CLIMATE SYSTEM BASICS

Mark J. McCready
Chemical and Bimolecular Engineering
3/28/17

OUTLINE

- Goal today is to try to attain a basic understanding of how the climate of the earth is determined

  - Incident radiation by sun

  - Earth radiates back

  - Atmosphere is absorbing and re-emitting

  - Large-scale natural convection flows in atmosphere cause mixing

  - Water evaporation and condensation is very important (clouds…

  - Ocean currents carry heat around…

PREQUEL: WHAT WE THOUGHT THE EARTH'S TEMPERATURE WAS BEFORE ~2001

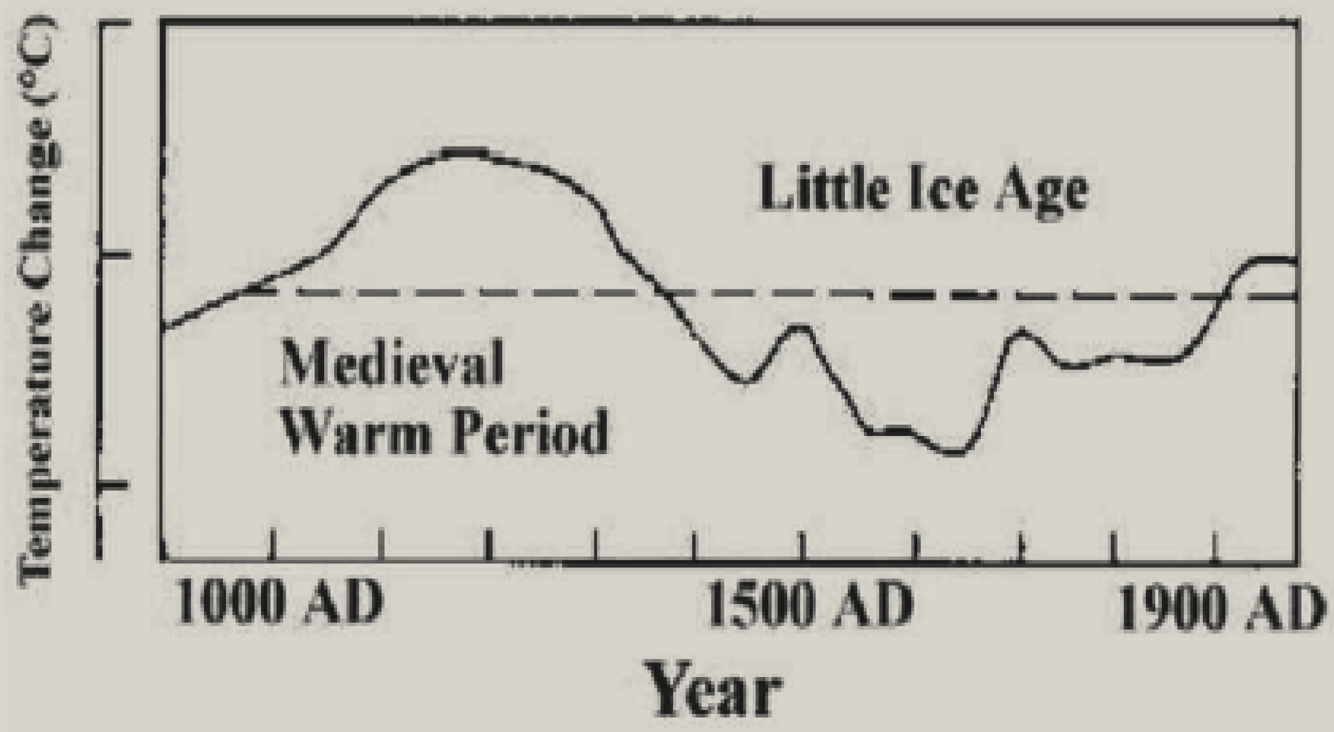
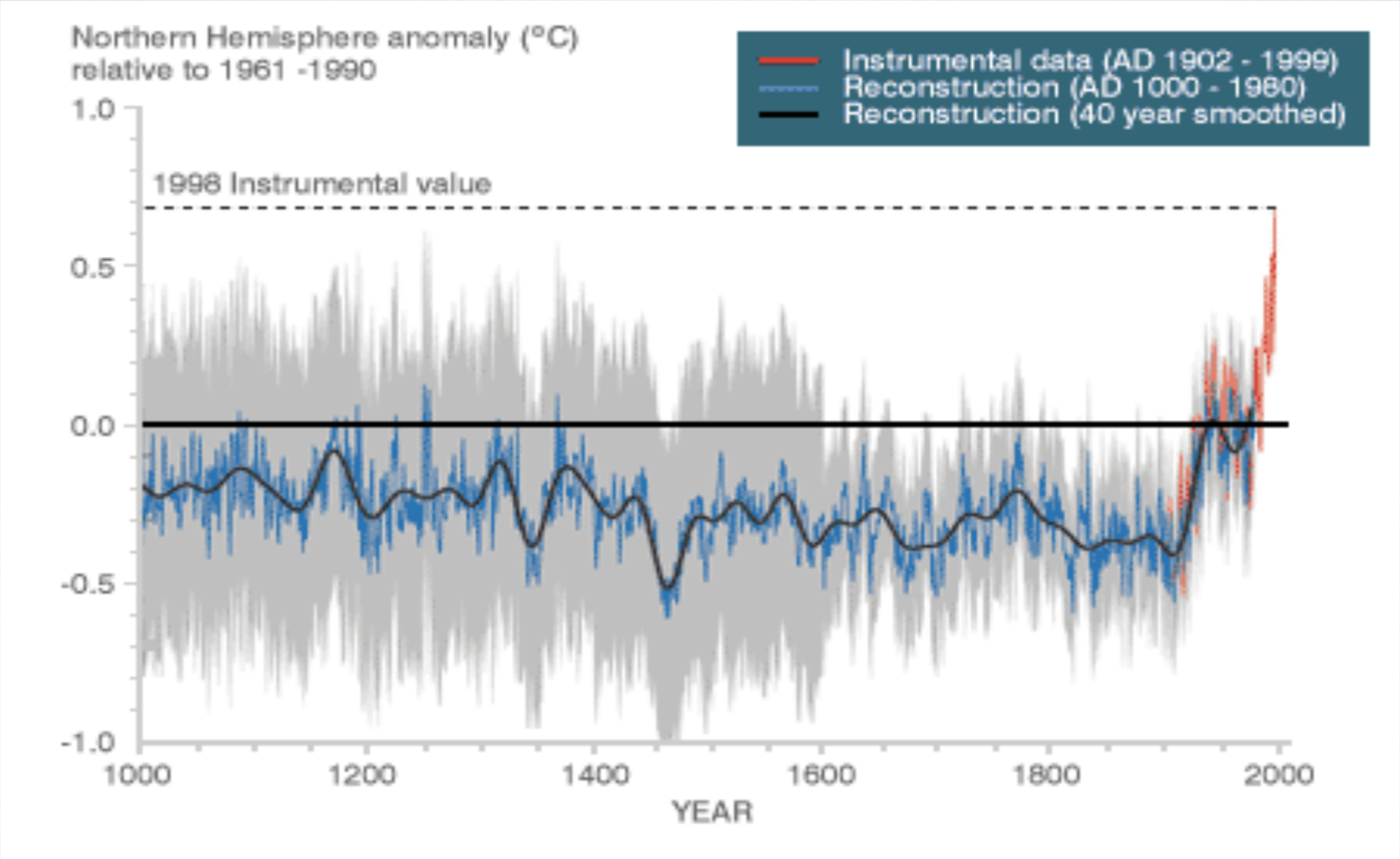


Figure 3: World Climate History According to IPCC in 1990.

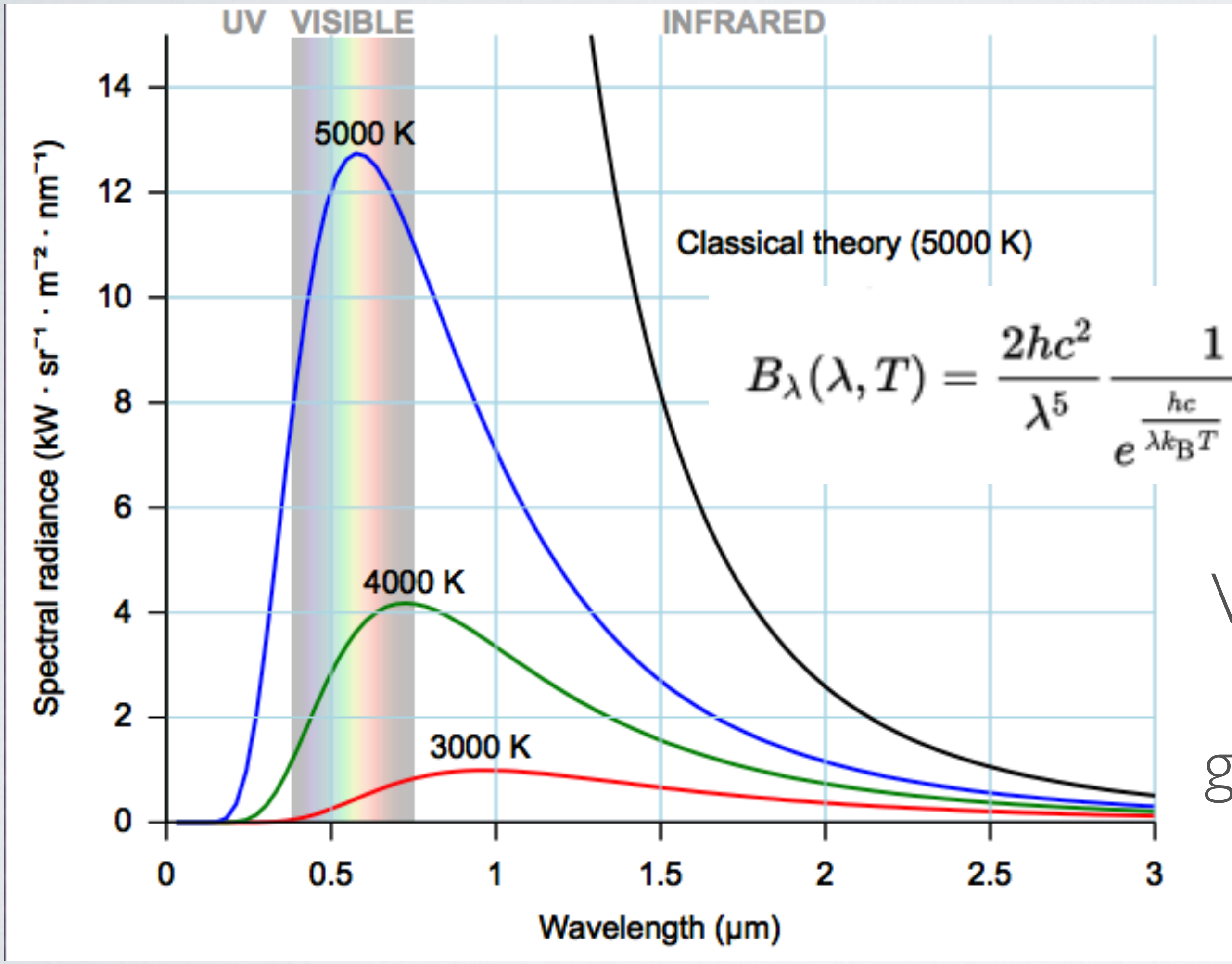
THE "HOCKEY STICK"

This figure catalyzed various actions and processes that made the climate a high intensity, contentious topic



IPCC 2001

THE SUN

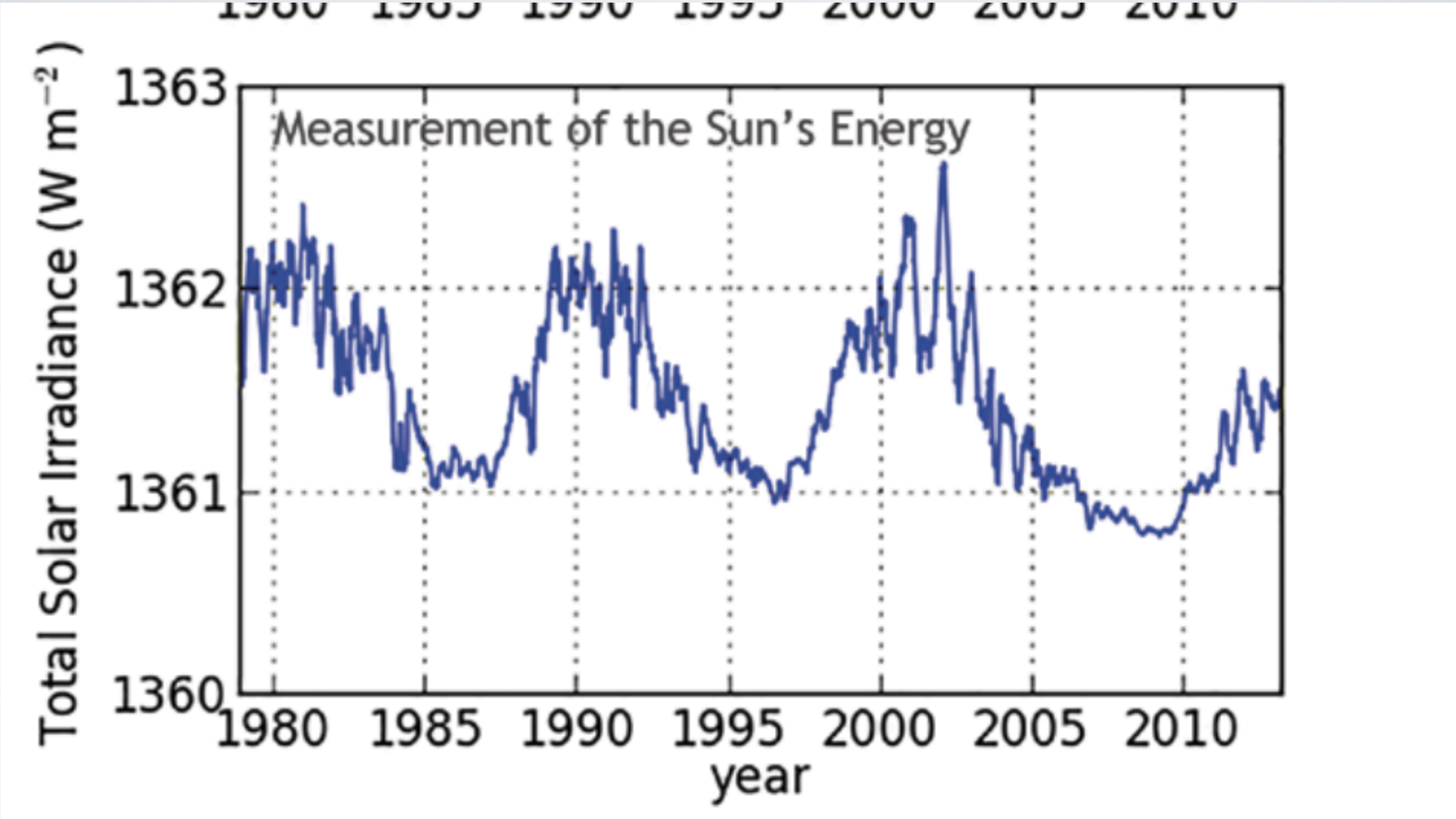


$$j^{\star} = \sigma T^4,$$

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}.$$

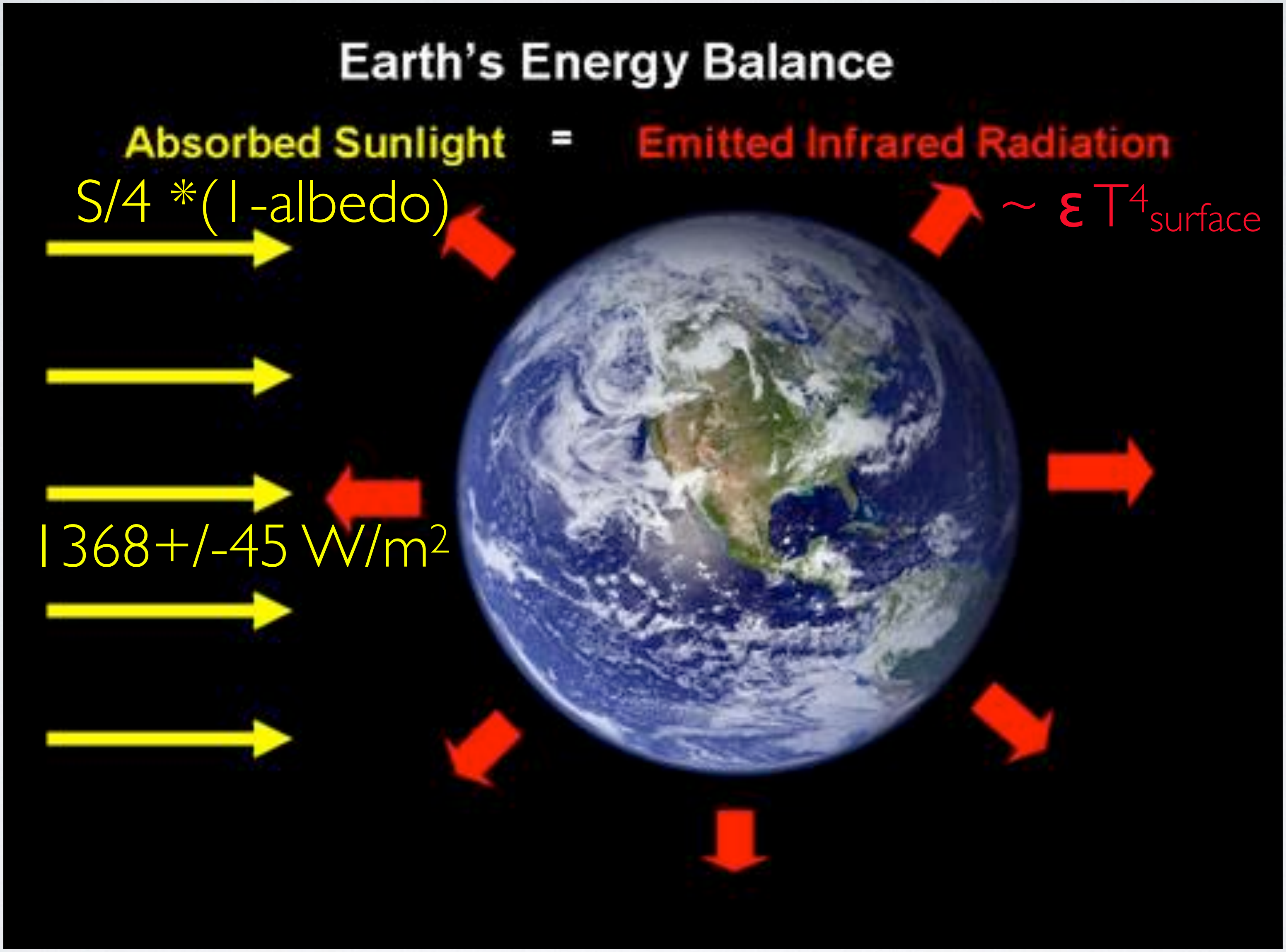
We know that the sun has not been constant over geologic time scale and has various ongoing cycles of ~decade/+ length

A SUN CYCLE



Measurement of the Sun's Energy
Total Solar Irradiance (W m⁻²)
1363
1362
1361
1360
1980
1985
1990
1995
2000
2005
2010
year

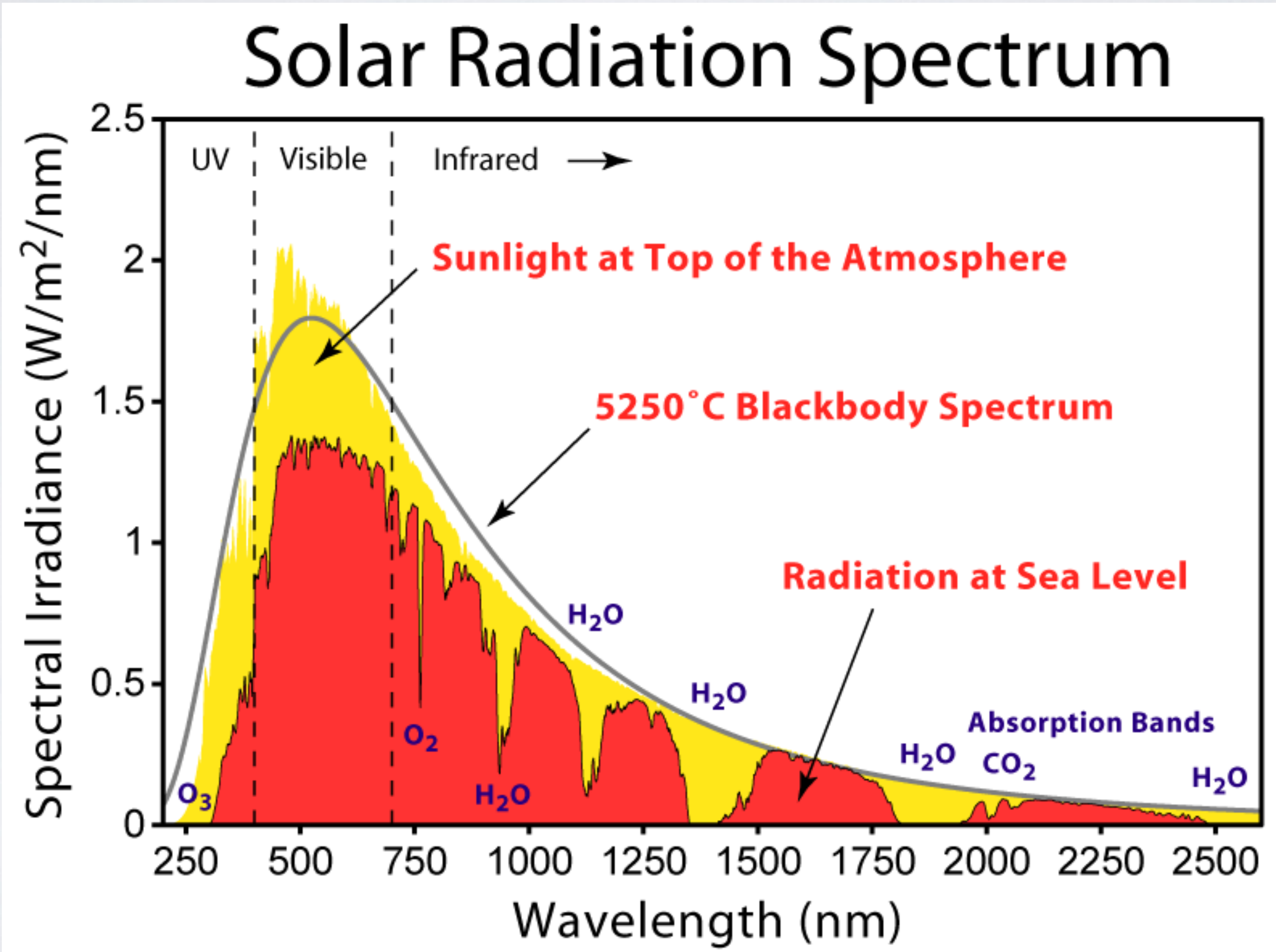
WOULD REALLY LIKE: ENERGY (IM)BALANCE



Need comparative fluxes over decades

SOLAR RADIATION

- Sun:



SOLAR FLUX

```
In[110]:= 63 × 10^6 W/m^2 (700000 km)^2/(93000000 mile)^2
```

Out[110]= $\frac{3430000\ \text{km}^2\ \text{W}}{961\ \text{m}^2\ \text{mile}^2}$

```
In[111]:= % /. mile → 1.609 km
```

Out[111]= $\frac{1378.66\ \text{W}}{\text{m}^2}$

- Evaporation rate for water would be:

```
1.4 kJ/s/m^2/(40.65 kJ/mole mole/.018/kg)/(1000 kg/m^3)
```

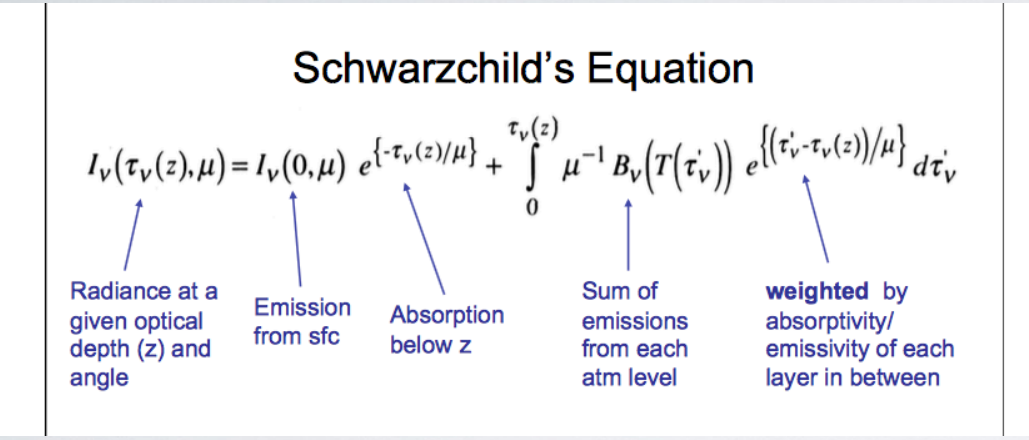
$\frac{6.19926\times 10^{-7}\ \text{m}}{\text{s}}$

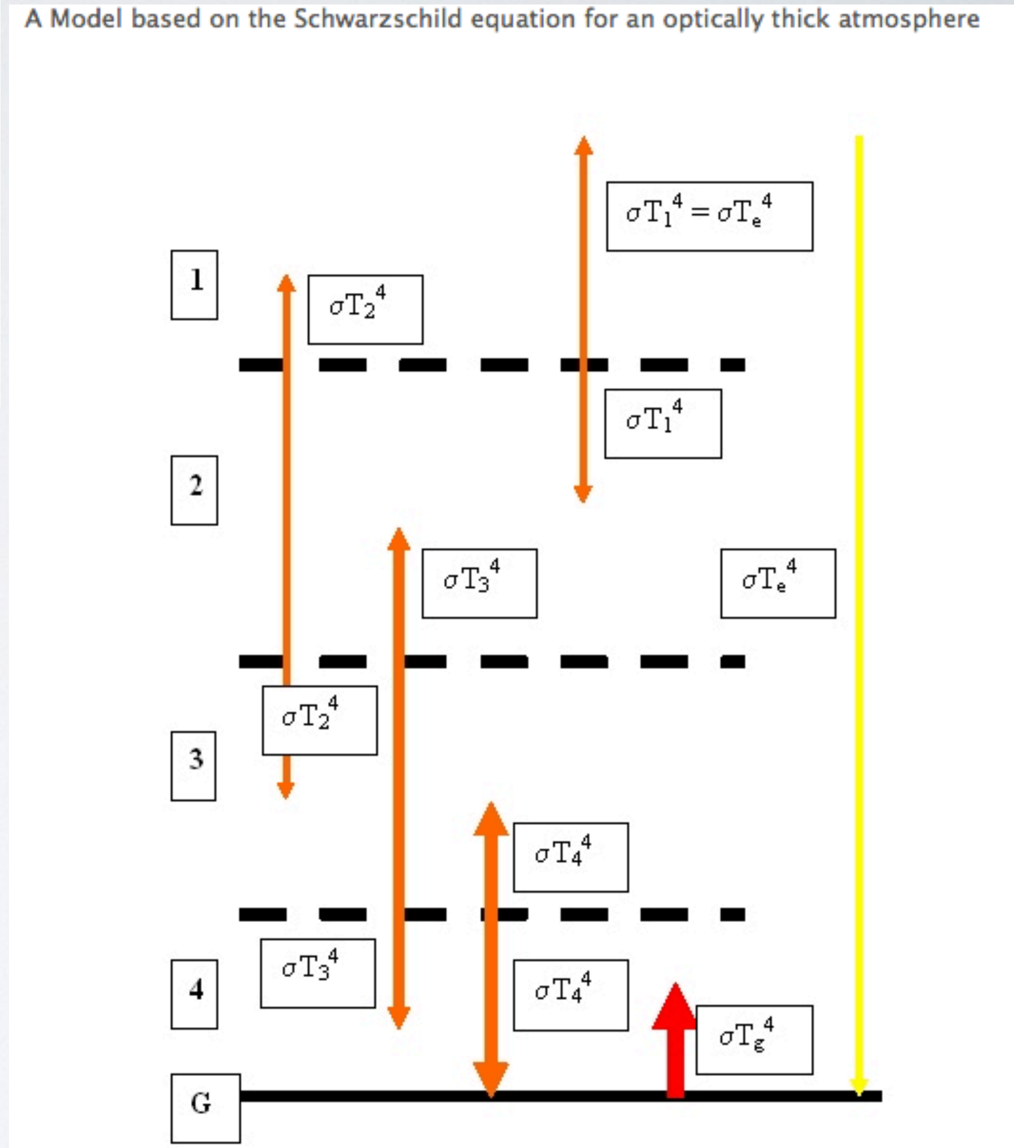
```
% /. {m → 1000 mm, s → 1/3600 hr}
```

$\frac{2.23173\ \text{mm}}{\text{hr}}$

- This explains why solar power is limited, but also that this flux must be essentially balanced by the outgoing radiation

TEMPERATURE PURE RADIATION

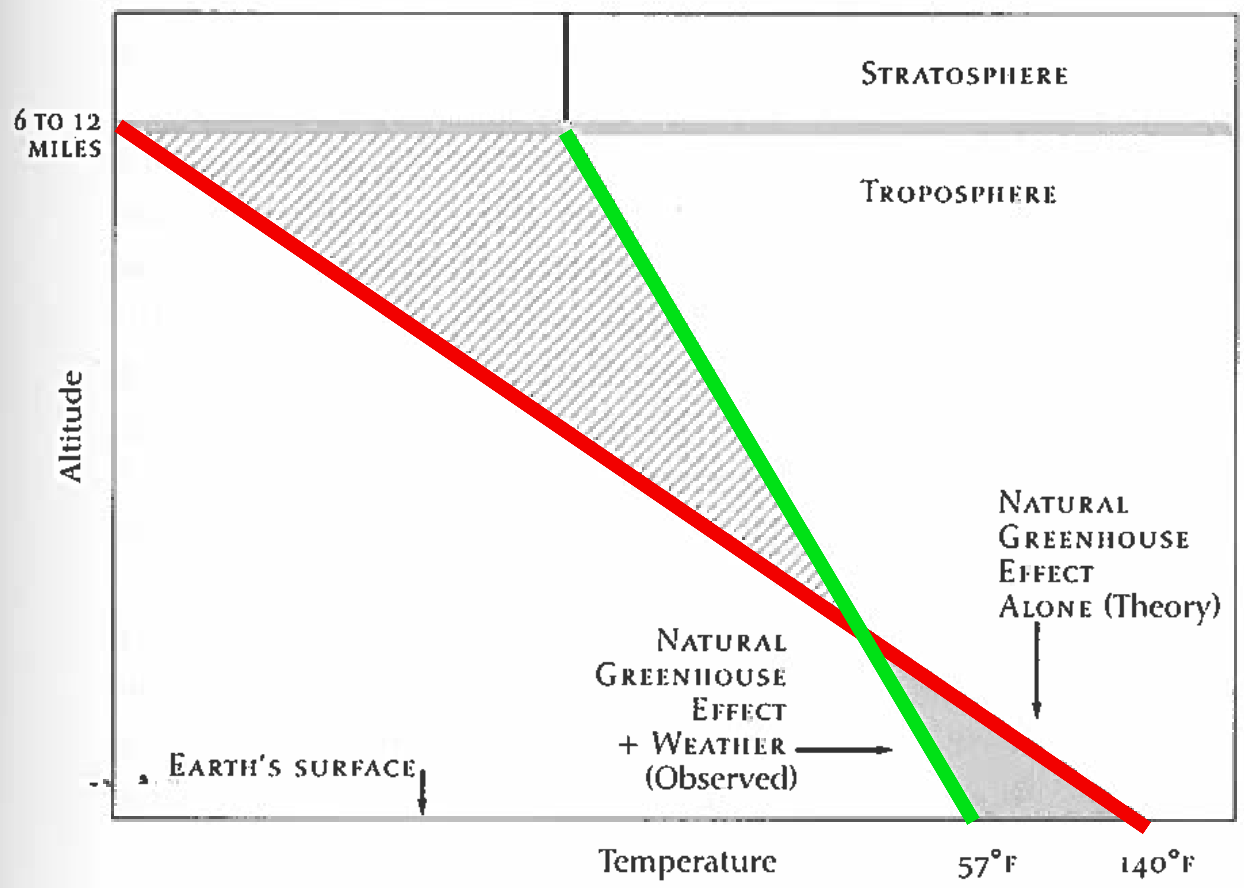




- I think that the flux out ~ equals the flux down, the question is what temperature(s) are necessary for this to occur

TEMPERATURE PROFILE

- Radiative perturbations (e.g., CO2 concentration increases) should be considered a perturbation of the red profile, not the green one!



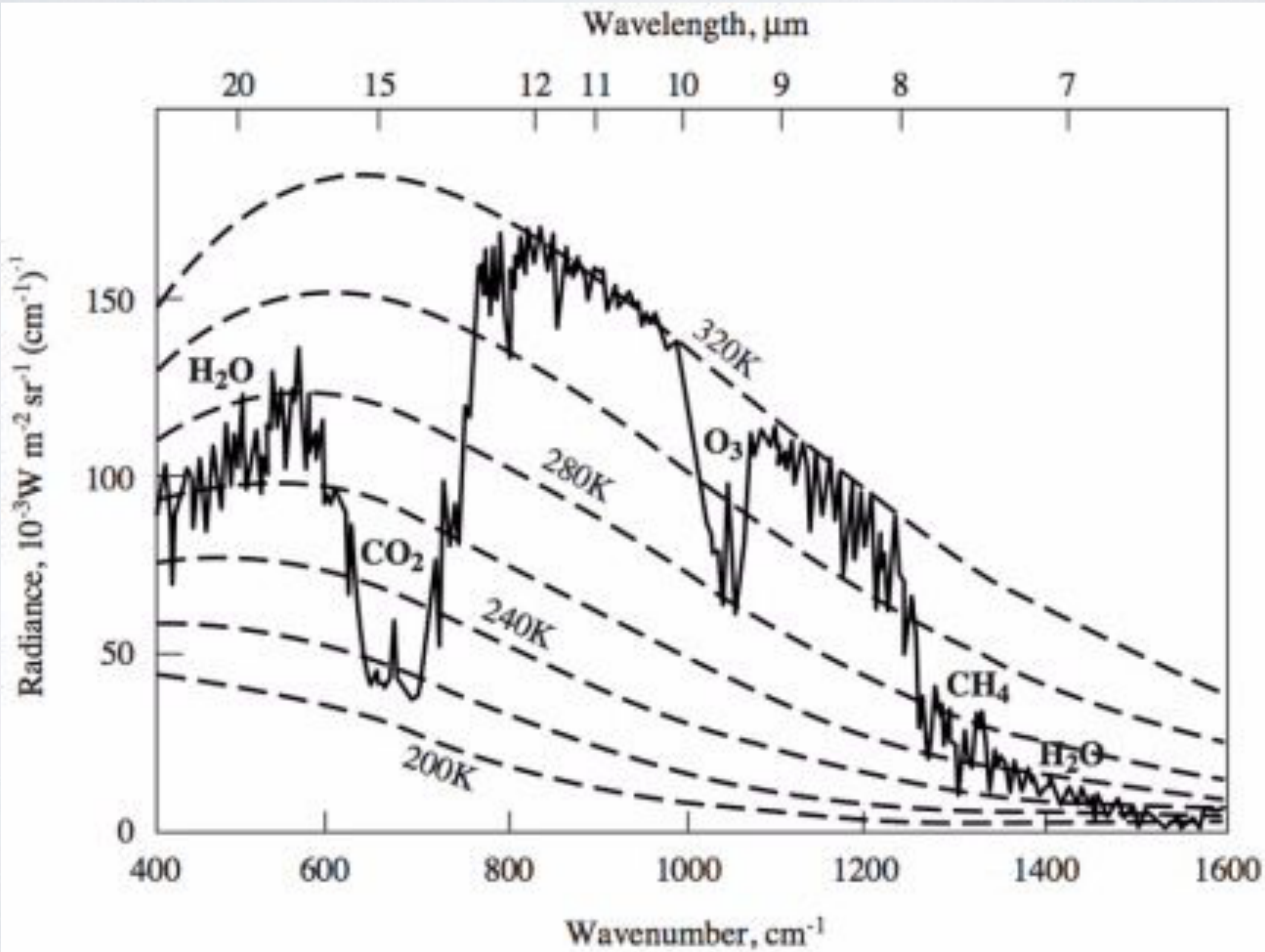
The Earth's natural greenhouse effect "wants" to make the Earth's surface unbearably hot, but the cooling effects of weather prevent most of that warming from occurring.

KEY PROCESS

- Without atmospheric absorption, the earth temperature would be ~0 F instead of ~59 F
- Re-absorption of Infra-red wavelengths by water, carbon dioxide and methane constitute the "greenhouse" effect.

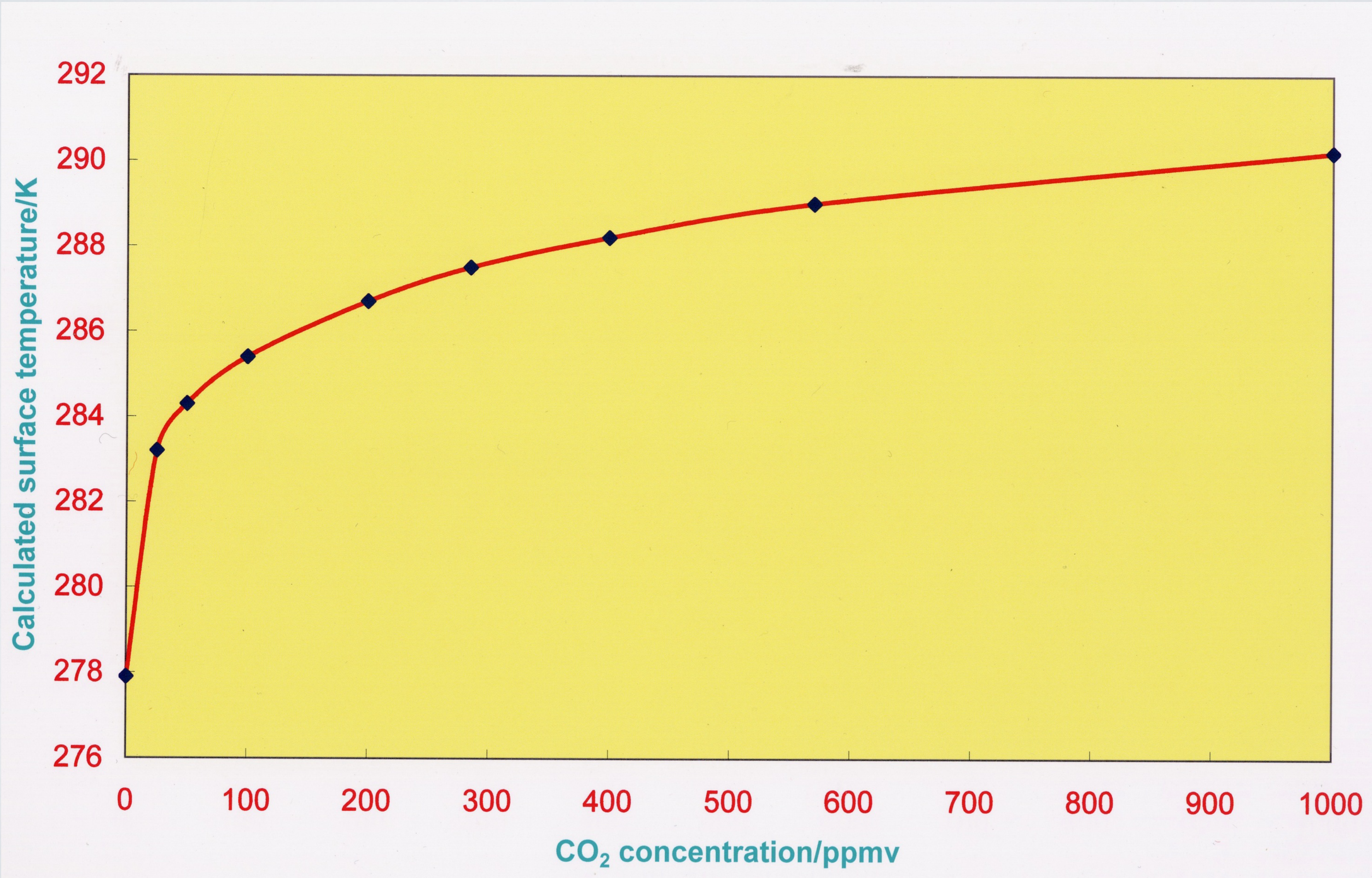
GREENHOUSE GAS ABSORPTION

http://www.barrettbellamyclimate.com/page19.htm

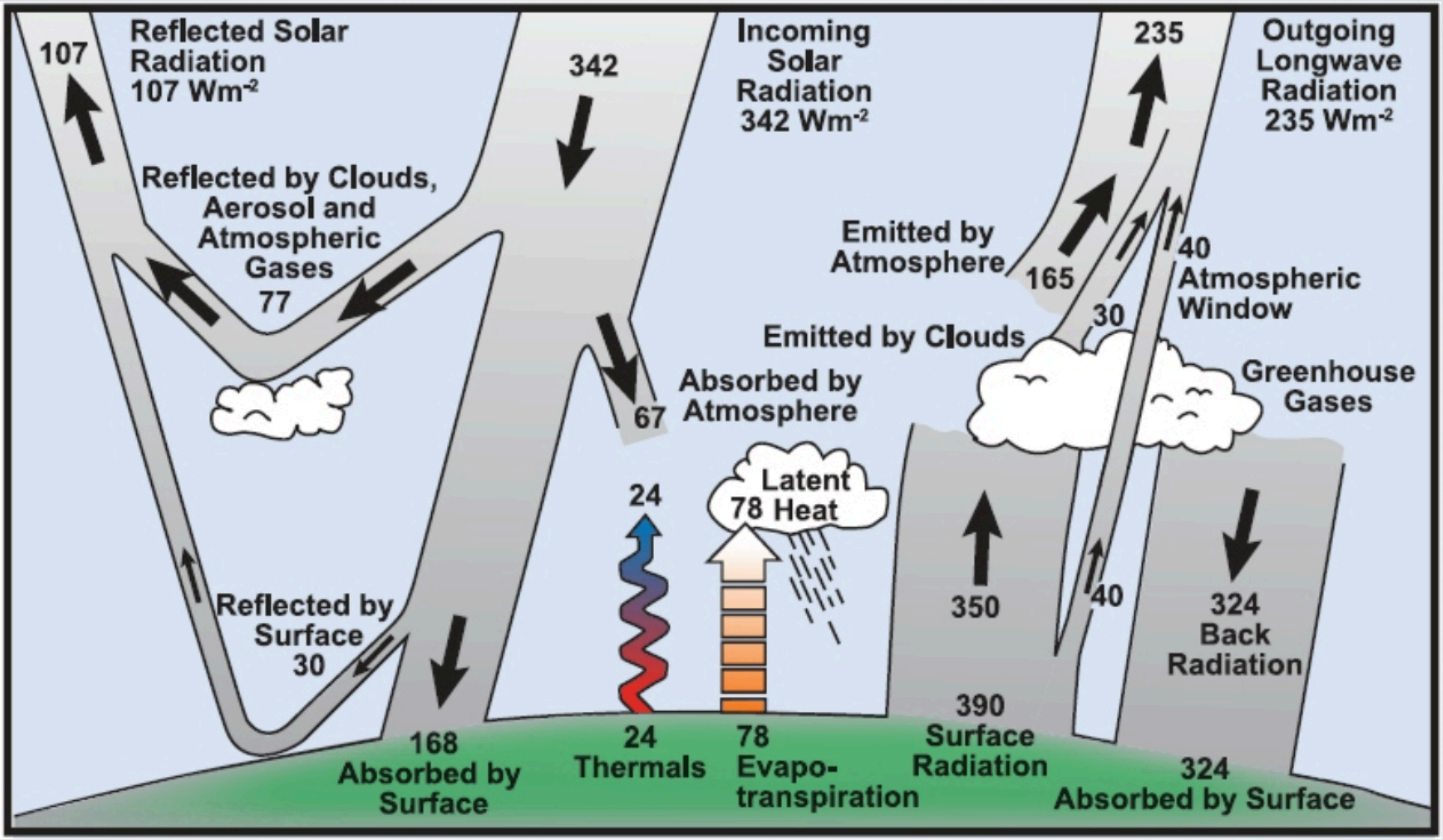


"RADIATIVE" CONTRIBUTION FROM CO2

http://www.barrettbellamyclimate.com/page28.htm

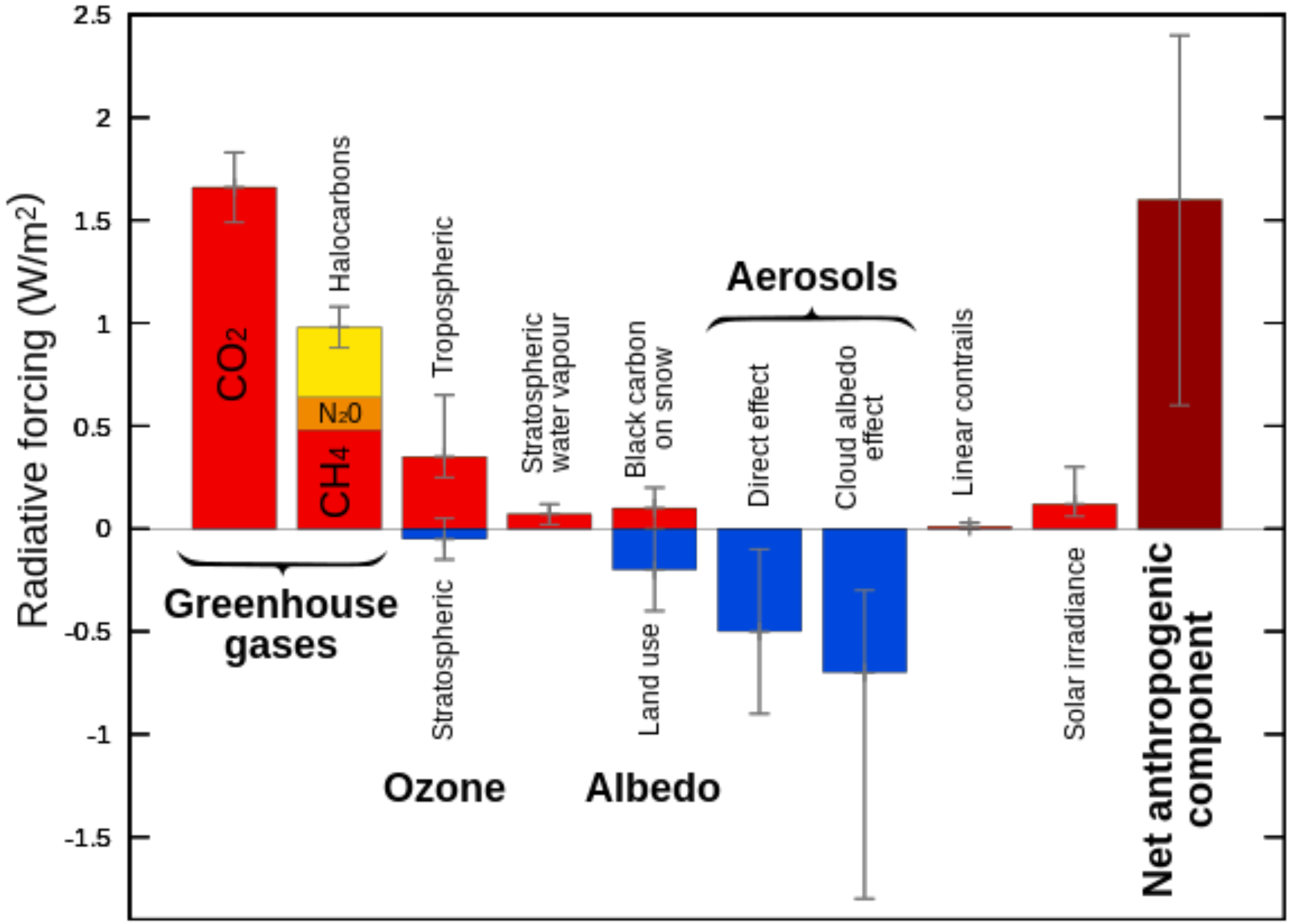


DETERMINATION OF CLIMATE

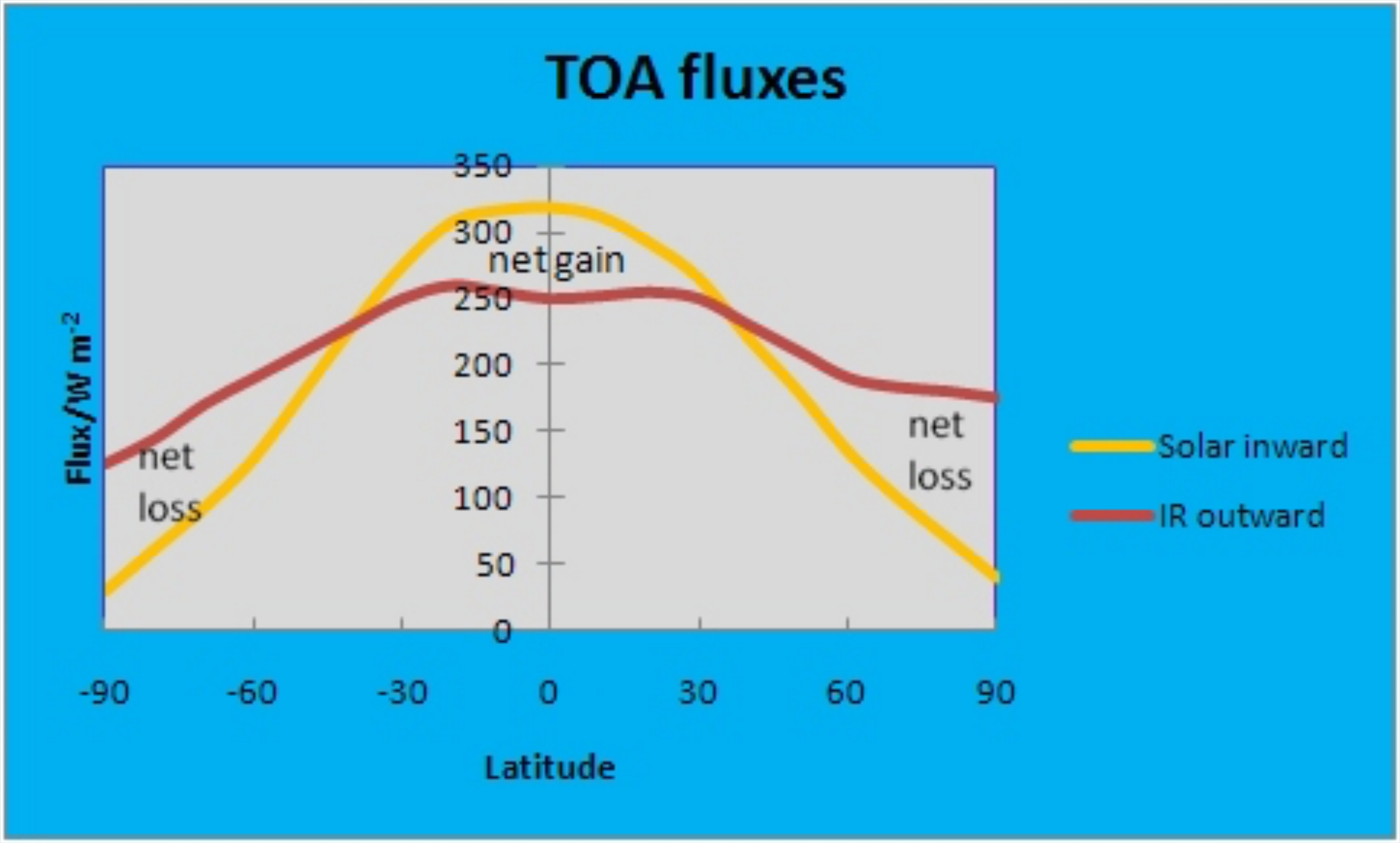


http://www.barrettbellamyclimate.com/page9.htm

Radiative forcing components

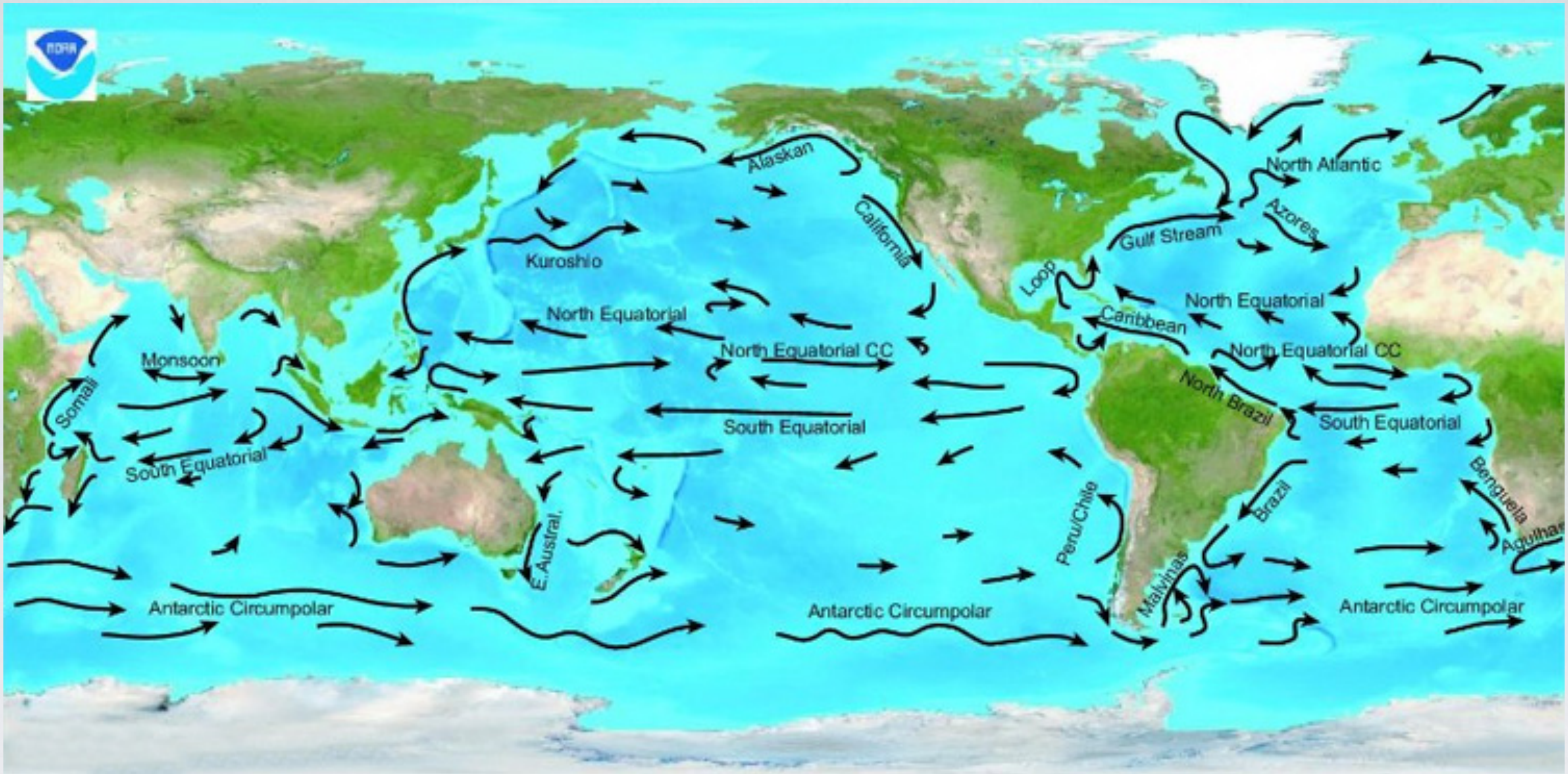


EFFECT OF LATITUDE



- Atmospheric/oceanic circulation processes cause a large flow of heat from the low latitudes to higher latitudes.

OCEAN CURRENTS



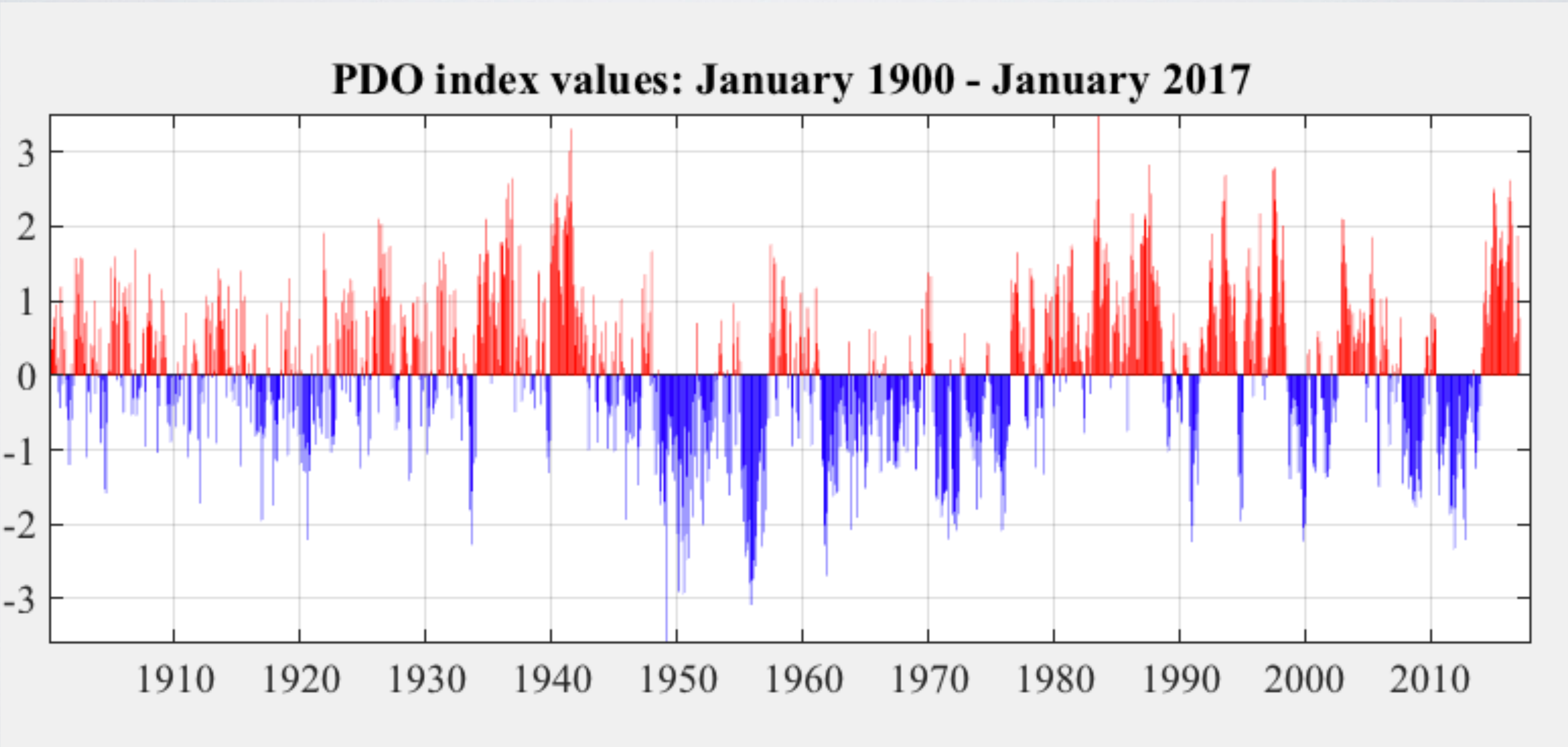
- The ocean currents have various (significant) oscillations that vary on the scale of years and decades

GULF STREAM

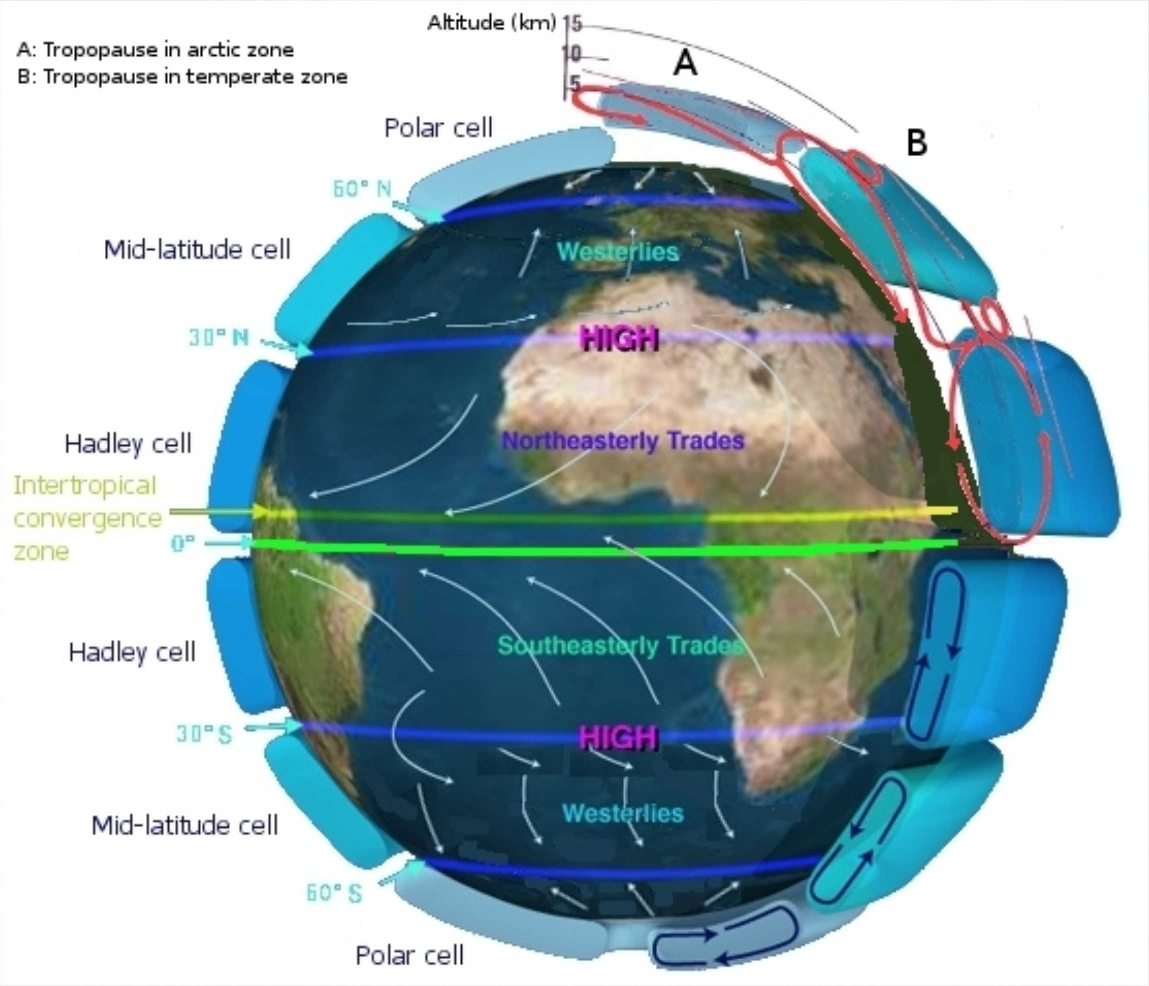
London, England in winter.

Quebec City, Quebec in winter.

PACIFIC DECADAL OSCILLATION



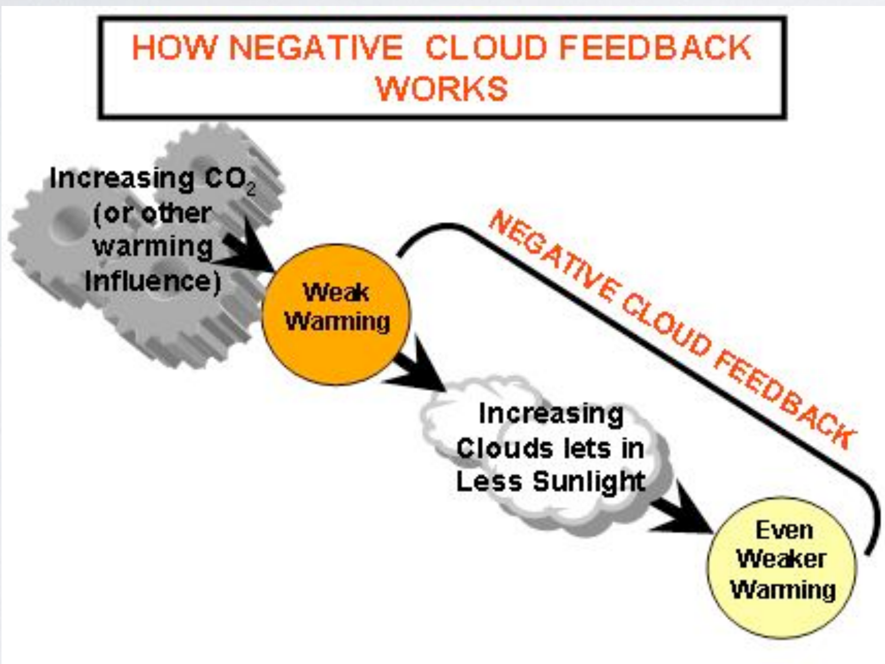
ATMOSPHERIC CIRCULATION

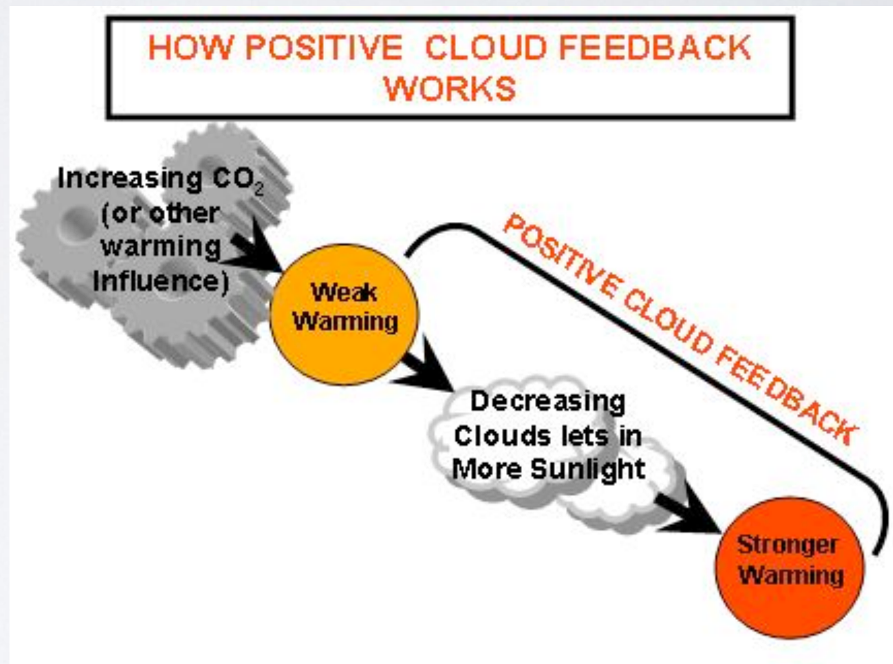


CLOUDS

- You may have noticed that precipitation processes come with some associated clouds(!)
  - Clouds can be either cooling or warming, although "moderating" might be a nominal result
  - We don't understand this well and we have no idea how the clouds have changed over the 20th century

EFFECT OF CLOUDS?





We don't know which it is?

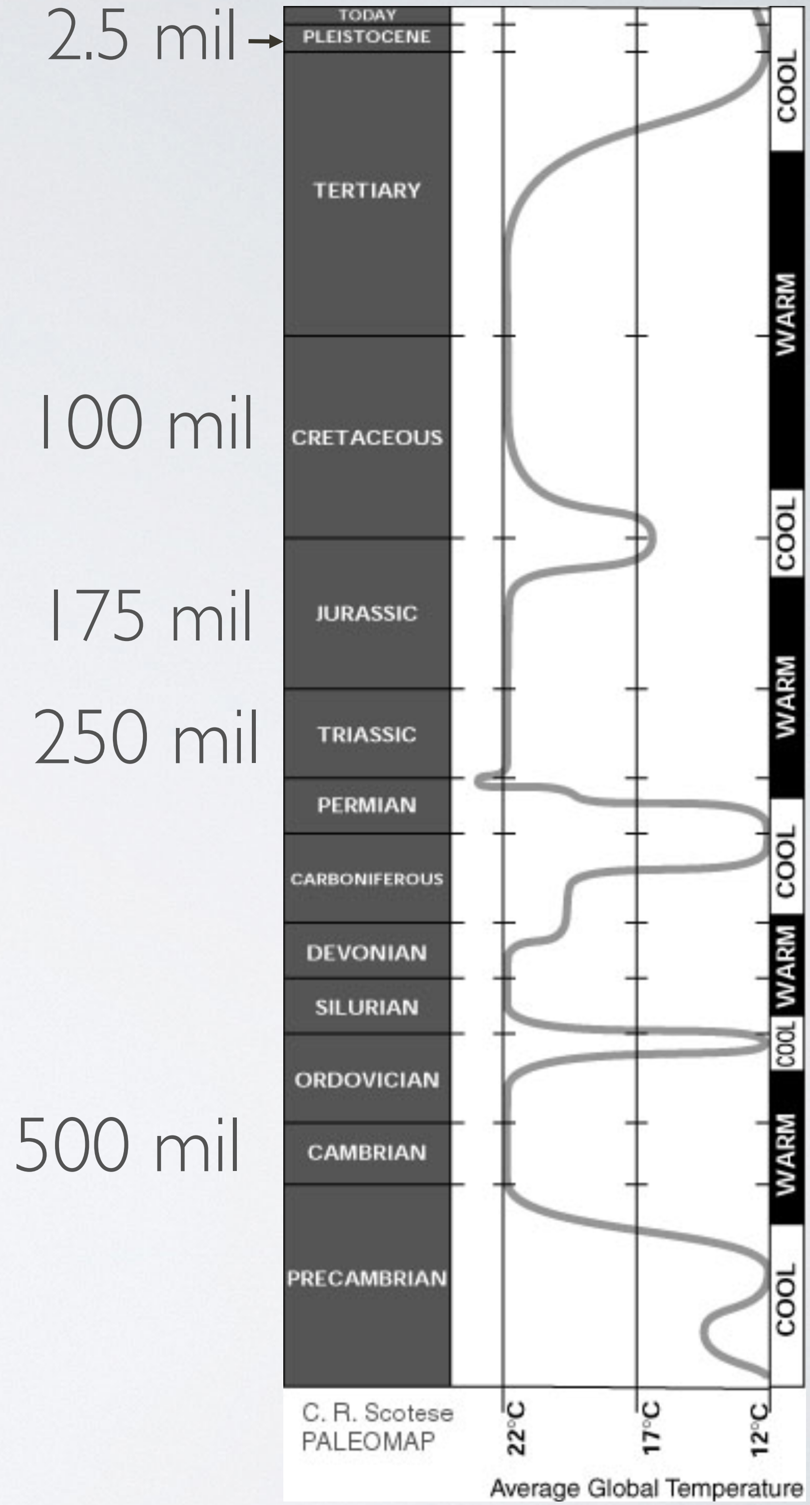
EFFECT OF WEATHER

- As noted in the "green line" from about 15 minutes ago, the processes of weather mix the atmosphere, contribute to water evaporation, cloud formation and destruction and cause a net cooling, although the higher latitudes are warmed.

TEMPERATURE

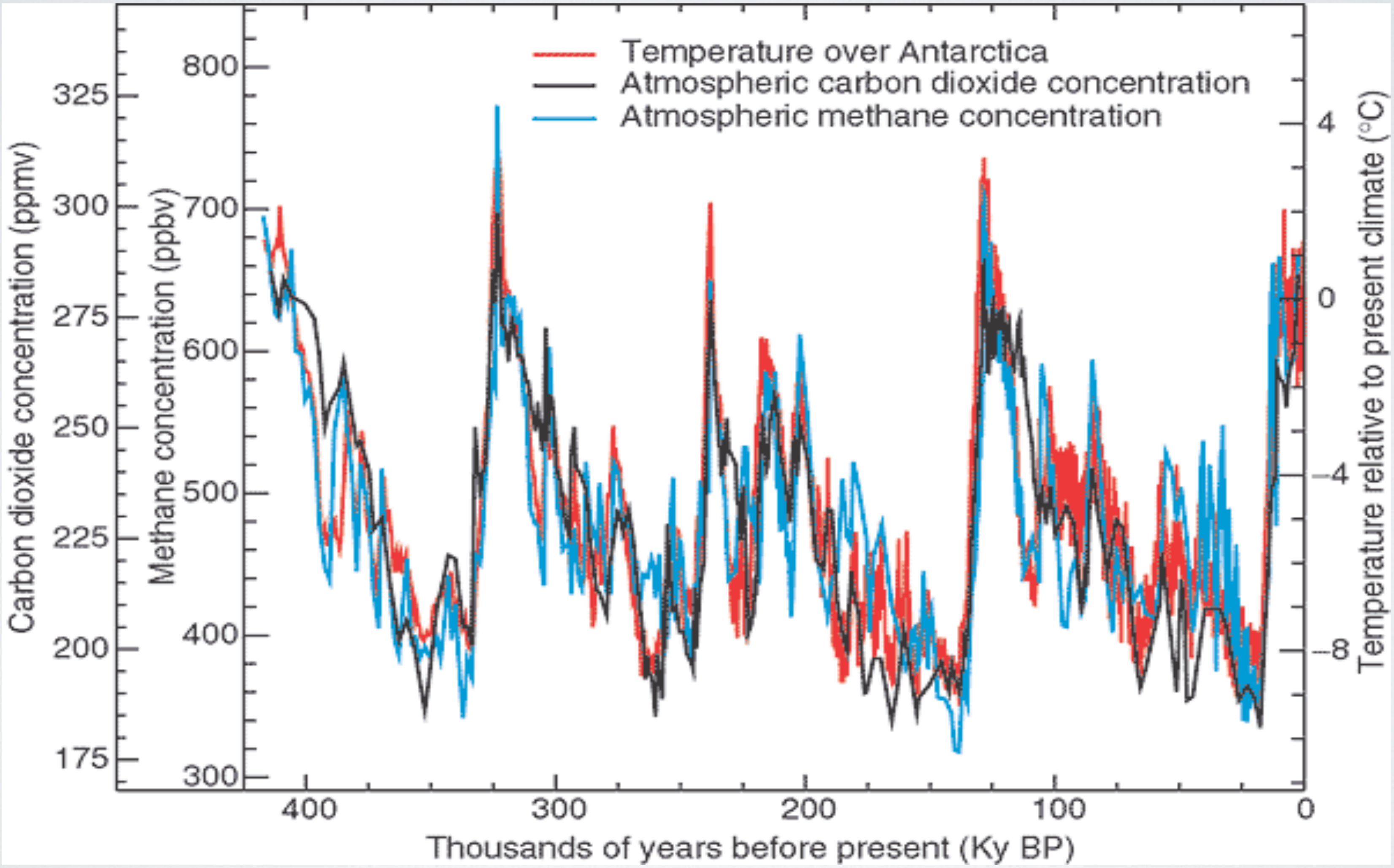
- We might worry about ocean pH, ice extent, or storm frequency…
- Since it gets the most attention, let's focus on temperature for a while

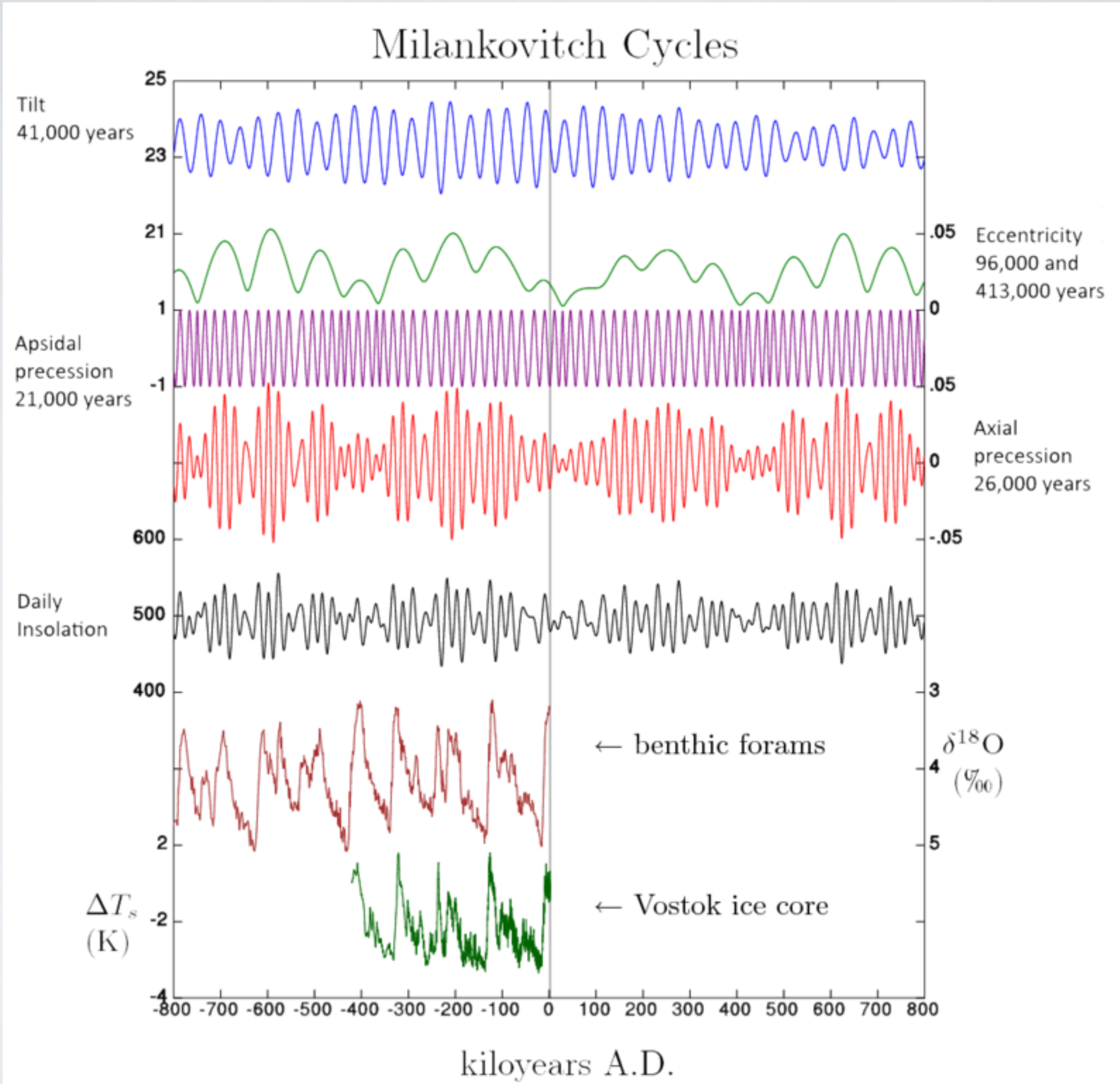
GEOLOGIC SCALES



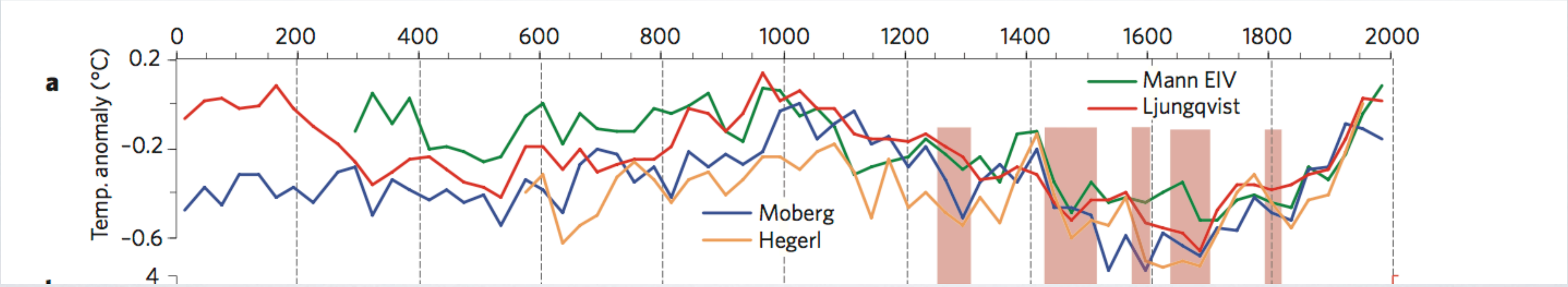
TEMPERATURE VARIATION

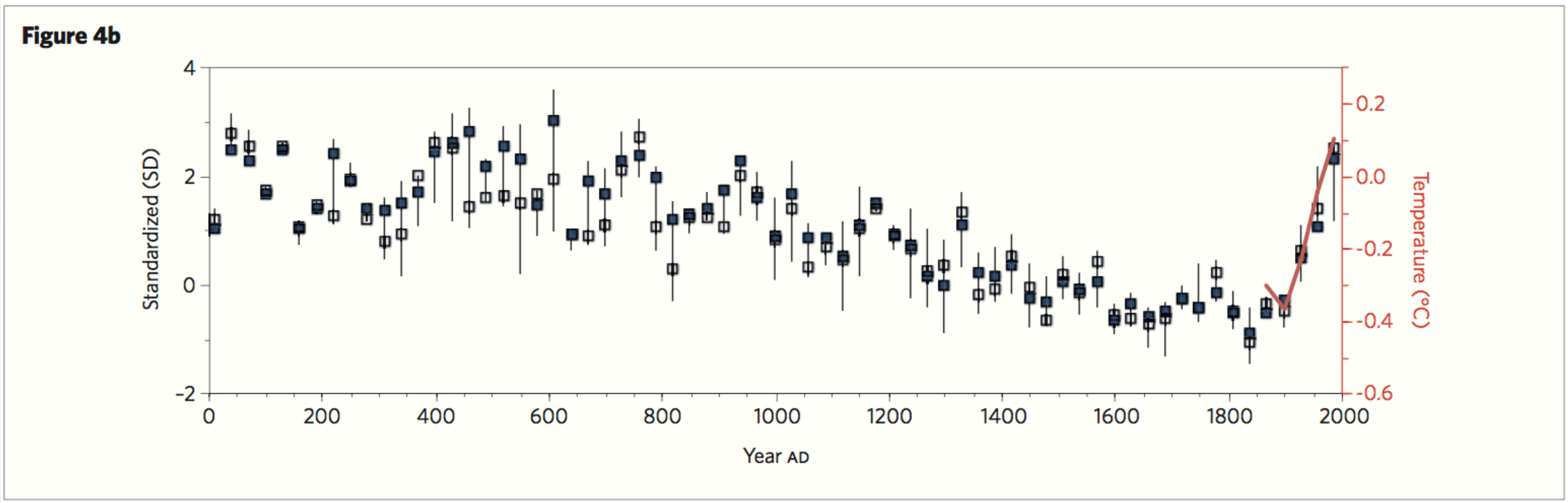
MILANKOVICH CYCLES




Milankovitch Cycles
Tilt
41,000 years
Eccentricity
96,000 and
413,000 years
Apsidal
precession
21,000 years
Axial
precession
26,000 years
Daily
Insolation
← benthic forams
$\delta^{18}O$
(‰)
← Vostok ice core
ΔT_s
(K)
25
23
21
1
-1
600
500
400
2
-2
-4
.05
0
.05
0
-.05
3
4
5
-800 -700 -600 -500 -400 -300 -200 -100 0 100 200 300 400 500 600 700 800
kiloyears A.D.

“RECENT” TEMPERATURES





- Proxies: ice cores, lake/marine sediments tree rings, coral, pollen

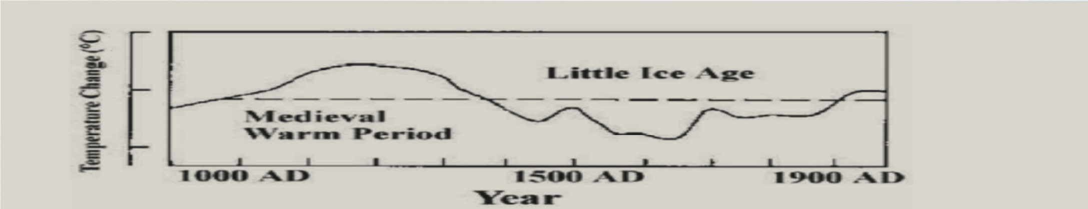
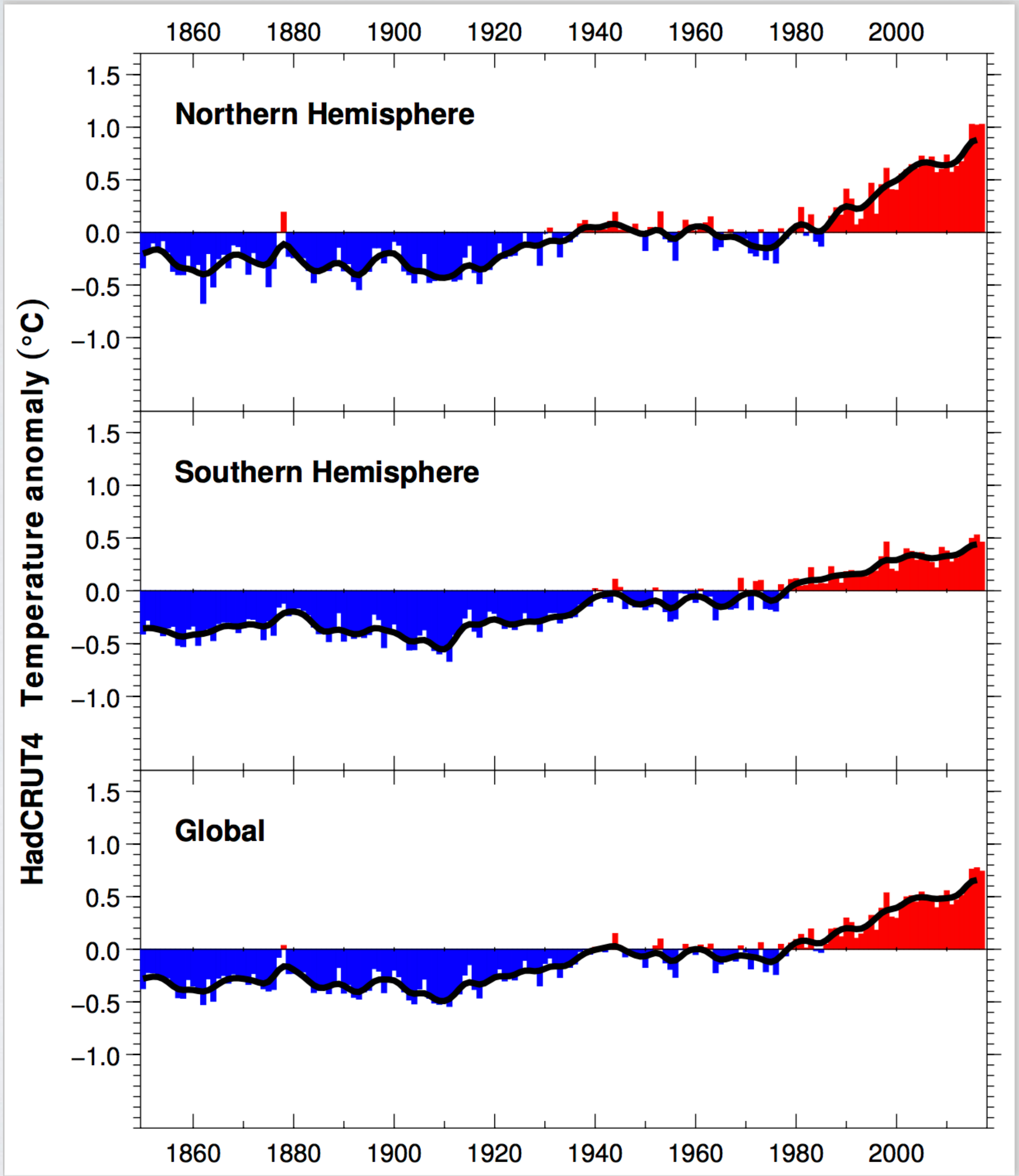
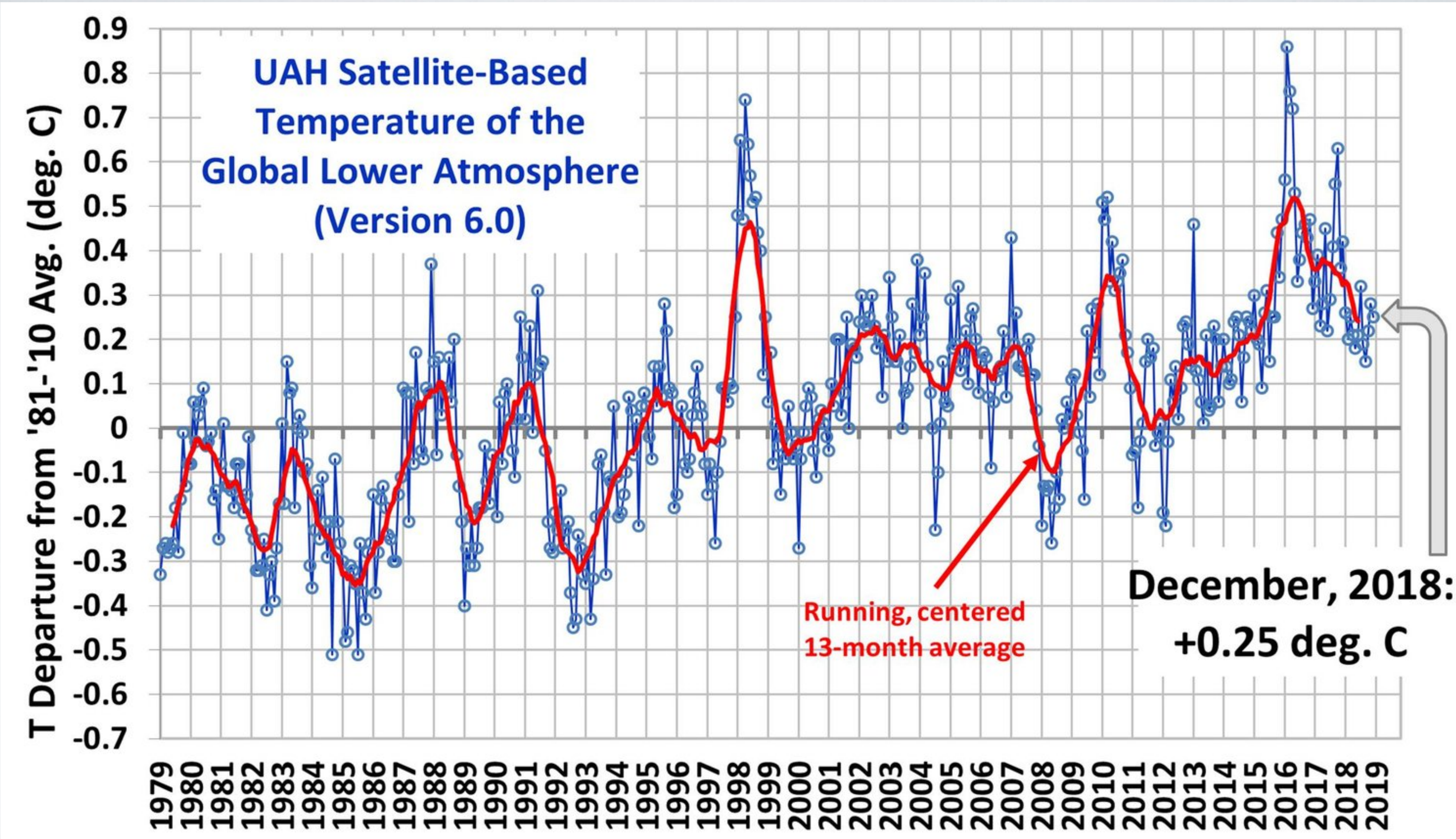


Figure 3: World Climate History According to IPCC in 1990.

TEMPERATURE MEASUREMENTS



SATELLITE TEMPERATURES



http://www.drroyspencer.com/latest-global-temperatures/

EARTH STATIONS V. SATELLITES

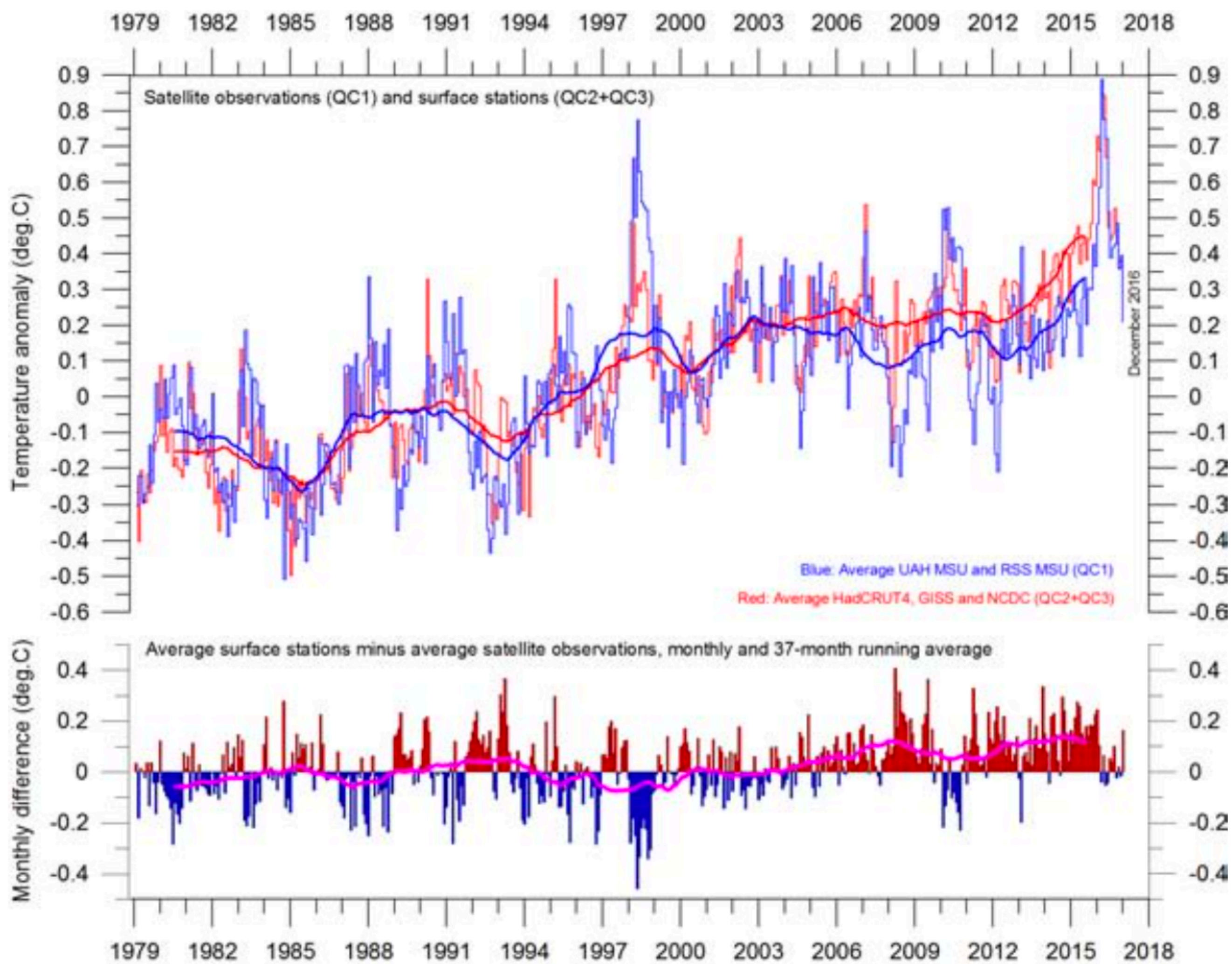
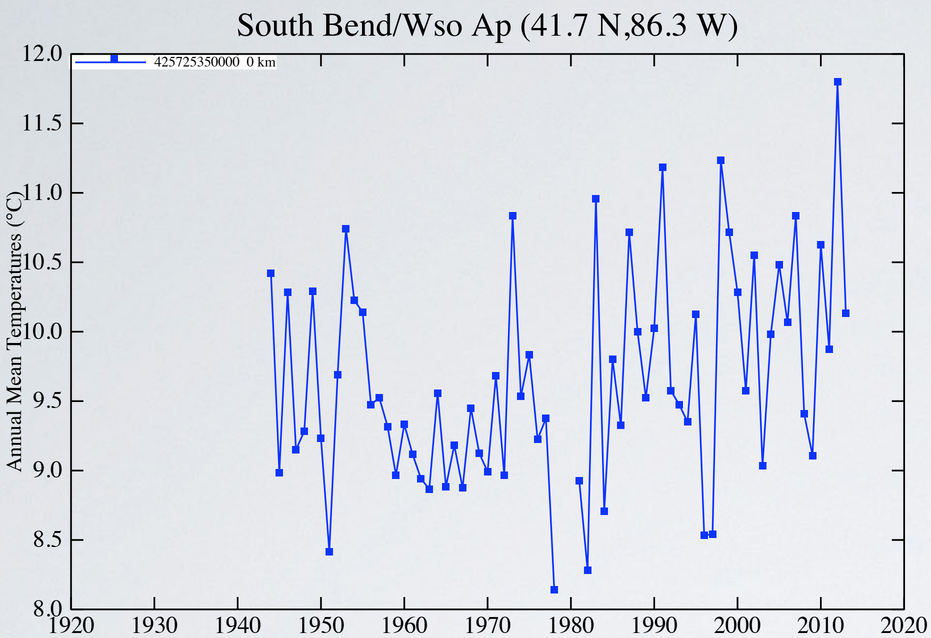
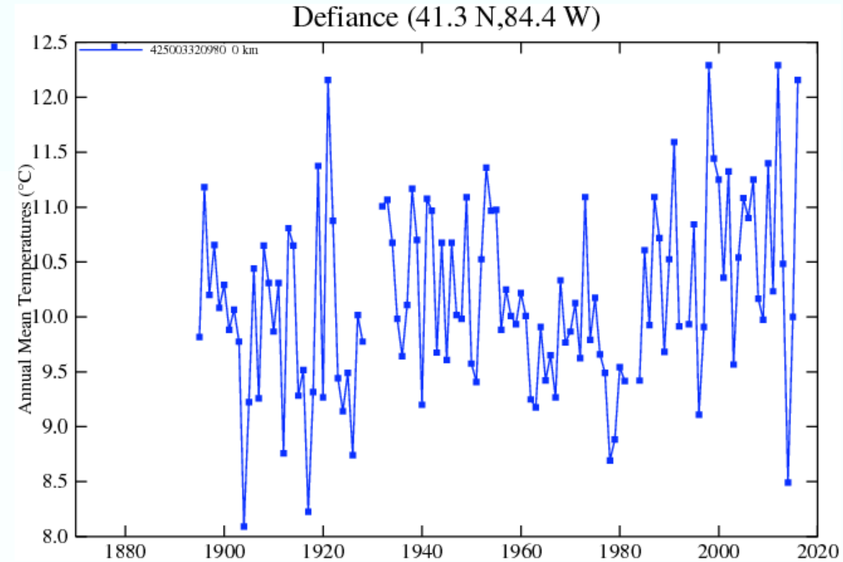


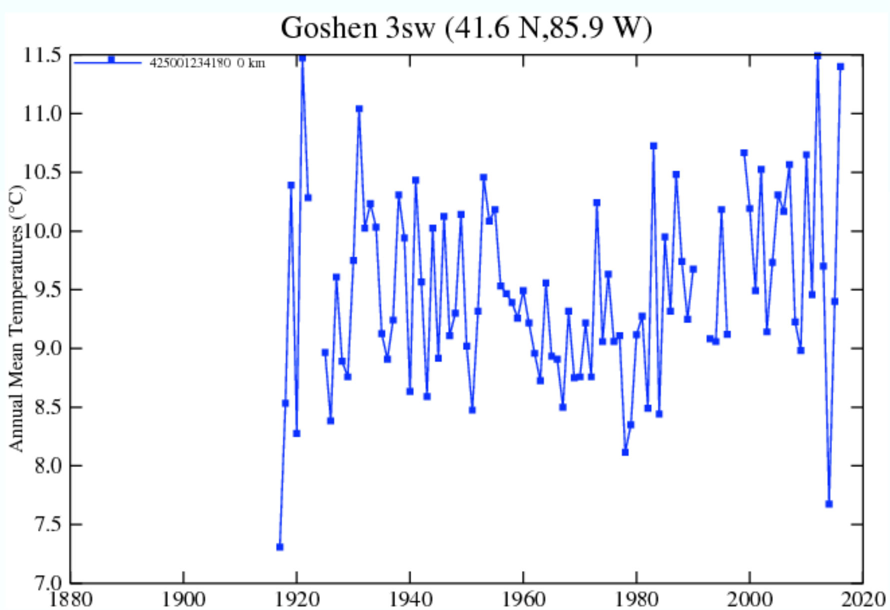
Figure 9: Plot showing the average of monthly global surface air temperature estimates (HadCRUT, NCDC and GISS) and satellite-based temperature estimates (UAH and RSS).



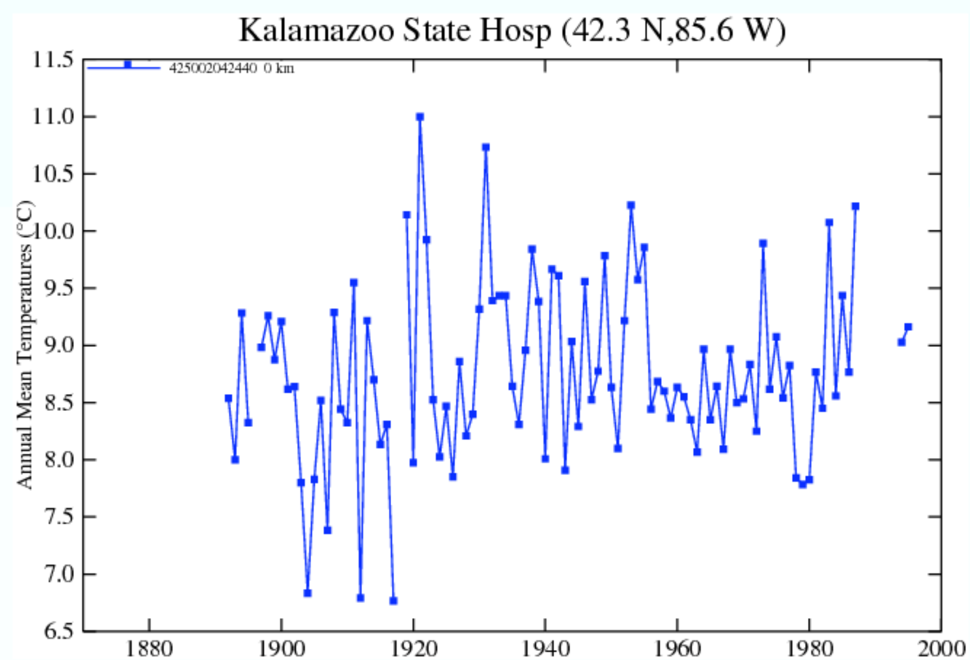
Station Data: Defiance (41.3 N,84.4 W)



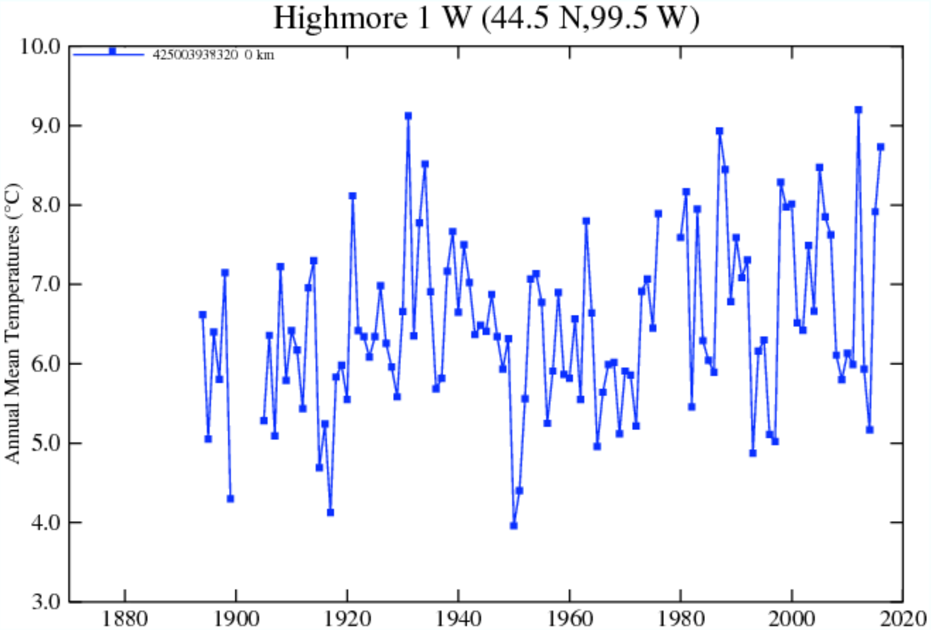
Station Data: Goshen 3sw (41.6 N,85.9 W)



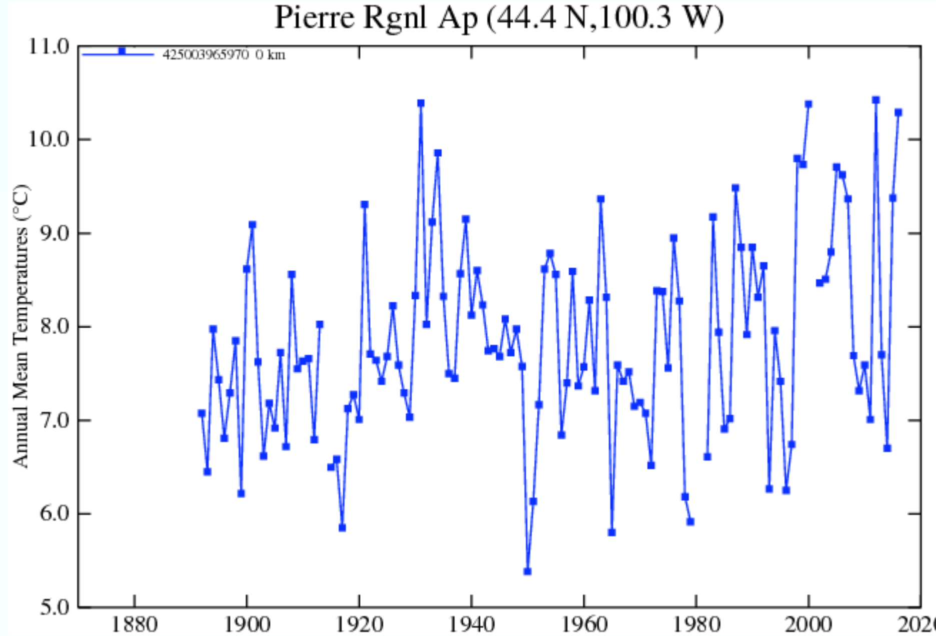
Station Data: Kalamazoo State Hosp (42.3 N,85.6 W)

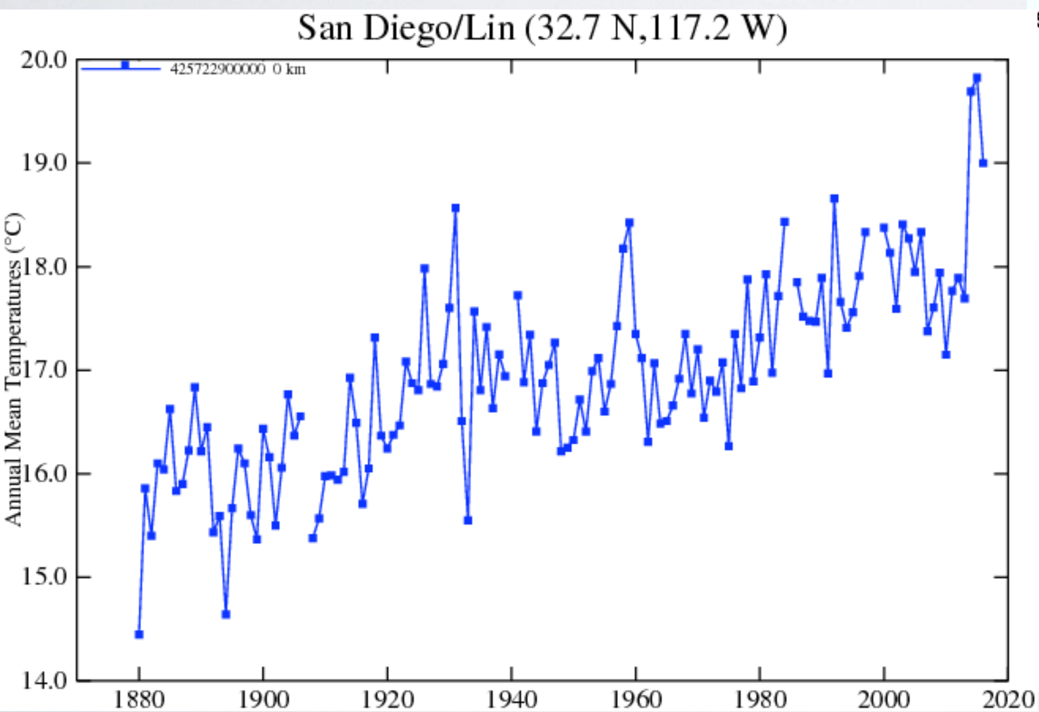


Station Data: Highmore 1 W (44.5 N,99.5 W)

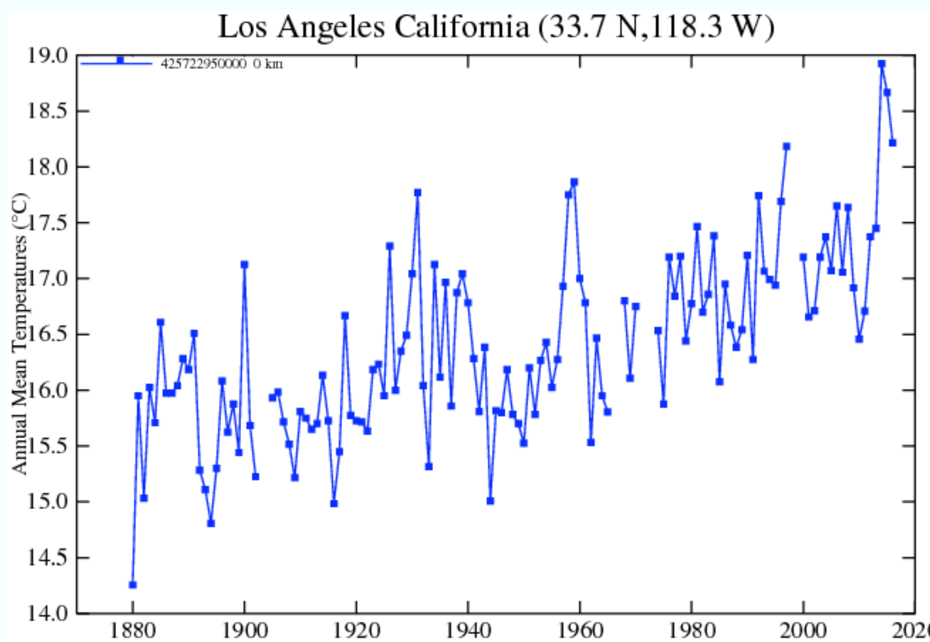


Station Data: Pierre Rgnl Ap (44.4 N,100.3 W)

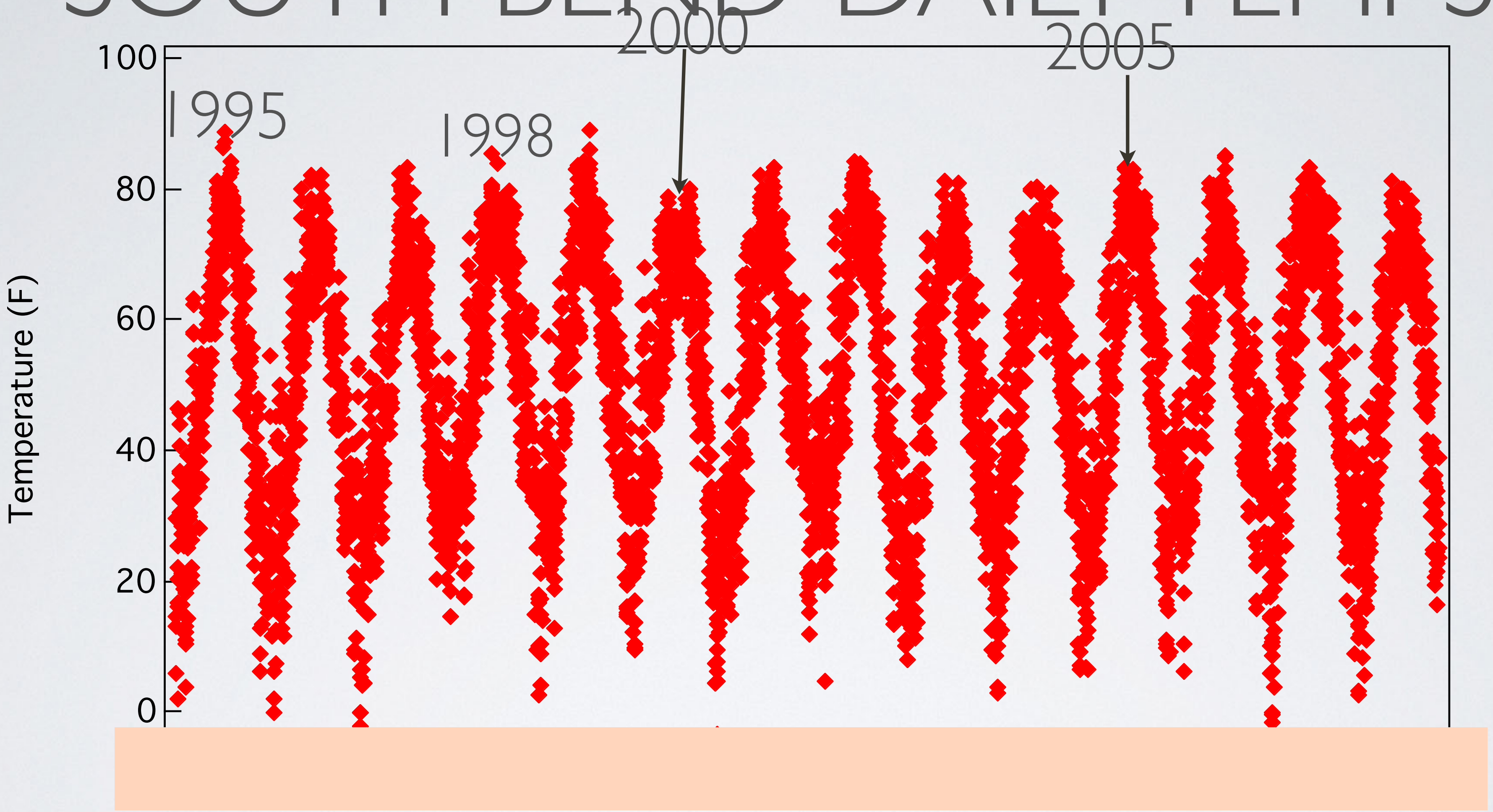




Station Data: Los Angeles California (33.7 N,118.3 W)

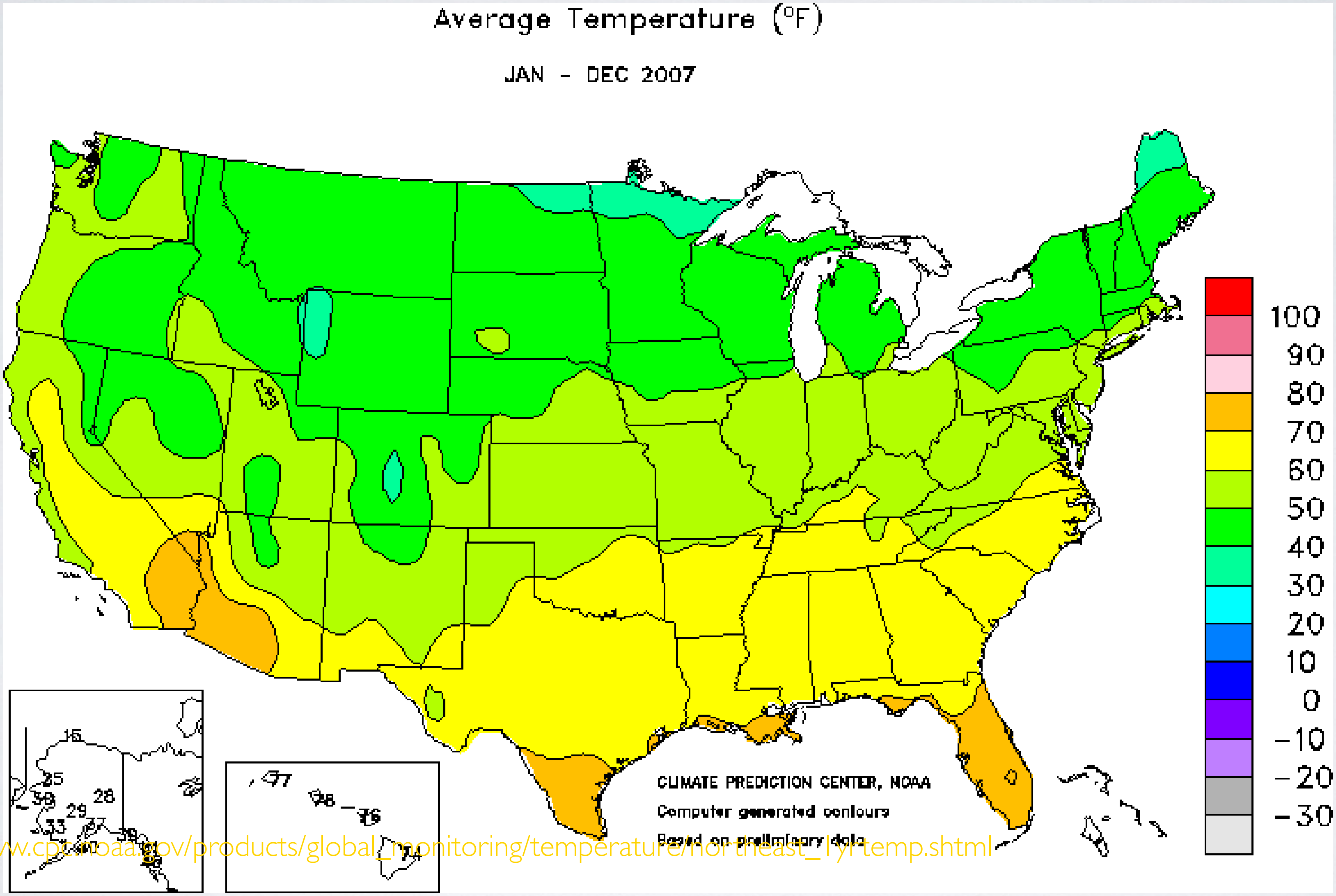


SOUTH BEND DAILY TEMPS



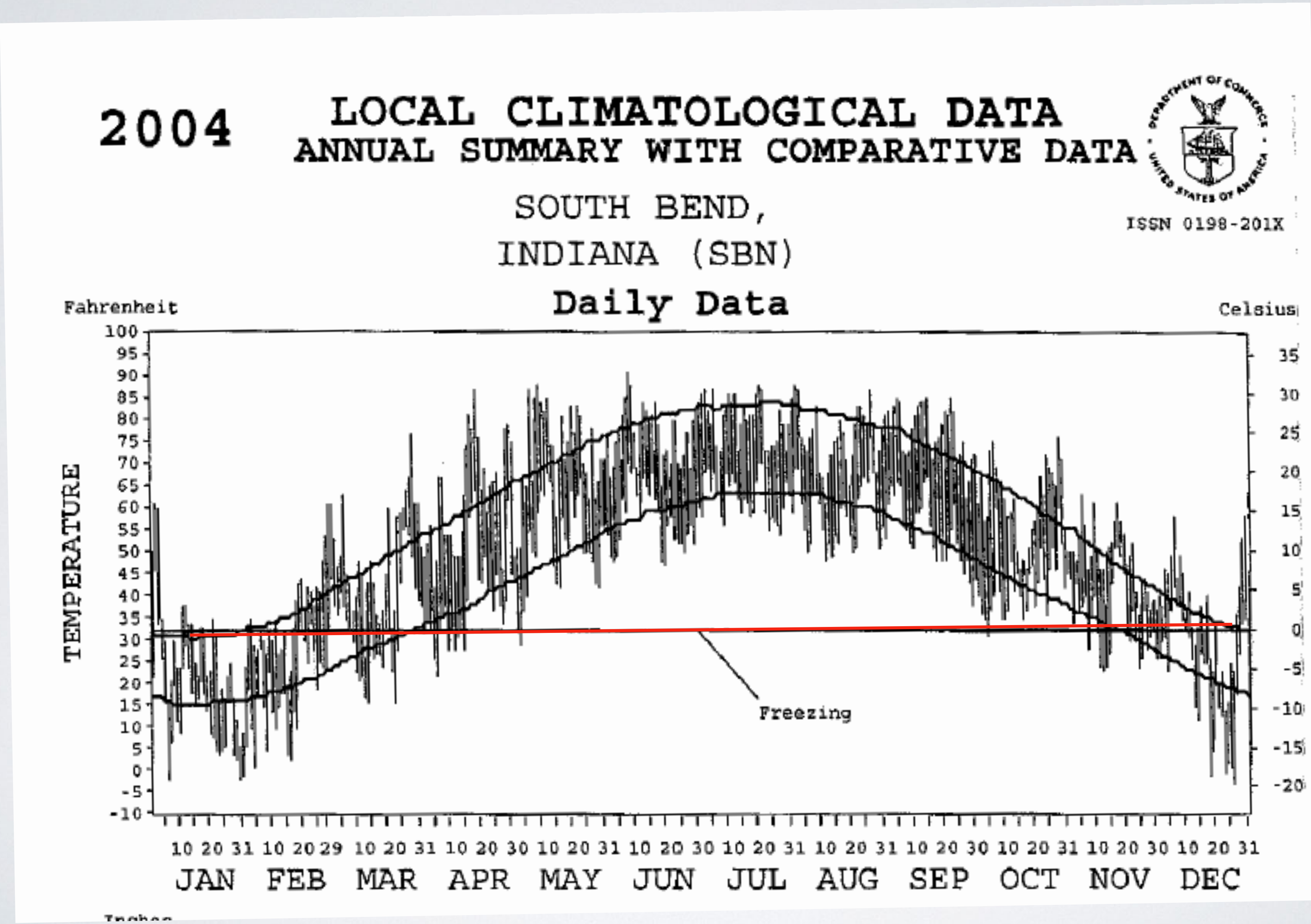
1995 - 2008

US AVERAGE TEMPS



http://www.cpc.noaa.gov/products/global_monitoring/temperature/northeast_1yr-temp.shtml

EFFECT OF TEMPERATURE ON GROWING SEASON



WHAT DIRECT EFFECT OF CO_2 INCREASE CAN BE SEEN?

- Day v. Night Temps (nights got warmer during 1950-1997)

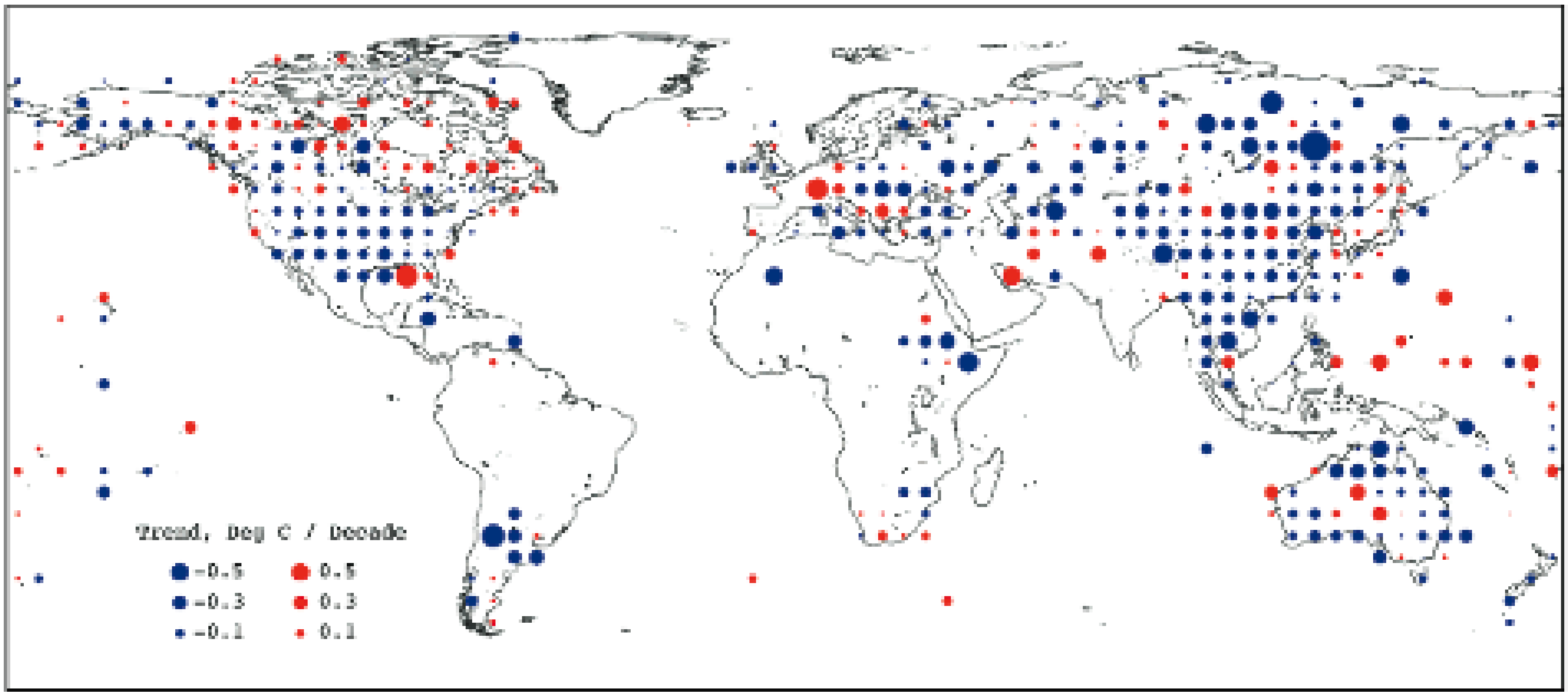


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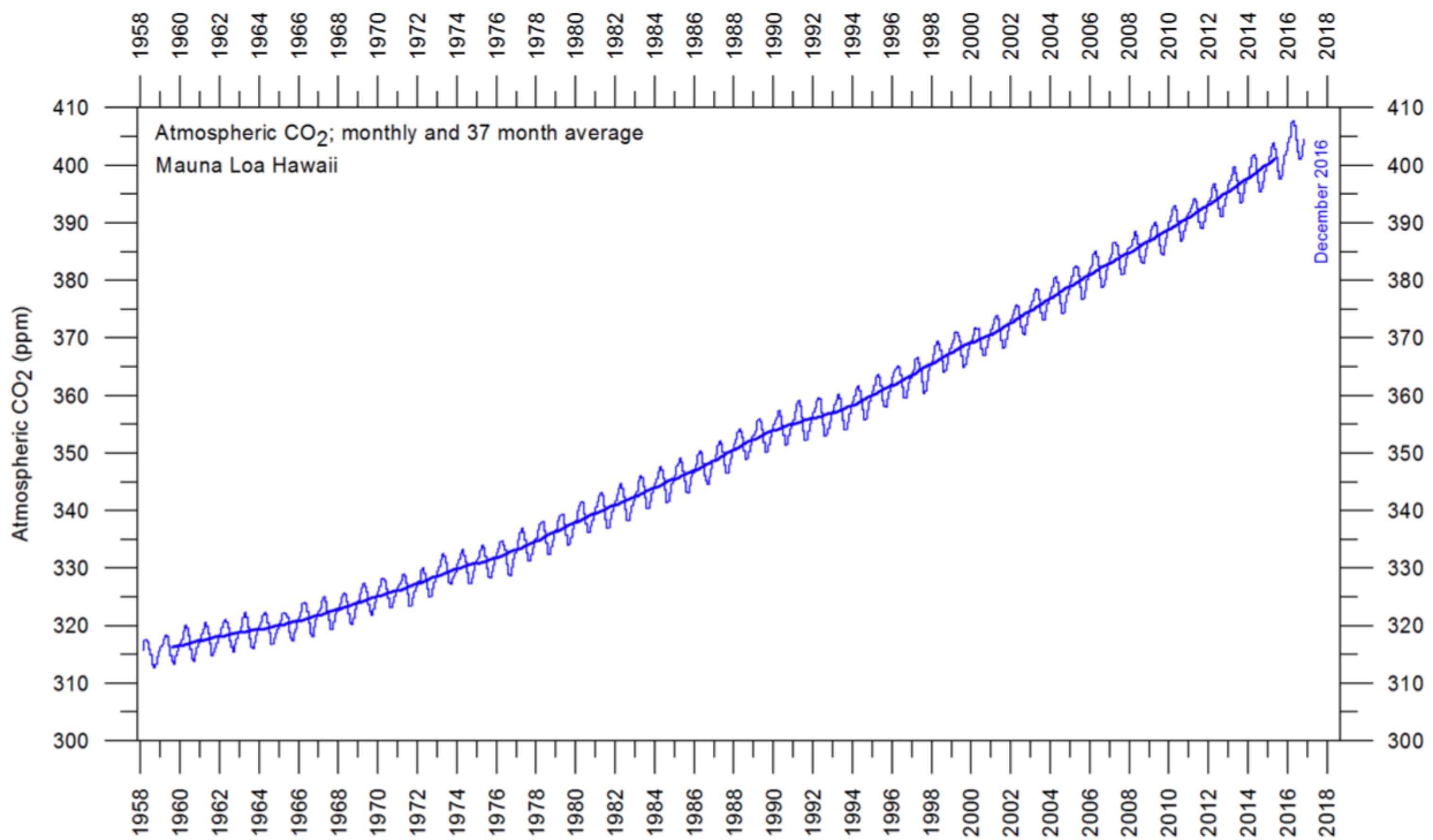
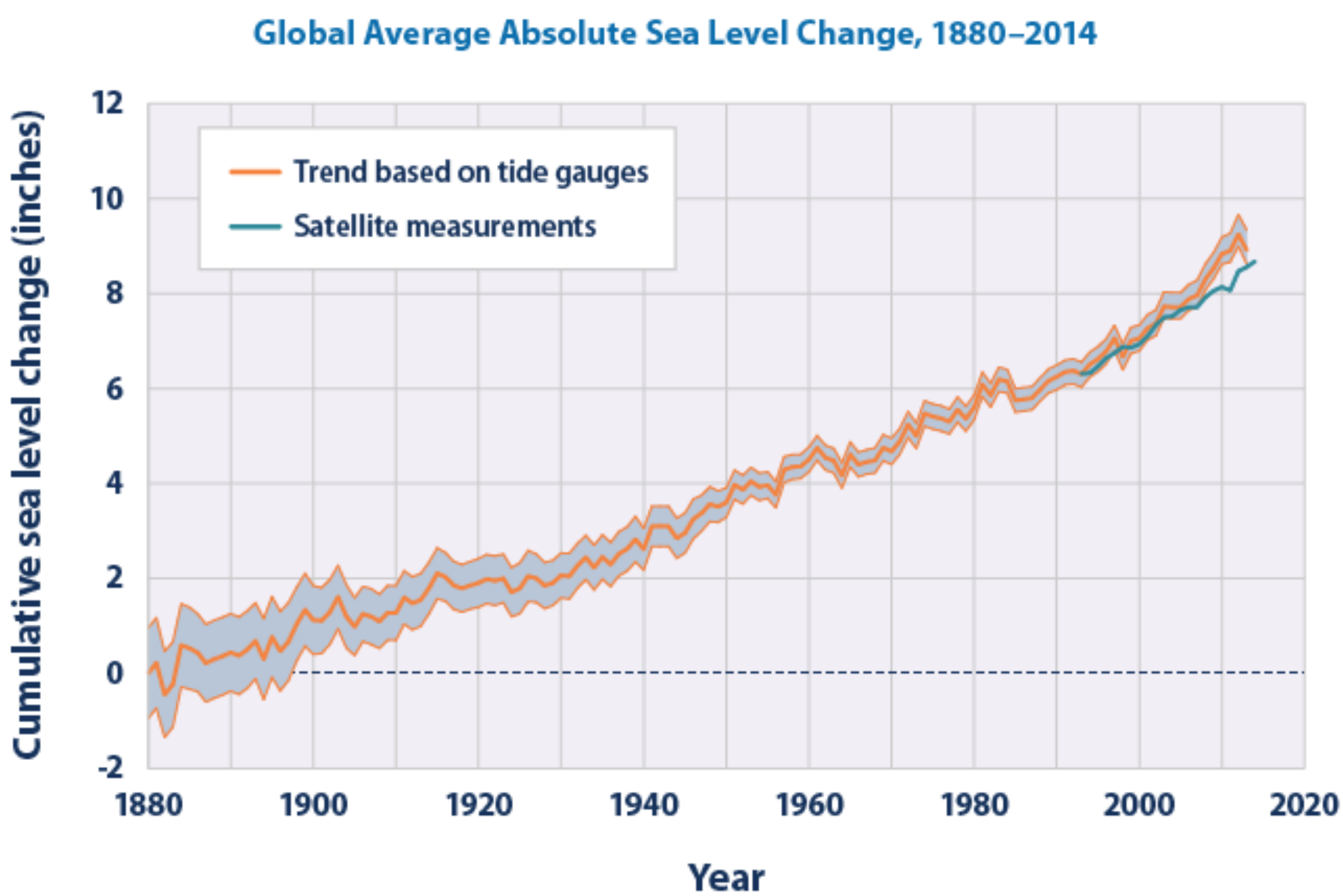
Figure. 2.2: Trends in annual diurnal temperature range (DTR, °C/decade), from 1950 to 1993, for non-urban stations only, updated from Easterling *et al.* (1997). Decreases are in blue and increases in red. This data set of maximum and minimum temperature differs from and has more restricted coverage than those of mean temperature used elsewhere in Section 2.2.

BEST INSTRUMENTAL CO2 RECORD



(a) Monthly concentrations since March 1958; thin line, monthly values; thick line, simple running 37-month average, nearly corresponding to a running 3-yr average.

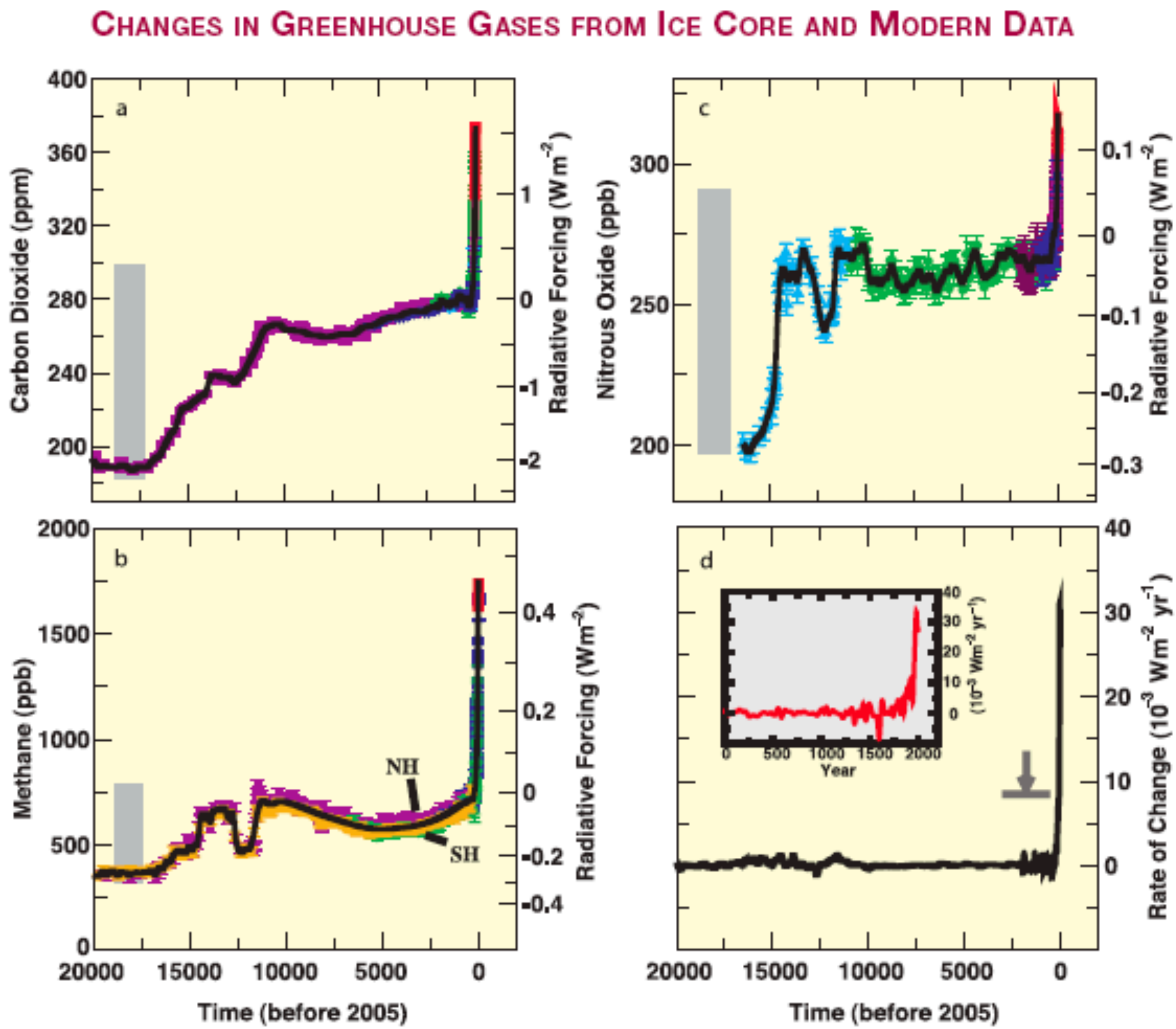
SEA LEVEL



Data sources:

- CSIRO (Commonwealth Scientific and Industrial Research Organisation). 2015 update to data originally published in: Church, J.A., and N.J. White. 2011. Sea-level rise from the late 19th to the early 21st century. Surv. Geophys. 32:585–602. www.cmar.csiro.au/sealevel/sl_data_cmar.html.
- NOAA (National Oceanic and Atmospheric Administration). 2015. Laboratory for Satellite Altimetry: Sea level rise. Accessed June 2015. http://ibis.grdl.noaa.gov/SAT/SeaLevelRise/LSA_SLR_timeseries_global.php.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climatechange/indicators.



CHANGES IN GREENHOUSE GASES FROM ICE CORE AND MODERN DATA
a
Carbon Dioxide (ppm)
Radiative Forcing (W m^{-2})
c
Nitrous Oxide (ppb)
Radiative Forcing (W m^{-2})
b
Methane (ppb)
Radiative Forcing (Wm^{-2})
NH
SH
d
Year
(10^{-3} Wm^{-2} yr^{-1})
Rate of Change (10^{-3} Wm^{-2} yr^{-1})
Time (before 2005)
Time (before 2005)

IPCC 2007

NOW IT'S A SCYTHE!

SO, WHAT ARE THE ISSUES?

- Will the temperature continue to increase and if so, at what rate? (depending on rate of CO_2 emissions)
  - The only way to access this is by computer models of the climate!
- How will precipitation be affected?
- Will crop yields be affected?
- Does the CO_2 in the atmosphere cause a change in ocean pH and affect marine life
- Will the sea level increase at a higher rate?
- Could anything (actually) be done about the CO_2 emissions?

SOME MUSINGS

- Missing Carbon(http://www.nature.com/climate/2007/0708/full/climate.2007.35.html)
- Things we thought we knew:
  - Margarine was considered a health food
  - Stomach Ulcers are caused by stress
  - Plants absorb CO2 and emit O2
  - The adult brain has no capacity to regenerate itself
  - Komodo Dragons bit their prey and waited for them to succumb to bacterial infections
  - Planets, other than earth, that are in "Goldilocks" orbits around stable stars are very rare.

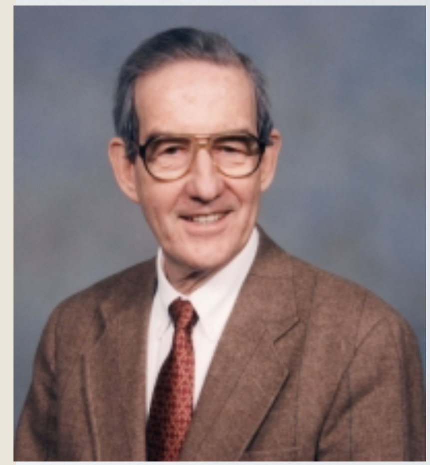
- You lost me at hello!

- https://www.youtube.com/watch?v=AyrP-pwDayE

Geoff Hewitt

2. How do scientists know that recent climate change is largely caused by human activities?

Human activity leads to emissions of greenhouse gases (causing warming), and of other pollutants that produce small particles in the atmosphere (which can have both cooling and warming effects). The dominant influence of human activities on recent climate change is clear from an understanding of the basic physics of the greenhouse effect and from comparing the detailed patterns of recent climate change with those expected from different human and natural influences. Only when human influences on the composition of the atmosphere are incorporated can models reproduce observed changes in climate.



Tom Hanratty

THE BASIC CORRECTNESS AND RELIABILITY OF THE MODELS IS IN DOUBT

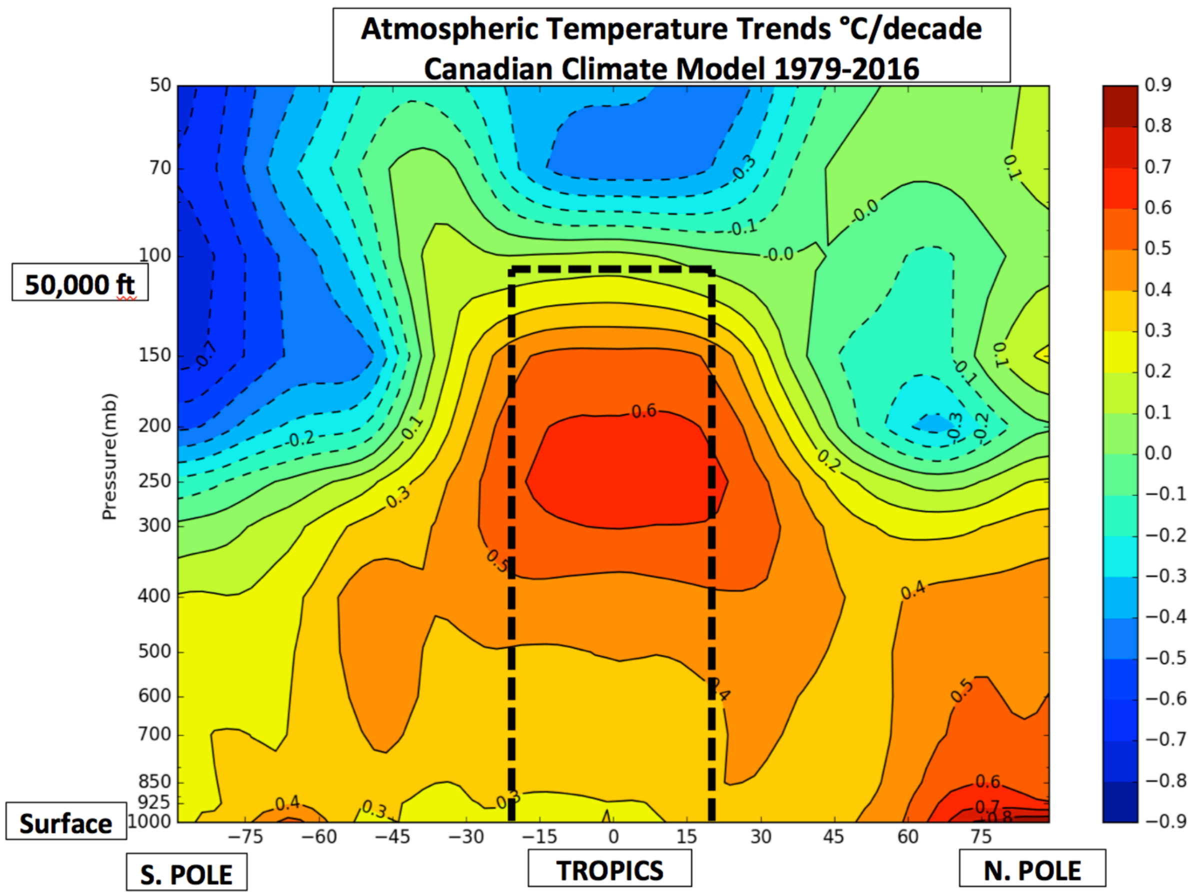


Figure 1 Temperature trends (°C/decade) for 1979-2016 of the cross-section of the atmosphere as simulated by the Canadian Climate Model. The tropical band (20°S-20°N) is outlined for the bulk layer (surface to 50,000 ft) that represents the microwave T_{MT} measurement (Temperature Mid-Troposphere). This outlined-layer is the region of prominent warming for the 1979-2016 period as depicted in all models and thus is the region to examine relative to observations (Figure by Rob Junod, UAH).

https://science.house.gov/sites/republicans.science.house.gov/files/documents/HHRG-115-SY-WState-JChristy-20170329.pdf

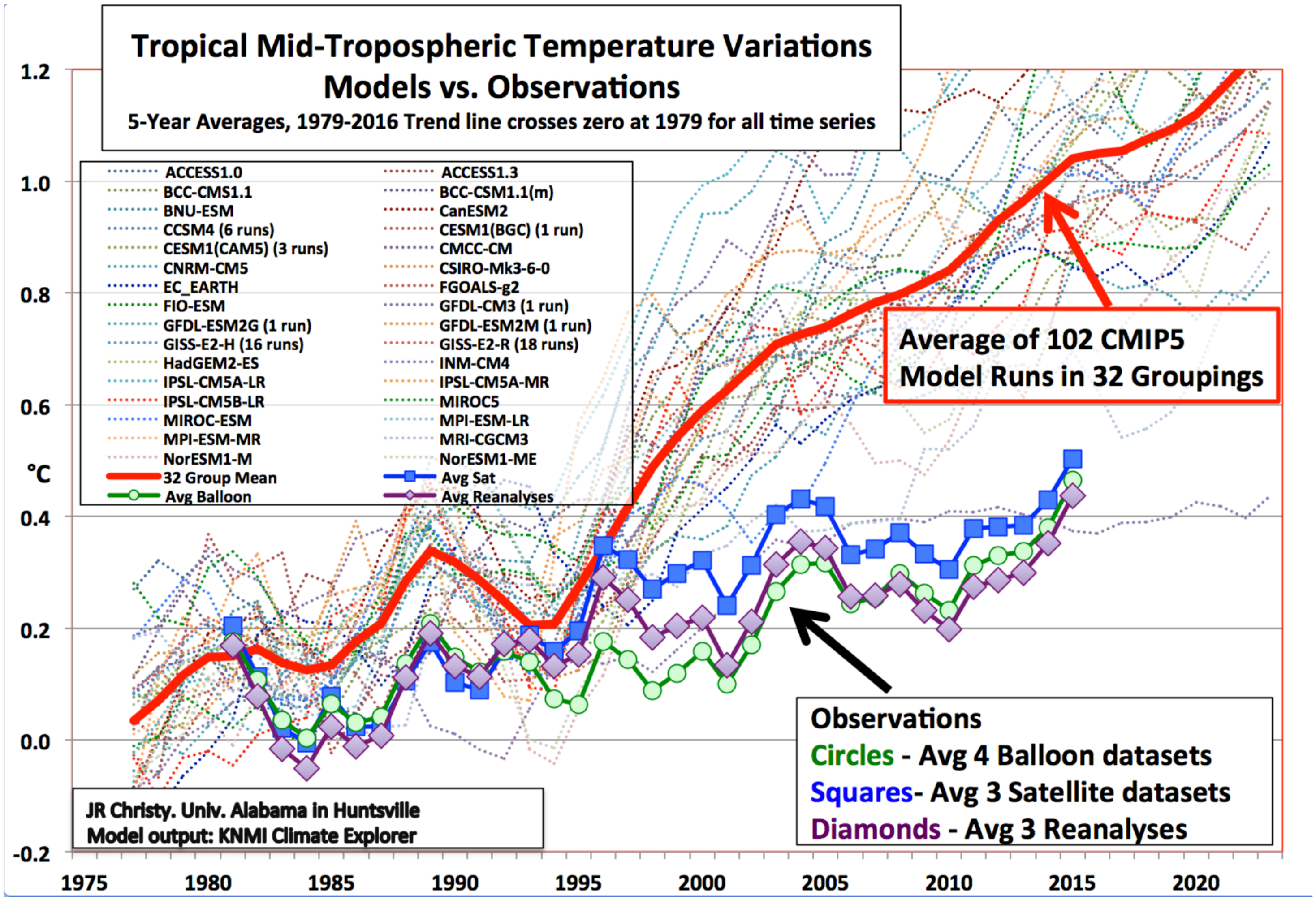


Figure 2: Five-year averaged values of annual mean (1979-2016) tropical bulk T_{MT} as depicted by the average of 102 IPCC CMIP5 climate models (red) in 32 institutional groups (dotted lines). The 1979-2016 linear trend of all time series intersects at zero in 1979. Observations are displayed with symbols: Green circles - average of 4 balloon datasets, blue squares - 3 satellite datasets and purple diamonds - 3 reanalyses. See text for observational datasets utilized. The last observational point at 2015 is the average of 2013-2016 only, while all other points are centered, 5-year averages.

https://science.house.gov/sites/republicans.science.house.gov/files/documents/HHRG-115-SY-WState-JChristy-20170329.pdf

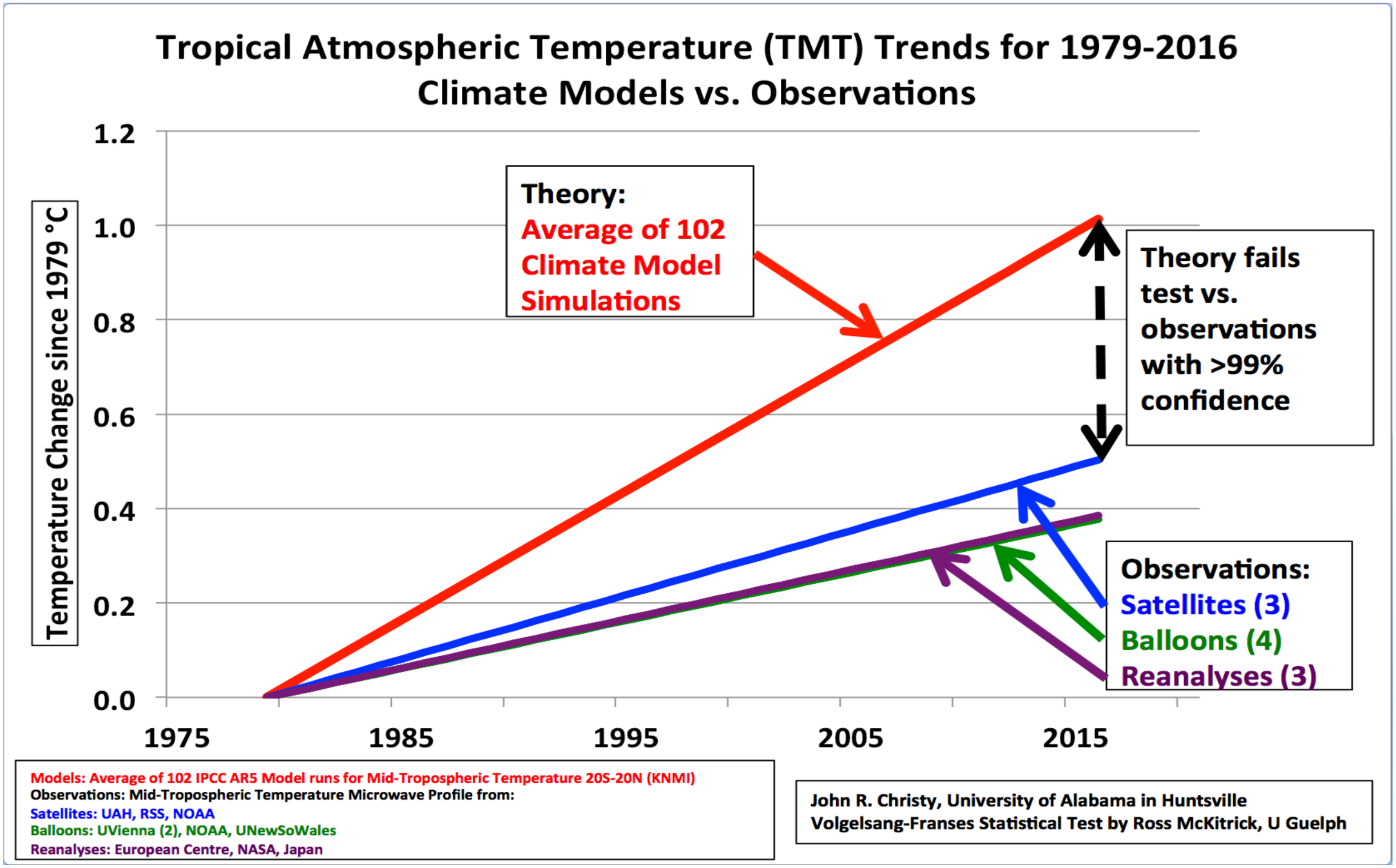


Figure 3. The linear trends of the average of the climate model simulations (red) and the averages of the three types of observational datasets described in the text.

https://science.house.gov/sites/republicans.science.house.gov/files/documents/HHRG-115-SY-WState-JChristy-20170329.pdf

MODEL BASICS

- The next few slides give some overview of the general circulation climate models

Climate system

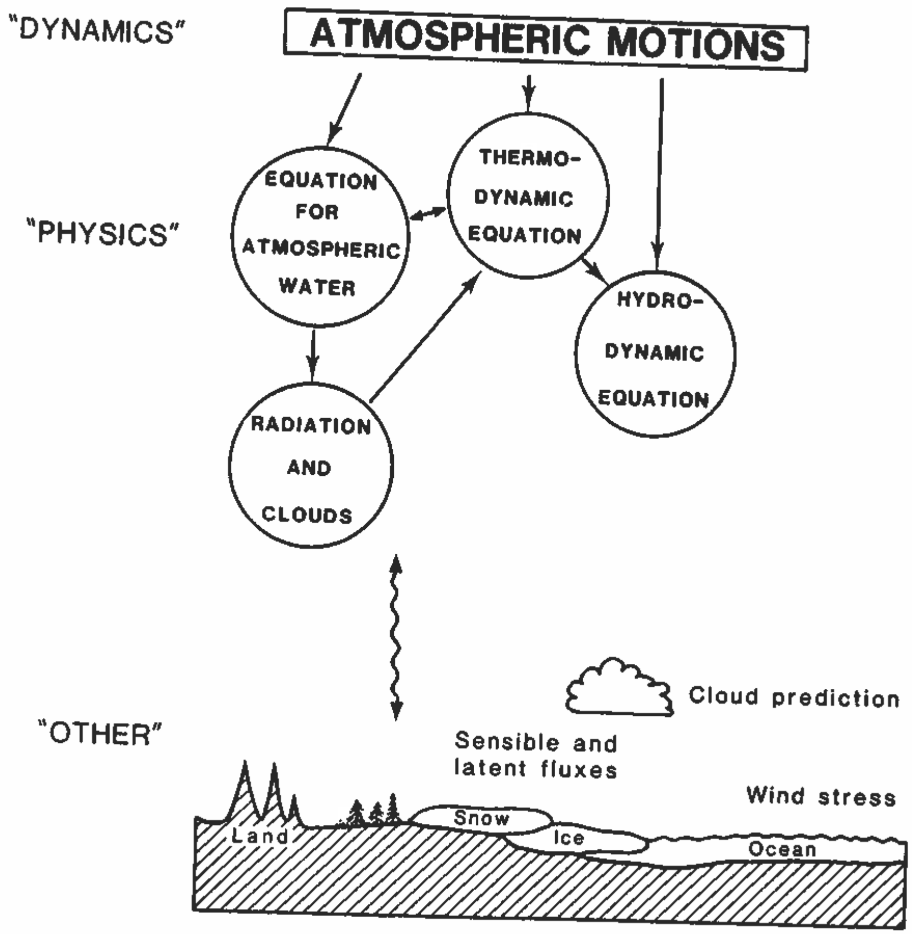


Figure 5.1 The processes incorporated in an AGCM. It is generally true that more computational effort is expended on the dynamics and the physics than on the other processes incorporated in AGCMs

Schematic of climate system

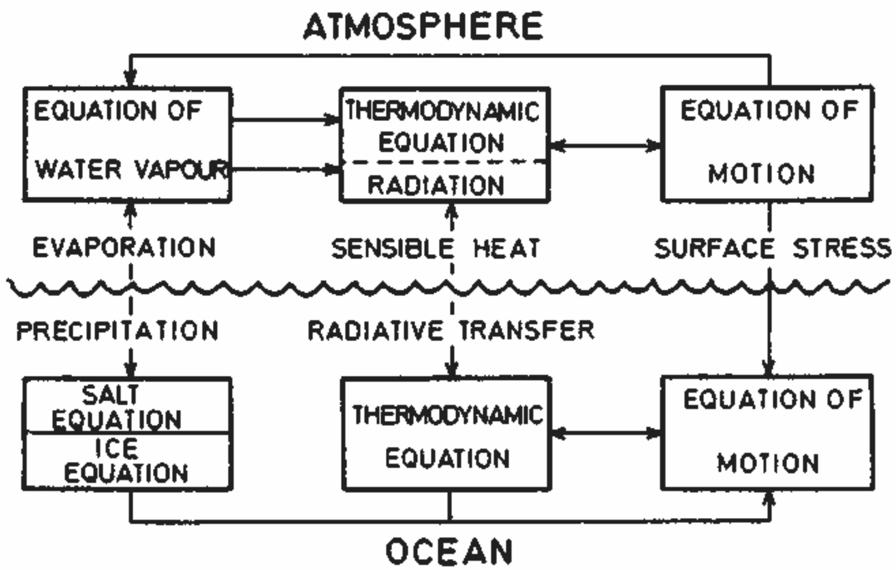


Figure 5.19 Box diagram illustrating the major components of a joint ocean–atmosphere model and the interaction among the components (reproduced by permission from Manabe *et al.*, 1979)

Basic Equations

weather forecasts. Any AGCM must be formulated with some fundamental considerations for:

1. conservation of momentum

$$\frac{\mathrm{D}\mathbf{v}}{\mathrm{D}t} = -2\boldsymbol{\Omega} \times \mathbf{v} - \rho^{-1}\nabla p + \mathbf{g} + \mathbf{F} \tag{5.1}$$

2. conservation of mass

$$\frac{\mathrm{D}\rho}{\mathrm{D}t} = -\rho\nabla \cdot \mathbf{v} + C - E \tag{5.2}$$

3. conservation of energy

$$\frac{\mathrm{D}I}{\mathrm{D}t} = -p\,\frac{\mathrm{d}\rho^{-1}}{\mathrm{d}t} + Q \tag{5.3}$$

4. ideal gas law

$$p = \rho RT \tag{5.4}$$

Variables in equations

where $\mathbf{v}$ = velocity relative to the rotating Earth,

t = time,

$$\frac{D}{Dt} = \text{total time derivative} \left[= \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right]$$

$\boldsymbol{\Omega}$ = angular velocity vector of the Earth,

ρ = atmospheric density,

$\mathbf{g}$ = apparent gravitational acceleration,

p = atmospheric pressure,

$\mathbf{F}$ = force per unit mass,

C = rate of creation of atmospheric constituents,

E = rate of destruction of atmospheric constituents,

I = internal energy per unit mass [$= c_v T$],

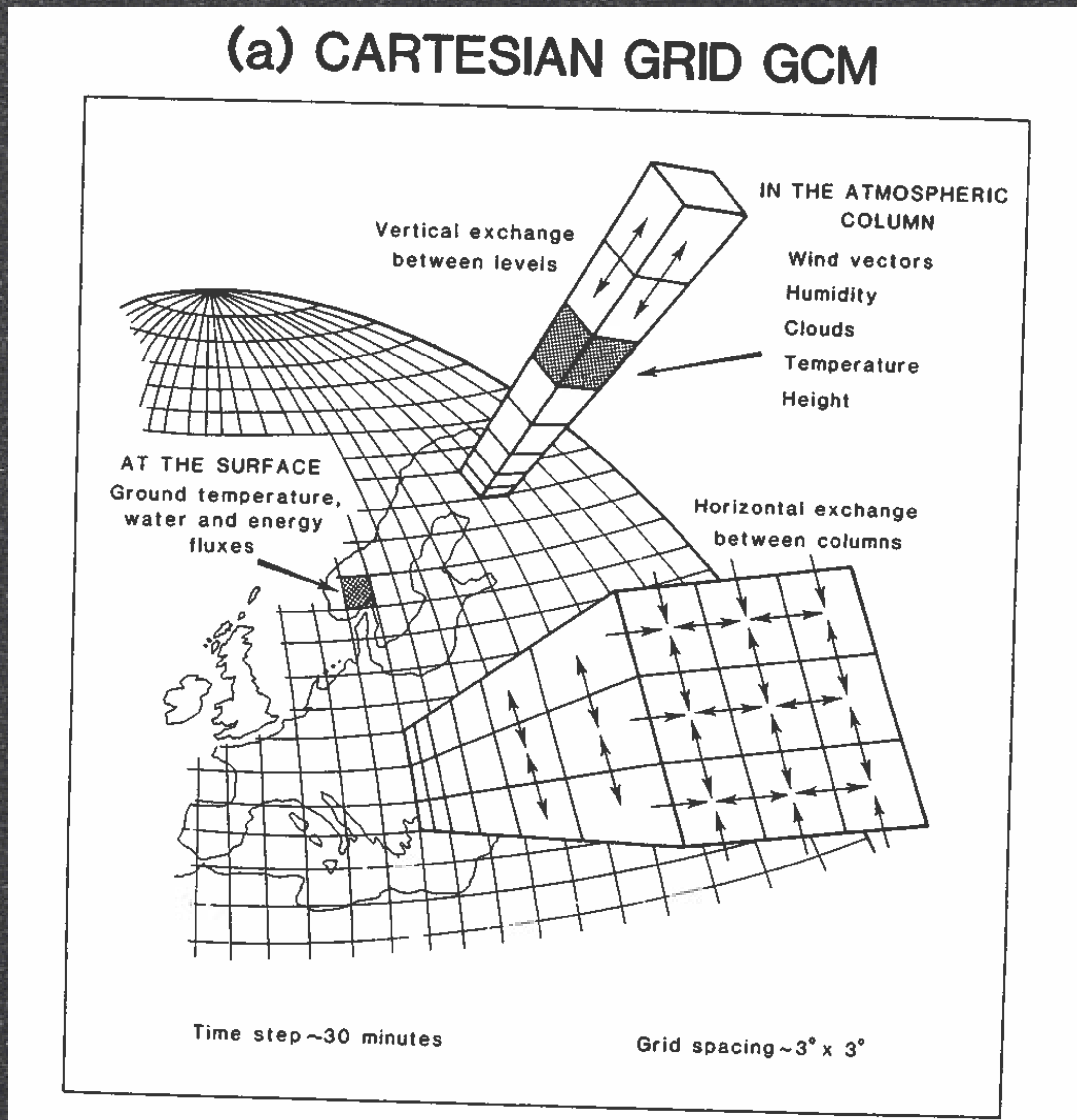
Q = heating rate per unit mass,

R = gas constant,

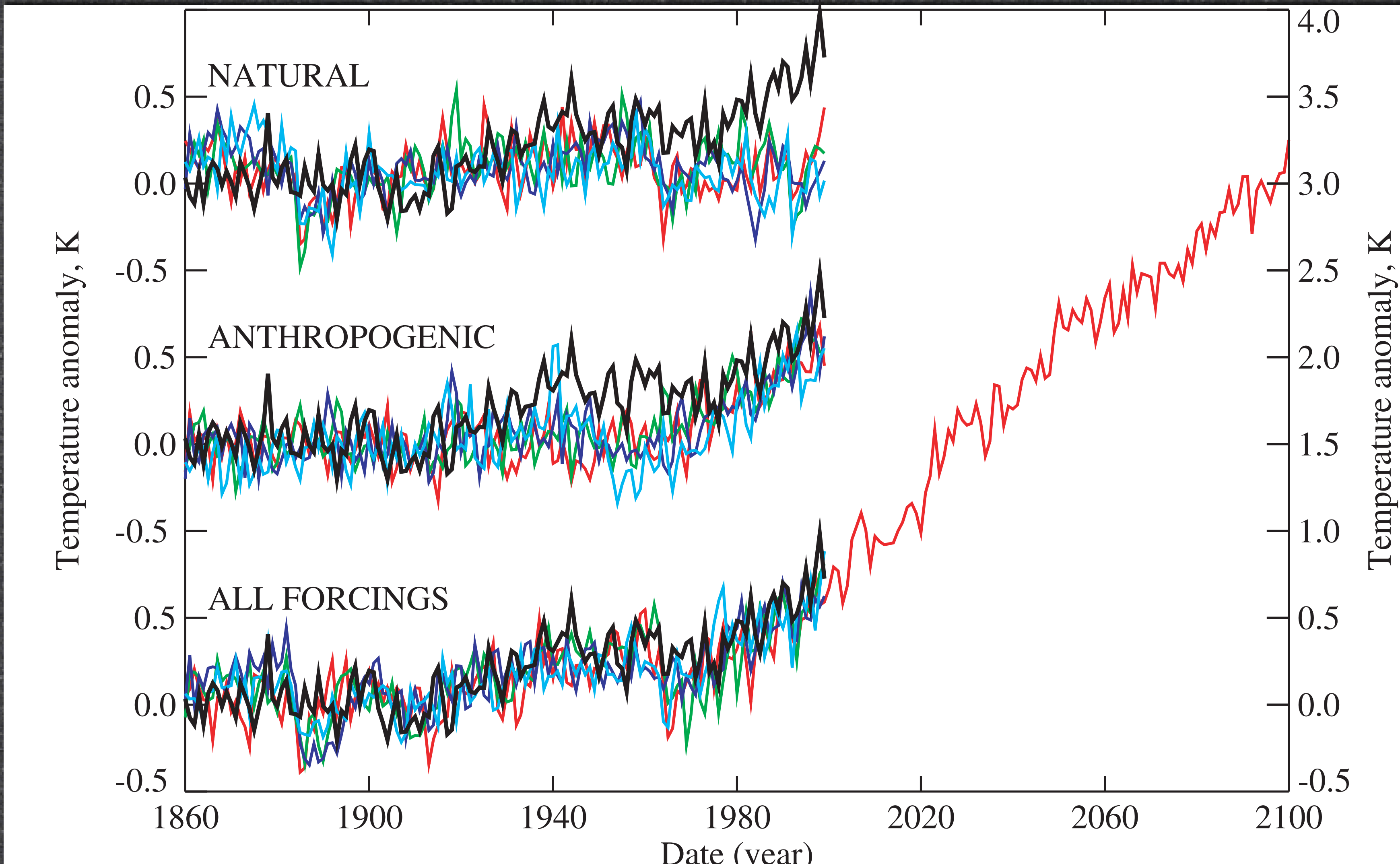
T = temperature,

c_v = specific heat of air at constant volume.

“Conceptual” calculational grid



“Key” modeling result



Here is the temperature modeling result

from Stott et al.[2000] Science 290, p 2133

More simulations

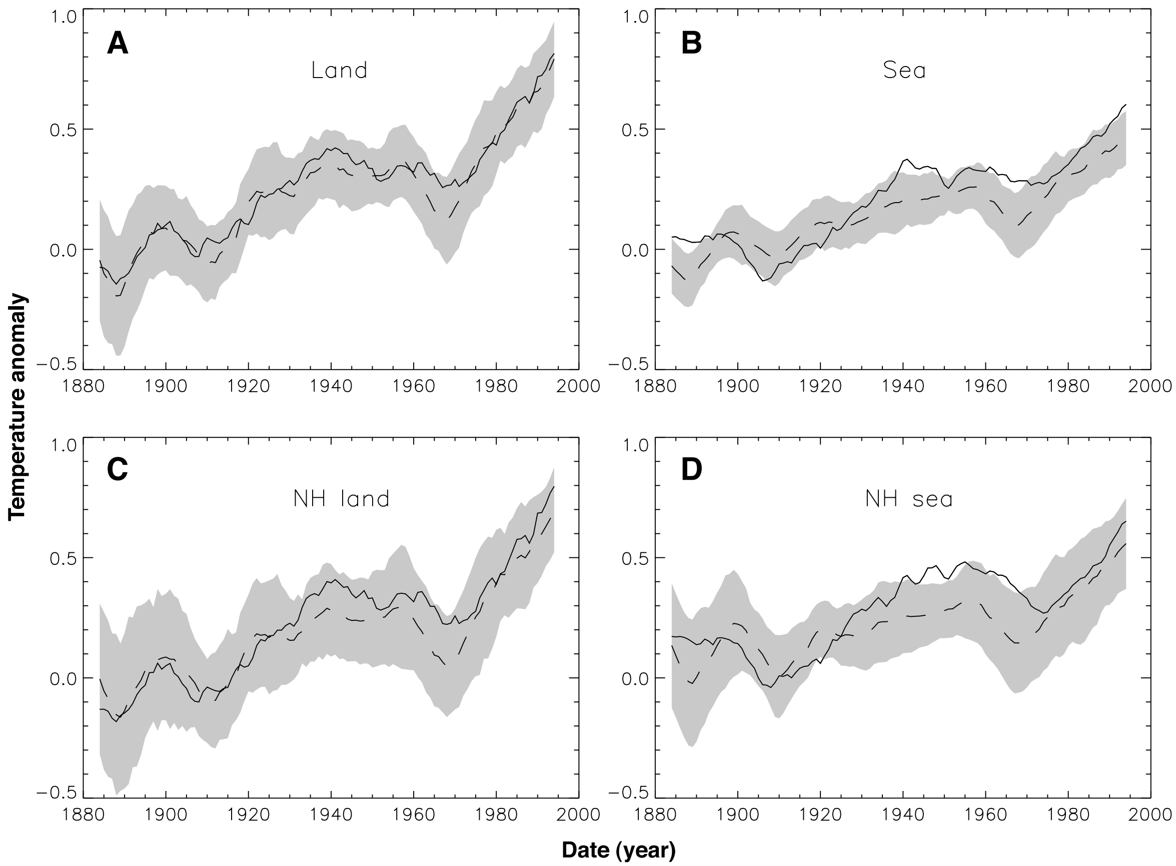


Fig. 2. Running decadal-mean global mean surface (1.5 m) temperature anomalies for (**A**) land, (**B**) ocean (sea), (**C**) Northern Hemisphere (NH) land, (**D**) Northern Hemisphere ocean (sea). Data are expressed as anomalies relative to the period 1961–1990 and masked as in Fig. 1. Solid black line, observations; dashed line, ALL ensemble mean. The gray shading shows the 5 and 95 percentiles of the expected uncertainty distribution of possible deviations from the model ensemble mean calculated from a long control simulation of HadCM3.

Simulations of the past

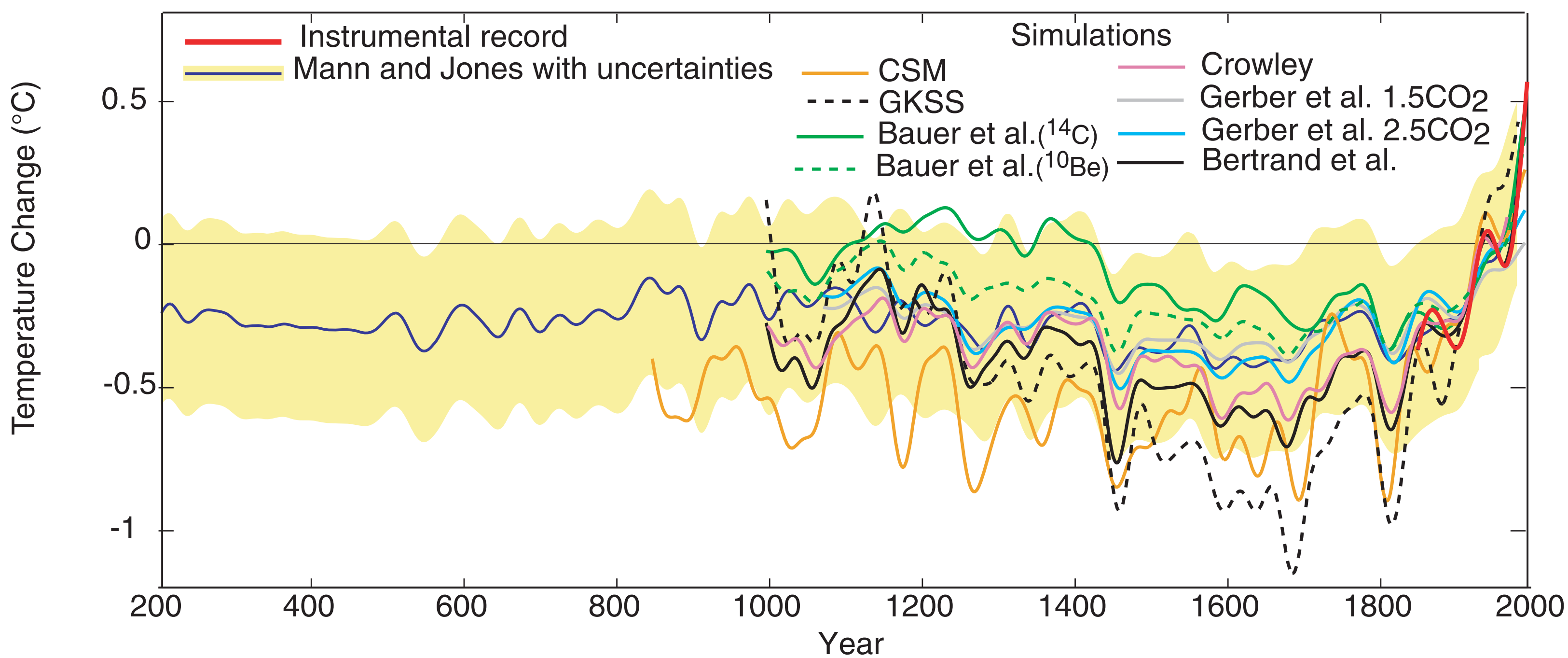
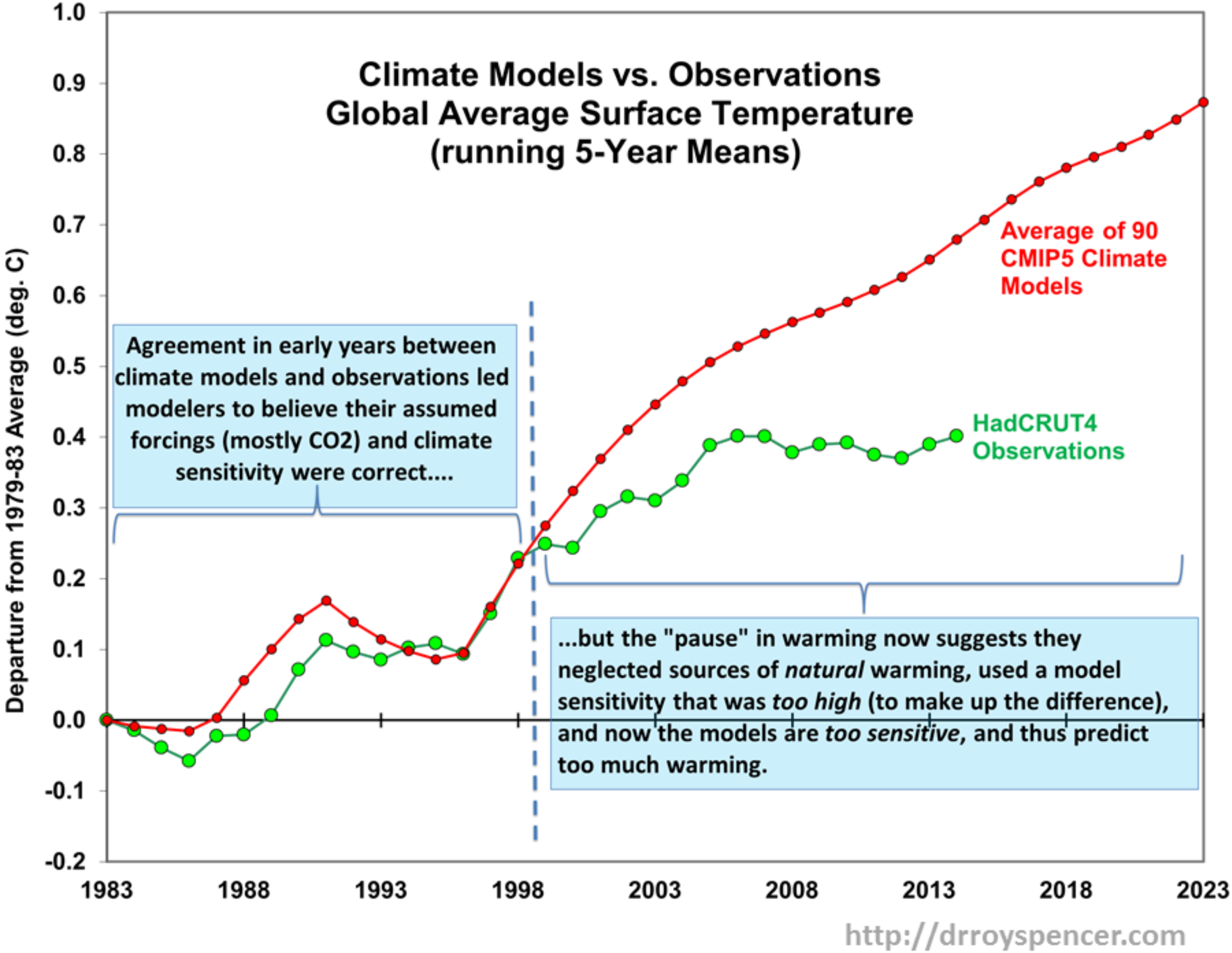
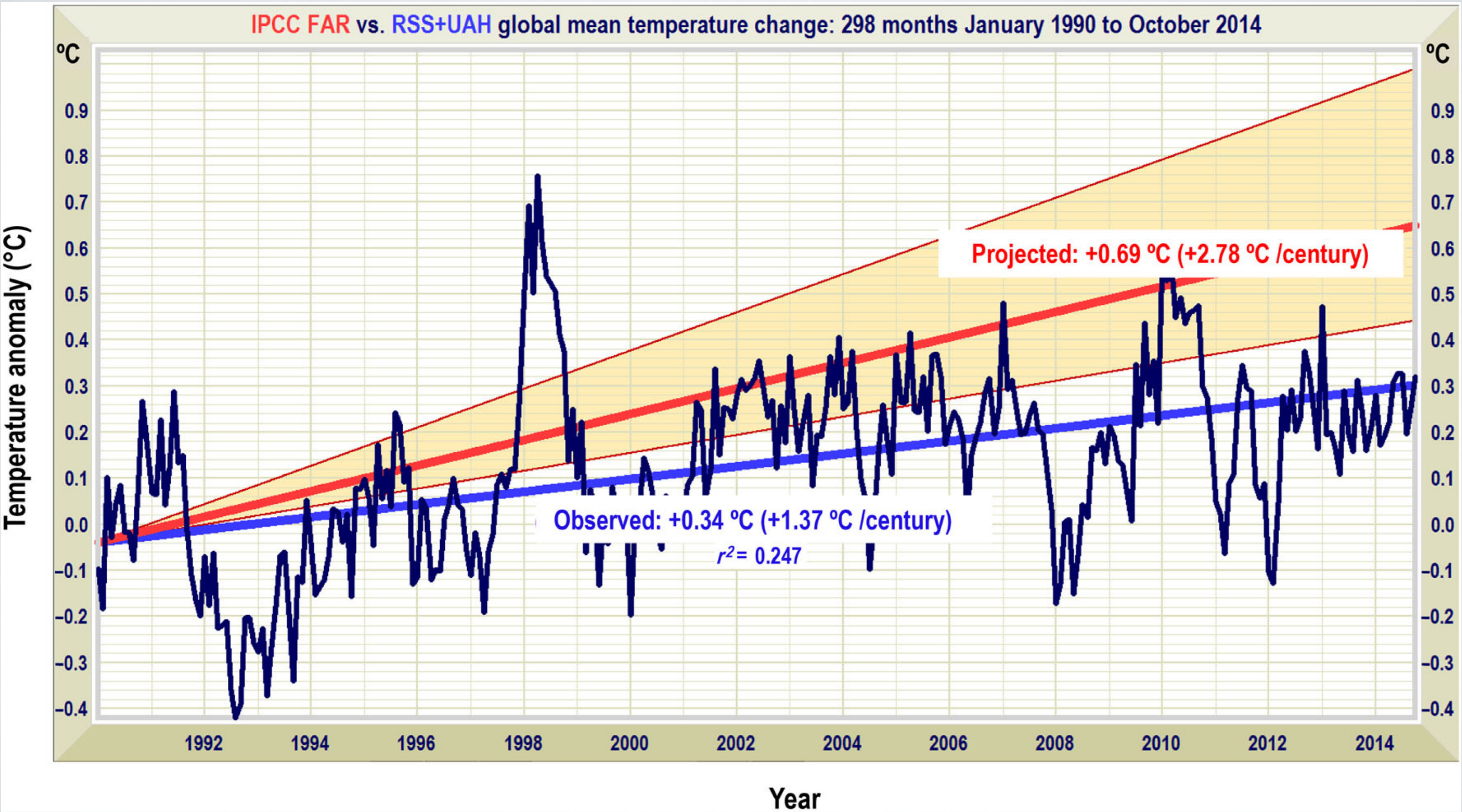


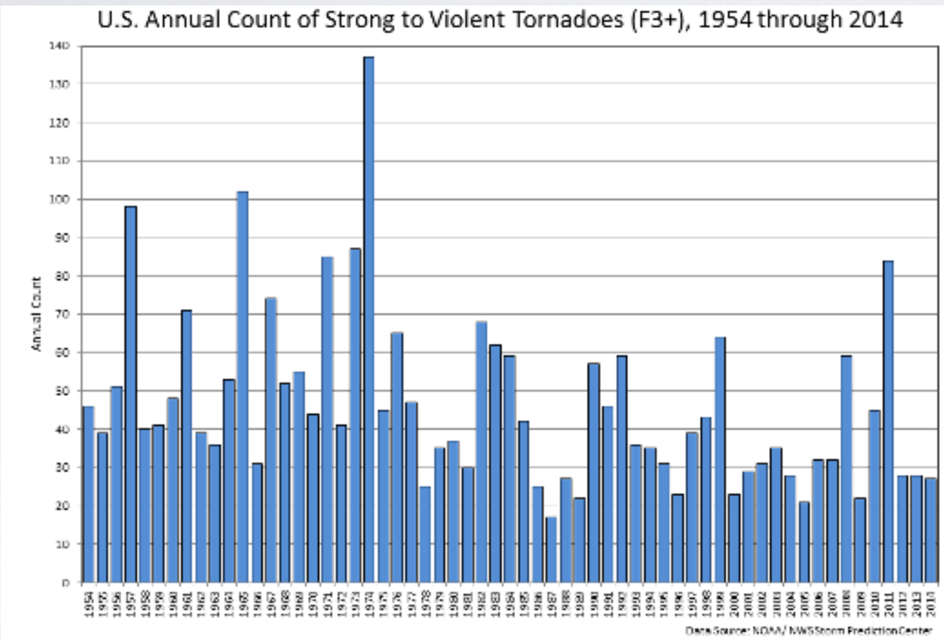
FIGURE 10-4 Estimates of Northern Hemisphere surface temperature variations over the last two millennia. Shown are 40-year smoothed series. Models have been aligned to have the same mean over the common 1856–1980 period as the instrumental series (which is assigned zero mean during the 1961–1990 reference period). The model simulations are based on varying radiative forcing histories and employ a hierarchy of models. SOURCE: Jones and Mann (2004b). Reproduced by permission of American Geophysical Union; copyright 2004.

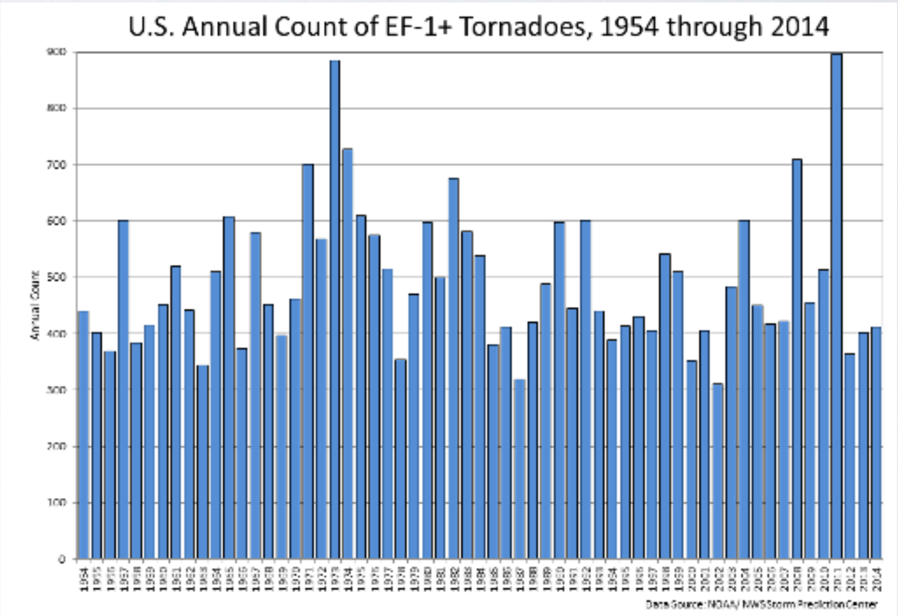

Climate Models vs. Observations
Global Average Surface Temperature
(running 5-Year Means)
Departure from 1979-83 Average (deg. C)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
1983
1988
1993
1998
2003
2008
2013
2018
2023
Average of 90 CMIP5 Climate Models
HadCRUT4 Observations
Agreement in early years between climate models and observations led modelers to believe their assumed forcings (mostly CO2) and climate sensitivity were correct....
...but the "pause" in warming now suggests they neglected sources of *natural* warming, used a model sensitivity that was *too high* (to make up the difference), and now the models are *too sensitive*, and thus predict too much warming.
http://drroyspencer.com

MODEL PREDICTIONS



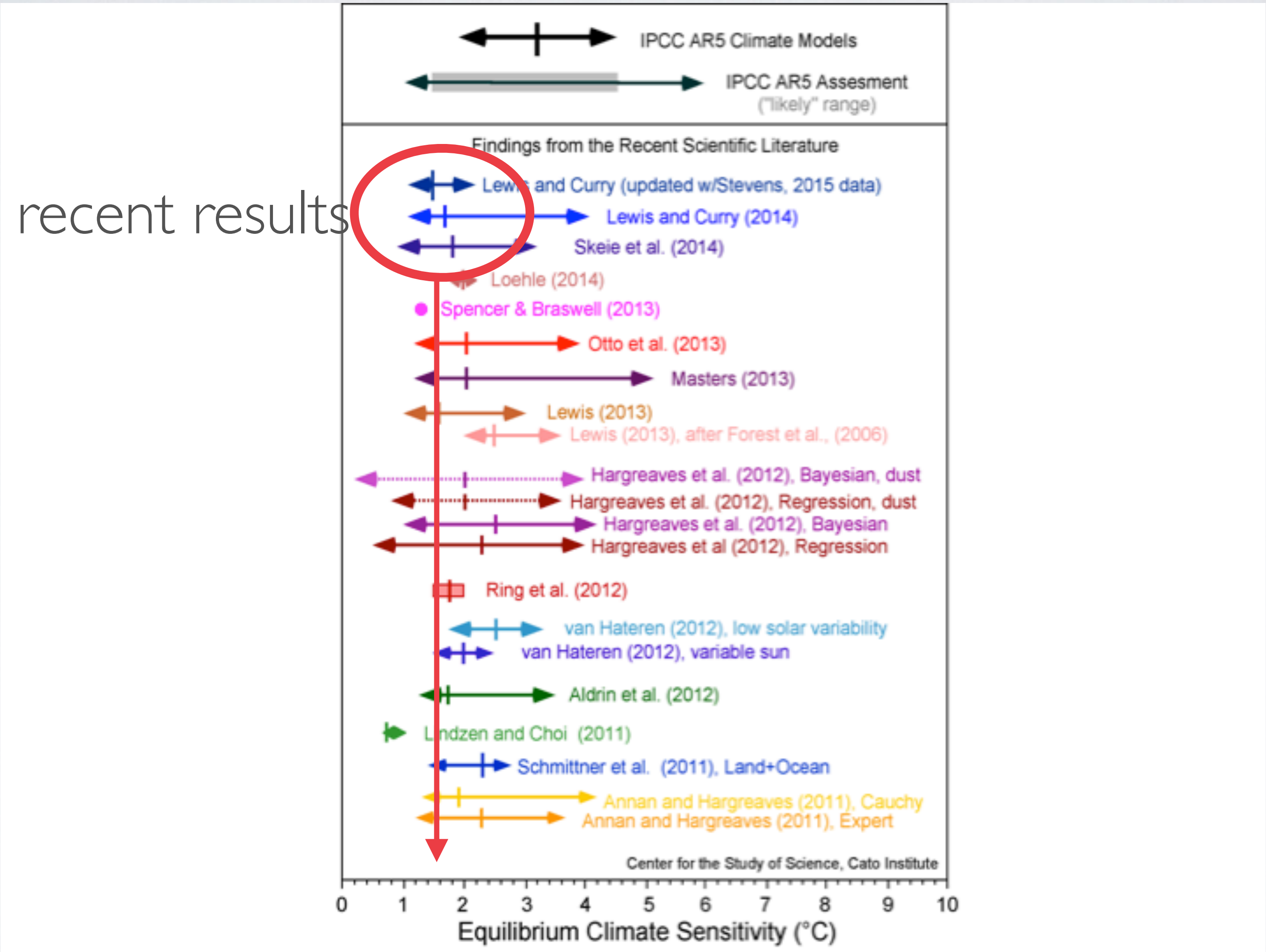
- No change in tornados





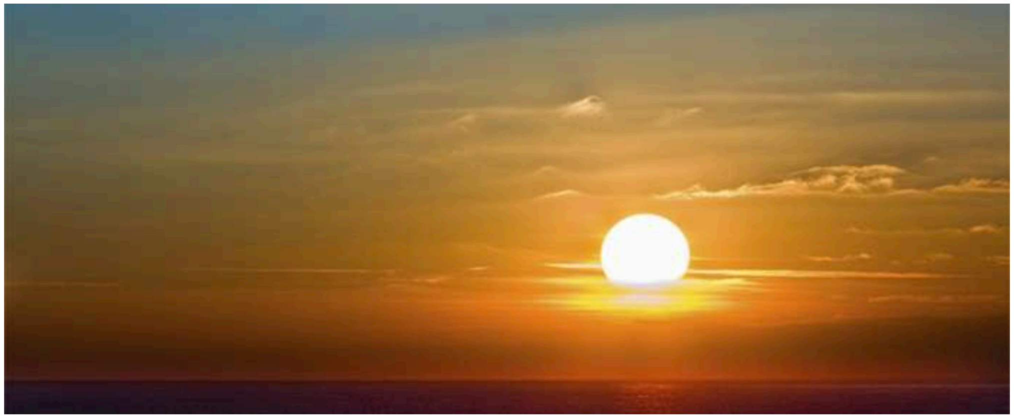
EFFECT OF CO2 DOUBLING

Most recent results



Solar activity has a direct impact on Earth's cloud cover

August 25, 2016 by Morten Garly Andersen



Credit: Technical University of Denmark

A team of scientists from the National Space Institute at the Technical University of Denmark (DTU Space) and the Racah Institute of Physics at the Hebrew University of Jerusalem has linked large solar eruptions to changes in Earth's cloud cover in a study based on over 25 years of satellite observations.

The solar eruptions are known to shield Earth's atmosphere from cosmic rays. However the new study, published in *Journal of Geophysical Research: Space Physics*, shows that the global cloud cover is simultaneously reduced, supporting the idea that cosmic rays are important for cloud formation. The eruptions cause a reduction in cloud fraction of about 2 percent corresponding to roughly a billion tonnes of liquid water disappearing from the atmosphere.

Since clouds are known to affect global temperatures on longer timescales, the present investigation represents an important step in the understanding of clouds and climate variability.

"Earth is under constant bombardment by particles from space called galactic cosmic rays. Violent eruptions at the Sun's surface can blow these cosmic rays away from Earth for about a week. Our study has shown that when the cosmic rays are reduced in this way there is a corresponding reduction in Earth's cloud cover. Since clouds are an important factor in controlling the temperature on Earth our results may have implications for climate change", explains lead author on the study Jacob Svensmark of DTU.

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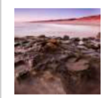
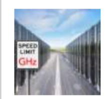
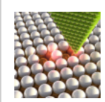
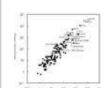

'Unparalleled' number of dinosaur tracks found in Australia Mar 27, 2017 4


Quantum computers may have higher 'speed limits' than thought Mar 27, 2017 1


Expect more deadly heat from climate change, study says Mar 27, 2017 27


Researchers create artificial materials atom-by-atom Mar 27, 2017 0


Physics can predict wealth inequality Mar 28, 2017 18

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Phys.org

Barrett Bellamy Climate
MODTRAN calculations

- Welcome to our site
- Personnel
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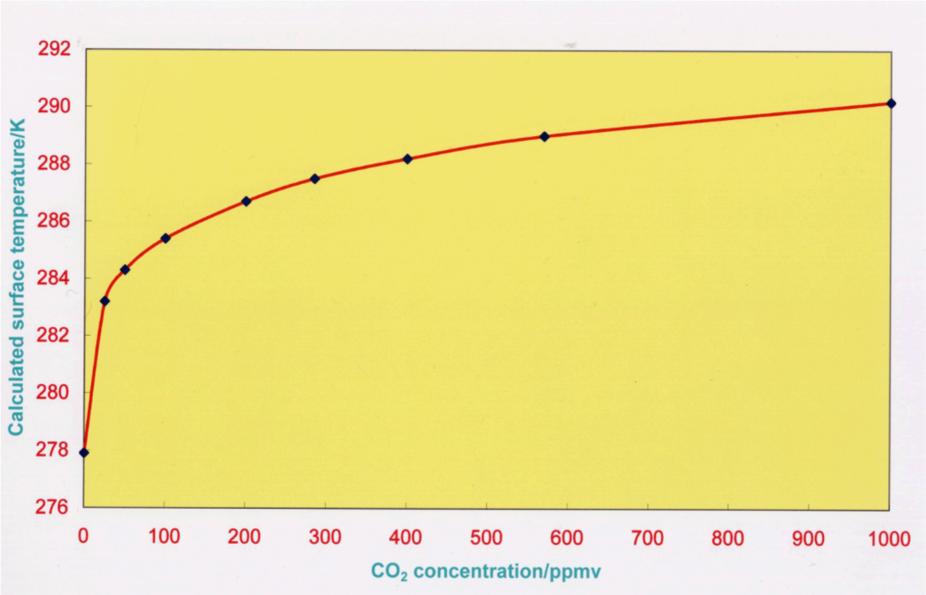
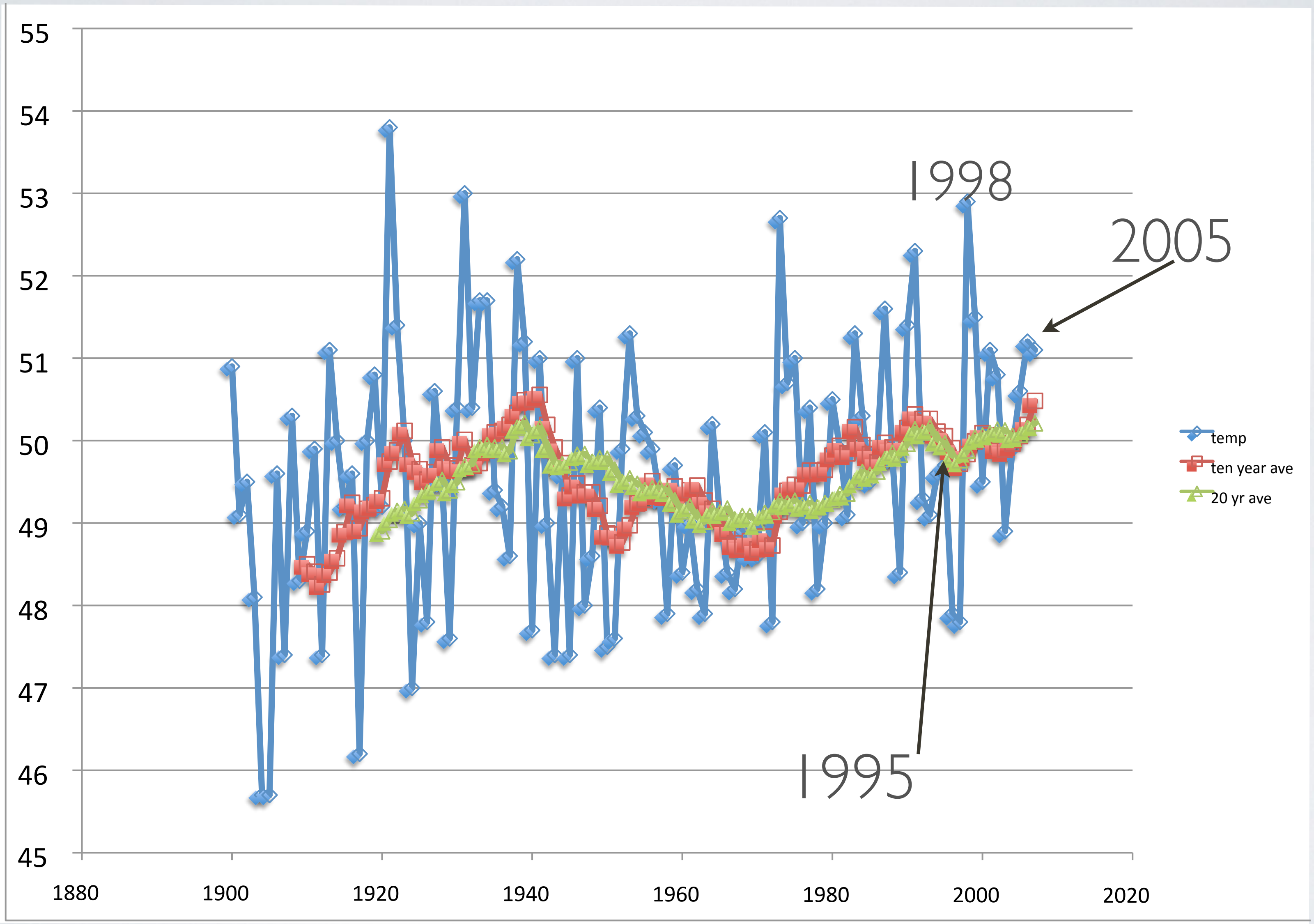
- Breaking News
- Breaking News Extra
- No warming since 1979?!
- CO2 last month
- The Greenhouse Effect
- Harder greenhouse effect
- Greenhouse gases
- How large is the greenhouse?
- The vibrators
- The rotators
- Spectral transitions
- Greenhouse gas spectra
- Selective absorption

The MODTRAN programme is described on a previous page. Here are some calculations which put the suggested effect of doubling the atmospheric carbon dioxide concentration into perspective



This is a plot of some MODTRAN results for the temperature of the atmosphere in which the CO_2 concentration varies from zero to 1000 ppmv. The intention is to show the logarithmic nature of the relationship between CO_2 and surface temperature, i.e., the temperature rises non-linearly with every successive addition of CO_2 causing smaller effects.

SOUTH BEND YEARLY TEMPS



OTHER "RECONSTRUCTIONS"

Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia

Michael E. Mann*[†], Zhihua Zhang*, Malcolm K. Hughes[‡], Raymond S. Bradley[§], Sonya K. Miller*, Scott Rutherford[¶], and Fenbiao Ni[‡]

Text

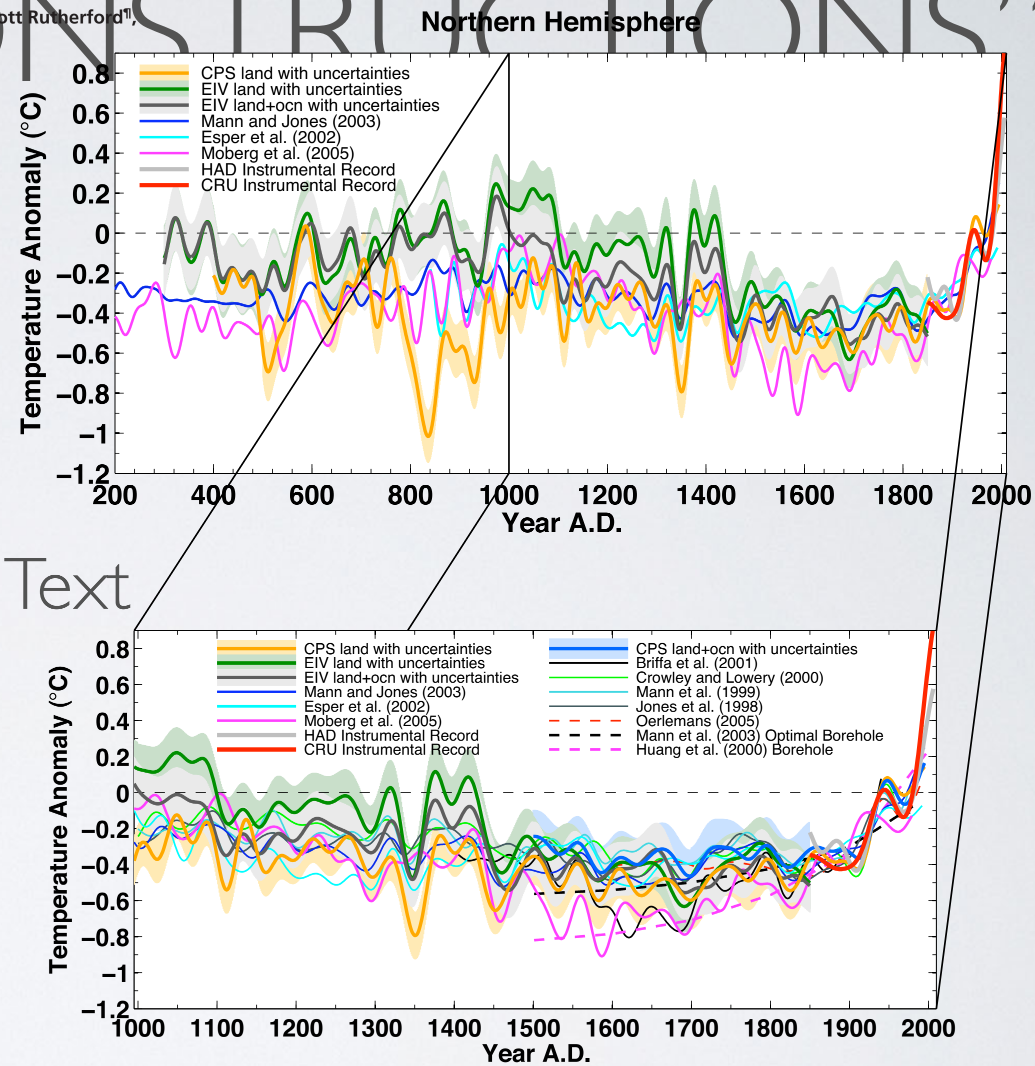
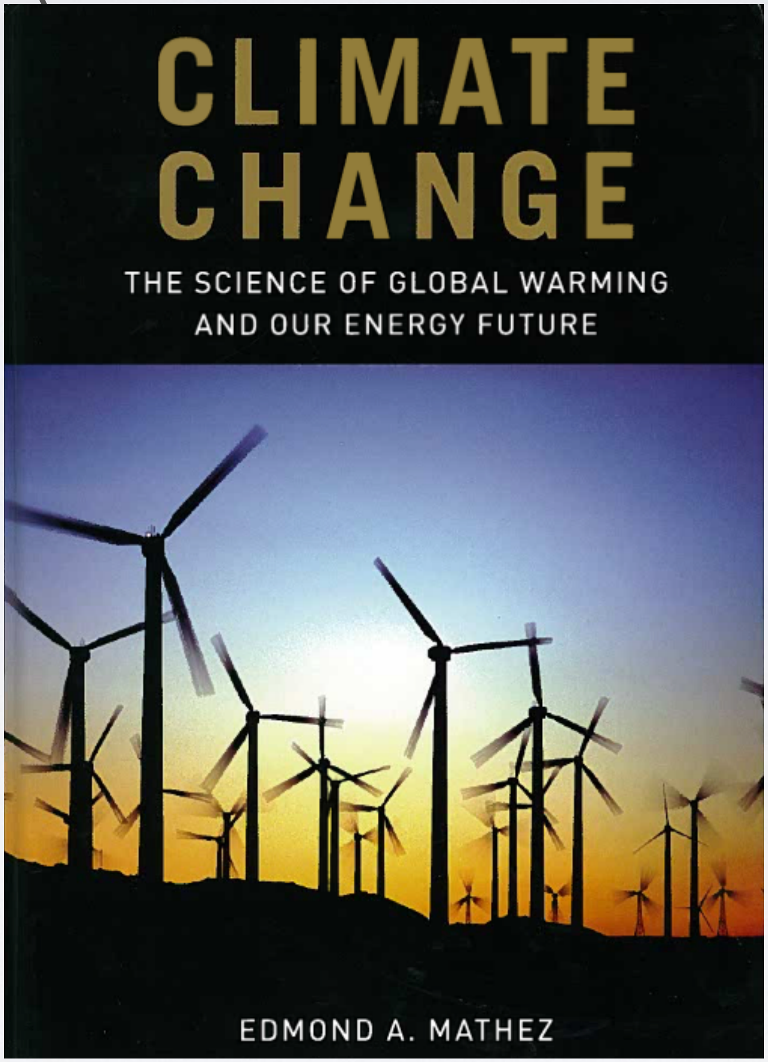


Fig. 3. Composite CPS and EIV NH land and land plus ocean temperature reconstructions and estimated 95% confidence intervals. Shown for comparison are published NH reconstructions, centered to have the same mean as the overlapping segment of the CRU instrumental NH land surface temperature record 1850–2006 that, with the exception of the borehole-based reconstructions, have been scaled to have the same decadal variance as the CRU series during the overlap interval (alternative scaling approaches for attempting to match the amplitude of signal in the reconstructed and instrumental series are examined in *SI Text*). All series have been smoothed with a 40-year low-pass filter as in ref 33. Confidence intervals have been reduced to account for smoothing.

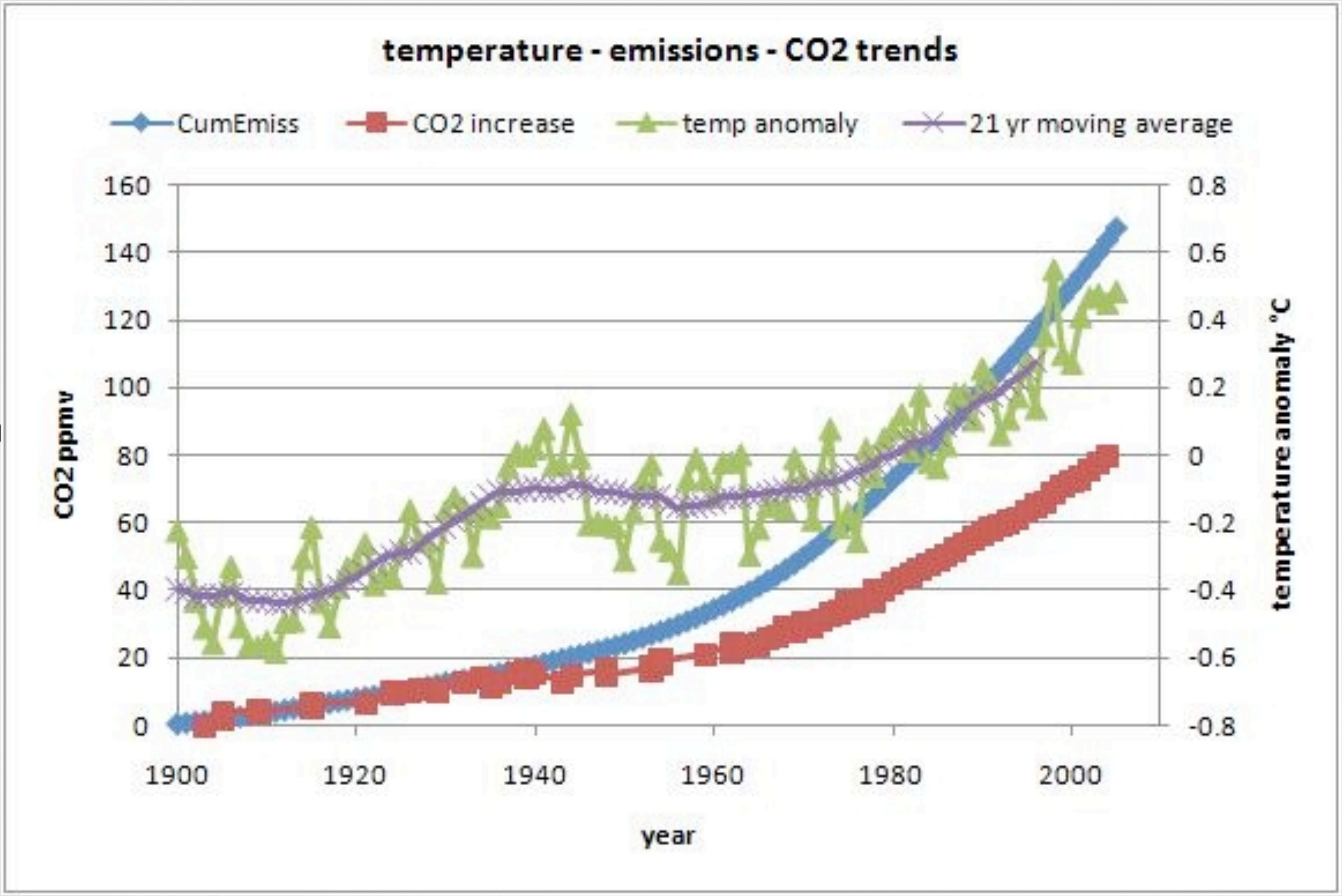
FORTUNATELY...

- As far as I can tell, there is no impending climate calamity on the horizon
    - Co2 levels have increased, but this does not directly mean that there will be
        - more extreme weather events
        - reduced crop yields, more insects, more disease spread...
    - Even if we cut CO2 emissions, there is no evidence that China and other big growth countries will
    - Even if there was hardship coming, society has two choices, mitigate or adapt
        - Adaptation would be possible and substantially cheaper
- Even if there is a chance of cataclysmic event, the normal course of action is a proportioned degree of prevention

CASE FOR HUMAN-CAUSED WARMING (ANTHROPOGENIC): AGW



LOOKING FOR CAUSE OF WARMING



- S