The Sun, the Climate System and Global Warming

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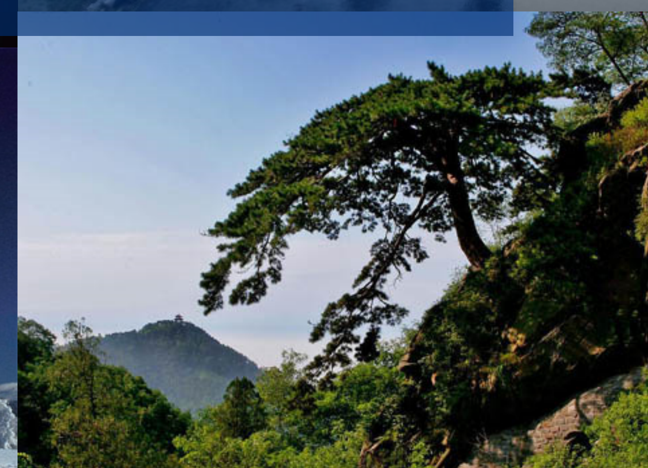
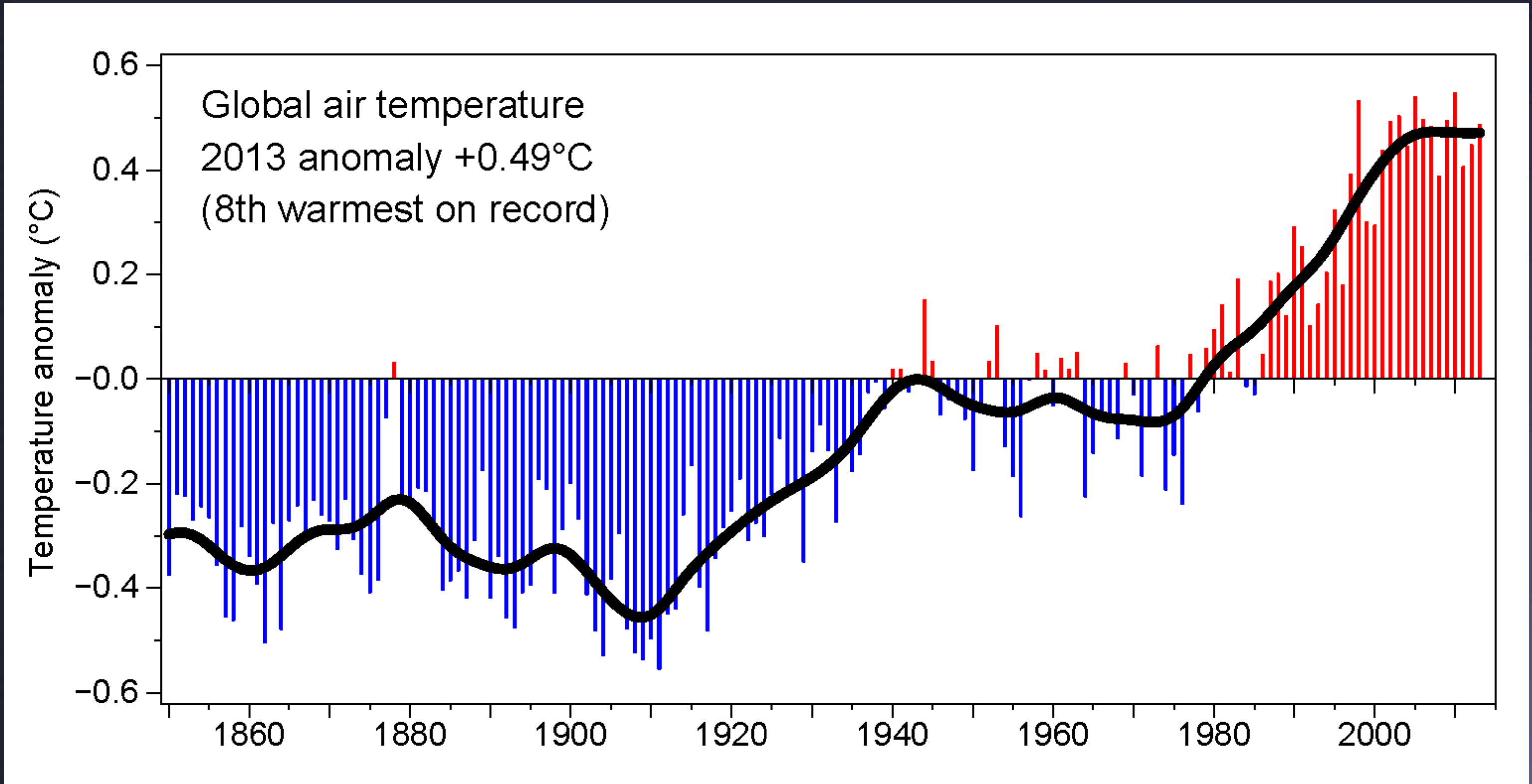
Climate

= average, or typical, weather conditions observed over a long period of time for a given area



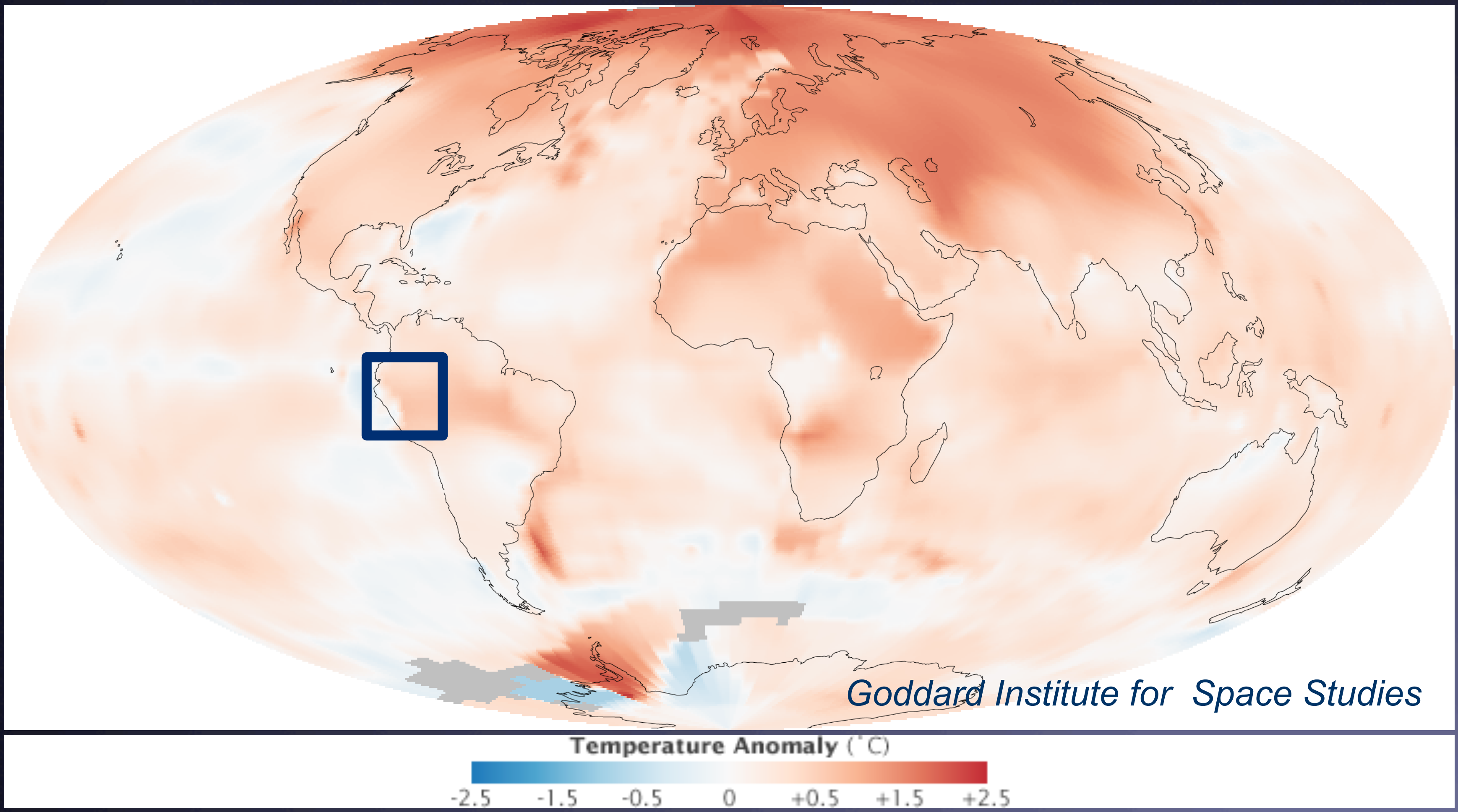
Temperature records



Data compilation and plot: Hadley Center , UK

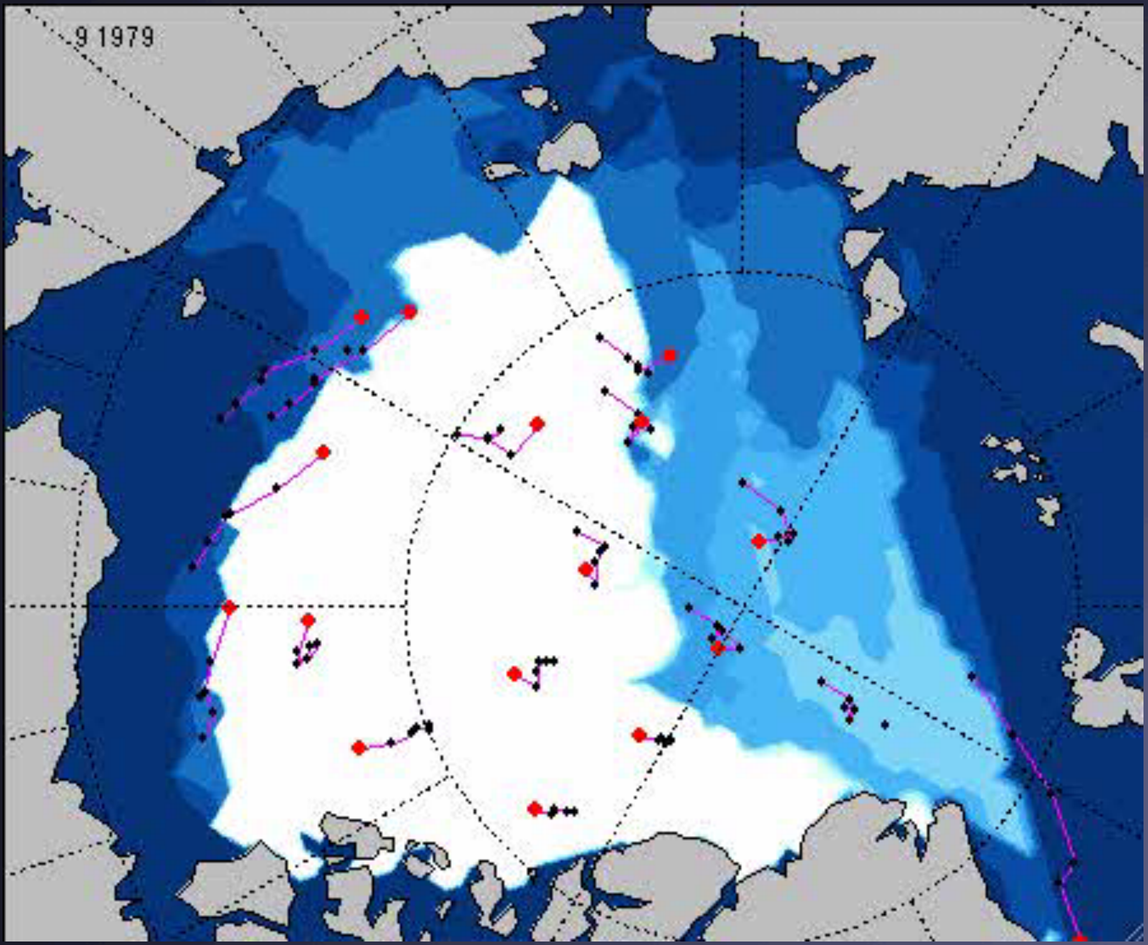
- 18 of the last 19 years (1995-2013) are warmest on record!
- 2001-2009 was 0.19° warmer than 1991-2000, but no general increase over last 10 years

Global temperature change



- Compared to the 1951-1980 mean
- Grey areas – no data
- Most extreme warming in the Arctic
- Land warmed more than sea

Changes in the extent and age of polar ice

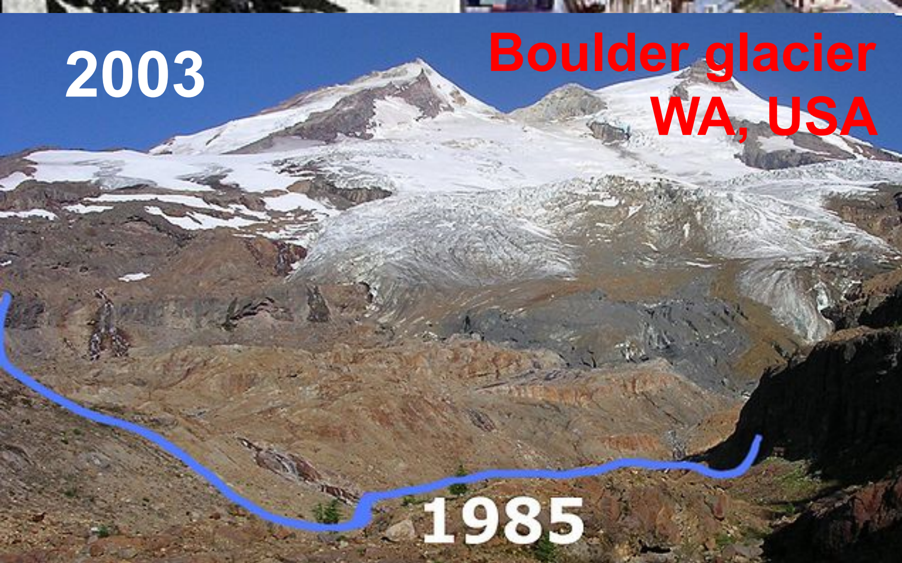


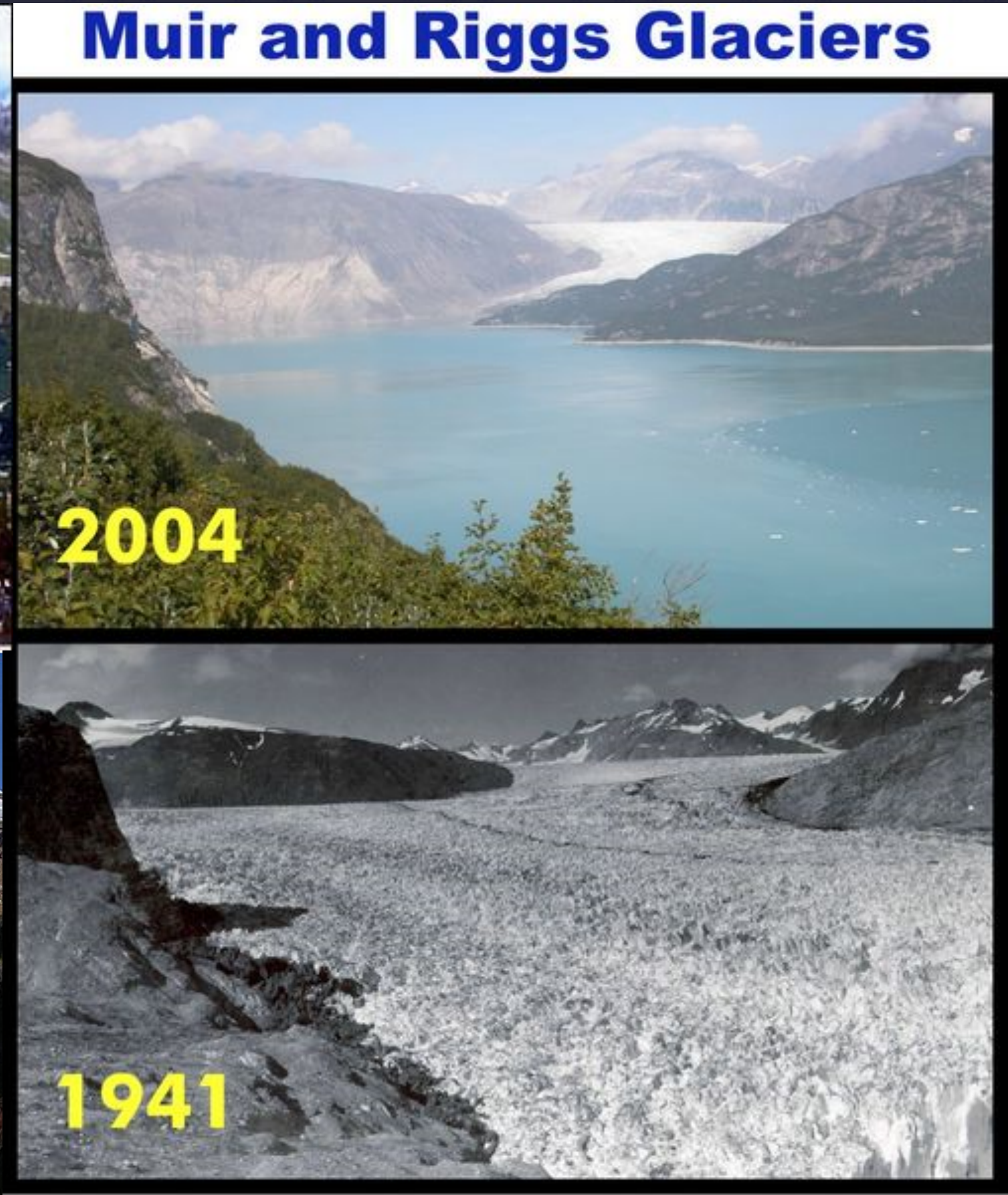
WWF, UK

- Winter growth rate reduced
- Amount of multi-year ice reduced
- First-year ice doesn't reach a thickness that is enough to withstand the summer melt

Multi-year ice: white   Younger ice: plotted darker   Dark blue: no ice

Retreat of glaciers

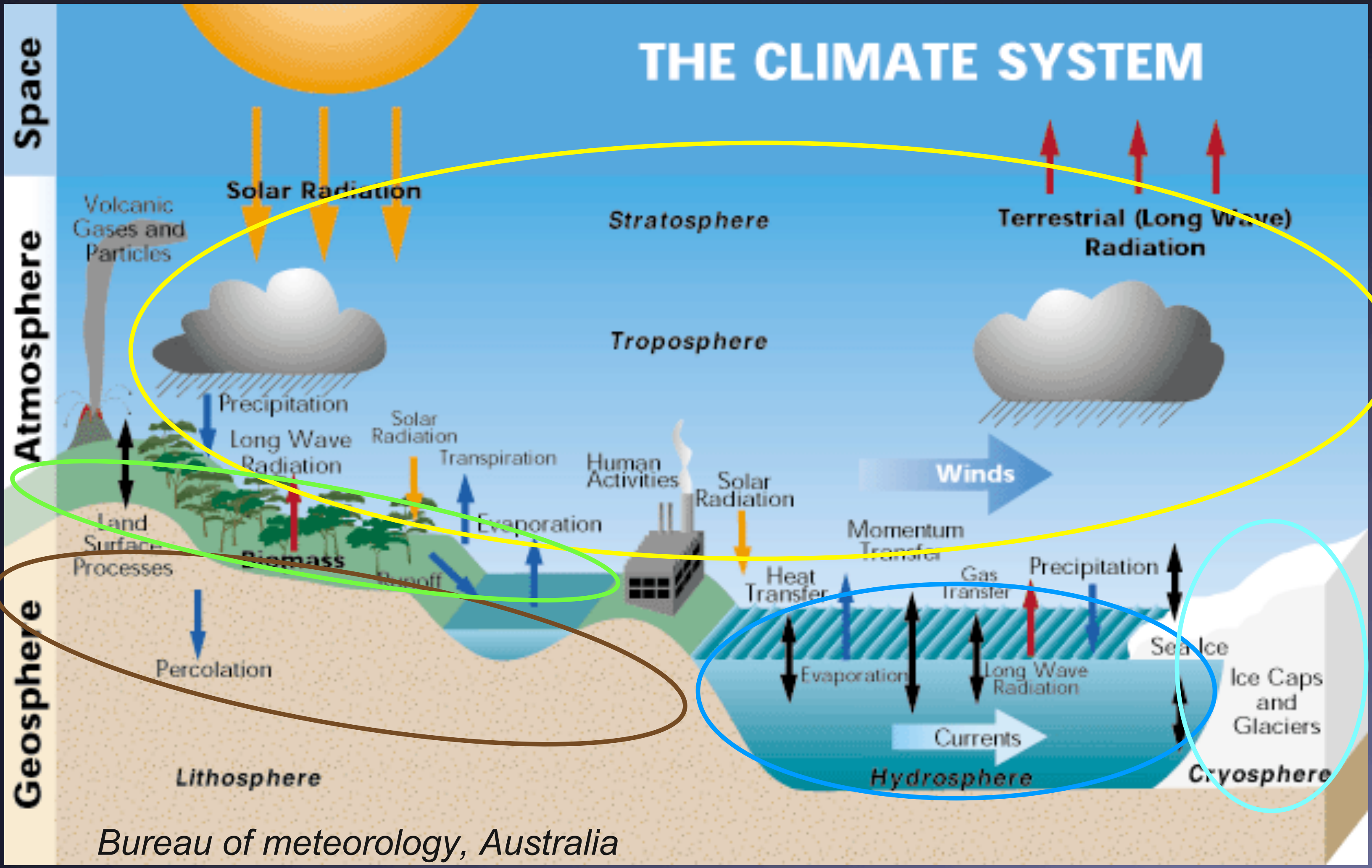




More Consequences of Global Climate Change

Climate system and causes of climate change

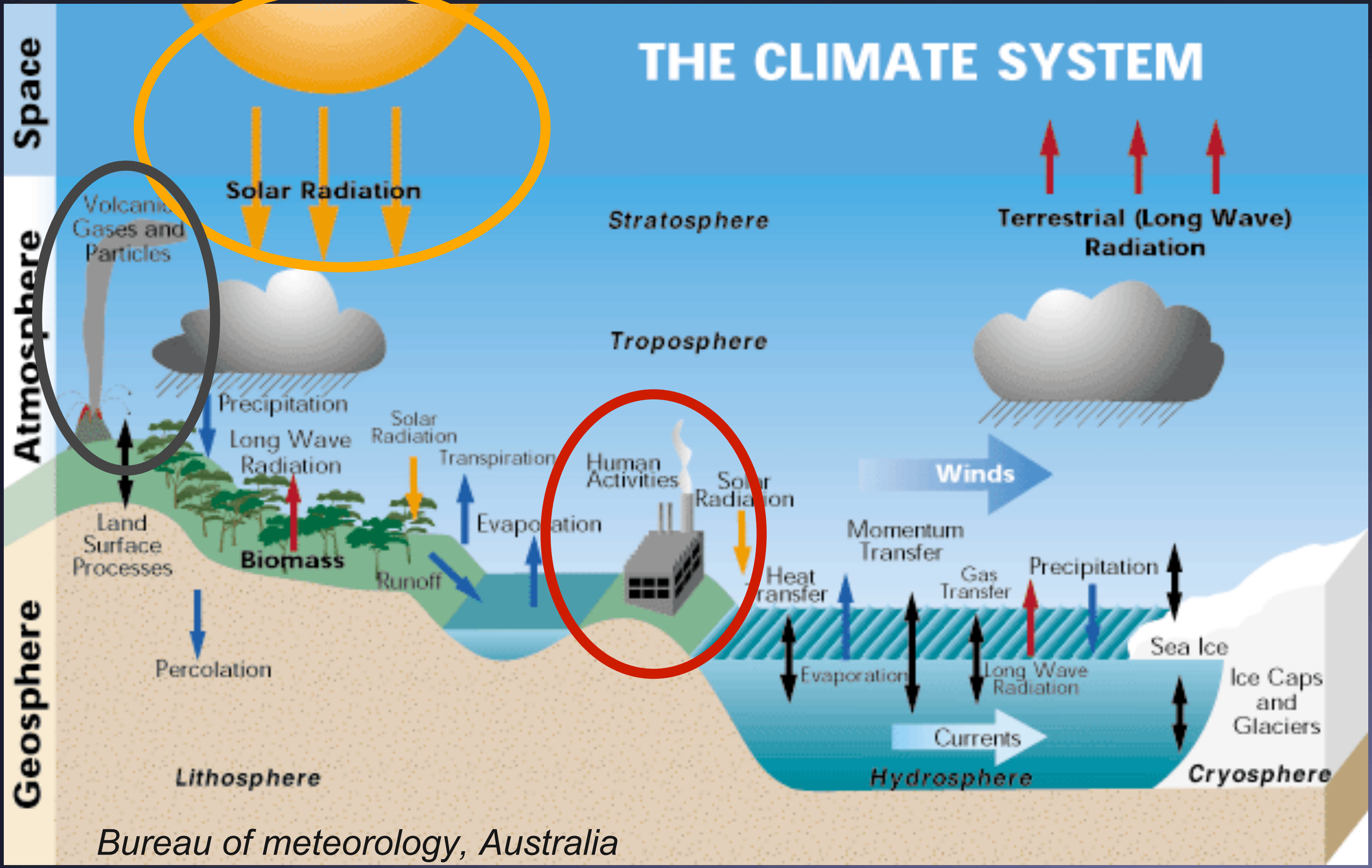
Earth's climate system



Components:

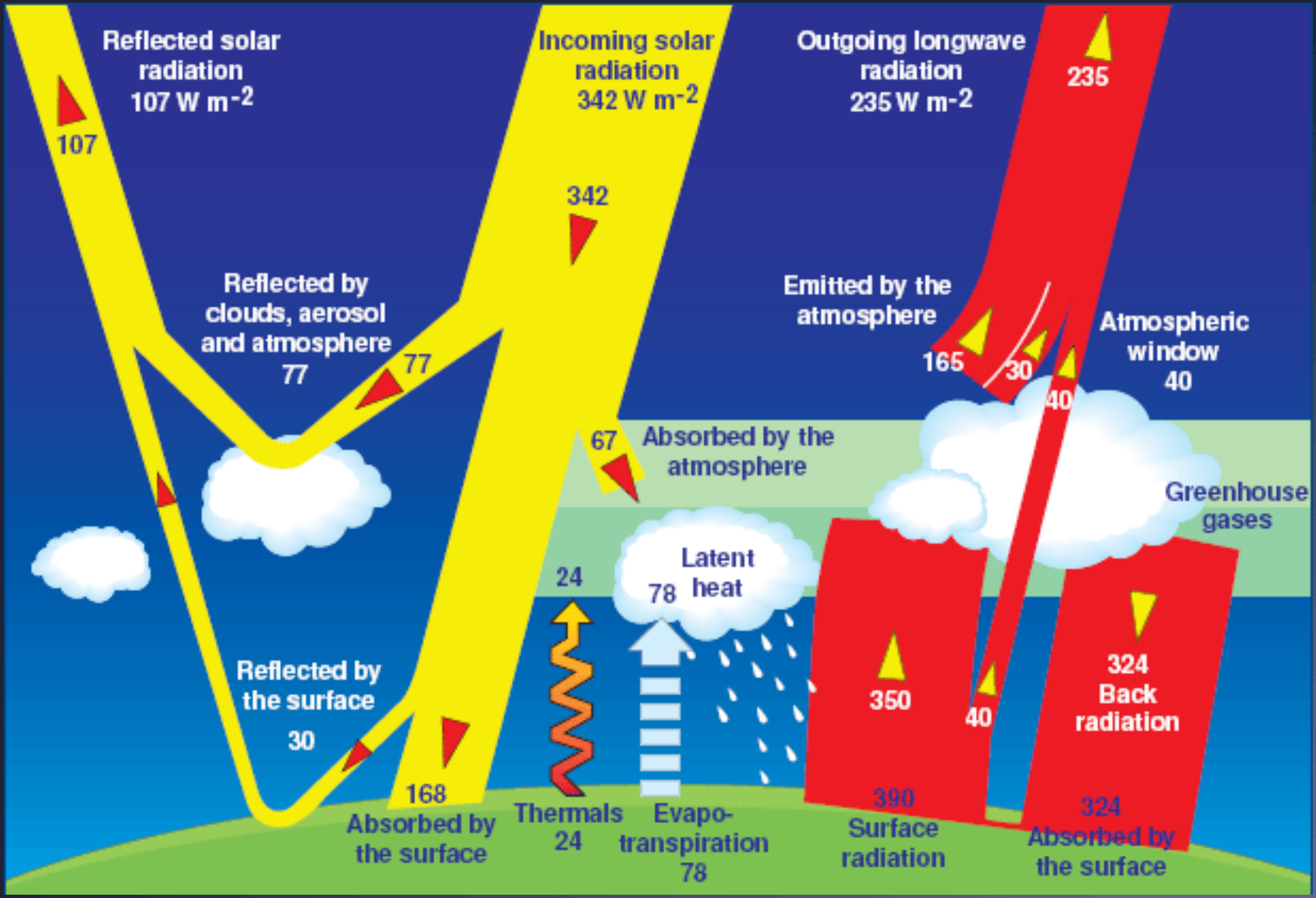
atmosphere, oceans, land, ice, biosphere

Inputs to Earth's climate system



Main external forcing agents: The Sun, volcanos and Humans
Sun provides basically all the energy reaching Earth from outside
Humans change albedo (e.g. agriculture) & atmospheric chemistry

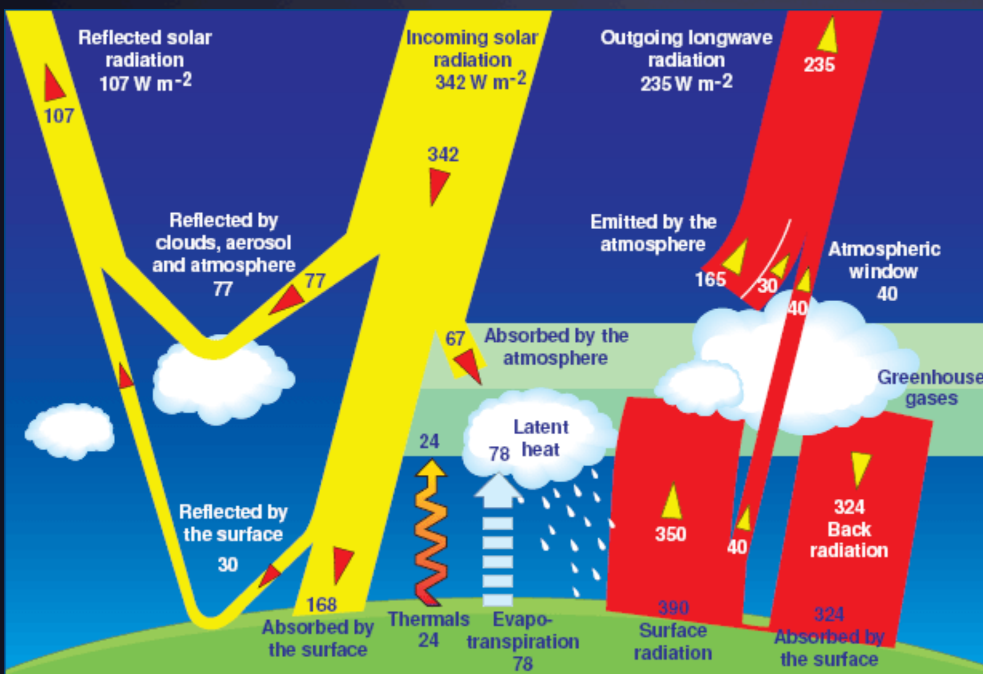
Earth's radiation budget



NASA

Global average equilibrium T from balance between absorbed solar radiation and emission of IR radiation. Absorbed solar energy depends on incoming irradiance & on Earth's reflective properties. If either changes then T structure of atmosphere-surface system adjusts to restore equilibrium

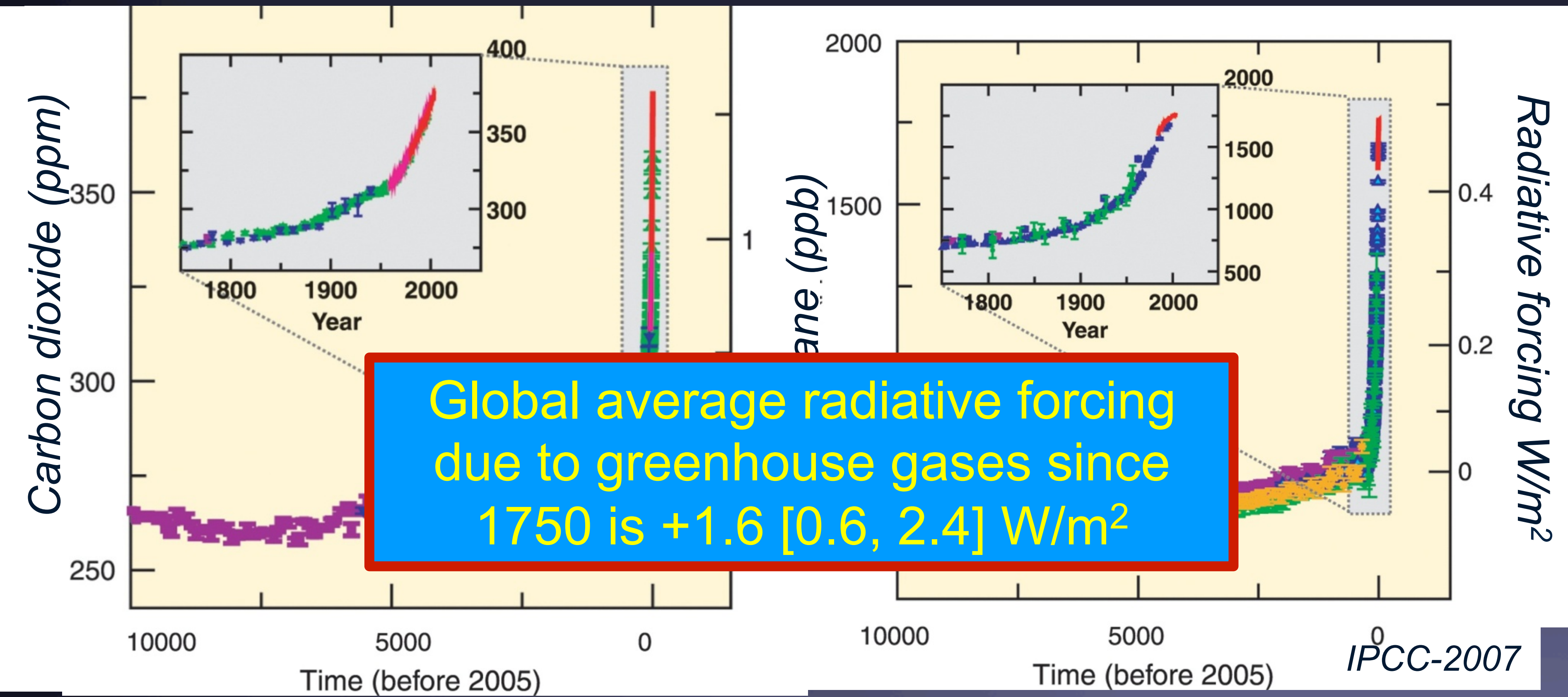
Radiative forcing of climate change



NASA

- In equilibrium, net global & annual mean flux at top of the atmosphere is 0
- Perturbation of absorbed solar or emitted IR radiation, changes in albedo or atmosph chemistry alter the balance
- Any such alteration is called Radiative Forcing (RF). RF is change in net radiative flux at the tropopause;
  RF>0: system warms, until new equilibrium is reached
- RF causes $\Delta T_g = \lambda \cdot RF$
- λ = sensitivity parameter.
  Range: $0.3 < \lambda < 1$ K(Wm^{-2})$^{-1}$
  Exact value depends on global circulation models

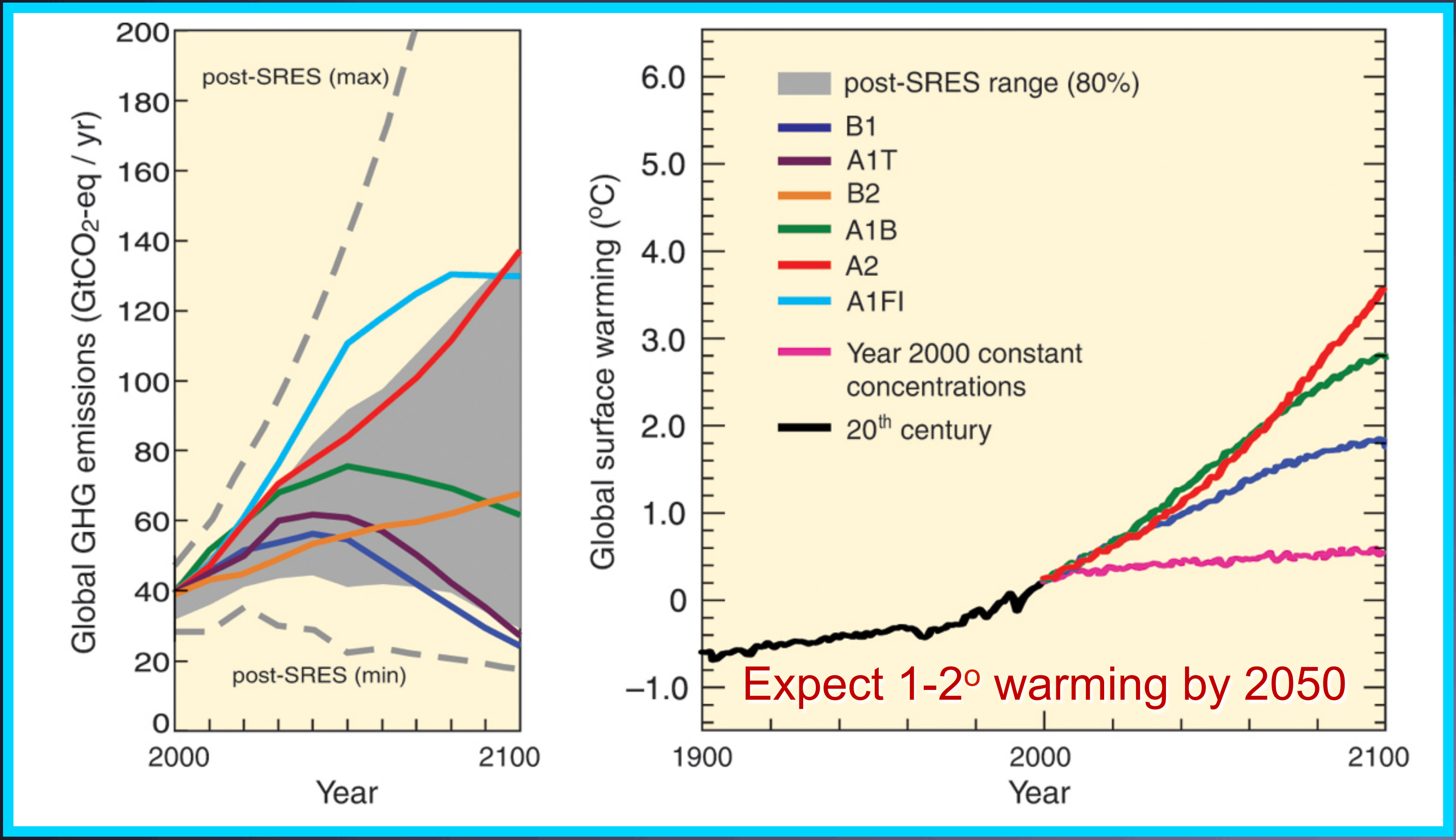
Concentrations of greenhouse gases



- 4 long-lived GHGs emitted into atmosphere: CO_2, CH_4, N_2O and halocarbons
- Global atmos concentrations of CO_2, CH_4 and N_2O far exceed pre-industrial values over 10000 yrs; in case of CO_2 and CH_4 over 650 000 yrs
- CO_2 mainly from fossil fuel burning and partly land-use change; CH_4 due to agriculture and fossil fuel; N_2O just agriculture

IPCC Predictions until 2100

Scenarios for emission of Greenhouse Gases → Predicted temperature over next 90 years



How does the current climate compare with past climate?

No dinos in ice age

Ice age was rather dry (sea level lower, since much of the water bound in ice)

Dinos didn’t wear clothes, nor did they sell ice cream ☺

There are various errors in this cartoon: can you spot them?

years

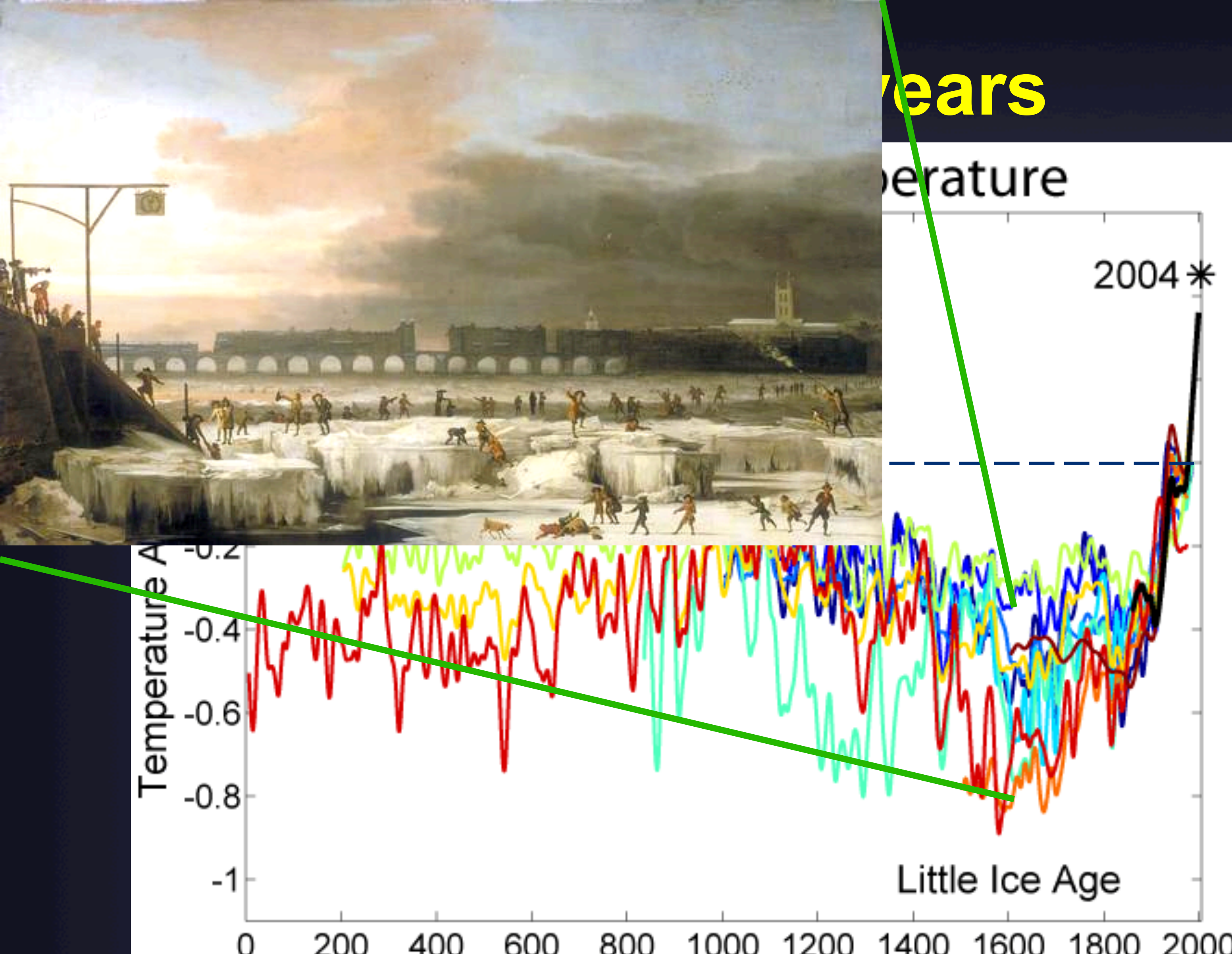
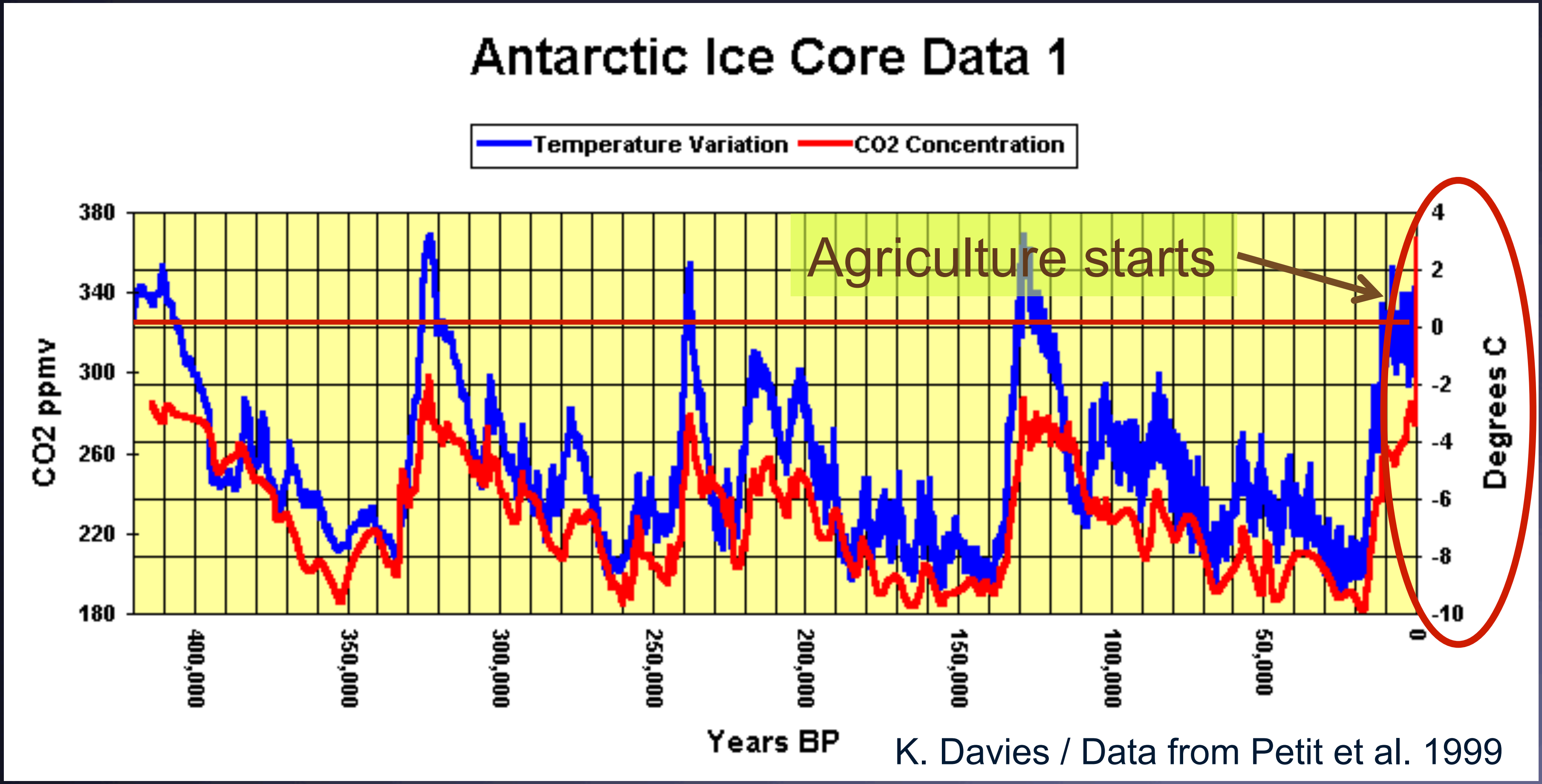


Image created by R. A. Rohde/ Global Warming Art

Before the onset of the industrial revolution global T changes are thought to be due to changes in solar and volcanic activity, and deforestation (especially in the last few hundred years), overlaid onto internal climate 'noise'.

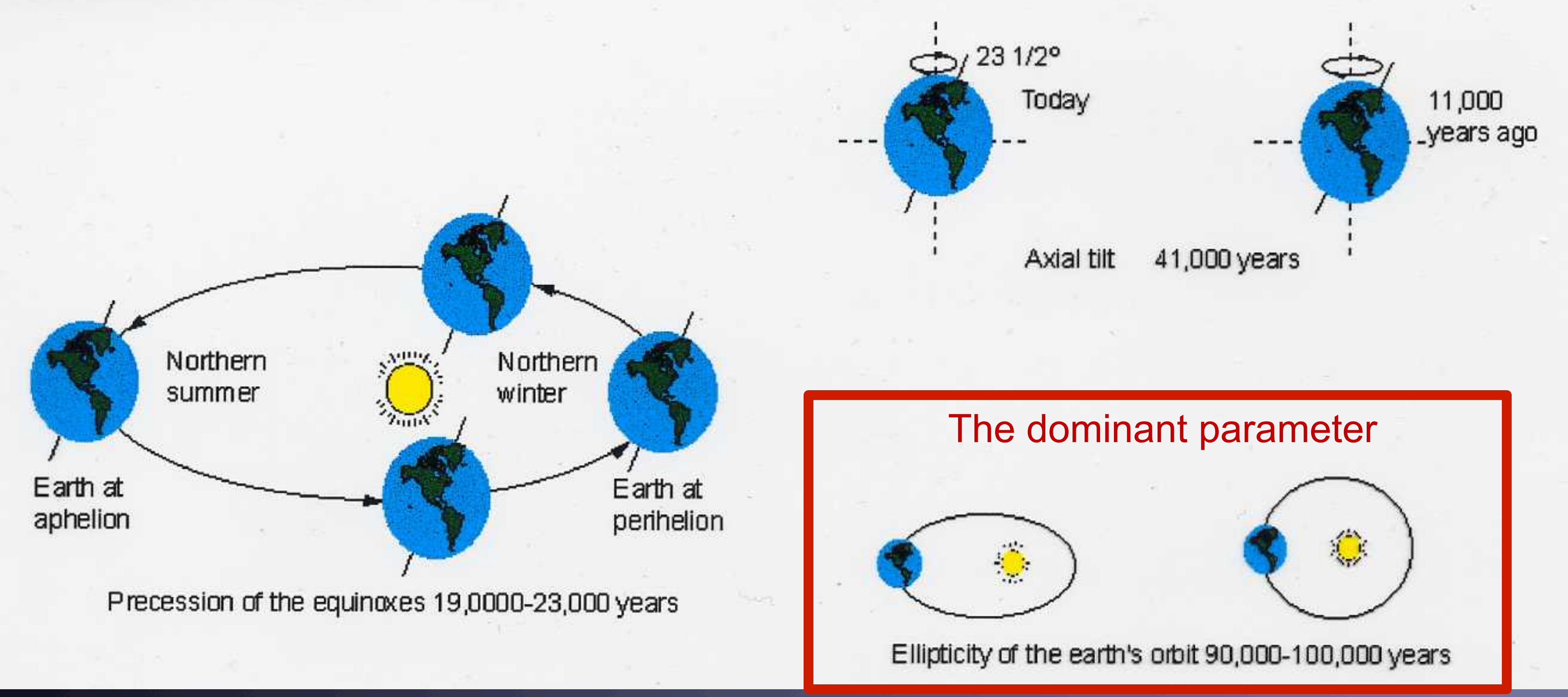
Ice age temperature changes



- Ice Ages & interglacials triggered by Milankovitch cycles
- Milkanovic heating triggers natural CO_2 release by ocean and biosphere → feedback greenhouse effect → sudden warming

Milankovitch theory

Ice ages are due to variations of Earth's orbit

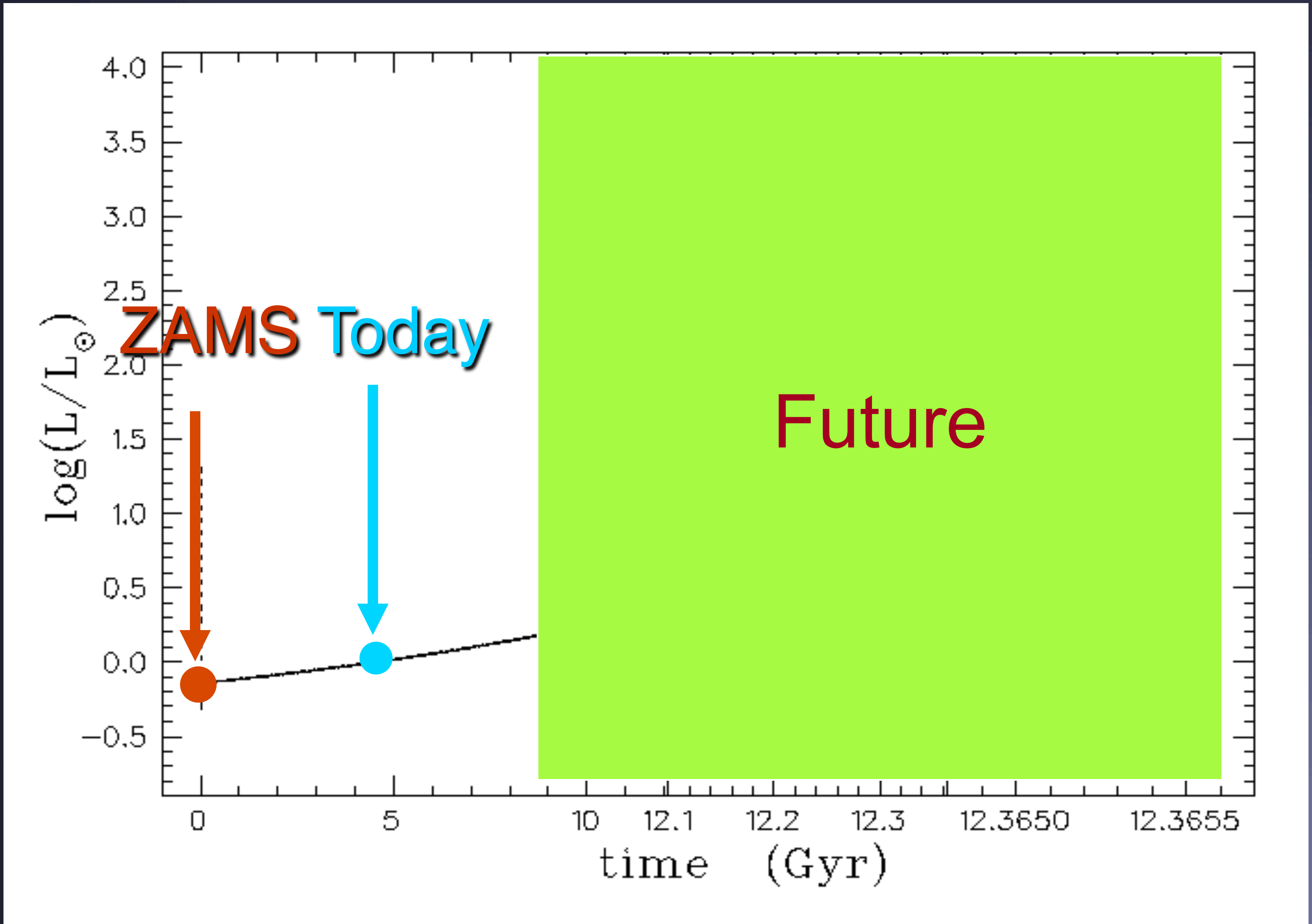


Does the Sun influence climate?

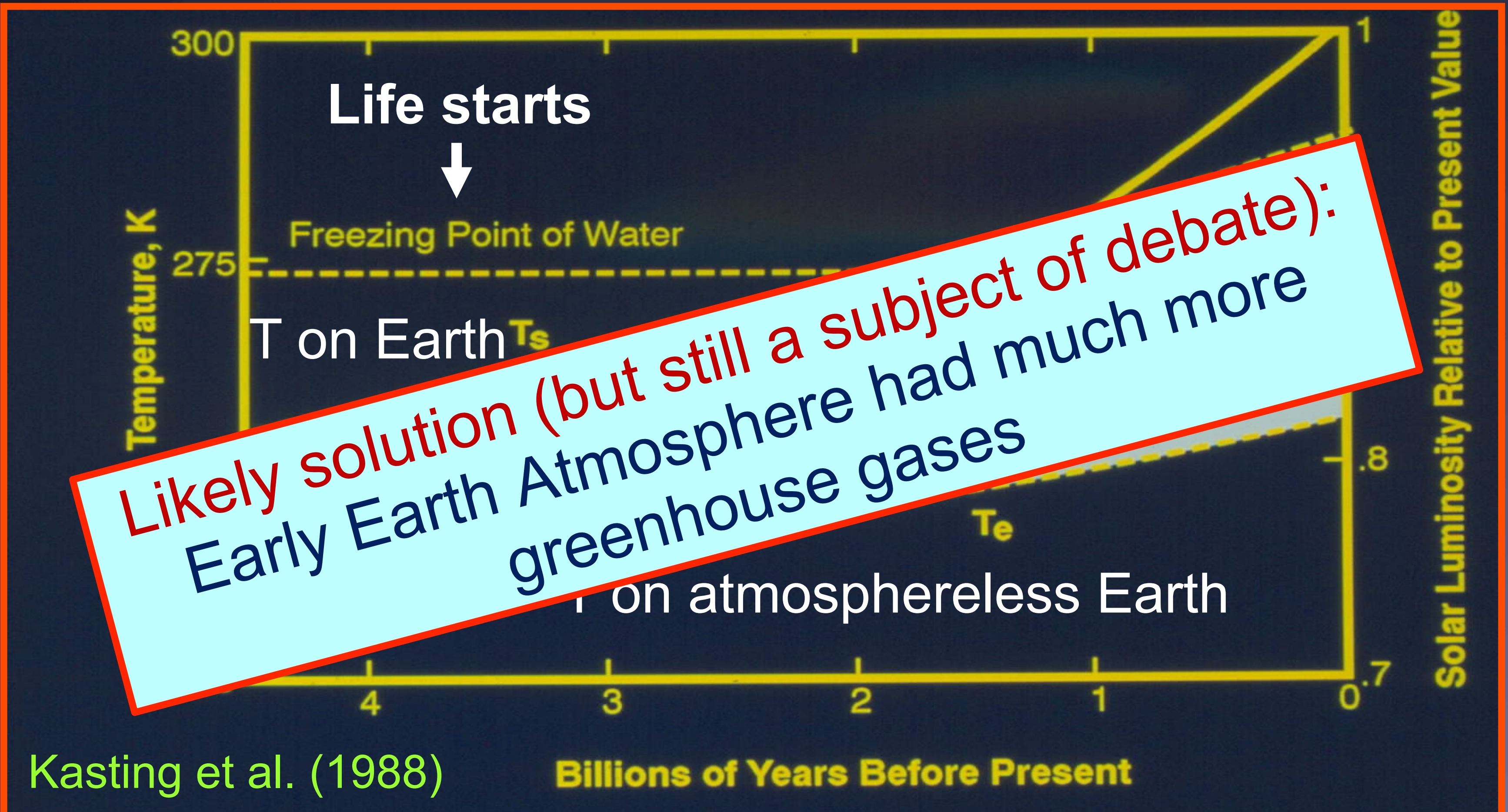
Answer depends on the considered time scale

- Time scales of billions of years: yes! The Sun’s evolution makes it increasingly brighter
- Time scales of 10^5-10^6 years: Indirectly. Ice ages are probably caused by changes in the Earth’s orbital parameters
- Time scales of decades to millenia: Probably. There are increasing indications of a solar contribution to global climate change
- days to a year: this is not climate, but rather weather. Possibly. There is some evidence for such effects

Evolution of Sun's past luminosity



Faint Young Sun leaves Earth frozen

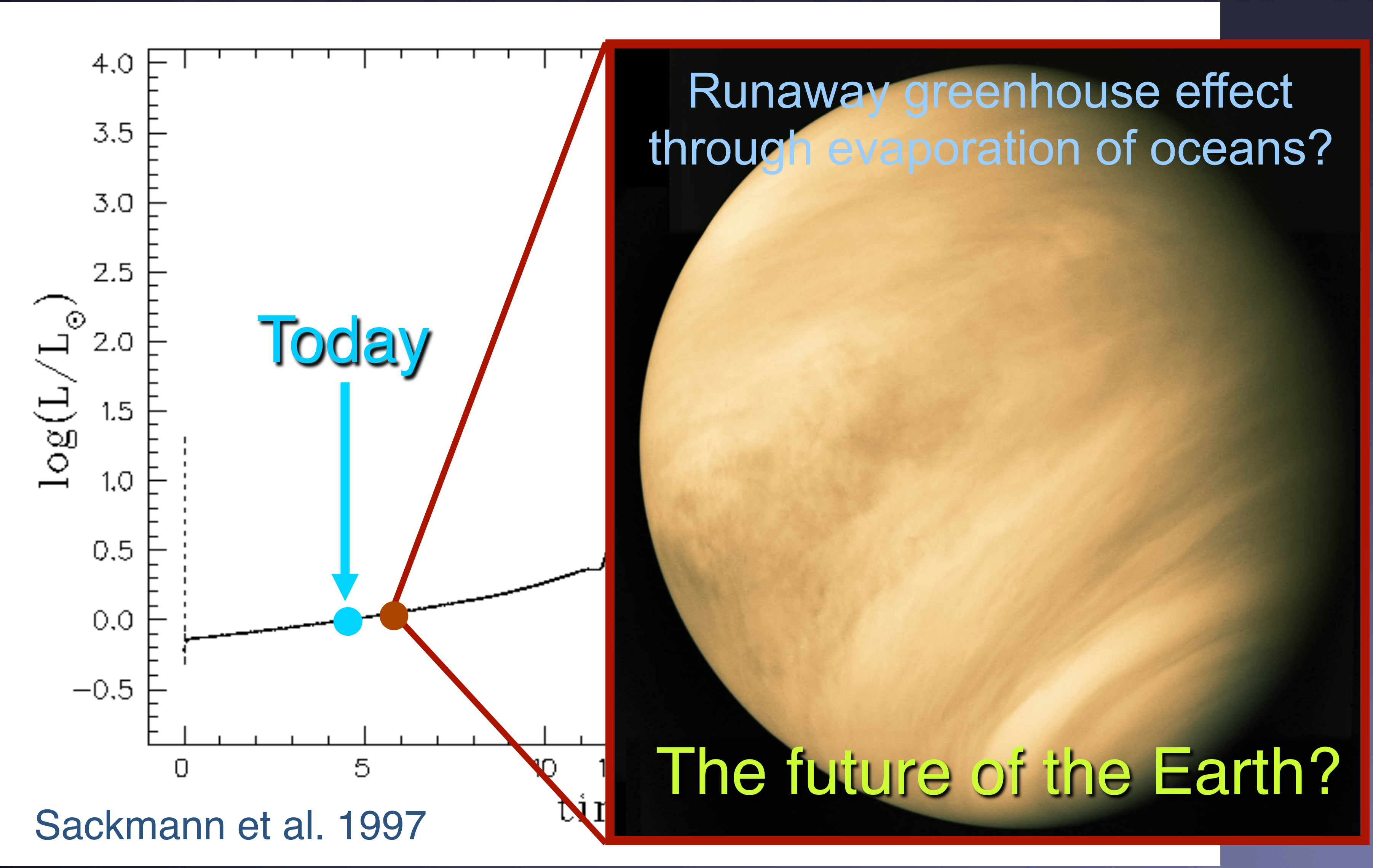


Kasting et al. (1988)

... and the future?

- Sun will continue to grow **brighter**... and **bigger**, first gradually, then rapidly.
- It will get 4000 times brighter than today!
- Will the Sun eventually cook the Earth, even evaporate it? When will it become too hot for life?

Evolution of solar luminosity

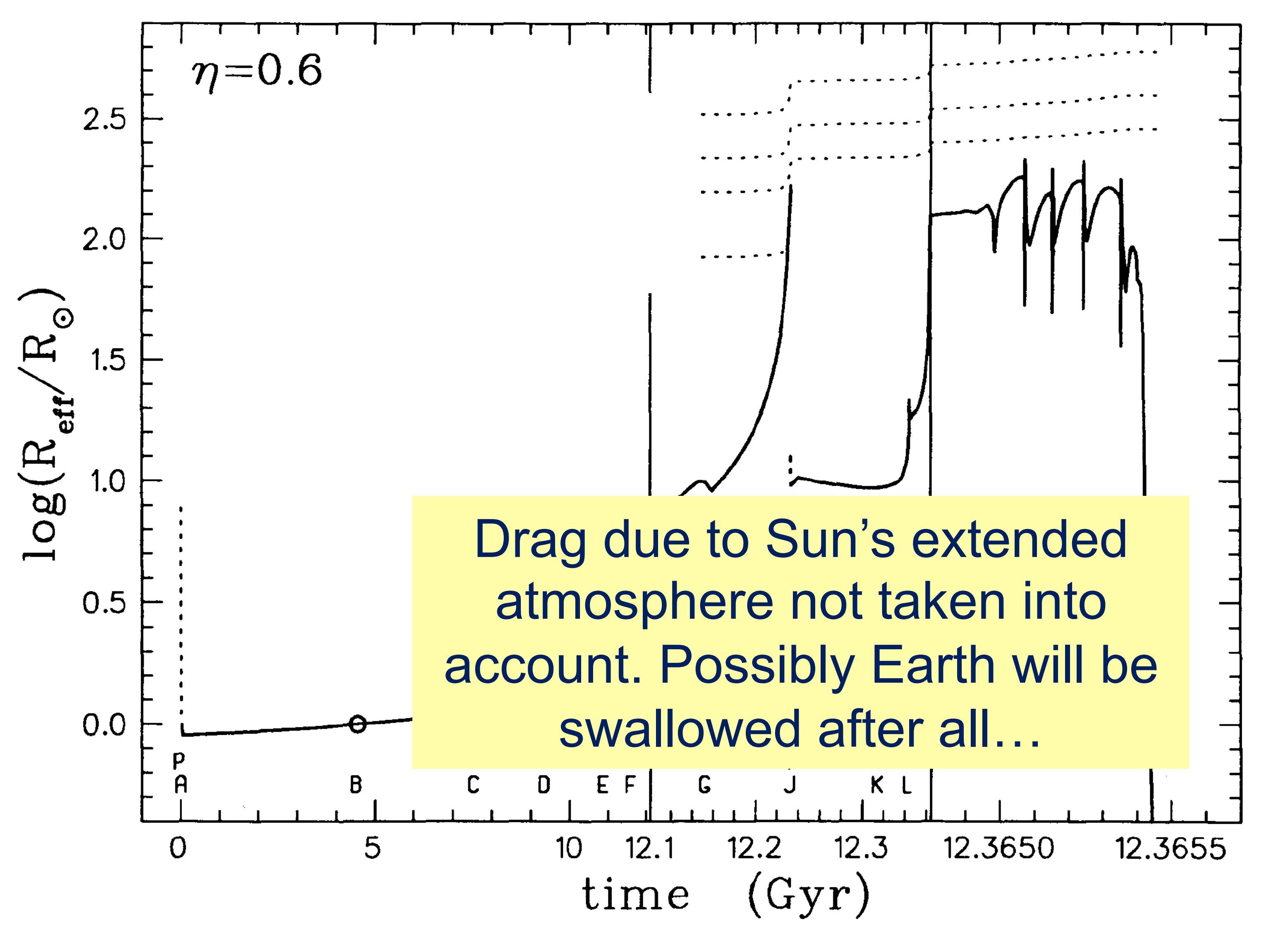


Sackmann et al. 1997

... and the future?

- Sun will continue to grow **brighter**... and **bigger**, first gradually, then rapidly.
- It will get 4000 times brighter than today!
- Will the Sun eventually cook the Earth, even evaporate it? When will it become too hot for life?
- It will eventually be so bloated that it will extend up to today's orbit of Earth!
- Will the Sun eventually swallow the Earth?

Will the Sun swallow the Earth?

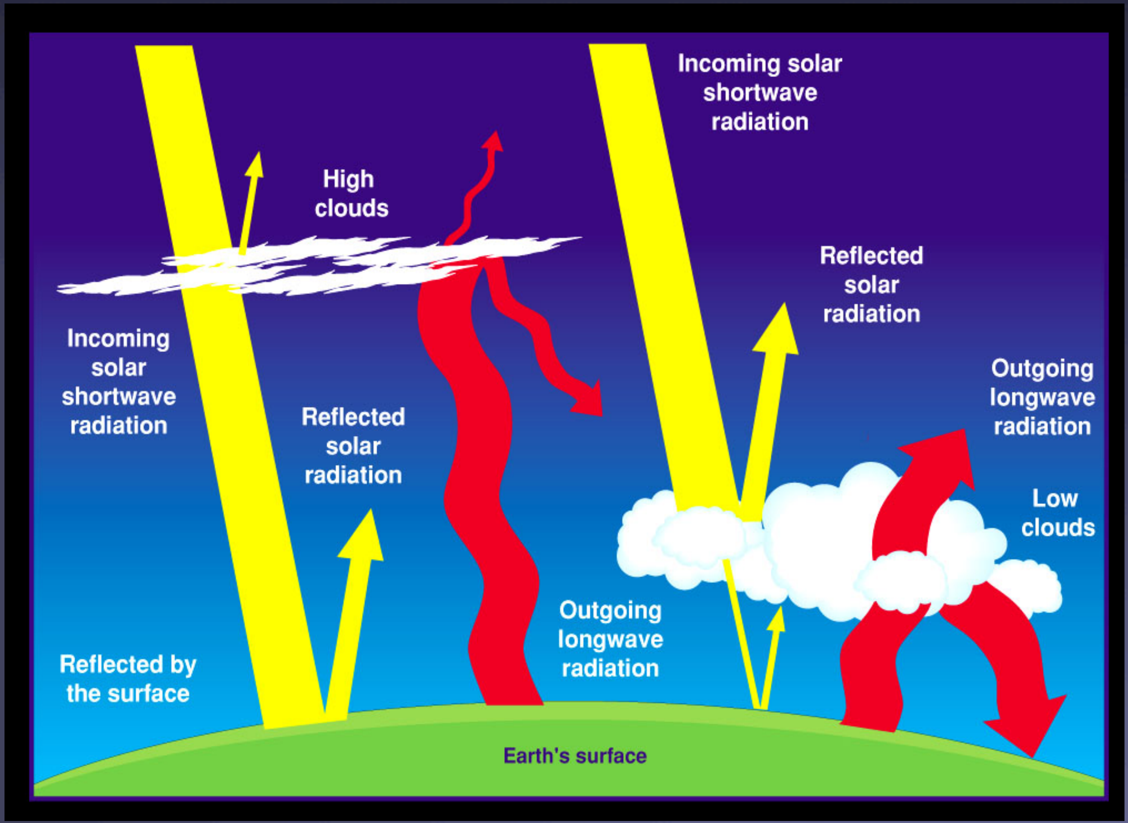


Drag due to Sun's extended atmosphere not taken into account. Possibly Earth will be swallowed after all…


Will the Earth really get away?

Could the Sun be to blame for global warming?

- The Sun delivers 1.36 kW / m^2. We get ≈ 1 kW / m^2 (at equator, at noon, if no clouds)
- In 20-30 min the Sun provides to Earth the yearly energy needs of Humanity



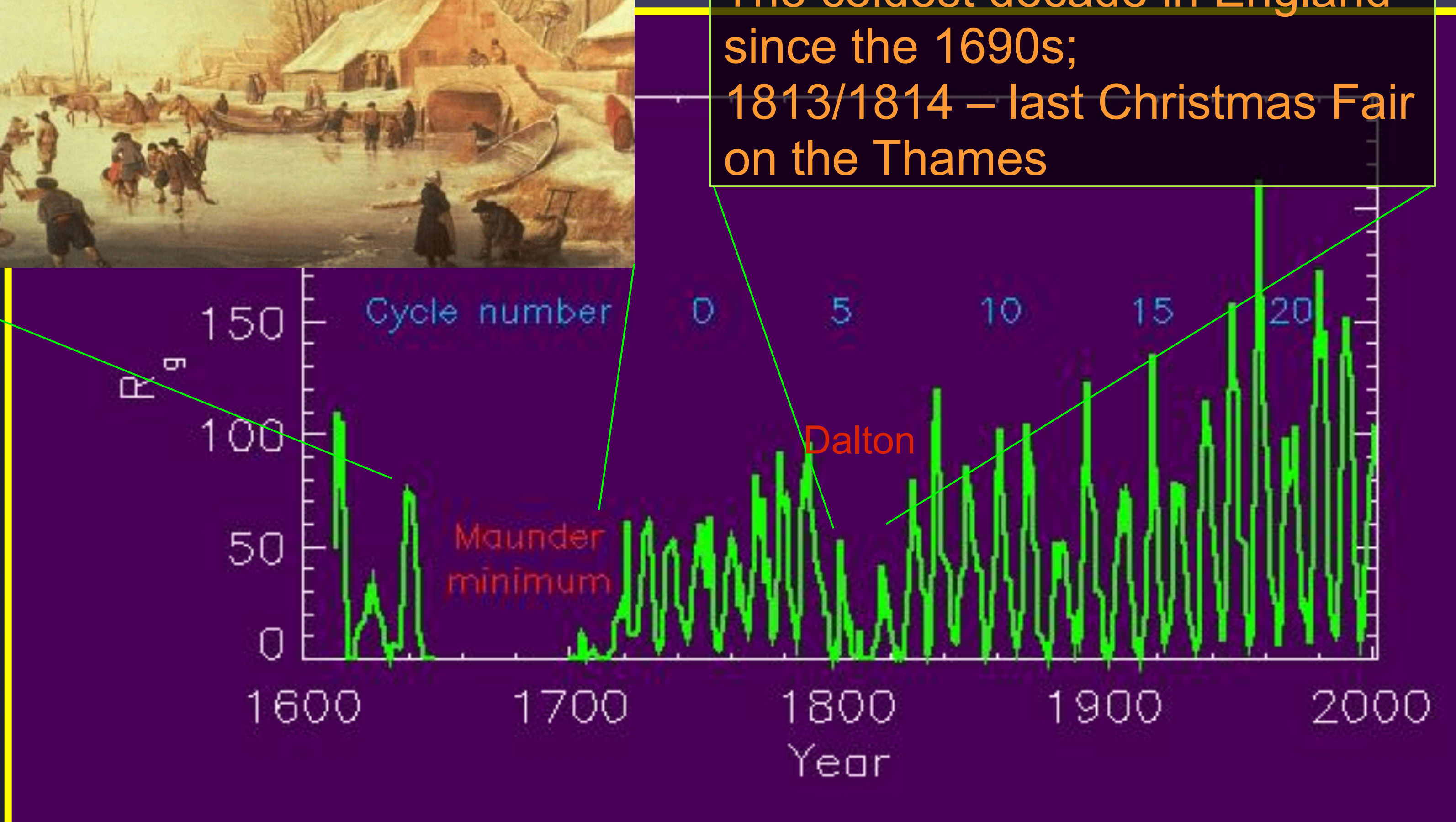
Without sunlight, no life

(Our atmosphere would cool to below -200º C within weeks)

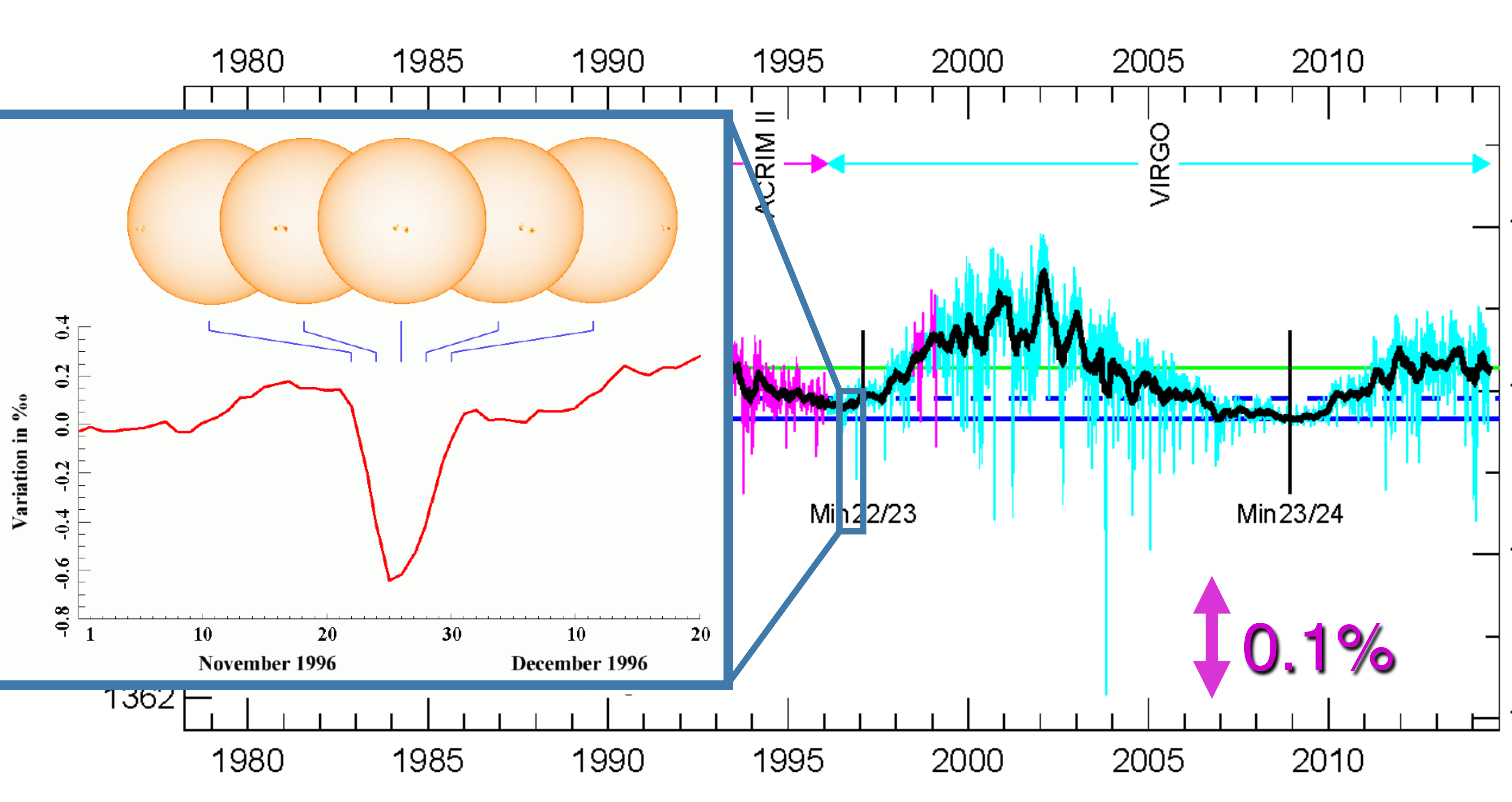
Maunder Minimum & Little Ice Age

The Maunder Minimum corresponded to the Little Ice Age: Is there a connection?

The coldest decade in England since the 1690s;
1813/1814 – last Christmas Fair on the Thames



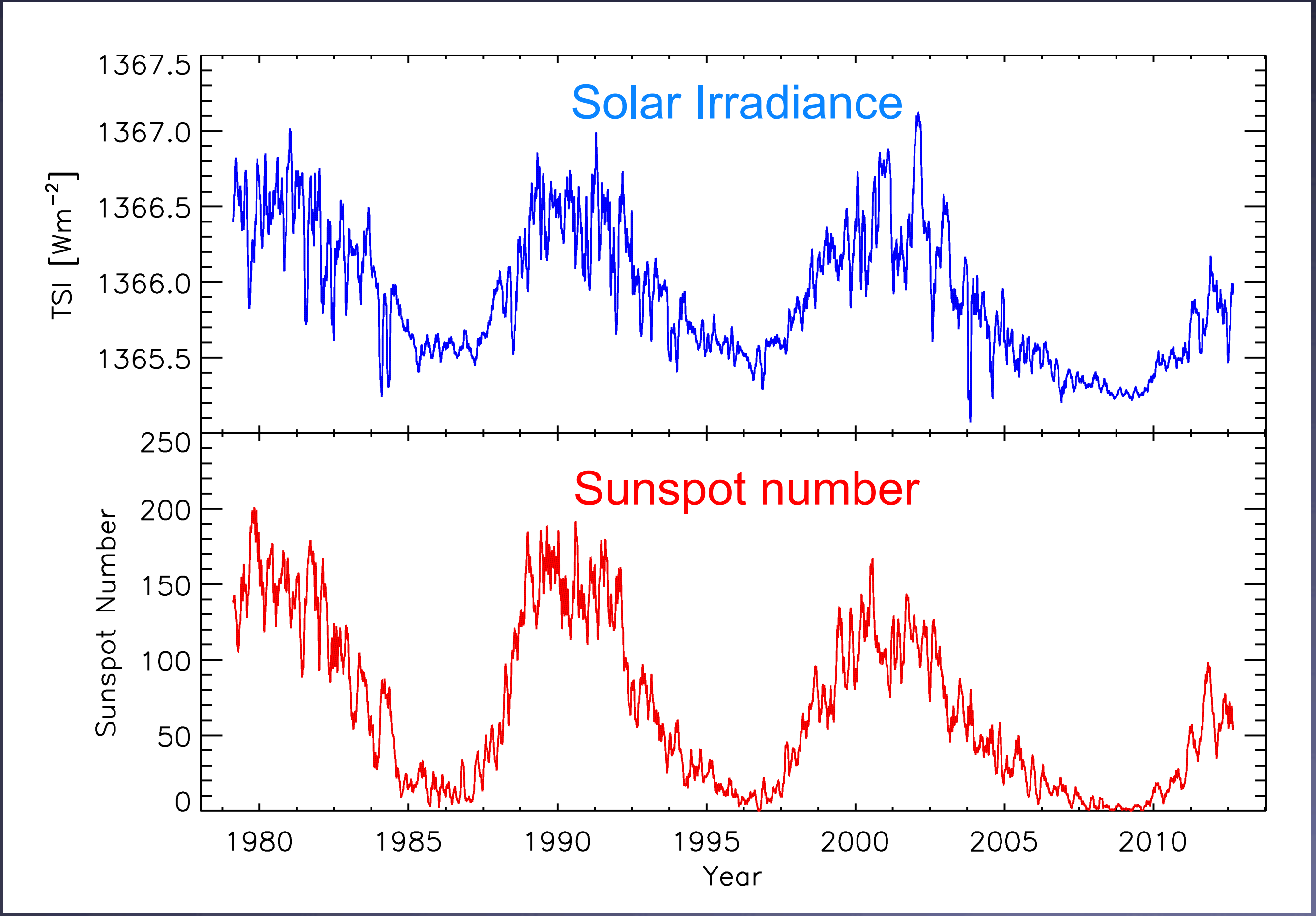
Measured total irradiance



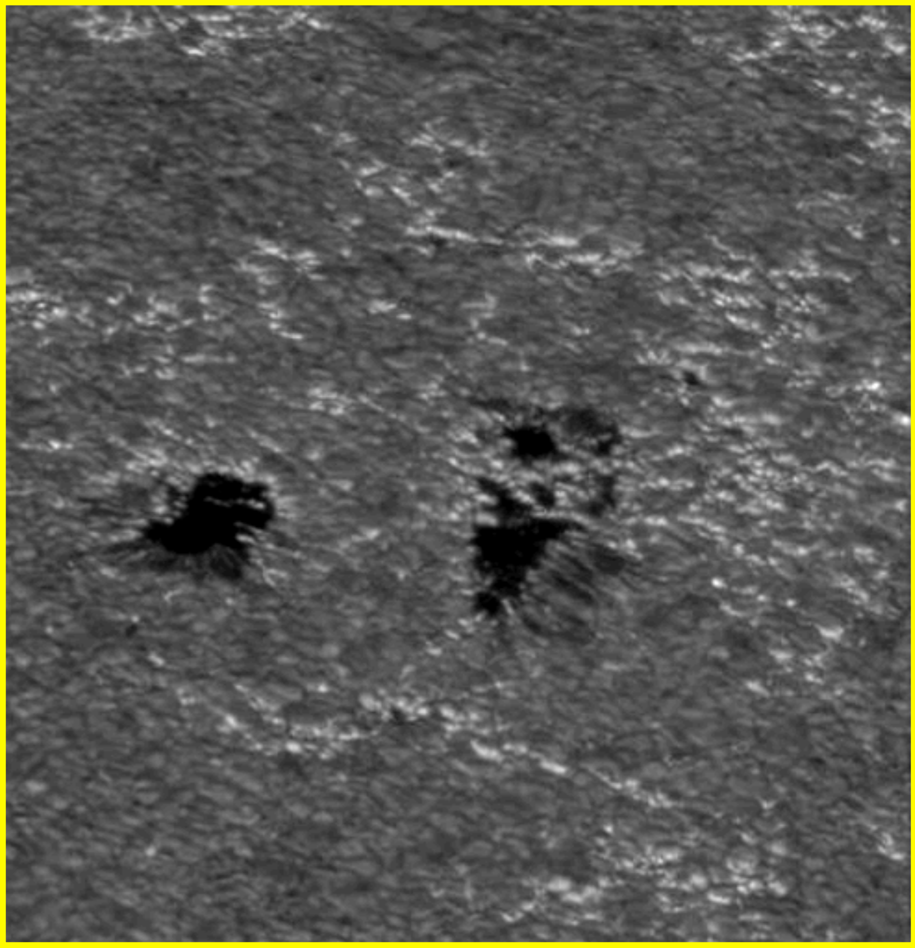
C. Fröhlich, PMOD

Sunspots and solar irradiance

During activity maximum, when the number of sunspots is largest, the Sun is also brightest. How can this be consistent with what we have seen on the last slide?



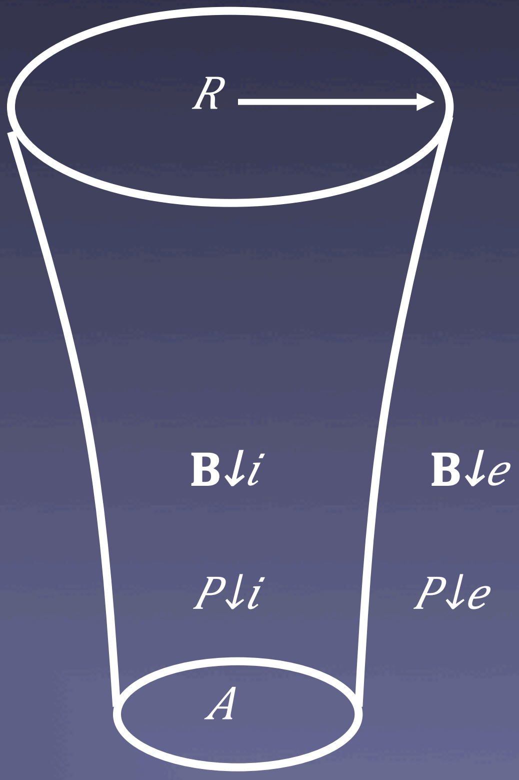
Faculae and Plage



Area increase of faculae from activity min to max is factor of 10-20 greater than of sunspots

Magnetic flux tubes

- In convection zone and in photosphere most of magnetic energy is in concentrated magnetic flux tubes: bundles of magnetic field (bounded by topologically simple surface)
- The flux tube has a current sheet at its boundary
- Consider a thin flux tube ($R<H_P$) that is homogeneous inside (no variation of $\mathbf{B}$ and P across cross-section)



Rump of a flux tube

Simplified force balance: pressure balance

- MHS force balance: $\nabla P = 1/c\, \mathbf{j} \times \mathbf{B} - \rho g$ { Lorentz force / Gravity
- Consider a static, vertical, thin magnetic flux tube, FT (typical in lower solar atmosphere):
  - Interior of FT: field $\mathbf{B}_i$, pressure p_i, density ρ_i
  - Exterior of FT: field $\mathbf{B}_e$, pressure p_e, density ρ_e

➔ Vertical force balance is independent in the individual components

  - For a vertical field (for each comp): $\nabla p - \rho g = 0$

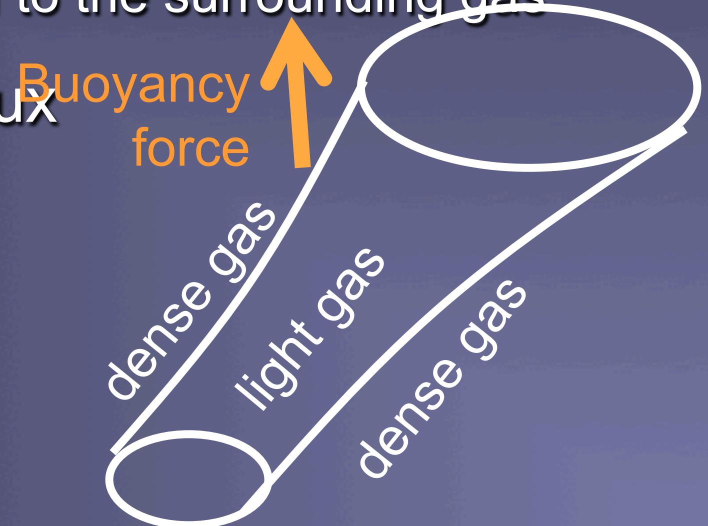
- Horizontal force balance between the components is then reduced to pressure balance

Pressure balance

- Pressure balance betw. thin flux tube interior i and exterior e

$$B_i^2/8\pi + P_i = P_e + B_e^2/8\pi \quad \Rightarrow$$
$$B_i^2/8\pi + P_i = P_e \quad \text{for } B_e = 0$$

- If $B_e = 0$, then $P_i < P_e$. If also $T_i = T_e$, then also $\rho_i < \rho_e$
  - ➔Magnetic features are evacuated compared to surroundings
  - ➔ Magnetic features are buoyant compared to the surrounding gas



➔ in convection zone: rising magnetic flux tubes keep rising (unless stopped by, e.g. magnetic curvature force) ➔ field cannot be stably stored in convection zone

➔ In atmosphere: strong fields are

Pressure balance

- Pressure balance betw. thin flux tube interior i and exterior e

$$B_i^2/8\pi + P_i = P_e + B_e^2/8\pi \quad \Rightarrow$$
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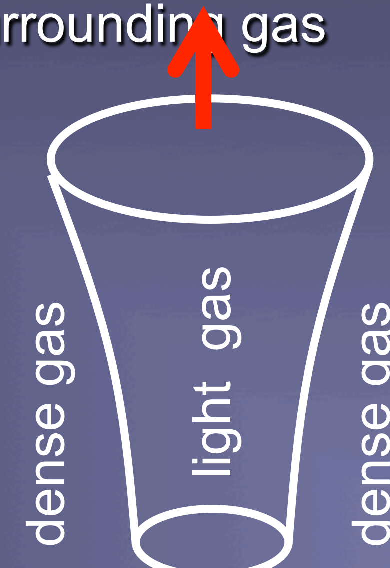
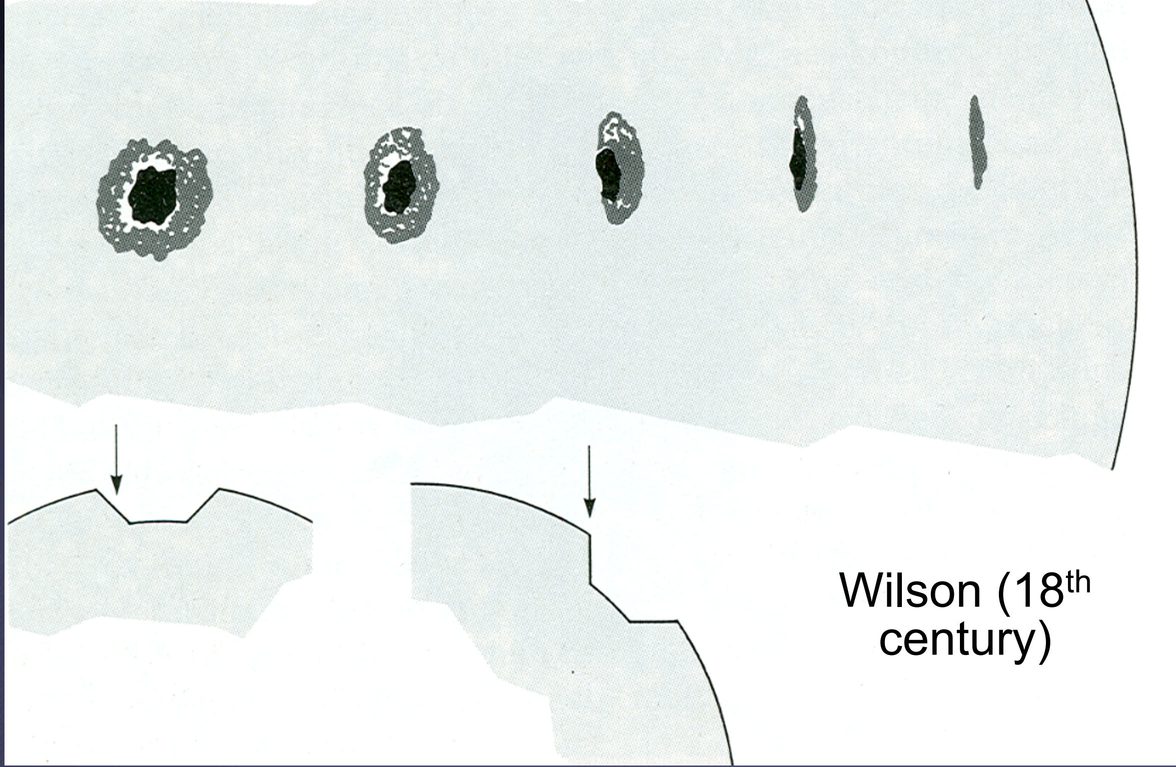
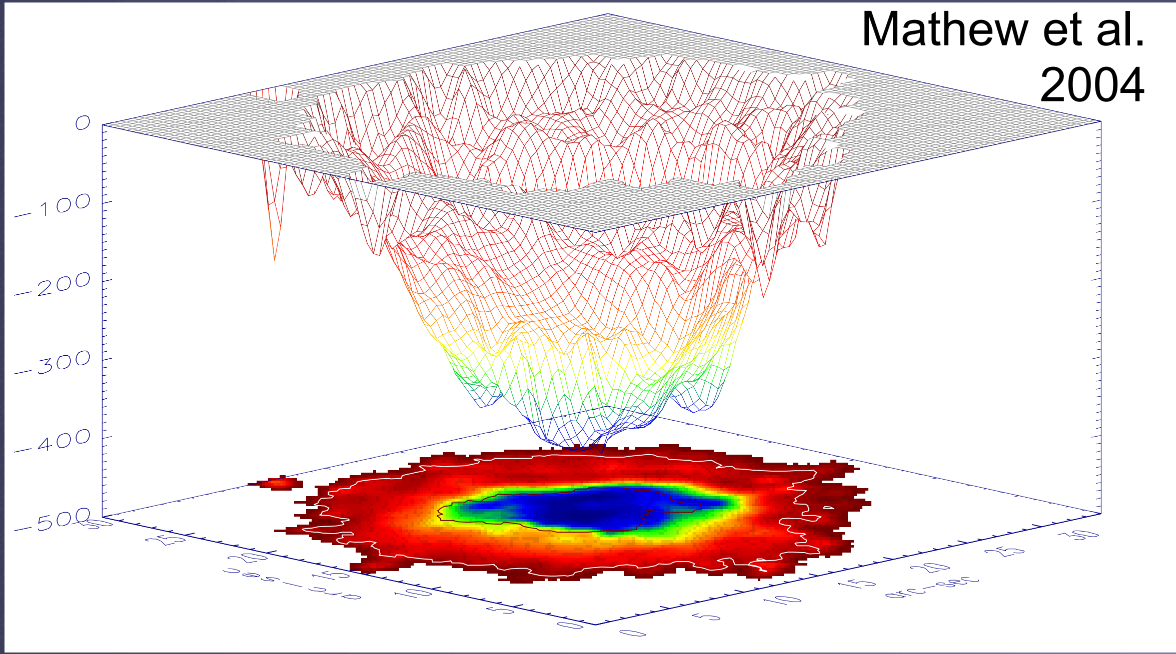


➔ In atmosphere: strong fields are

Sunspots: the Wilson effect

- Near solar limb, the umbra and centre-side penumbra disappear
- ➔ We see 400-800km deeper into sunspots than in photosphere
- $B^2/8\pi + p = \text{const.}$
- ➔ p lower in spot than outside
- ➔ density lower
- ➔ opacity lower
- ➔ we see deeper into spot

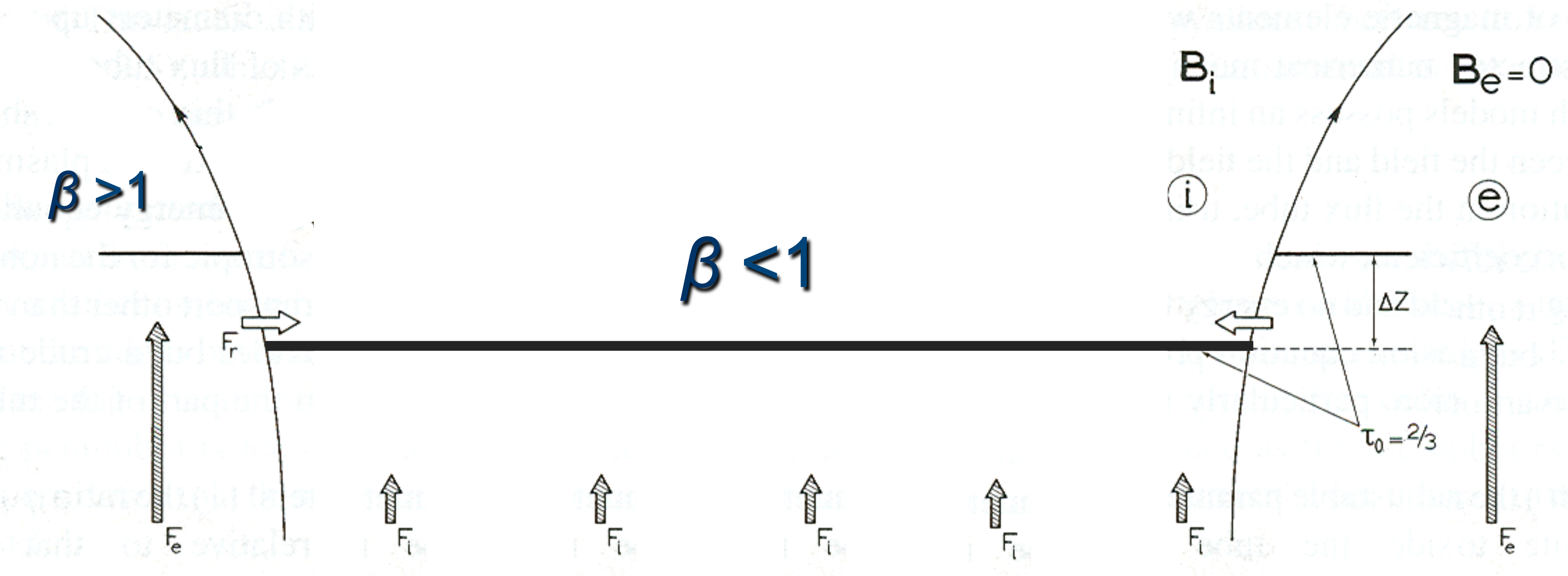

Wilson (18th century)



Mathew et al. 2004

Why are sunspots dark?

- Strong nearly vertical magnetic field in umbra leads to plasma $\beta = 8\pi P / B^2 < 1$ ➔ suppresses motions across field lines ➔ quenches most convection inside the spot's umbra
- Since convection is the main source of energy transport just below solar surface, less energy reaches the surface through

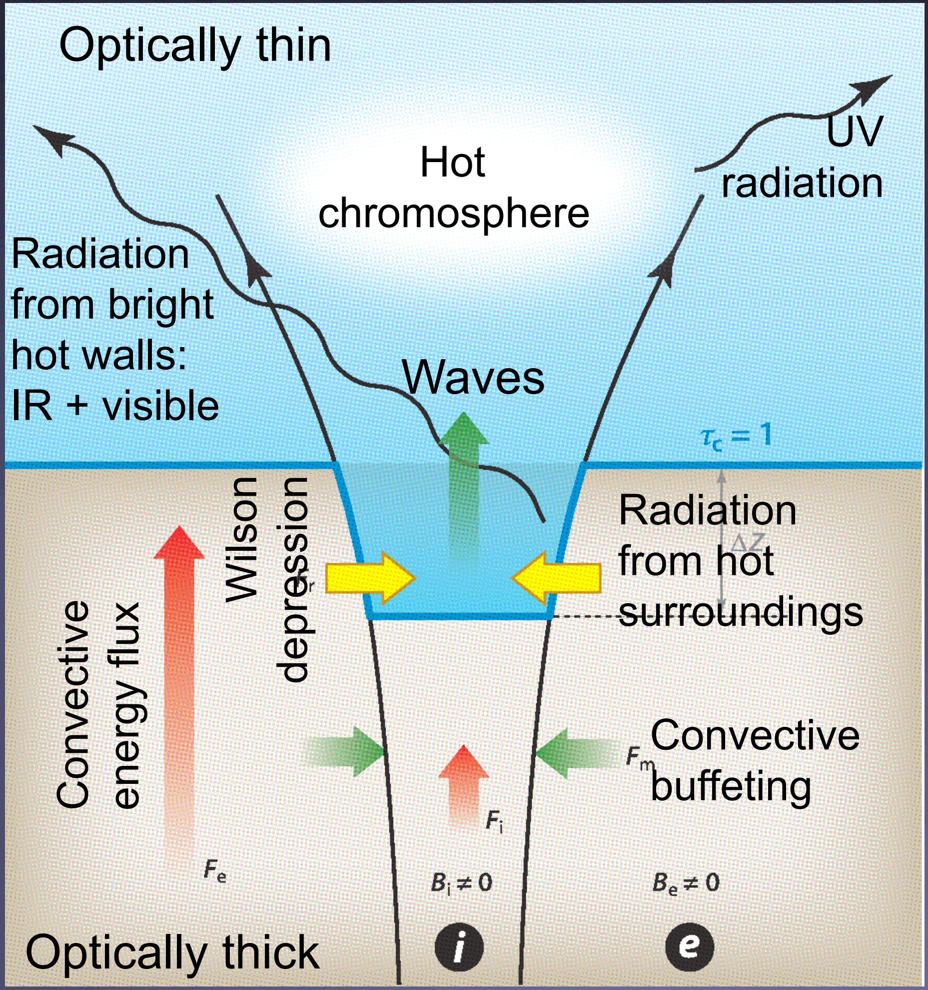


Magnetic elements: brightness

- Convective energy flux (red arrows) quenched by B-field ➔ heat blocked
- Inflow of radiation (heat) into evacuated flux tube through hot walls (yellow arrows).

➔ Enhanced emission. Inflow wins over reduced convection, since FTs are narrow: diameter ≈ Wilson depress

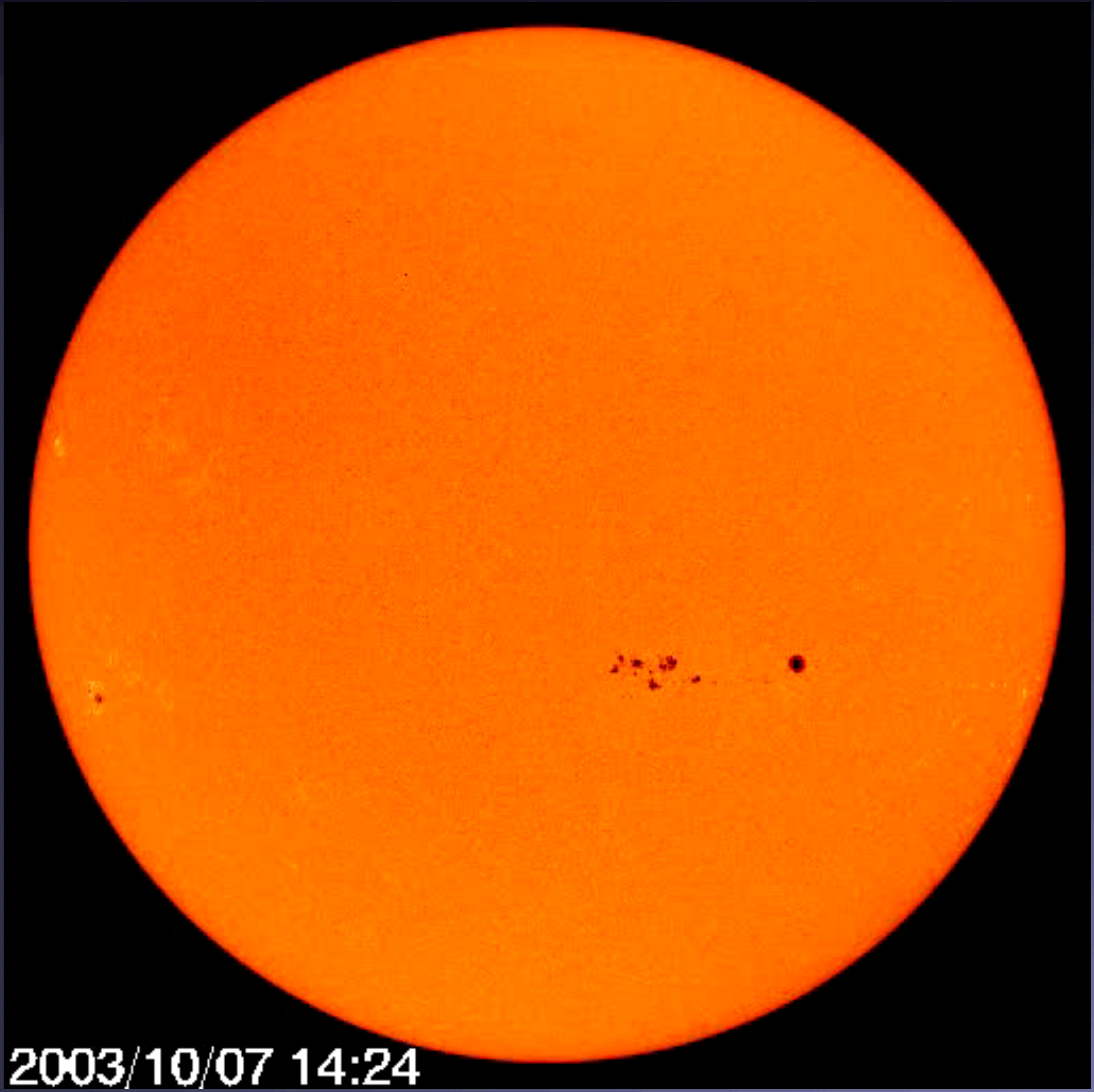
- Excess energy comes partly from deep convection zone, which returns to equilibrium on Kelvin-Helmholtz timescale (~10^5 years)



Field expands with height ➔ upper atmosphere fully magnetic

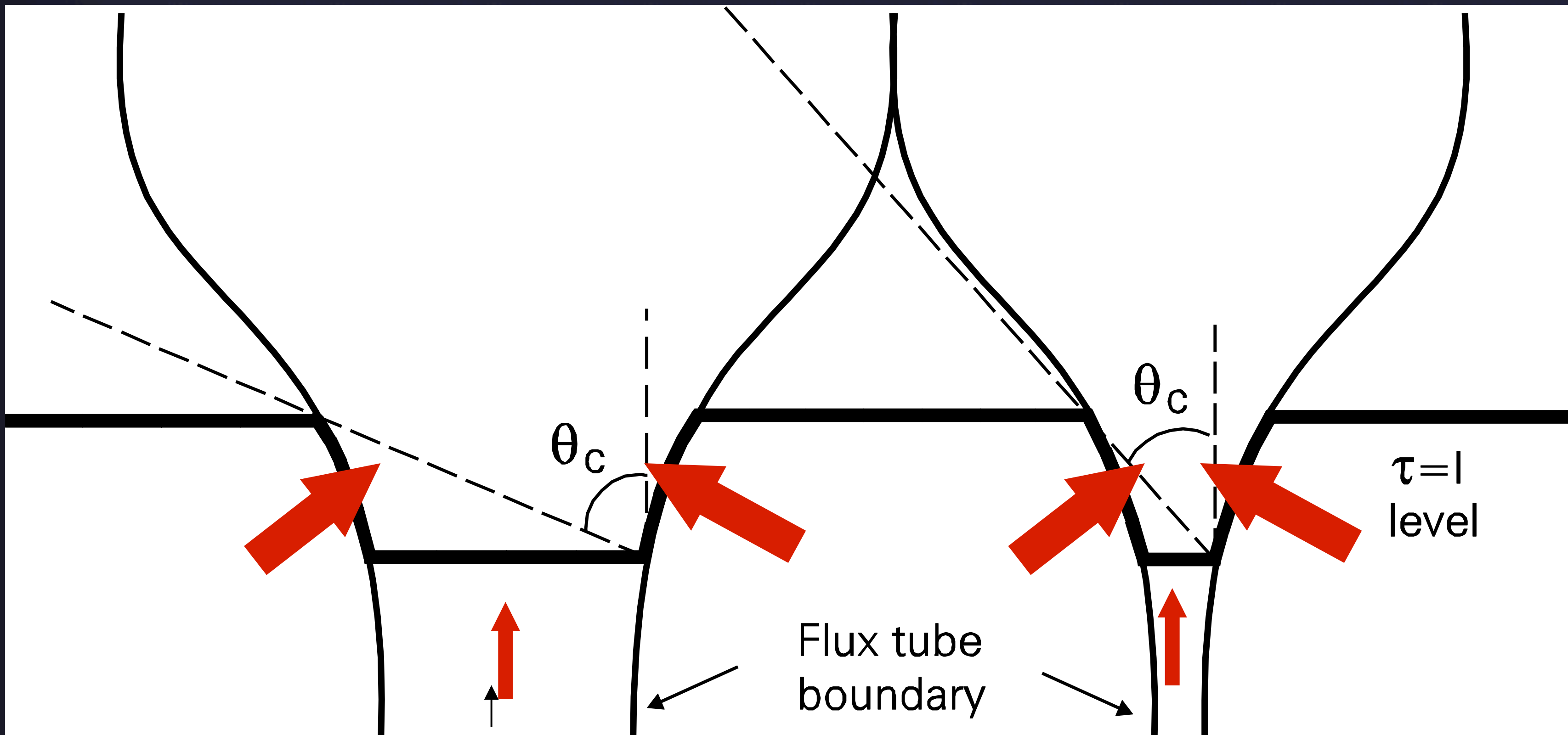
Why are faculae best seen near limb?

The Sun in White Light, with limb darkening removed



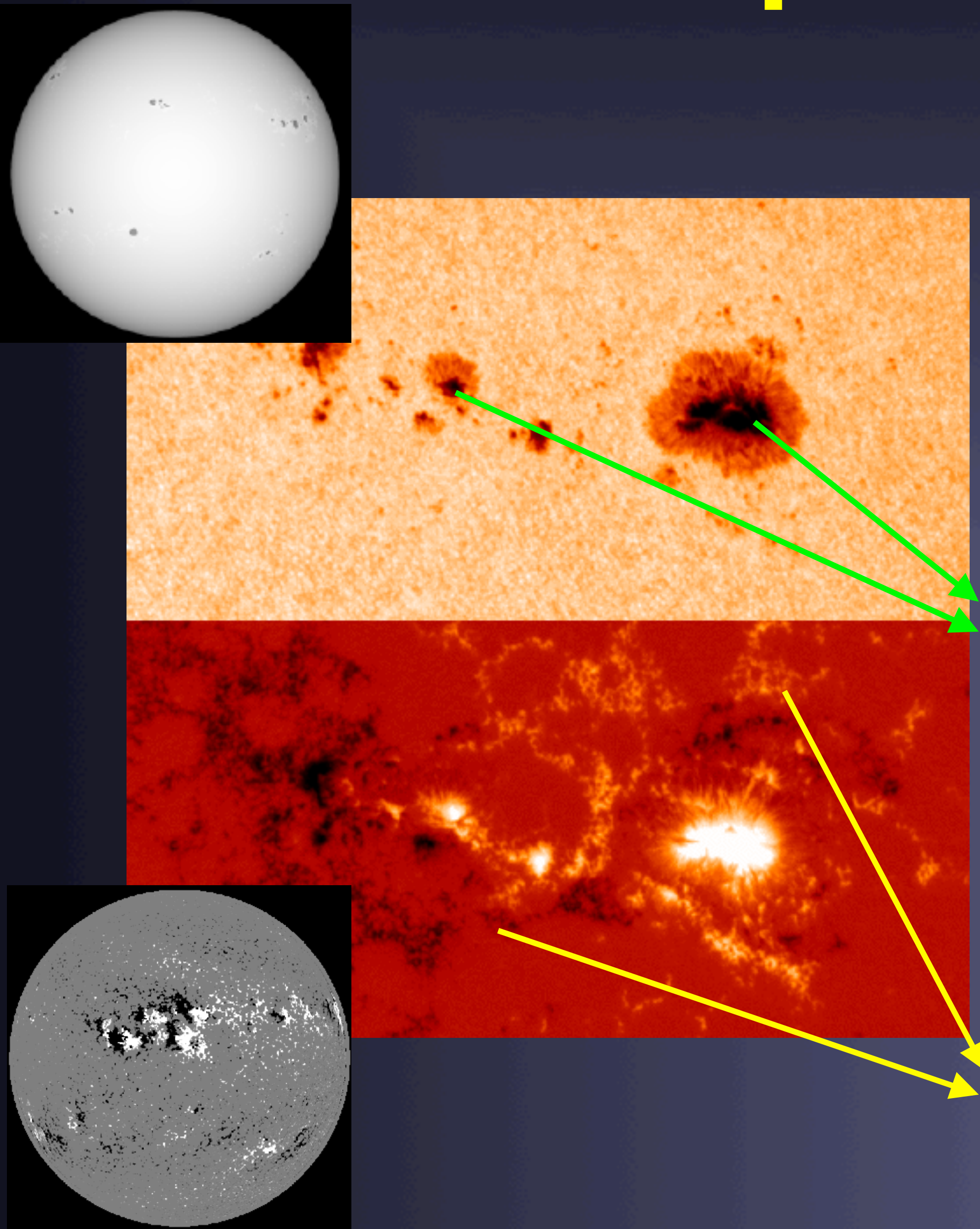
MDI on SOHO

Flux-tube brightening near limb



- FTs are evacuated due to pressure balance ➔ hot walls
- Most energy radiates away from FTs through their hot walls
- FTs appear brightest when hot walls are well seen, i.e. near limb (closer to limb for larger tubes)

3- Component Model



$F(\lambda)$ quiet Sun flux
(Fontenla et al. 1993)

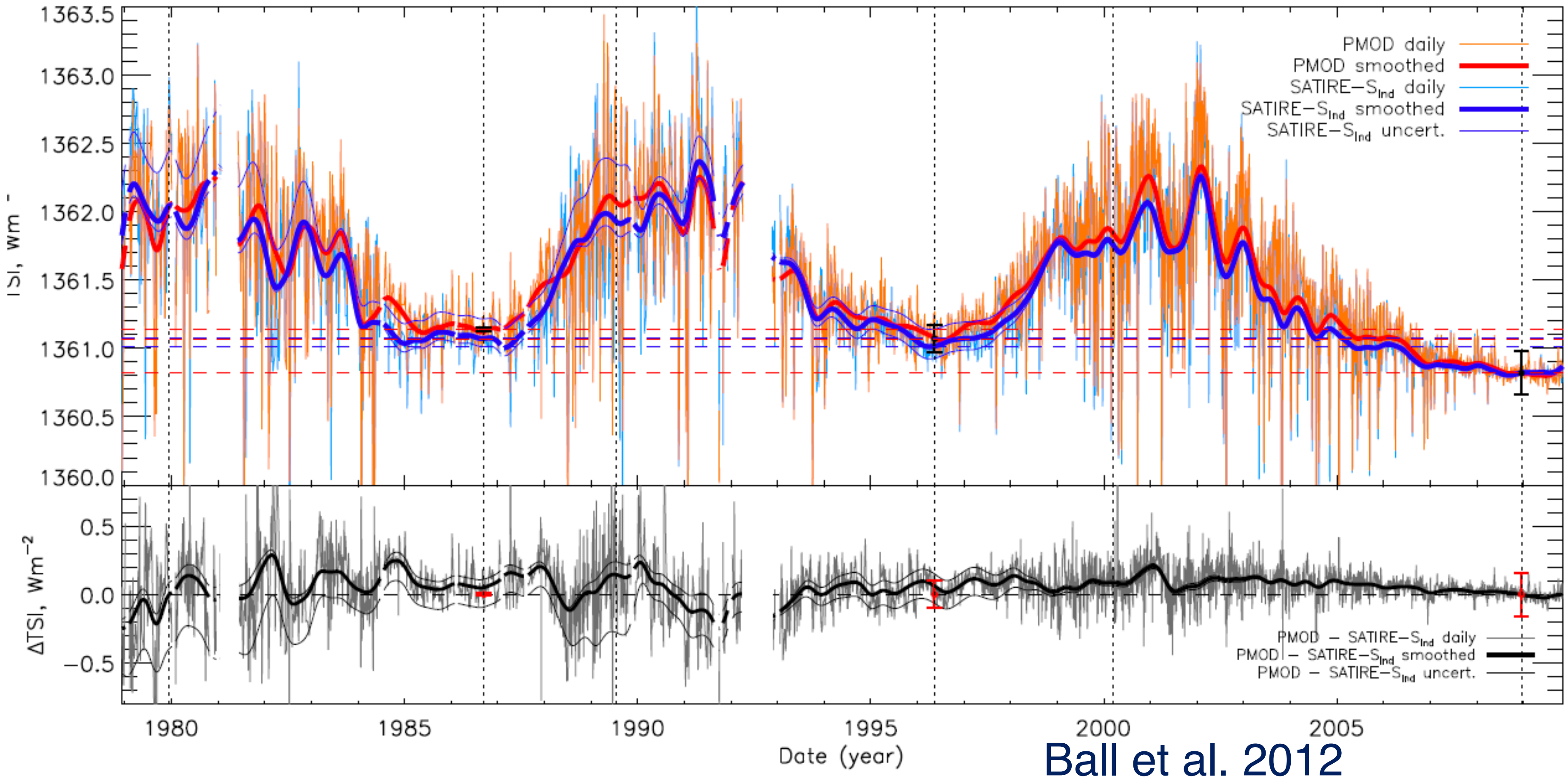
$F(\lambda)$ sunspot flux; separate umbra/penumbra
(cool Kurucz models)

$\alpha_s(t)$ filling factor of sunspots
(MDI continuum)

$F(\lambda)$ facular flux
(modified model-F; Fontenla et al. 1993; Unruh et al. 2000)

$\alpha_f(t)$ filling factor of faculae
(MDI magnetograms)

B as source of irradiance changes



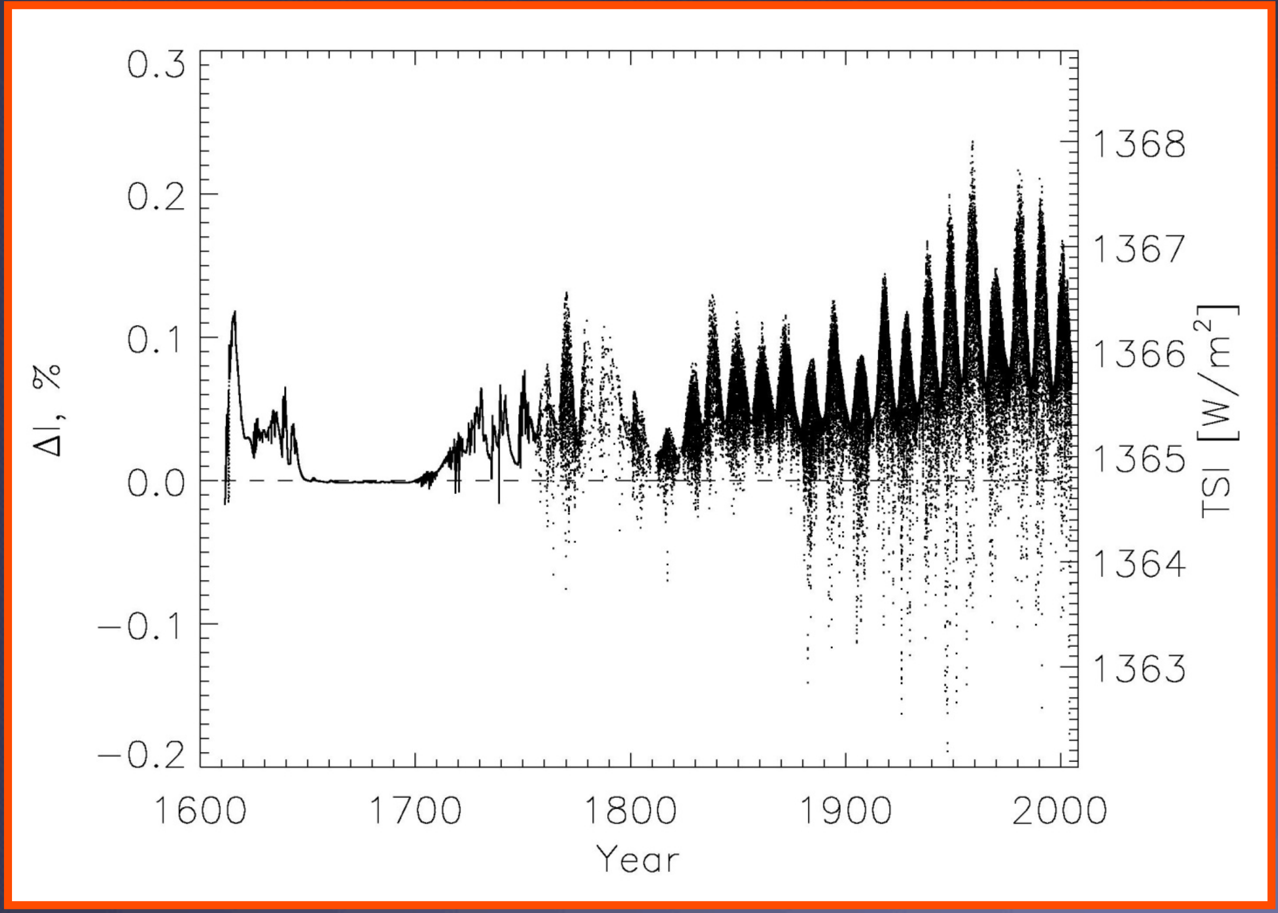
Ball et al. 2012

Models that assume that solar irradiance changes are produced by magnetic fields at the solar surface reproduce total solar irradiance measurements with high accuracy

Solar irradiance since 1610 based on magnetic field reconstruction

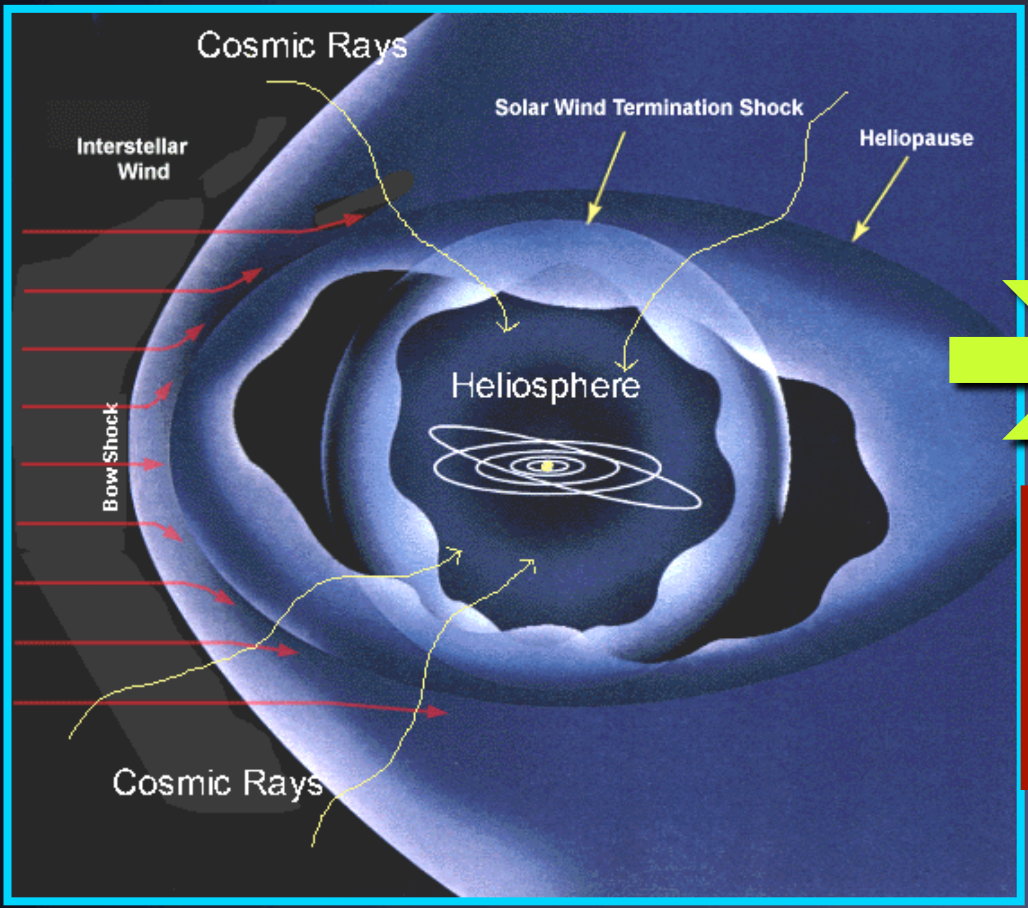
There is a clear long-term (secular) trend in total solar irradiance from the Maunder minimum till today

Estimates of rise in total solar irradiance since Maunder minimum
≈1-1.5 W/m^2
(but there is some controversy about this value)

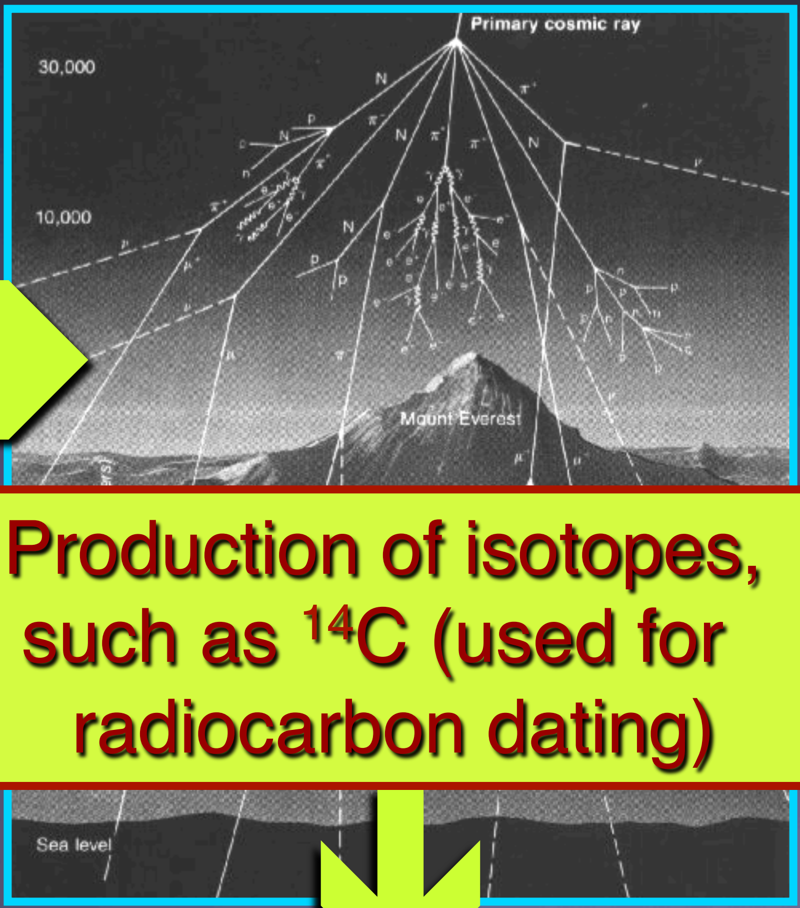


Krivova et al. 2007, 2010

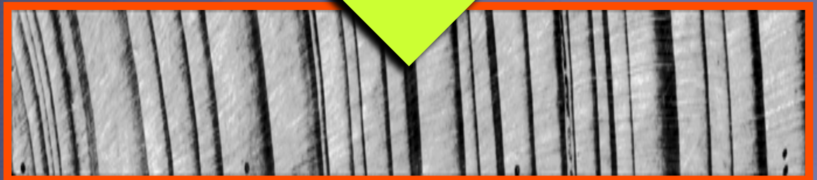
Cosmic Rays, the Sun & Tree Rings



Flux of cosmic rays is changed by solar activity

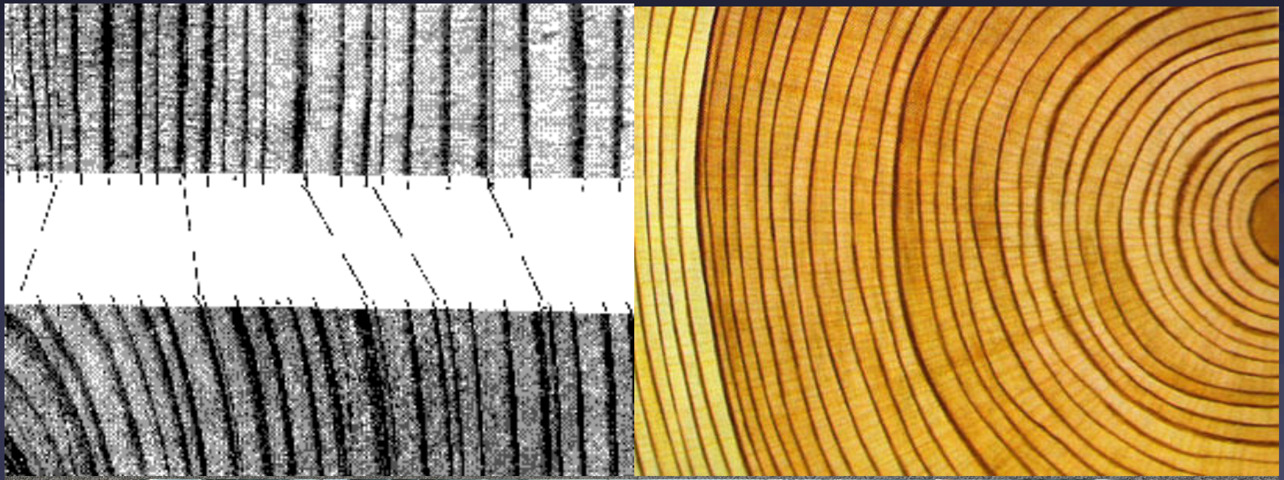


Production of isotopes, such as ^{14}C (used for radiocarbon dating)



Natural archives of cosmogenic isotopes

Accumulation of ^{14}C ($t_{1/2}$= 5730 yr) in plants & trees, dating through dendrochronology (tree rings)

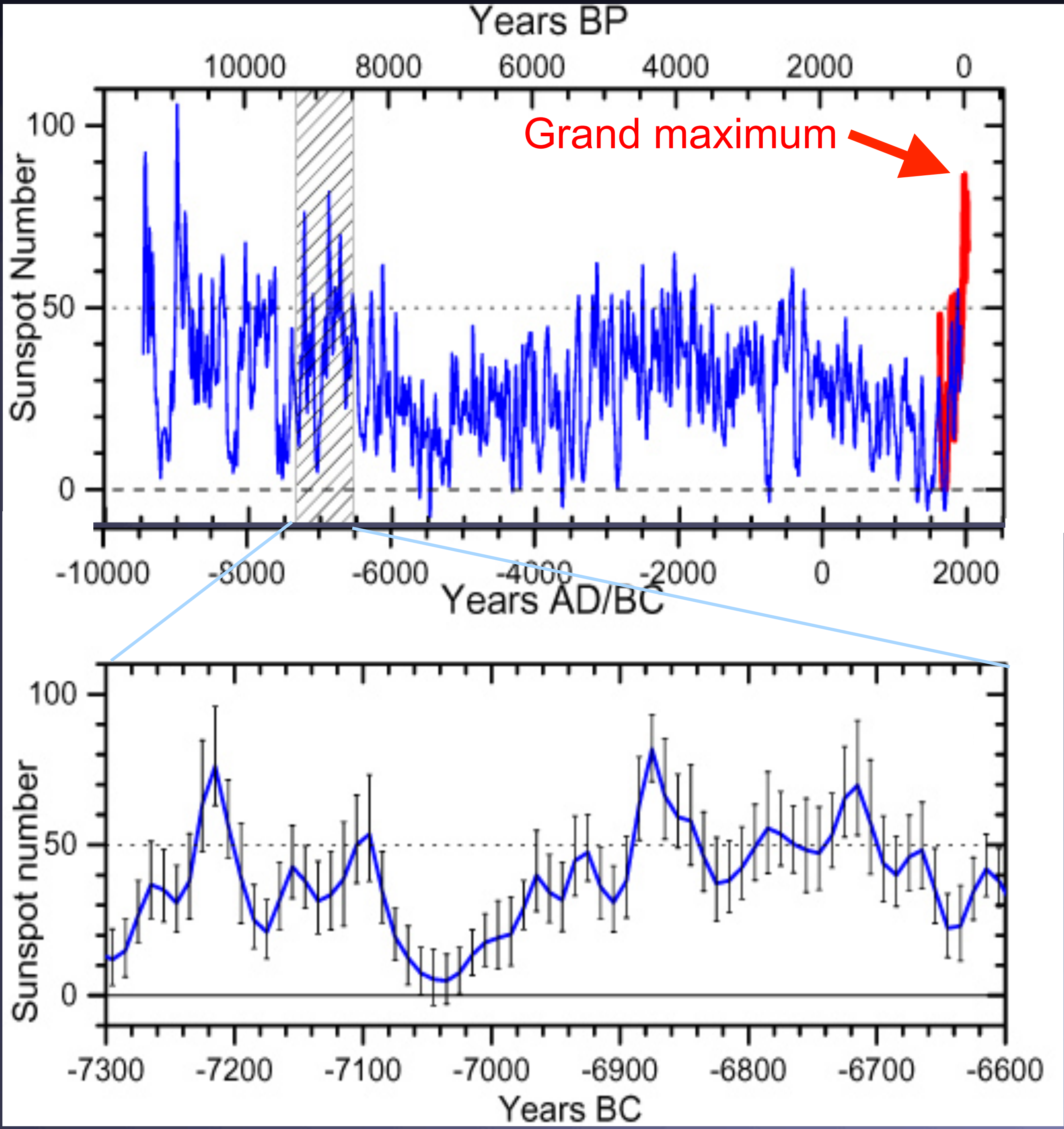


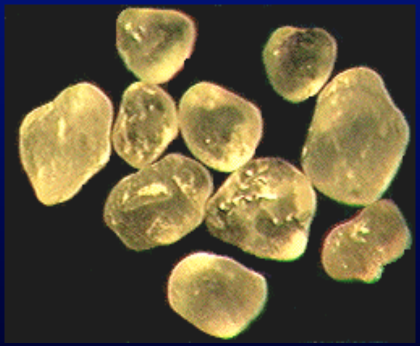
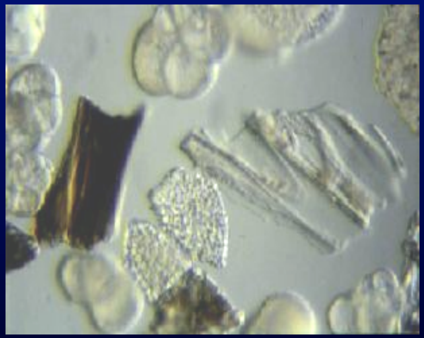
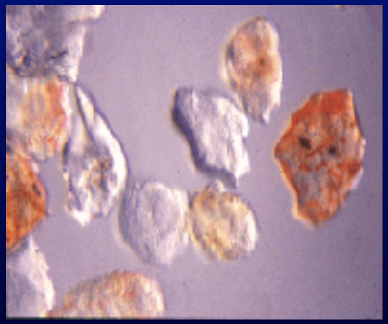
Accumulation of ^{10}Be ($t_{1/2}$ = 1.5 million years) in glacial ice, dating through annual layers in ice

How did the Sun Behave since last Ice Age?

Number of sunspots over last 11400 years reconstructed from ^{14}C in tree rings ➔ Sun is very active **today** compared to last **11000 years**

Solanki et al. 2004 Nature



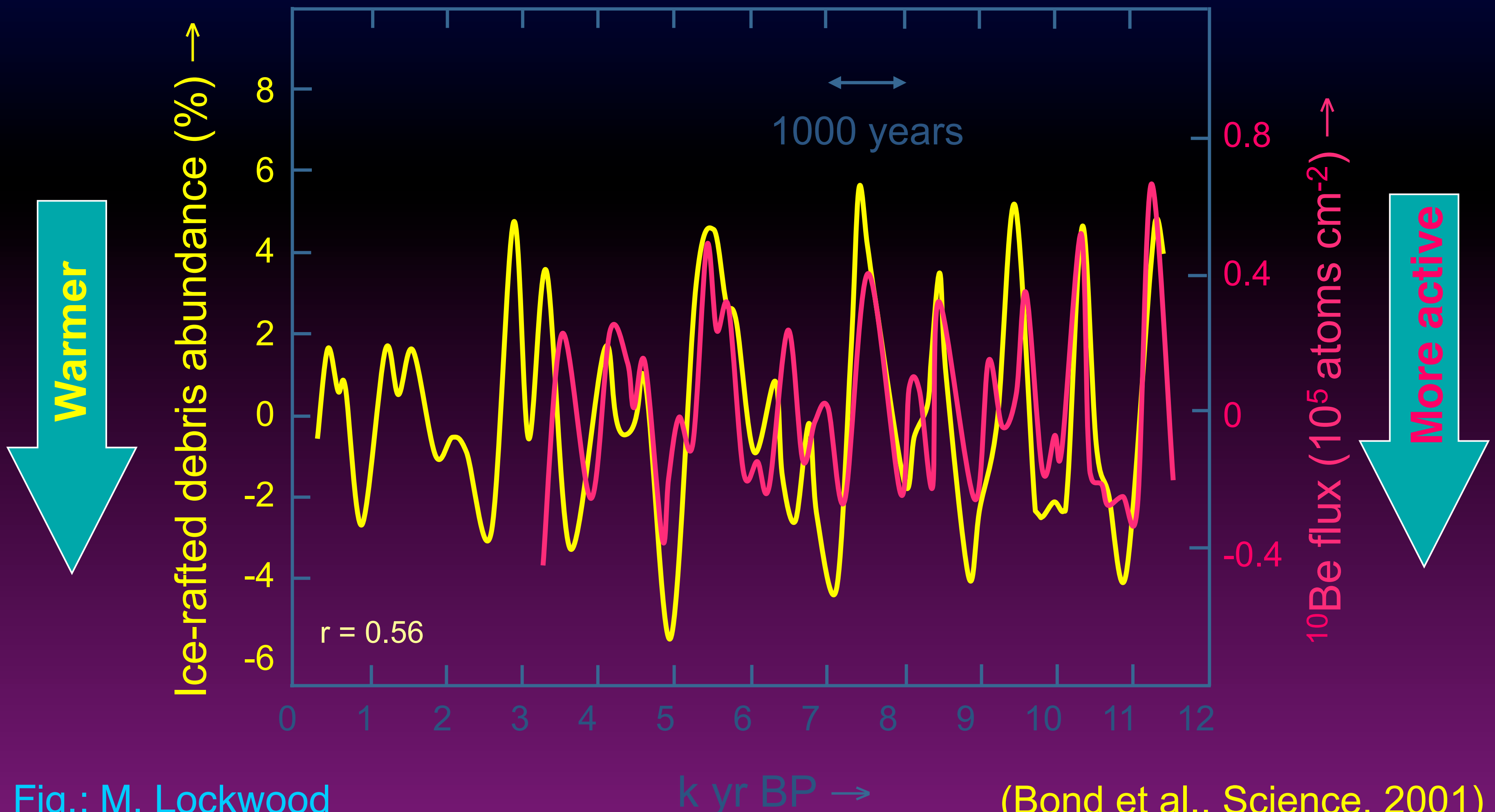
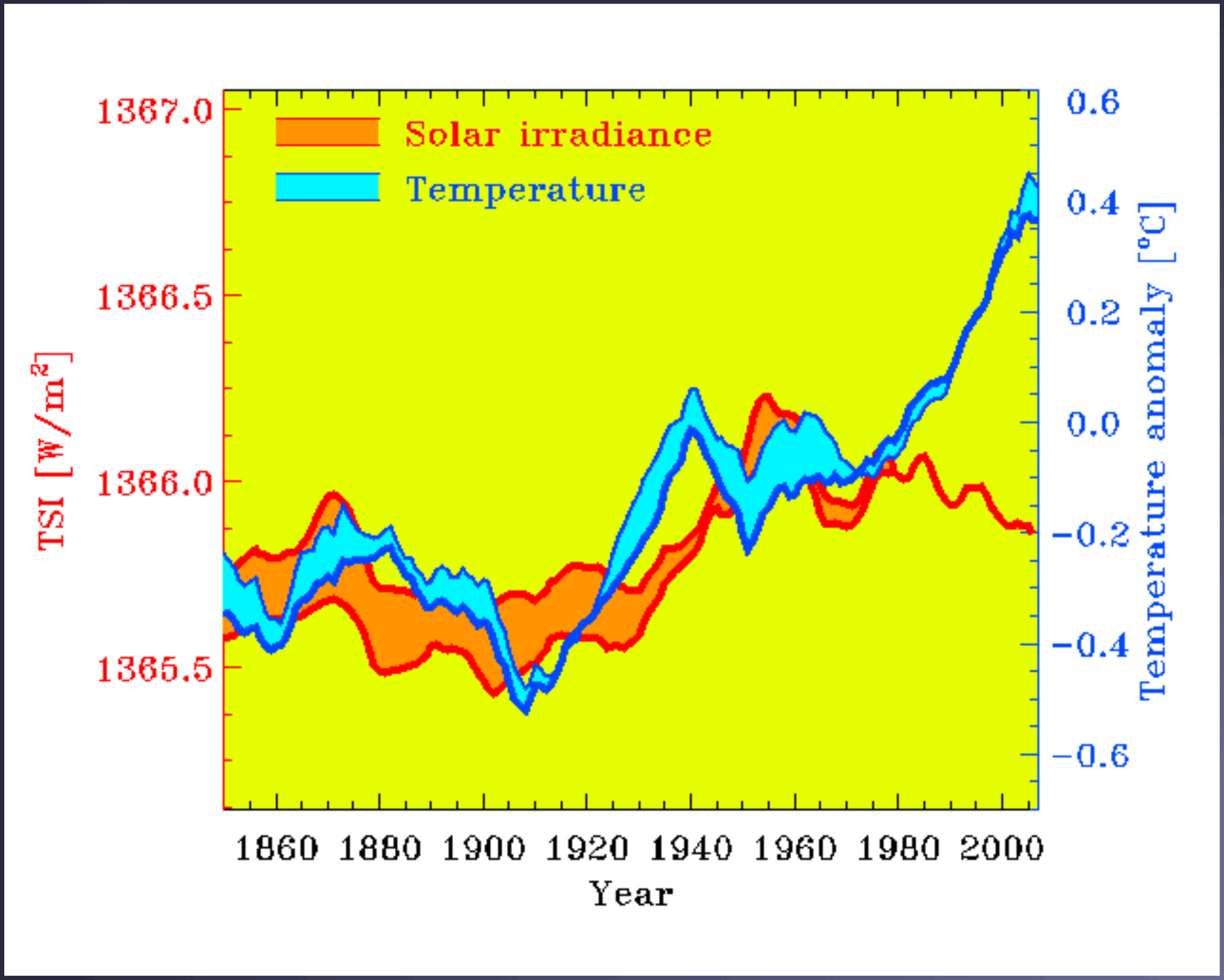


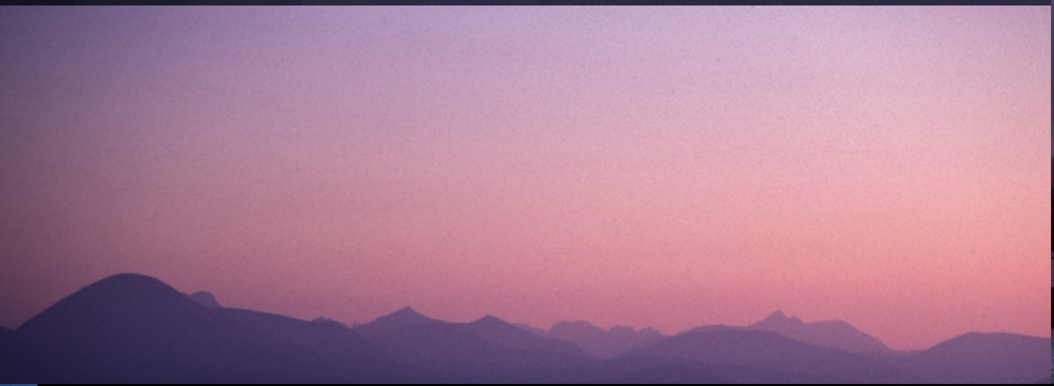
Fig.: M. Lockwood

(Bond et al., Science, 2001)

Solar Irradiance and Climate



We have started a gigantic experiment with the only home we have, the Earth




... and we won't be able to quickly undo the results if we don't like the results



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- Questions?

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