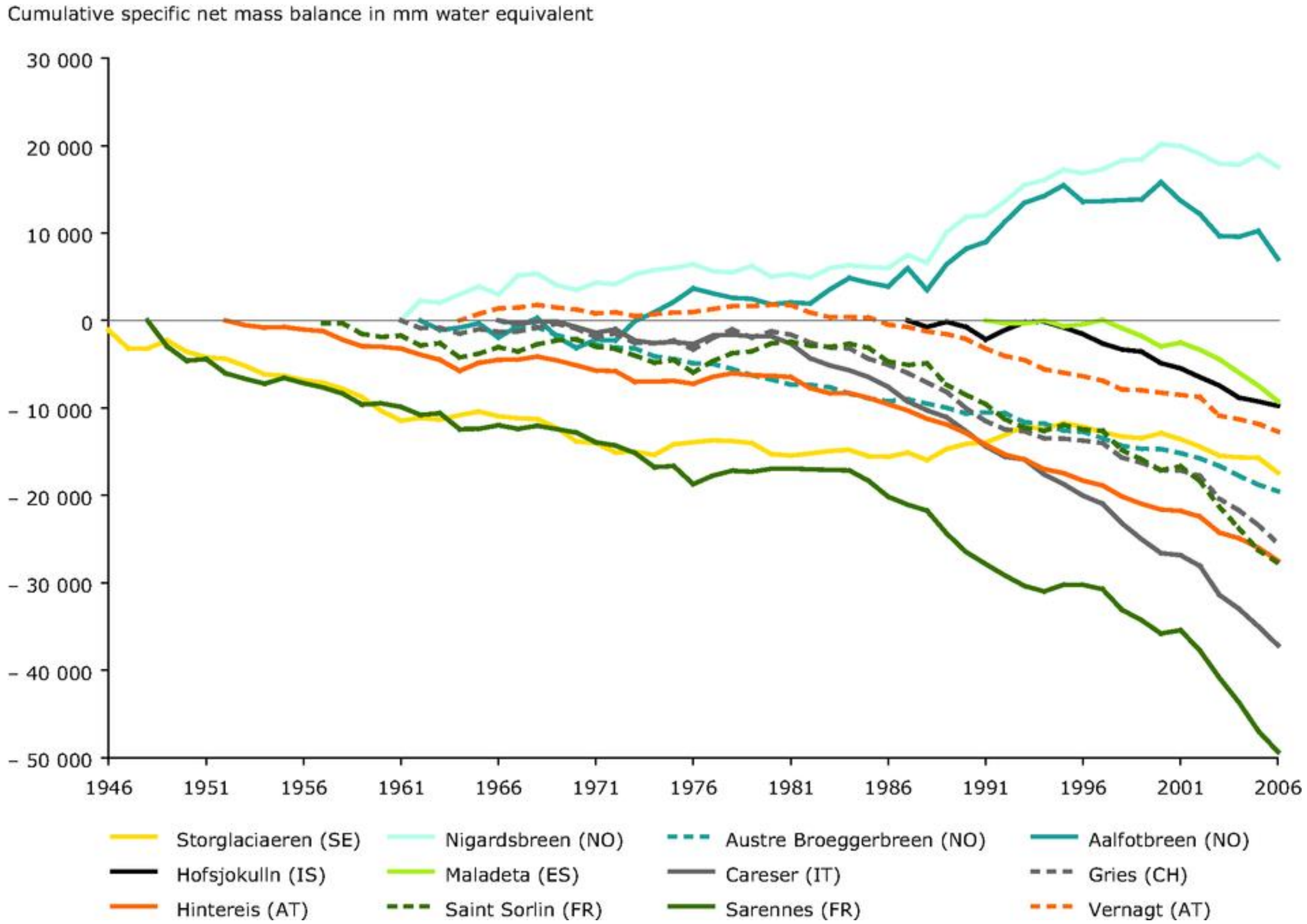
Other Trends

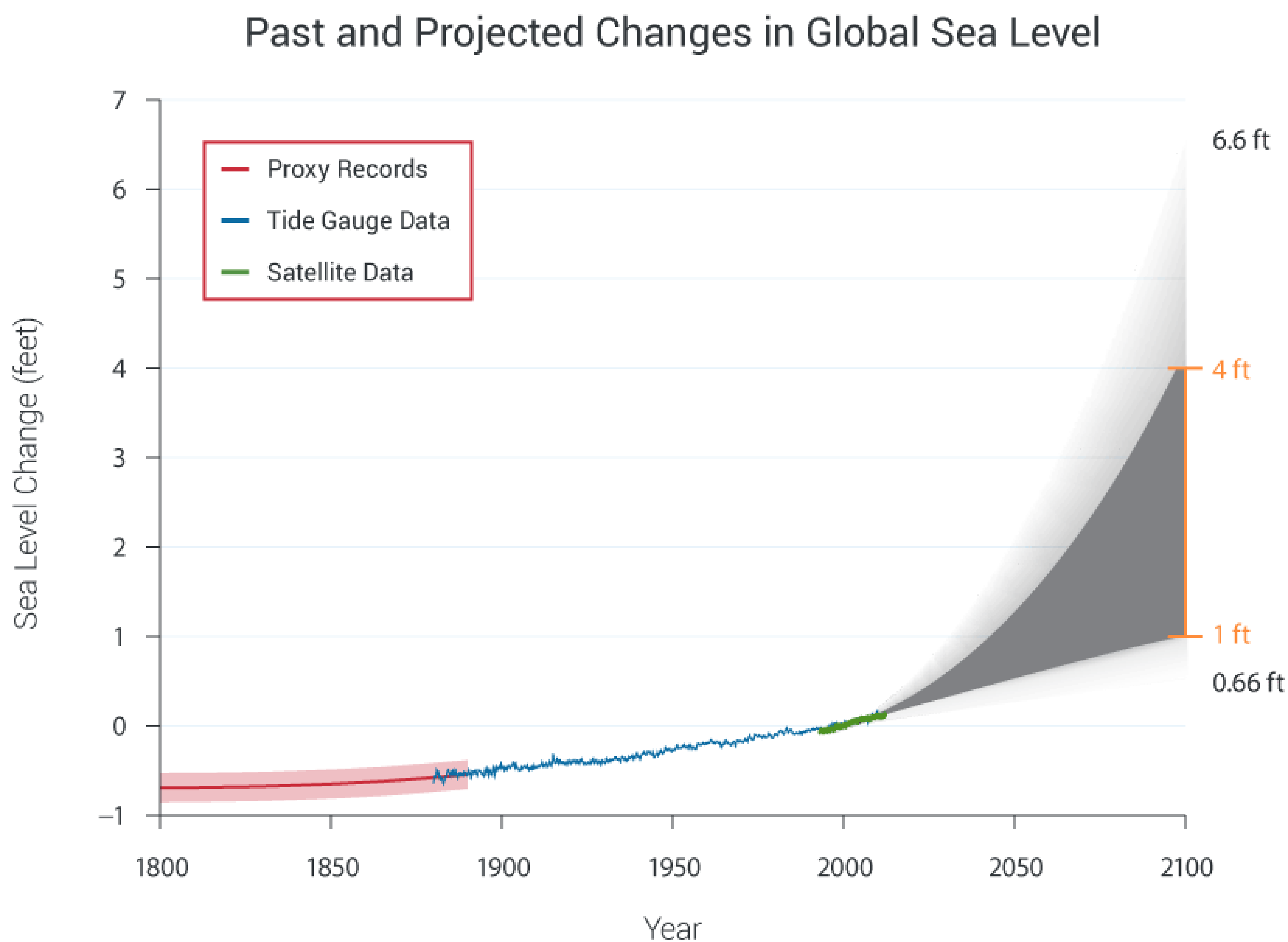
September Arctic Sea Ice Extent



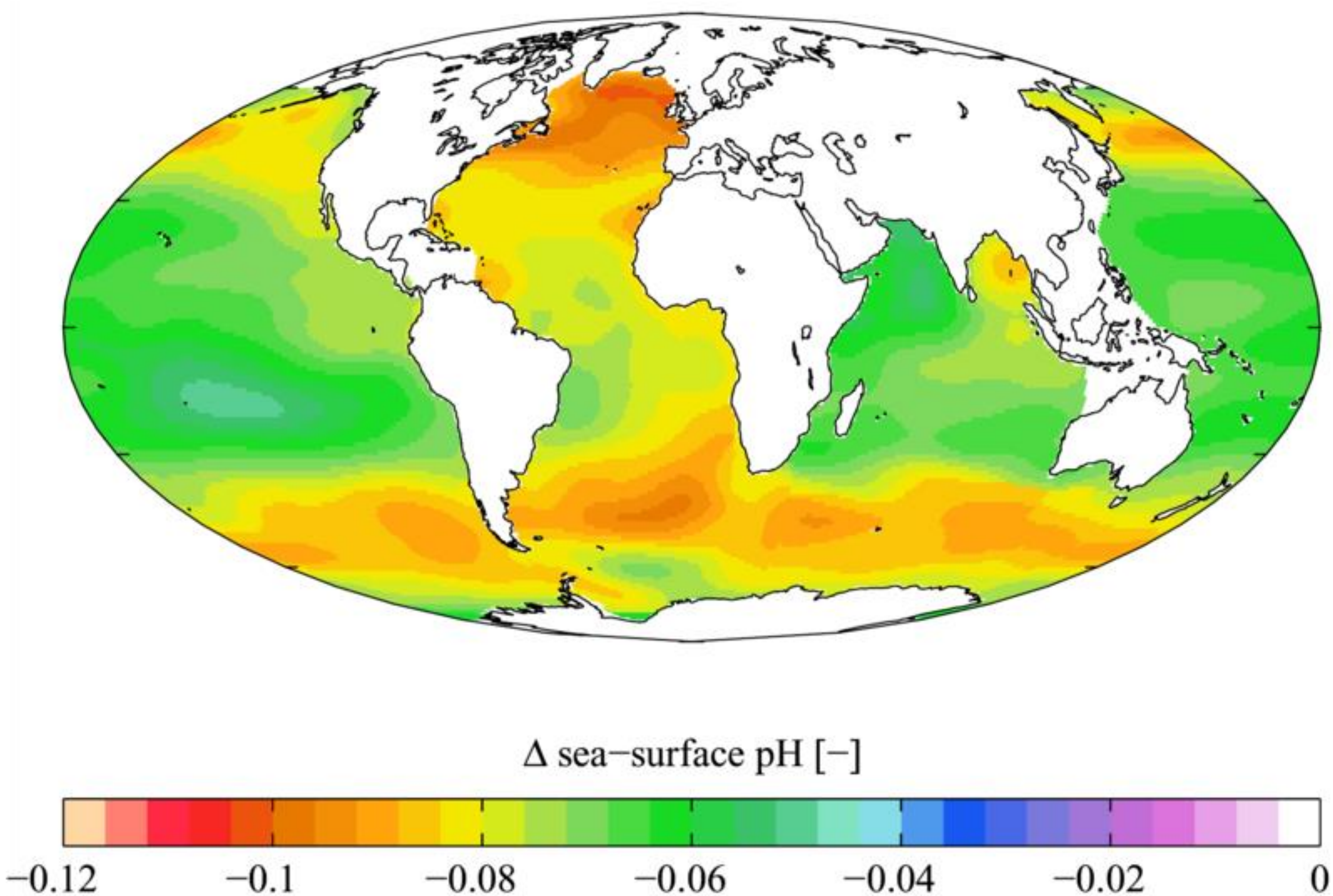
Credit: National Snow and Ice Data Center courtesy Stroeve et al. 2012

European Alpine Glaciers




Past and Projected Changes in Global Sea Level
Proxy Records
Tide Gauge Data
Satellite Data
Sea Level Change (feet)
7
6
5
4
3
2
1
0
–1
1800
1850
1900
1950
2000
2050
2100
Year
6.6 ft
4 ft
1 ft
0.66 ft

The Oceans Are Becoming More Acidic



- Acidification through CO_2 threatens marine life

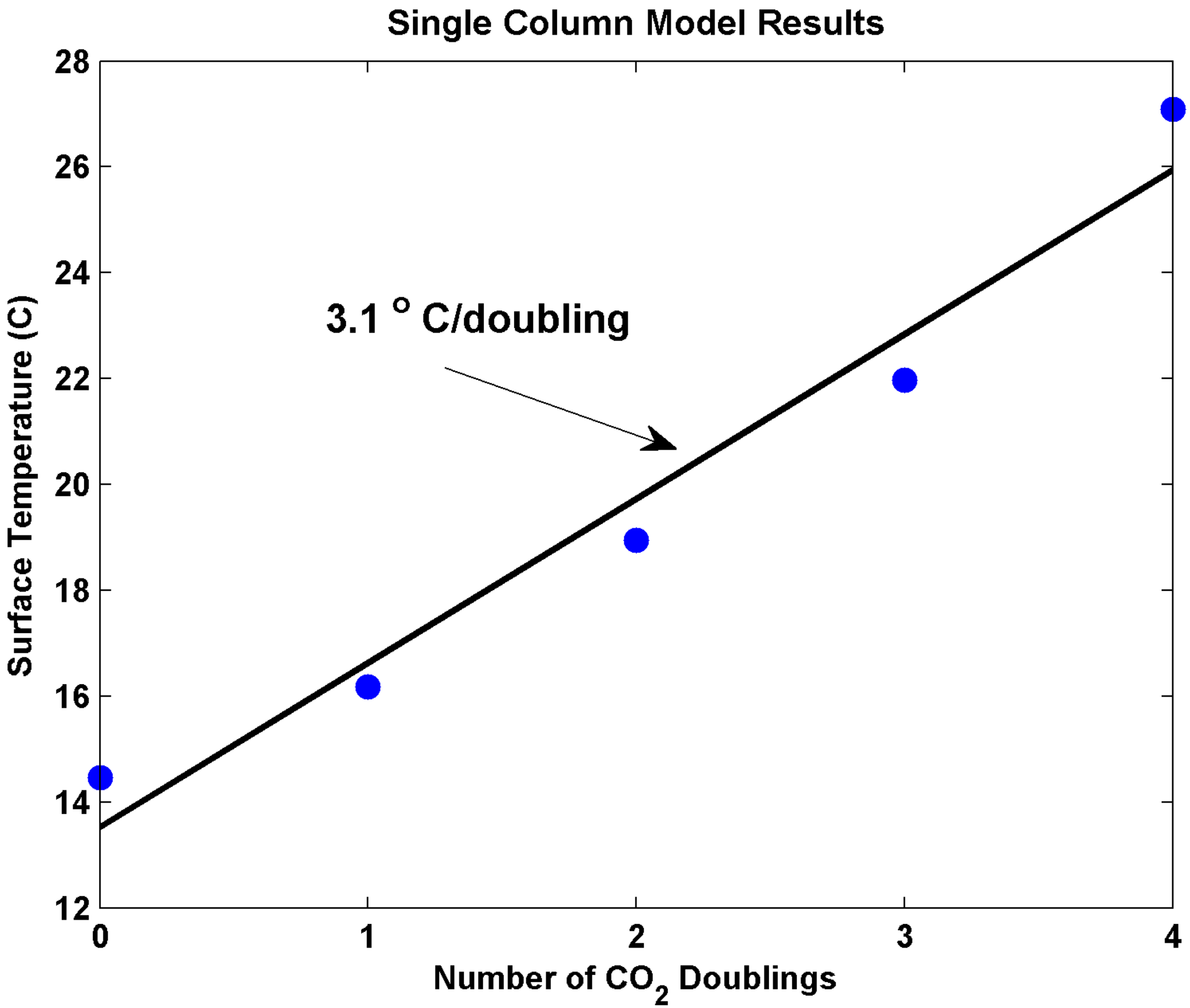
Plankton

Coral Reefs

The Future

Simple Models

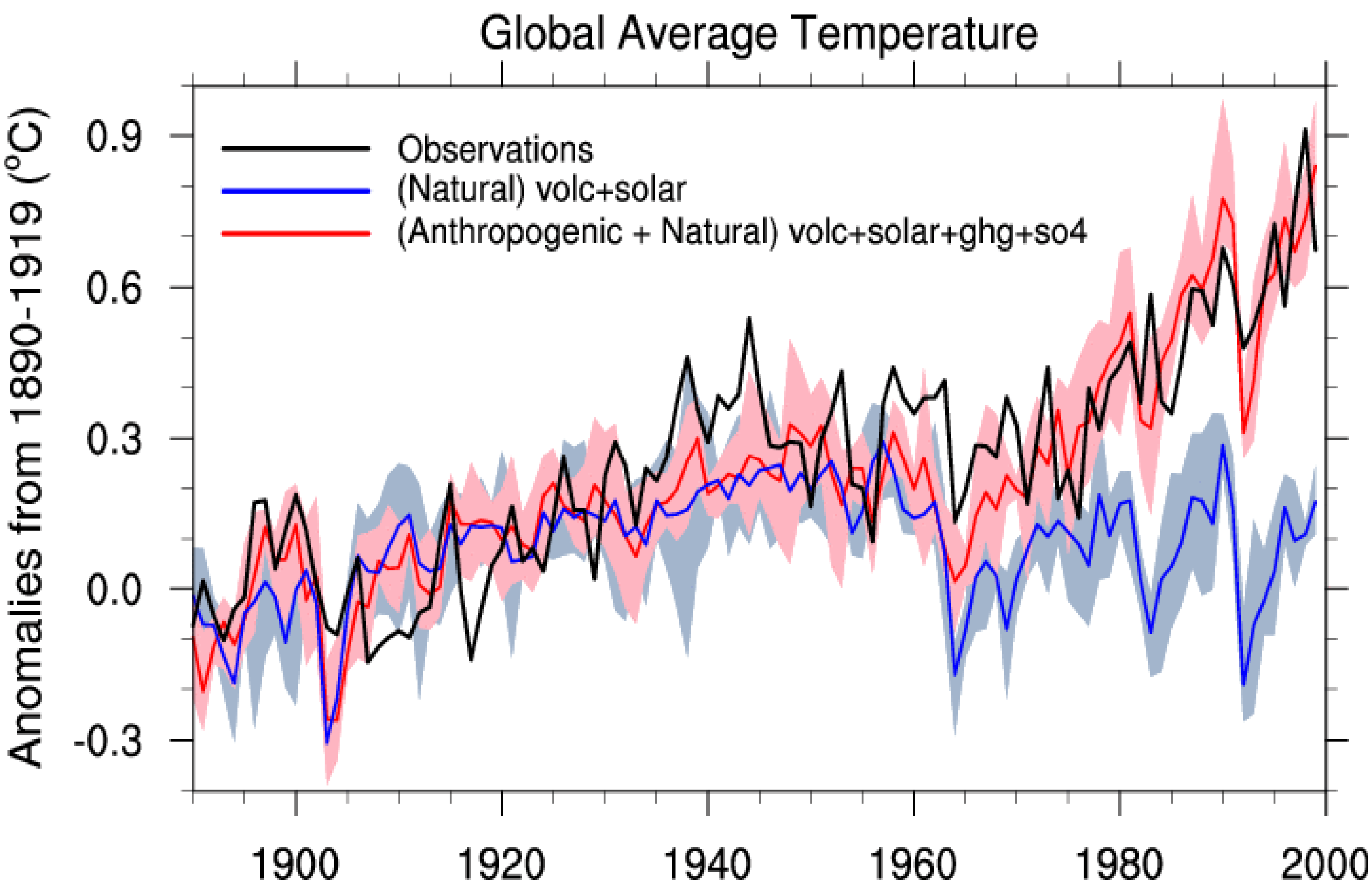
MIT Single Column Model



IPCC
Estimate:
2-4.5 ^{o}C

Global Climate Models

20th Century With and Without Human Influences

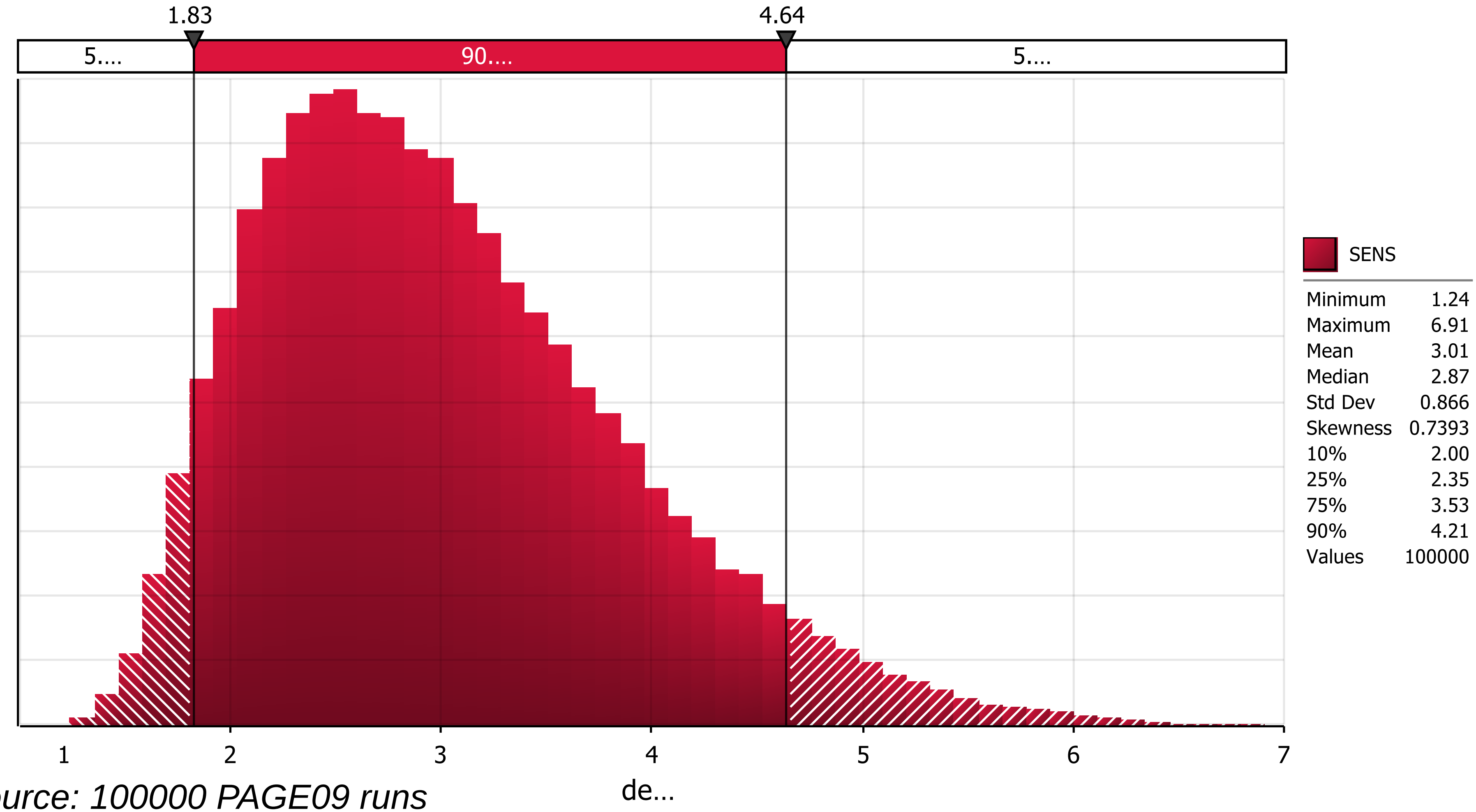


Based on 4-member PCM ensembles, Meehl et al., *J. Climate*, 2004

Sources of Uncertainty

- Cloud Feedback
- Water Vapor Feedback
- Ocean Response
- Aerosols

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



Source: 100000 PAGE09 runs

SEI

ClimateCost

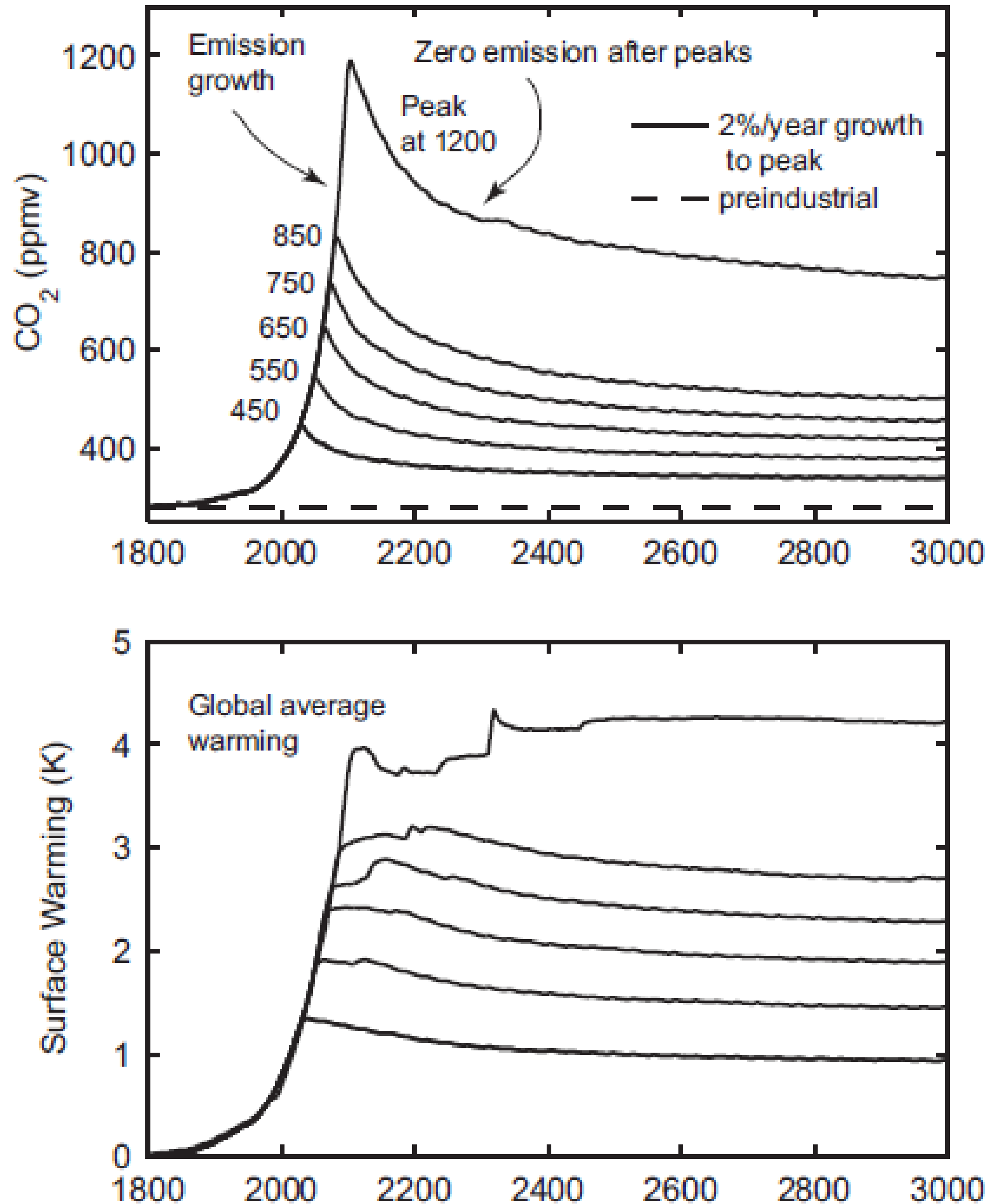
Chris Hope, U. Cambridge
courtesy Tim Palmer

IPCC 2007: Doubling CO_2 will lead to an increase in mean global surface temperature of 2 to 4.5 °C.

Atmospheric CO_2 assuming that emissions stop altogether after peak concentrations

Global mean surface temperature corresponding to atmospheric CO_2 above

Courtesy Susan Solomon



Summary of Main Points

- Several aspects of climate science are well established
- Earth's climate is strongly bounded but shows strong sensitivity within the bounds
- Climate science dates back well into the 19th century and is well established

Summary of Main Points

- Earth's greenhouse effect triples the amount of radiation absorbed by the surface though it is regulated by trace gases comprising no more than 0.04% of the mass of the atmosphere. The concentration of CO_2 has increased by ~45% since the dawn of the industrial revolution

- Beginning with the calculations of Arrhenius more than 100 years ago, simple models predict an increase in global mean surface temperature of around 3 ^oC for each doubling of CO_2. These are consistent with the results of global climate models

- Long atmospheric lifetime (~1000 years) of CO_2 limits window of time in which serious risks could be curtailed