Global, and Local, Climate Change

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many thanks

to Michael Mann (Penn State) and Eli Tziperman (Harvard) for material used in these lectures!!

"The balance of evidence suggests that there is a discernible human influence on global climate"

UN's *Intergovernmental Panel on Climate Change*
Second Assessment Report, 1996

"There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activity"

UN's *Intergovernmental Panel on Climate Change*
Third Assessment Report, 2001

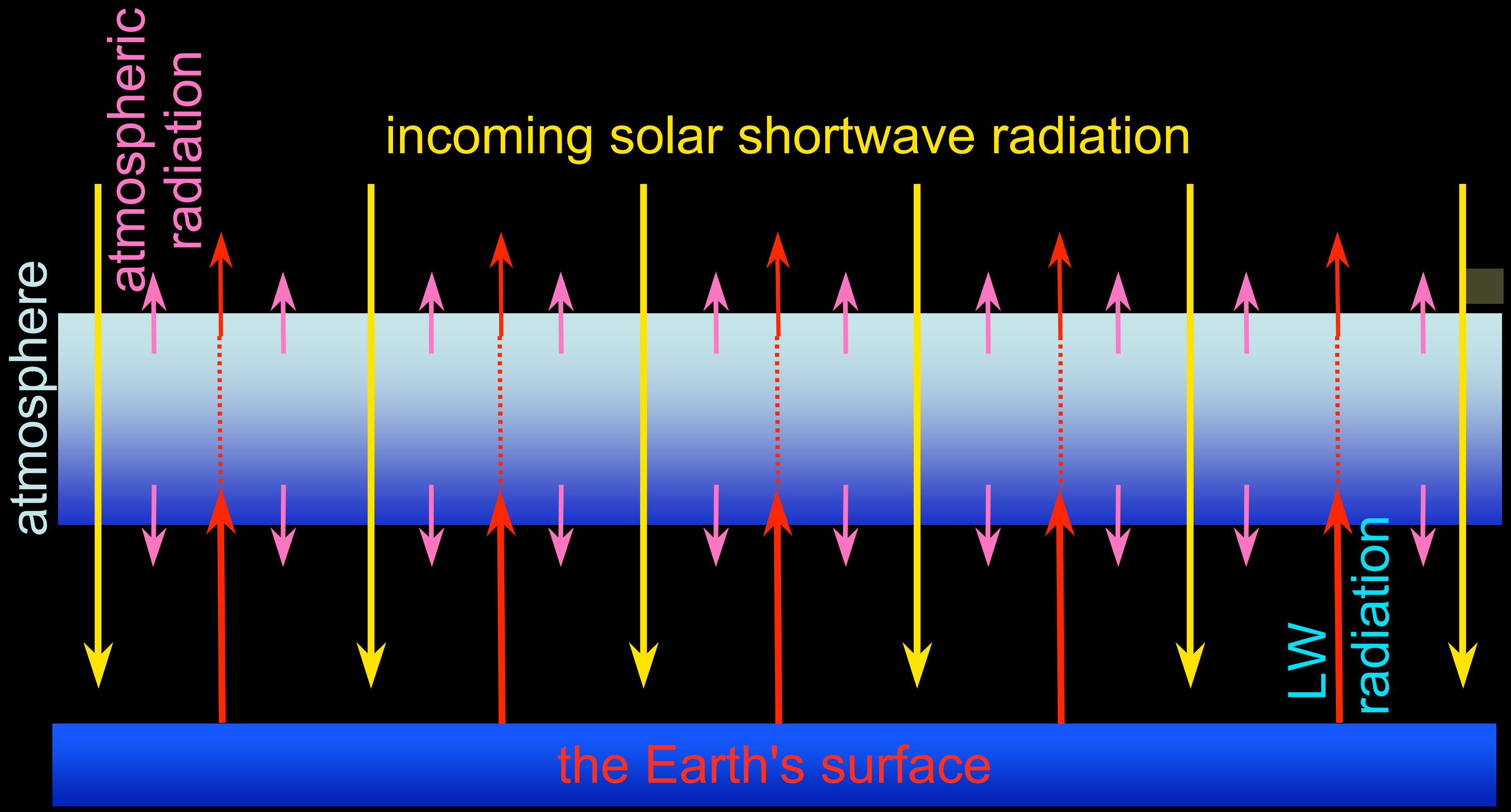
"Warming of the climate system is unequivocal, as is now evident from observations…"

"Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases."

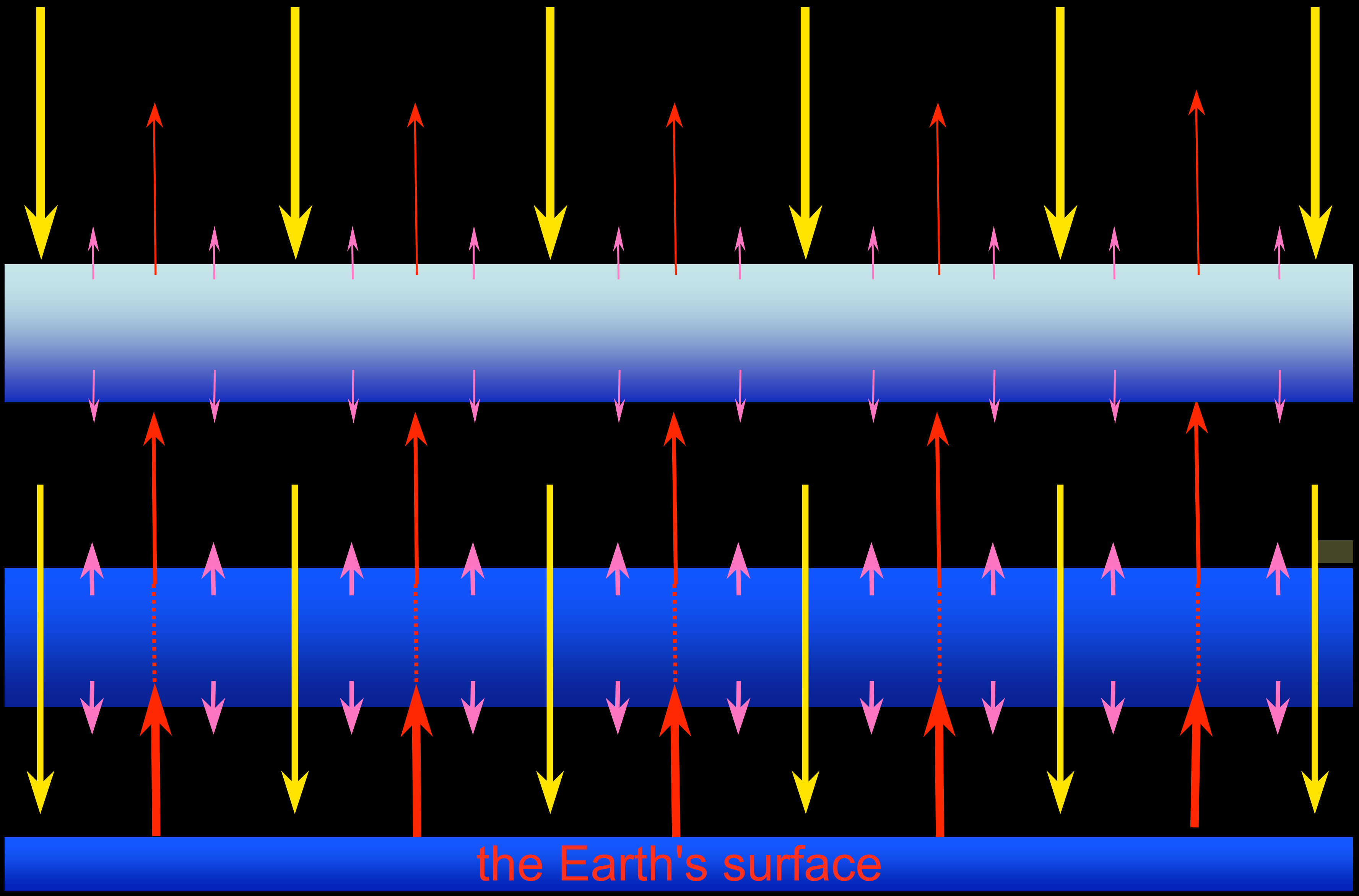
"Most of the observed increase in global average temperatures since the mid-20th century is ***very likely*** due to the observed increase in anthropogenic GHG concentrations. It is likely that there has been significant anthropogenic warming over the past 50 years averaged over each continent (except Antarctica)."

UN's *Intergovernmental Panel on Climate Change*
Fourth Assessment Report, 2007

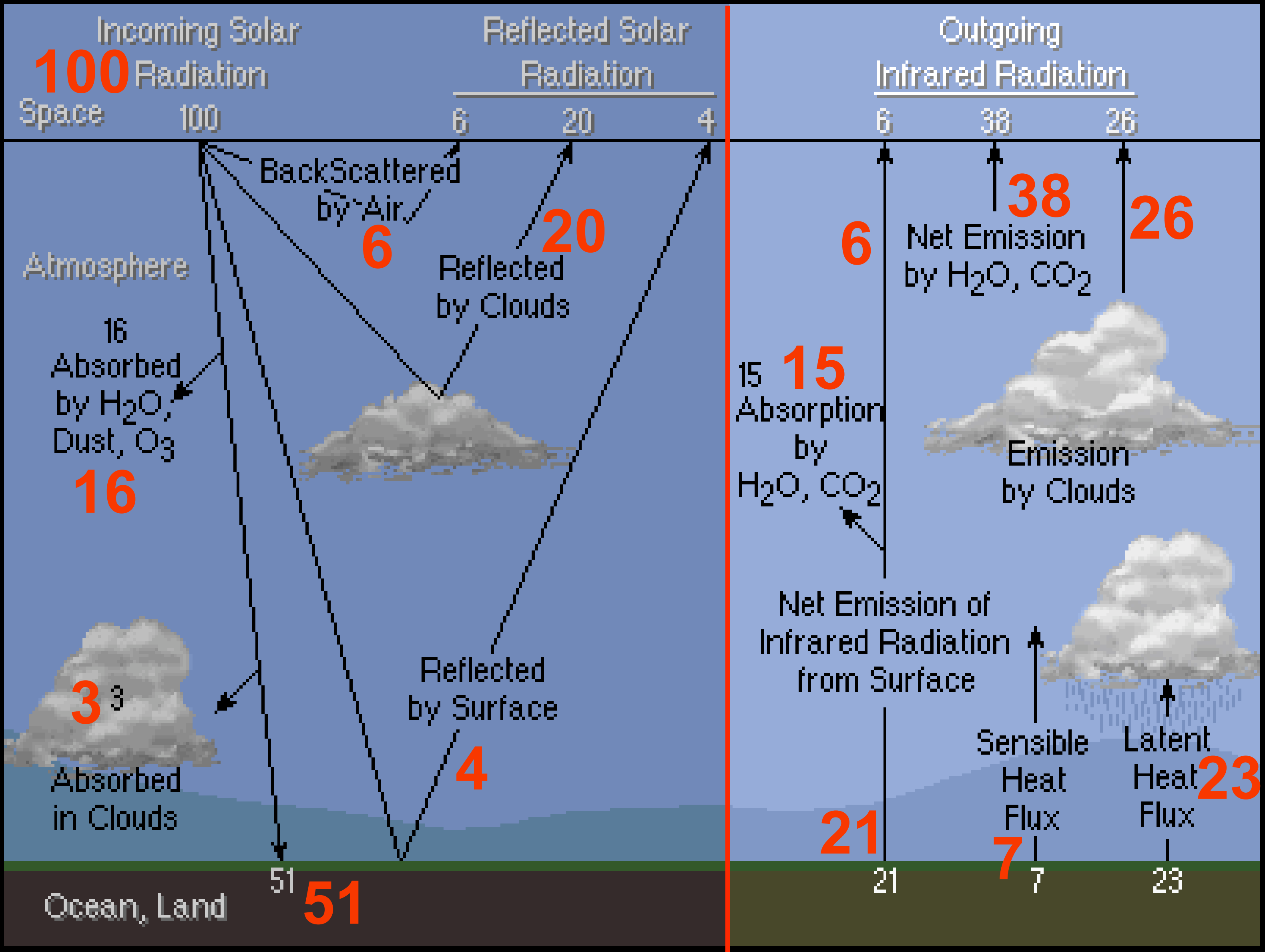
at the center of the debate is the (natural and anthropogenic) greenhouse effect



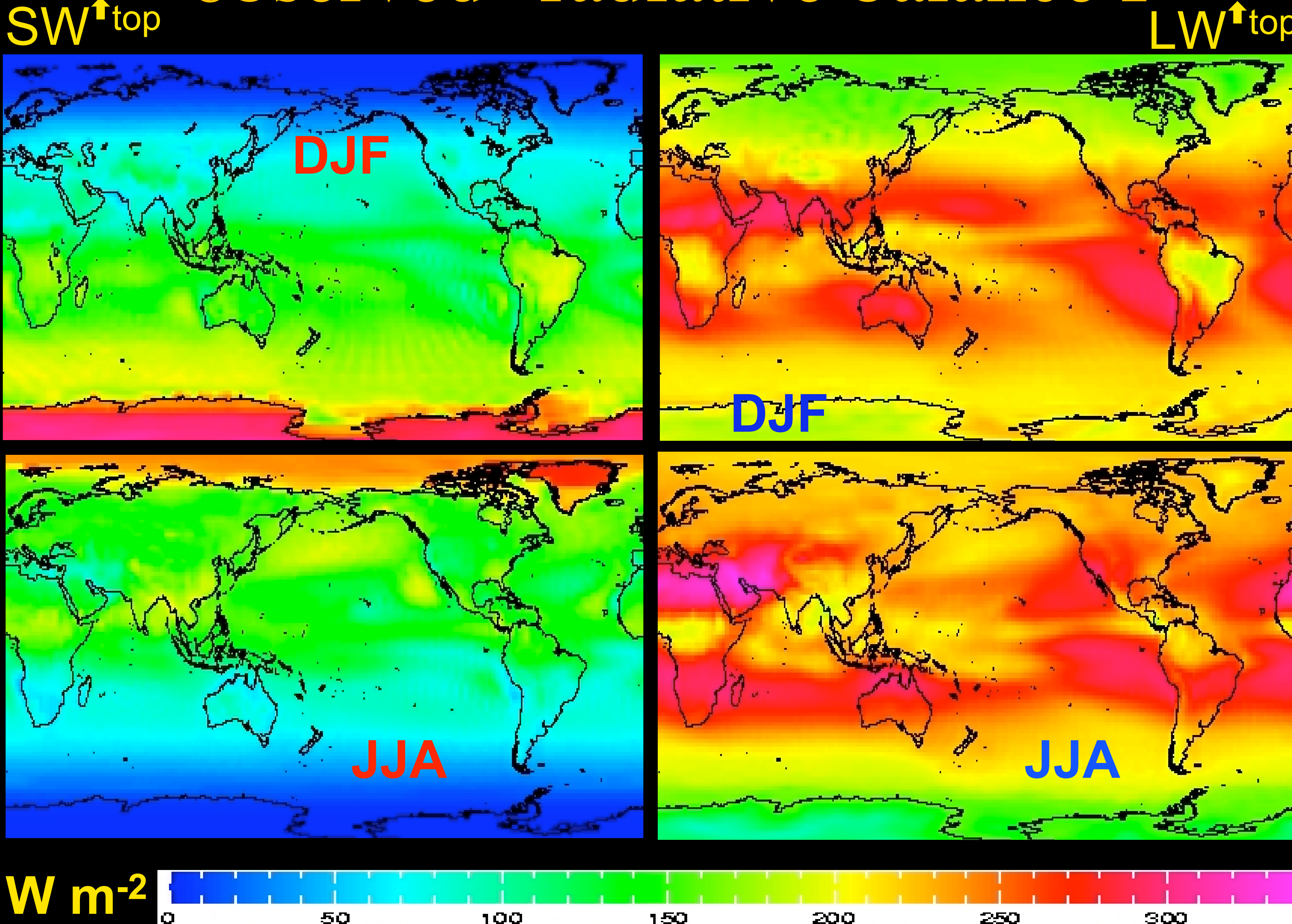
or, with two atmospheric layers



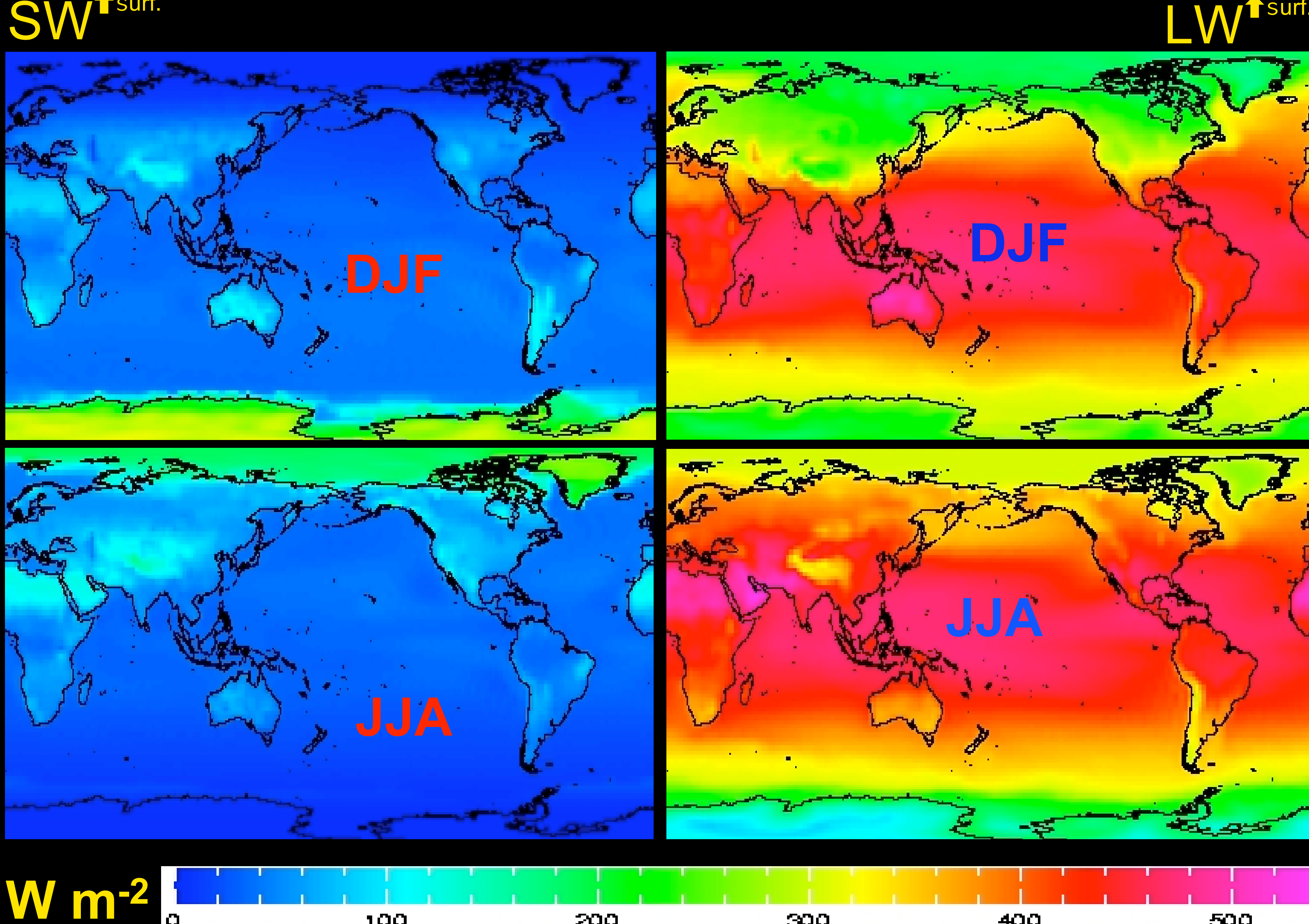
observed "facts" about the Earth's radiative budget



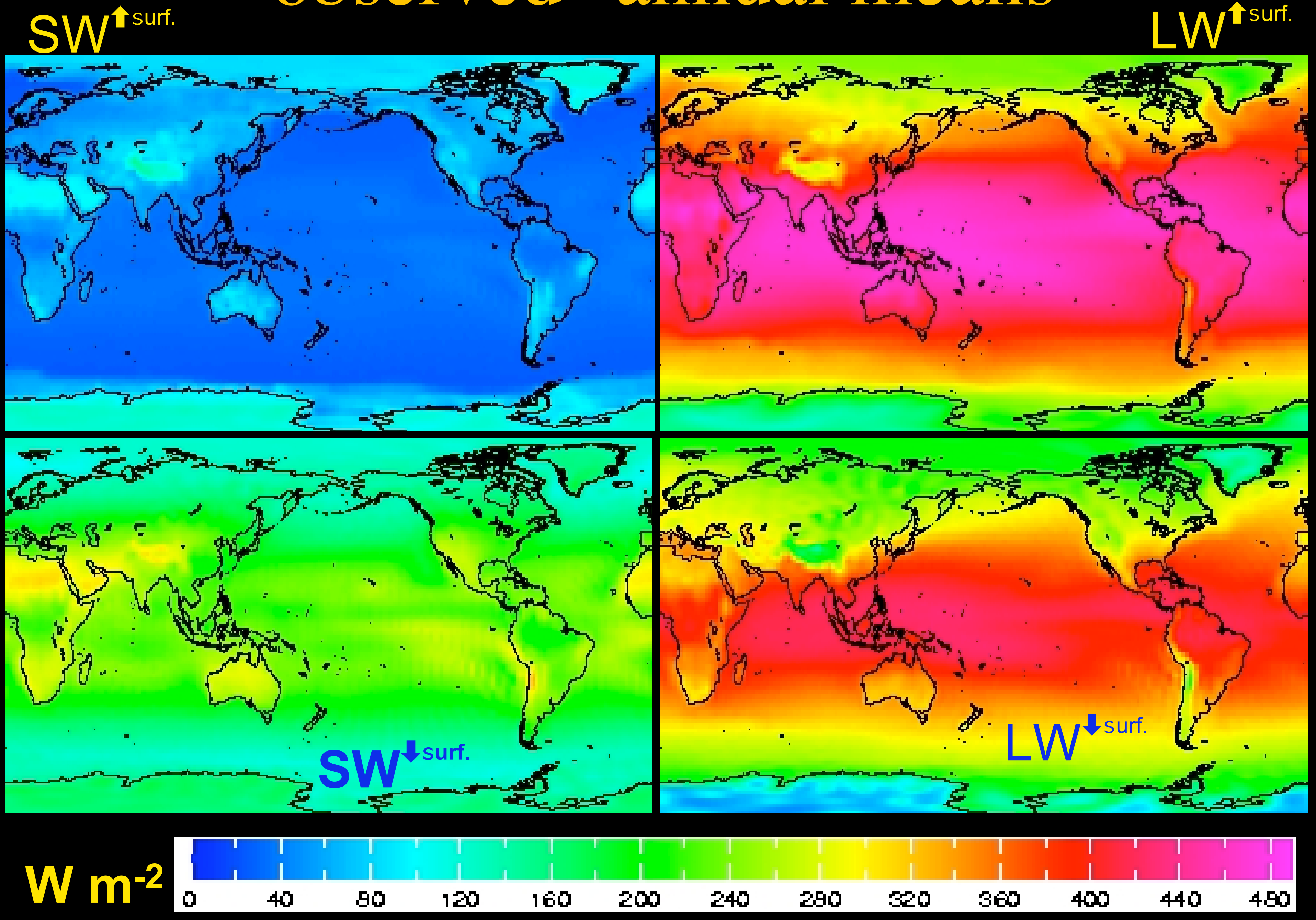
"observed" radiative balance I



"observed" radiative balance II



"observed" annual means

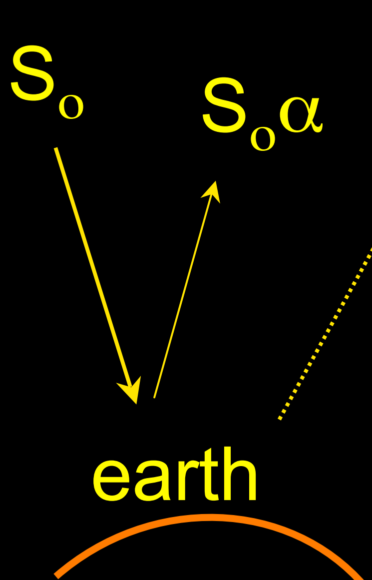


radiative equilibrium: incoming = outgoing

1) no atmosphere:

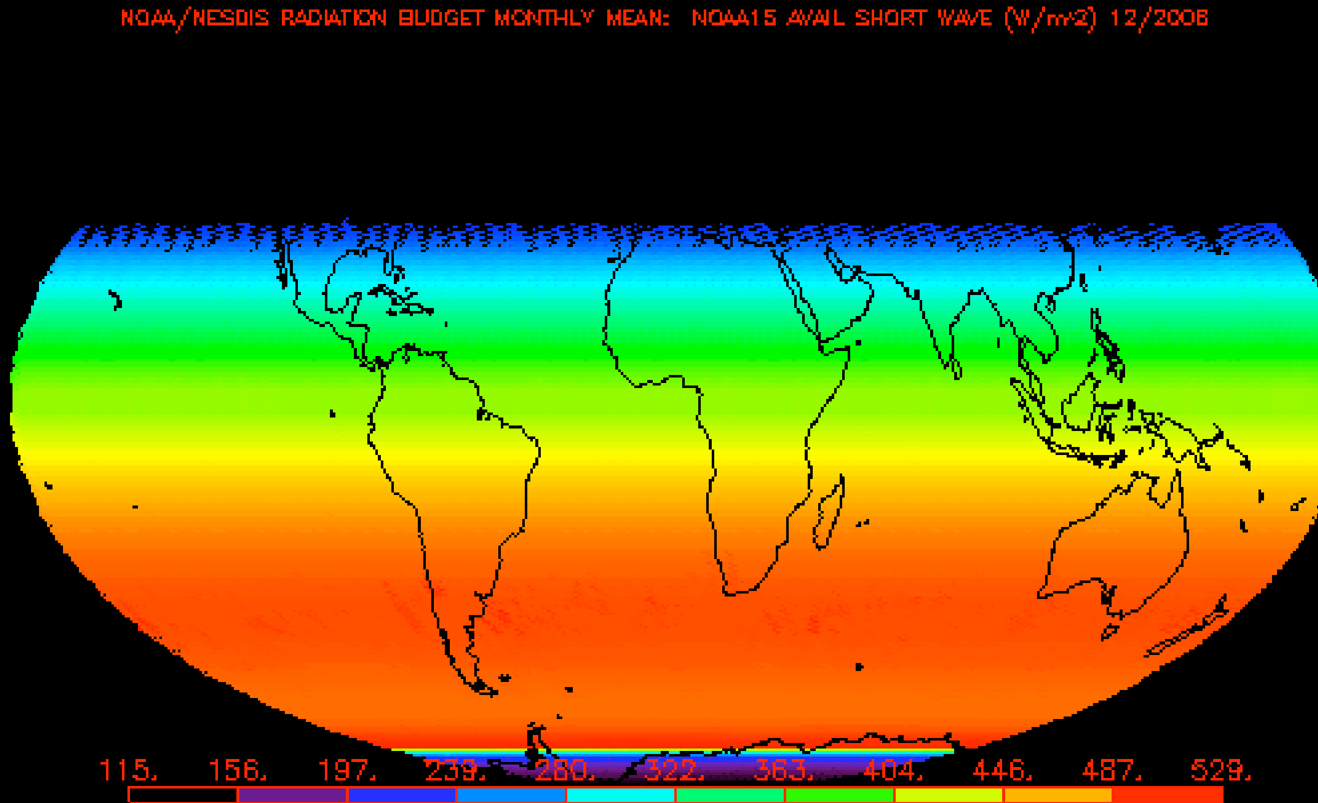
$$S_o\,(1-\alpha) = 4\sigma T_g^4$$

$$T_g = \sqrt[4]{\frac{S_o\,(1-\alpha)}{4\sigma}}$$



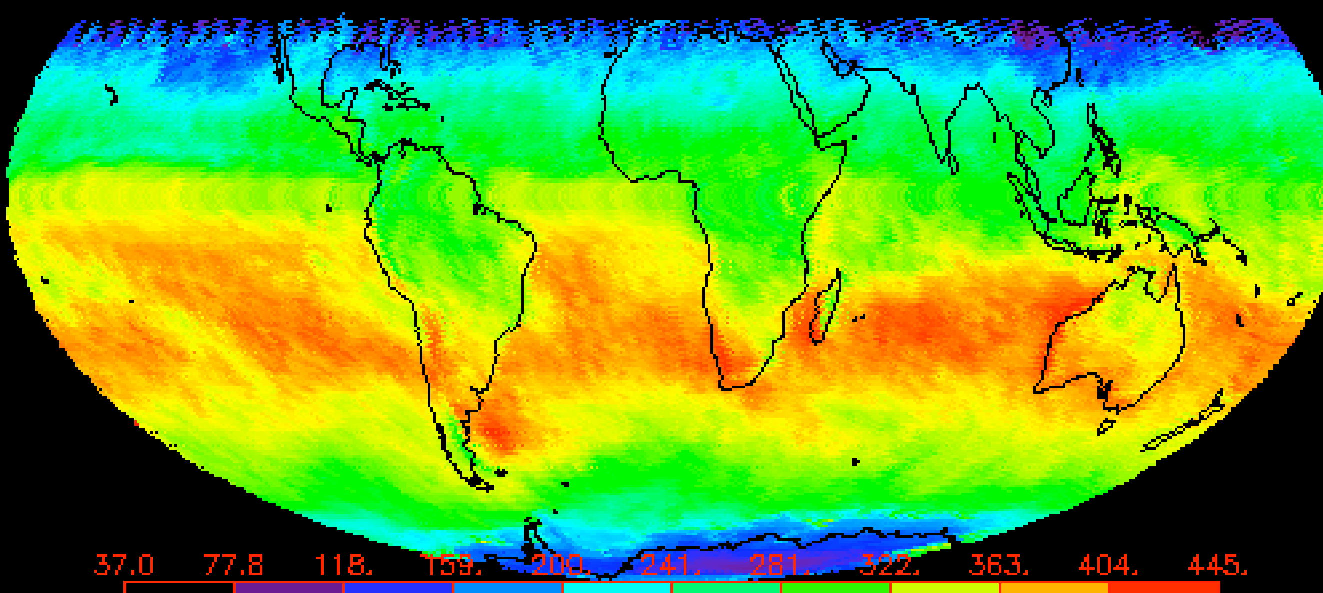
where
$\sigma \approx 5.7 \cdot 10^{-8}$ W m^{-2} K^{-4}
is the Boltzmann constant, and
$S_o \approx 1380$ W m^{-2} is the solar "constant"

Dec. '06: notice the difference!



available⬆

NOAA/NESDIS RADIATION BUDGET MONTHLY

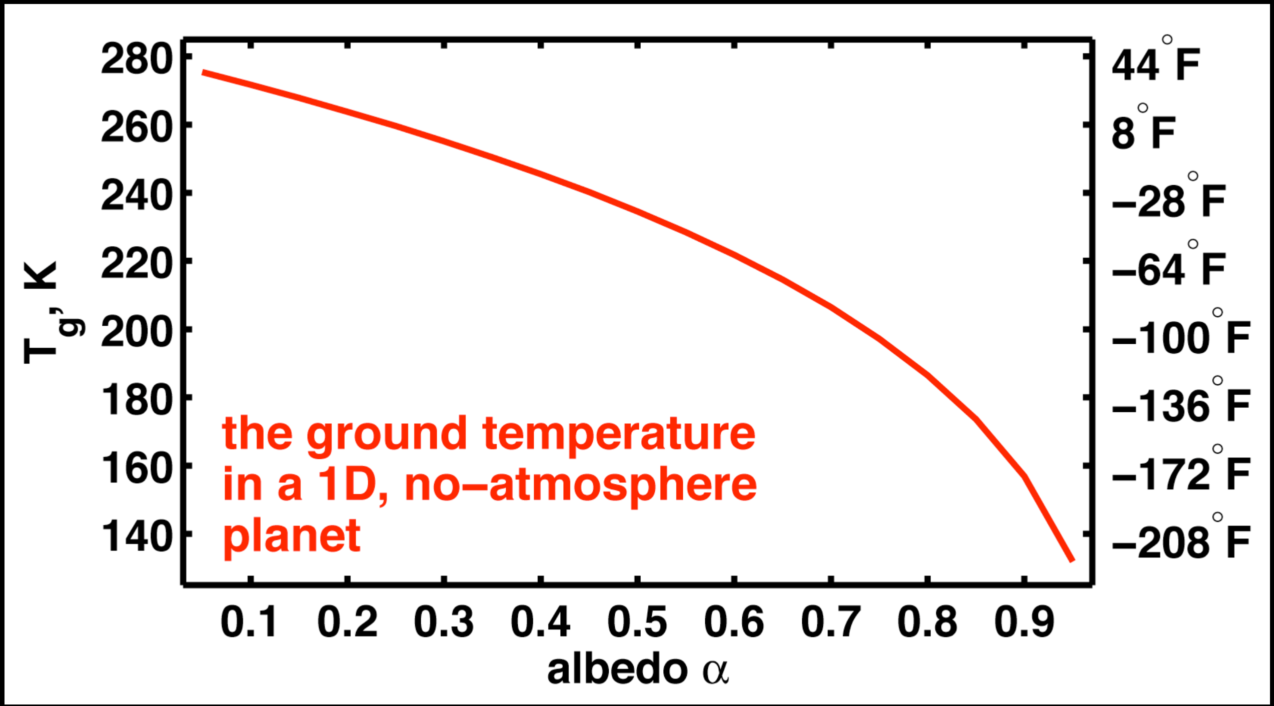


⬅ actually absorbed

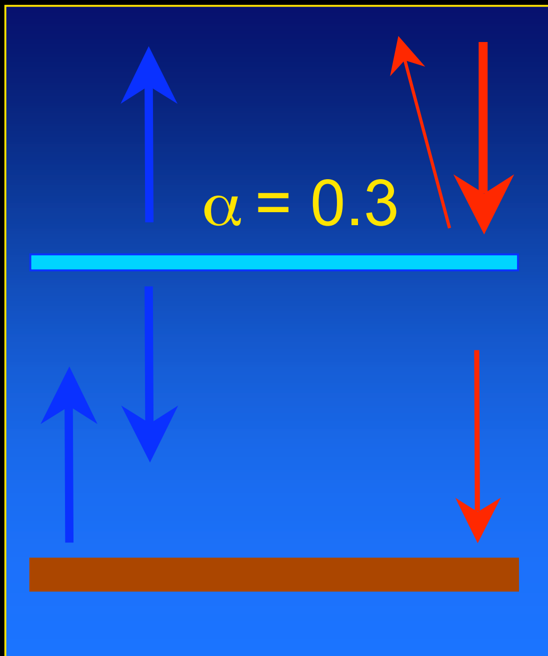
with planetary α ≈ 0.3

$$T_g = \sqrt[4]{\frac{0.7 \cdot 1380 \text{ W m}^{-2}}{4 \cdot 5.7 \cdot 10^{-8} \text{ W m}^{-2}\text{K}^{-4}}} \approx 255 \text{ K}$$

and, for other values of α,



introduce an idealized atmosphere



S_o top of atmosphere downward shortwave radiation (SW ↓)

T_a = atmospheric temperature

T_g = ground temperature

$S_o\,(1-\alpha)$ SW ↓ absorbed by ground

$$4\sigma T_g^4 = S_o\,(1-\alpha) + 4\sigma T_a^4$$ ground heat balance

$$2\sigma T_a^4 = \sigma T_g^4$$ atmosphere heat balance

using the two equations,

$$2\sigma T_a^4 = \sigma T_g^4$$

$$4\sigma T_g^4 = S_o\,(1-\alpha) + 4\sigma T_a^4$$

$$4\sigma T_a^4 = 2\sigma T_g^4$$

$$2\sigma T_g^4 = S_o\,(1-\alpha)$$

$$T_g = \sqrt[4]{\frac{S_o\,(1-\alpha)}{2\sigma}}$$

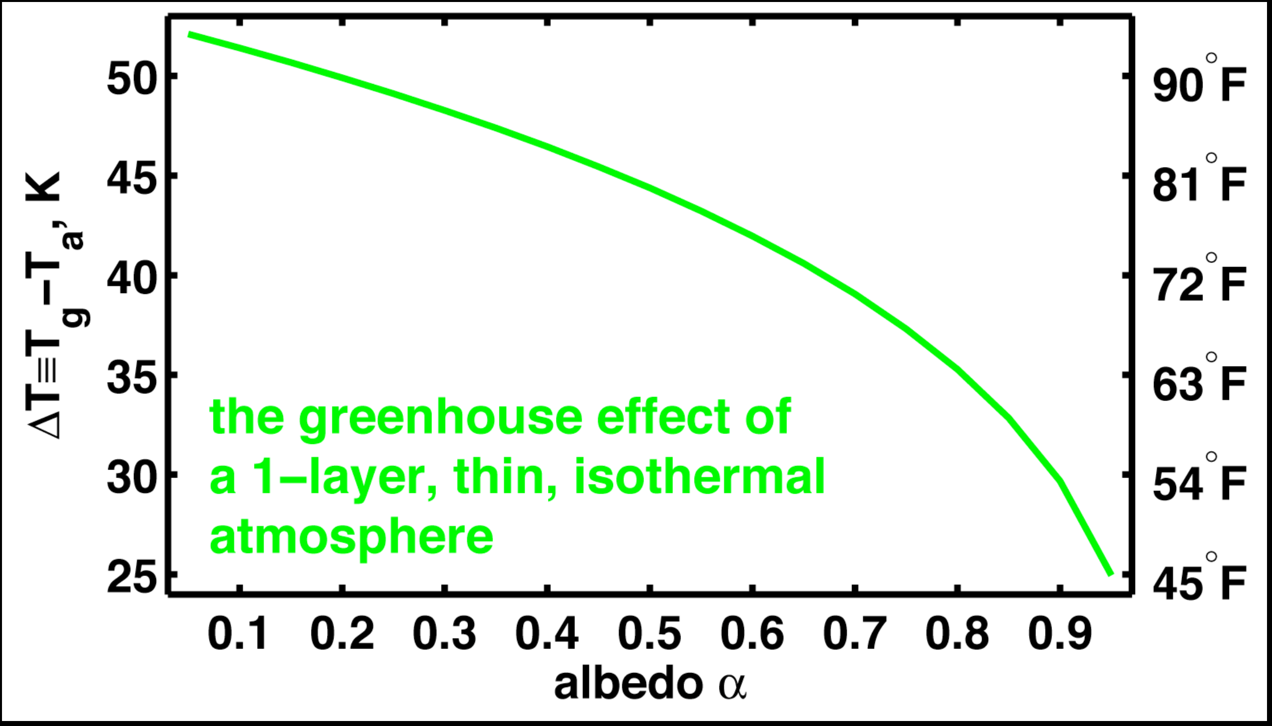
$$T_g = \sqrt[4]{\frac{1380 \cdot 0.7}{2 \cdot 5.7 \cdot 10^{-8}}} \approx 303\ \mathrm{K}$$

so the "*greenhouse effect*" of our "atmosphere" switches

$T_g \approx 255\ \mathrm{K}$ → $T_g \approx 303\ \mathrm{K}$

$\Delta T_g^{GH} \approx 48\ \mathrm{K} \approx 87^{o}\mathrm{F}$!!!

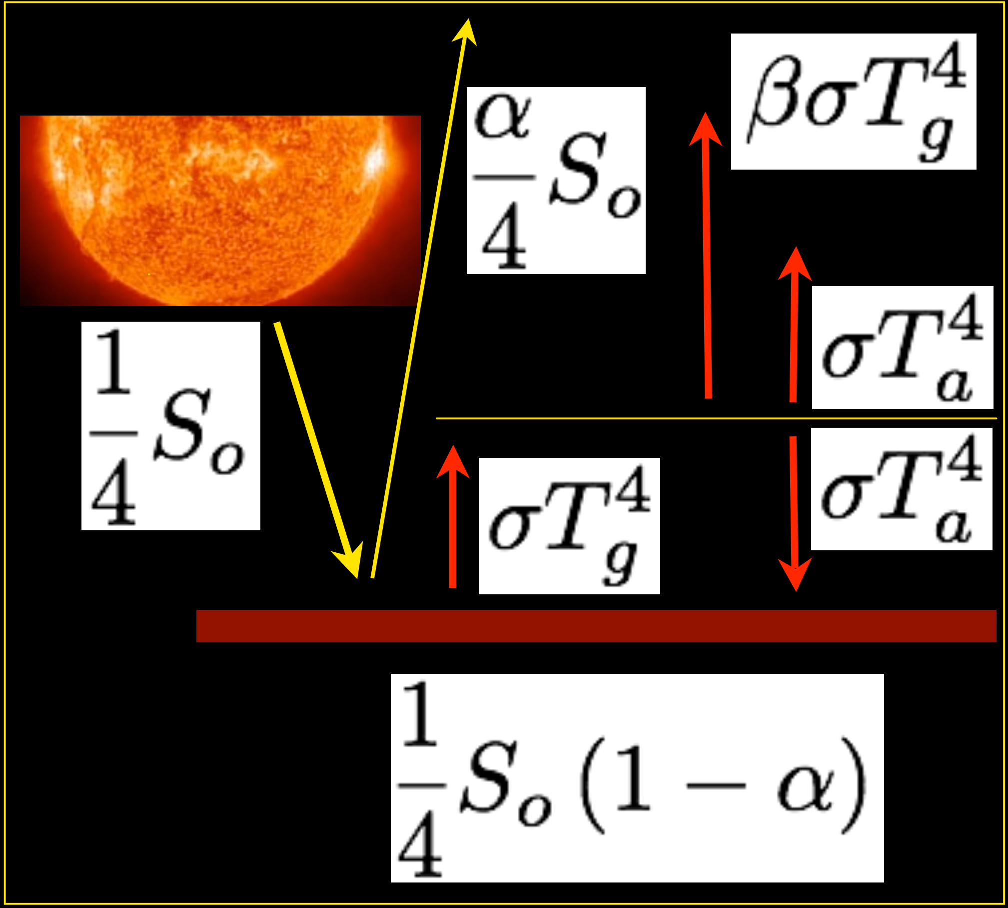
or, for other values of α, the greenhouse effect, defined as the ground minus air temperature difference, is



the sensitivity to atmospheric opacity

suppose (as is indeed the case), that the atmosphere absorbs only a fraction (1-β) of the upwelling longwave radiation, letting a fraction of it, β, to pass through.

Then the configuration is



and the atmosphere's heat balance is

$$(1-\beta)\sigma T_g^4 = 2\sigma T_a^4$$

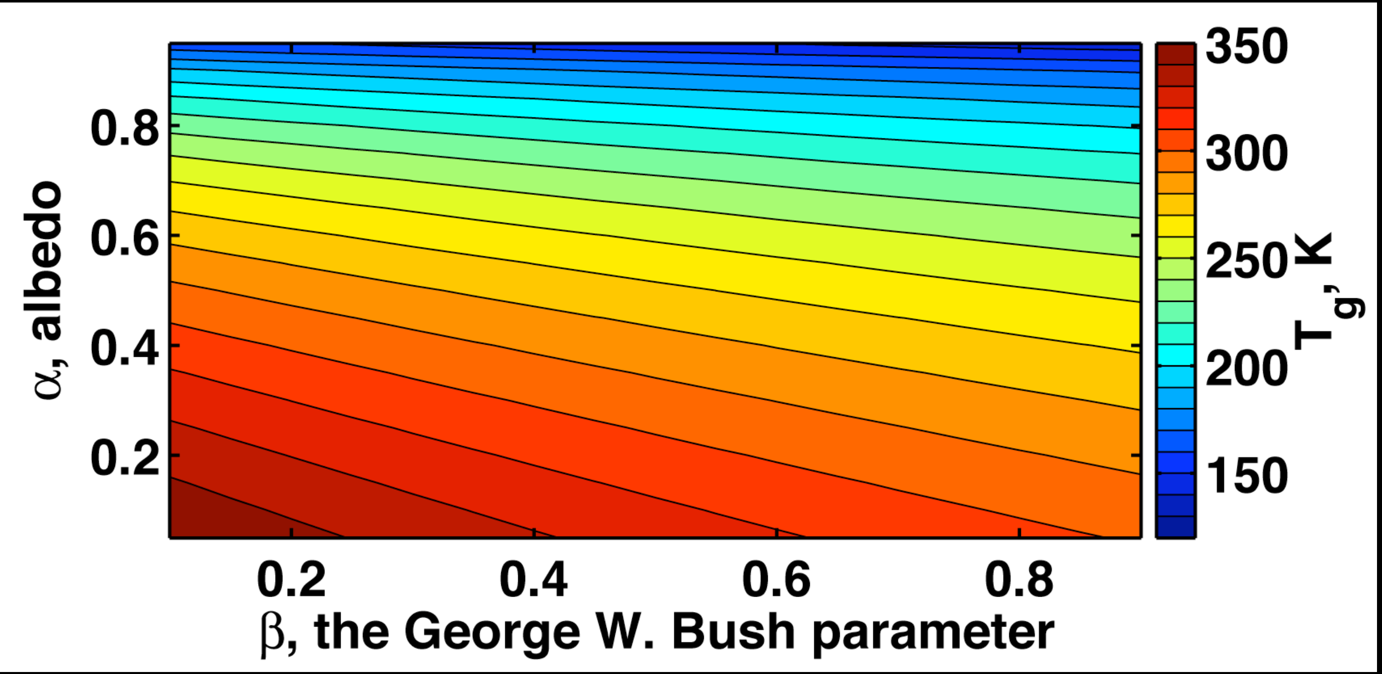
$$T_a = \sqrt[4]{\frac{1}{2}(1-\beta)T_g^4}$$

The ground heat balance is

$$\frac{1}{4}S_o(1-\alpha)+\sigma T_a^4=\sigma T_g^4$$

yielding

$$T_g=\sqrt[4]{\frac{S_o(1-\alpha)}{2\sigma(1+\beta)}}$$



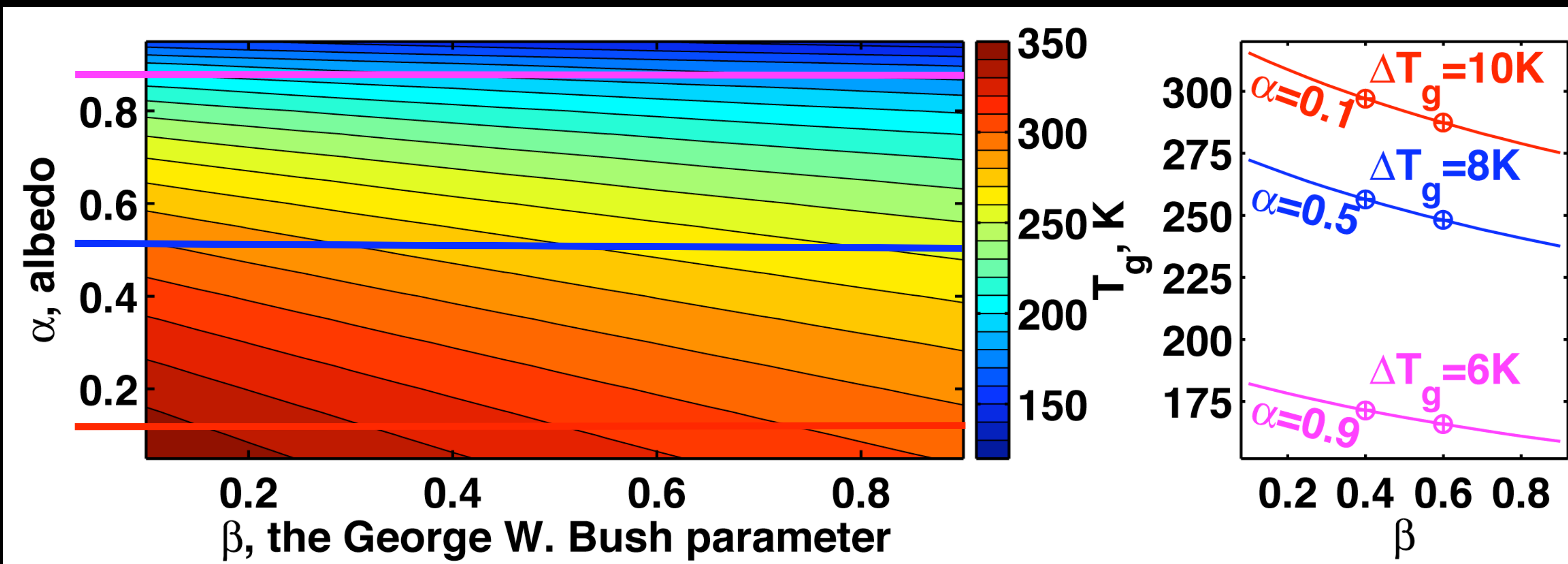
← more CO_2 and water vapor

The ground heat balance is

$$\frac{1}{4}S_o(1-\alpha)+\sigma T_a^4=\sigma T_g^4$$

yielding

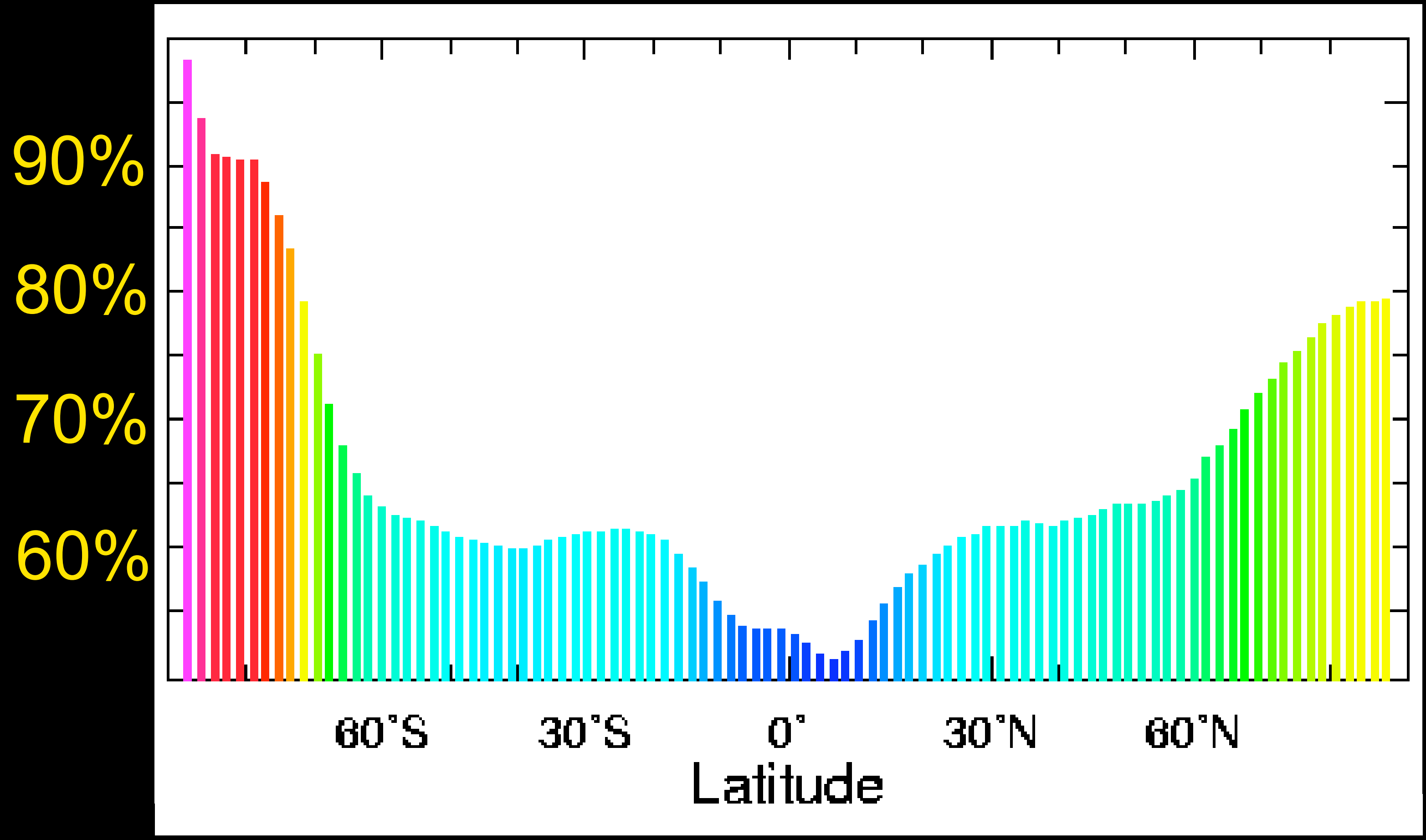
$$T_g=\sqrt[4]{\frac{S_o(1-\alpha)}{2\sigma(1+\beta)}}$$



⬅ more CO_2 and water vapor

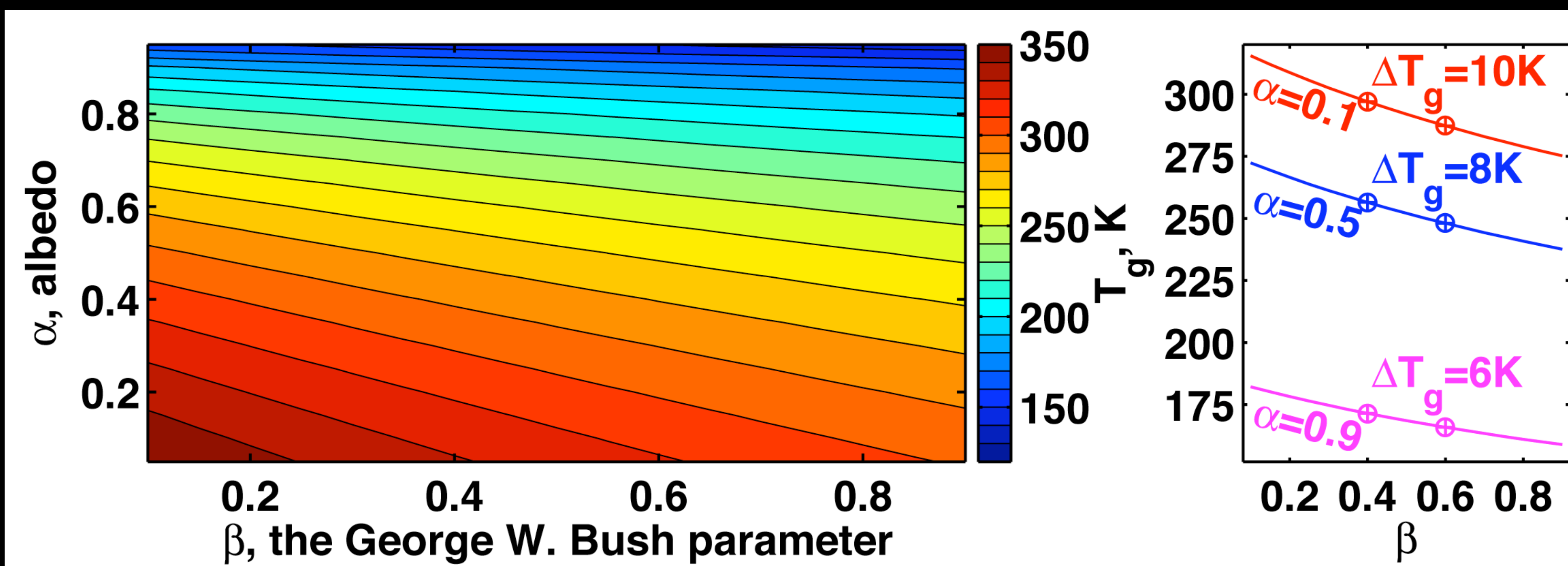
which is not all that unrealistic

zonal- and annual-mean climatological ratio
of ↑**LW, 100×(top/surface)**



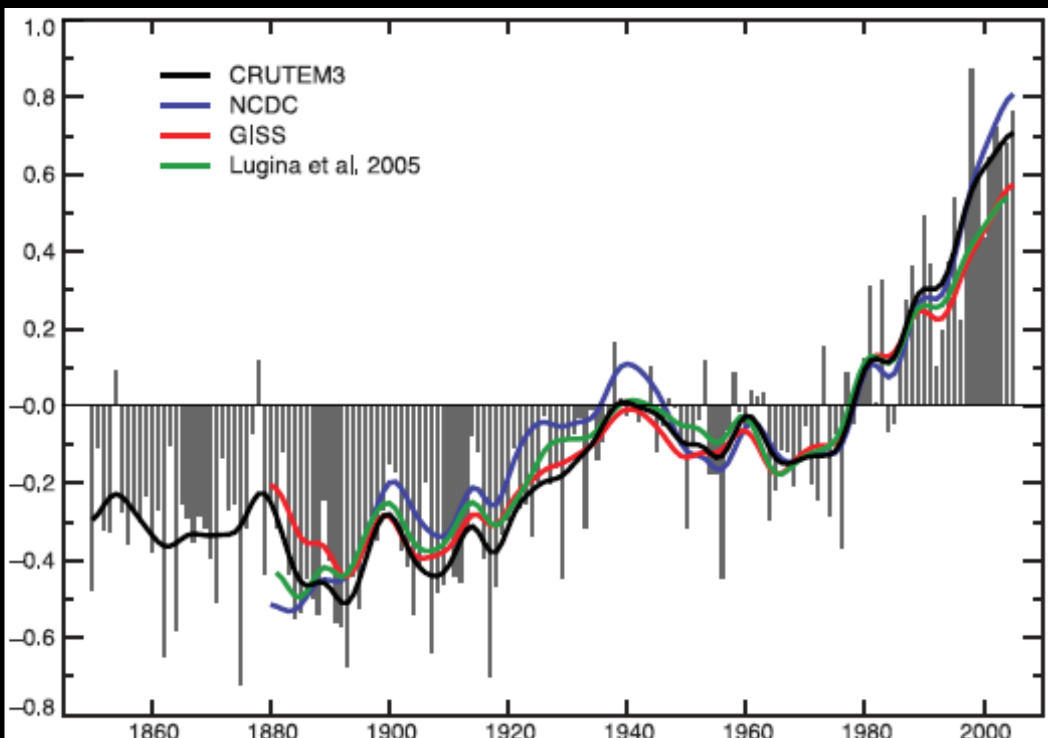
the moral of our brief intro to radiation transfer:

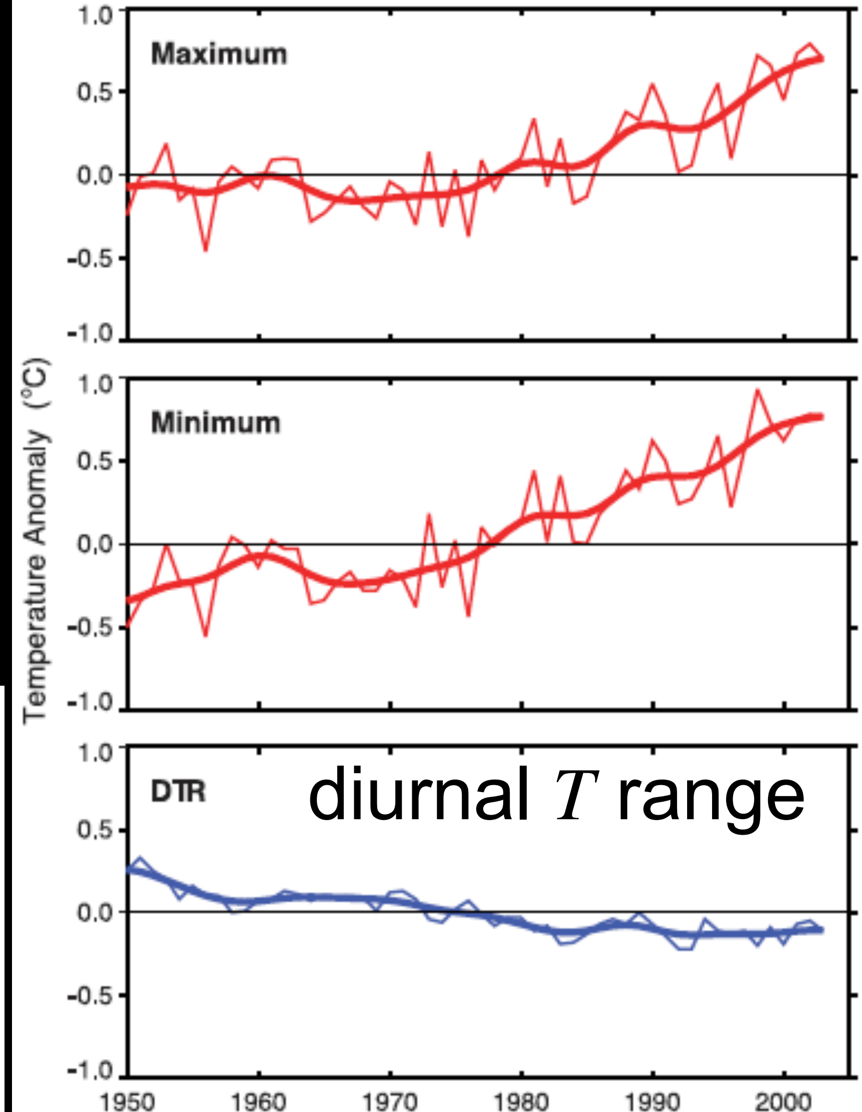
1. the natural greenhouse effect is a crucial element of life on earth
2. the more opaque the atmosphere - the warmer the ground



The Observed Record: it's getting hot

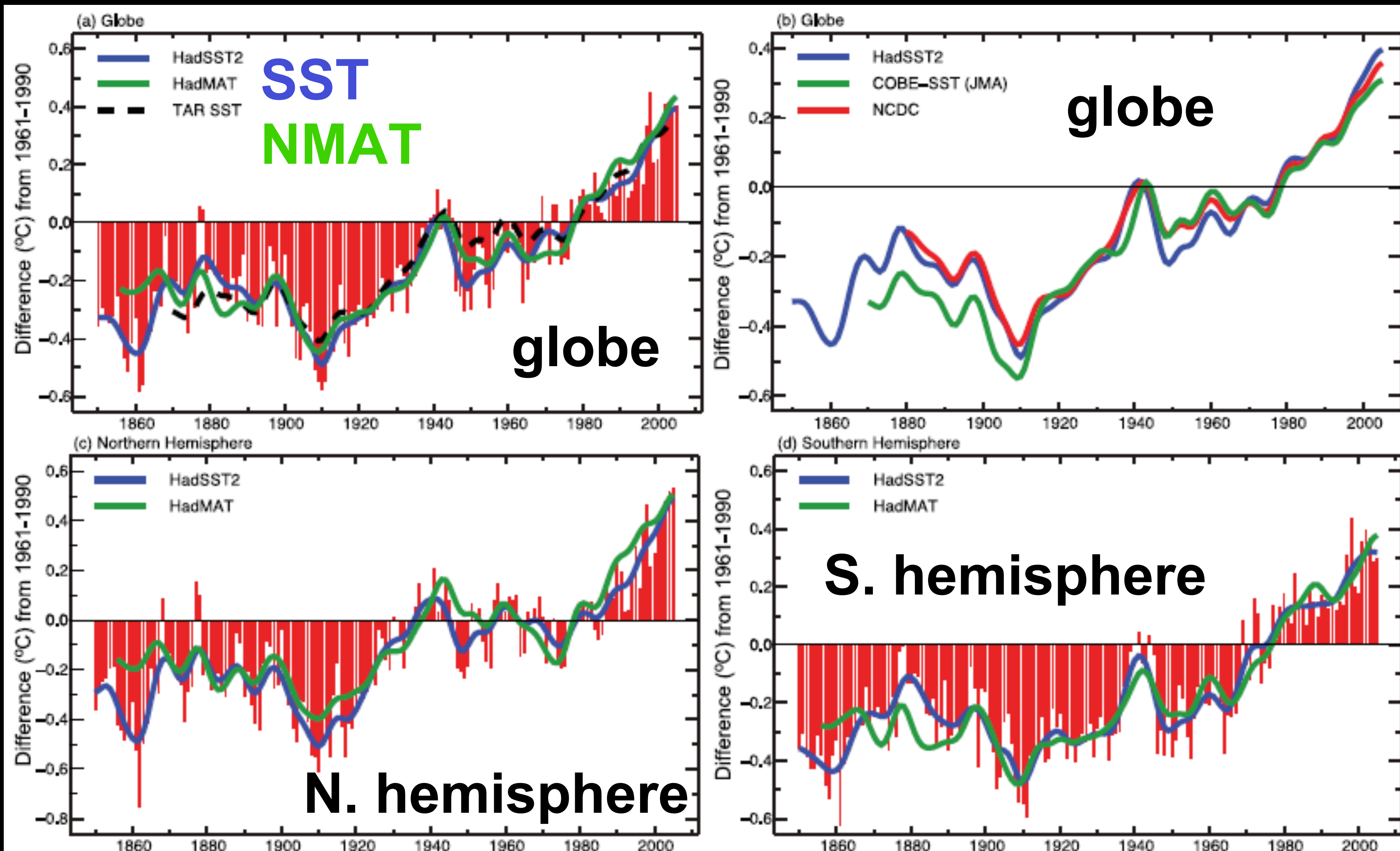
$\Delta T'$ from '61-'90 mean, K

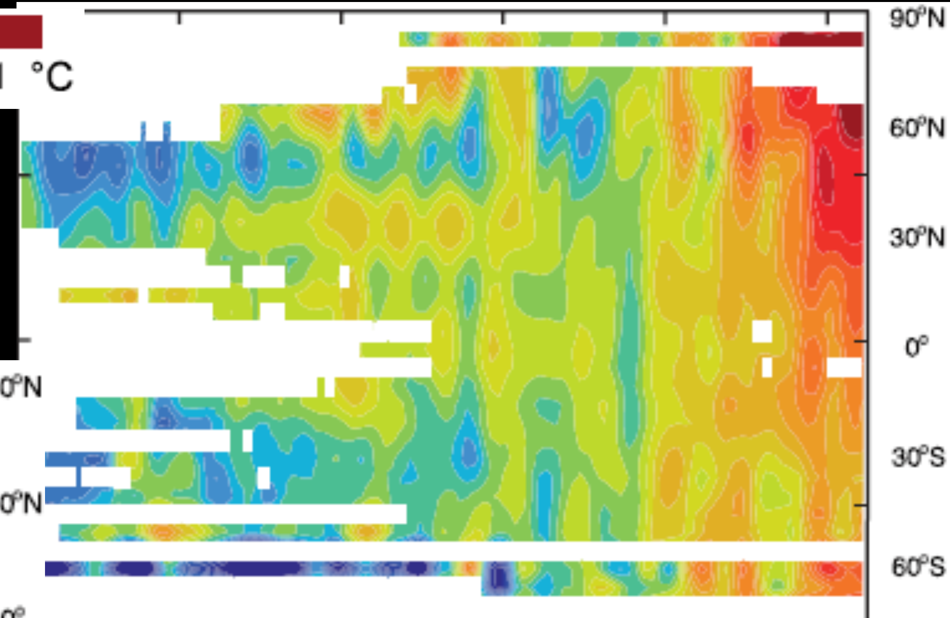


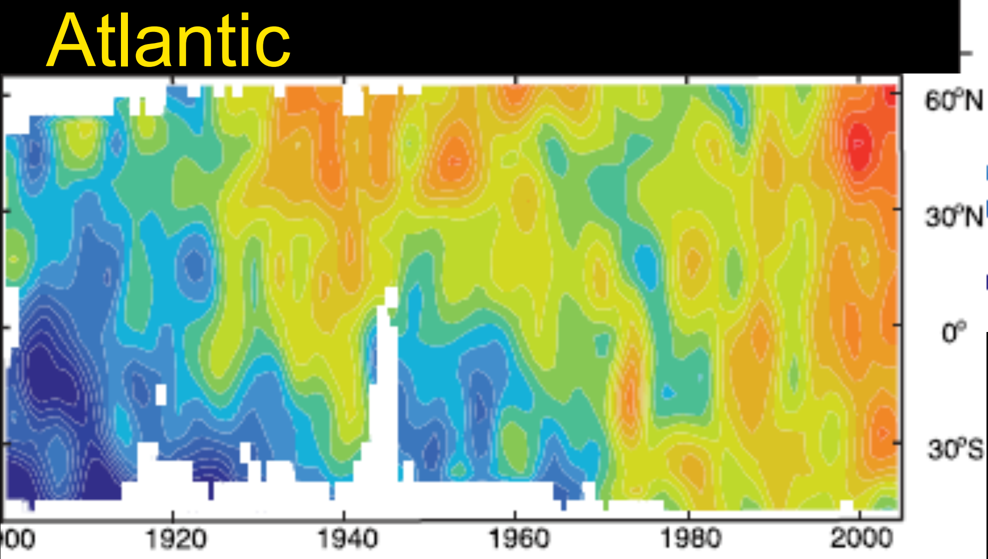


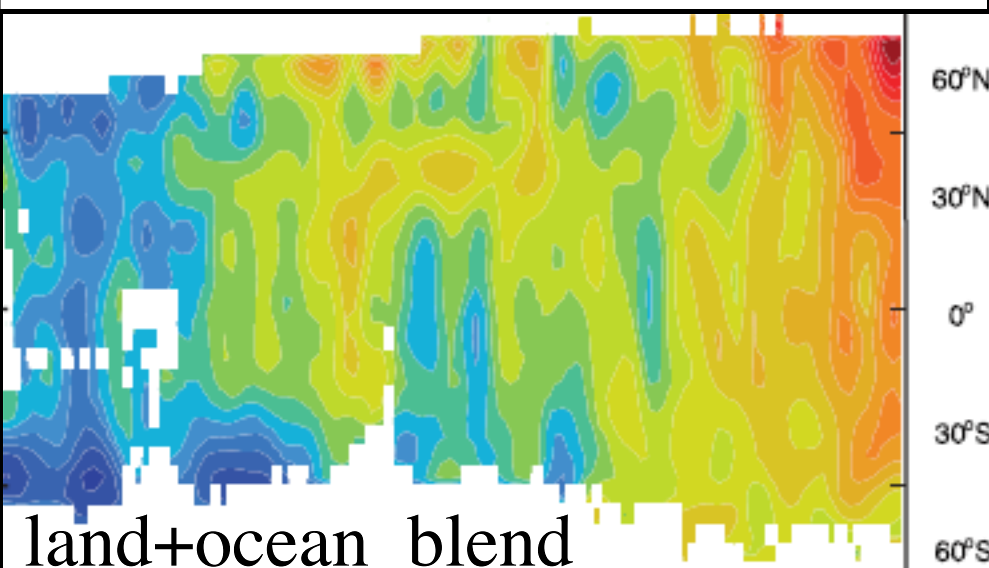
annual mean T' extremes, K; Δ from '61-'90 mean; 71% of land area

spatial-mean temperature anomalies



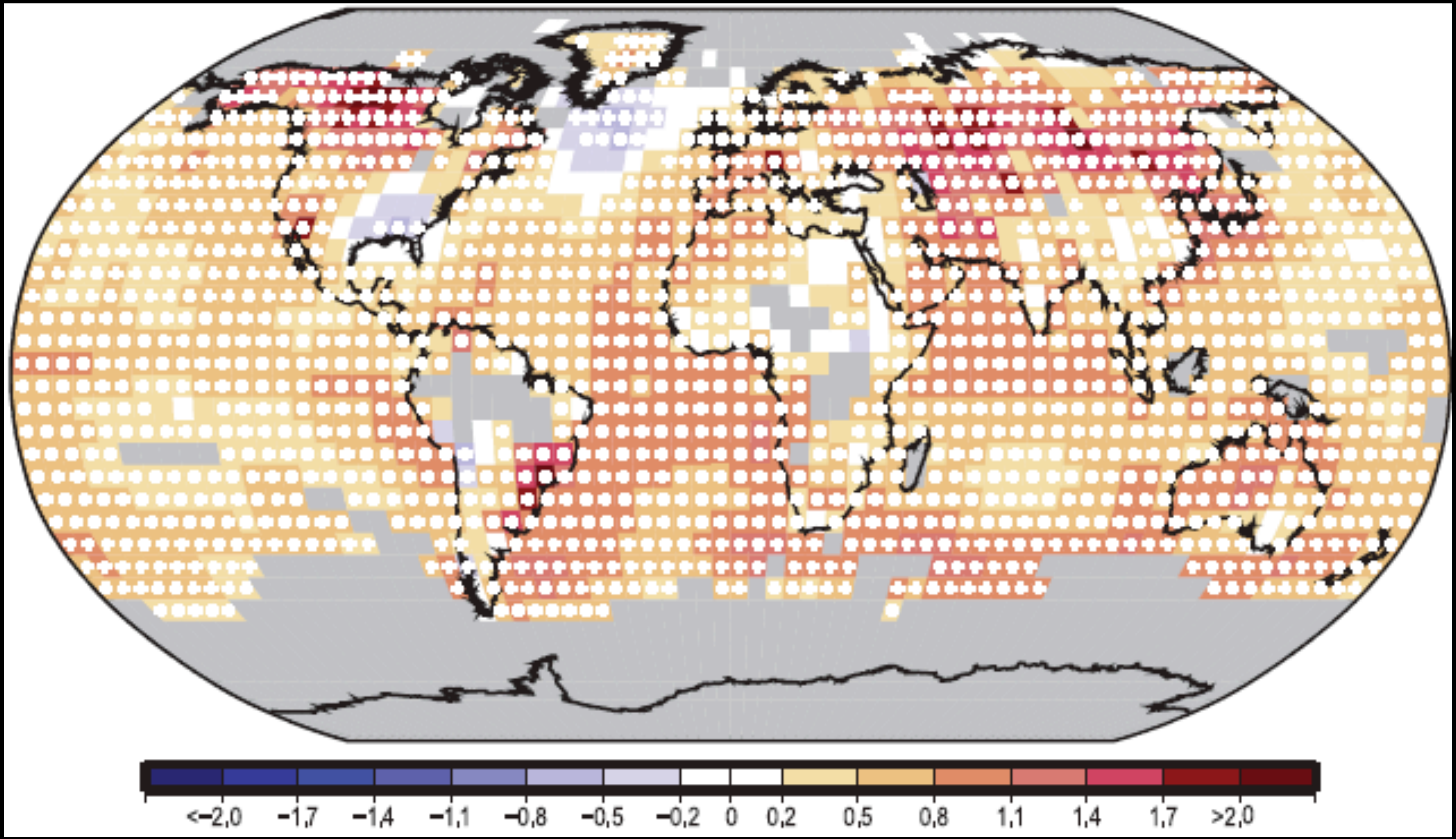




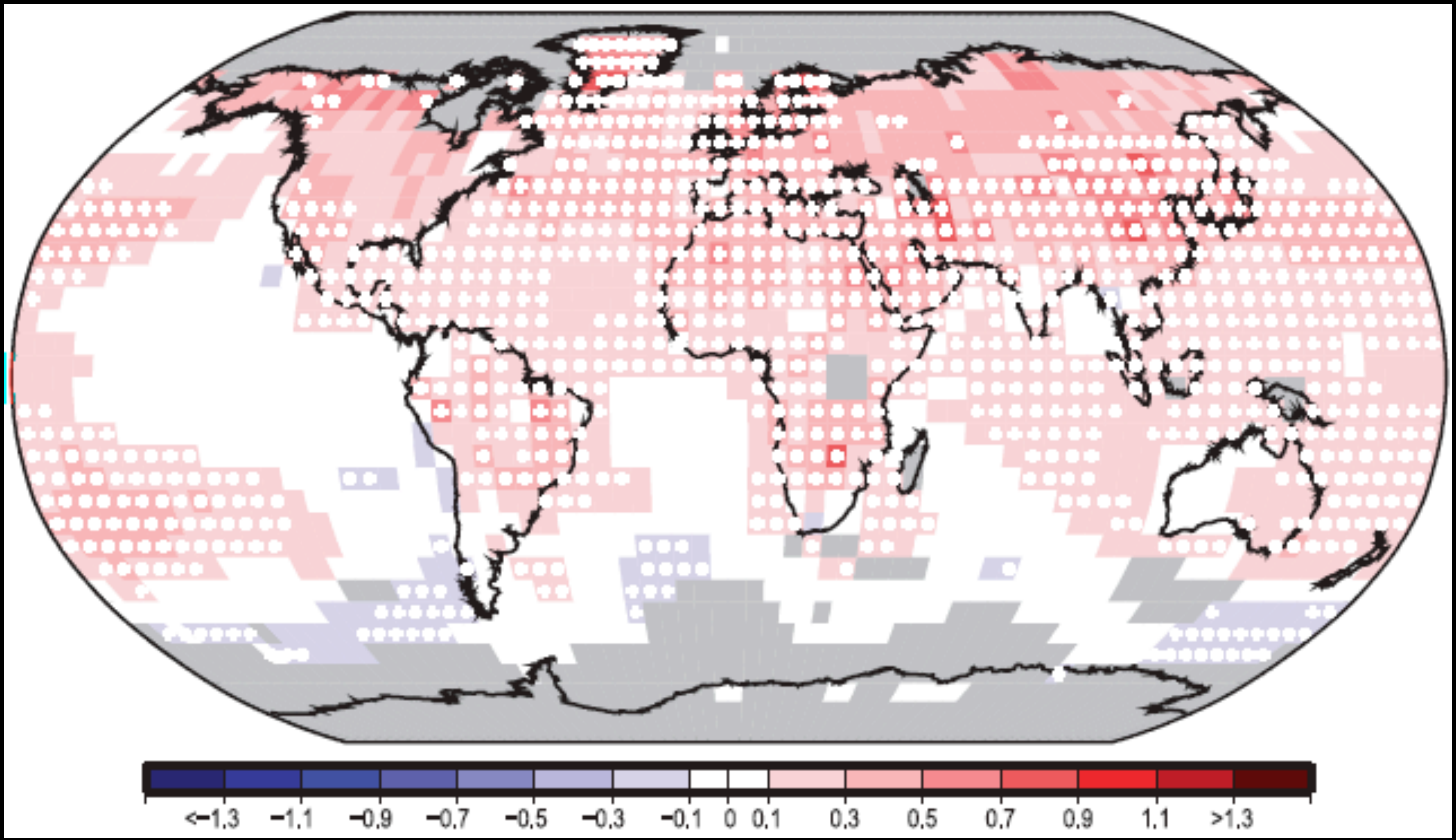


zonal-mean
1900-2005
surface temps.
departures from
'61-'90 mean

linear temp. trends, 1901-2005, K century^{-1}



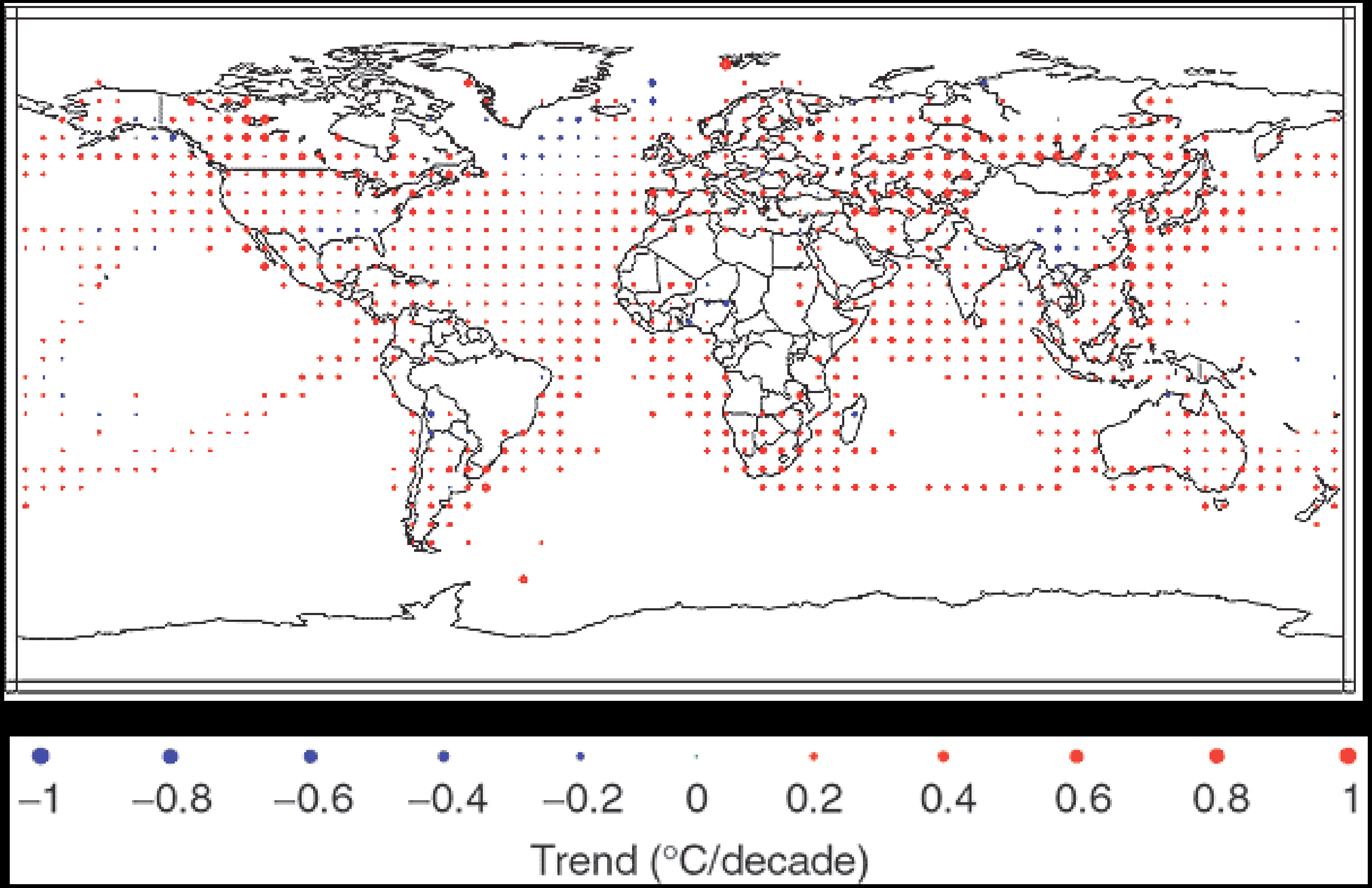
linear temp. trends, 1979-2005, K decade^{-1}



Annual-Mean Surface Temperature Changes

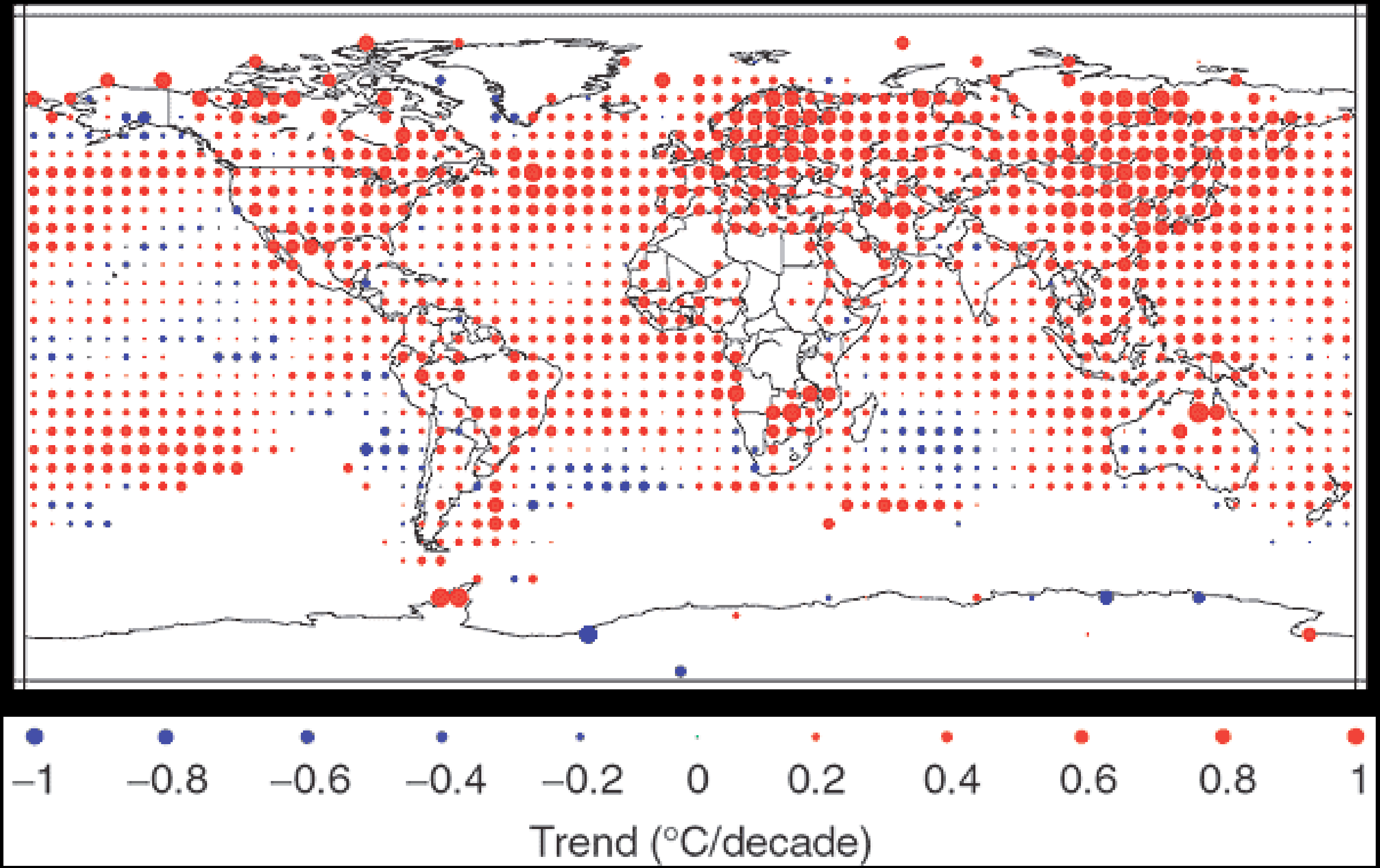
1901-2000

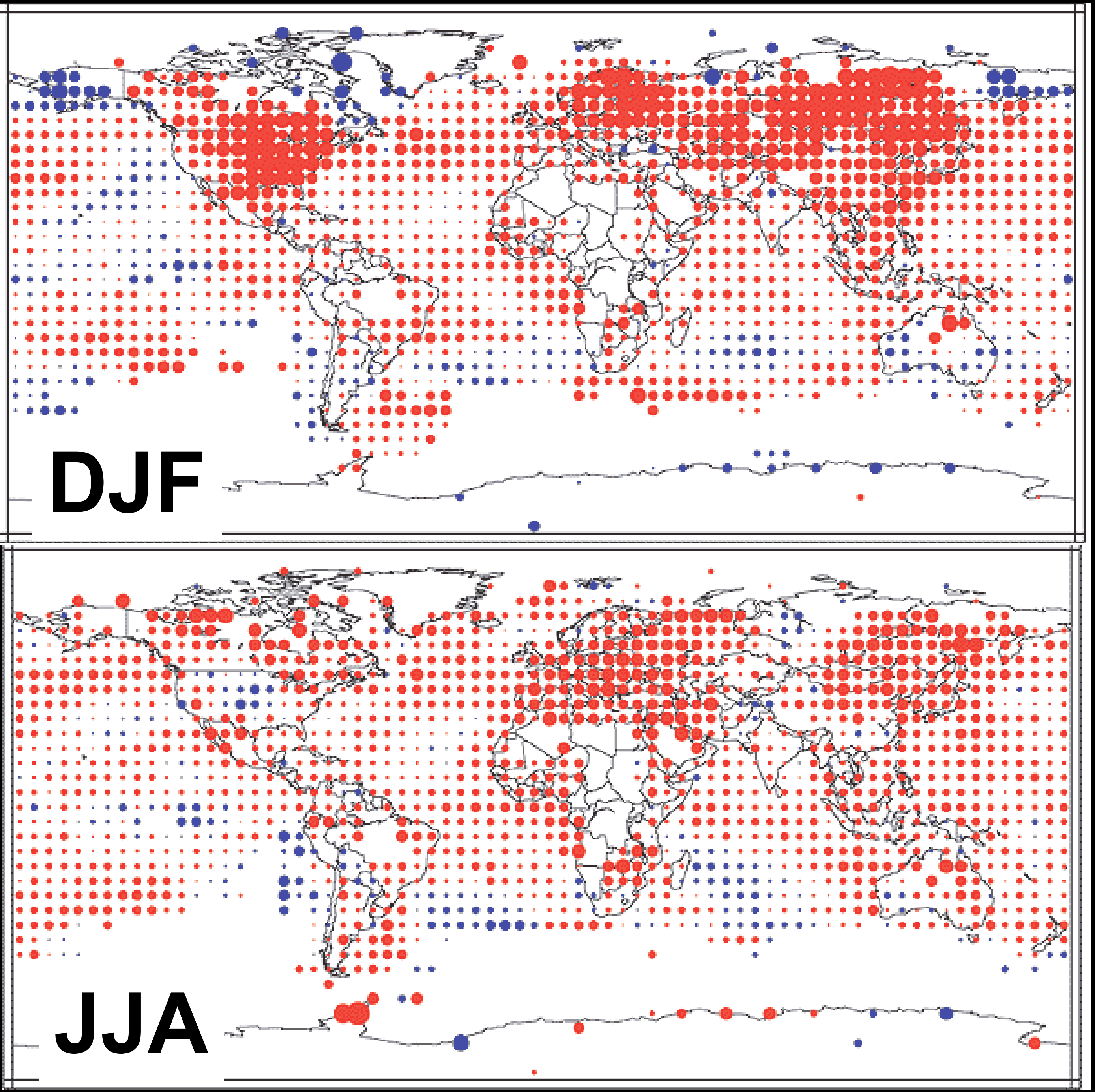
IPCC
2001



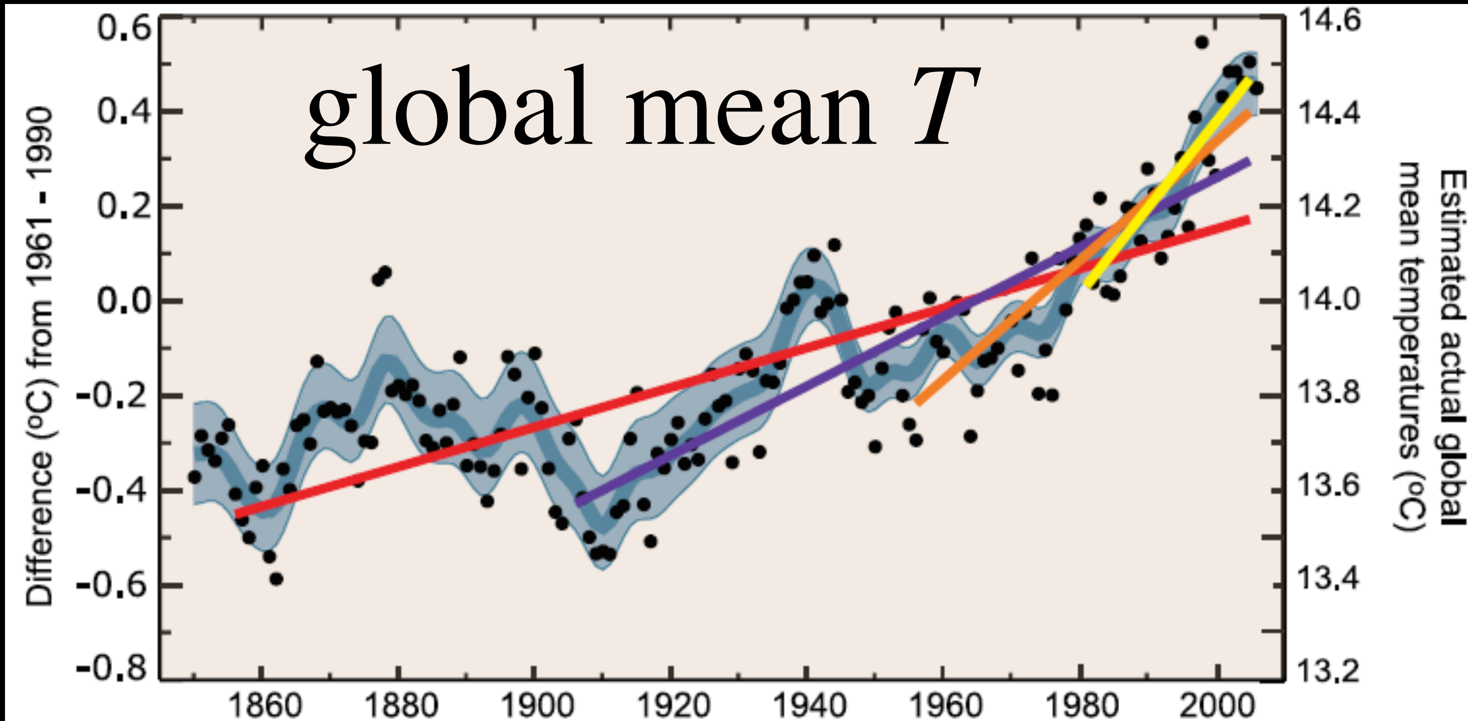
Annual-Mean Surface Temperature Changes

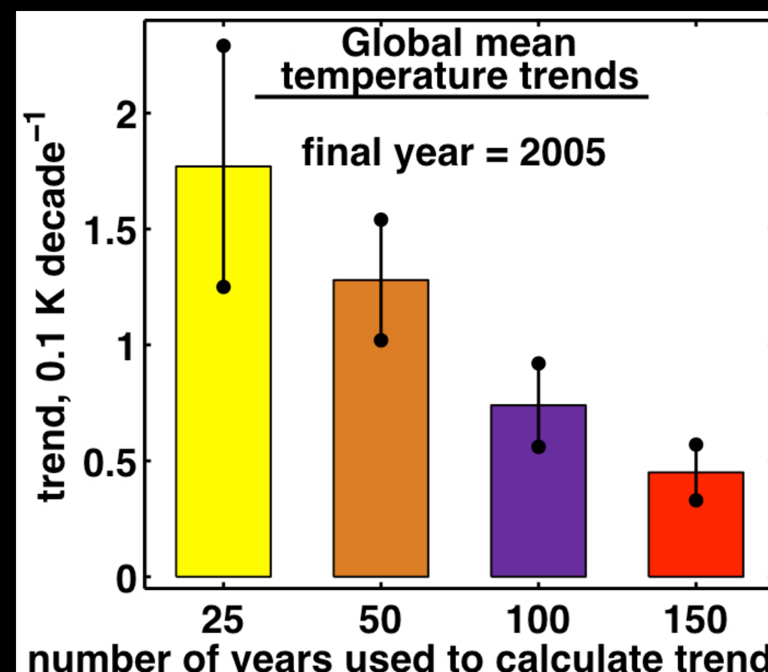
1976-2000



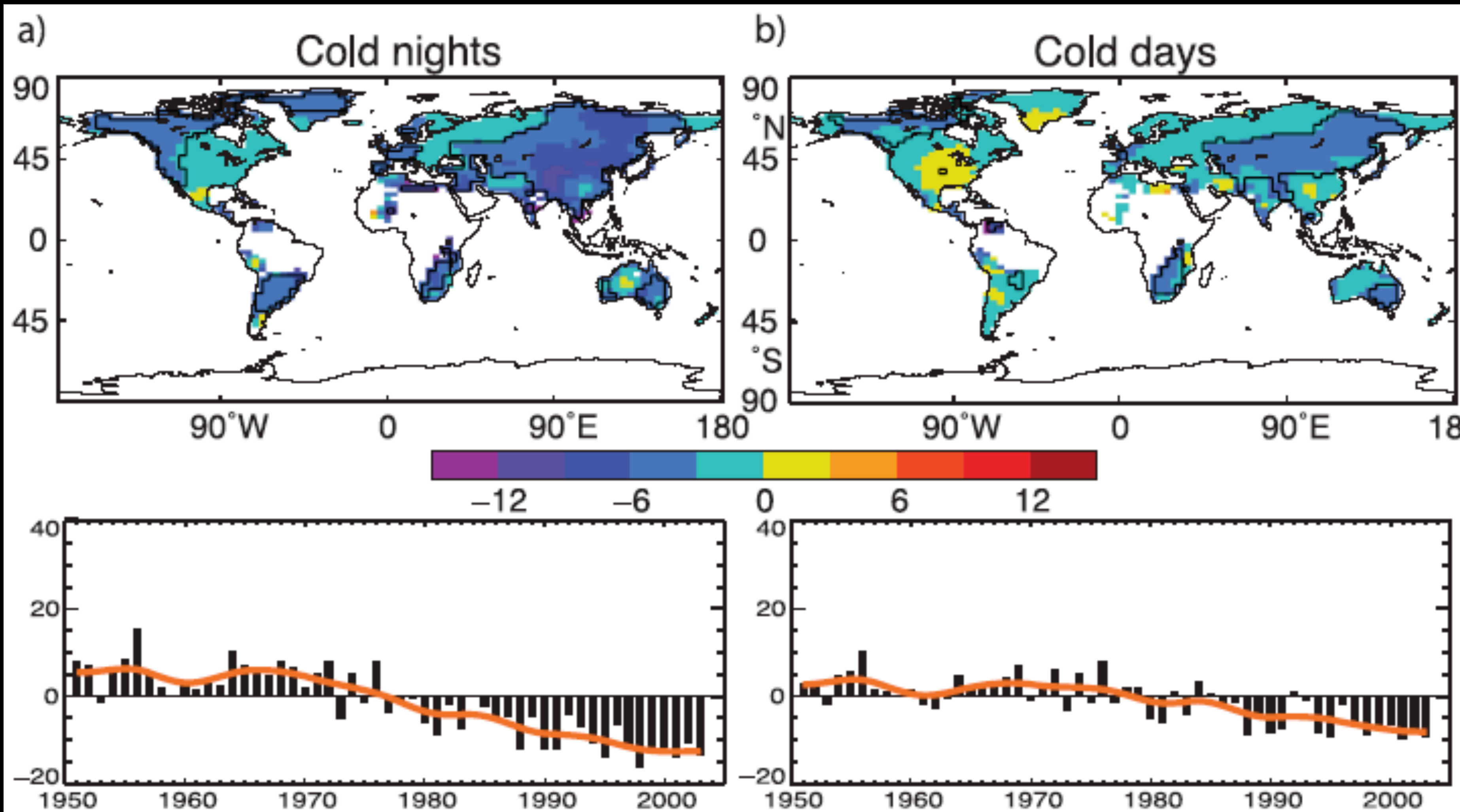


and seasonally


global mean T
Difference (°C) from 1961 - 1990
Estimated actual global mean temperatures (°C)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
14.6
14.4
14.2
14.0
13.8
13.6
13.4
13.2
1860
1880
1900
1920
1940
1960
1980
2000

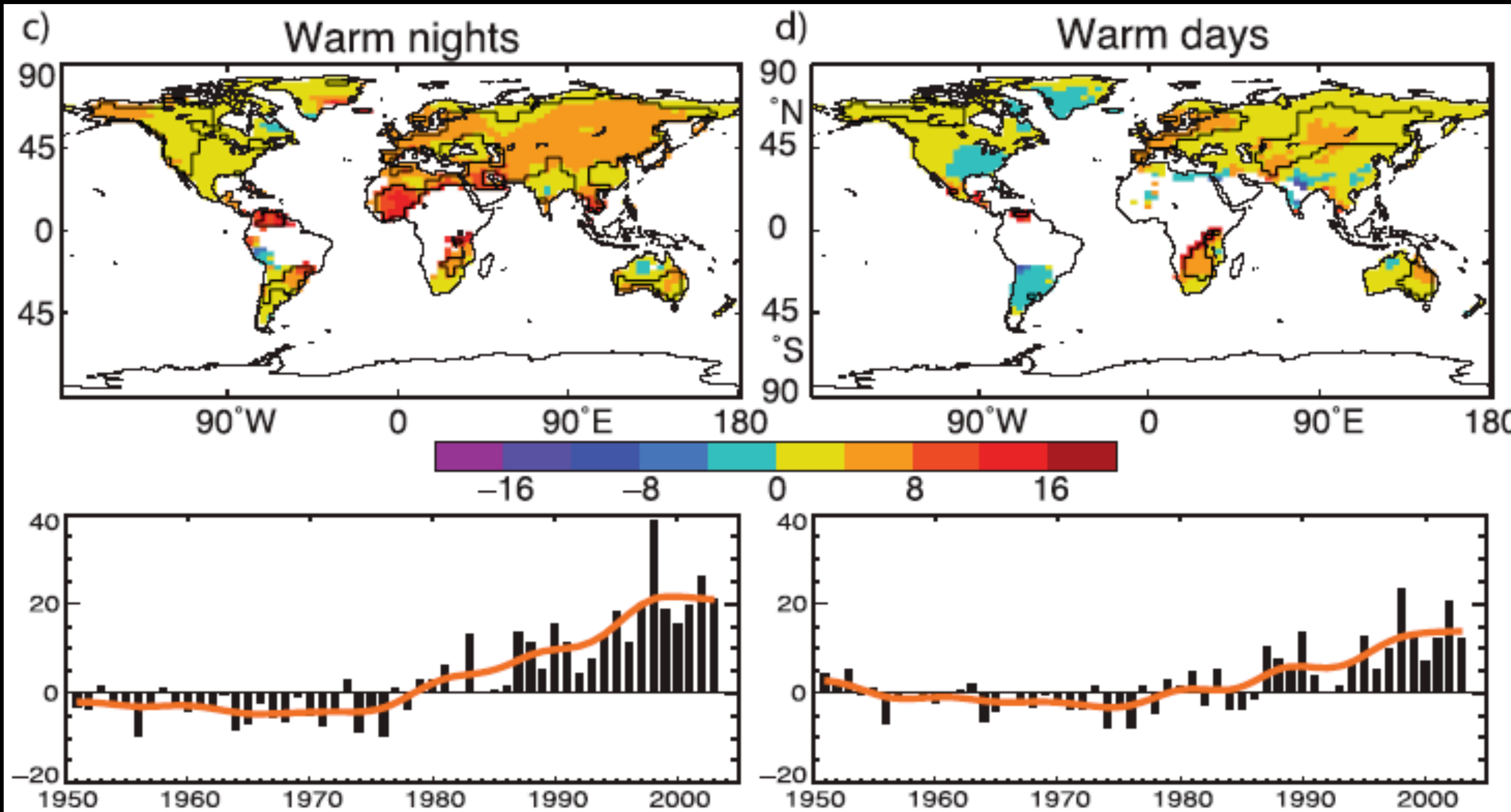

Global mean temperature trends
final year = 2005
trend, 0.1 K decade⁻¹
0
0.5
1
1.5
2
25
50
100
150
number of years used to calculate trend

extremes cold events



days per decade with
T<(1961-1990 PDF's 10th percentile)

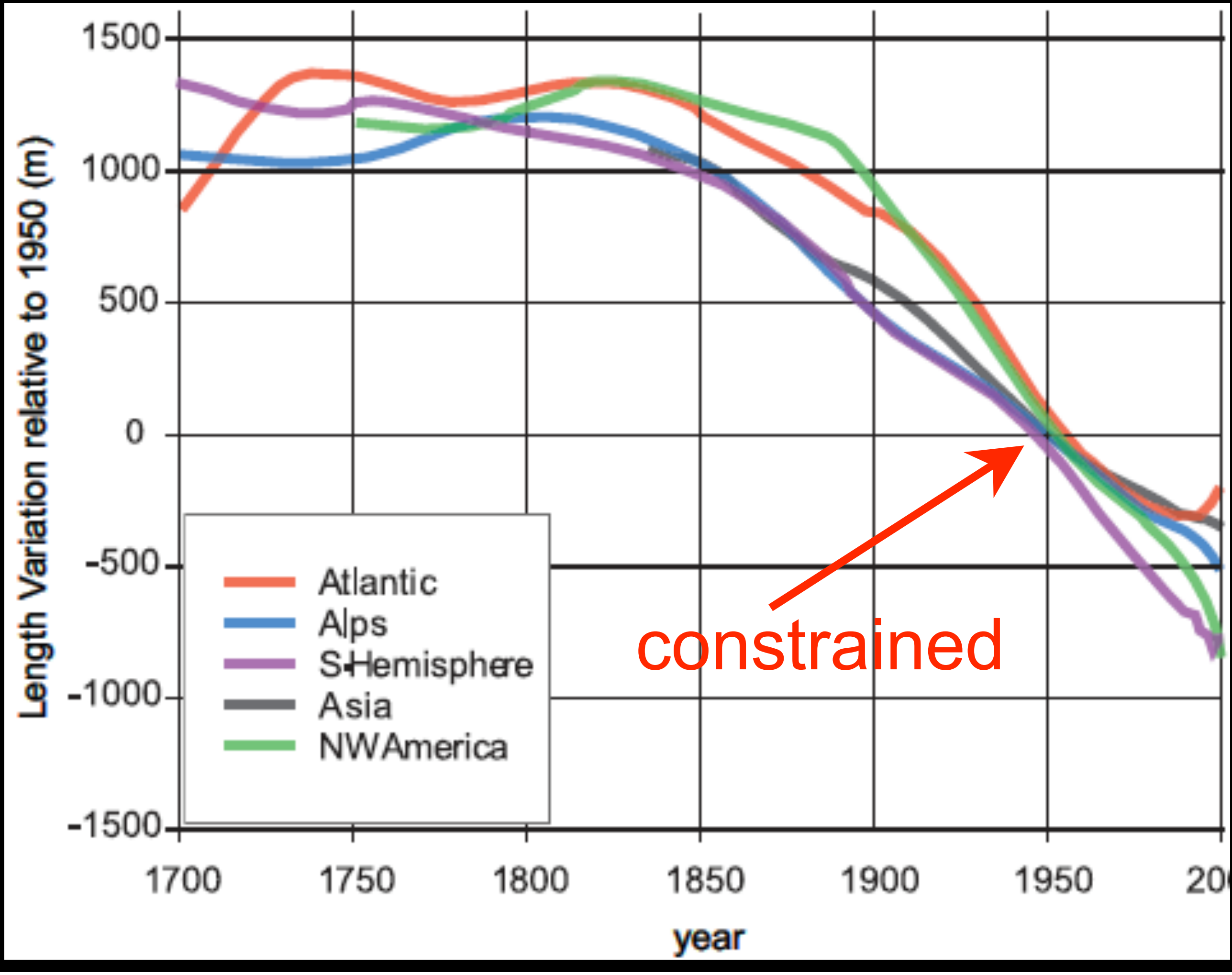
extremes warm events



days per decade with
T>(1961-1990 PDF's 90th percentile)

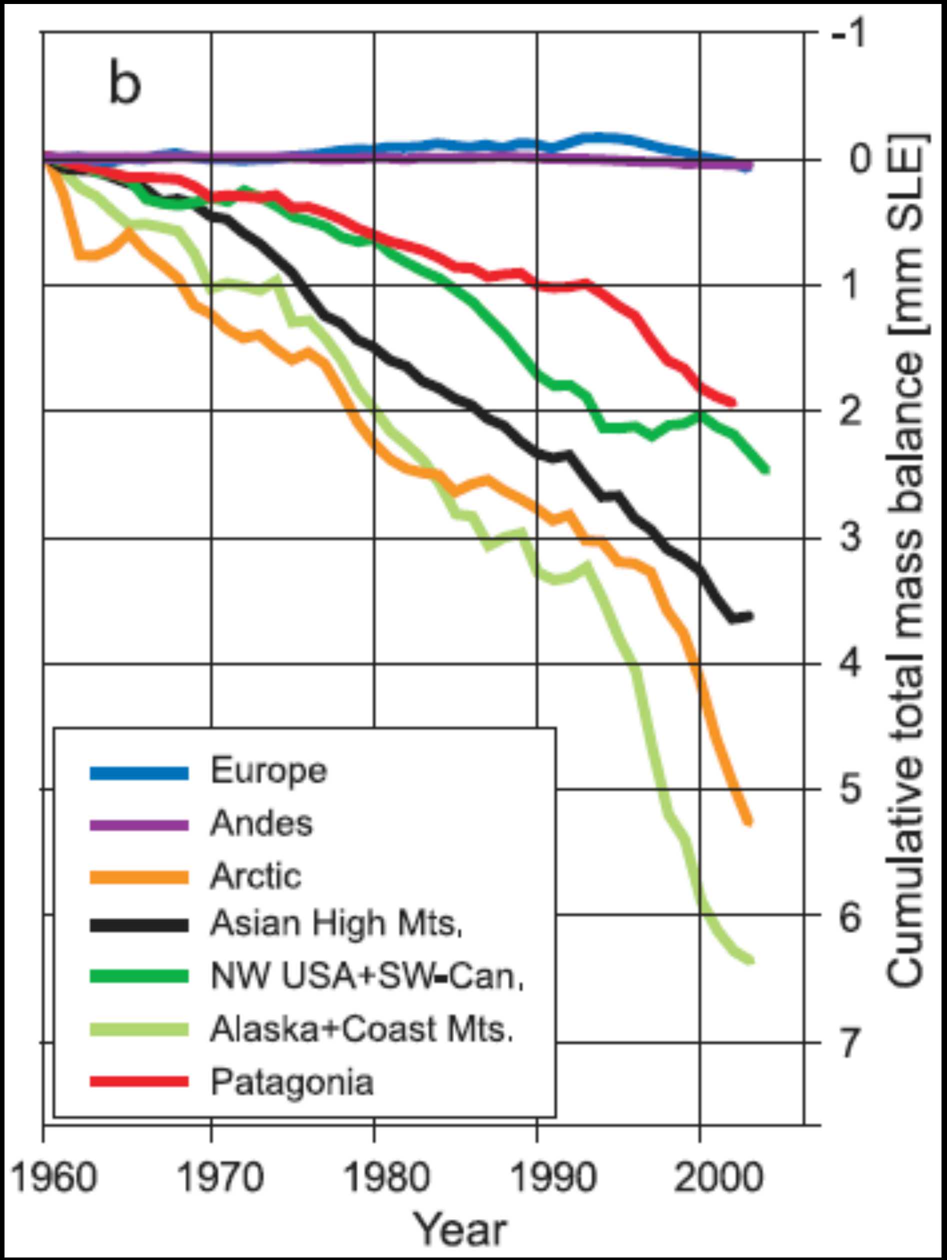
not surprisingly, ice responds

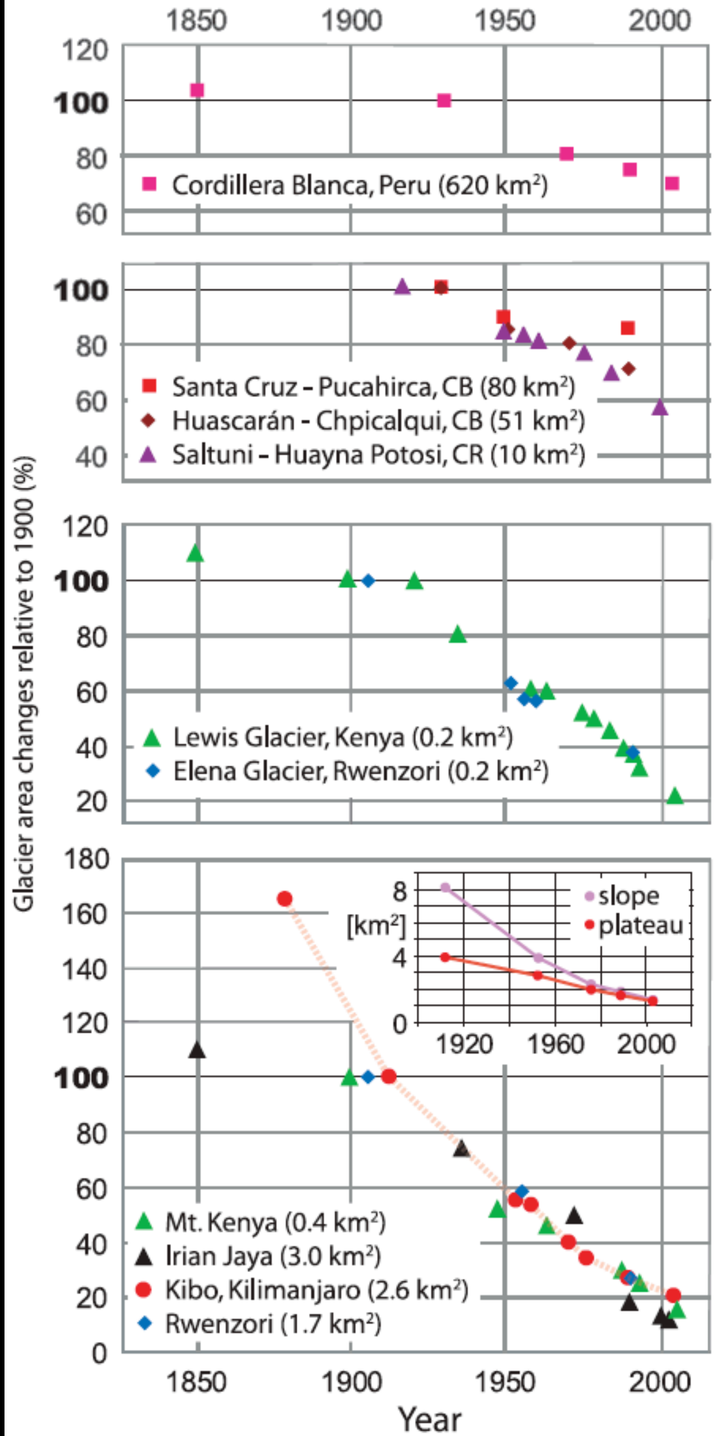
tongue length of major global glaciers



tropics, New Zealand, Patagonia, mainly Canadian Rockies, South Greenland, Iceland, Jan Mayen, Svalbard, Scandinavia, European Alps,Caucasus and central Asia

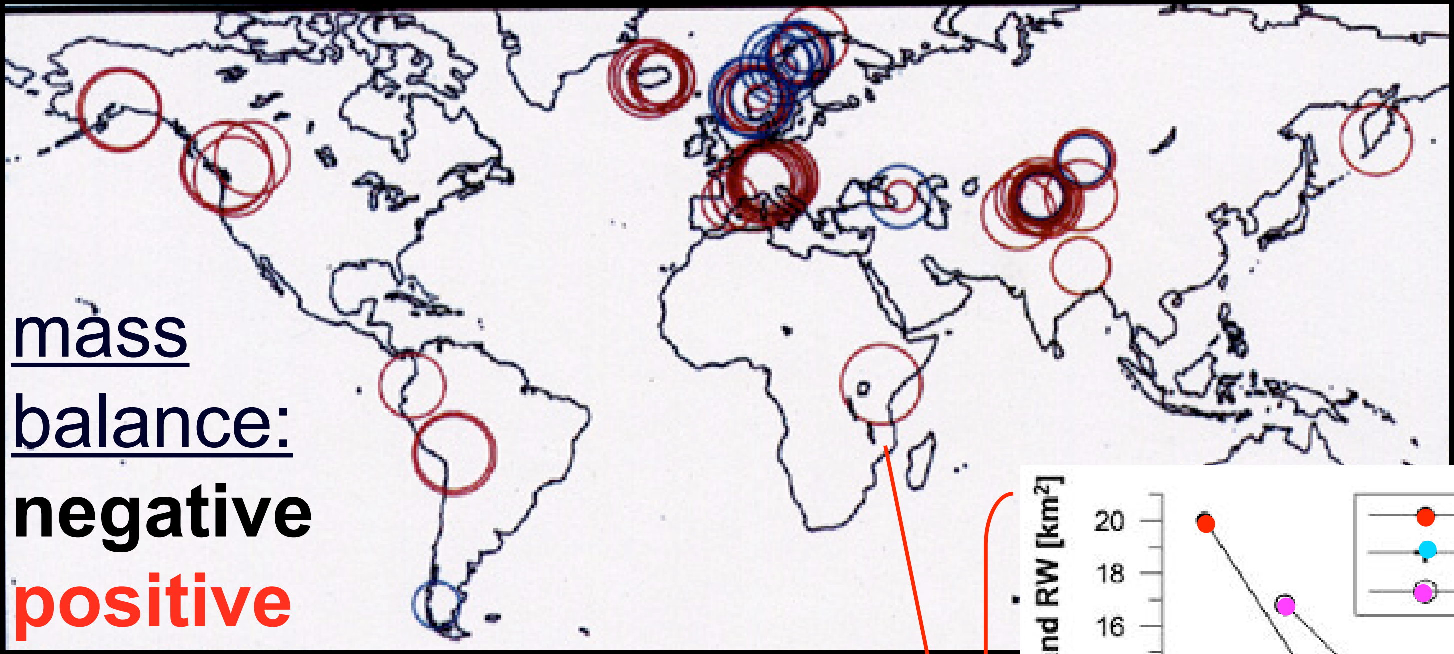
in all latitudes





global glacier mass balance, 1988-1998

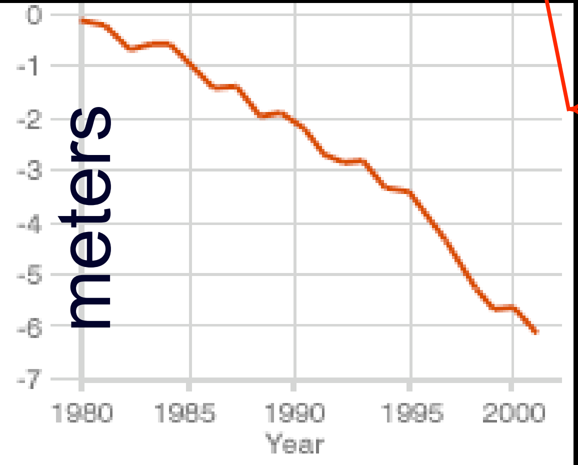
Area of circle is proportional to the log of the rate of mass loss or gain. Largest circles: 2-3m/yr

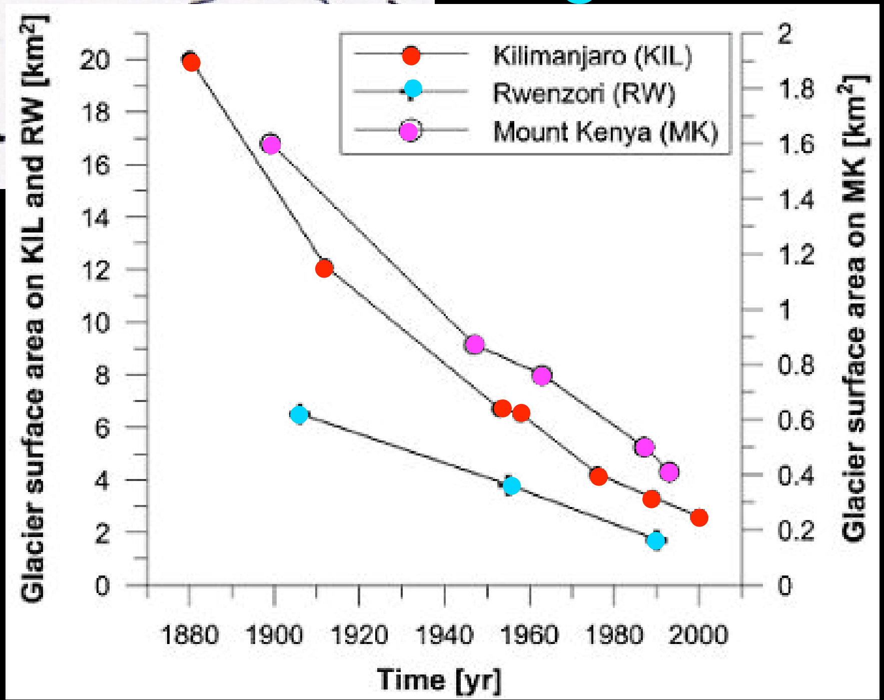


Kilimanjaro
Mt. Kenya
Uganda

global glacier mass balance

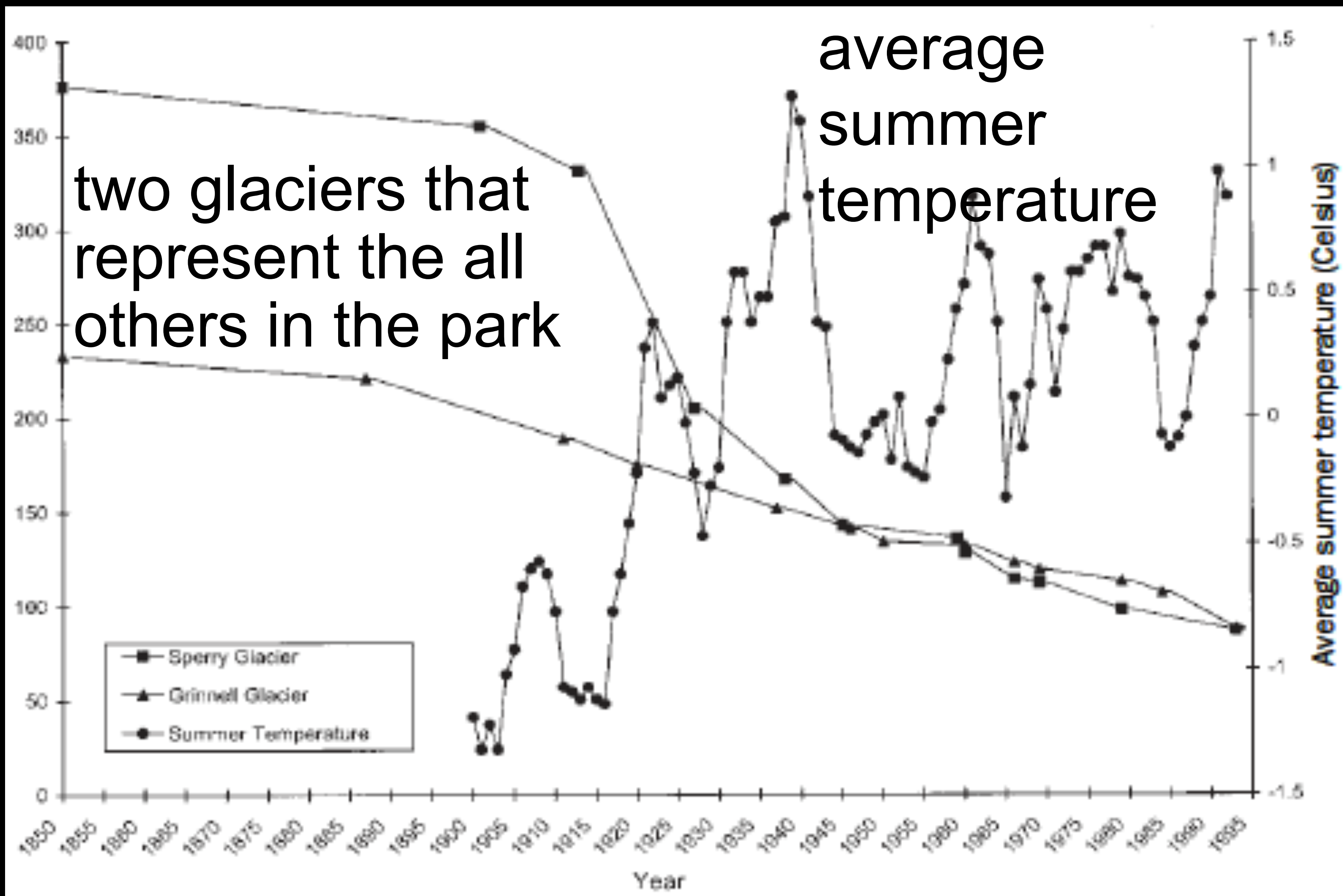
NY Times, 3/5/06





Glacier National Park, Montana

glacier size, hectares



1850 1900 1945 1995

Grinnell glacier, GNP, Montana

1910

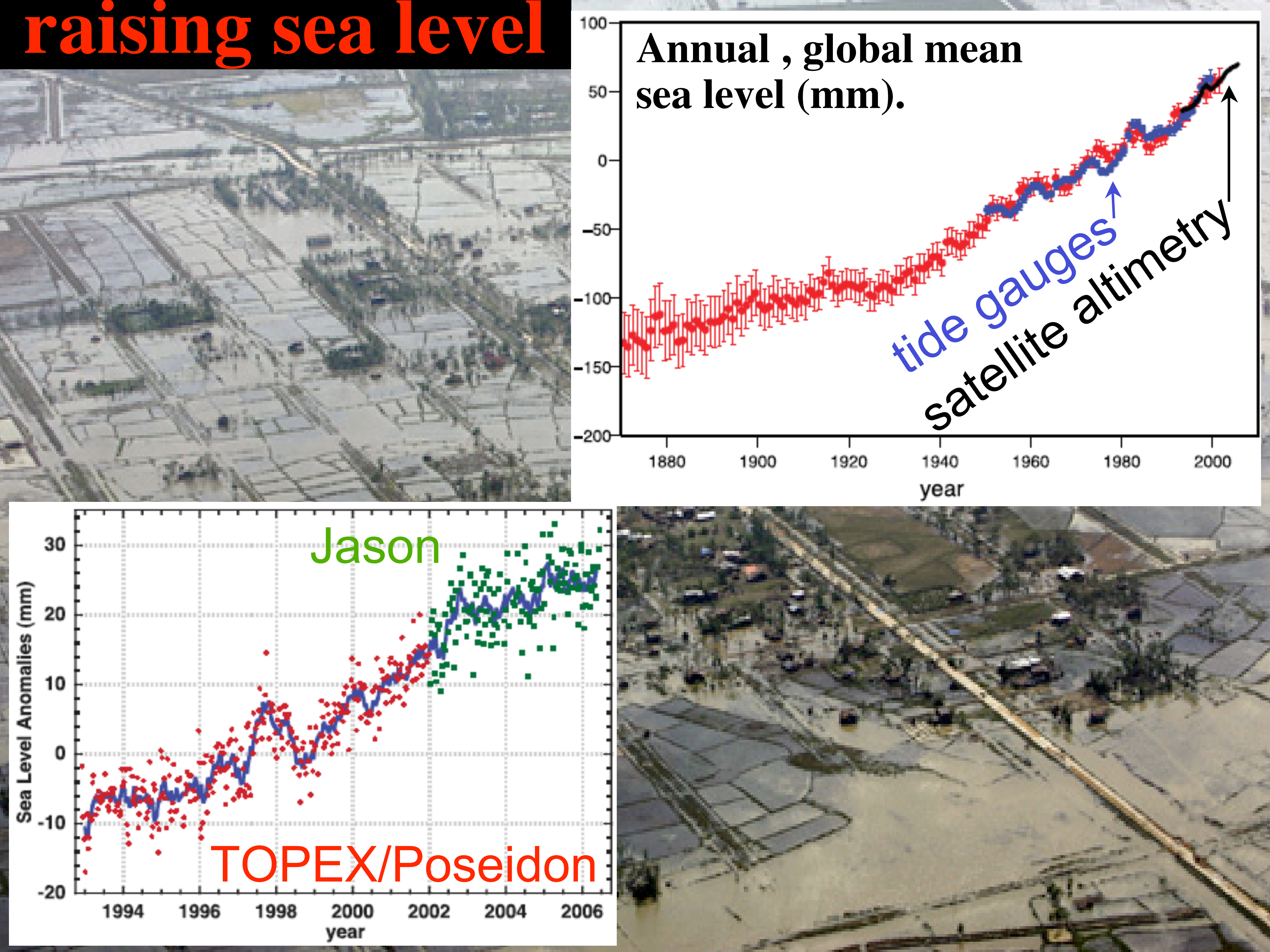
1998

Boulder glacier, GNP, Montana

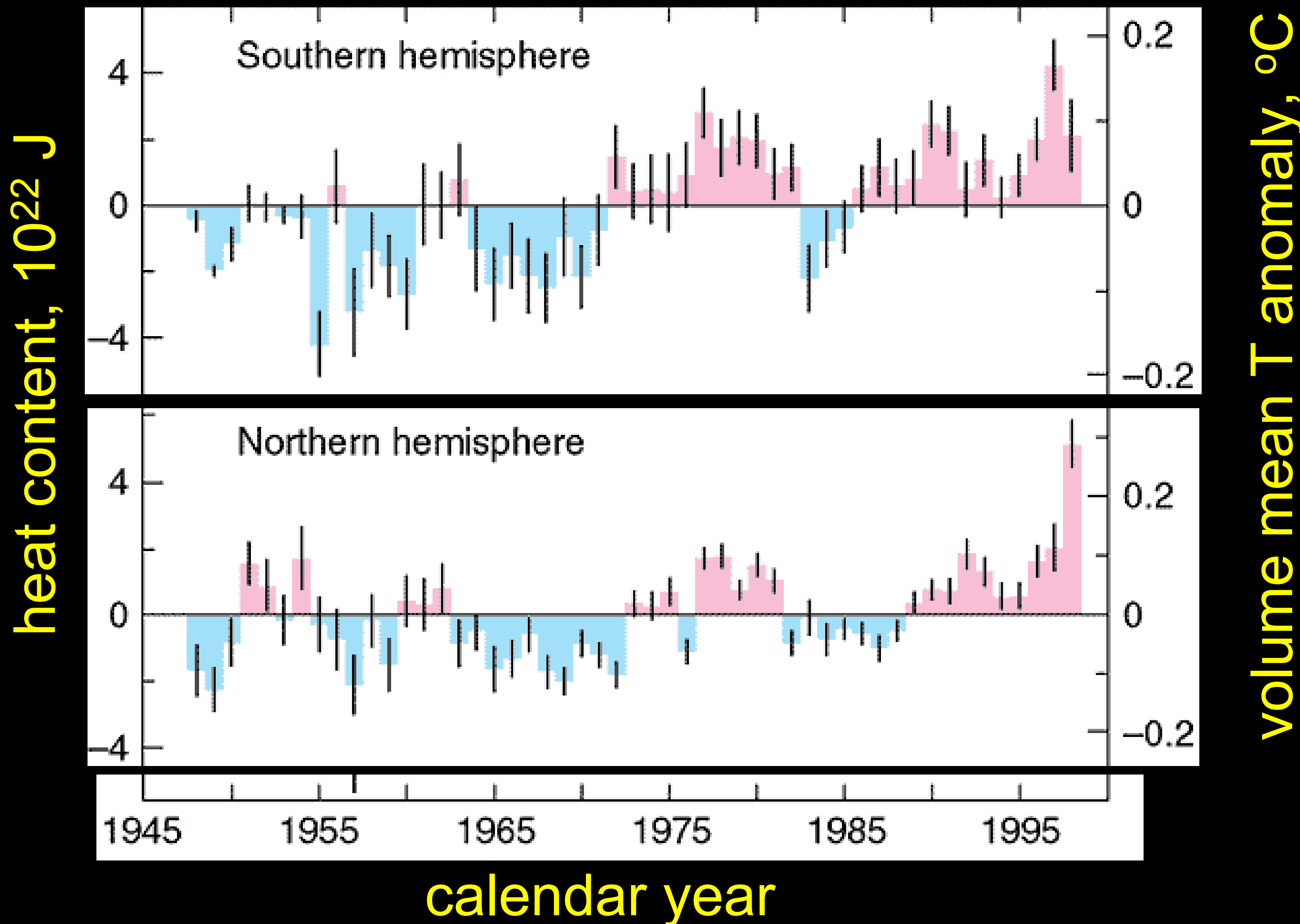
1932

1988

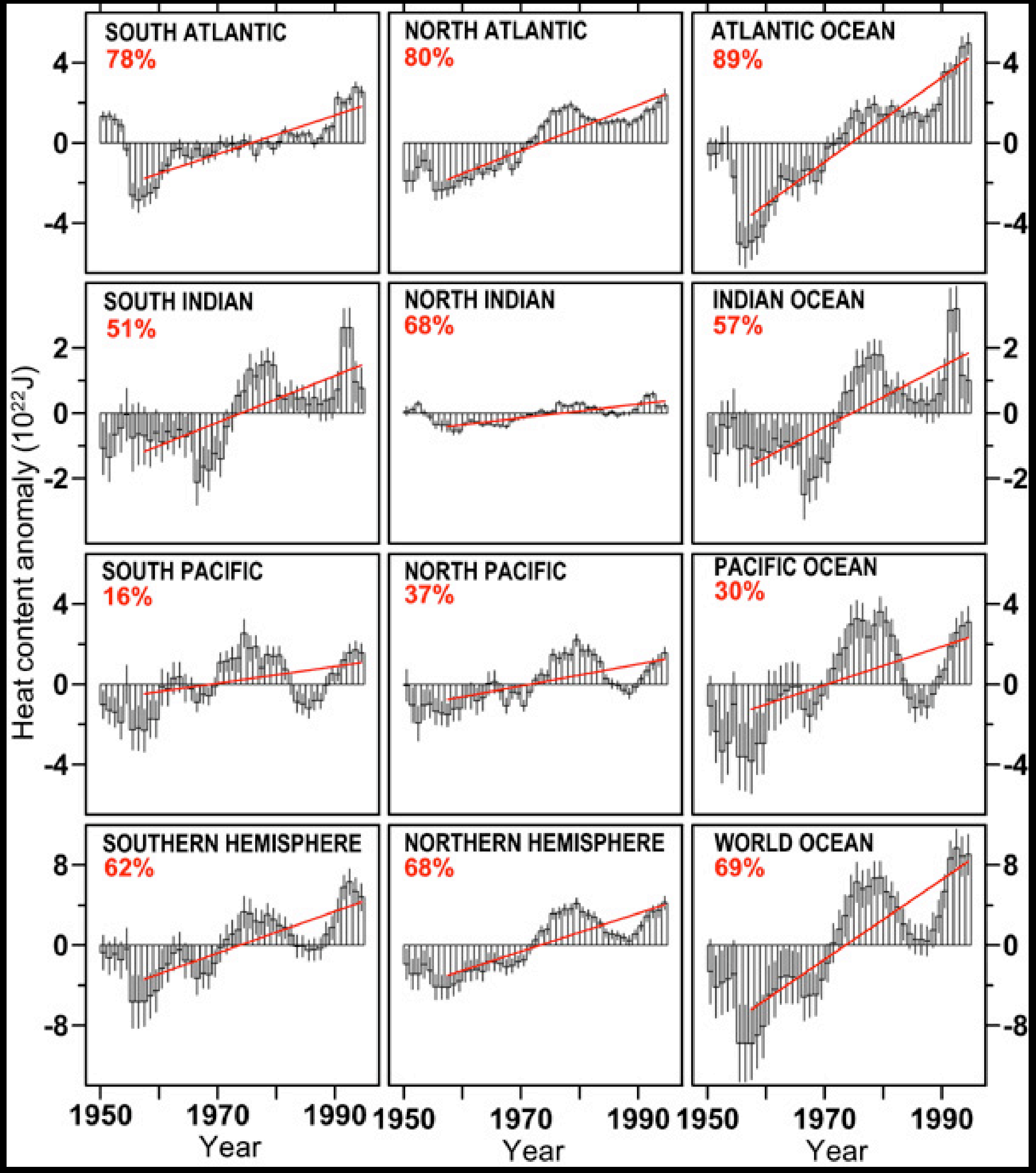
raising sea level



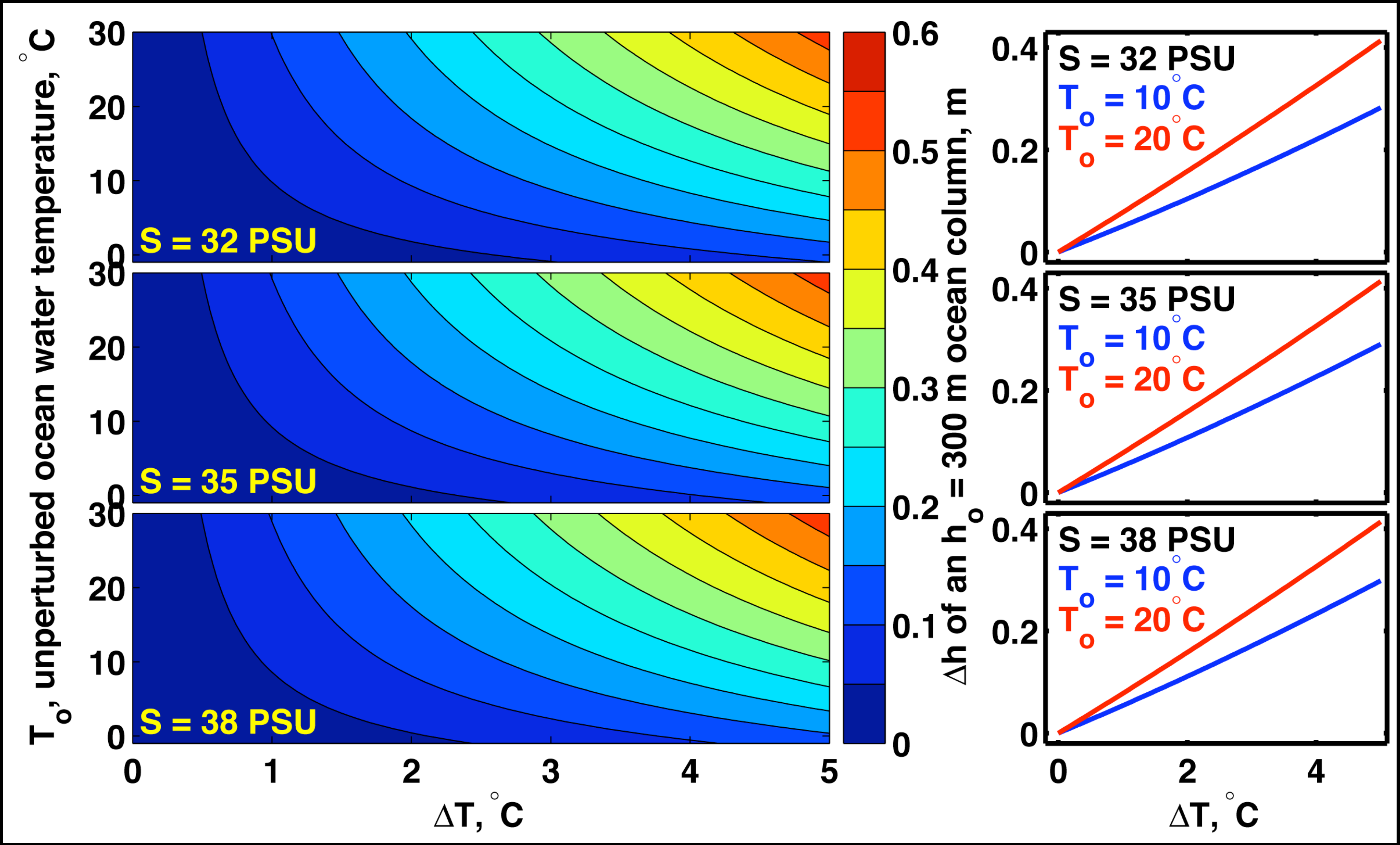
global ocean, upper 300 m



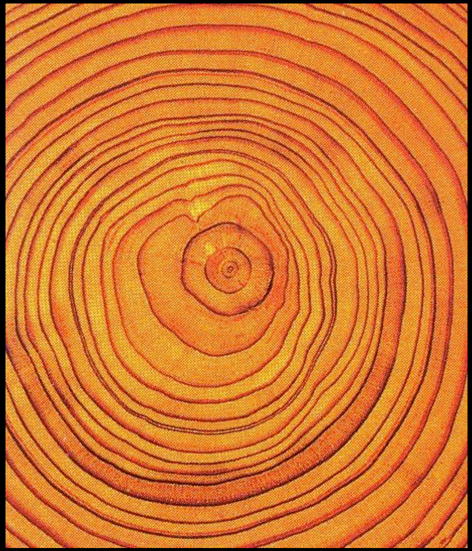
five-year running composites of heat content in the upper 3 km of the major ocean basins (Levitus)

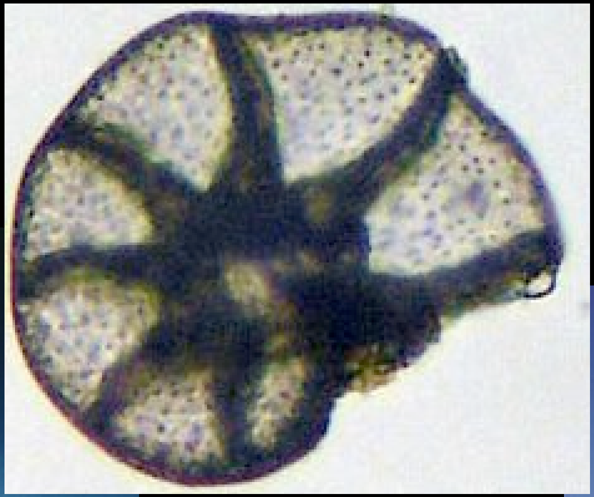


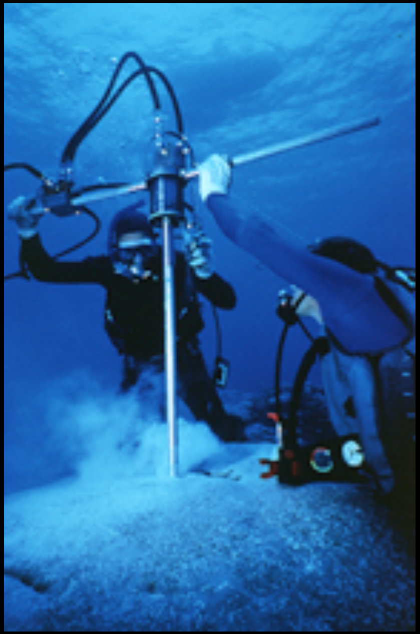
seawater thermal expansion

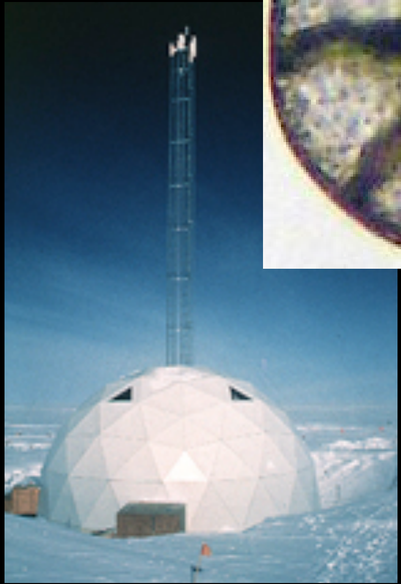


warming has been going on for a while

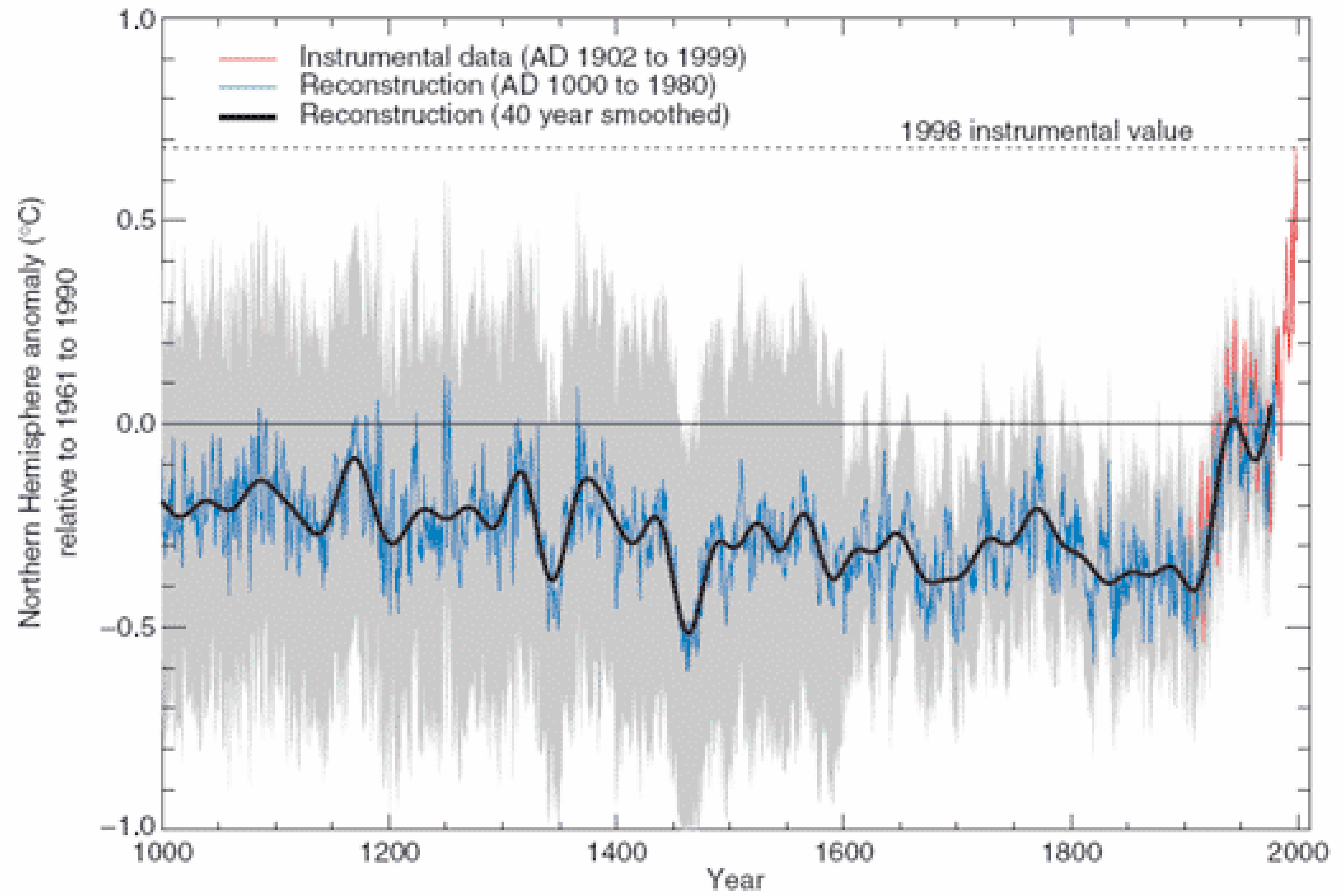




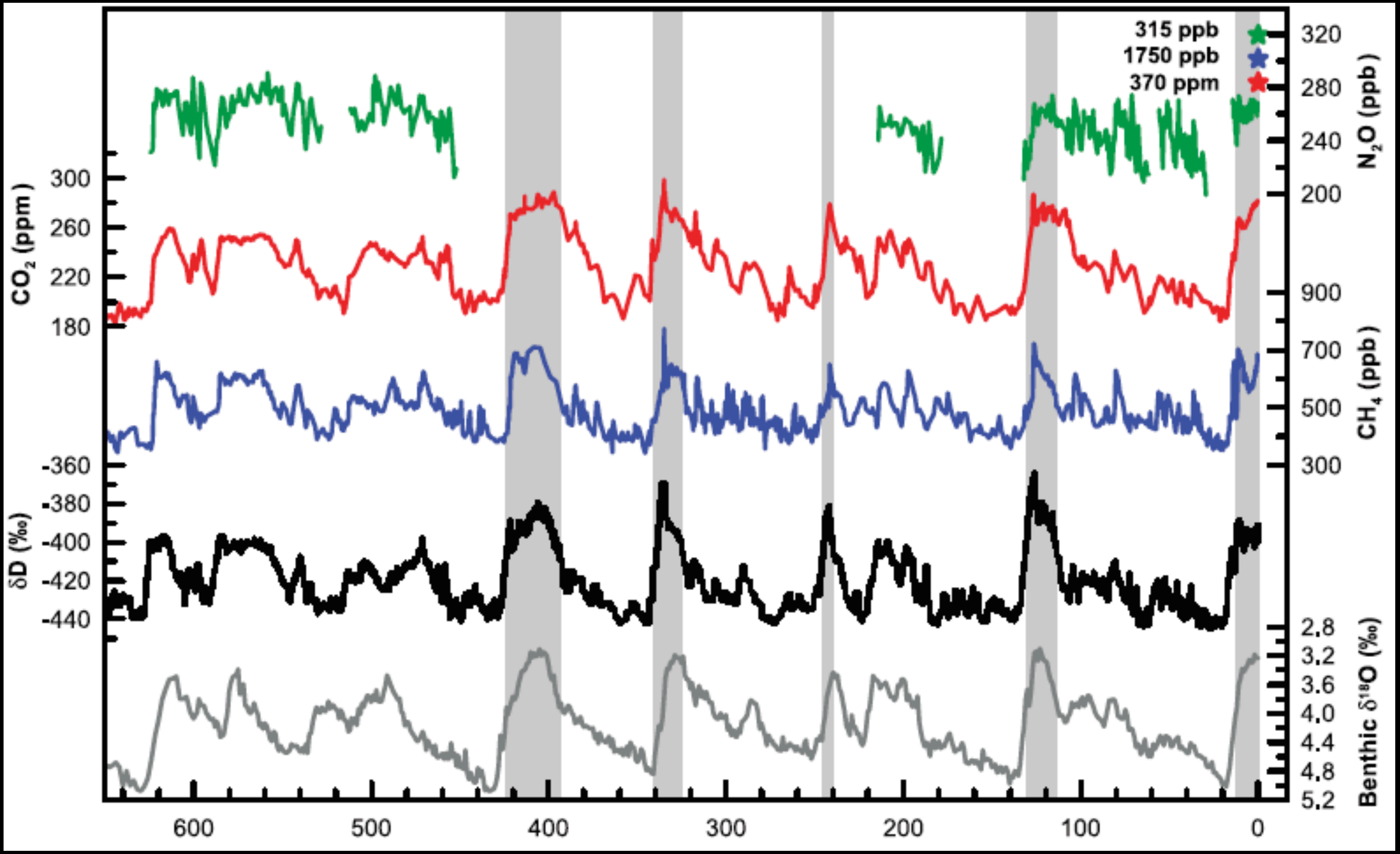




compilation of millennium-long reconstructions



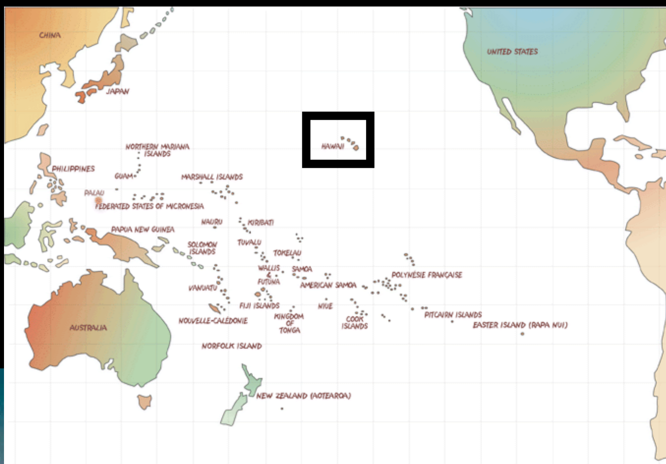
even on *really* long timescales

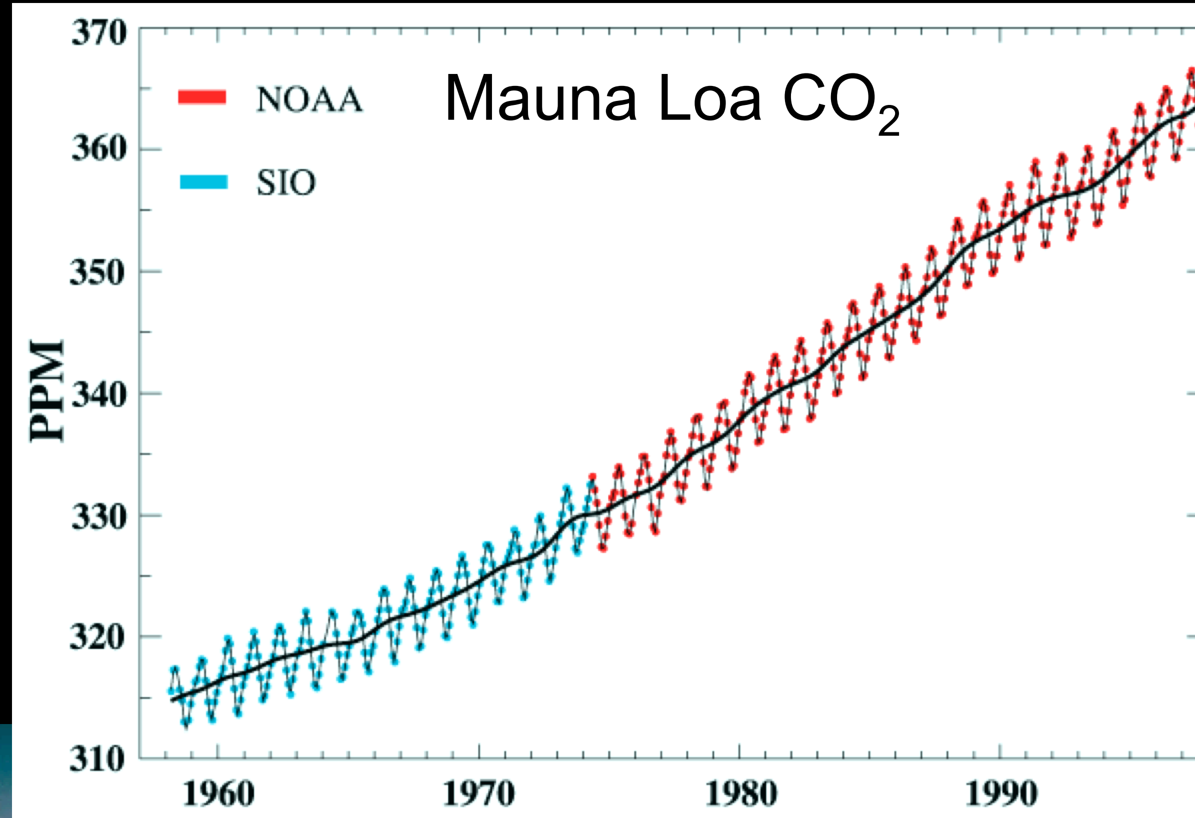


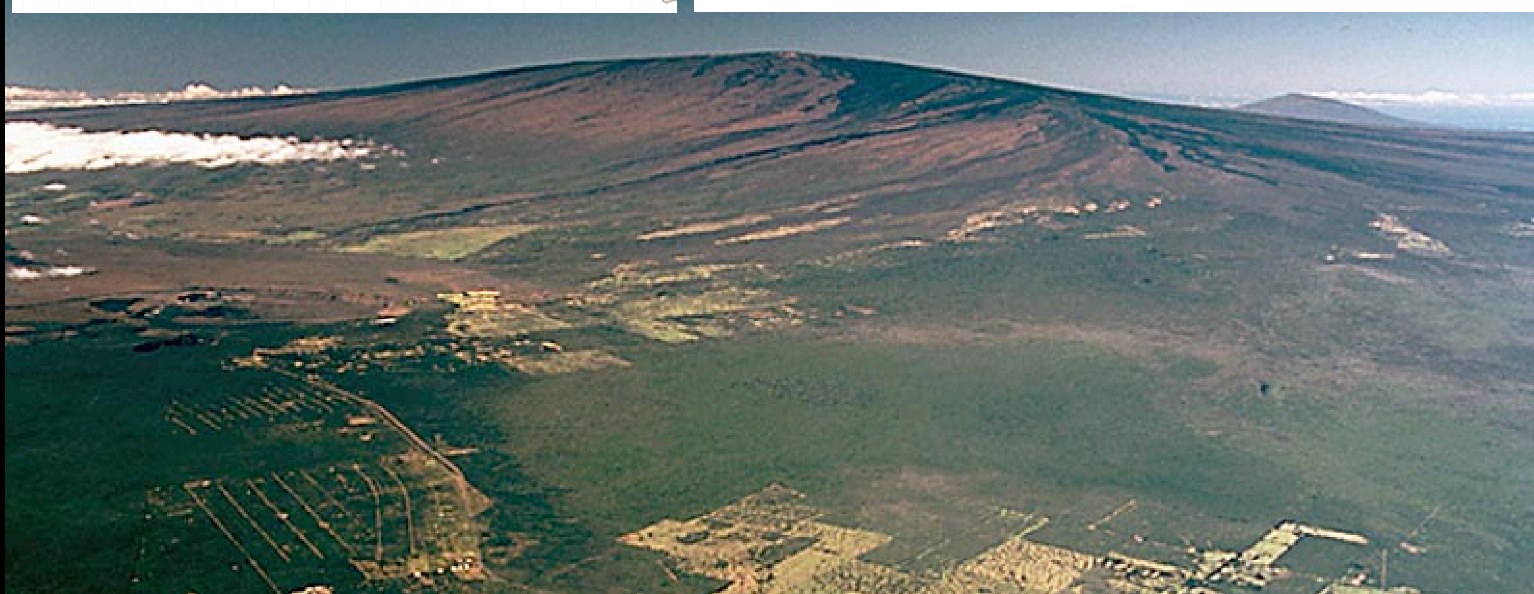
10^3 years before the present

at the same time, atmospheric concentrations of greenhouse gases are rising

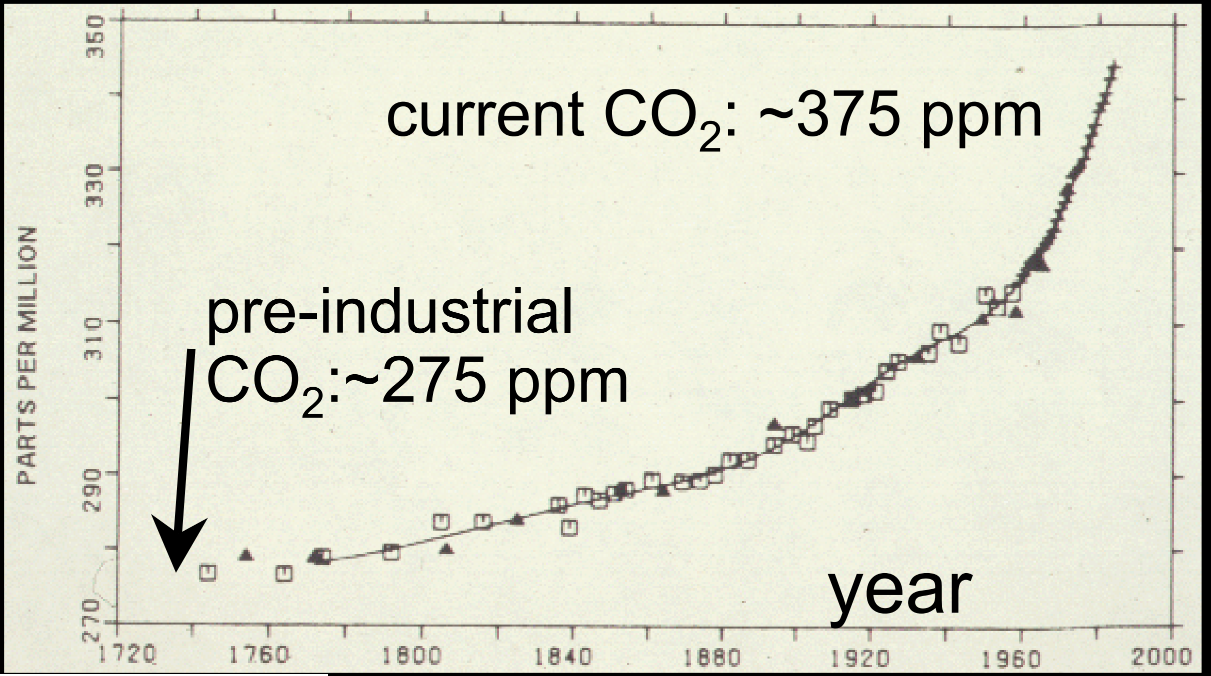
CO_2

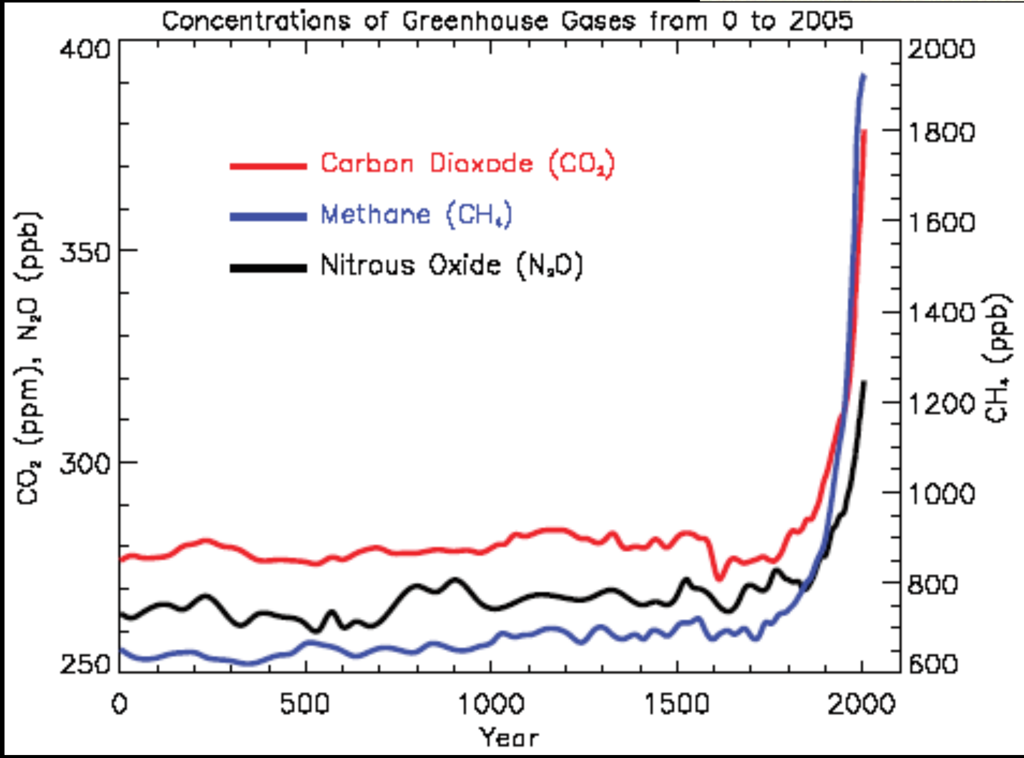

CHINA
JAPAN
UNITED STATES
HAWAII
NORTHERN MARIANA ISLANDS
PHILIPPINES
GUAM
MARSHALL ISLANDS
PALAU
FEDERATED STATES OF MICRONESIA
NAURU
KIRIBATI
PAPUA NEW GUINEA
SOLOMON ISLANDS
TUVALU
TOKELAU
WALLIS & FUTUNA
SAMOA
AMERICAN SAMOA
POLYNÉSIE FRANÇAISE
VANUATU
FIJI ISLANDS
NIUE
PITCAIRN ISLANDS
NOUVELLE-CALÉDONIE
KINGDOM OF TONGA
COOK ISLANDS
EASTER ISLAND (RAPA NUI)
AUSTRALIA
NORFOLK ISLAND
NEW ZEALAND (AOTEAROA)


Mauna Loa CO2
NOAA
SIO
PPM
310
320
330
340
350
360
370
1960
1970
1980
1990

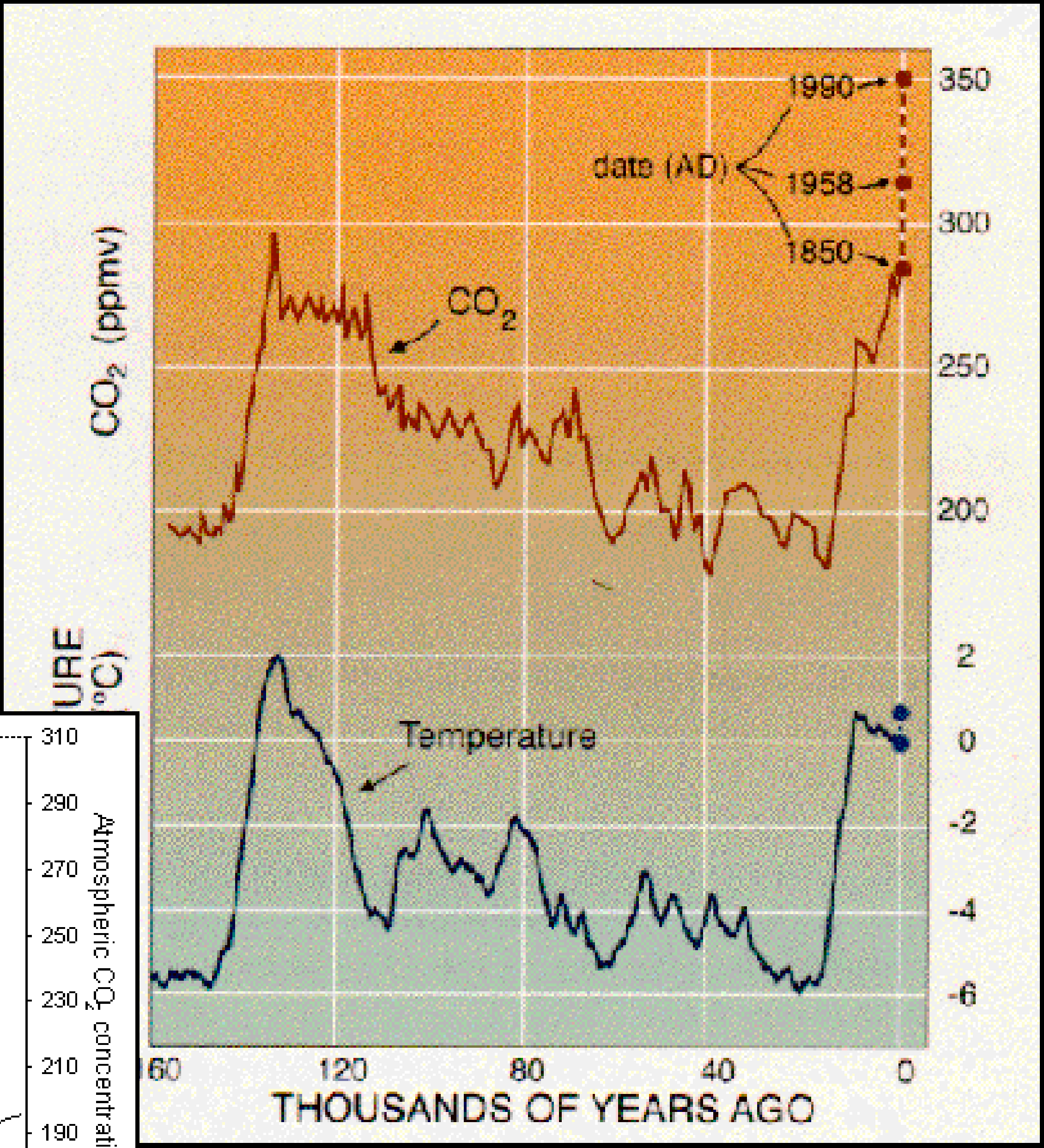


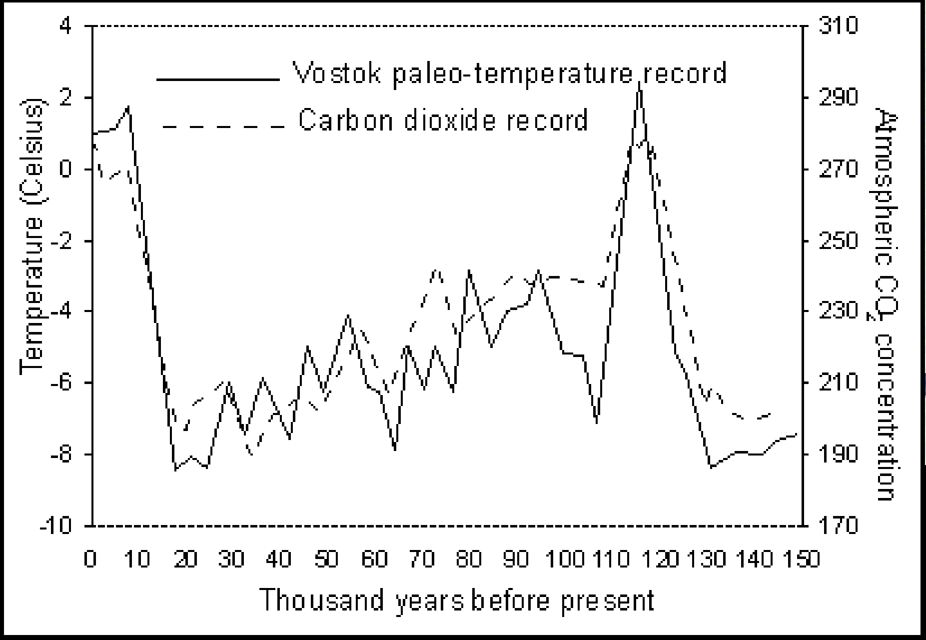
and for a while now



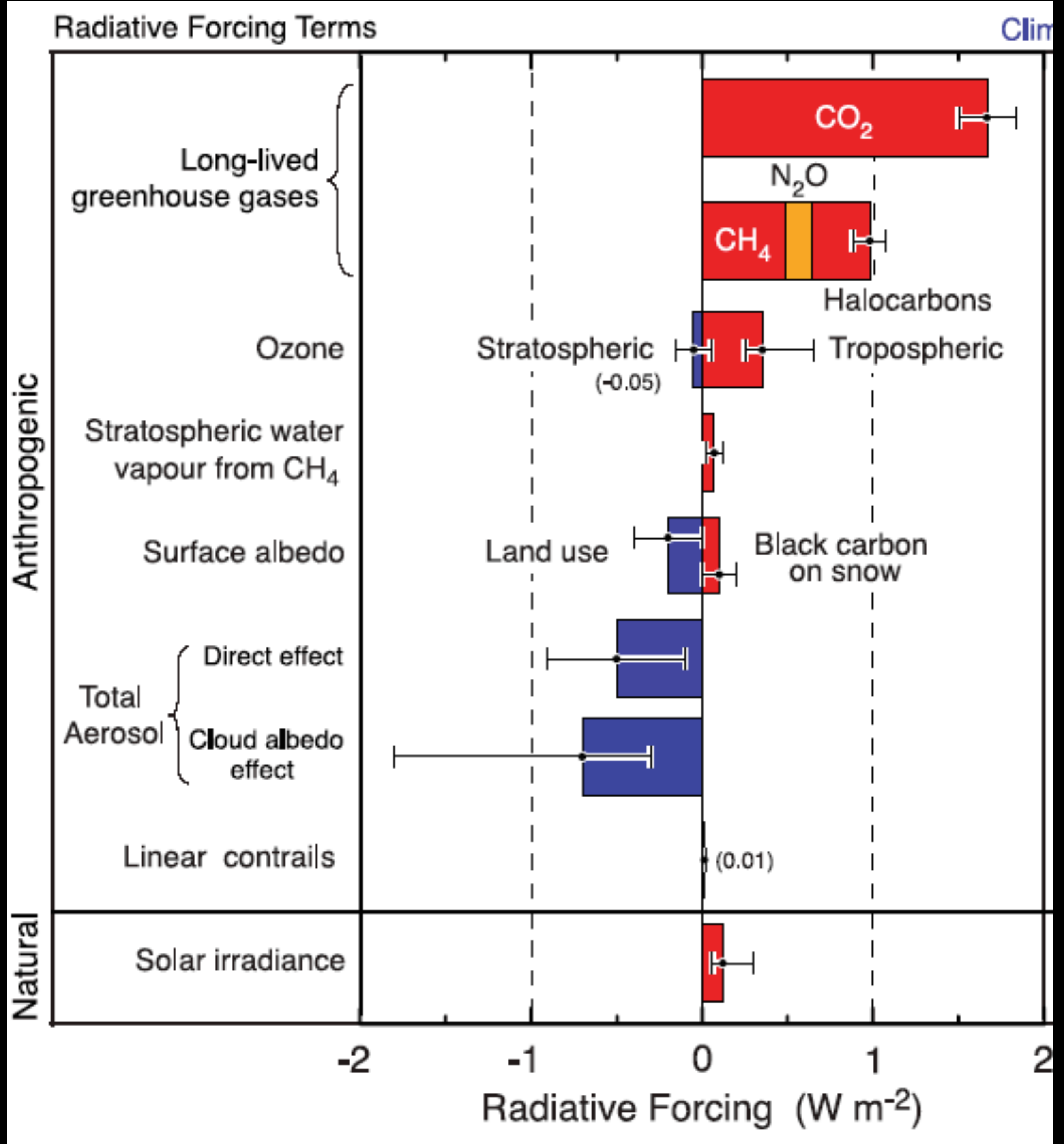


~2,000 yr history of the three main non-H_2O GHGs even for a *LONG* while!

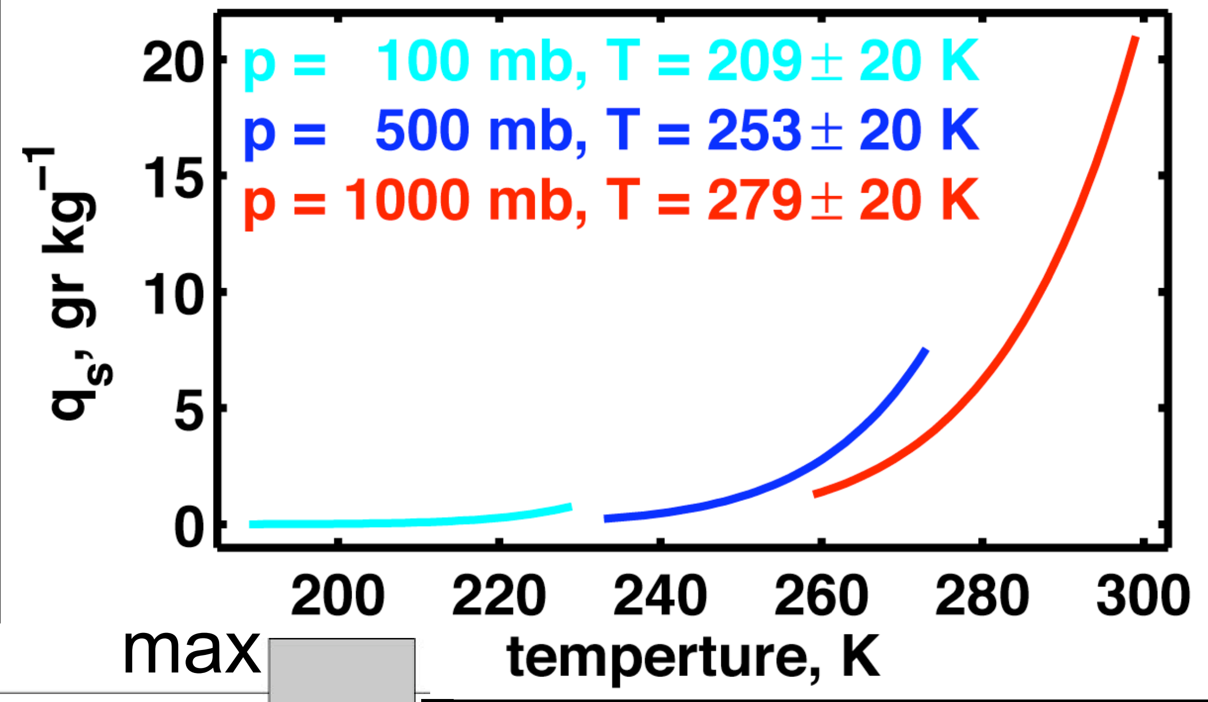


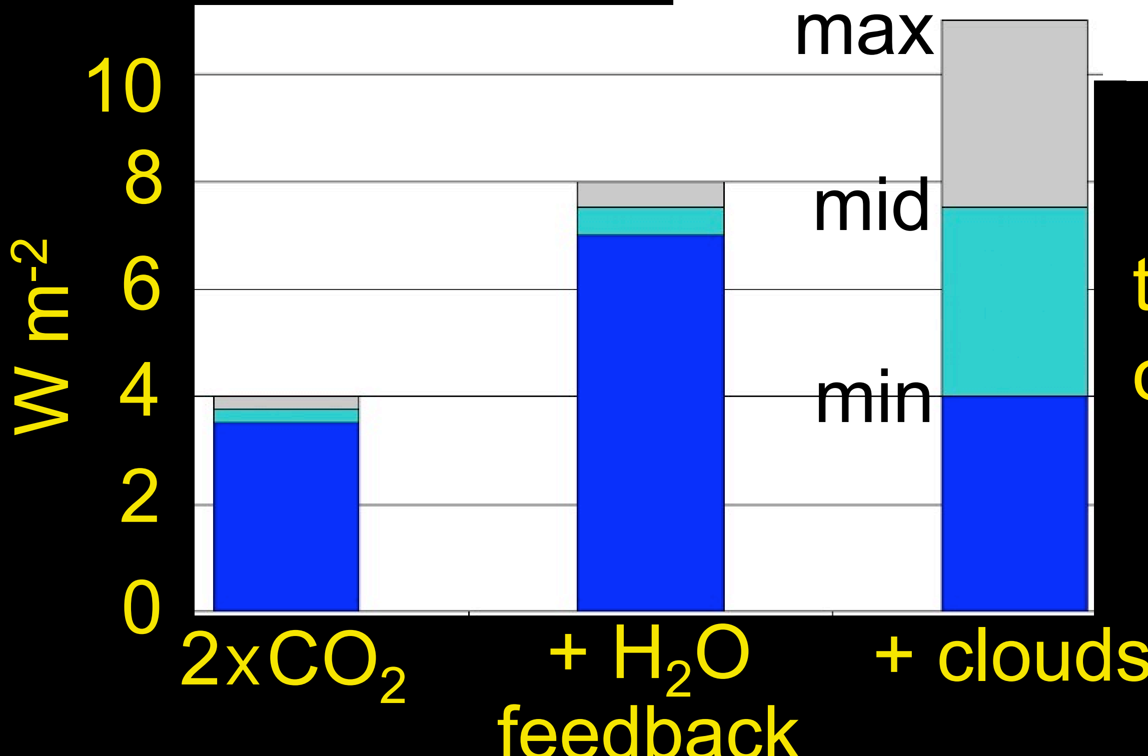


with the radiative effect (over 1750-2005) of



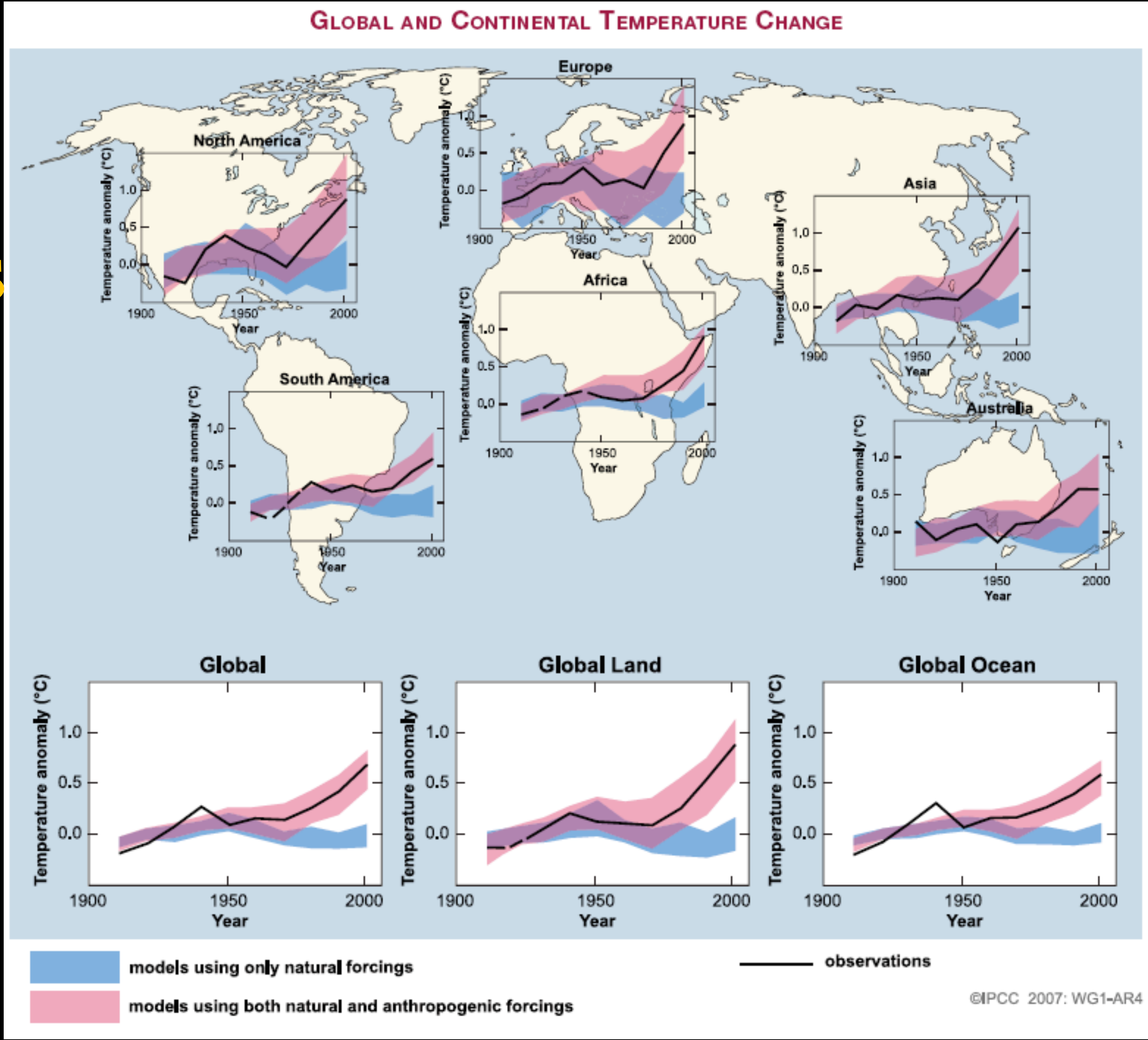
water vapor feedback



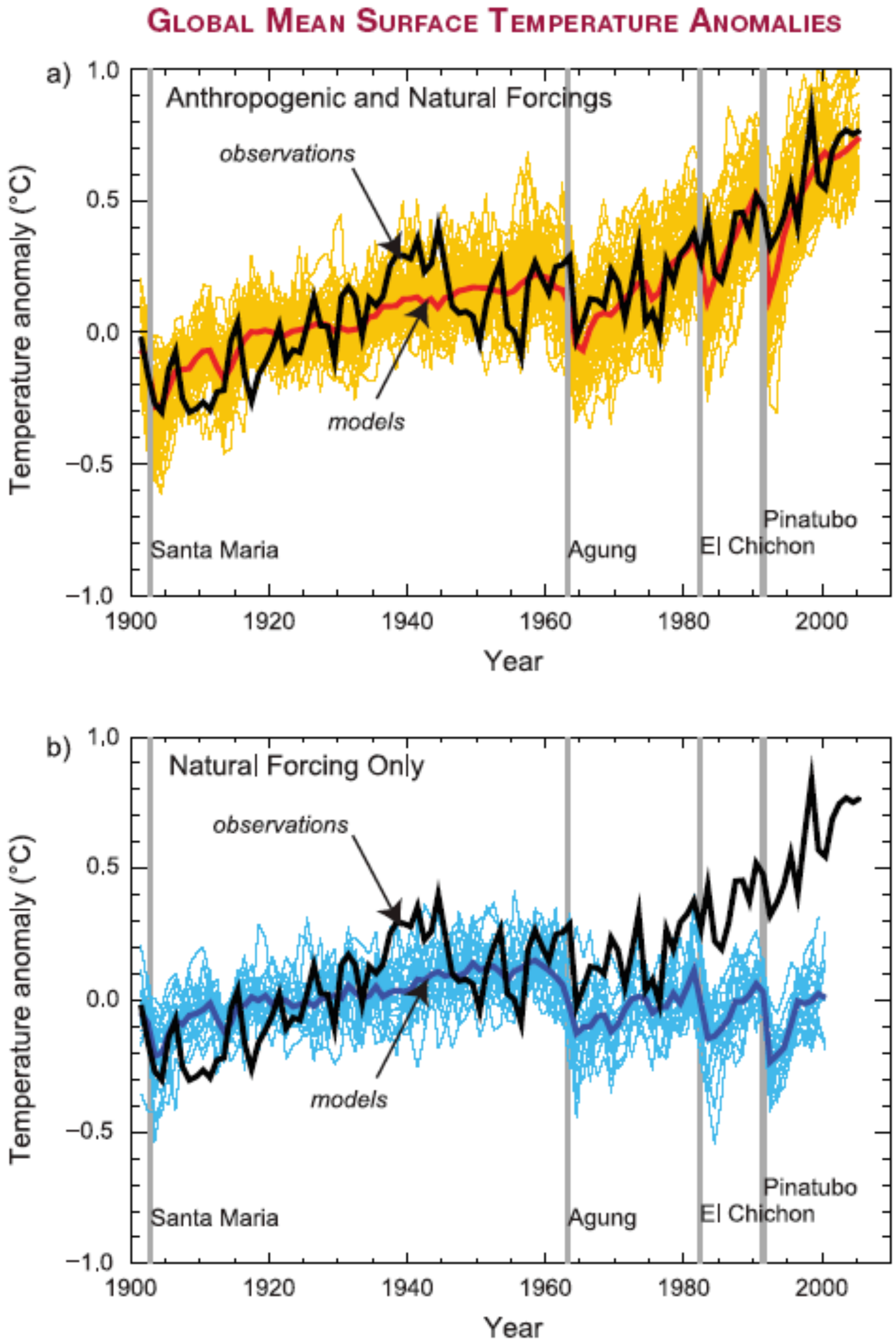


the consequences of CO_2 doubling

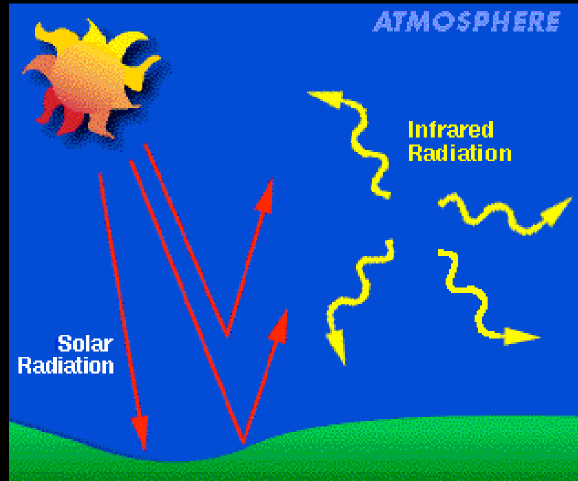
while models are not perfect

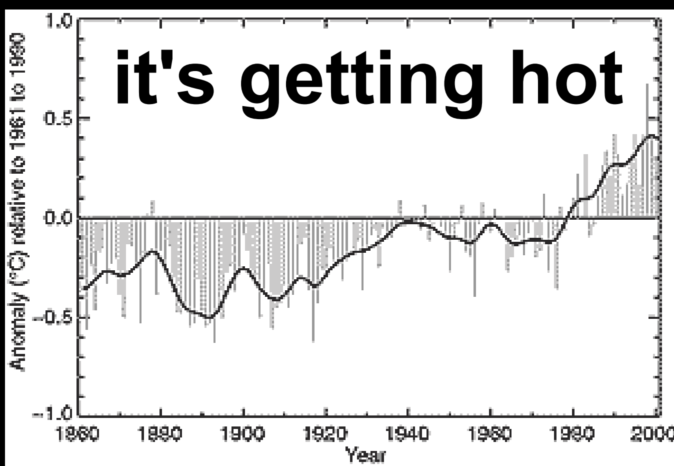


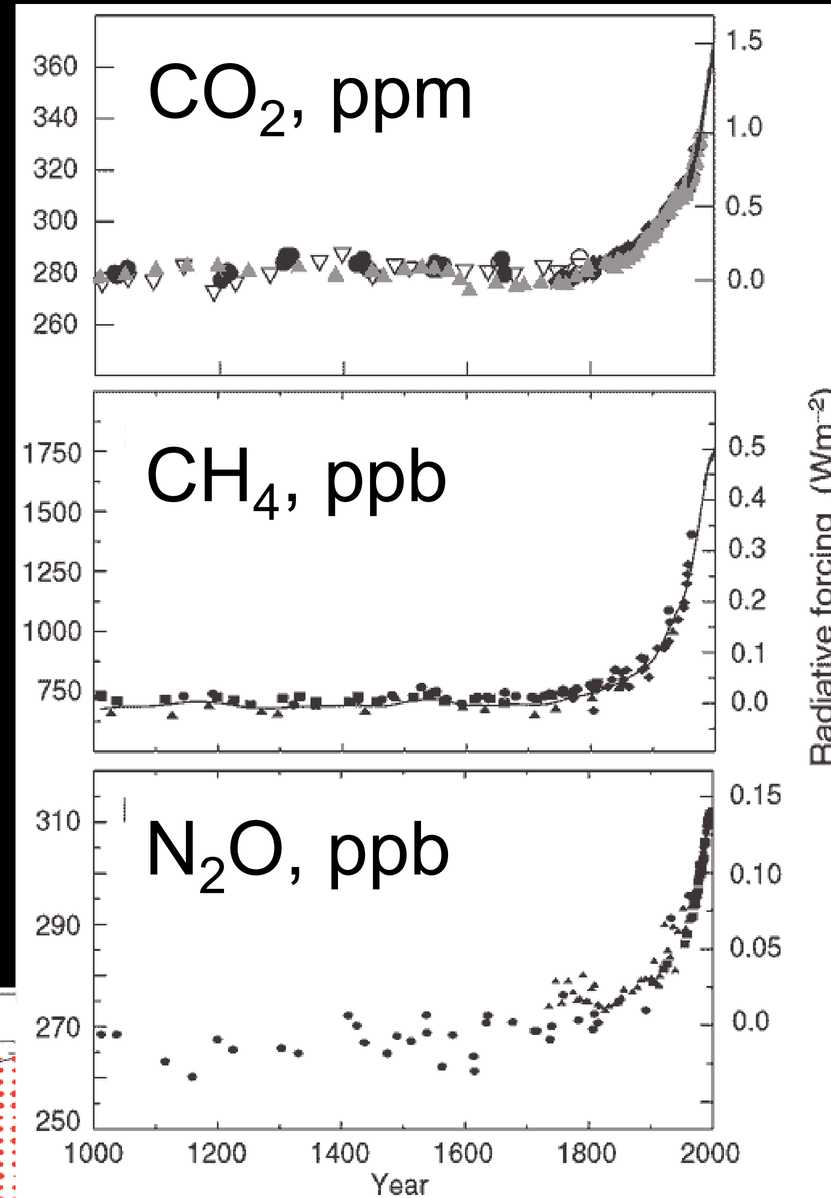
they seem not entirely useless either (remember: climate, not weather)

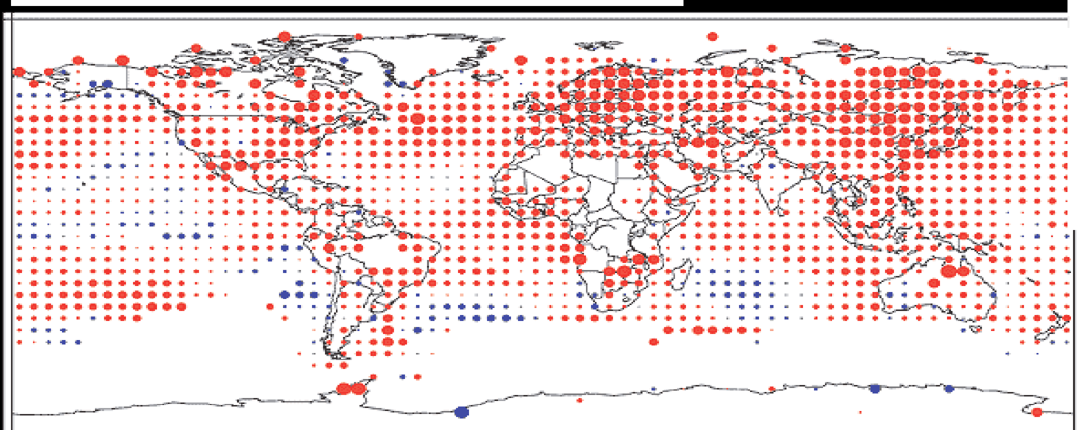


so:









most everywhere, but especially over land

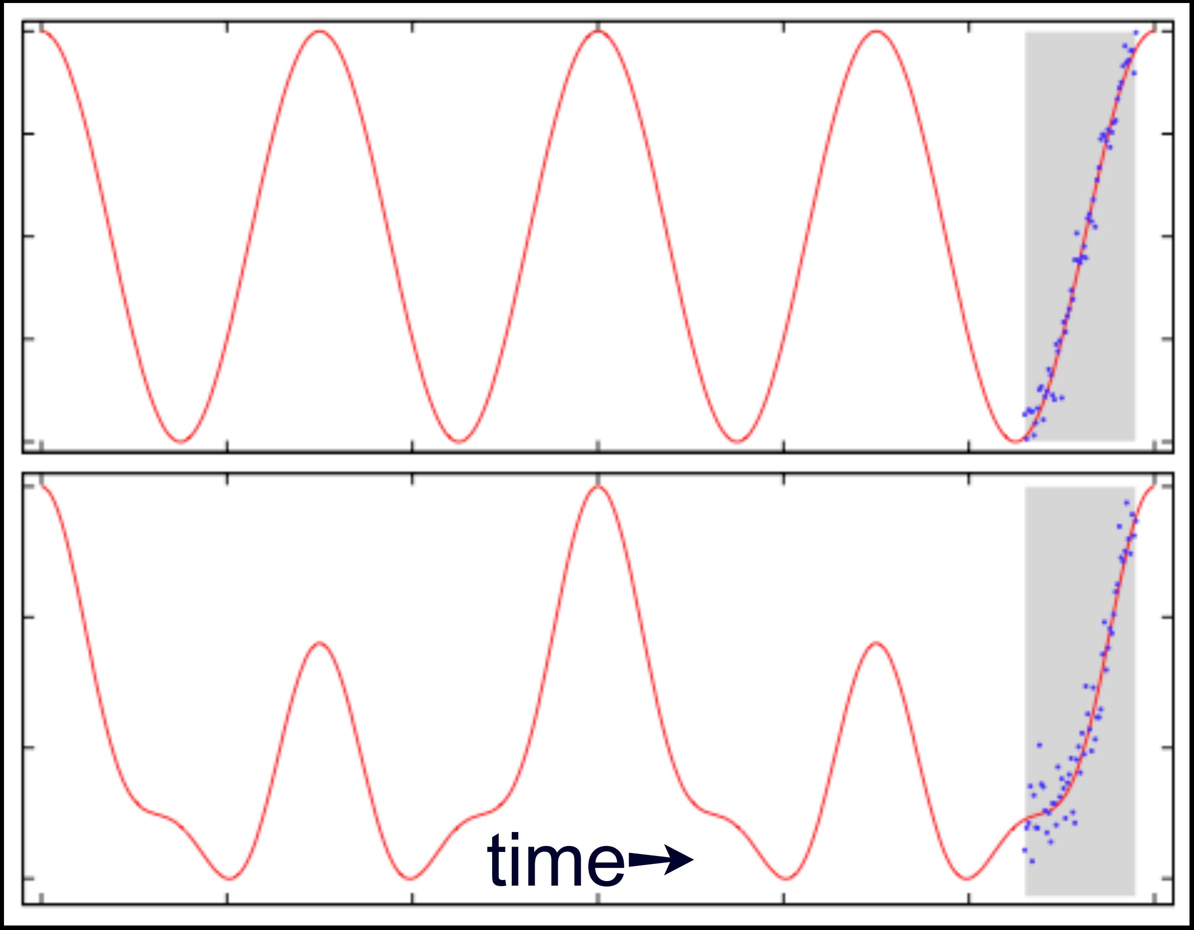
if it's so compelling, why is anthropogenic climate change so ***hotly*** contested?!

part of the problem is distinguishing a low-frequency cycle from a secular trend

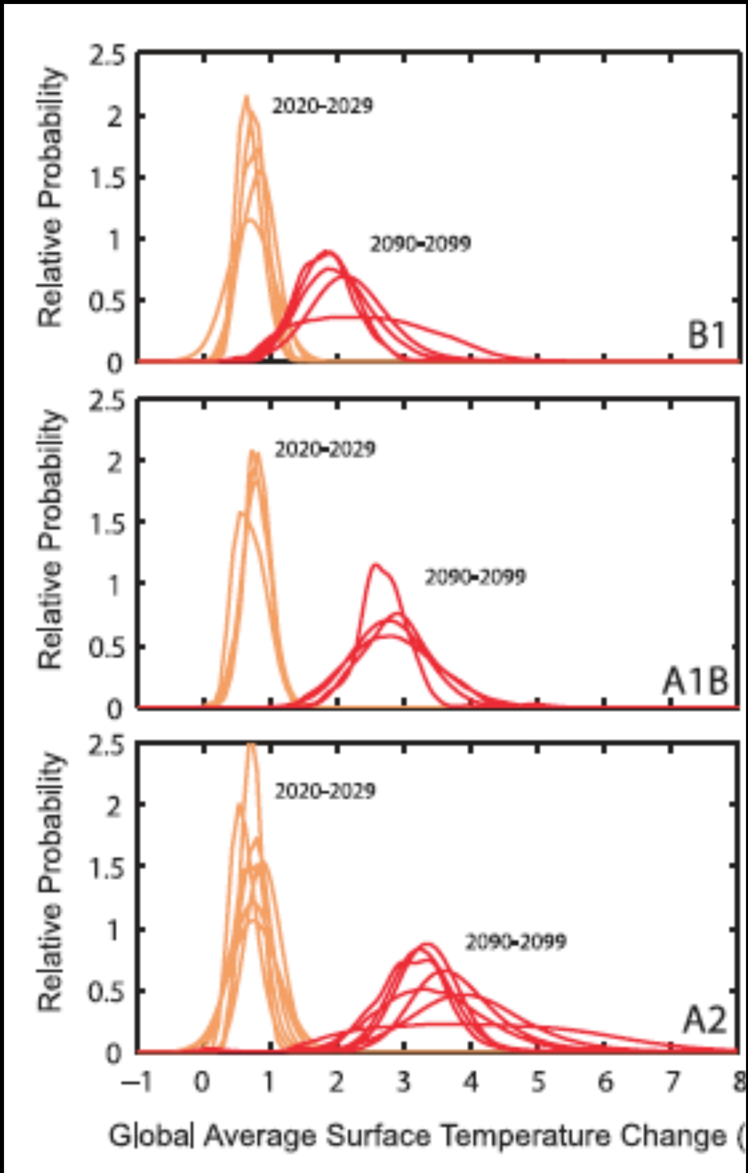
observation period

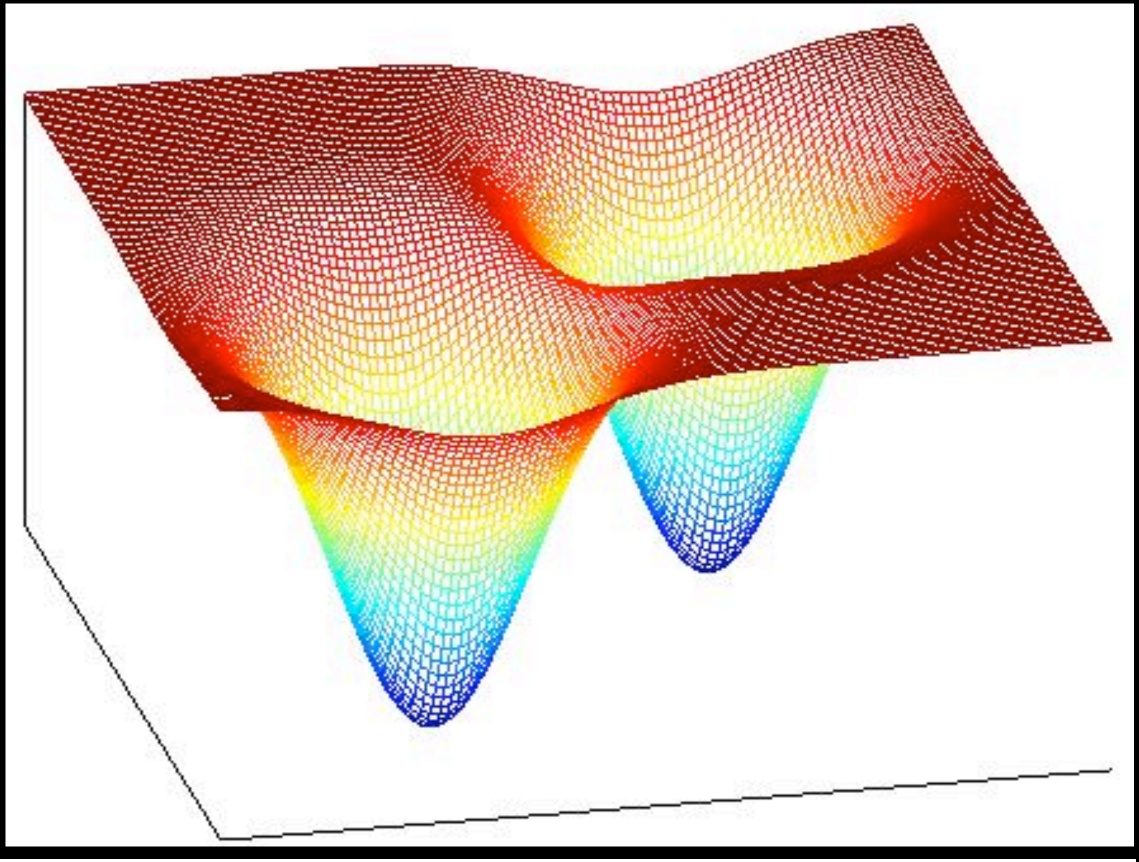
a single frequency

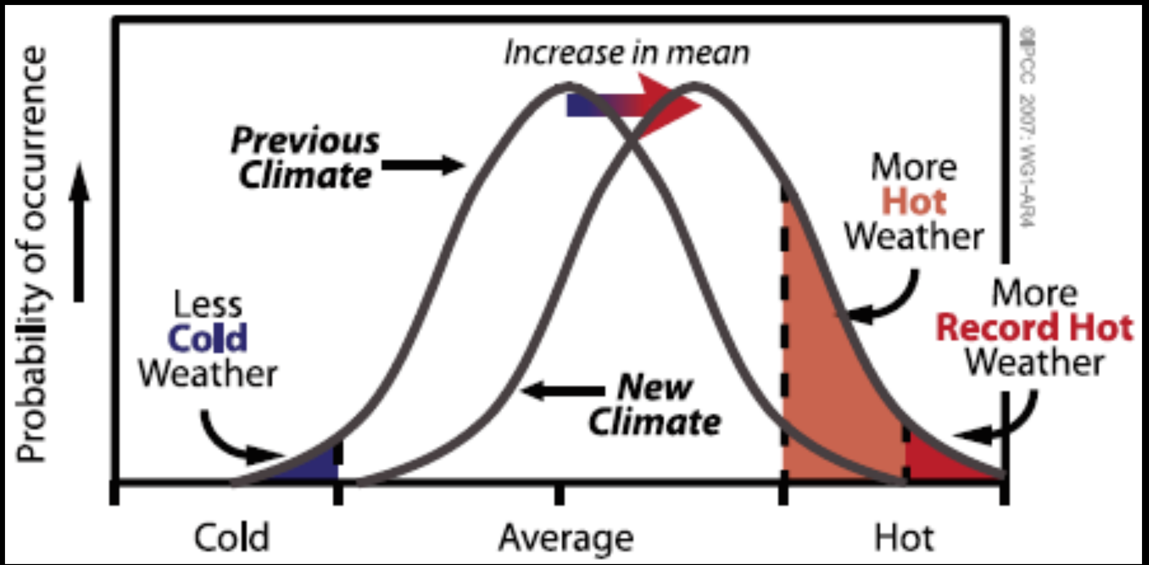
multiple frequencies



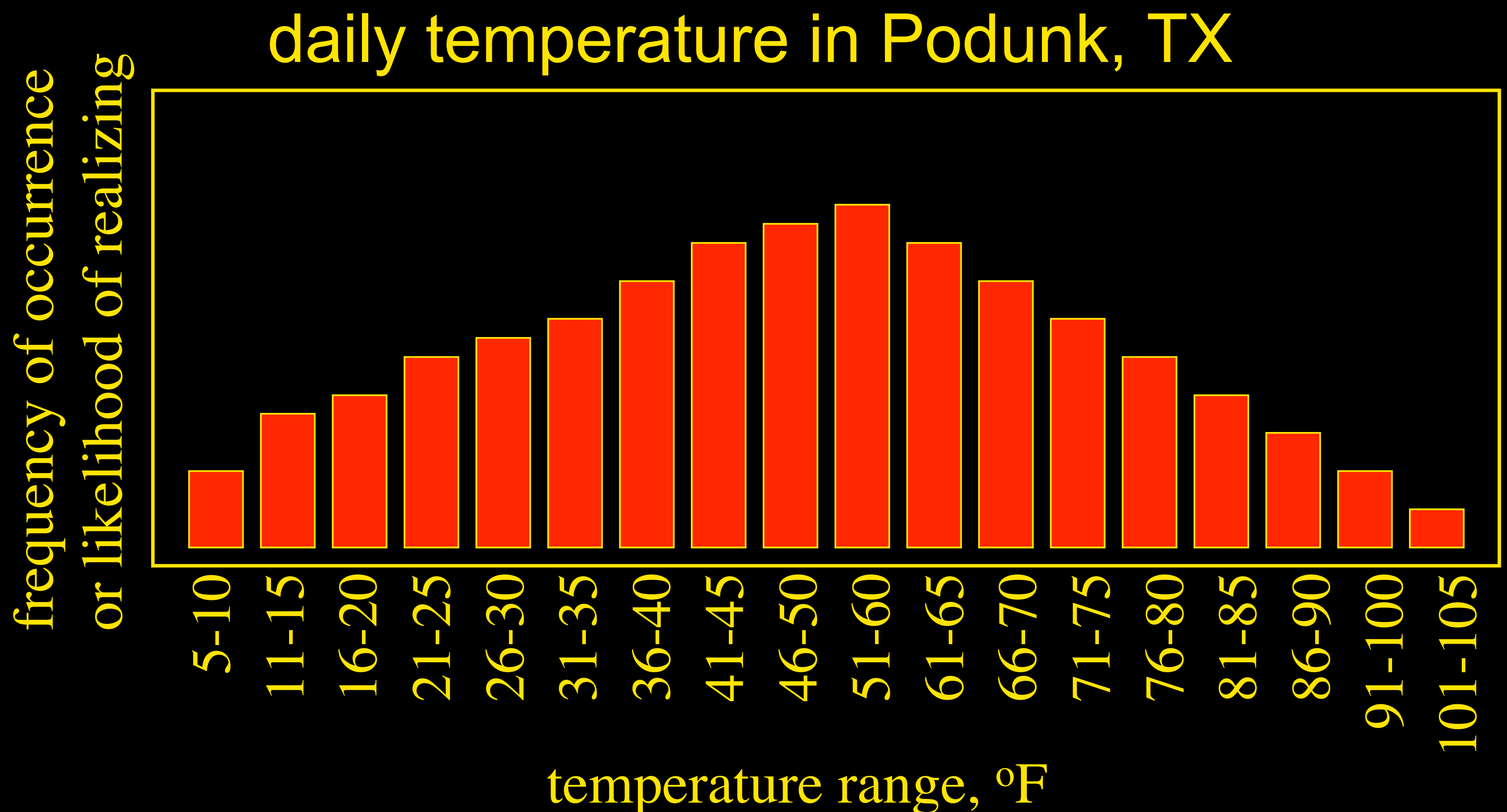
slow drift of PDFs



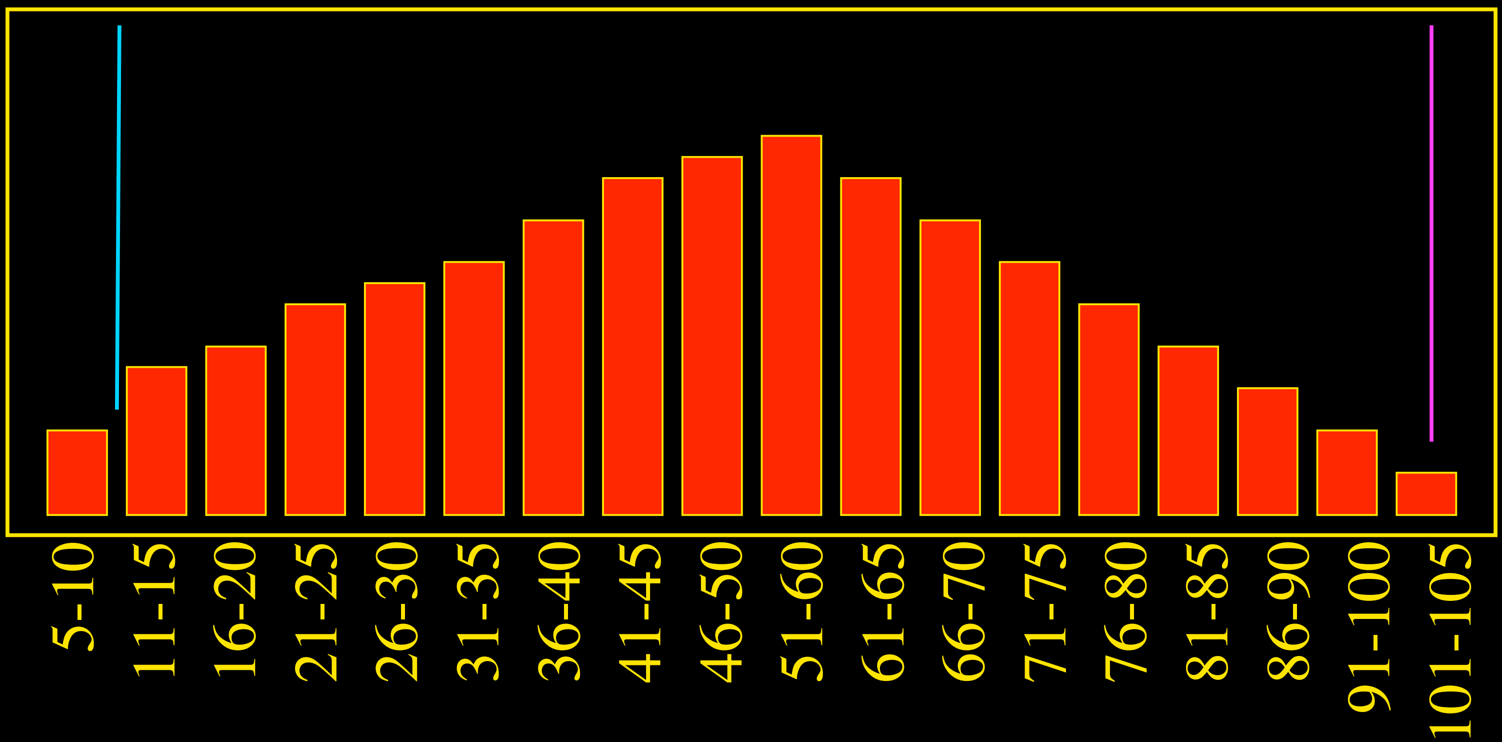




another issue: imperfectly known PDFs



now when you get a freaky event…



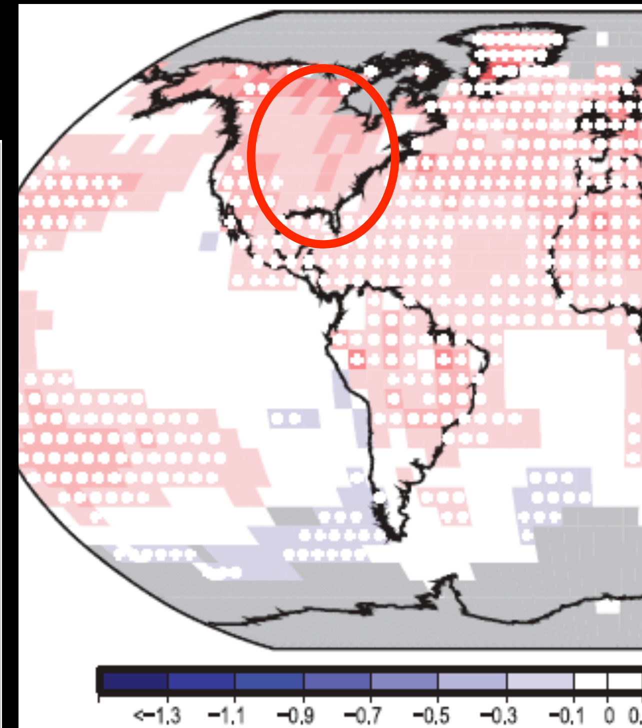
you naturally ask - how likely is that event?

and those questions are as likely to be answered to your fullest satisfaction as is the Gore-v.-Bush saga…

So:

- Recent global surface temperatures are unprecedented this century, and likely *at least* the past millennium
- It is difficult to explain the recent surface warming by invoking natural climate variability
- Recent surface warming is largely consistent with simulations of the effects of anthropogenic influence on climate

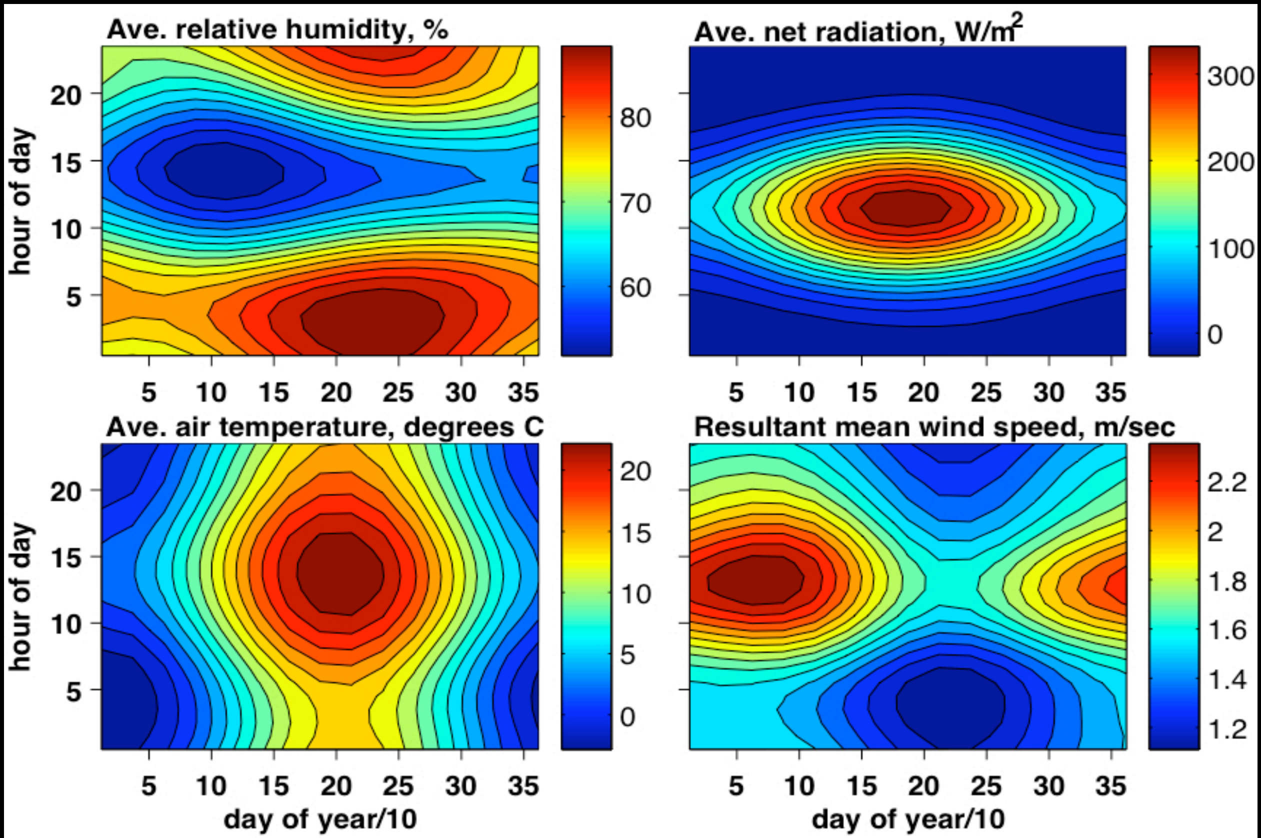
Millbrook, NY



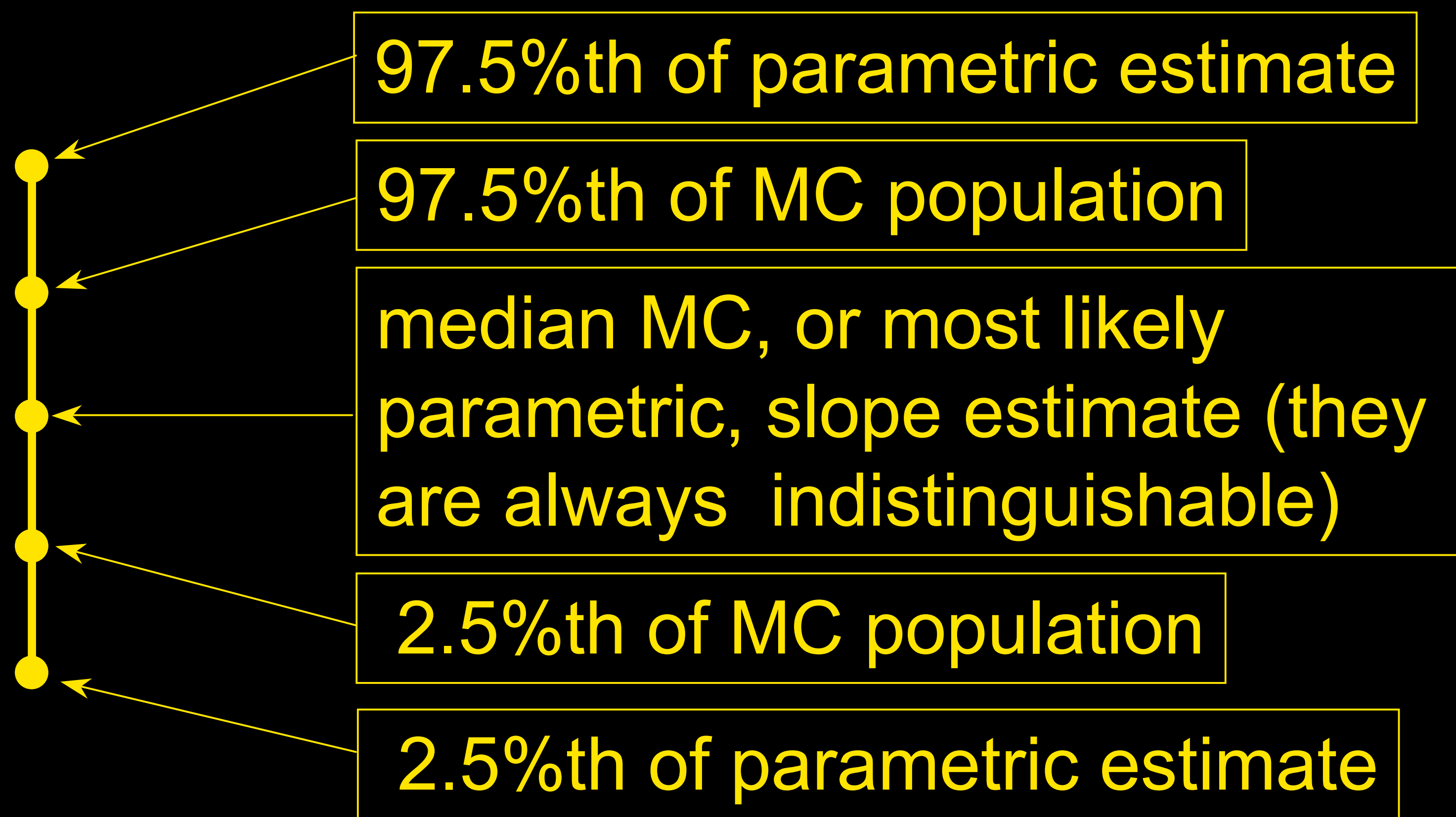
position:
41.785°N, 73.694°W
elevation: ~570 ft
population ('03):
~1,500

measurement since Jan. 1988.

- **sampling rate:** a measurement every 15 seconds
- **reported values:** hourly min./ave./max.
- **variables:** wind (speed, direction, rms) relative humidity, air temperature, near-full radiation set.
- **transform to:** hour-mean deviations from the diurnal and seasonal cycles by subtracting, such climatologies as, e.g., →

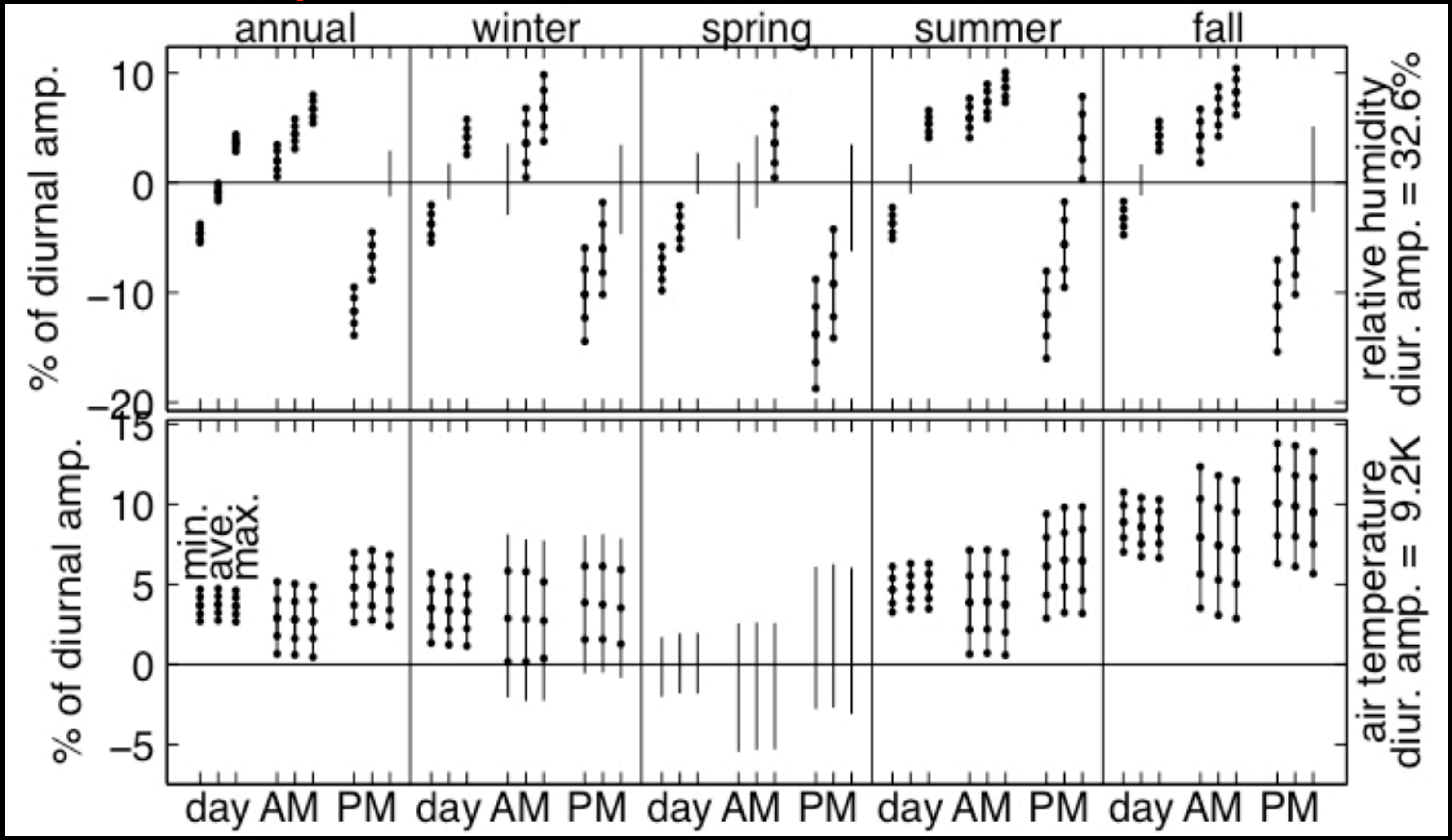


for each time series, compute linear trend, and perform a 500-member, 10% data withheld, Monte Carlo validation



normalized linear trends over 1988-'08

relative humidity

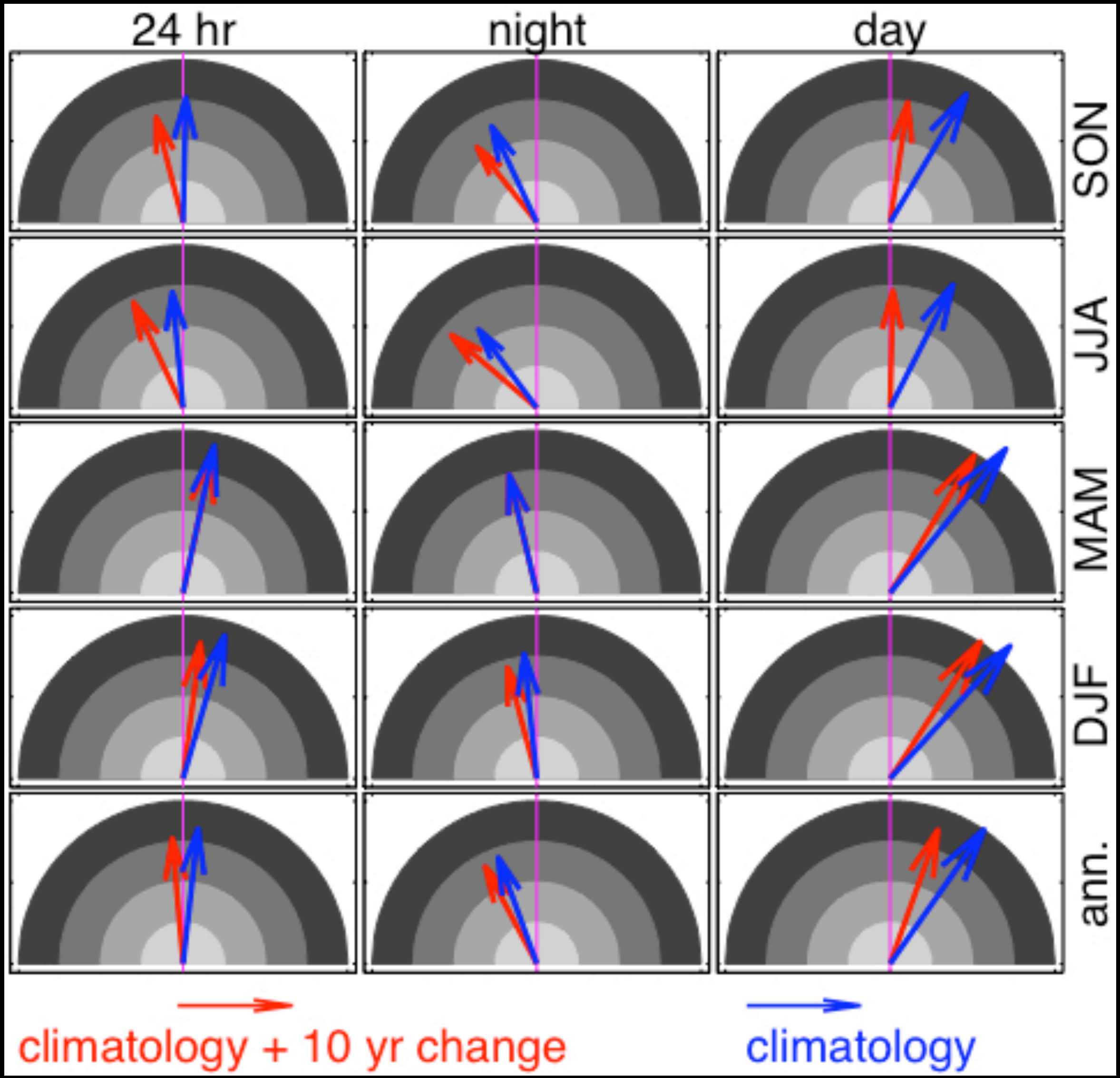


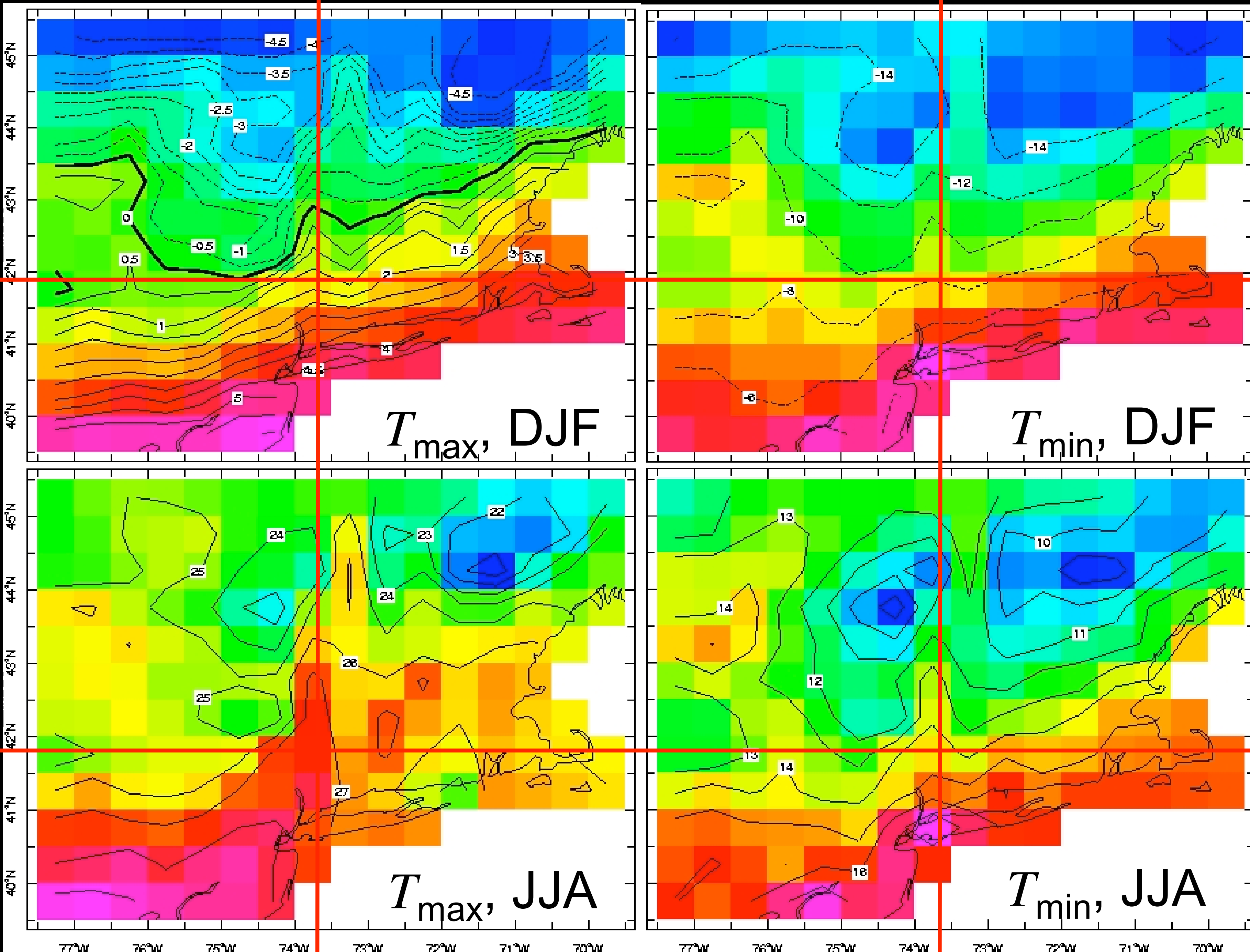
air temperature

the basics:

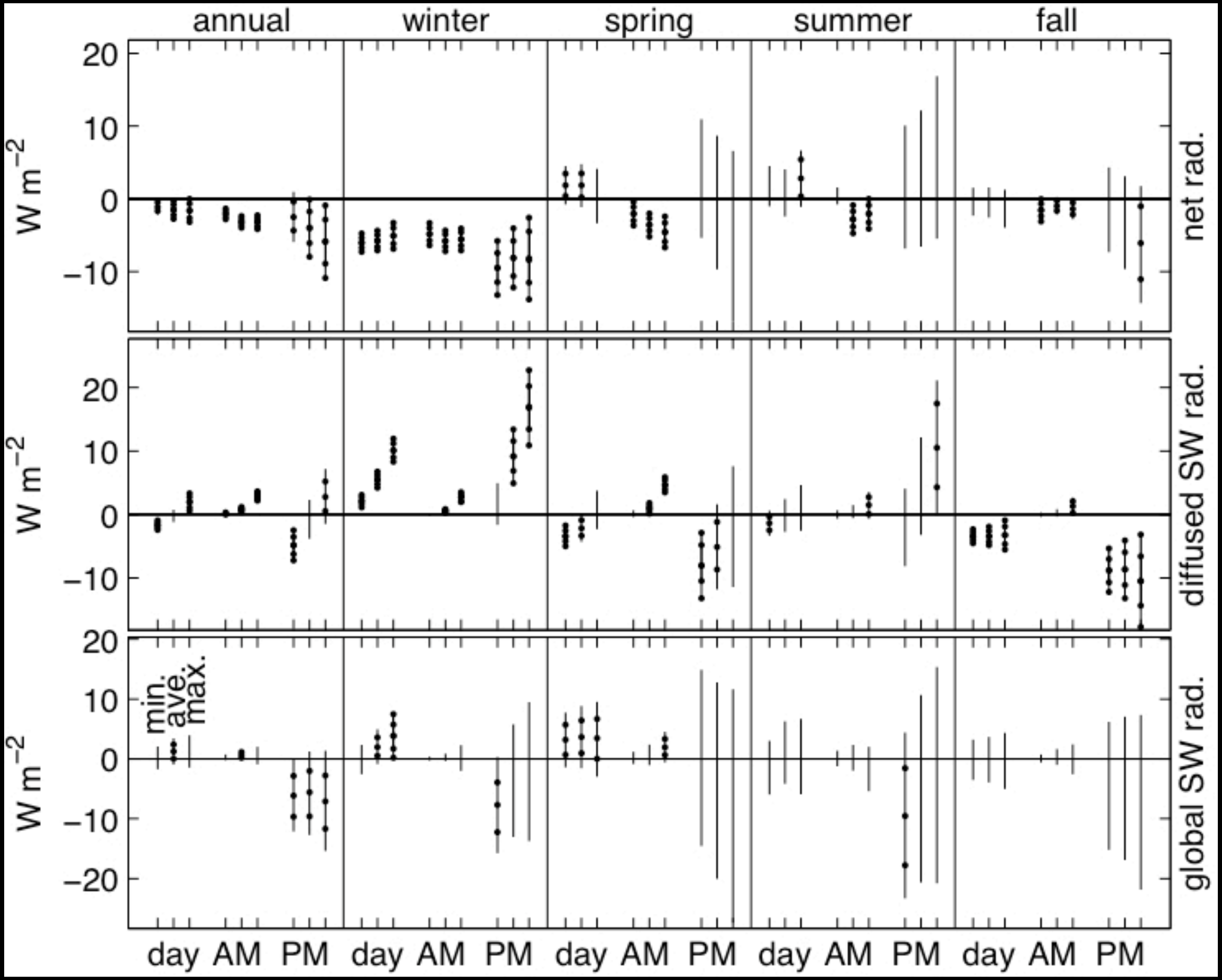
- T↑ actually significant except in spring
- summer T↑ is highest during the warmest hours and for T_{max} ; fall T↑ is also highest during the warmest hours
- summer AM rs also rise, with r_{max} rising most
- PM rs drop significantly, in accordance with CCE

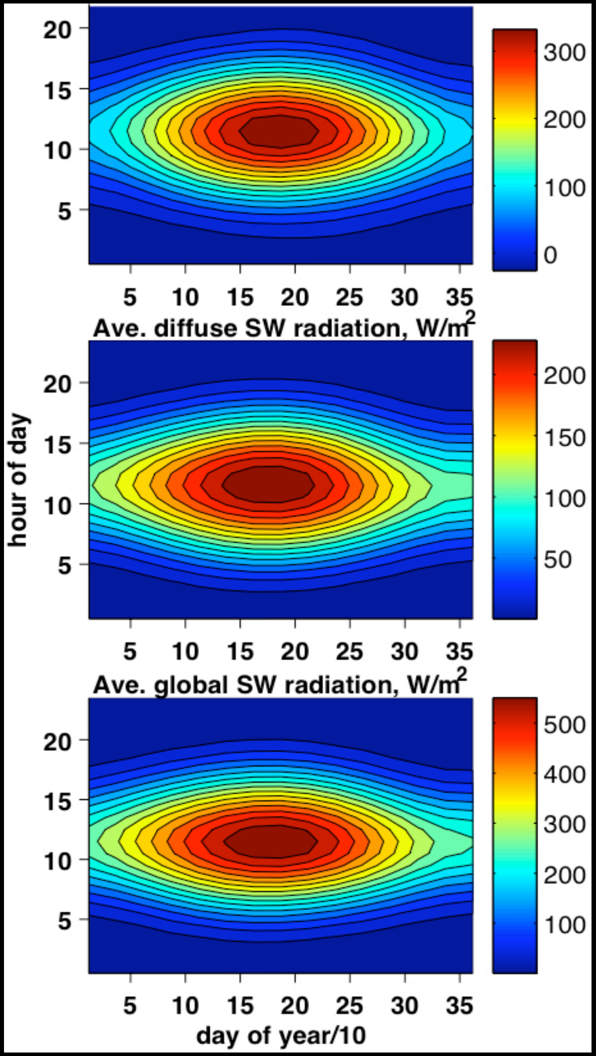
winds shift


24 hr
night
day
SON
JJA
MAM
DJF
ann.
climatology + 10 yr change
climatology

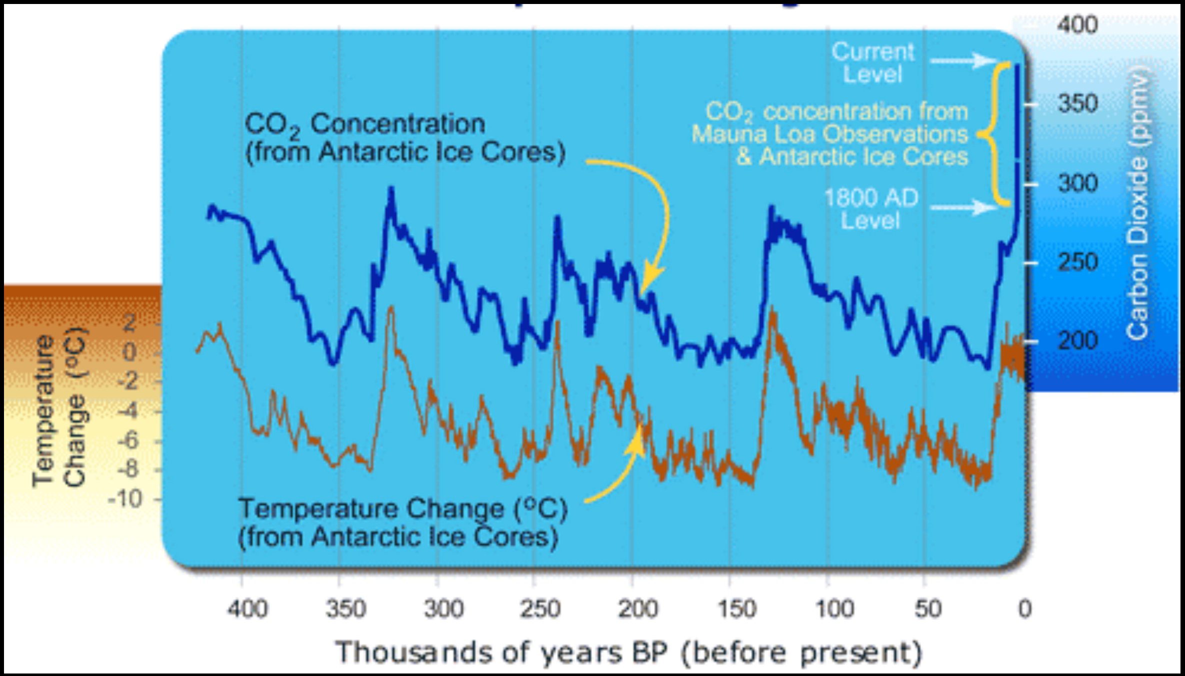

Tmax, DJF
Tmin, DJF
Tmax, JJA
Tmin, JJA
77°W 76°W 75°W 74°W 73°W 72°W 71°W 70°W
40°N 41°N 42°N 43°N 44°N 45°N

and curiously,





so:



- the earth is most definitely getting warmer
- there is a very strong and well-developed theory connecting greenhouse gases and surface temperatures
- many independent lines of evidence are consistent with the notion that the observed warming does result from elevated GHG concentrations in the atmosphere
- uncertainty remains, but keeps getting smaller
- puzzles abound…