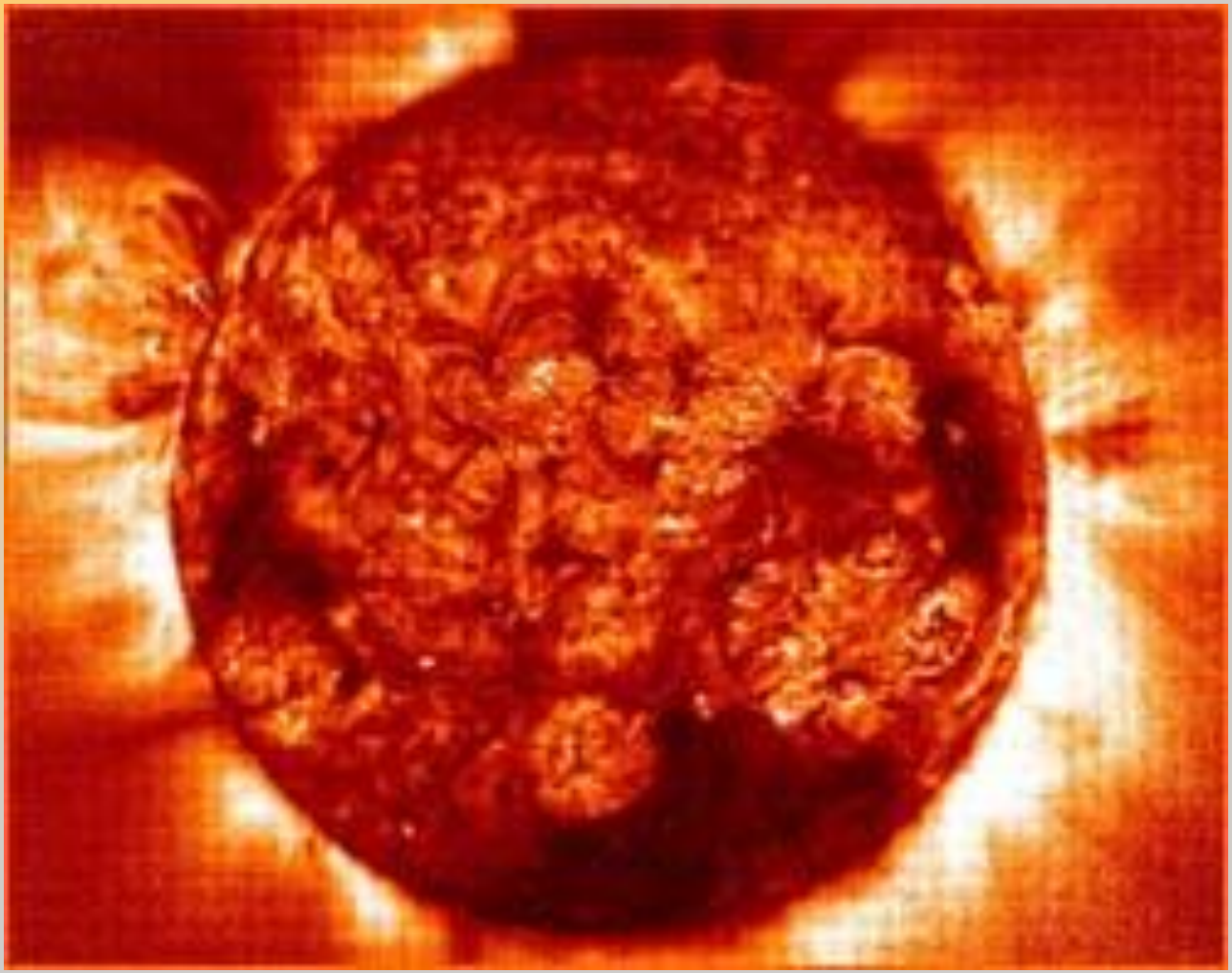
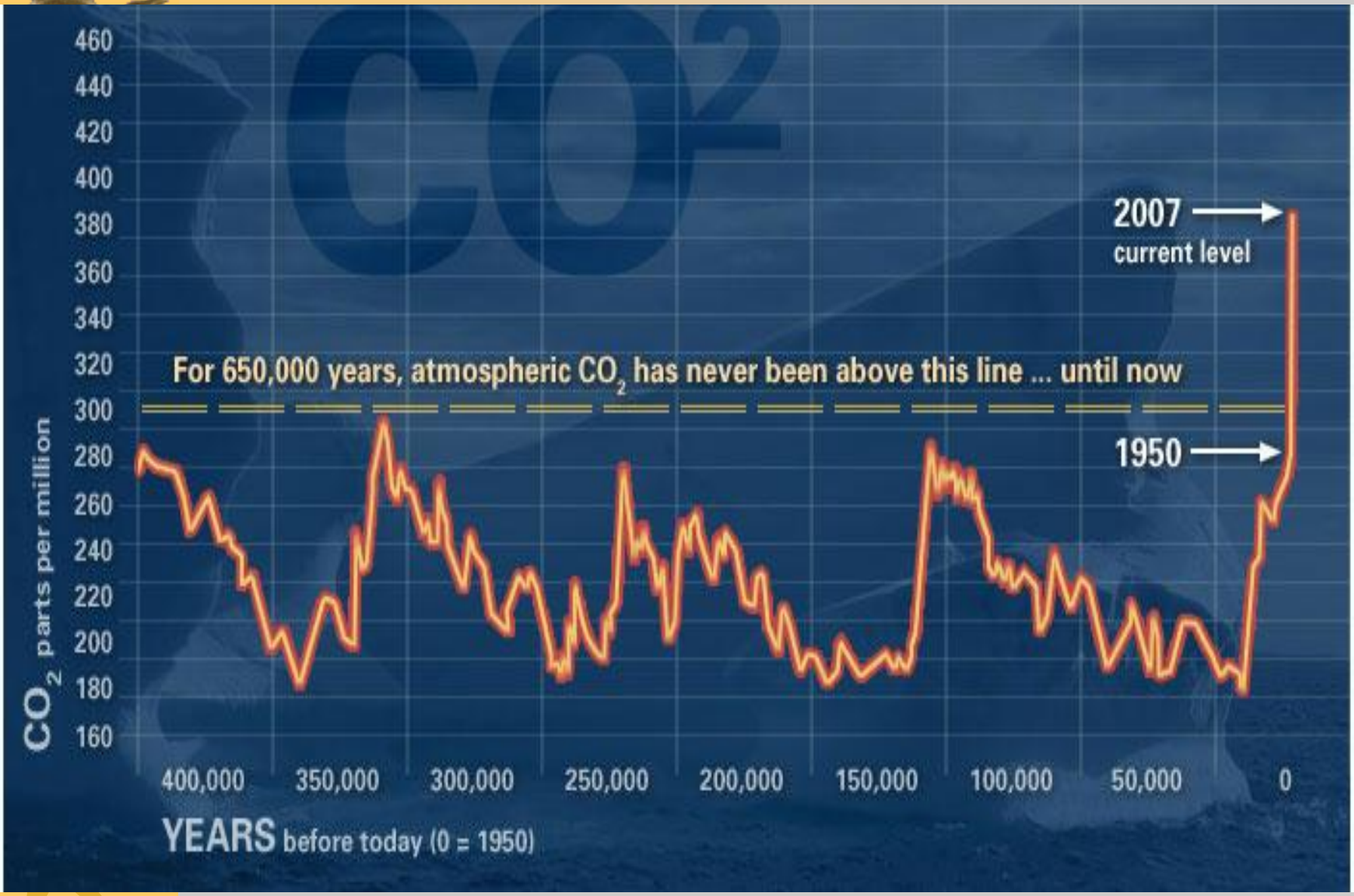
The Earth's Energy Balance



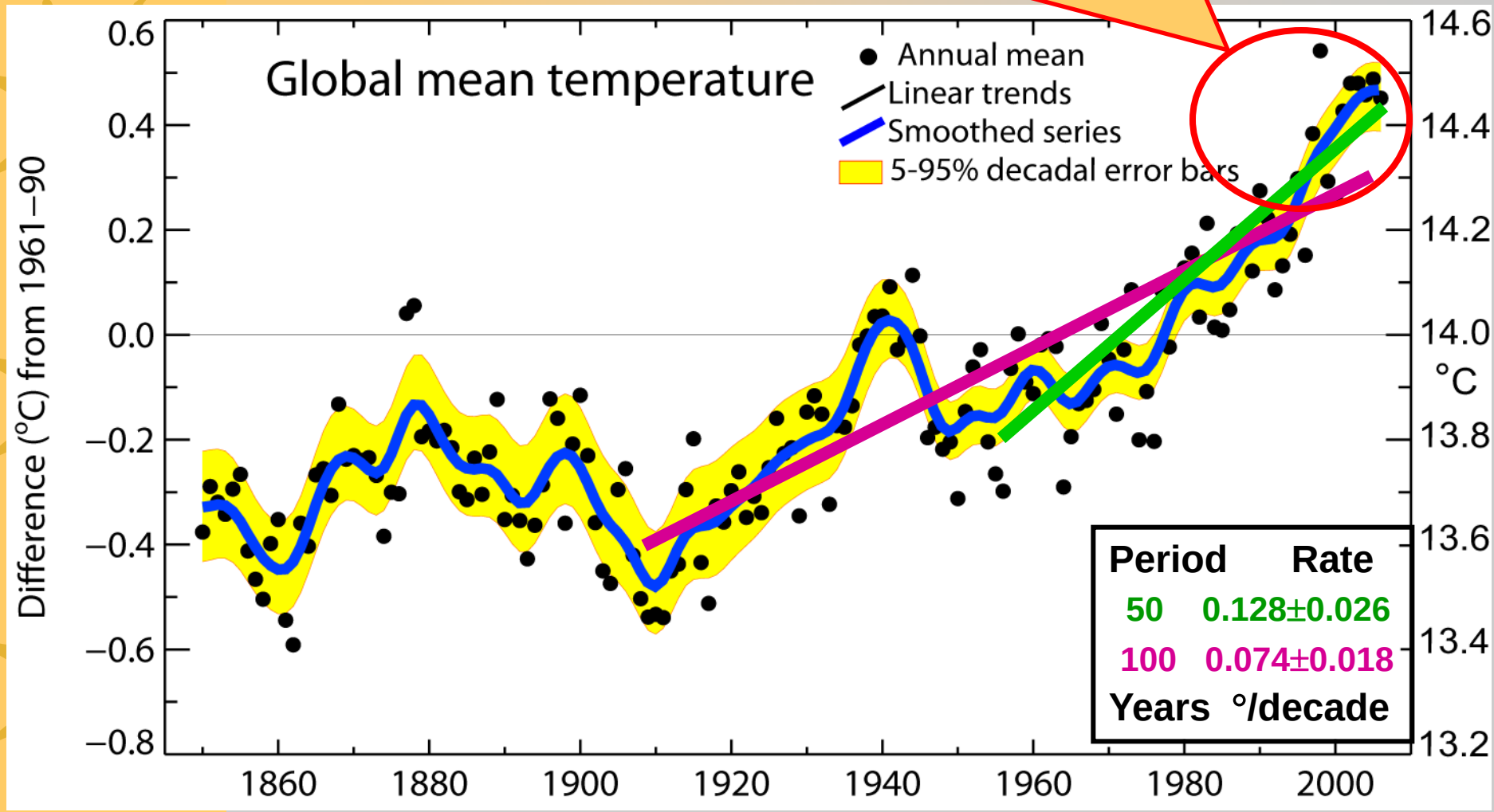
MAUNA LOA OBSERVATORY, HAWAII
MONTHLY AVERAGE CARBON DIOXIDE CONCENTRATION
MLO-145

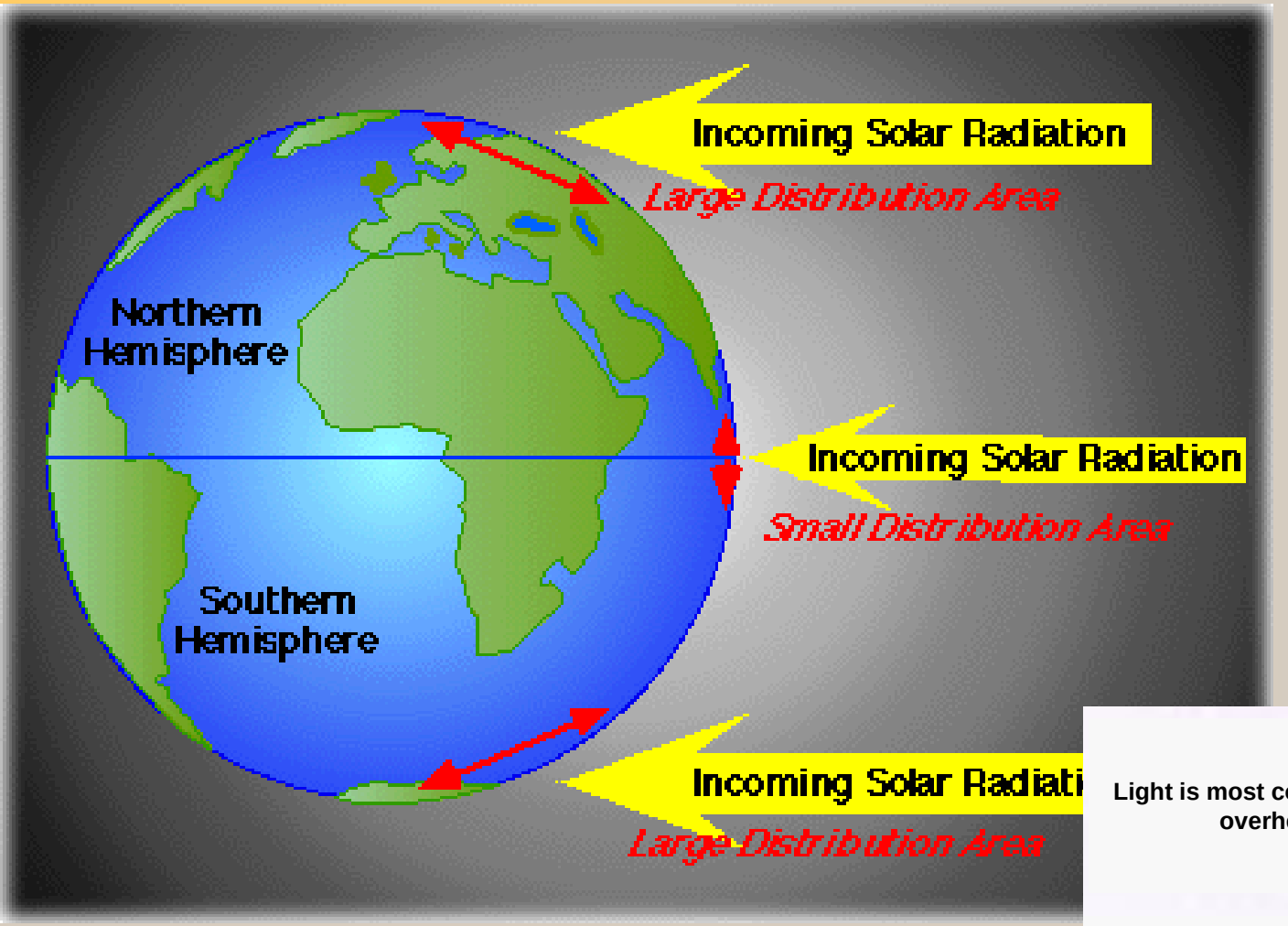
CO2 CONCENTRATION, (PPM)
390
385
380
375
370
365
360
355
350
345
340
335
330
325
320
315
310
1958 60 62 64 66 68 70 72 74 76 78 80 82 84 86 88 90 92 94 96 98 00 02 04
YEAR
19-May-05

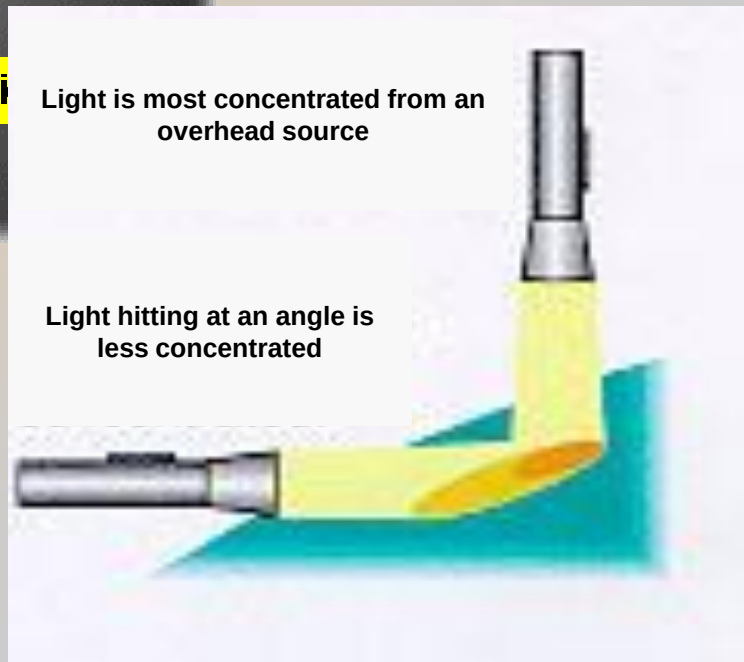

460
440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
CO2 parts per million
2007
current level
For 650,000 years, atmospheric CO2 has never been above this line ... until now
1950
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
YEARS before today (0 = 1950)

Global mean temper

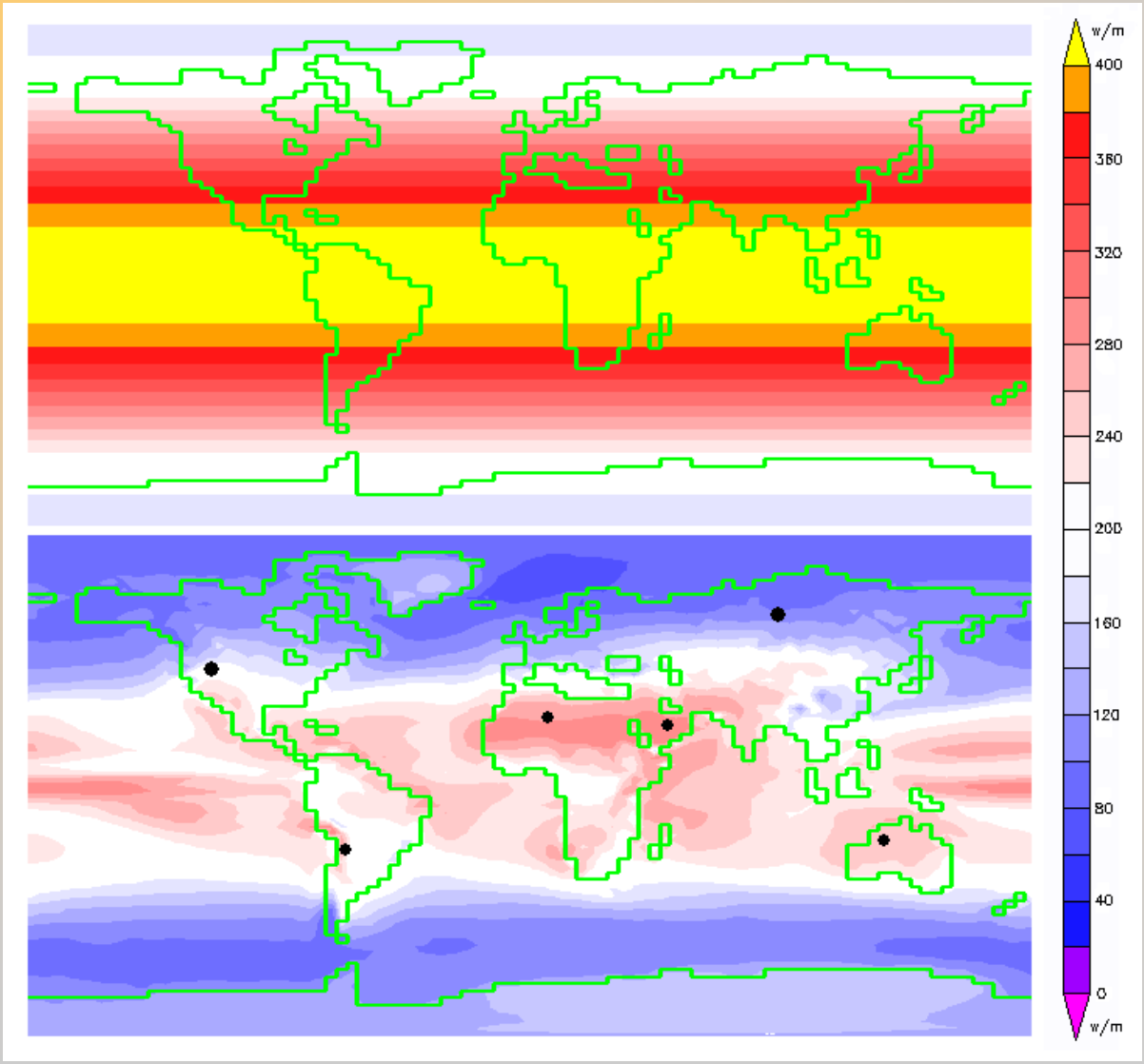
Warmest 12 years:
1998,2005,2003,2002,2004,2006,
2001,1997,1995,1999,1990,2000




Incoming Solar Radiation
Large Distribution Area
Northern Hemisphere
Incoming Solar Radiation
Small Distribution Area
Southern Hemisphere
Incoming Solar Radiati
Large Distribution Area

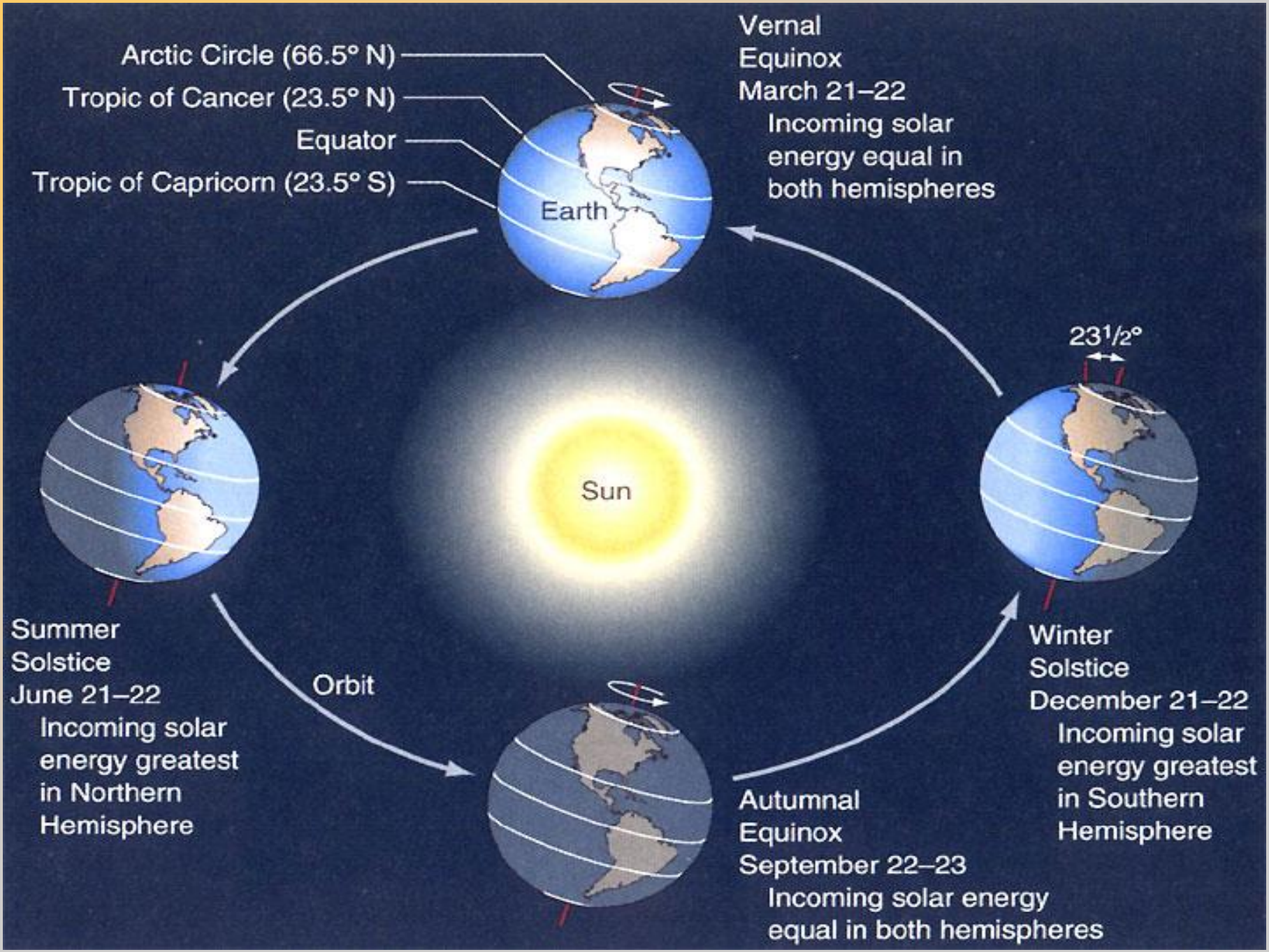

Light is most concentrated from an overhead source
Light hitting at an angle is less concentrated

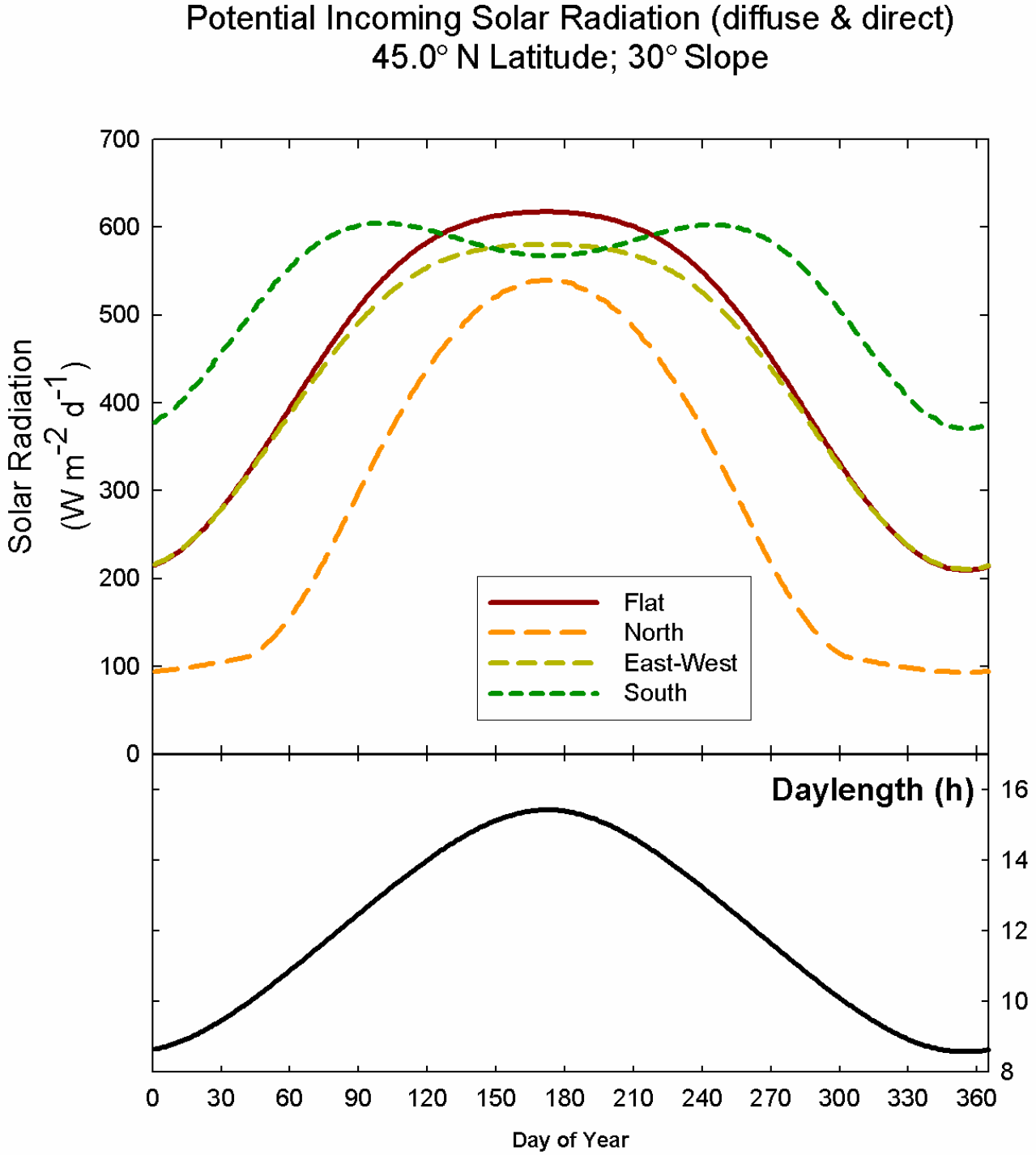
Annual Average Insolation



Top Of Atmosphere

Earth's Surface


Arctic Circle (66.5° N)
Tropic of Cancer (23.5° N)
Equator
Tropic of Capricorn (23.5° S)
Earth
Vernal
Equinox
March 21–22
Incoming solar
energy equal in
both hemispheres
23½°
Sun
Summer
Solstice
June 21–22
Incoming solar
energy greatest
in Northern
Hemisphere
Orbit
Winter
Solstice
December 21–22
Incoming solar
energy greatest
in Southern
Hemisphere
Autumnal
Equinox
September 22–23
Incoming solar energy
equal in both hemispheres


Potential Incoming Solar Radiation (diffuse & direct)
45.0° N Latitude; 30° Slope
Solar Radiation
(W m-2 d-1)
700
600
500
400
300
200
100
0
Flat
North
East-West
South
Daylength (h)
16
14
12
10
8
0
30
60
90
120
150
180
210
240
270
300
330
360
Day of Year

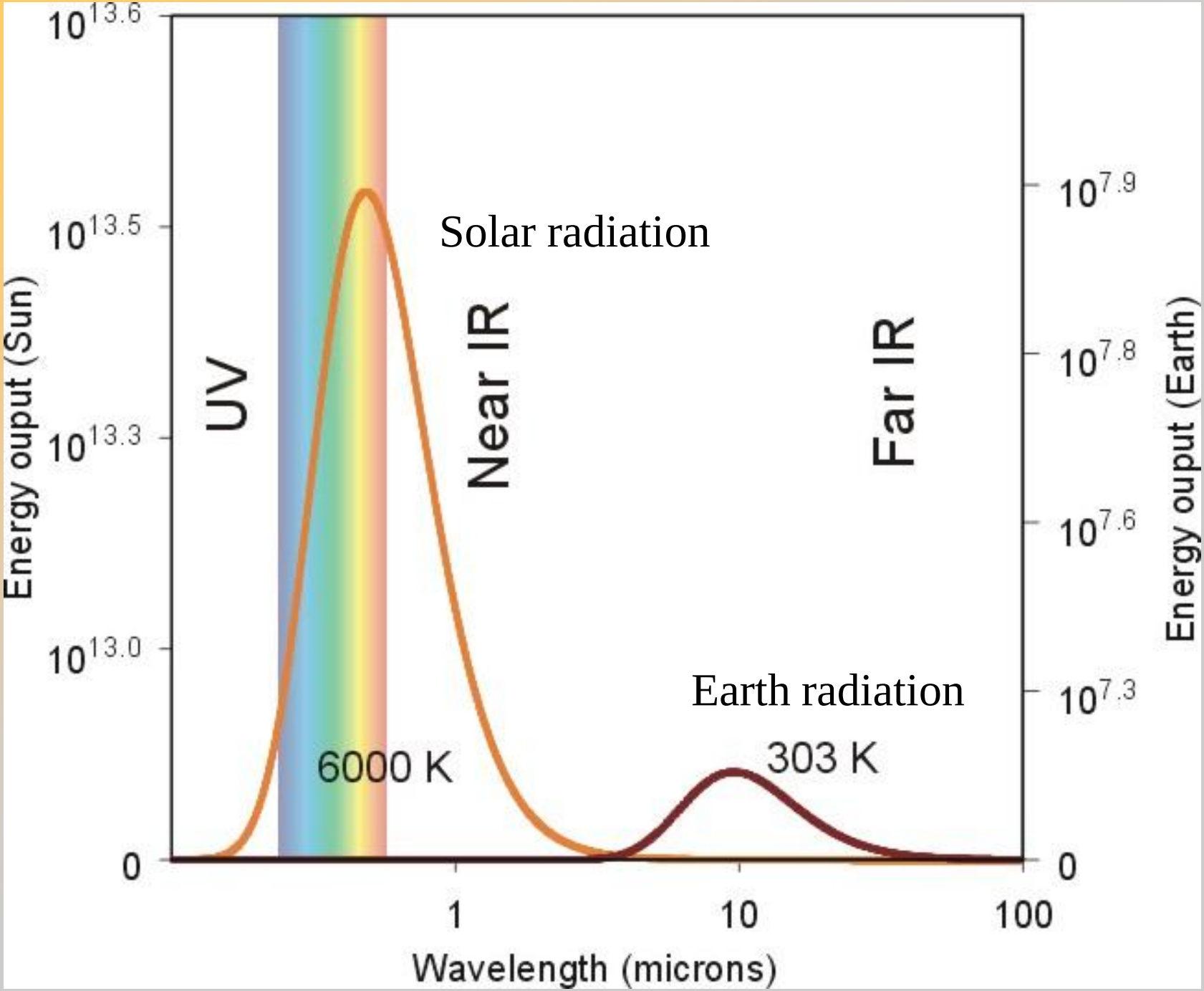
Important Radiation Laws & Concepts

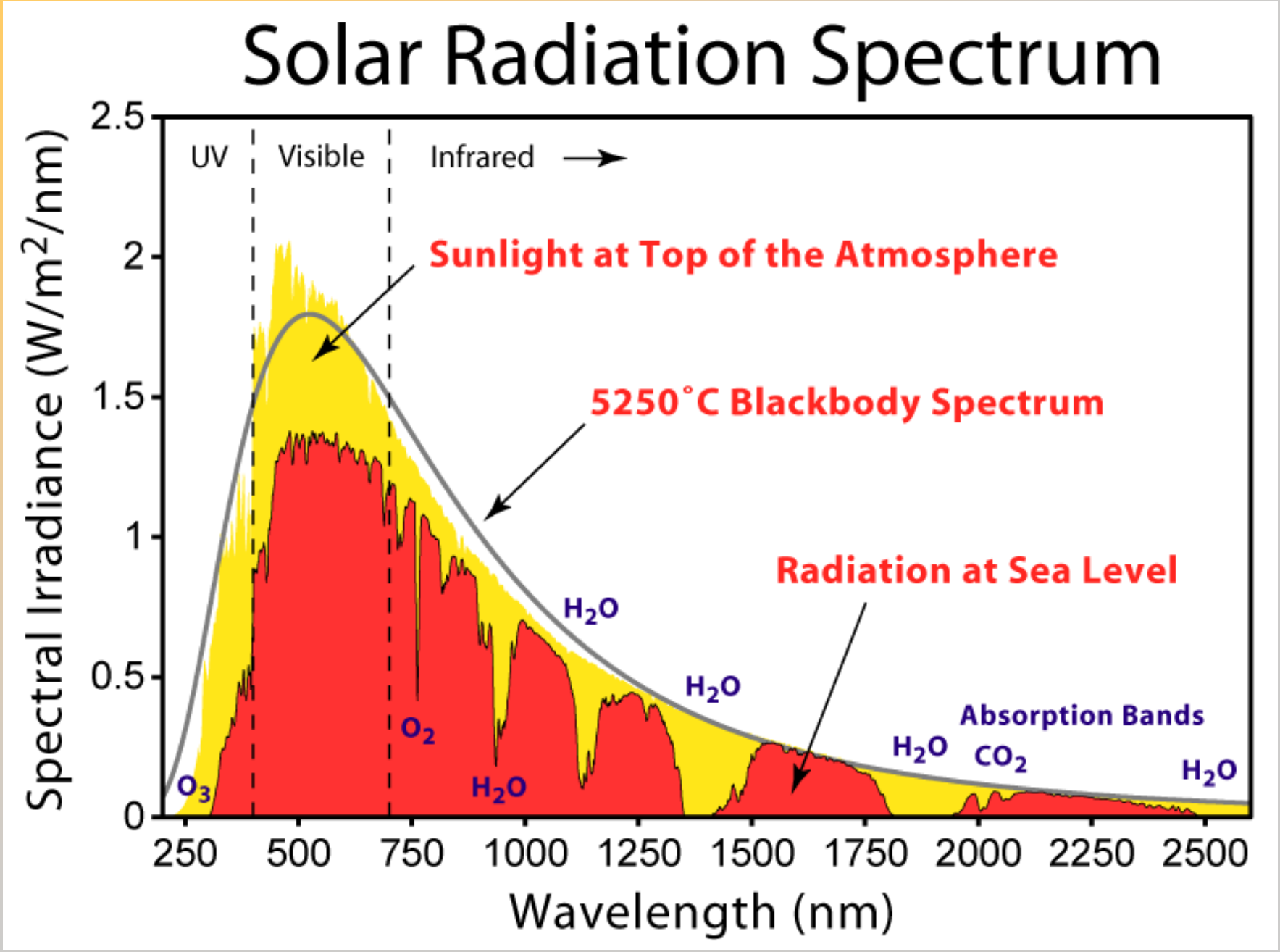
Wien's Law

$$\lambda_m\,(\mu m) = 2897 / T$$

$\lambda_m \equiv$ wavelength of maximum intensity; the higher the temperature, the shorter the wavelength & the more intense the light

Wilhelm Wien
(1864-1928)


Solar radiation
UV
Near IR
Far IR
Earth radiation
6000 K
303 K
Energy ouput (Sun)
Energy ouput (Earth)
Wavelength (microns)
10^13.6
10^13.5
10^13.3
10^13.0
0
10^7.9
10^7.8
10^7.6
10^7.3
0
1
10
100


Solar Radiation Spectrum
Spectral Irradiance (W/m²/nm)
2.5
2
1.5
1
0.5
0
UV
Visible
Infrared
Sunlight at Top of the Atmosphere
5250˚C Blackbody Spectrum
Radiation at Sea Level
O3
O2
H2O
H2O
H2O
H2O
CO2
H2O
Absorption Bands
250
500
750
1000
1250
1500
1750
2000
2250
2500
Wavelength (nm)

Important Radiation Laws & Concepts

Stefan-Boltzmann Law

$$E = \sigma \times T^4$$

Jožef Stefan
(1835-1893)

Ludwig Boltzmann
(1844-1906)

Radiation

Radiation

Conduction

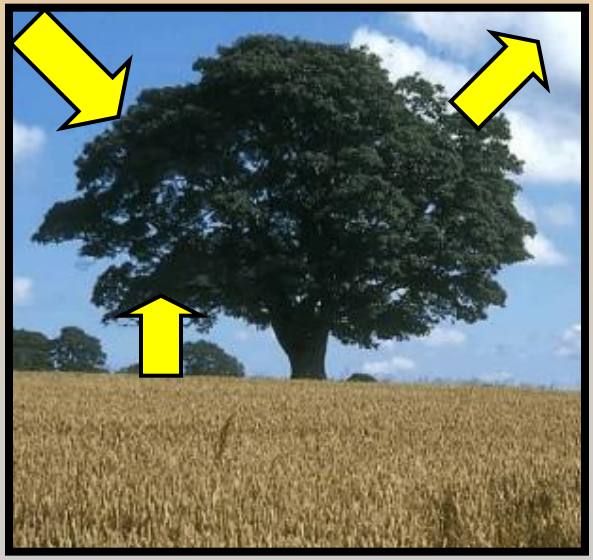
Convection

Important Radiation Laws & Concepts

Net radiation

$$Rn = \text{incoming} - \text{outgoing}$$

$$Rn = (1-\alpha)I_s + E_L\,\sigma T^4(\text{surface}) - \sigma\,T^4(\text{sky})$$



α is ***albedo***, which is the reflectivity of a surface

fresh snow has a high albedo (0.9)
dark forest has a low albedo (0.05 – 0.15)
light colored soils are in between (0.4 – 0.5)
mean albedo for earth ≈ 0.36

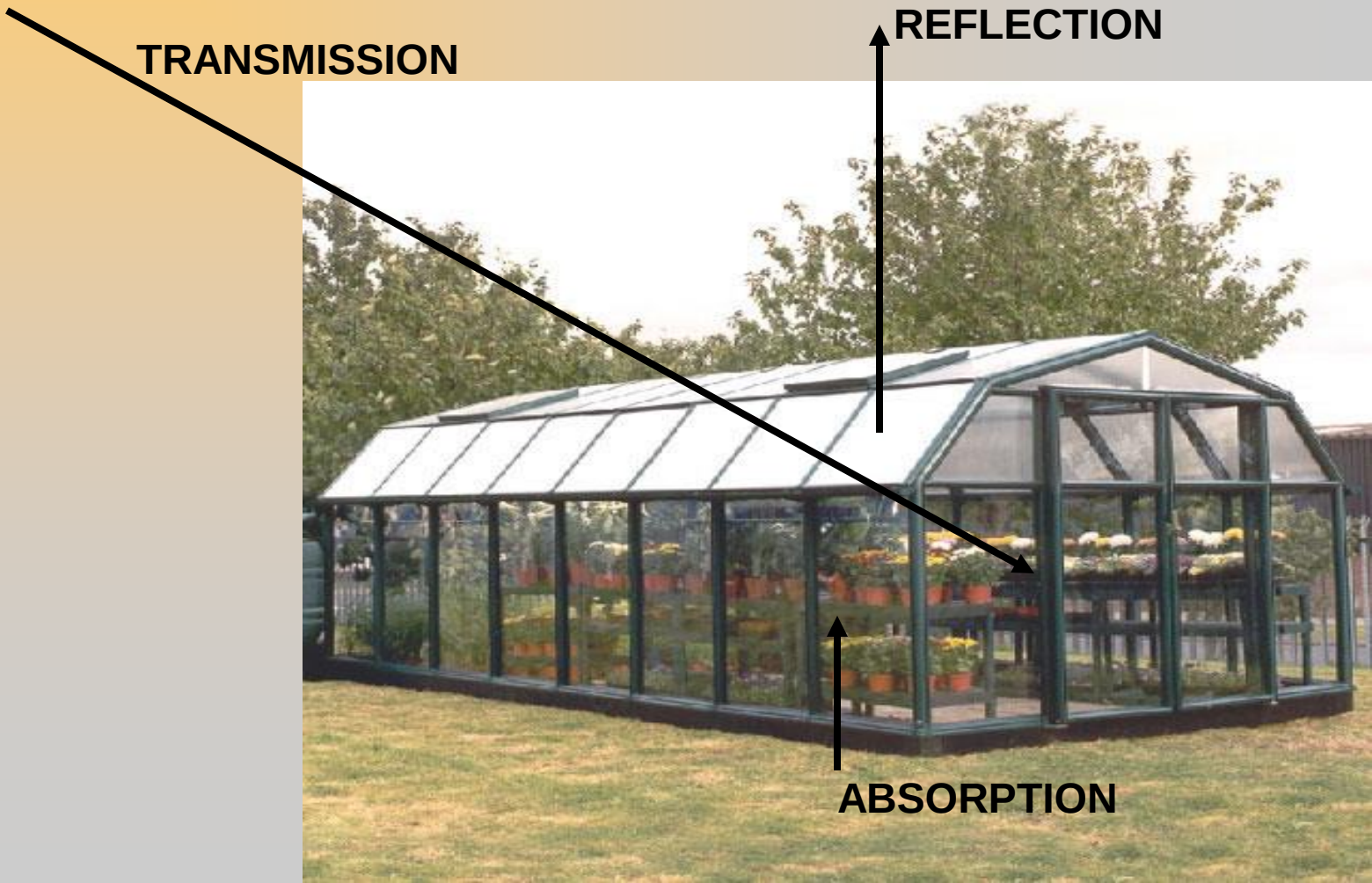
Bowen Ratio

$$\beta = H / \lambda E$$

$\beta = 10 / 1 =$ **10**

$\beta = 10 / 100 =$ **0.1**

RADIATION TRANSFER



The Greenhouse Effect

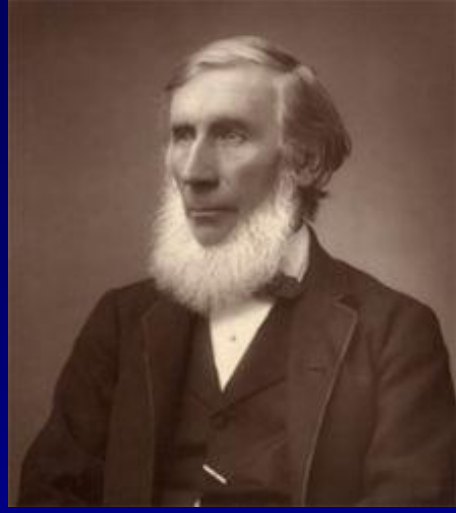
Some of the infrared radiation passes through the atmosphere, and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.

Some solar radiation is reflected by the Earth and the atmosphere

Solar radiation passes through the clear atmosphere

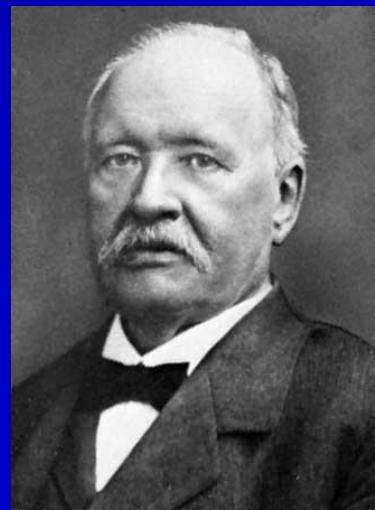
Infrared radiation is emitted from the Earth's Surface

Most radiation is absorbed by the Earth's surface and warms it



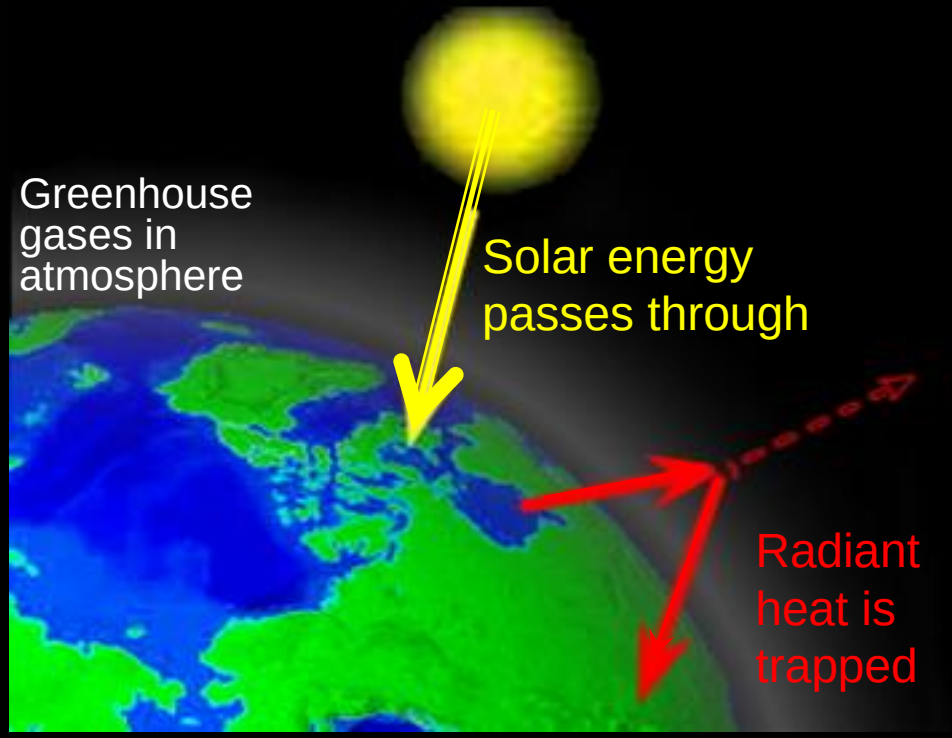
John Tyndall

Svante Arrhenius

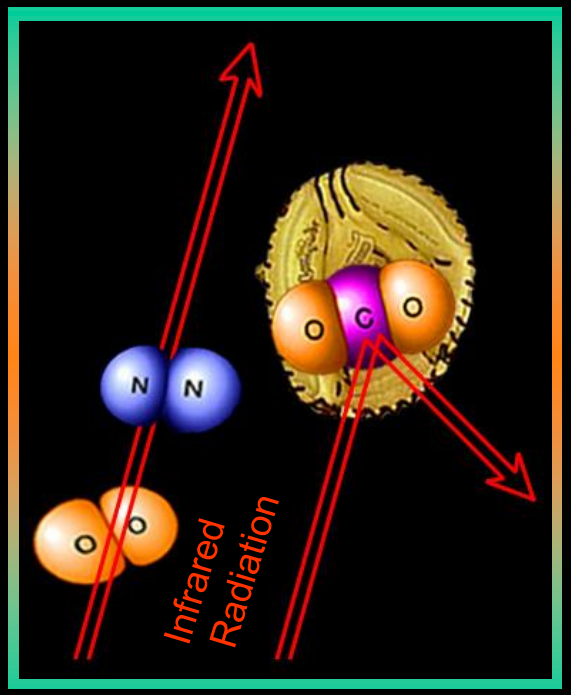


Pollution is the Primary Cause

The "Greenhouse gases" (e.g., carbon dioxide, methane, nitrous oxide, CFC's) trap heat in the earth's atmosphere.



Diagrams: Jennifer Allen



Science understood since 1859 - John Tyndall

Greenhouse Gases

- Water vapor (H_2O)
- Carbon dioxide (CO_2)
- Methane (CH_4)
- Other - Direct
  - Nitrous oxide (N_2O)
  - Fluorocarbons
- Other - Indirect
  - Carbon monoxide (CO)
  - Nitrogen oxides (NO_x)

Greenhouse Gases – Water Vapor

- Most abundant and important GHG
- Keeps earth warm enough for liquid water to form
- Varies in concentration in the lower atmosphere from nearly 0% to 4%
- Not considered important in anthropogenic climate change
  - Naturally correcting

Greenhouse Gases – CO_2

- **2nd most important GHG**
  - **0.038% (380 ppm)**
- **Largest emission of GHG in US (82% of all GHGs)**
  - **Fossil fuel emission is only significant source of "non-natural" CO_2**
- **Projected to grow to to 0.06% (600 ppm) by 2050**
- **Sinks:**
  - **Sedimentary rock – "Lithification"**
    - **Very slow, not relevant to current climate change**
  - **Ocean**
    - **52X as much C as atmosphere; 19X as much as soils + biosphere**
    - **Marine phytoplankton**
  - **Soils – humus**
  - **Biosphere – actively growing vegetation (esp. forests)**
    - **30% of earth is land, 30% of land is forests (9% of earth)**
    - **Most important are tropical forests**

Greenhouse Gases – CH_4

- Until recently it was assumed to play a minor role
  - Concentration is 1.7 ppm (0.00017%)
- 10X more efficient than CO_2 as a GHG
- Increased greatly since Industrial Revolution
  - Around 0.8 ppm for 160,000 years prior
- Net emissions of CH_4
- Methane hydrates

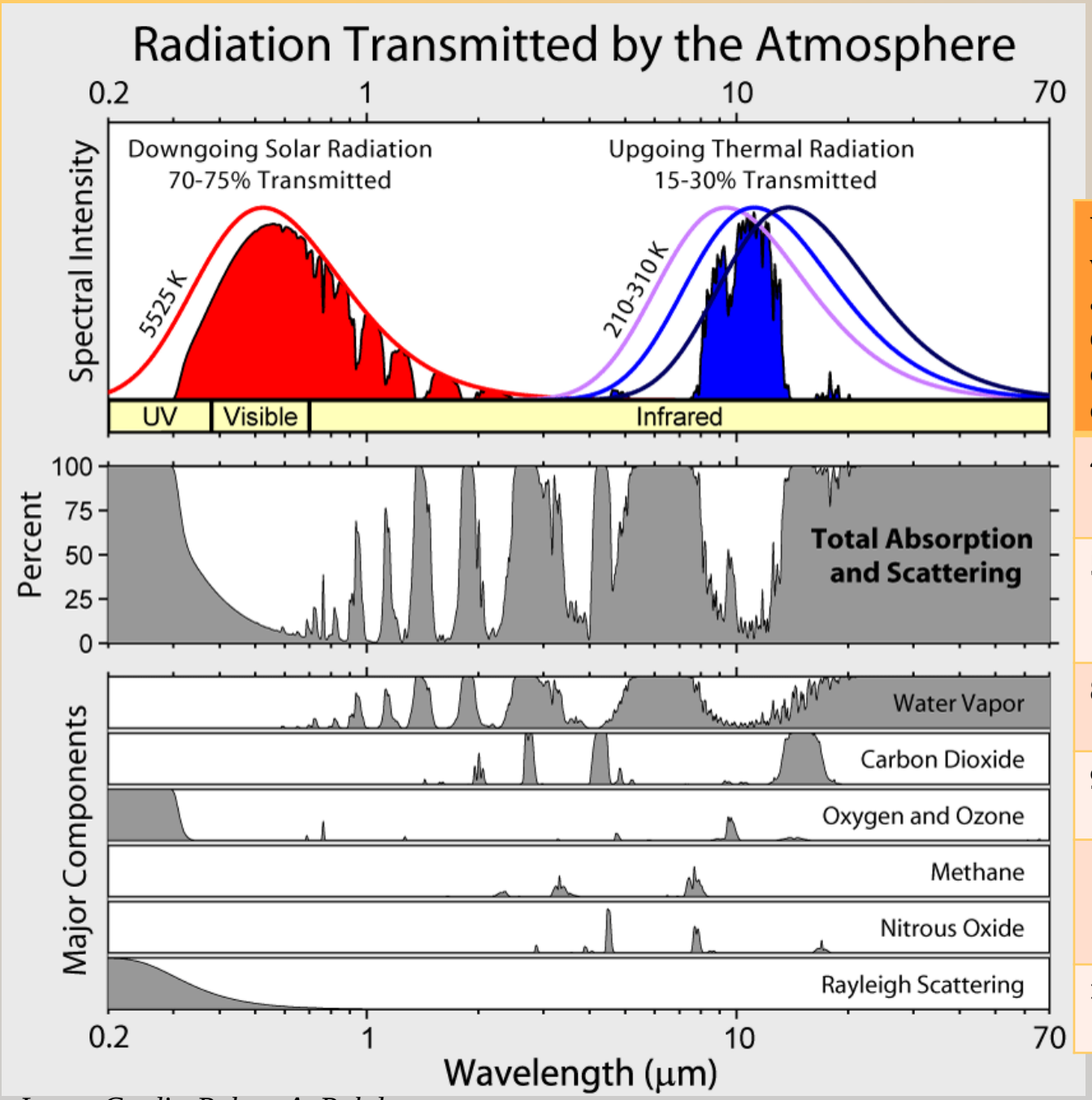


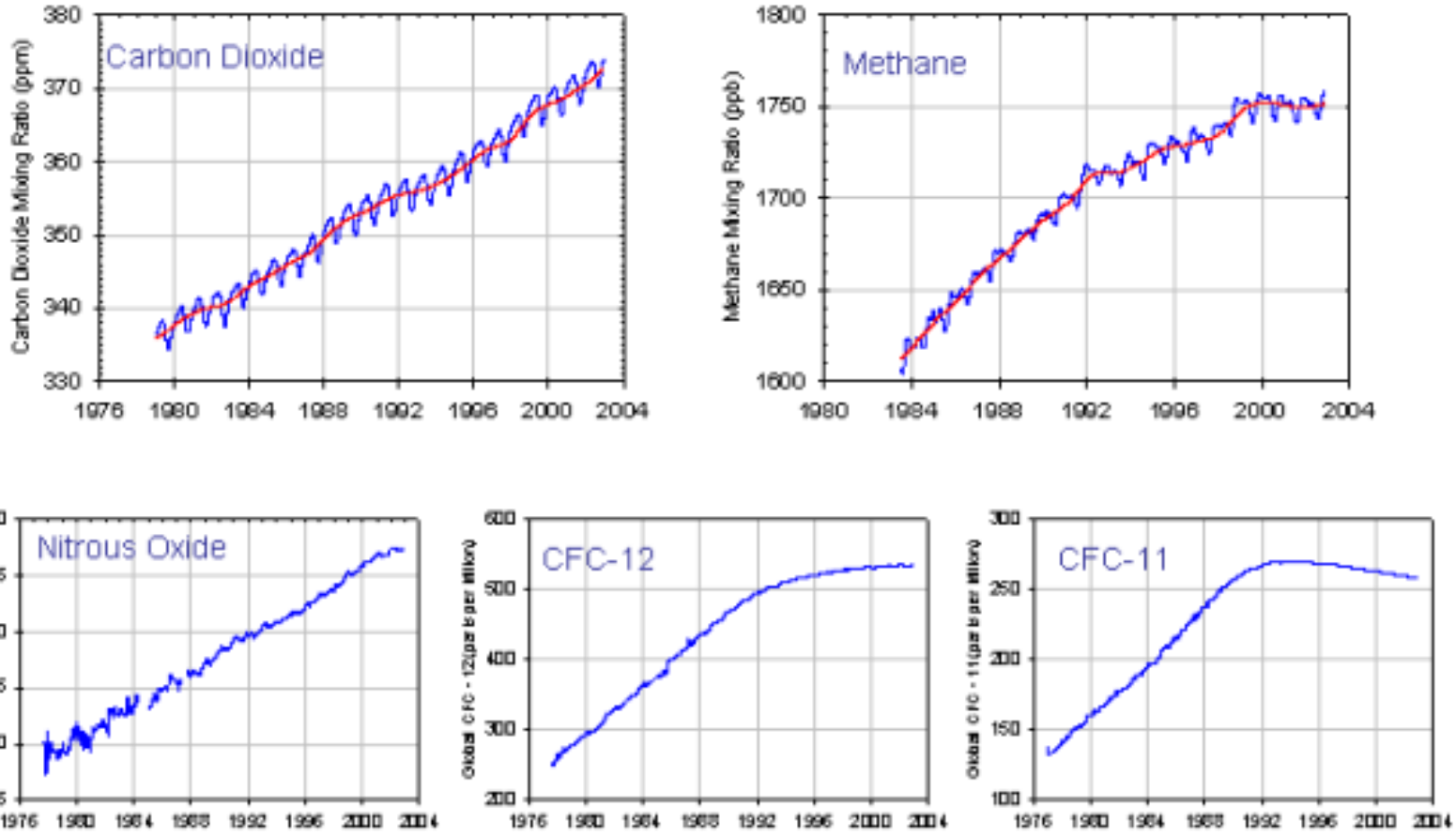
Image Credit: Robert A. Rohde, Global Warming Art

Peak emission of energy from earth and atmosphere at <u>10 μm</u>.

Wavelength at which GHGs absorb and emit radation, cloudless conditions	Primary Greenhouse Gas
4-5 μm	CO_2
5-8 μm	H_2O vapor (nearly complete at 5-6 μm)
8-13 μm	Atmospheric window
9.4-9.8 μm 13-17 μm	O_3 (strong) O_2 (strong)
17-24 μm	O_2 & H_2O vapor, partially transparent
>24 μm	H_2O vapor (complete)

Table Credit: Rohli & Vega Climatology, *2008*

Global Trends in Major Greenhouse Gases to 1/2003



Global trends in major long-lived greenhouse gases through the year 2002. These five gases account for about 97% of the direct climate forcing by long-lived greenhouse gas increases since 1750. The remaining 3% is contributed by an assortment of 10 minor halogen gases, mainly HCFC-22, CFC-113 and CCl_4.

Image Credit: Robert A. Rohde, Global Warming Art

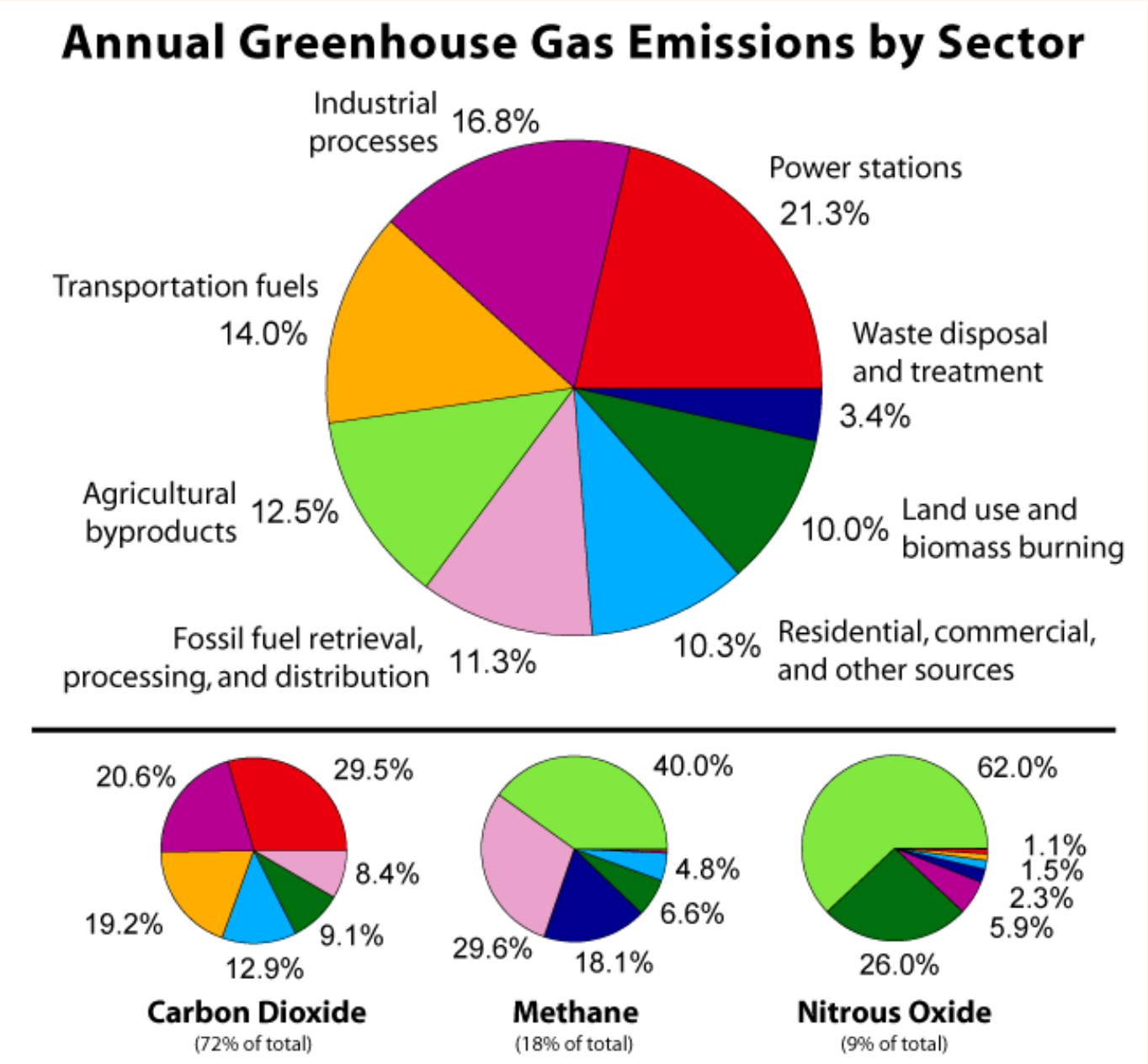
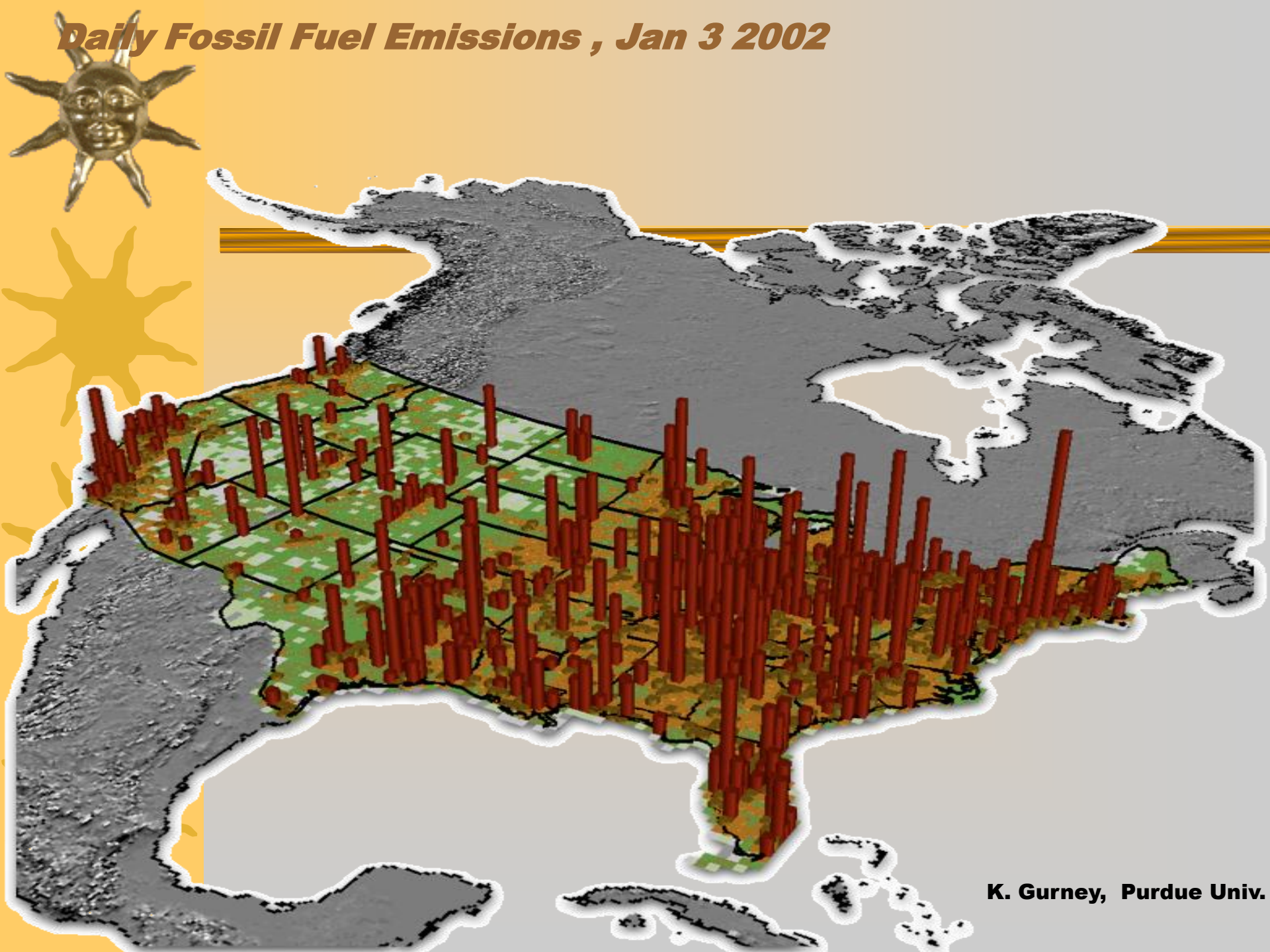


Image Credit: Robert A. Rohde,
Global Warming Art

Daily Fossil Fuel Emissions , Jan 3 2002



K. Gurney, Purdue Univ.

Partition of Anthropogenic Carbon Emissions into Sinks

[2000-2006]

45% of all CO_2 emissions accumulated in the atmosphere

The Airborne Fraction

The fraction of the annual anthropogenic emissions that remains in the atmosphere

55% were removed by natural sinks

Ocean removes _ 24%

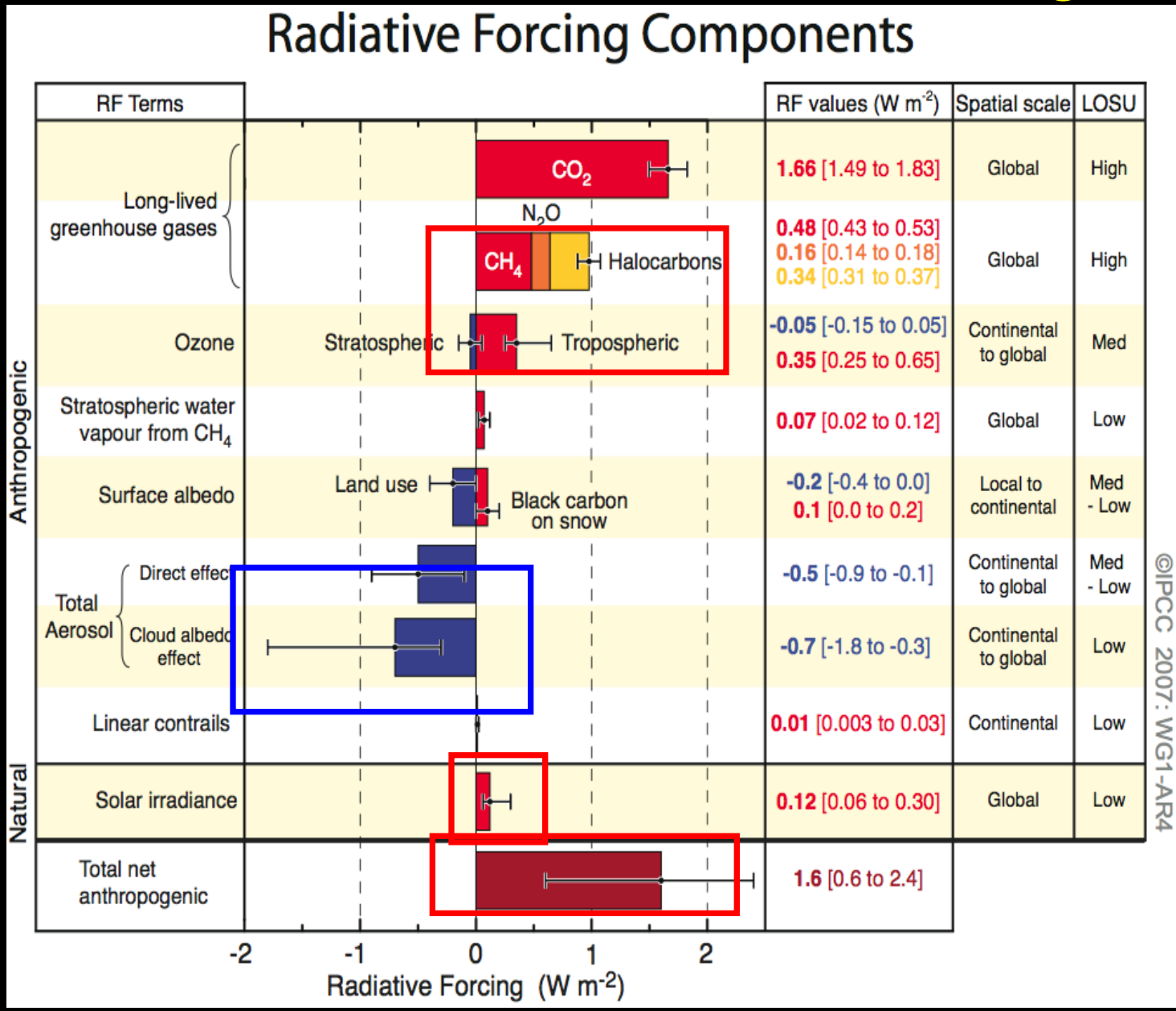
Land removes _ 30%

Canadell et al. 2007, PNAS

Human and Natural Drivers of Climate Change

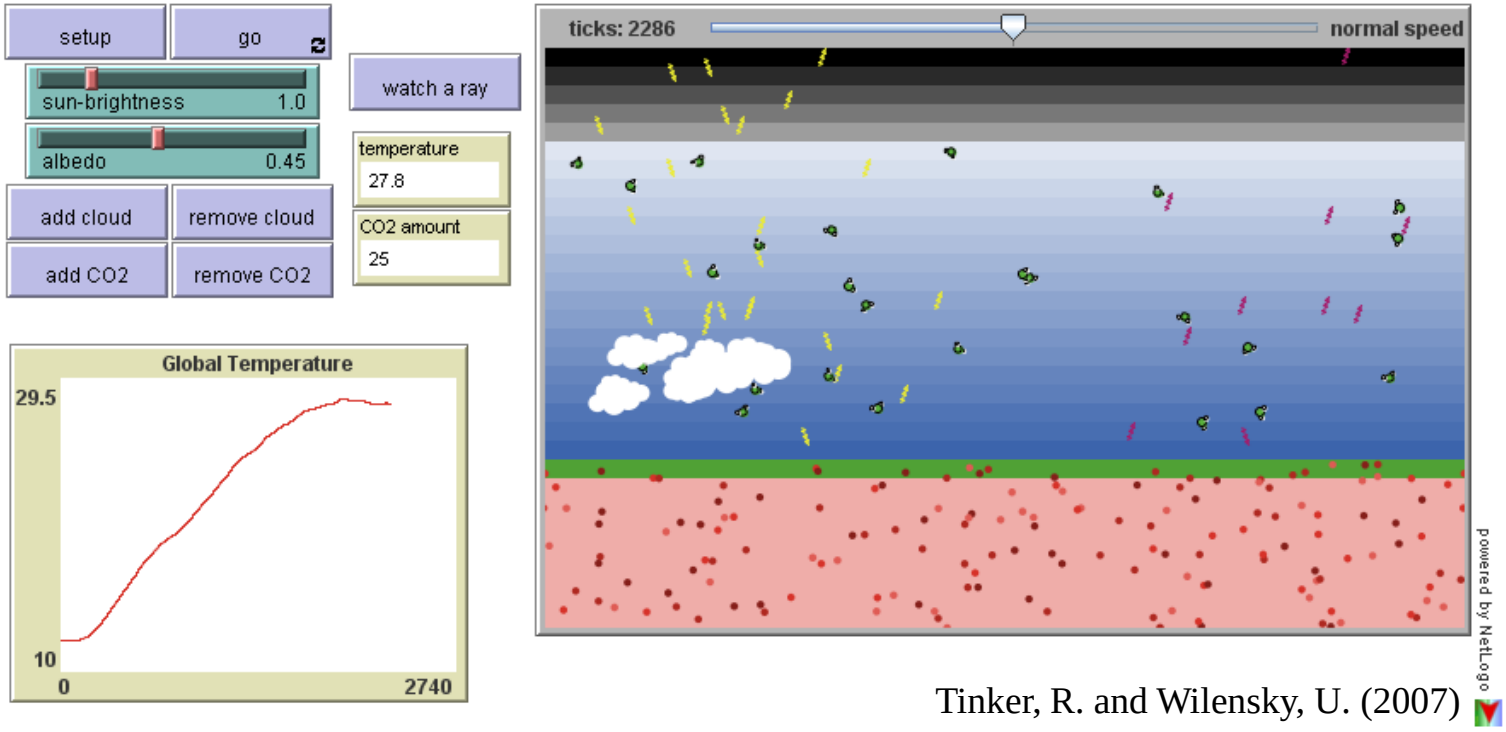
1.6 W m^{-2} warms like 1.6 Xmas tree lights over every m^2 on Earth.

Carbon dioxide is causing the bulk of the forcing, and it lives a long time in our atmosphere so every year of emission means commitments to climate change for future generations.



The Greenhouse Model

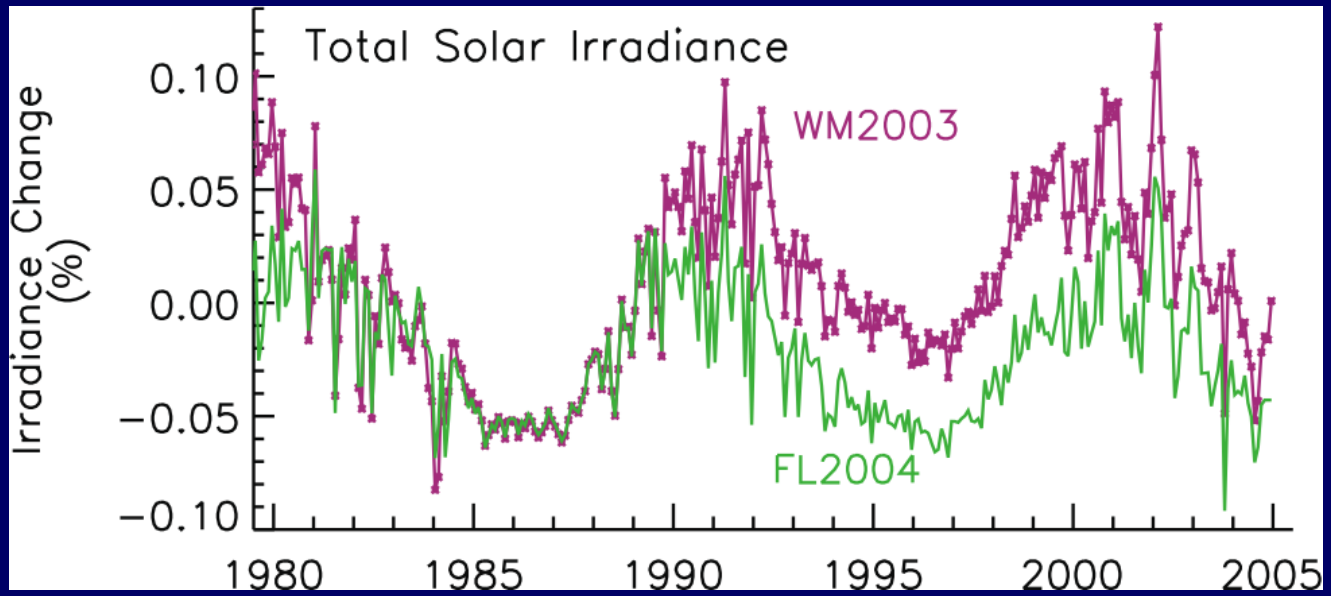
http://ccl.northwestern.edu/netlogo/models/ClimateChange



Tinker, R. and Wilensky, U. (2007)

- The Greenhouse Model is *not* a climate model; it is an energy balance model.

Better and longer satellite data about the Sun



Improved assessment:

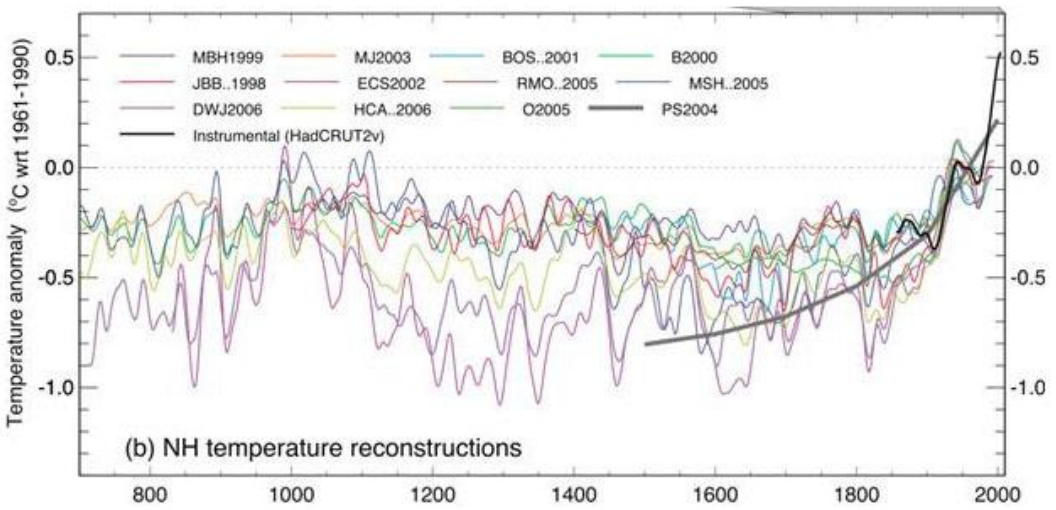
a) no observed trend in solar irradiance since 1978 using high quality inter-calibrated data; b) spectral information c) solar magnetic flux model rather than proxy data; d) re-evaluation of variations in Sun-like stars.

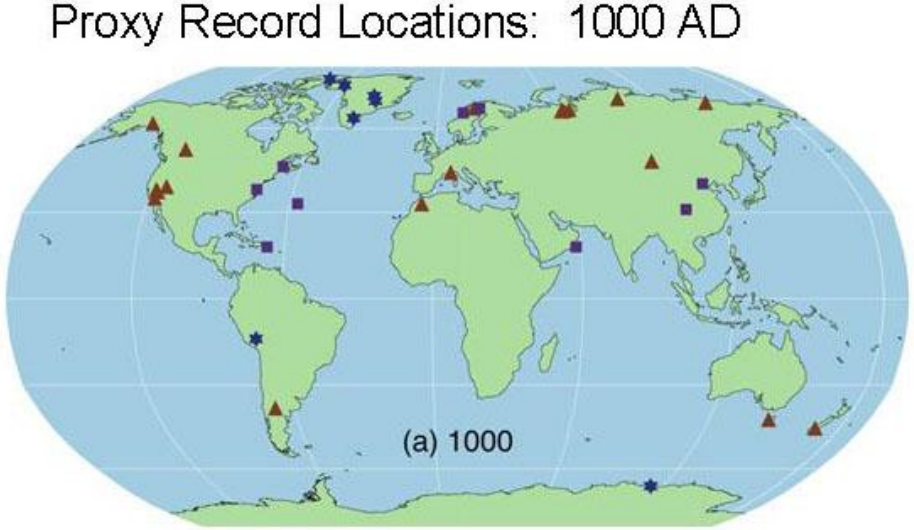
Solar irradiance forcing much smaller than GHG.

Paleoclimate: New and Independent Evidence From Many Types of Past Data

eg., changes in glaciers suggest global average temperature change in the 20th century consistent with the thermometers.
And the corals.
And the tree rings.
And the boreholes.
And the ice cores.

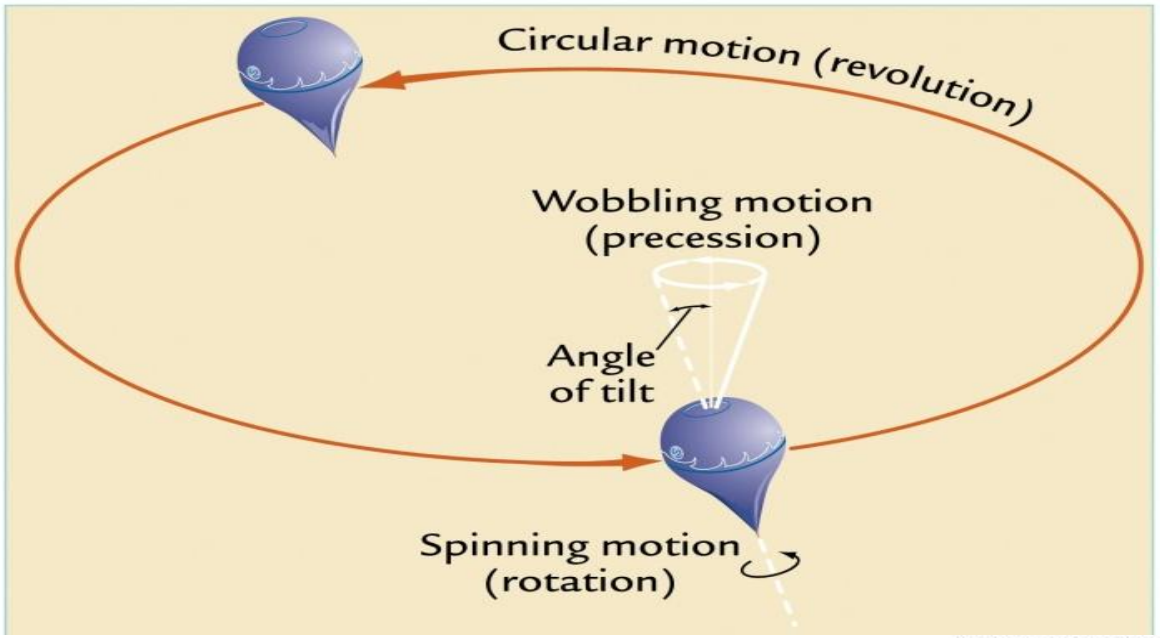
Last 50 yrs very likely warmest in last 500 yrs; likely warmest in 1300 yrs.

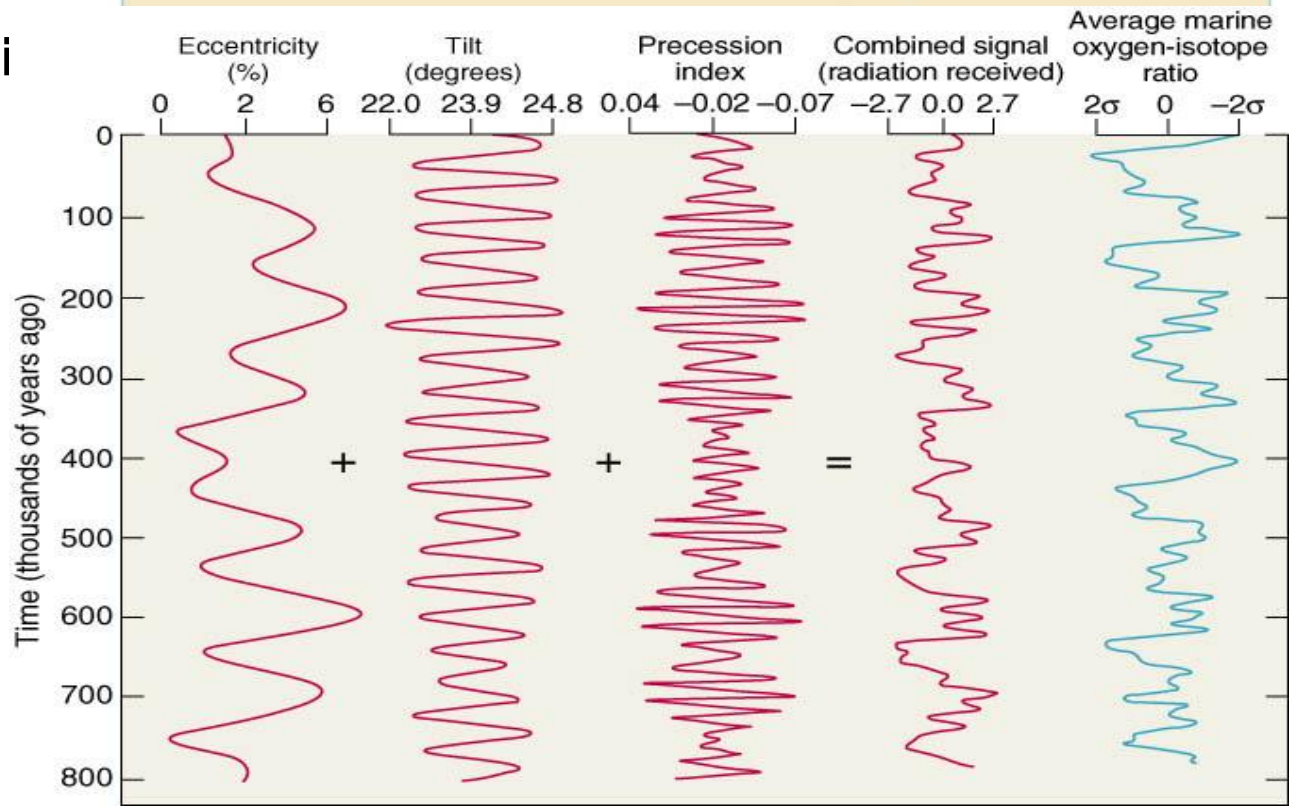




1911: Milutin Milankovitch proposes:

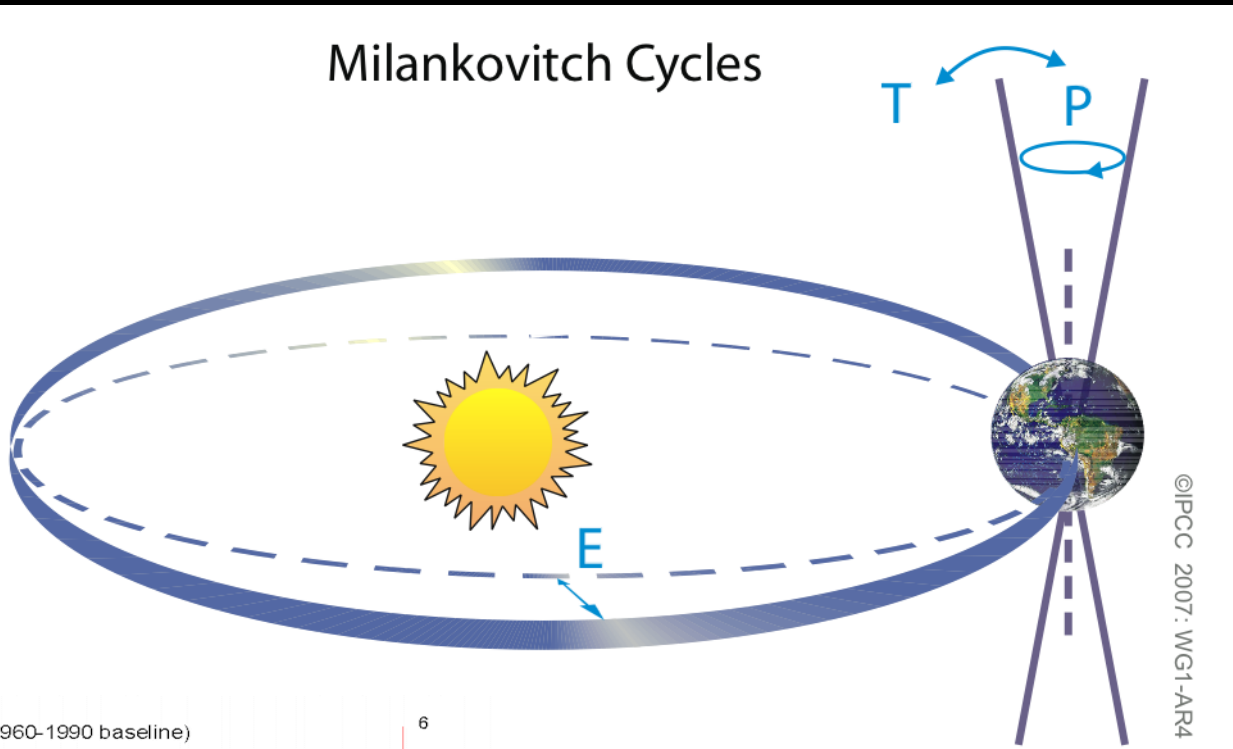
- **All 3 cycles (23, 41, & 100 KYA) together control ice ages**
- **Summer insolati is driver**

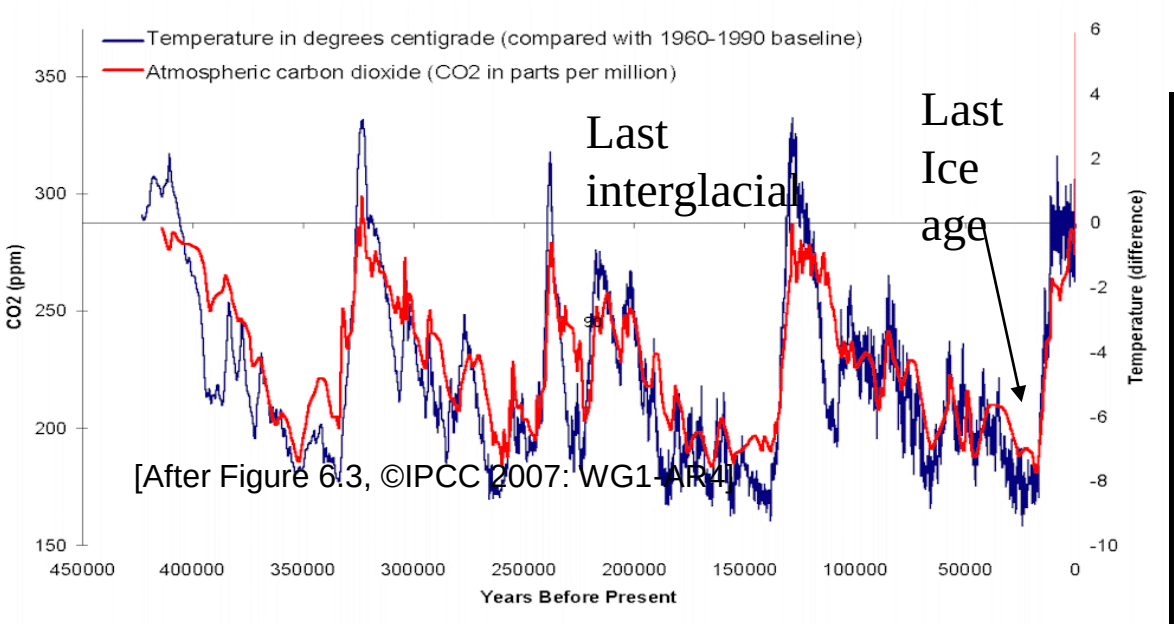




Credit: Anna Klene

Ice Age Forcing and Response





[After Figure 6.3, ©IPCC 2007: WG1-AR4]

Ice ages were not random - they were forced too…..