Long-term solar change and solar influences on global and regional climates

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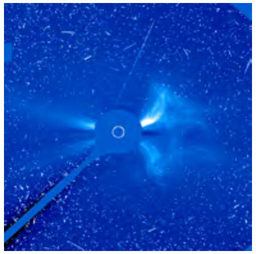
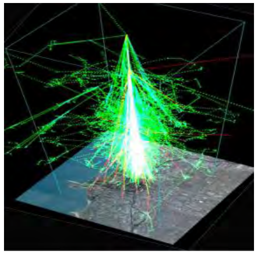
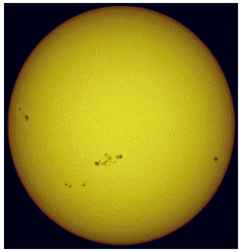
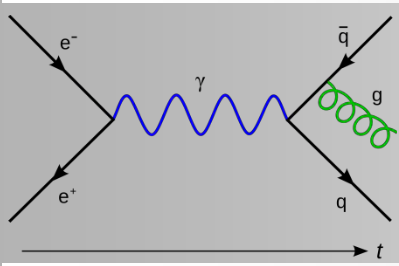
STFC Introductory Solar System Plasma Physics Summer School

Newcastle, 13th September 2017

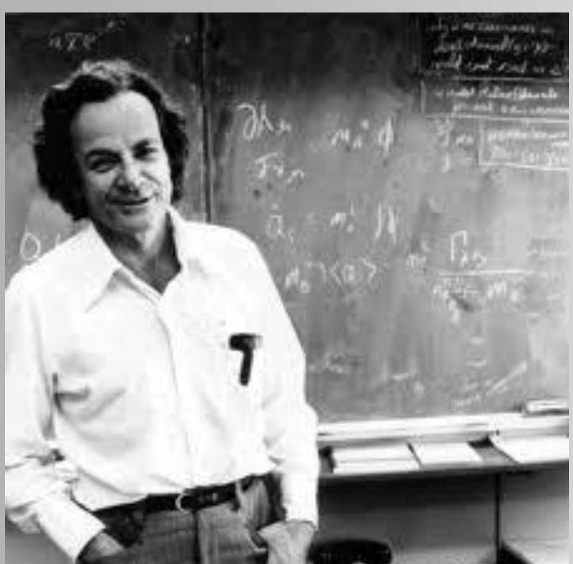








"The first principle is that you must not fool yourself and you are the easiest person to fool"

"reality must take precedence over public relations, for Nature cannot be fooled"



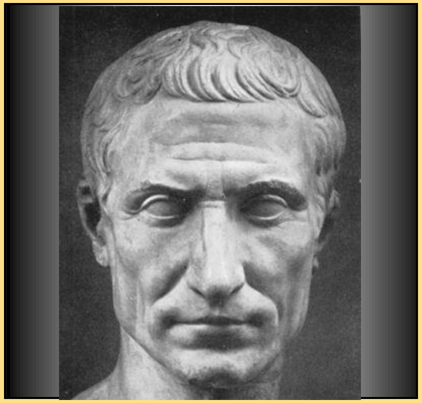
Richard P. Feynman
(1918-1988)

"Still, a man hears what he wants to hear and disregards the rest"

(Paul Simon, The Boxer, 1970)

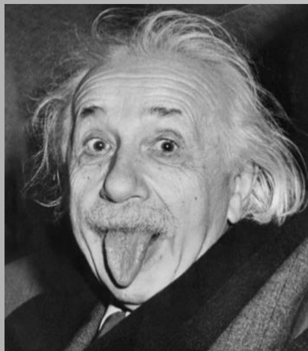
"men may construe things after their fashion, clean from the purpose of the things themselves"

(William Shakespeare, Julius Ceasar, 1599)



"men, in general are quick to believe that which they wish to be true."

(Julius Ceasar, 50BC)

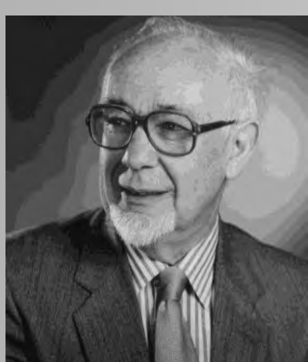


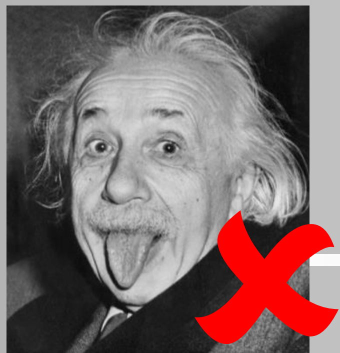
Science

sʌɪəns

(noun)

- Cambridge Dictionary: “(knowledge from) the careful study of the structure & behaviour of the physical world, especially by watching, measuring, and doing experiments, and the development of theories to describe the results of these activities”
- Wikipedia: “(from Latin *scientia*, meaning knowledge) is a systematic enterprise that builds and organizes knowledge in the form of testable explanations and predictions about the universe.”
- OED: “A systematically organized body of knowledge on a particular subject.”
- John Michael Ziman (1925-2005): “….′consensibility′, leading to **consensus**, is the touchstone of reliable knowledge”





Science Consensus

sʌɪəns kən ˈsɛnsəs

(compound noun)

- Wikipedia: “the collective judgment, position, and opinion of the community of scientists in a particular field of study. Consensus implies general agreement, though not necessarily unanimity”

Climate change: there IS an overwhelming scientific consensus

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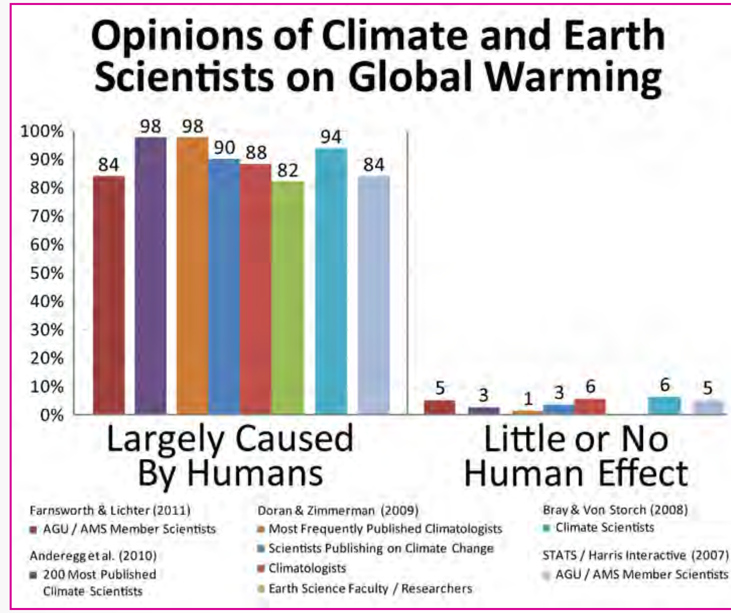
Environ. Res. Lett. 8 (2013) 024024 (7pp) doi:10.1088/1748-9326/8/2/024024

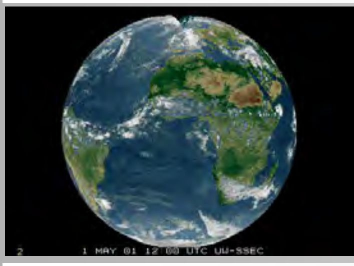
Quantifying the consensus on anthropogenic global warming in the scientific literature

John Cook[1,2,3], Dana Nuccitelli[2,4], Sarah A Green[5], Mark Richardson[6], Bärbel Winkler[2], Rob Painting[2], Robert Way[7], Peter Jacobs[8] and Andrew Skuce[2,9]

[1] Global Change Institute, University of Queensland, Australia
[2] Skeptical Science, Brisbane, Queensland, Australia
[3] School of Psychology, University of Western Australia, Australia
[4] Tetra Tech, Incorporated, McClellan, CA, USA
[5] Department of Chemistry, Michigan Technological University, USA
[6] Department of Meteorology, University of Reading, UK
[7] Department of Geography, Memorial University of Newfoundland, Canada
[8] Department of Environmental Science and Policy, George Mason University, USA
[9] Salt Spring Consulting Ltd, Salt Spring Island, BC, Canada

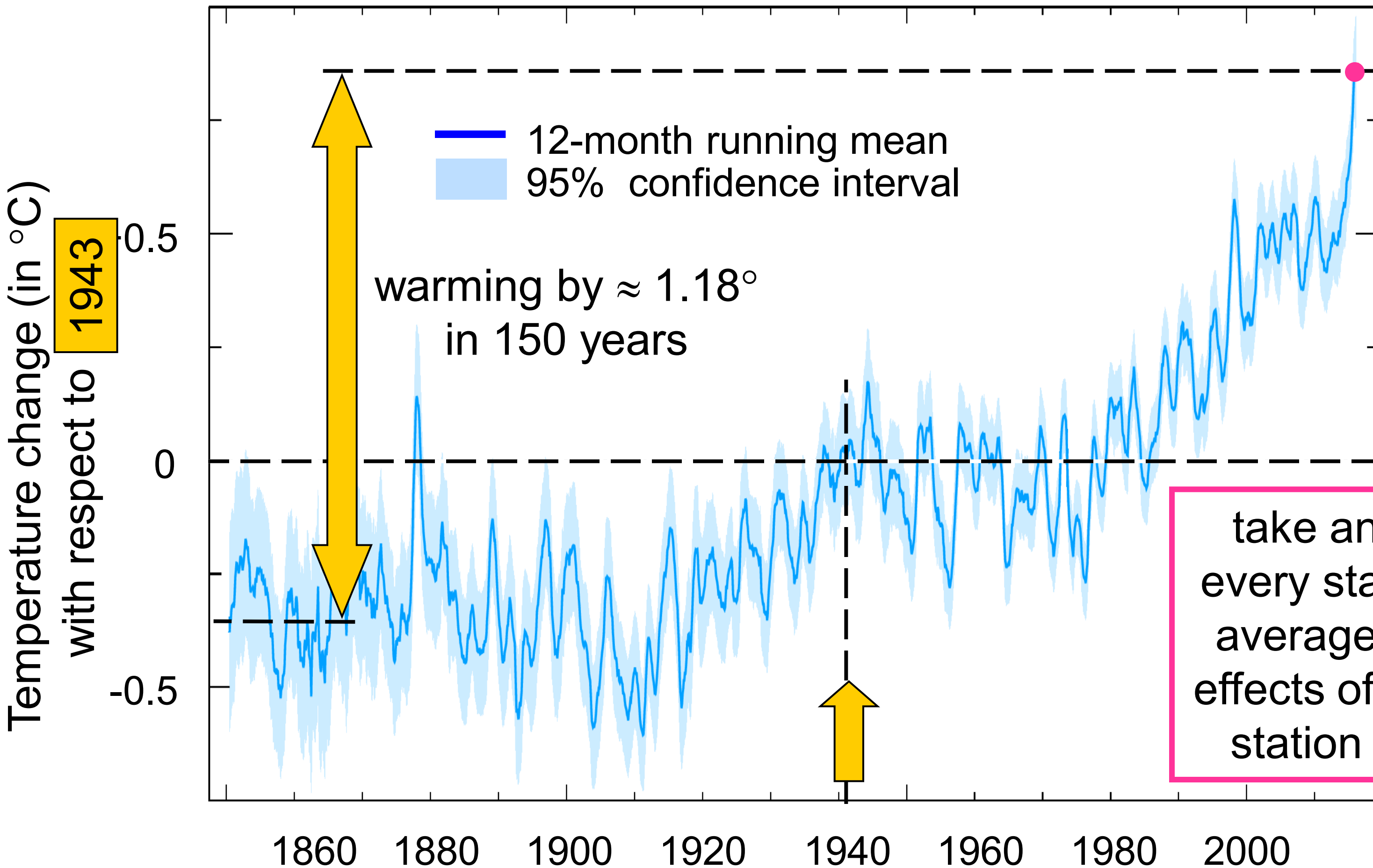


↑ Survey of all papers published 1991-2011 using keywords "climate change" and "global warming" (11944 of them)
97% of papers offering an opinion on climate change agreed that human activities are causing global warming



Is the Earth Warming?

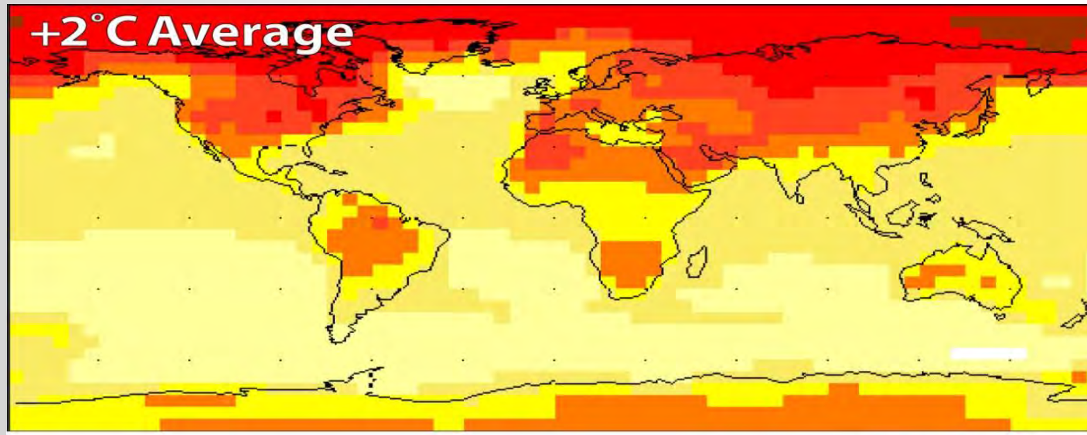
Average surface temperature anomaly measured by the global network of weather stations (data from CRU, UEA)



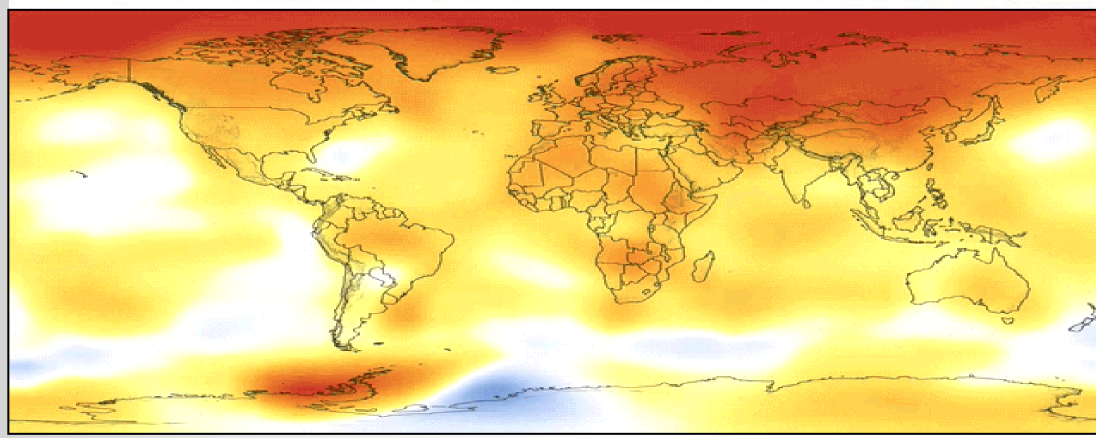
take anomaly for every station & then average (limits the effects of changes in station locations)

Map of Air Surface Temperature rise predicted in 1988

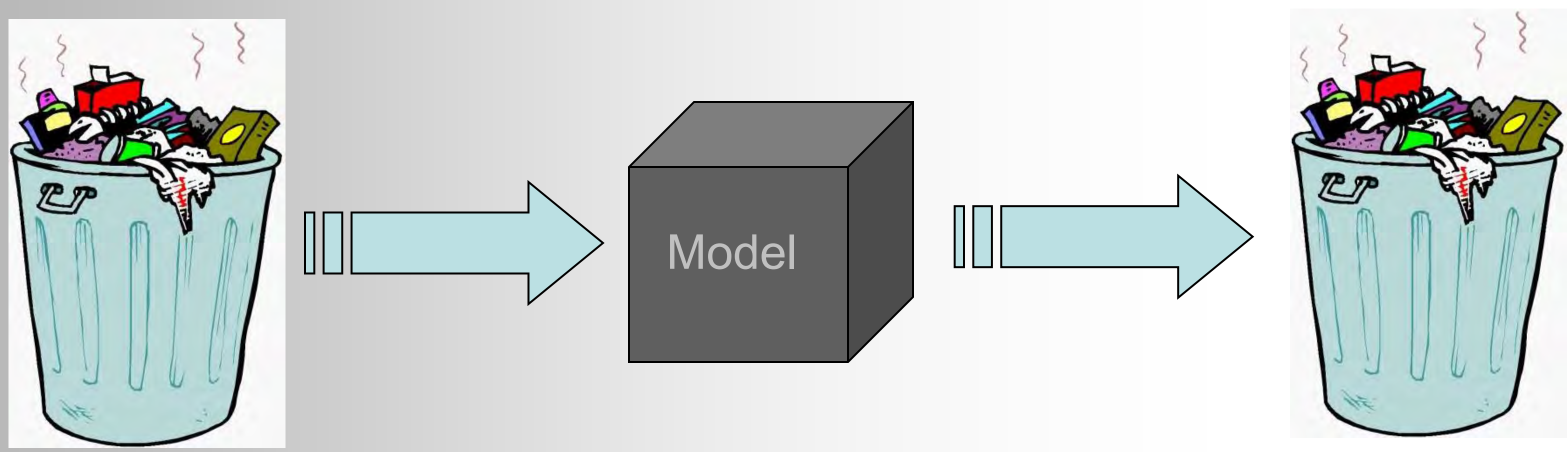
MODELLED AST MAP – for a GMAST rise of ΔT_S = +2ºC



OBSERVED AST MAP – NASA/GISS data for 1881-2008 (for which measured GMAST rise $\approx$ 1.1$\circ$C)



A sceptical view of models



This is **always** true

- hard to evaluate without detailed knowledge of model and its application

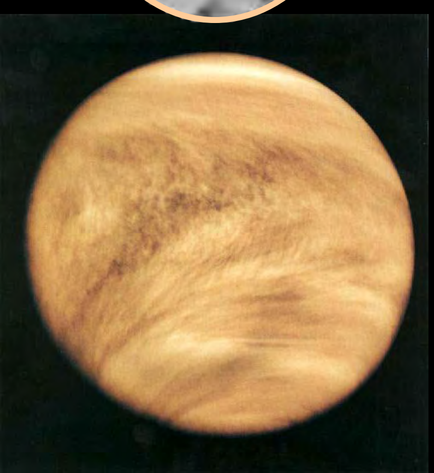
- when different models say the same thing, we need to take them seriously

- and note that we can be irrationally selective about which models we chose to believe and disbelieve! (such selection is often needed – we must ensure we sue rational and objective selection)

The Greenhouse Effect

- First suggested by Svante Arrhenius (1896)

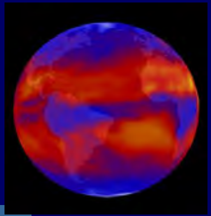
- CO_2 rise first linked to temperature rise by Guy Stewart Callendar (1939)



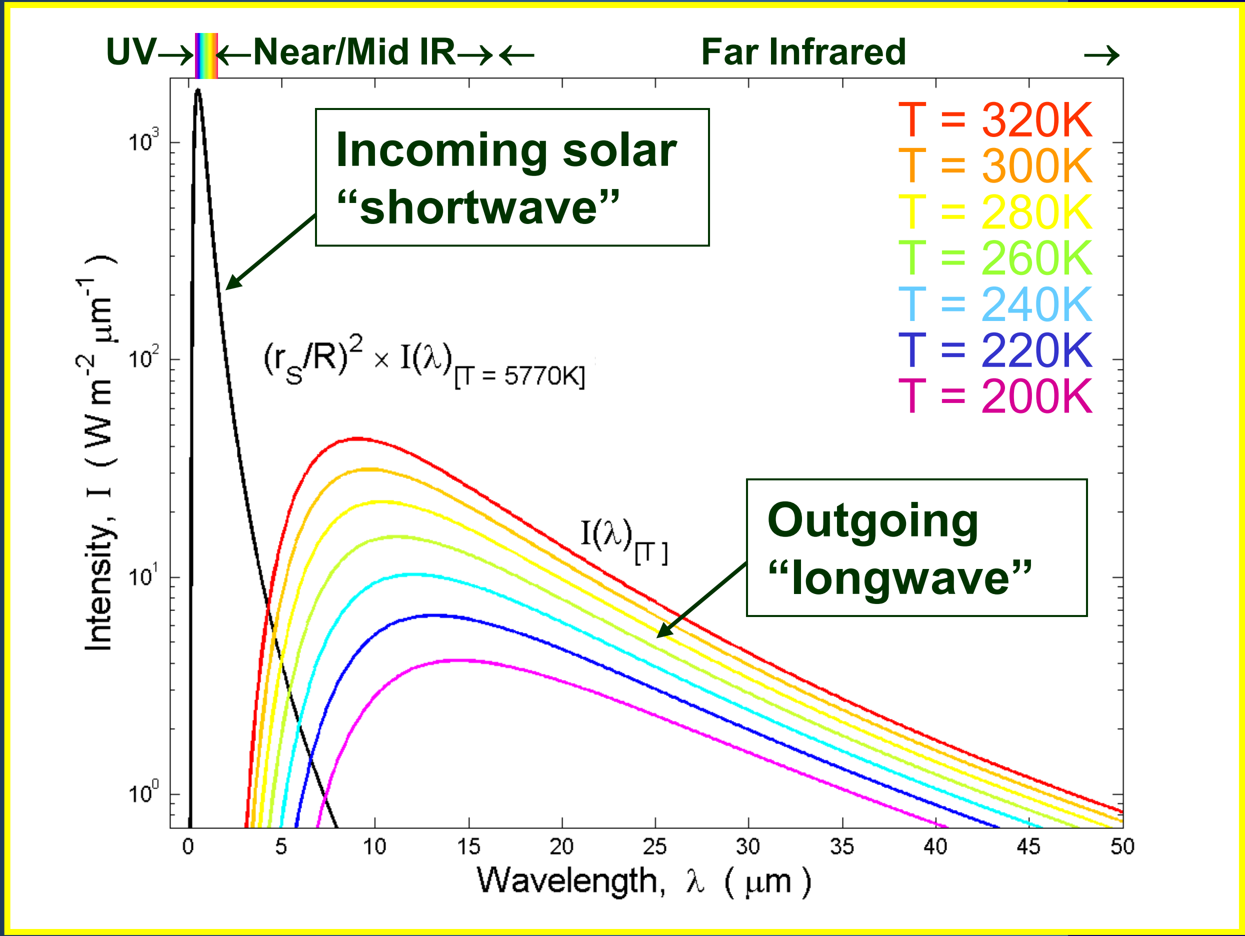
- Concern is that perturbations will cause runaway greenhouse effect suffered by Venus

- Venus was initially very similar to Earth but: (1) was closer to the Sun; (2) could not remove CO_2 by tectonic subduction and (3) never developed a biomass to keep CO_2 in its atmosphere in check

Spectra at the Heart of the Greenhouse Effect



- A “blackbody” is an ideal radiator, that is often seen in nature
- The sun is close to a blackbody of temperature T = 5770 K
- Different parts of Earth radiate with different T
- To show SW and LW on same plot we here use a logarithmic intensity scale

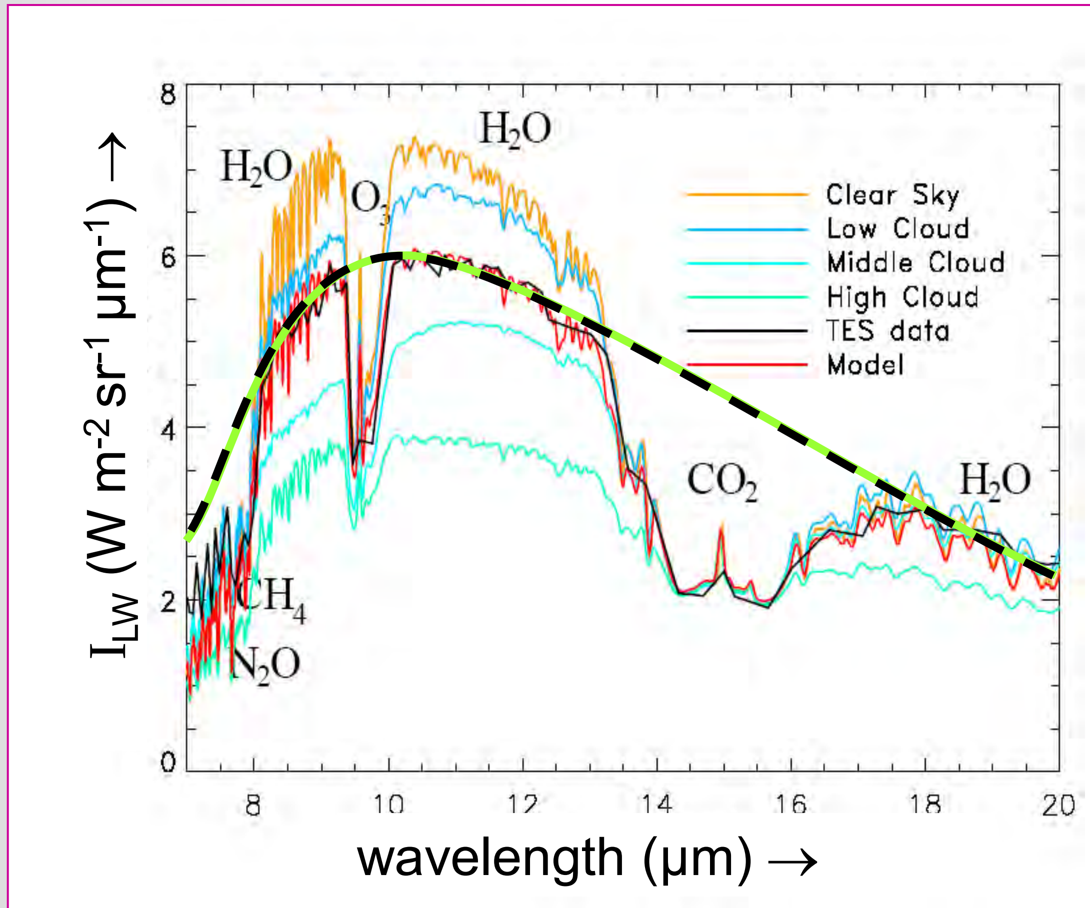


The greenhouse effect

Spectrum of outgoing longwave (infra red)

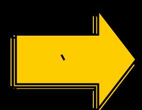
observations from Mars Global Surveyor (in black)

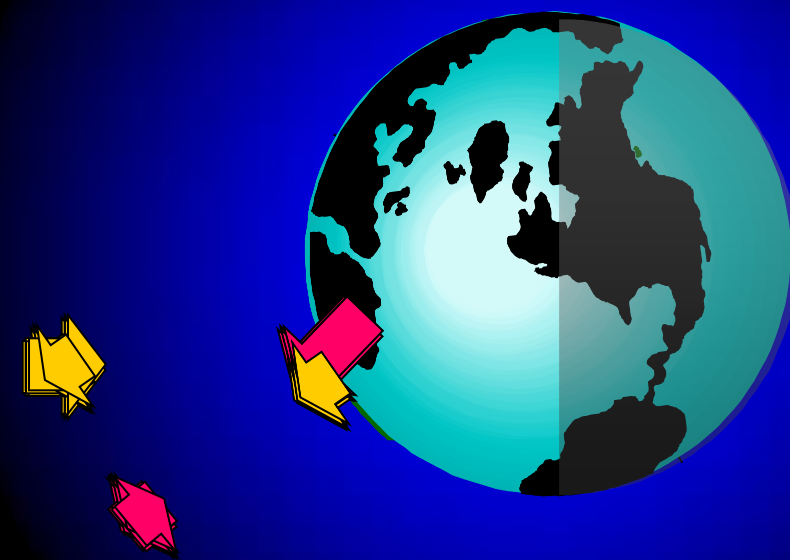
Model is he appropriate mix of Earth “scene” types (in red)



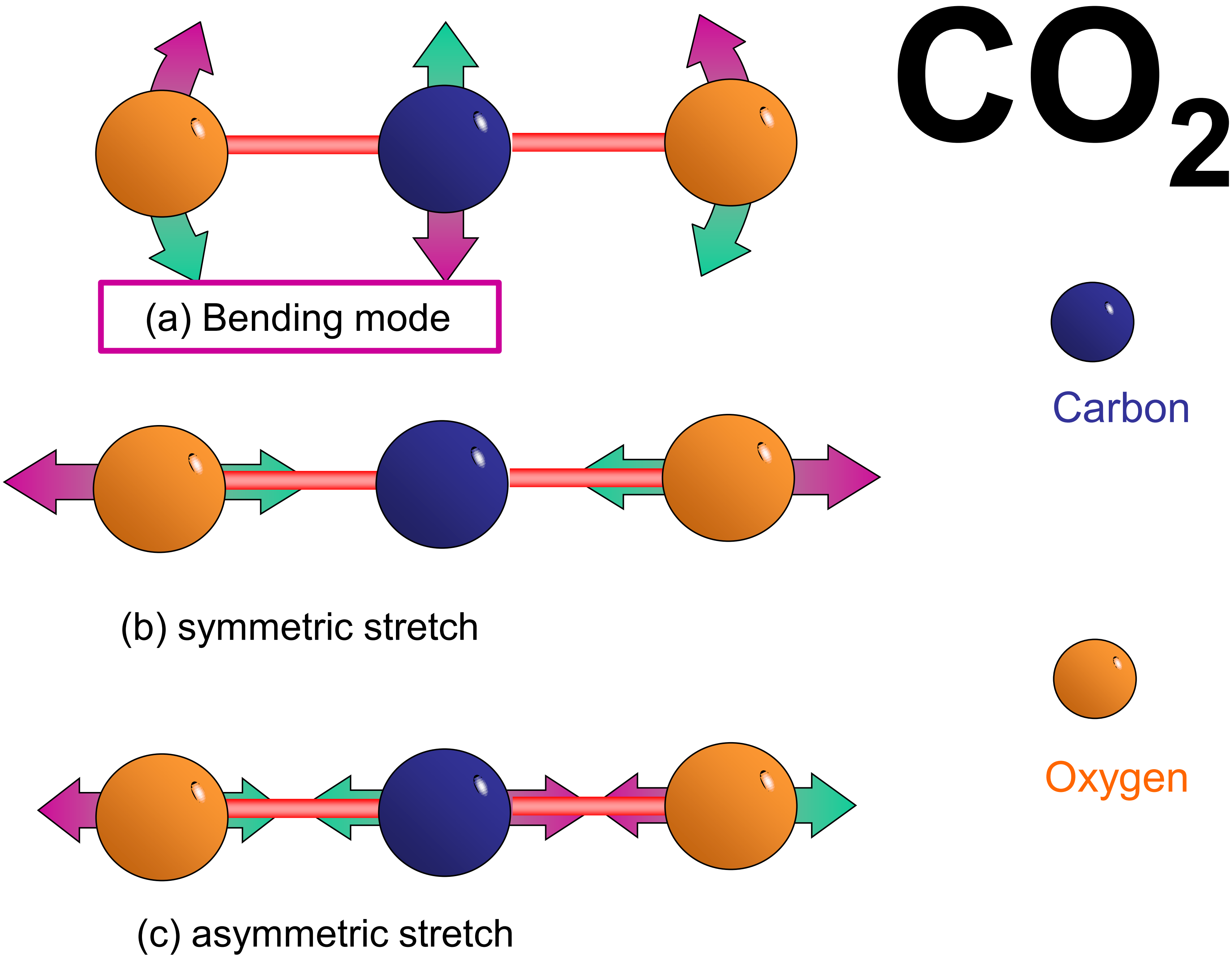
The Greenhouse Effect

- incoming solar power (called shortwave or SW)



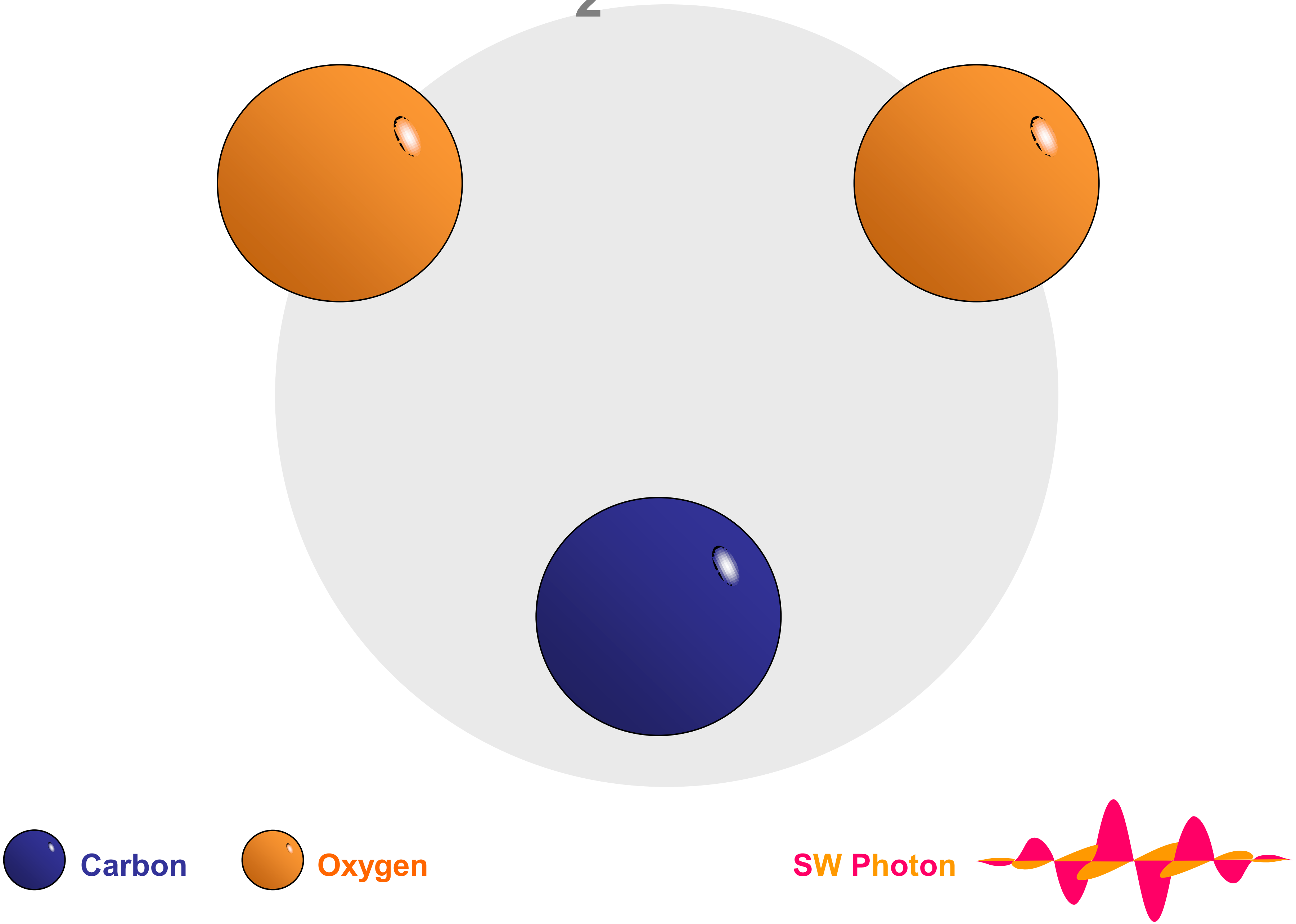


- about 1/3 reflected back into space ("albedo")
- the rest heats Earth's surface
- which re radiates thermal longwave (LW) radiation
- but the atmosphere traps in some of that re-radiated LW radiation – heats surface a bit more
- increasing the LW trapping causes T_{SE} to rise so that P_e rises enough to keep $P_{in} \approx P_{out}$

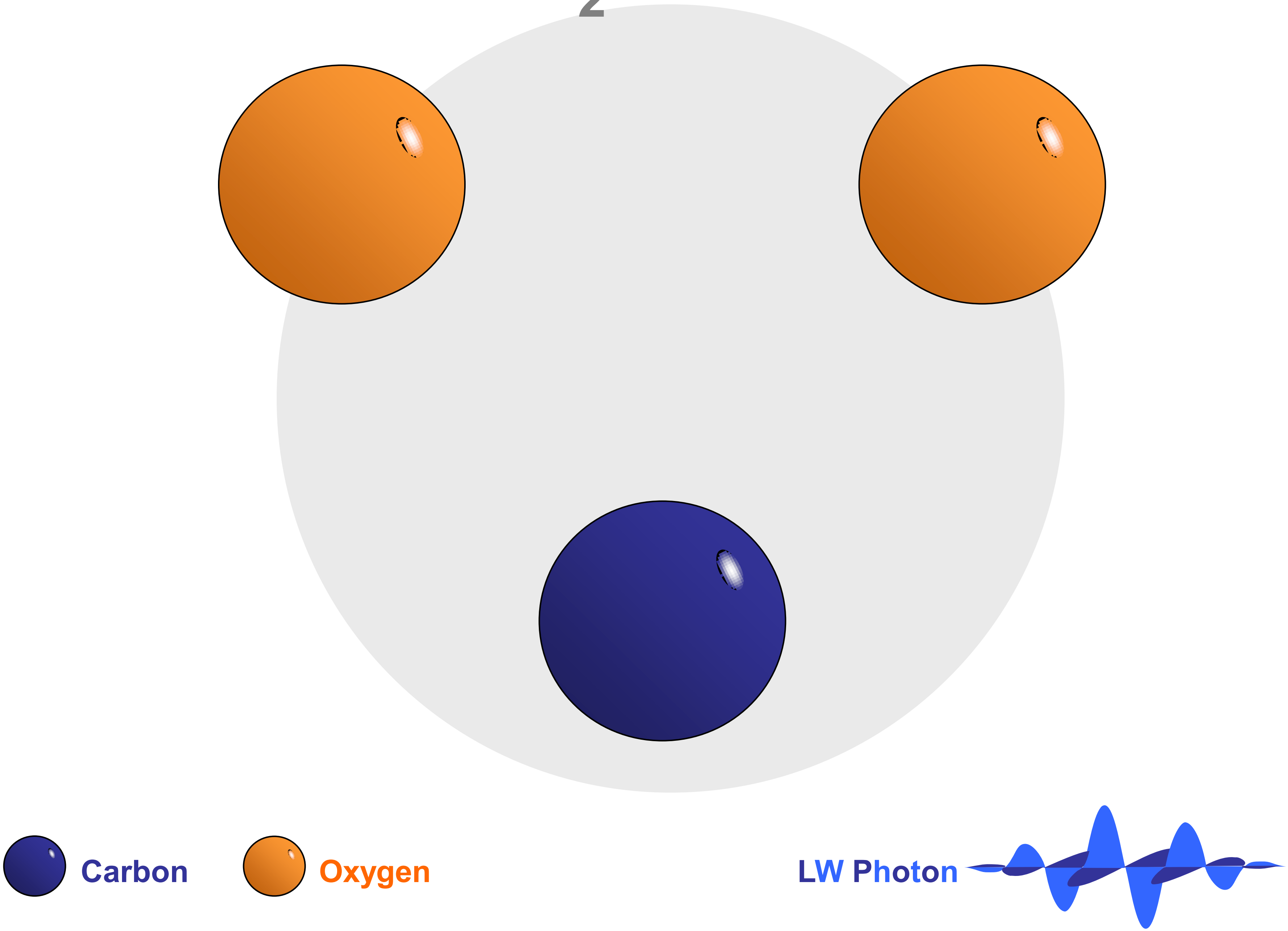


CO_2
(a) Bending mode
(b) symmetric stretch
(c) asymmetric stretch
Carbon
Oxygen

a CO_2 molecule

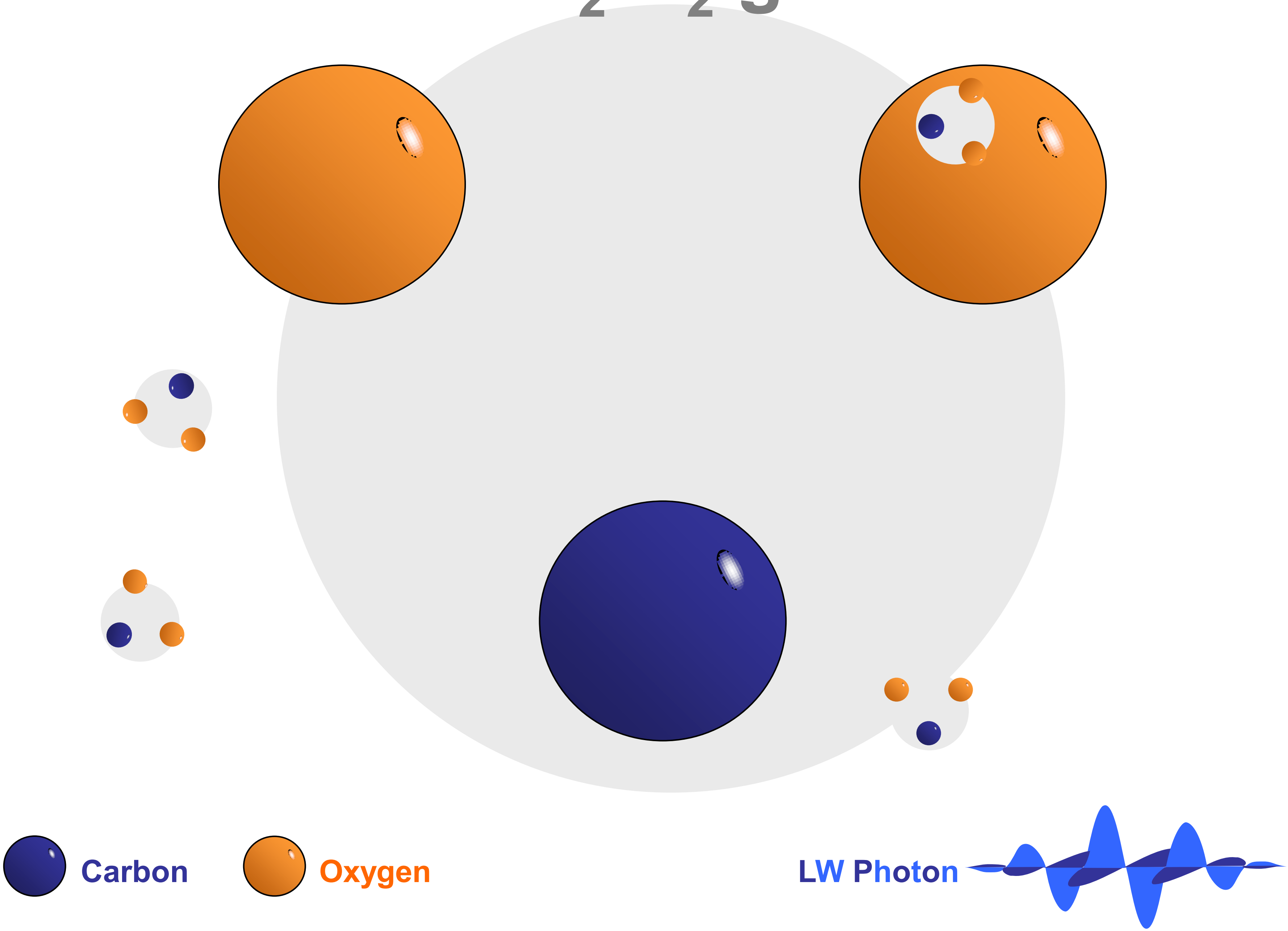


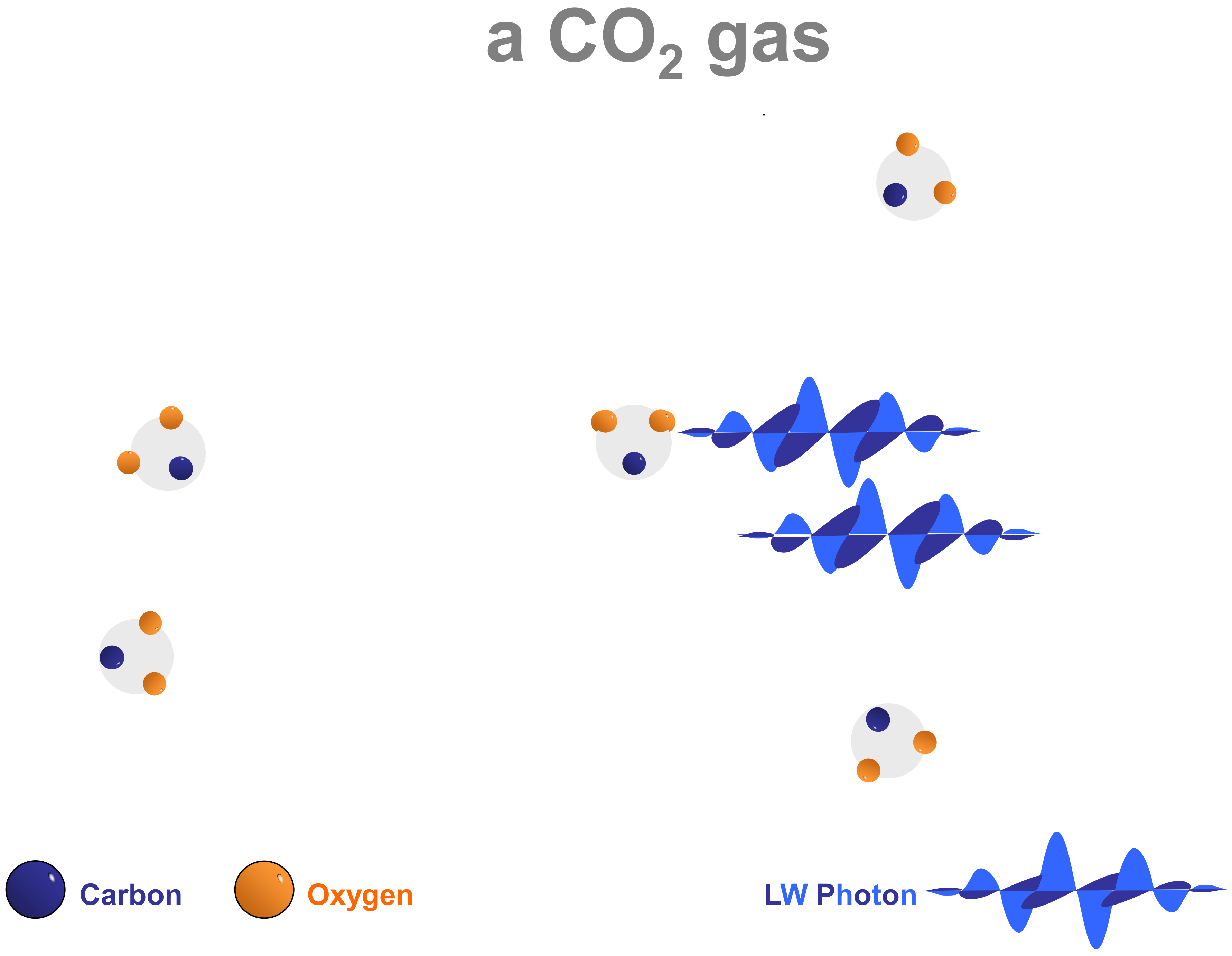
a CO_2 molecule



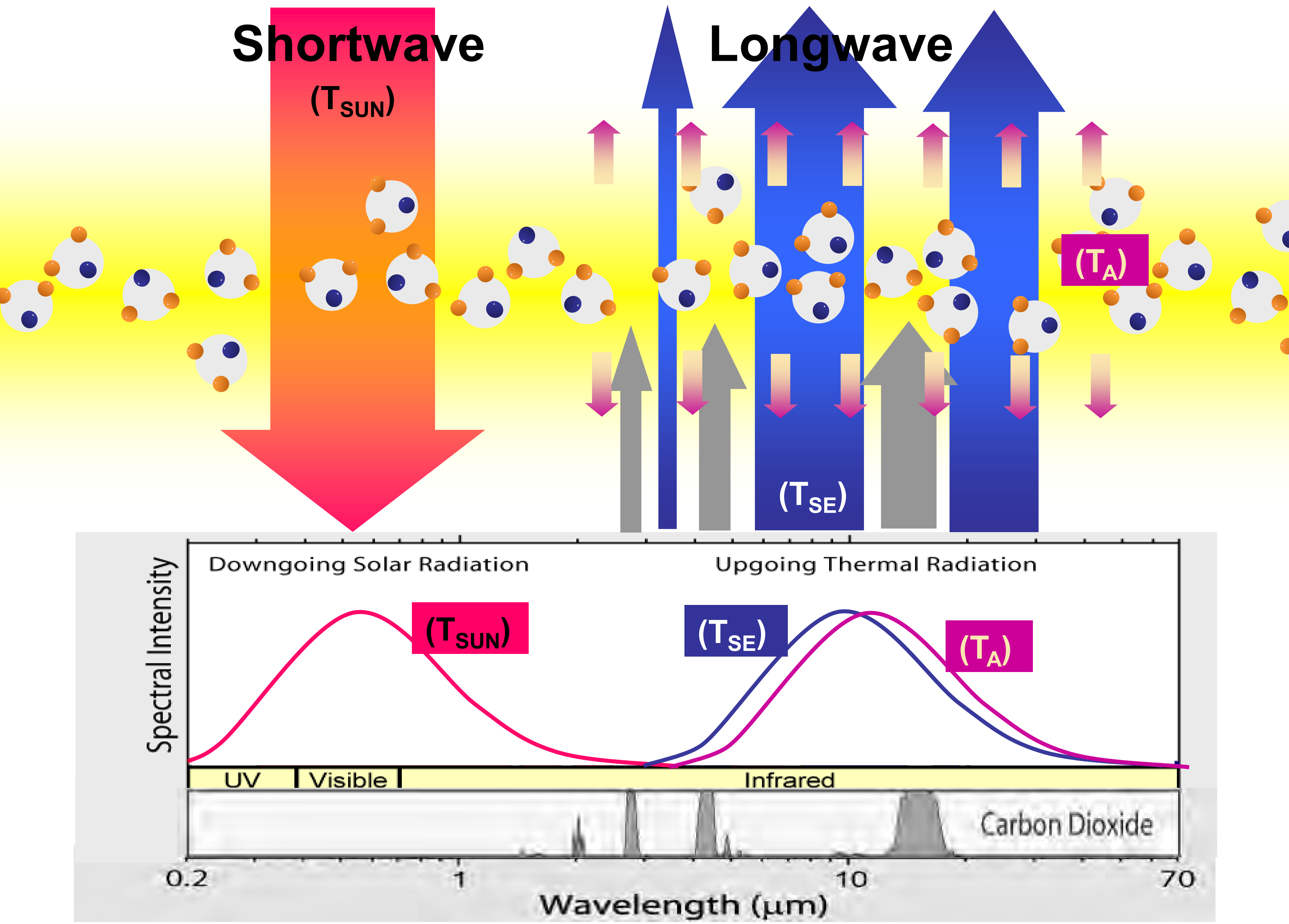
a CO_2 molecule

CO_2 gas

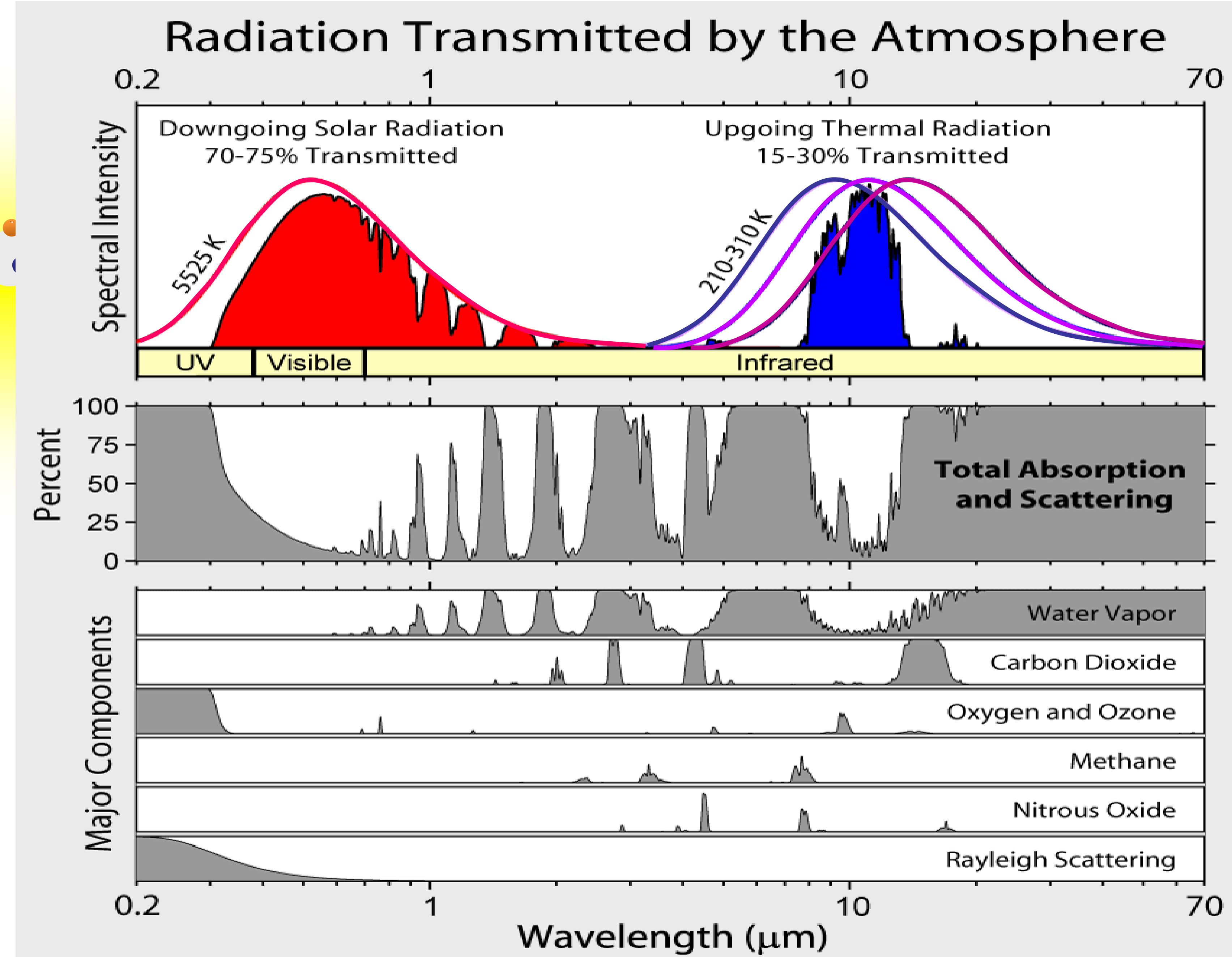




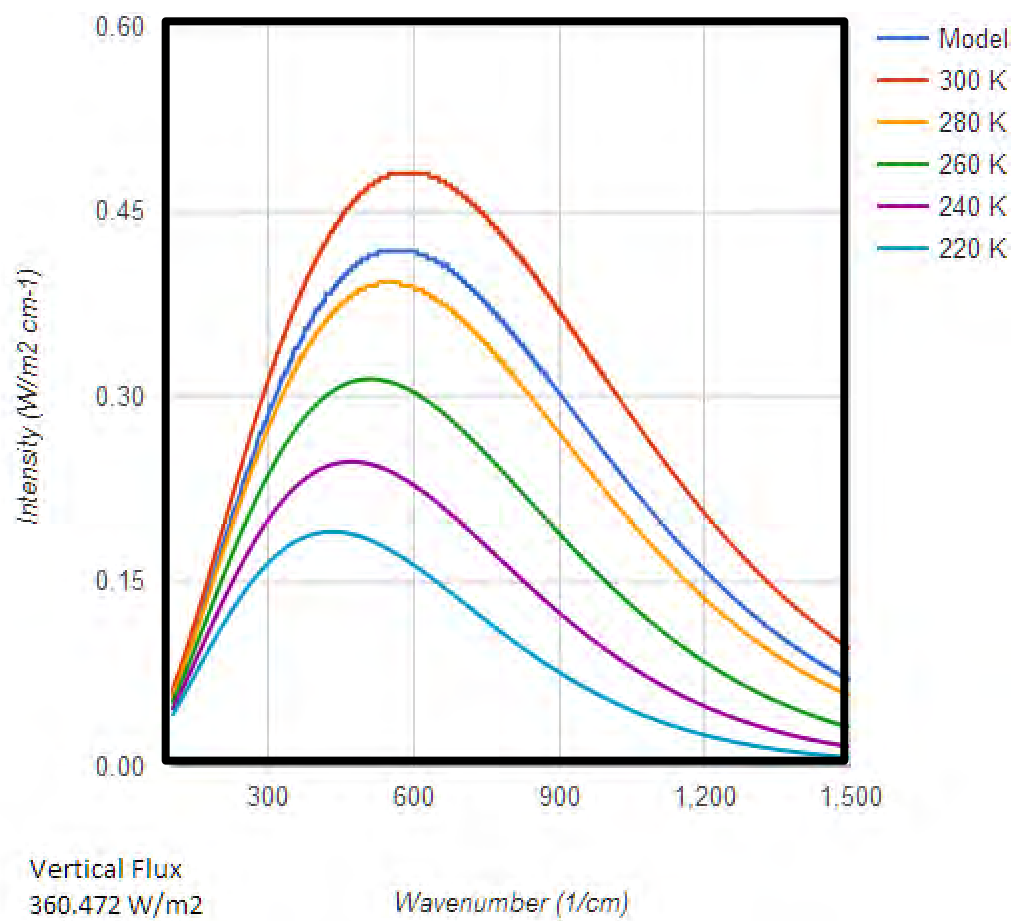
a CO_2 gas
Carbon
Oxygen
LW Photon



Shortwave
(T_{SUN})
Longwave
(T_A)
(T_{SE})
Spectral Intensity
Downgoing Solar Radiation
Upgoing Thermal Radiation
(T_{SUN})
(T_{SE})
(T_A)
UV
Visible
Infrared
Carbon Dioxide
0.2
1
10
70
Wavelength (μm)


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

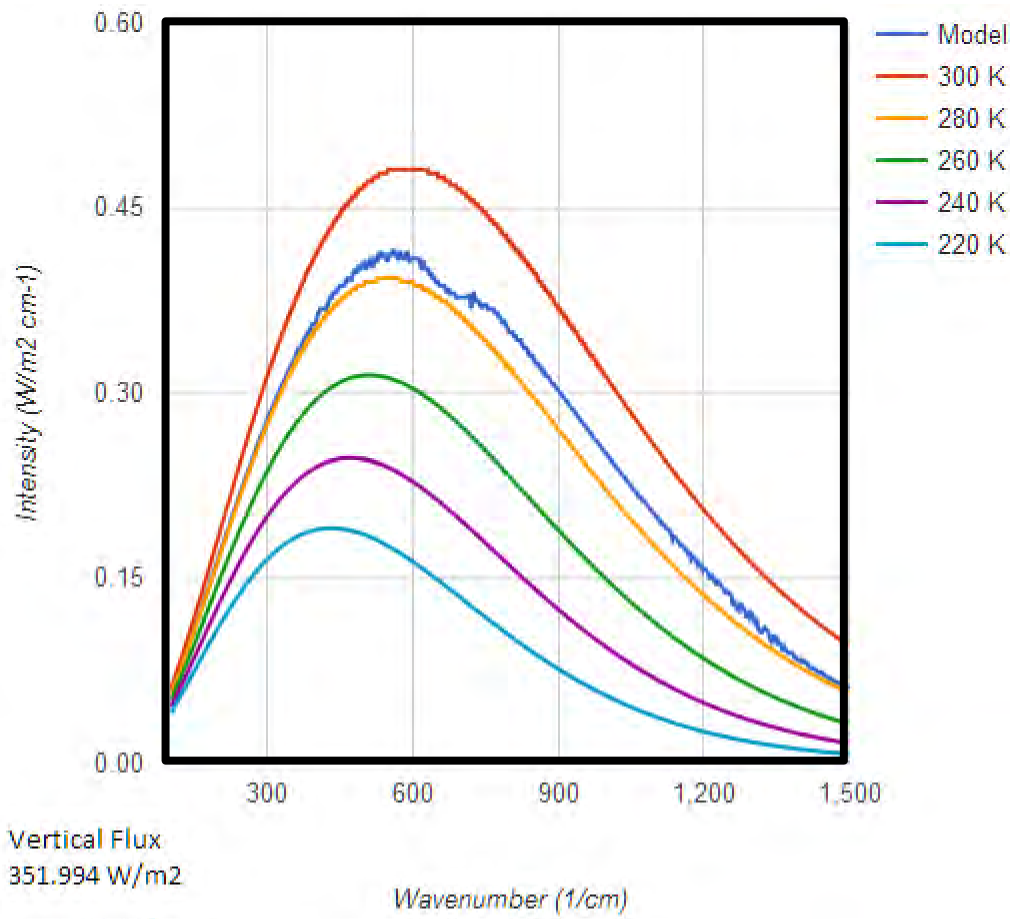
OLR spectrum looking down from h = 0 km



how does the Greenhouse effect work?

Modtran 3 v1.3 imulations with U.S. Standard Atmosphere

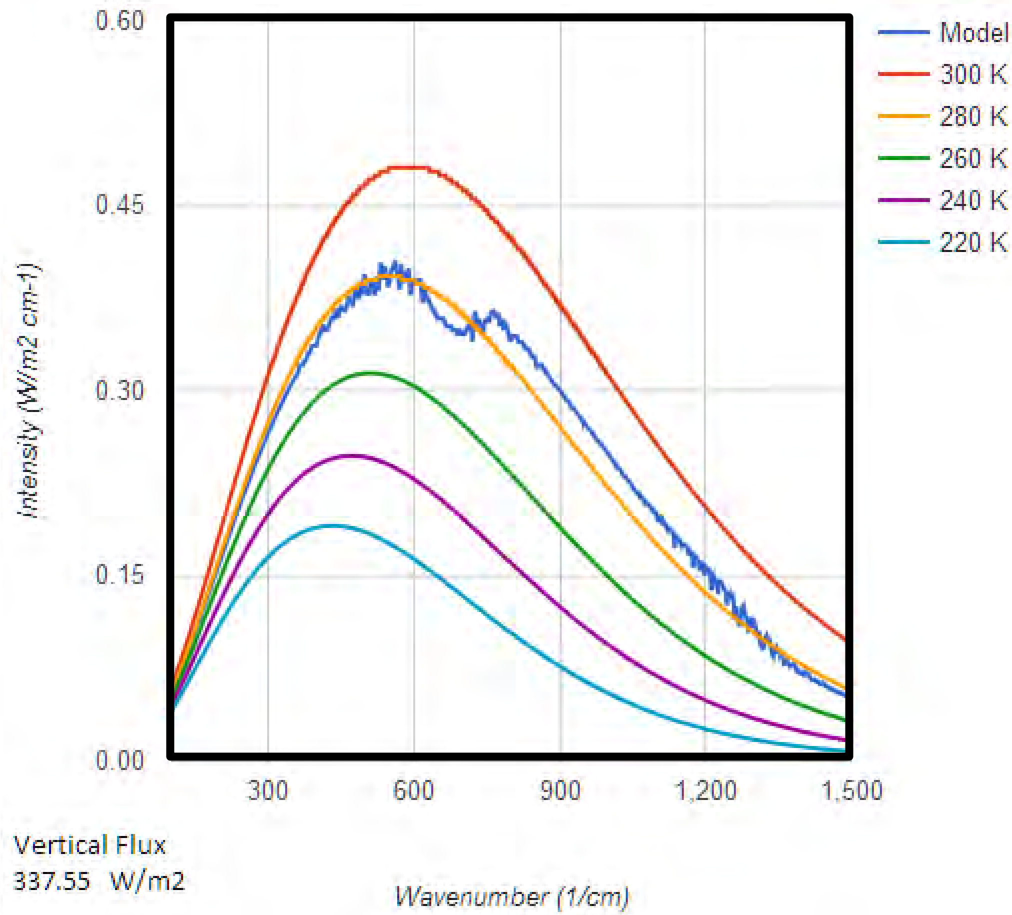
OLR spectrum looking down from h = 1 km



how does the Greenhouse effect work?

Modtran 3 v1.3 imulations with U.S. Standard Atmosphere

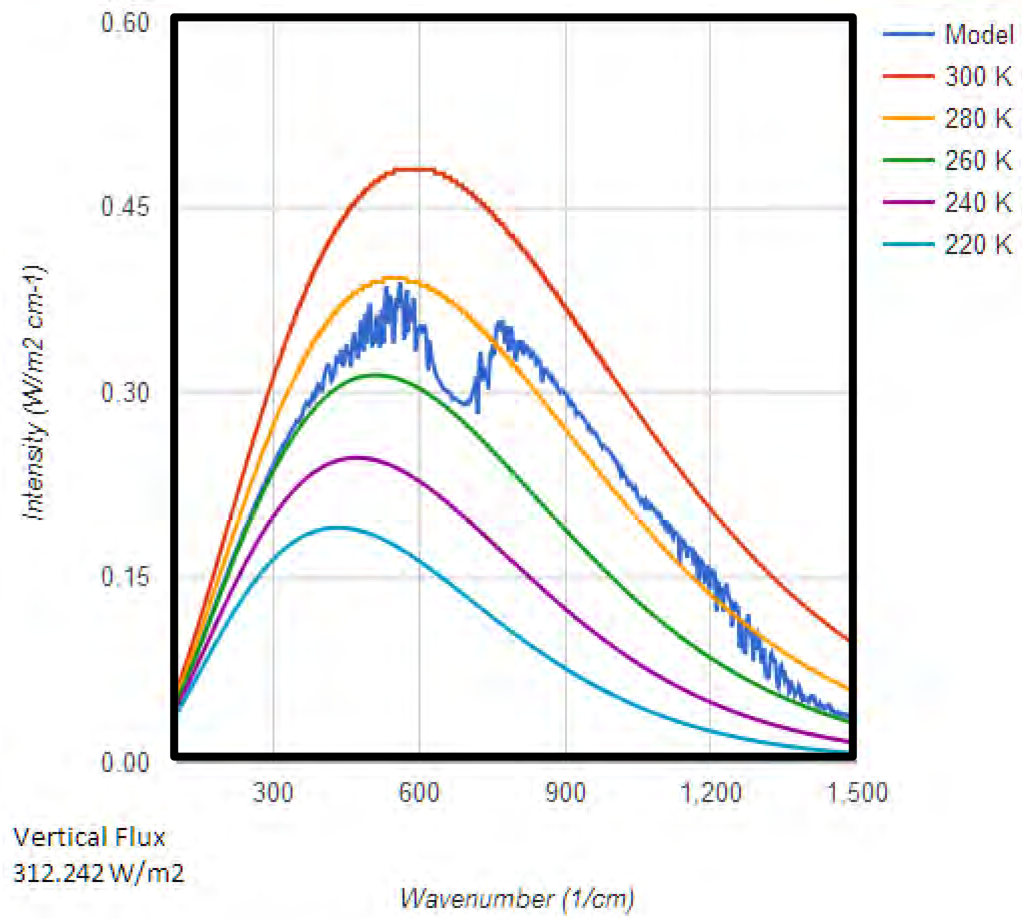
OLR spectrum looking down from h = 2 km



how does the Greenhouse effect work?

Modtran 3 v1.3 imulations with U.S. Standard Atmosphere

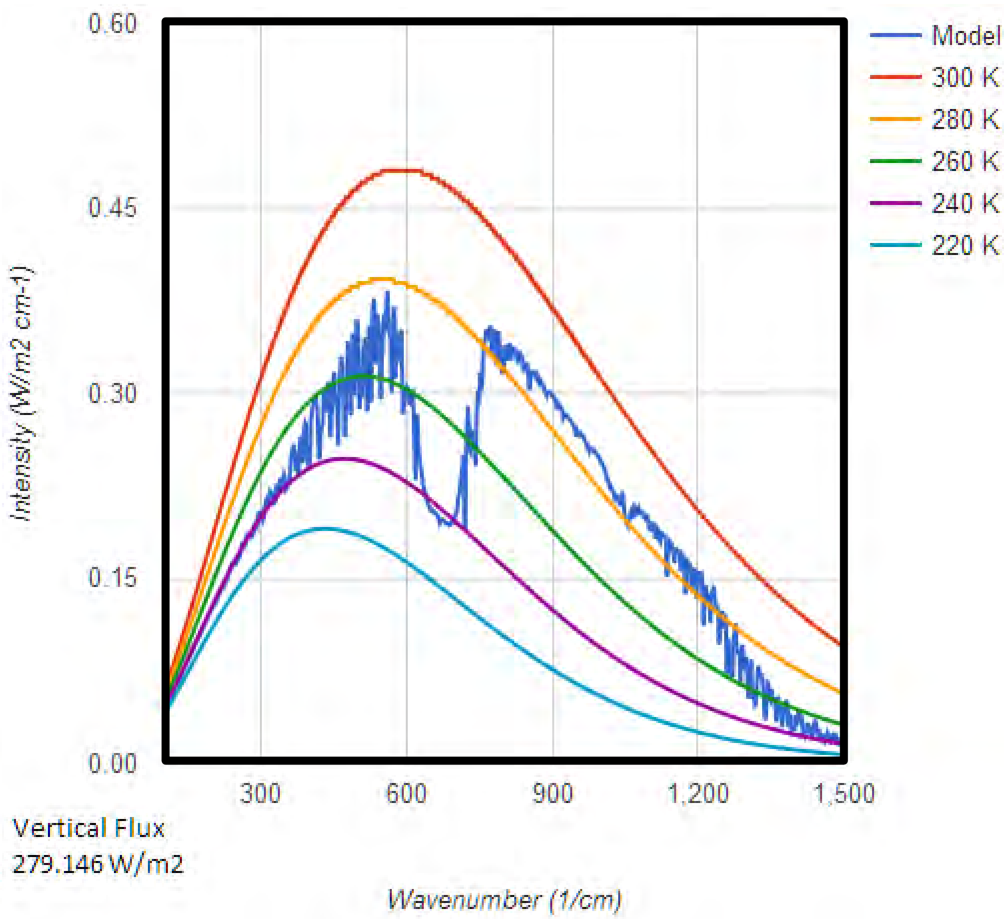
OLR spectrum looking down from h = 4 km



how does the Greenhouse effect work?

Modtran 3 v1.3 imulations with U.S. Standard Atmosphere

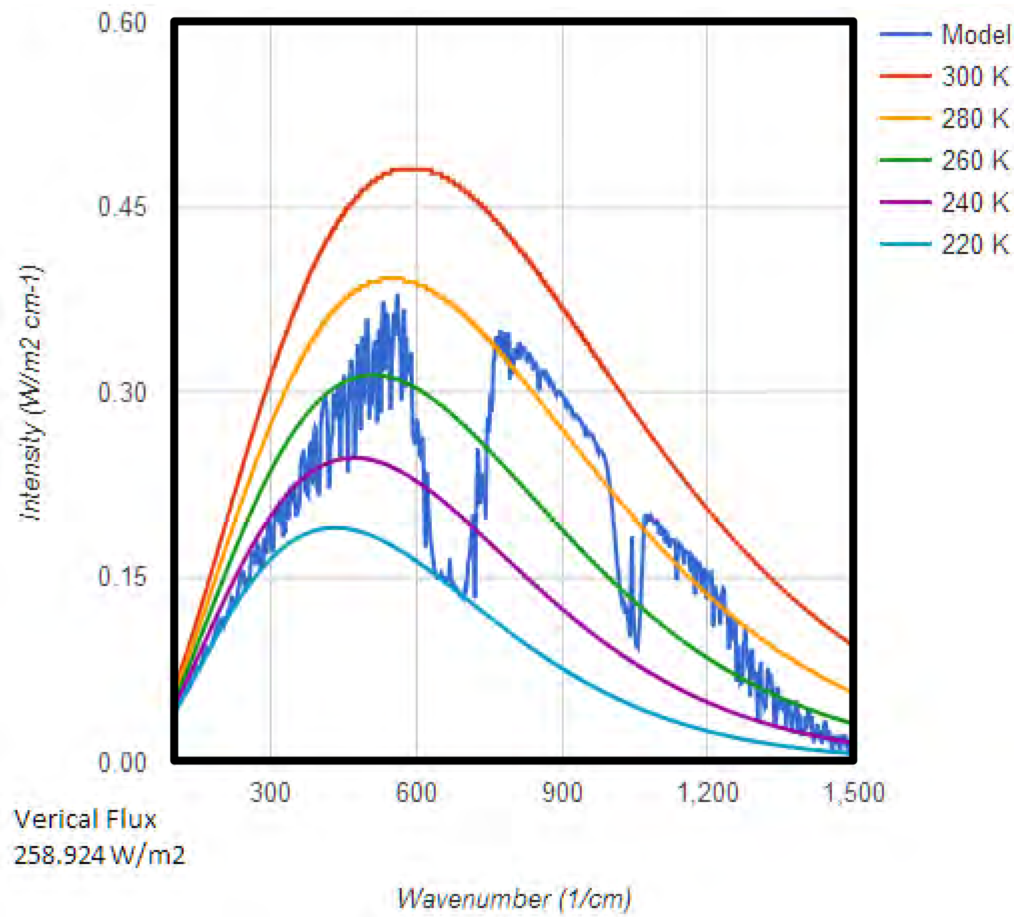
OLR spectrum looking down from h = 8 km



how does the Greenhouse effect work?

Modtran 3 v1.3 imulations with U.S. Standard Atmosphere

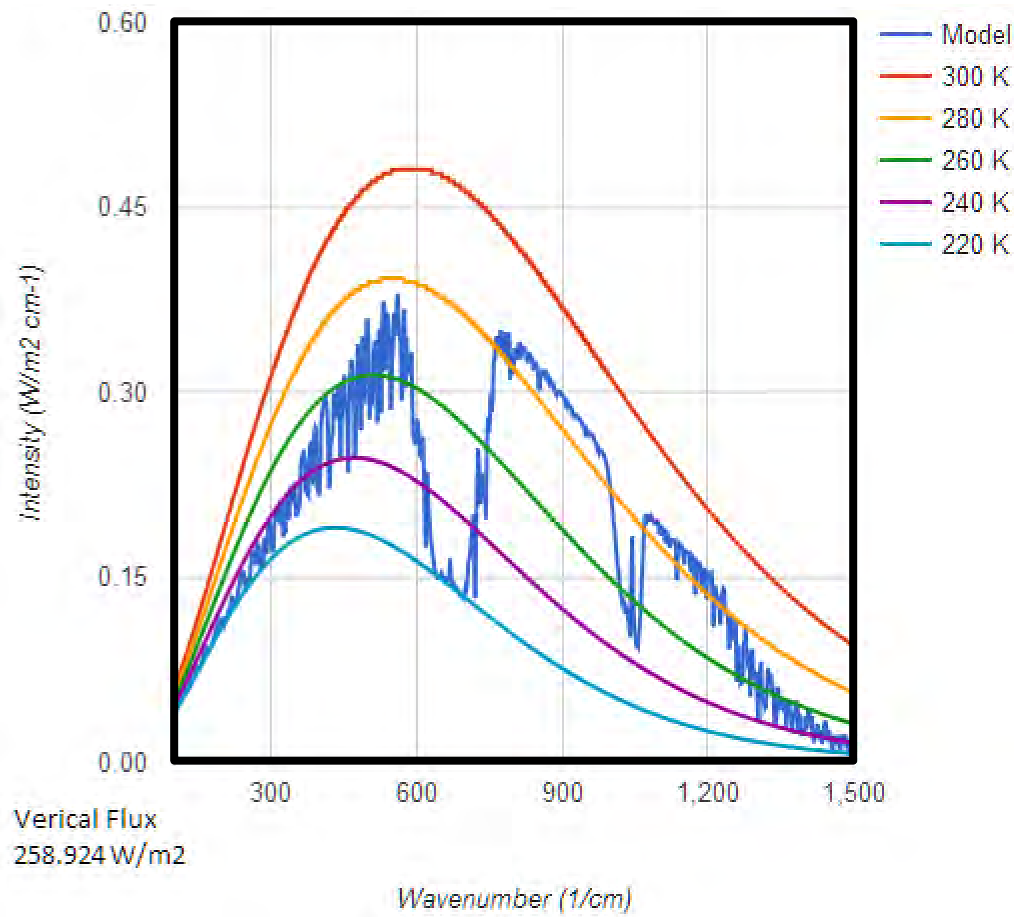
OLR spectrum looking down from h = 16 km



how does the Greenhouse effect work?

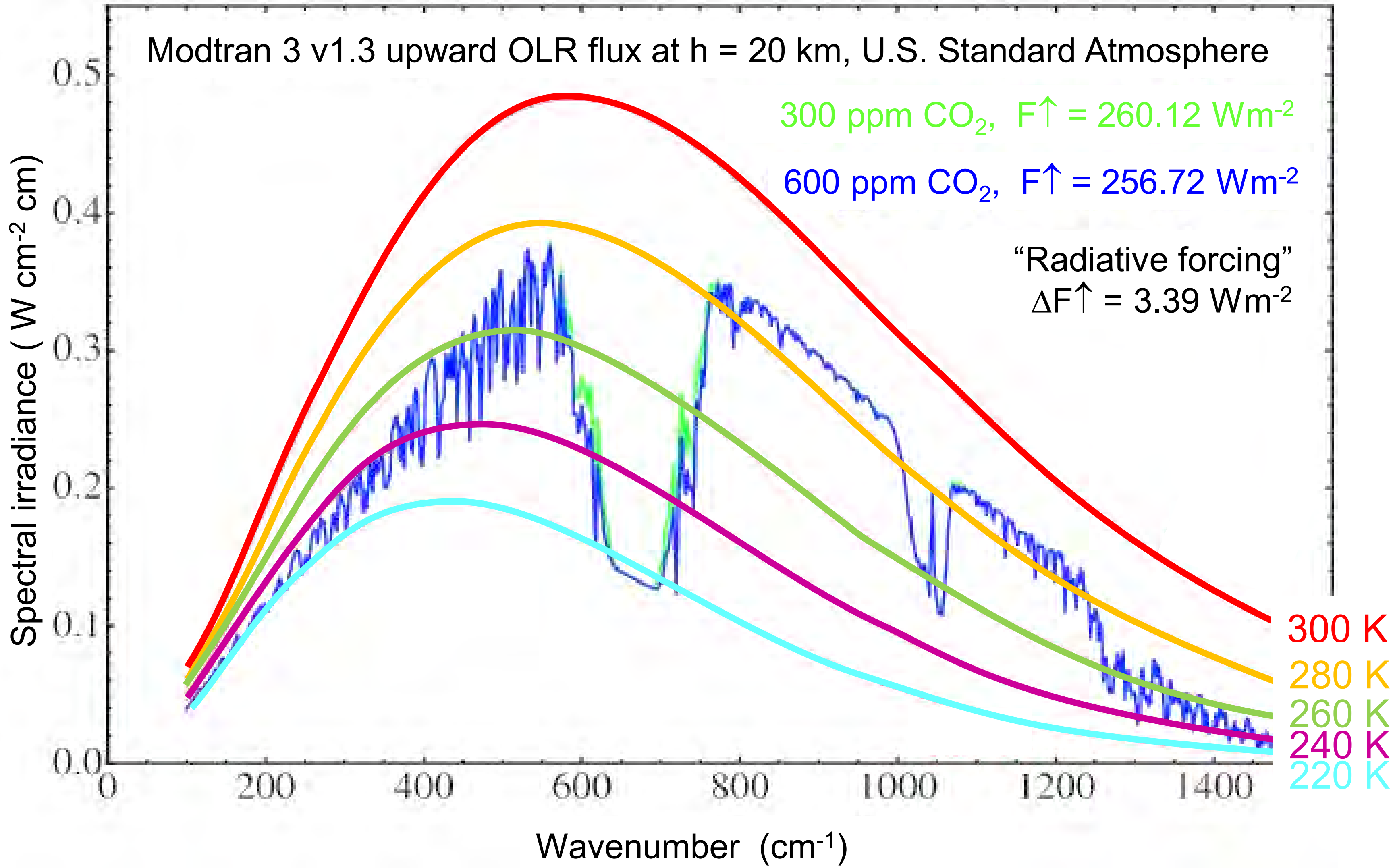
Modtran 3 v1.3 imulations with U.S. Standard Atmosphere

OLR spectrum looking down from h = 32 km



how does the Greenhouse effect work?

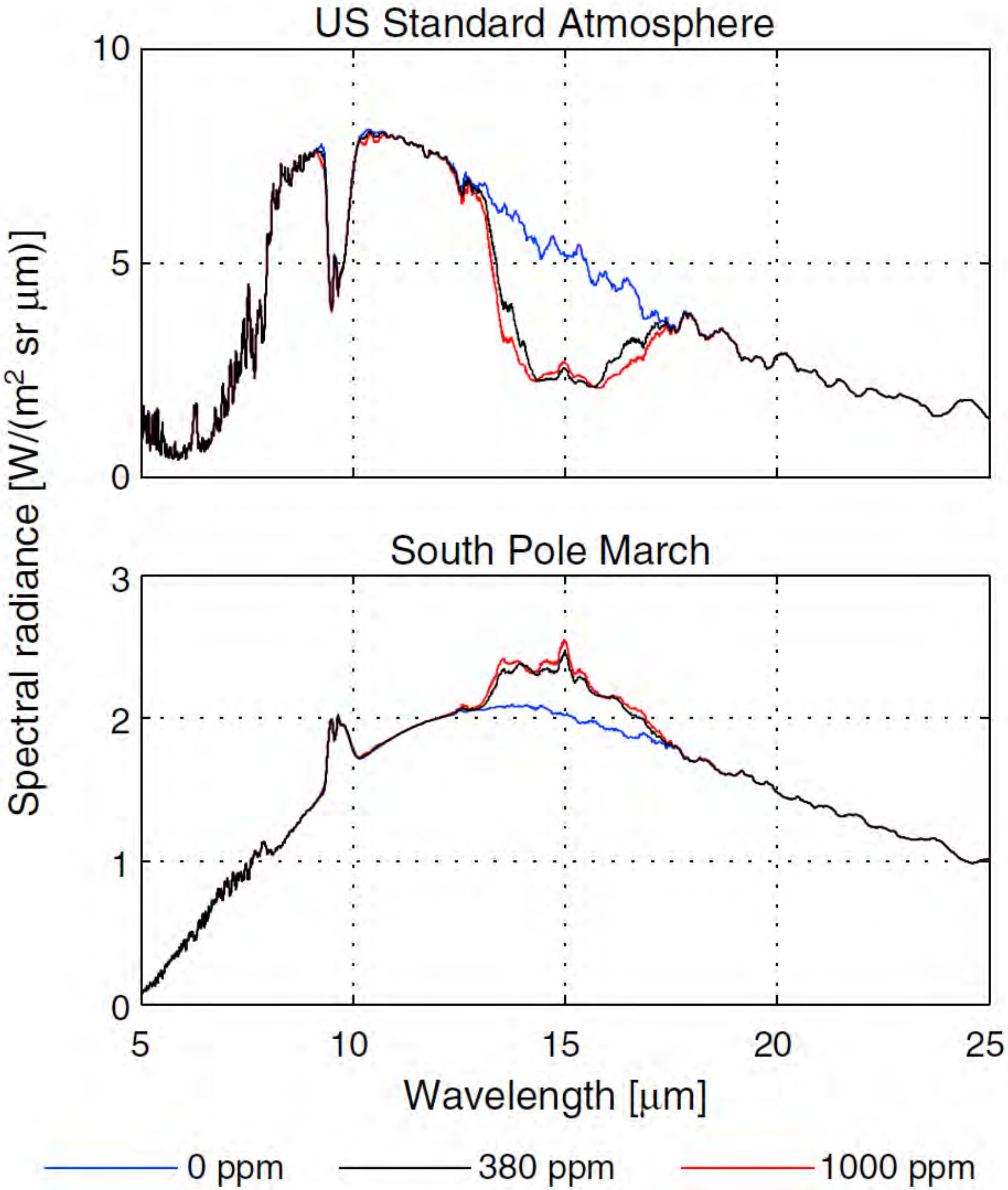
Modtran 3 v1.3 imulations with U.S. Standard Atmosphere



Modtran 3 v1.3 upward OLR flux at h = 20 km, U.S. Standard Atmosphere
300 ppm CO2, F↑ = 260.12 Wm-2
600 ppm CO2, F↑ = 256.72 Wm-2
“Radiative forcing”
ΔF↑ = 3.39 Wm-2
Spectral irradiance (W cm-2 cm)
Wavenumber (cm-1)
0.0
0.1
0.2
0.3
0.4
0.5
0
200
400
600
800
1000
1200
1400
300 K
280 K
260 K
240 K
220 K

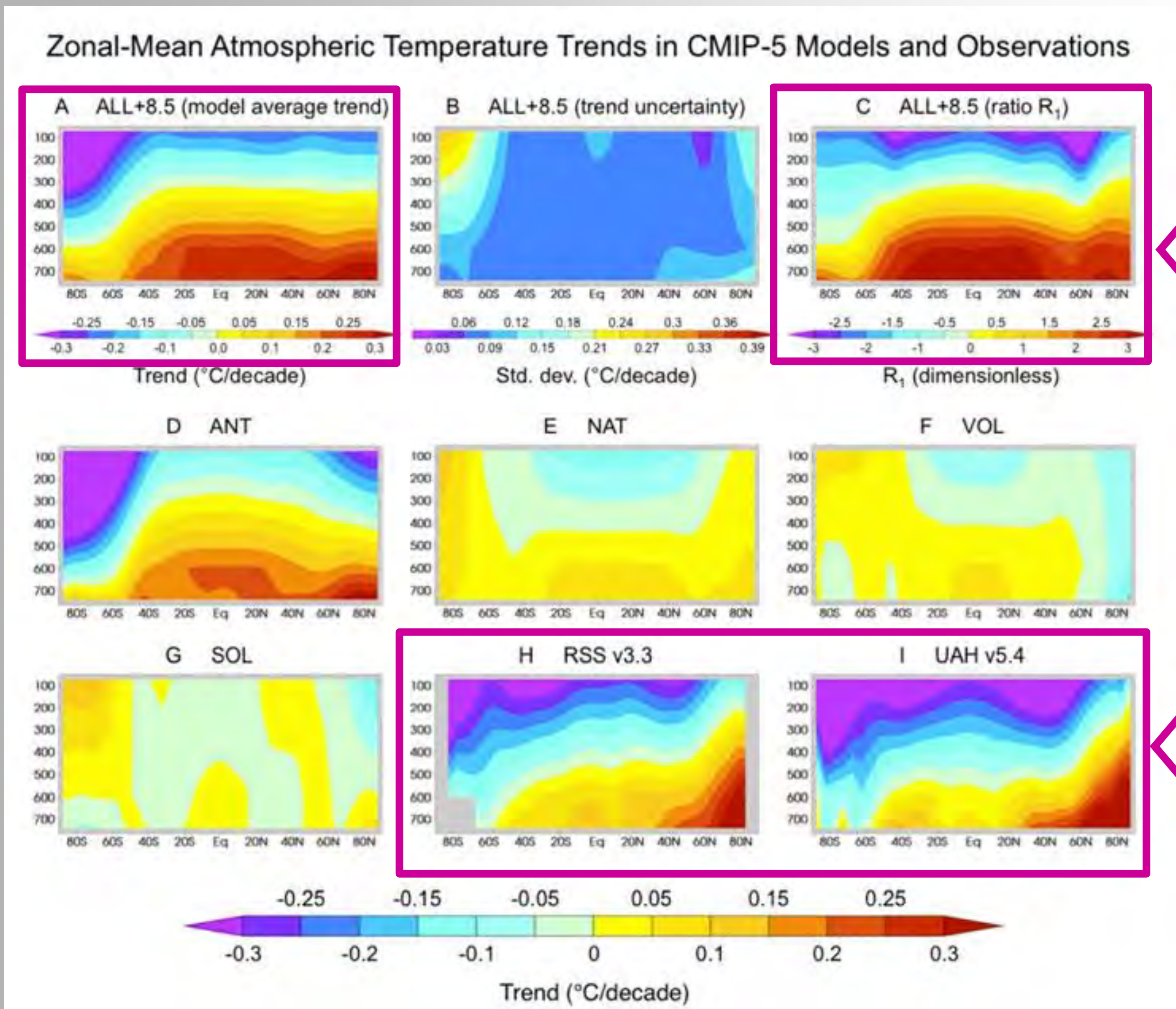
Negative greenhouse effect (observed to sometimes happen in Antarctica when atmosphere at 20-30 km is warmer than at surface)

NB. Plotted against wavelength, λ not wavenumber, $k = 1/\lambda$, so main CO_2 line around $k = 675\ cm^{-1}$ appears at $\lambda = 15\ \mu m$



(Schmithüsen et al, GRL, 2015)

Altitude Variations (observed and modelled zonal mean trends in latitude-altitude plots for 1979-2012) (*Santer et al., 2013*)

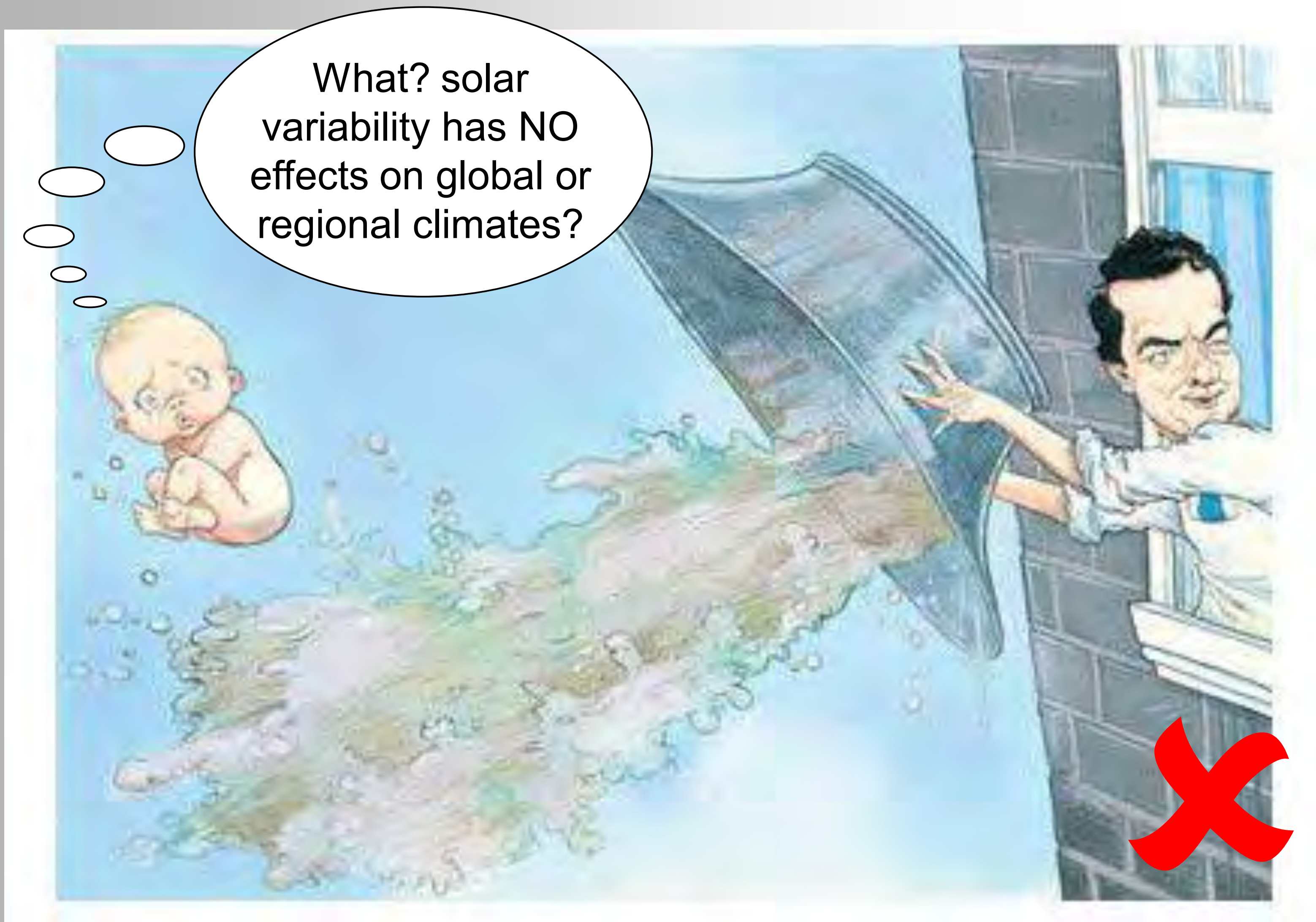


Modelled. Forcings:
ANT = anthropogenic
NAT = natural
VOL = Volcanic
SOL = Solar

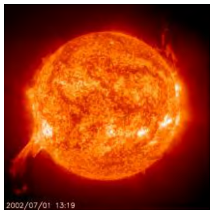
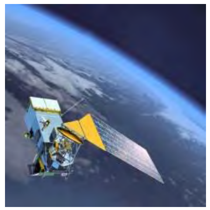
ALL = ANT+NAT
NAT =VOL+SOL

Observed (RSS and UAH analysis of satellite data)

Babies and Bathwater



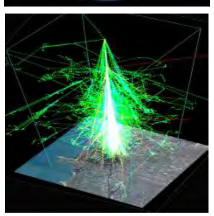
Solar Variability:
Effects on Climate?

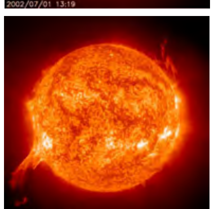
Solar Outputs


Solar Variability


Global Effects

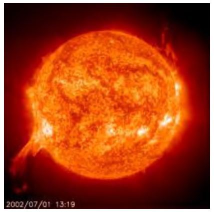



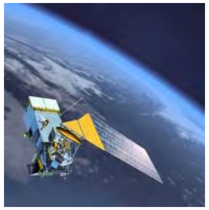
Regional & Seasonal Effects



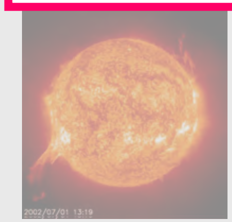

The Future

Solar Variability: Effects on Climate?

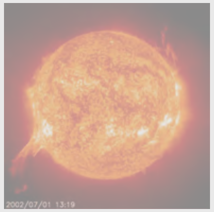
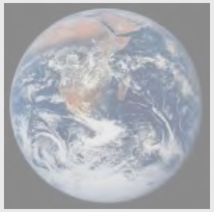




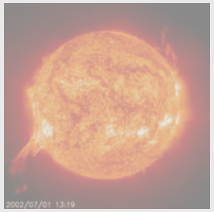
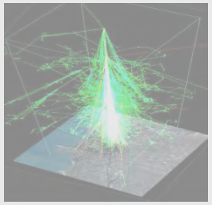
Solar Outputs



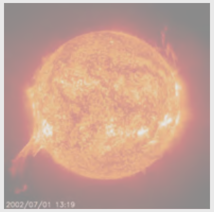

Solar Variability

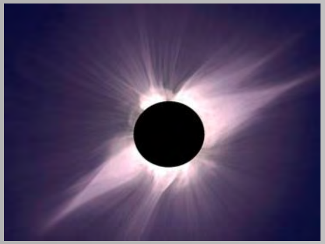
Global Effects

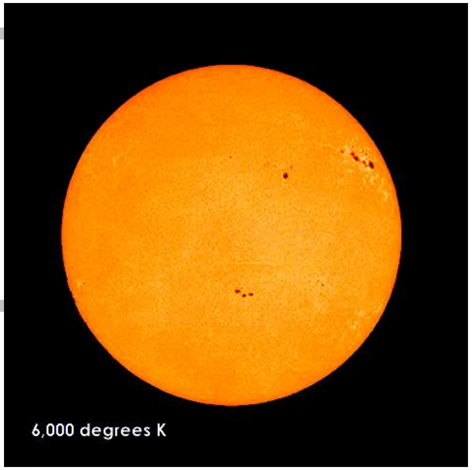
Regional & Seasonal Effects




The Future

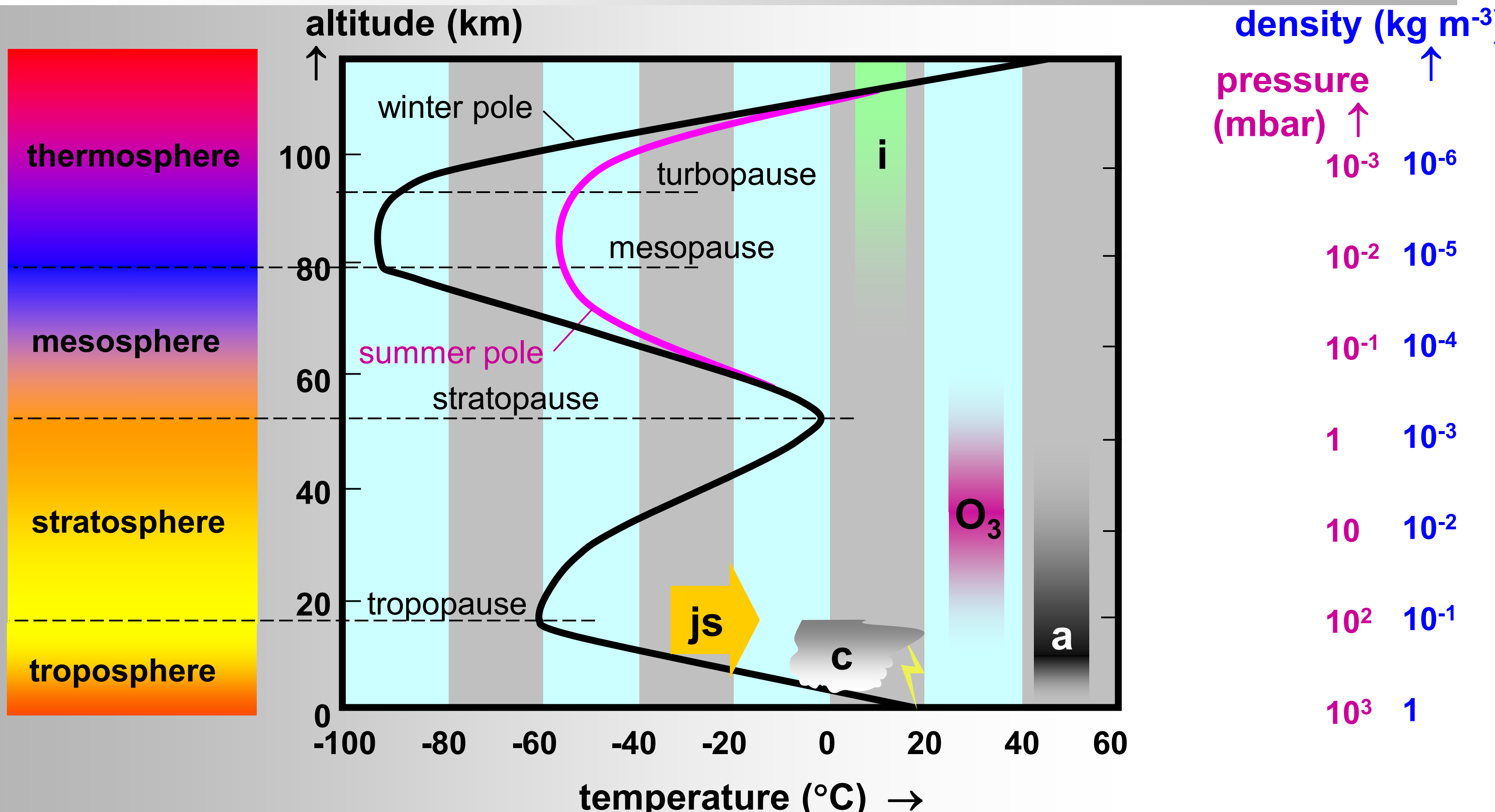


Solar Outputs



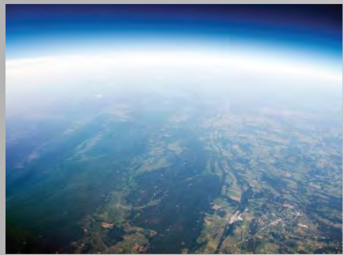
Visible/IR	weakly modulated (~0.1%) by magnetic field in photosphere
UV	modulated (~1%) by magnetic fields threading the lowest solar atmosphere (chromosphere)
EUV	strongly modulated (~50%) by magnetic fields in the solar atmosphere (corona)
X-Rays	fully dependent on (modulated ~90%) by magnetic fields in the solar atmosphere (corona)
Solar wind	~65% modulated over the solar magnetic cycle
Cosmic Rays	~20% - 40% modulated (at 10 - 1GeV) by solar magnetic field irregularities in heliosphere
SEPs	~100% modulated by transient magnetic fields in solar flares & ahead of interplanetary coronal mass ejections

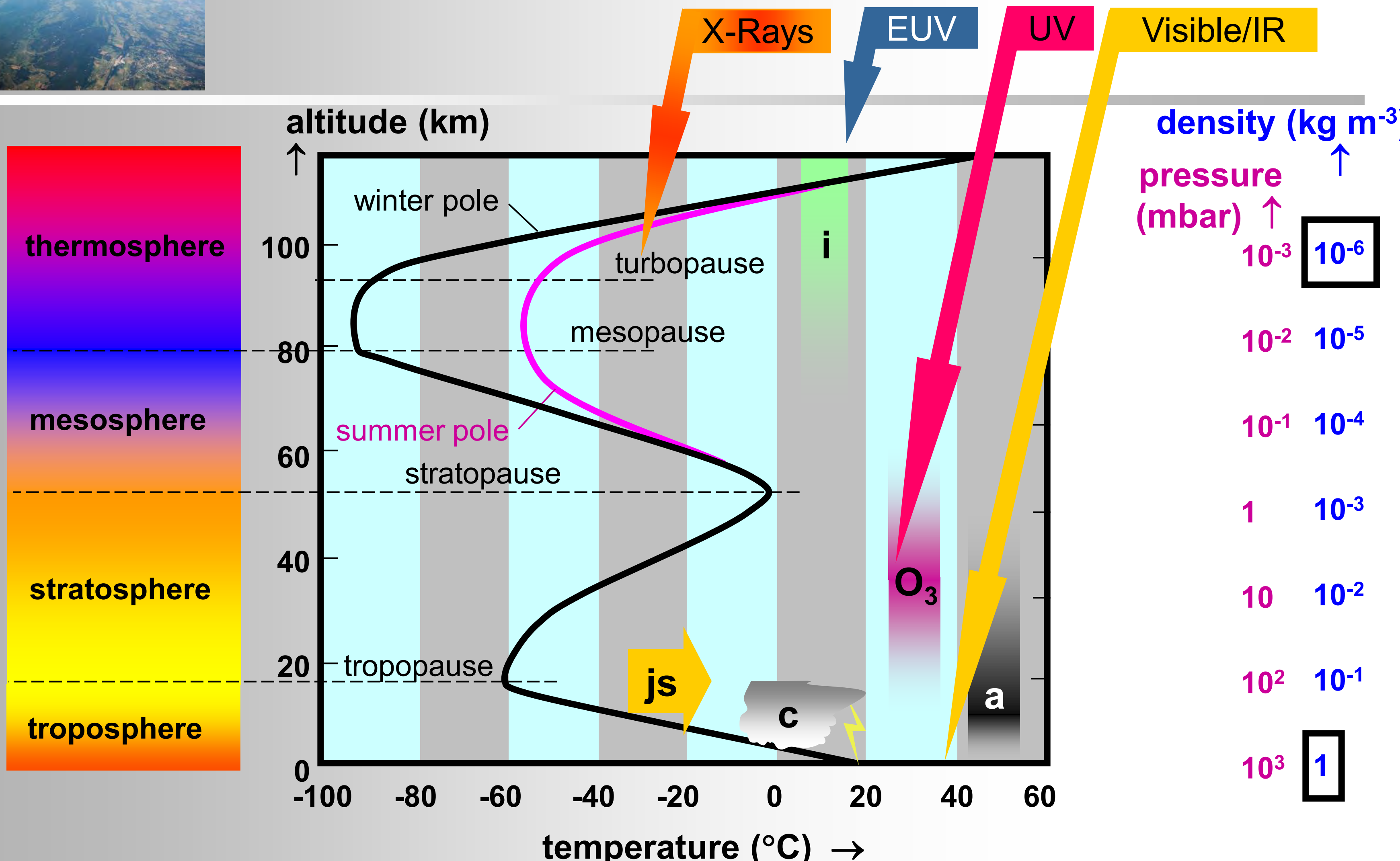
Earth’s atmosphere



O_3 = ozone layer	a = aerosols	js = jet stream
c = cloud	i = ionosphere	

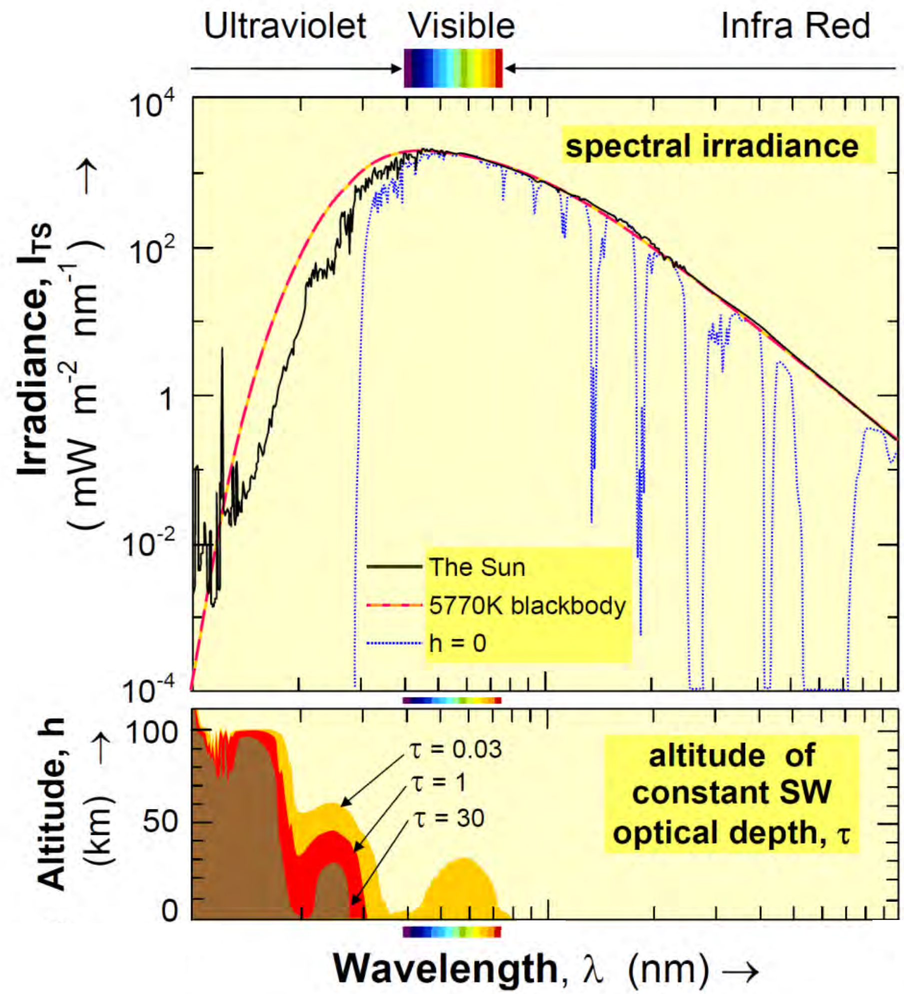
Electromagnetic solar inputs



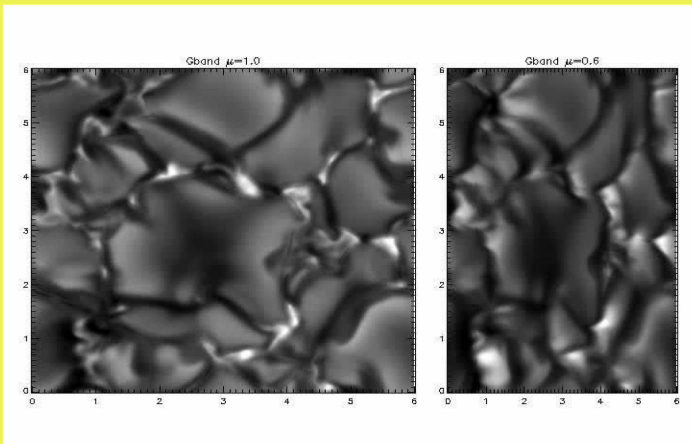


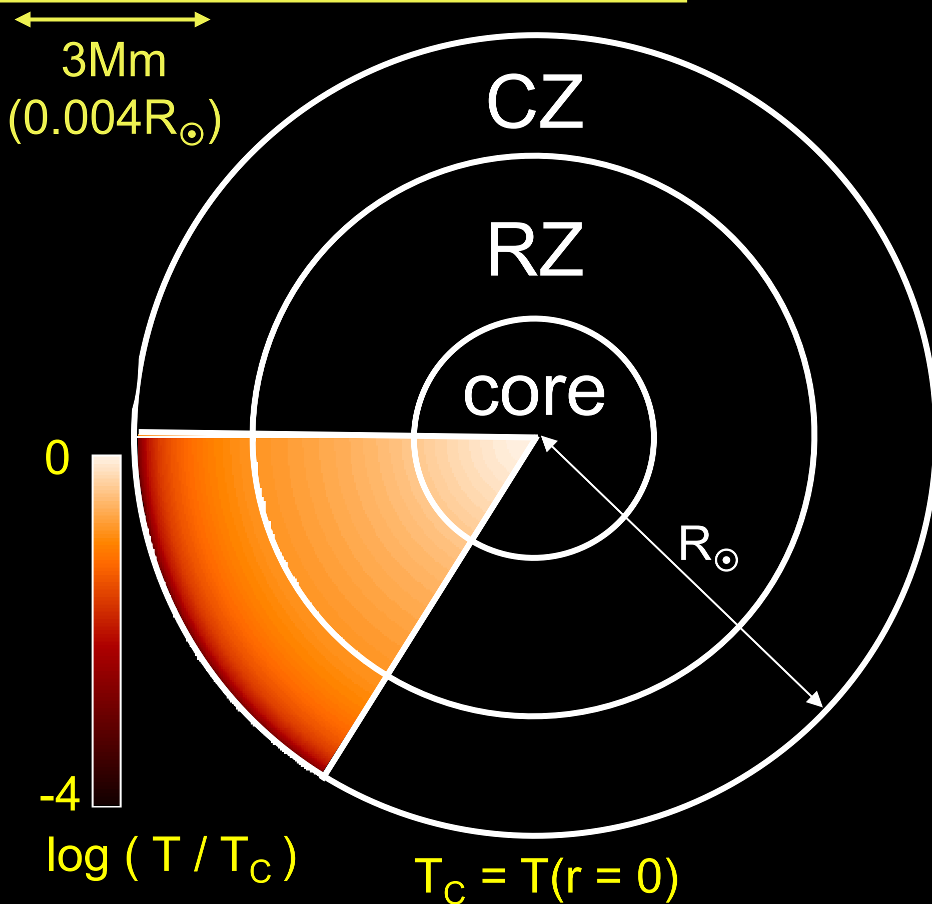
O_3 = ozone layer a = aerosols js = jet stream
c = cloud i = ionosphere

- The Sun’s e-m radiation spectrum
- Close to a 5770K blackbody radiator
- Emitted flux $F = \varepsilon\sigma T_{sun}^4$
- $\varepsilon \approx 1$ and surface temperature of Sun $T_S = 5770K$



Implications of high CZ mass





CZ contains ~3×10^{28}kg ($M_\odot/60$)

thermal timescale of the CZ as a whole = timescale for its warming or cooling, $\tau \approx 10^5$ yr

Switch off source at base of CZ and in t = 100 yr, T_{sun} changes by 1- exp(t/τ) = 0.001

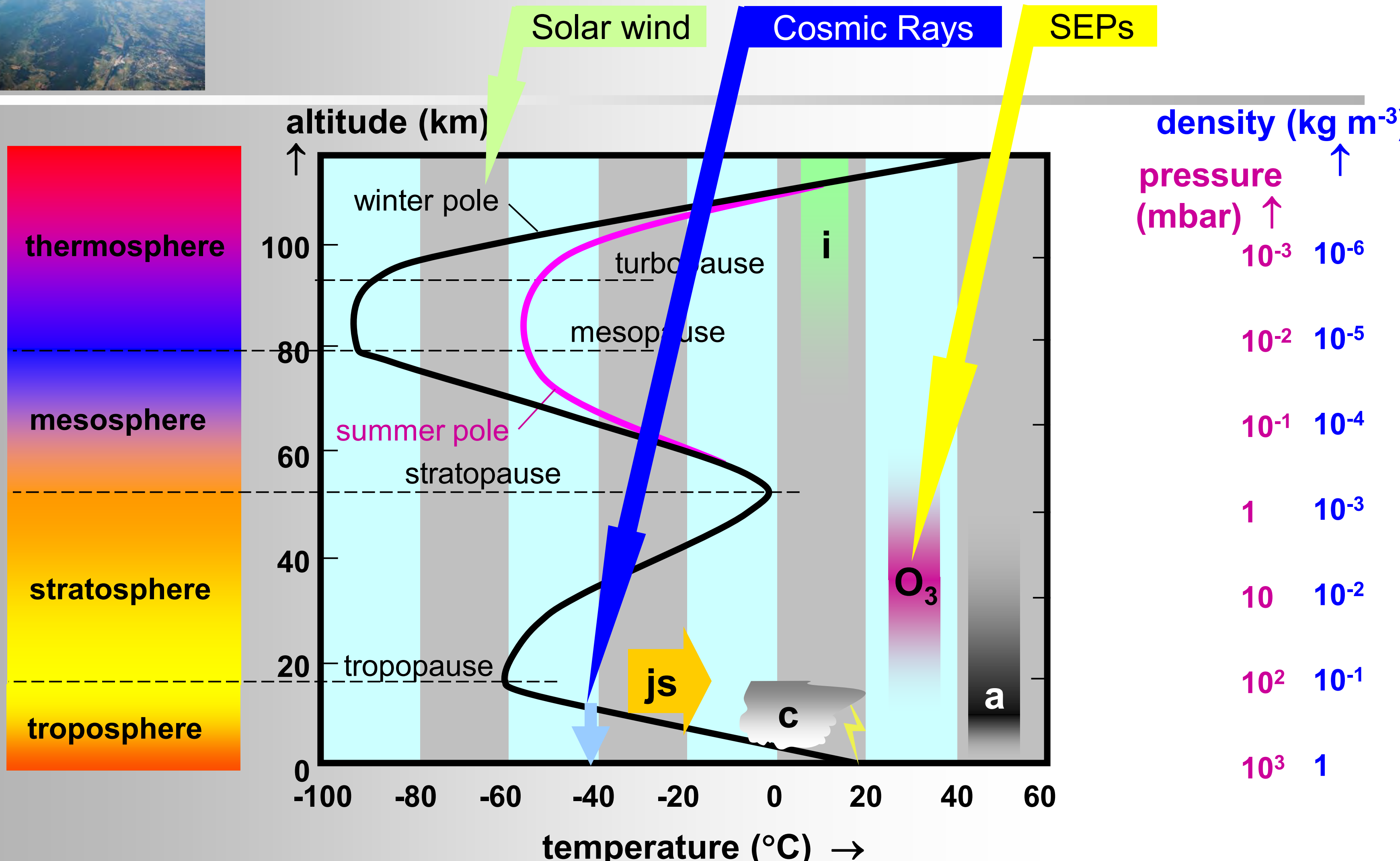
$F = \varepsilon\sigma T_{sun}^4$ so that

$F'/F = (T_{sun}'/T_{sun})^4$

$= 0.999^4 = 0.996$

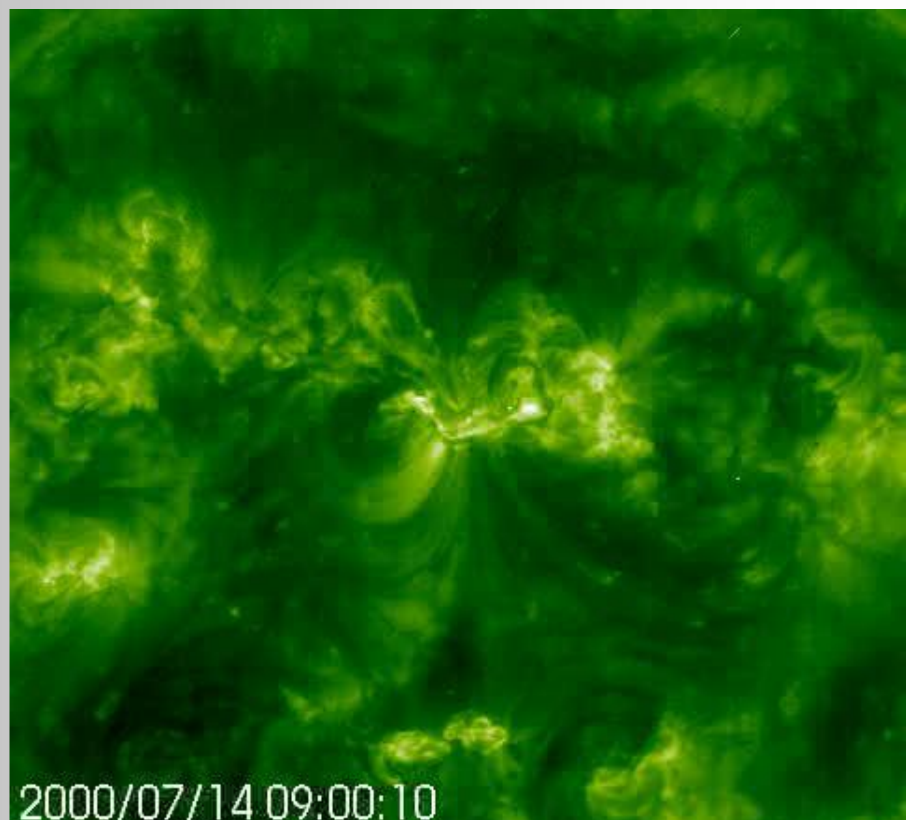
i.e. F changes by just 0.4%

Corpuscular solar inputs



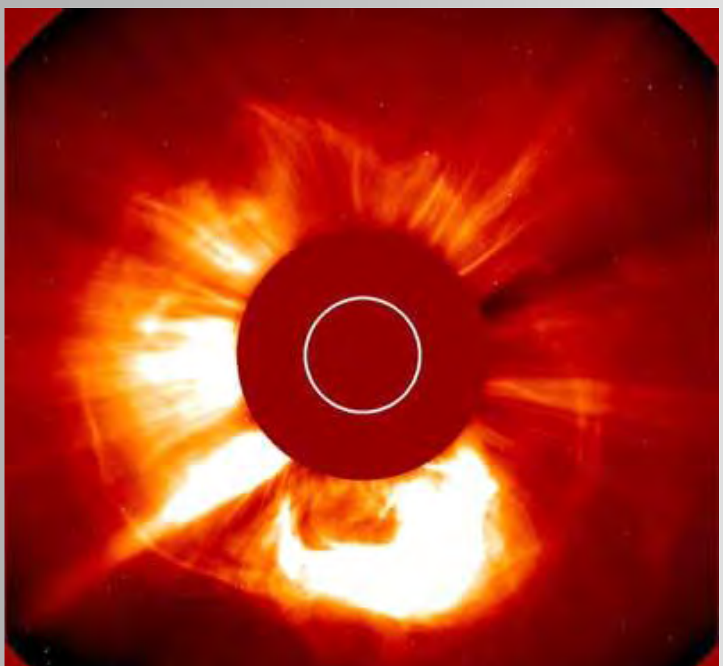
O_3 = ozone layer   a = aerosols   js = jet stream
c = cloud   i = ionosphere

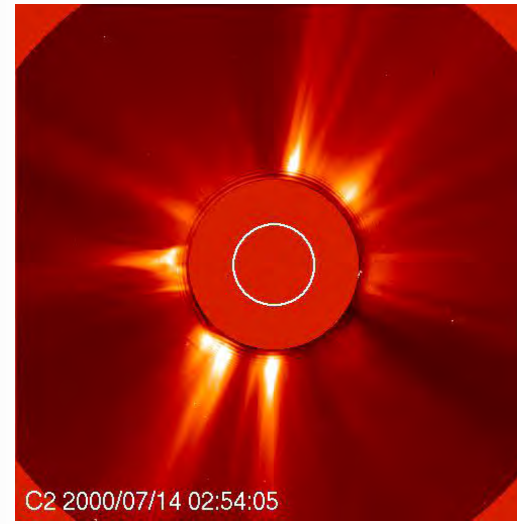
- CME hit Earth on 14th July 2000
- Start of the Story: the associated flare



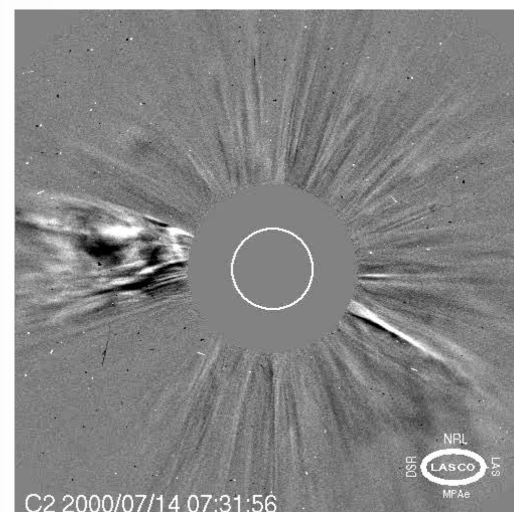
The Bastille Day Storm CME

seen by SoHO/Lasco C2 and C3 Coronographs





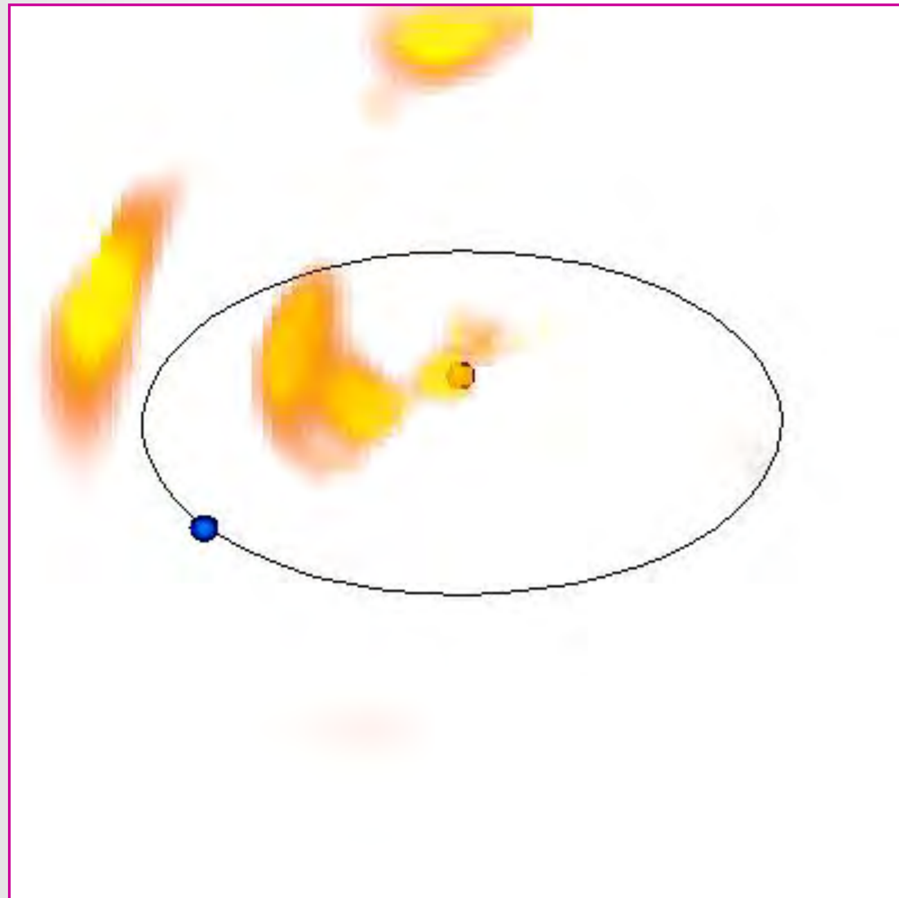
- "Halo" (Earthbound) form most easily seen in C2 difference movie ▸



The Bastille Day Storm

CMEs seen by IPS

- Tomographic reconstruction from interplanetary scintillations



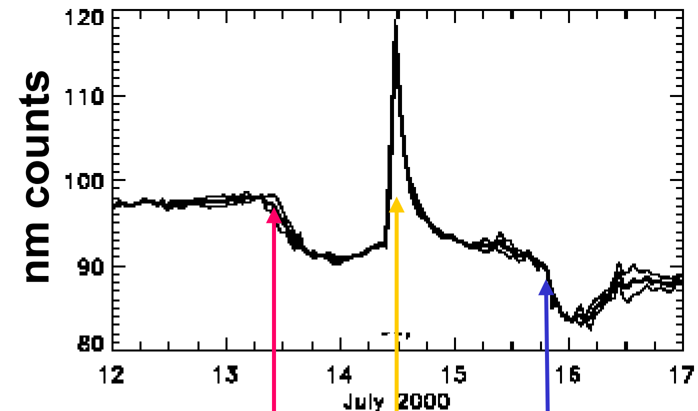
The Bastille Day Storm

GCRs and SEPs

- Ground-level enhancement (GLE) of solar energetic particles seen between Forbush decreases of galactic cosmic rays caused by shielding by the two CMEs

- Here seen at stations in both poles (McMurdo and Thule)

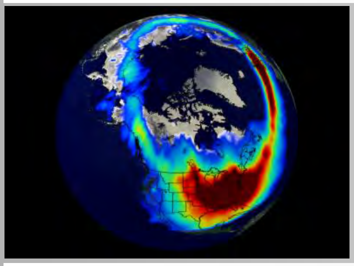
Neutron Monitor counts



GLE

Forbush decrease caused by 1st CME

Forbush decrease caused by CME associated with GLE



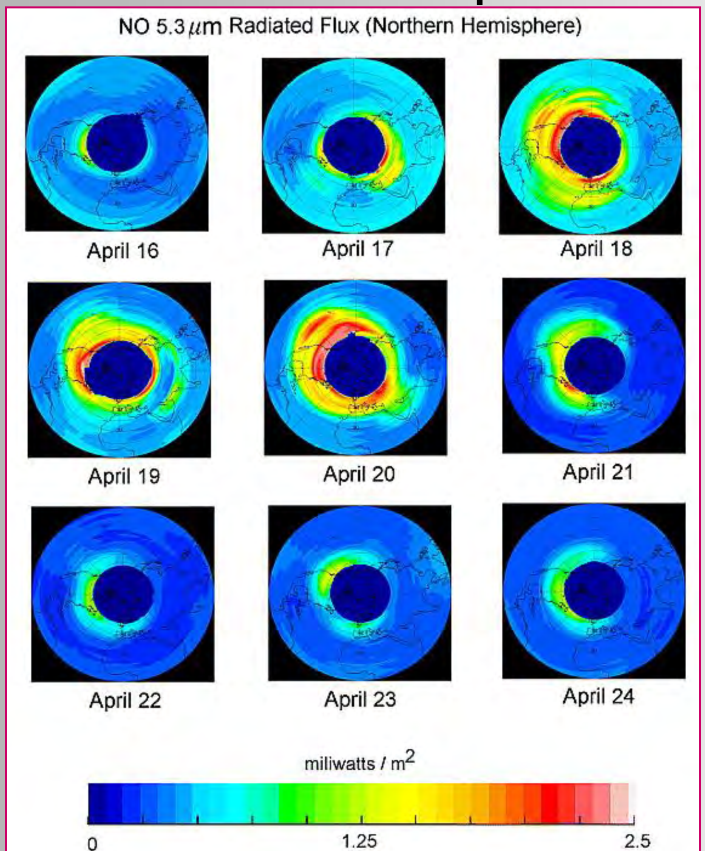
The Bastille Day Storm

SEP Proton Aurora – seen by Image FUV-SI12

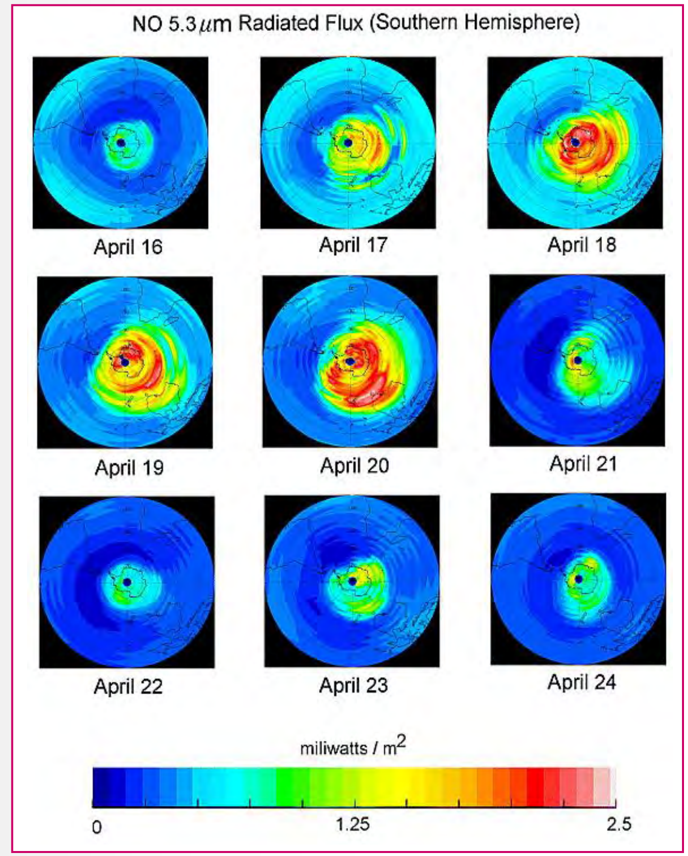
Polar Cap NO

From SEP event of April 2002

- Northern hemisphere



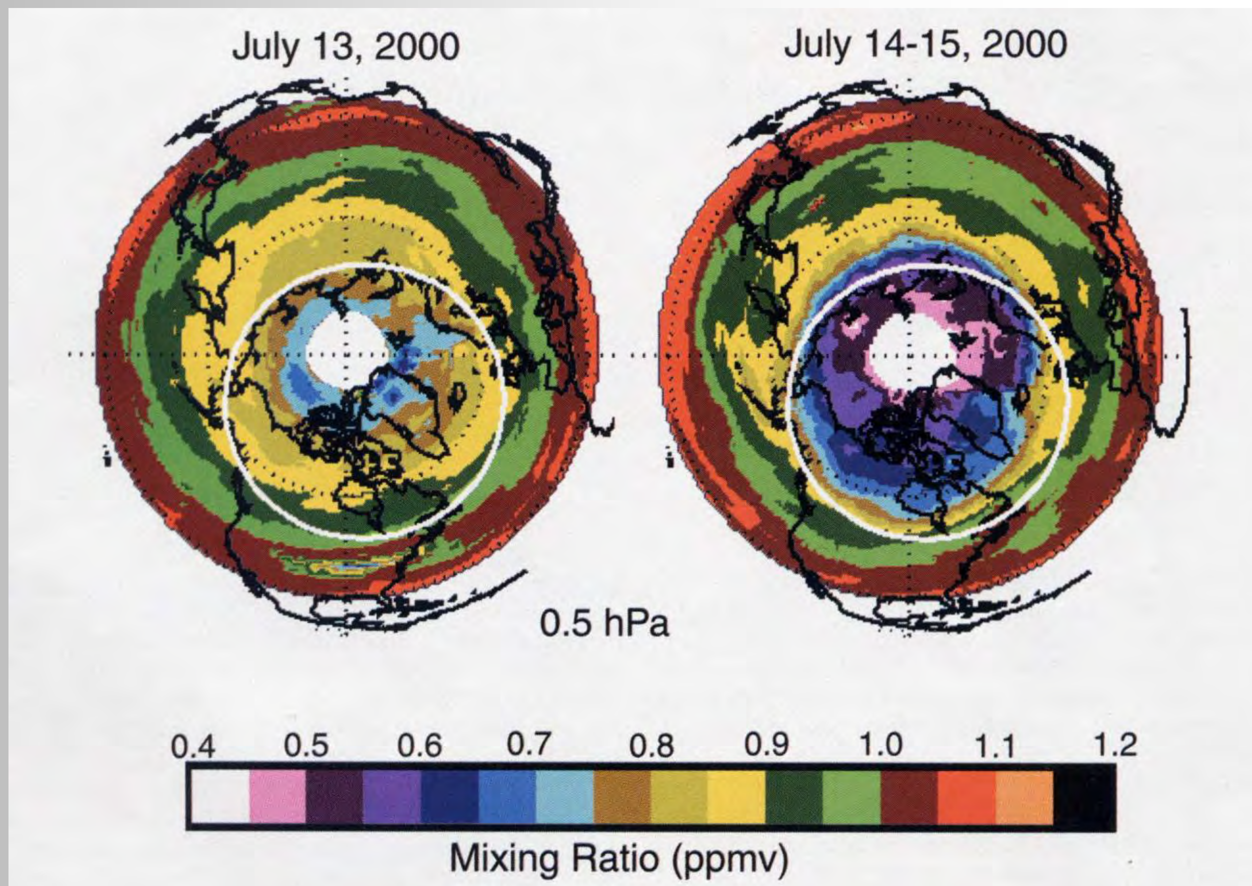
- Southern hemisphere



TIMED observations of 5.3 μm NO radiative fluxes (Wm^2)

(Mlynczak et al., 2003)

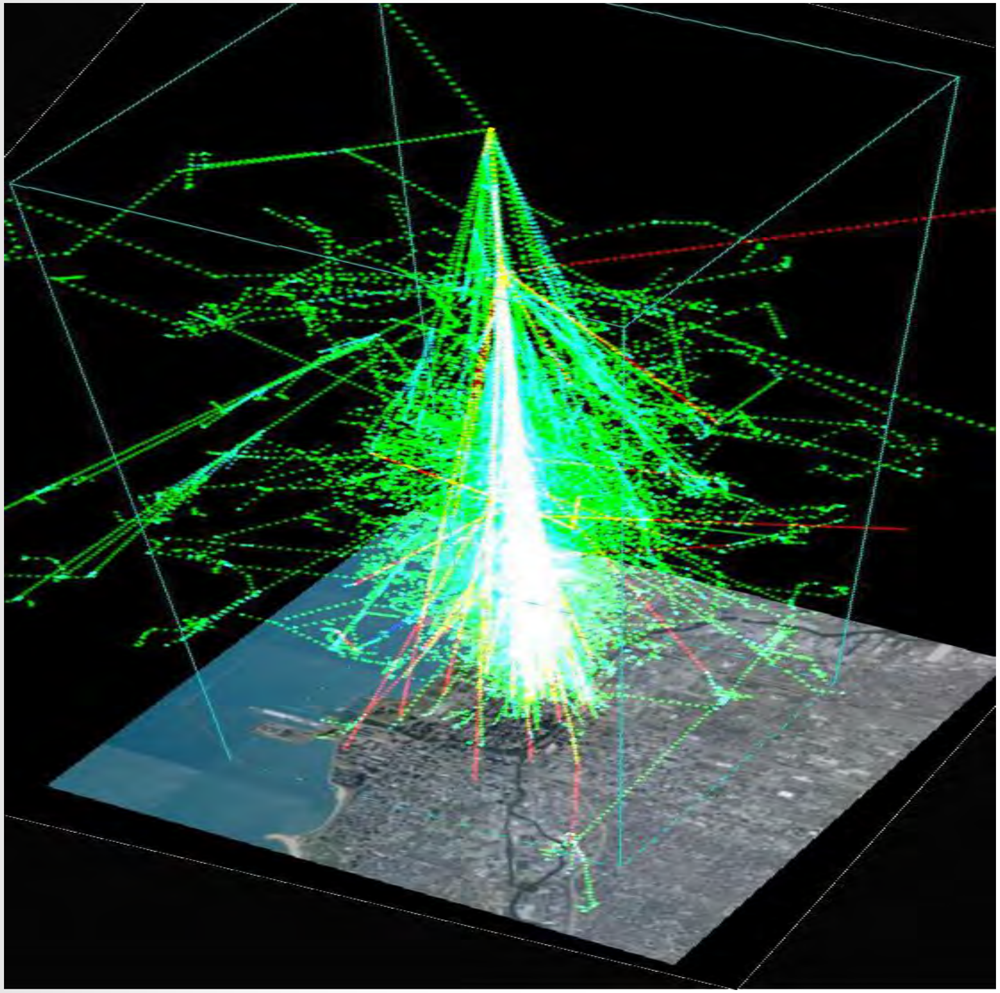
Storm Event – SEP Ozone Depletion



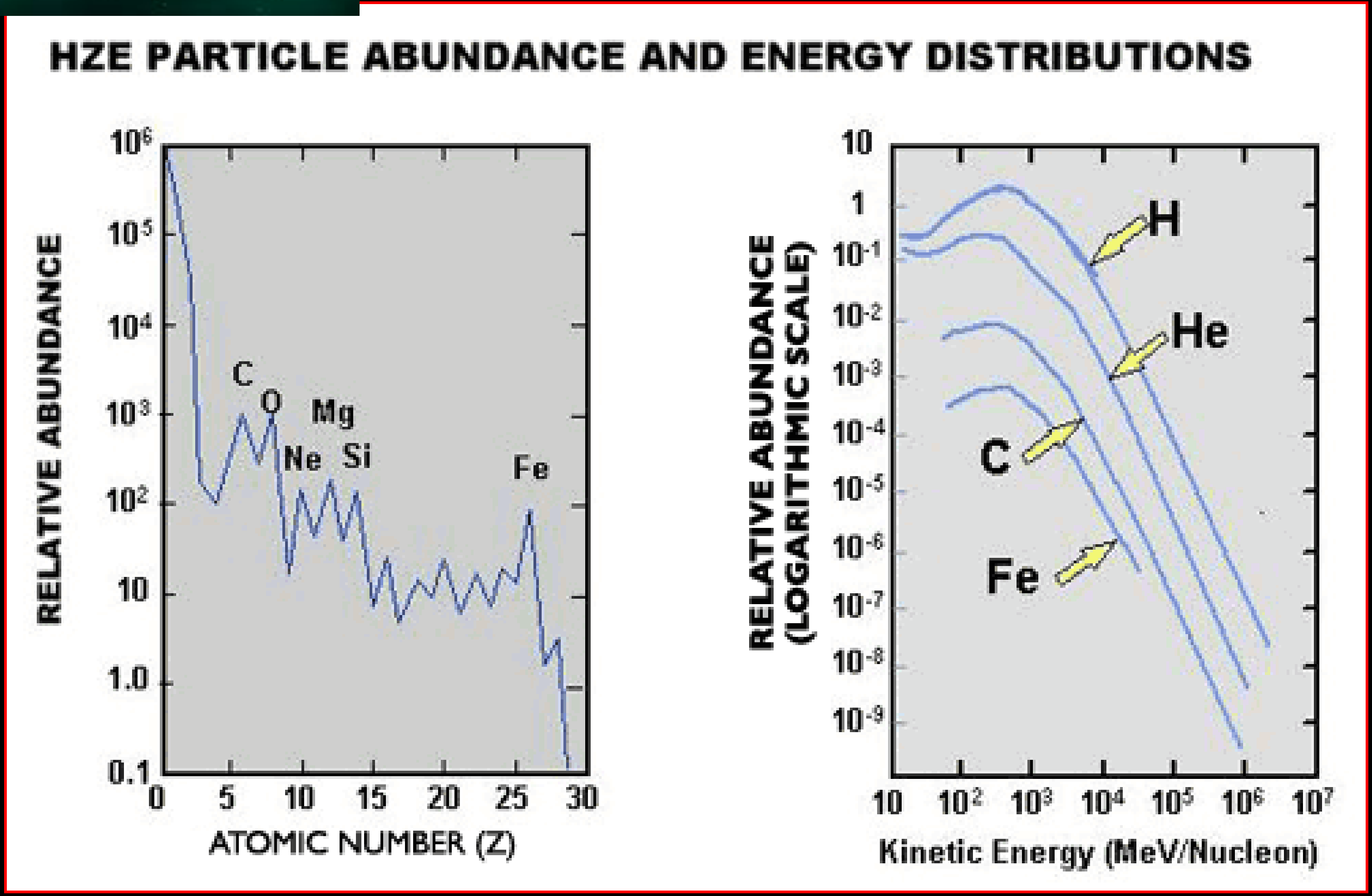
Energetic Particles

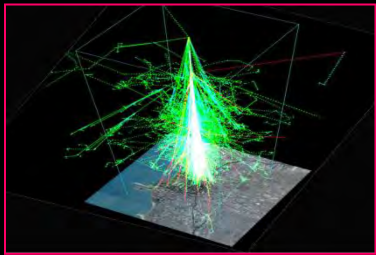
Galactic Cosmic Rays

- Generated at the shock fronts ahead of supernovae
- Protons up to iron ions, travelling at close to speed of light
- Three shields protect us on Earth's surface:
  - The heliospheric field
  - Earth's magnetic field
  - Earth's atmosphere

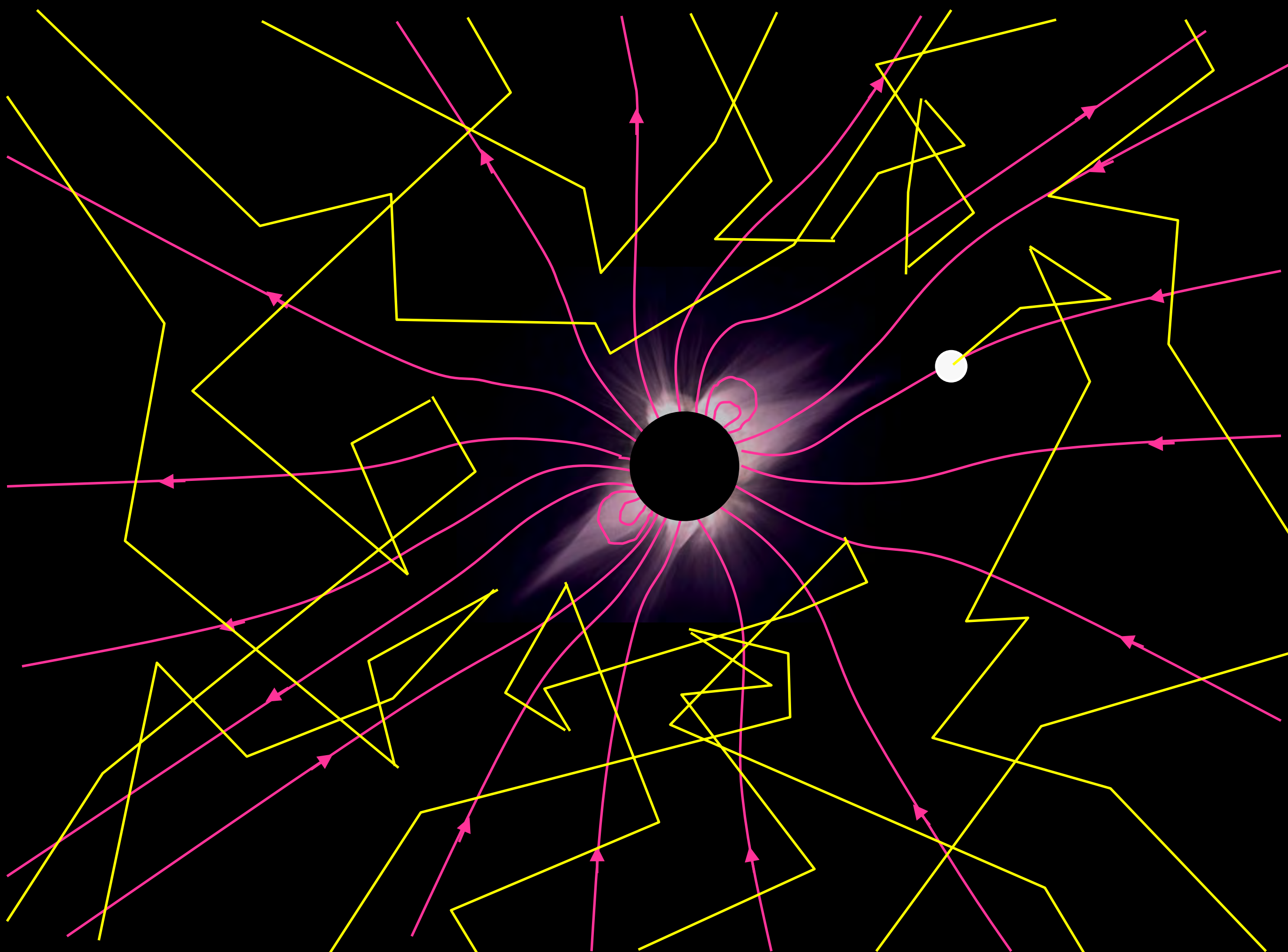



Galactic Cosmic Ray Spectra

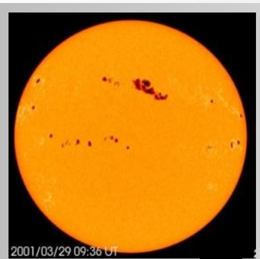




Galactic Cosmic Rays

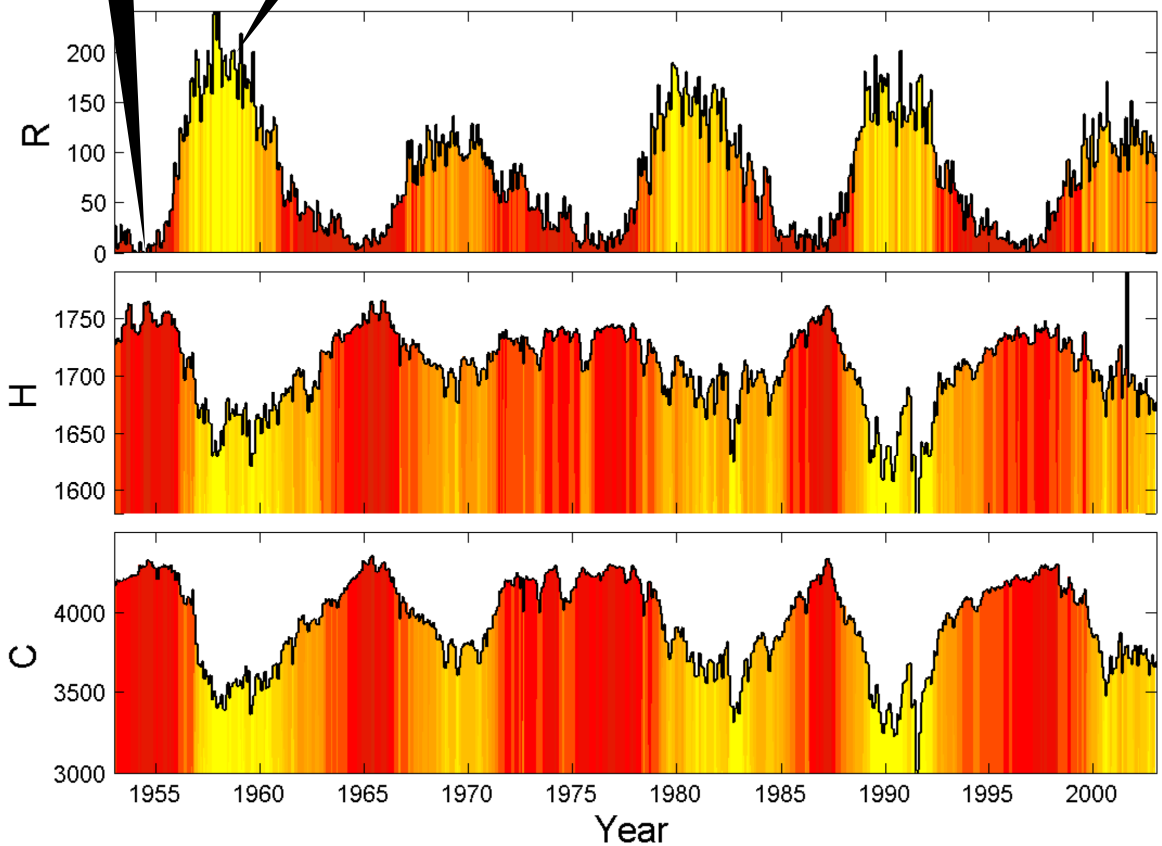


The coronal source flux is dragged out by the solar wind flow to give the heliospheric field which shields Earth from galactic cosmic rays



Cosmic Rays

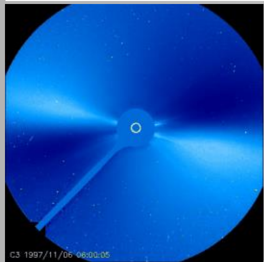
Anticorrelation with sunspot numbers



Sunspot Number

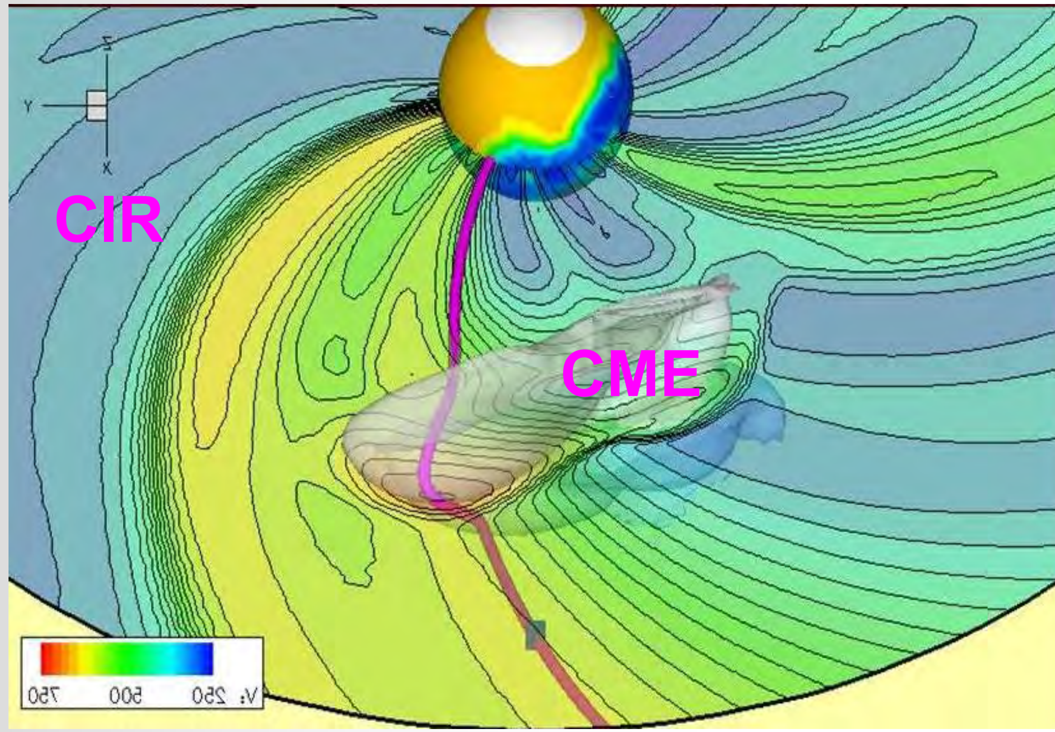
Huancauyo – Hawaii neutron monitor counts (>13GV)

Climax neutron monitor counts (>3GV)



CMEs, CIRs, GCRs and SEPs

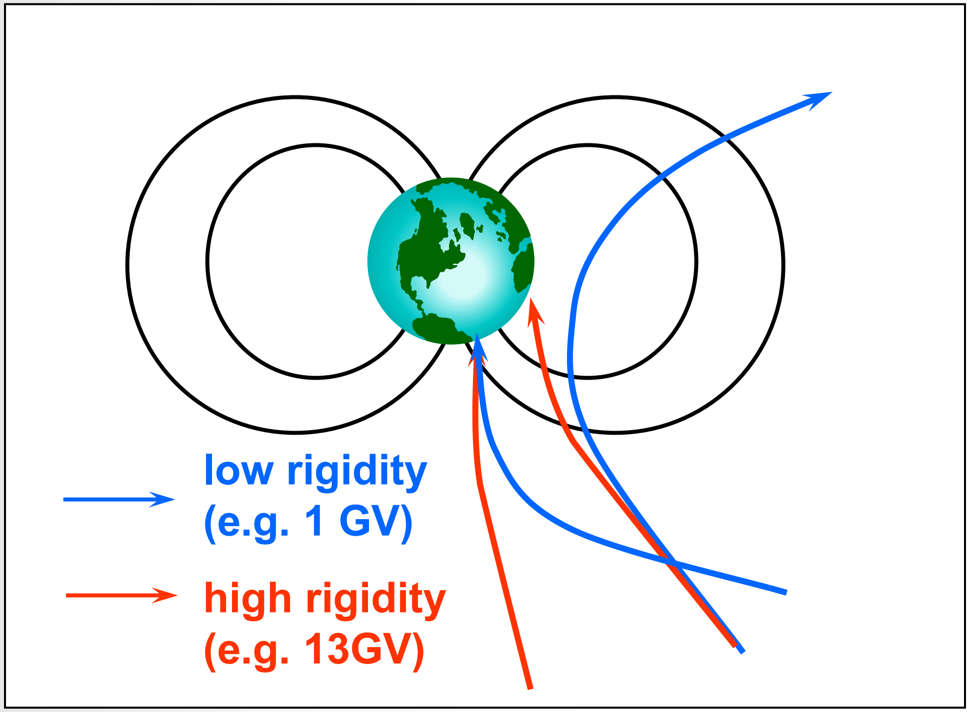
- Both CME fronts and CIRs shield Earth from Galactic Cosmic Rays by scattering
- Both CME fronts and CIRs generate SEPs
- Both CMEs and CIRs are more common and more extensive at sunspot maximum



Geomagnetic Shielding of GCRs

(Cut-off rigidity)

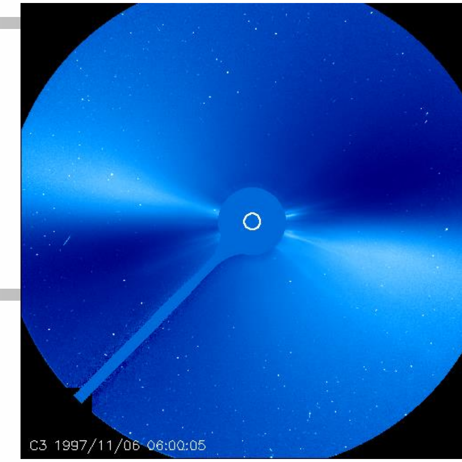
- **Rigidity** is a measure of the extent to which cosmic rays maintain their direction of motion
- It is measured in GV (v ≈ c, nGV rigidity ≡ energy ≈ nGeV)
- Higher rigidity GCRs can penetrate to lower geomagnetic latitudes



- minimum rigidity that can be seen at a magnetic latitude called the "rigidity cut-off" (e.g.) for Hawaii and Huancayo ≈ 13GV for Climax (Boulder) ≈ 3GV
- At highest latitudes rigidity cut-off set by atmosphere at ≈ 1GV

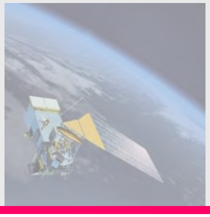
Cosmic ray tracks in a bubble chamber

Solar Output
Signals in Troposphere



Visible/IR	at most, very small “bottom up” signals reported in troposphere
UV	clear heating effects in statosphere (ozone layer) – may have subtle “top down” effects on troposphere
EUV	dominates thermosphere, no evidence nor credible mechanism for coupling to the troposphere
X-Rays	major effects in thermosphere, no evidence or credible mechanism for for coupling to the troposphere
Solar wind	same as for EUV and X-rays
Cosmic Rays	proposed modulation of cloud cover: effect on surface temperatures depends critically on cloud height
SEPs	destroy ozone so may have similar effects to UV

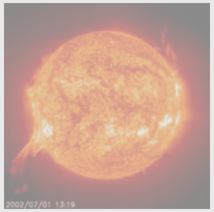
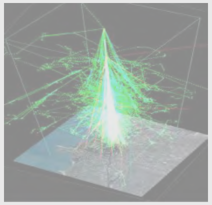
Solar Variability: Effects on Climate?

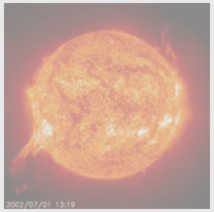
Solar Outputs

Solar Variability


Global Effects

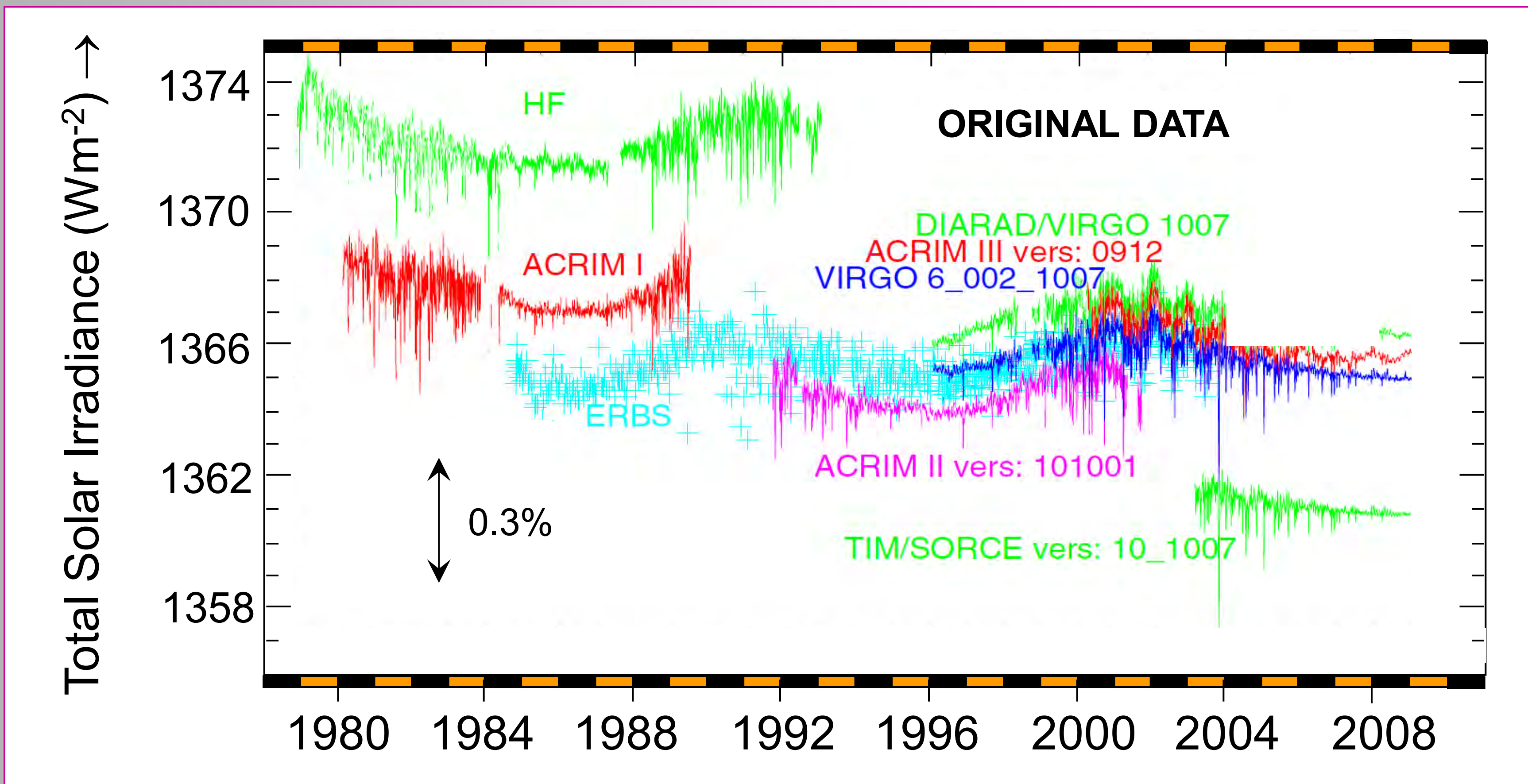
Regional & Seasonal Effects




The Future

Total Solar Irradiance Observations

Systematic errors and drifts due to instrument degradation



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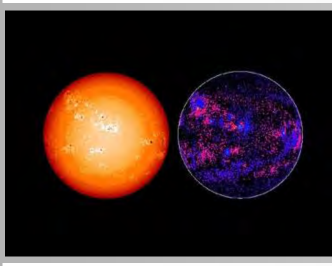
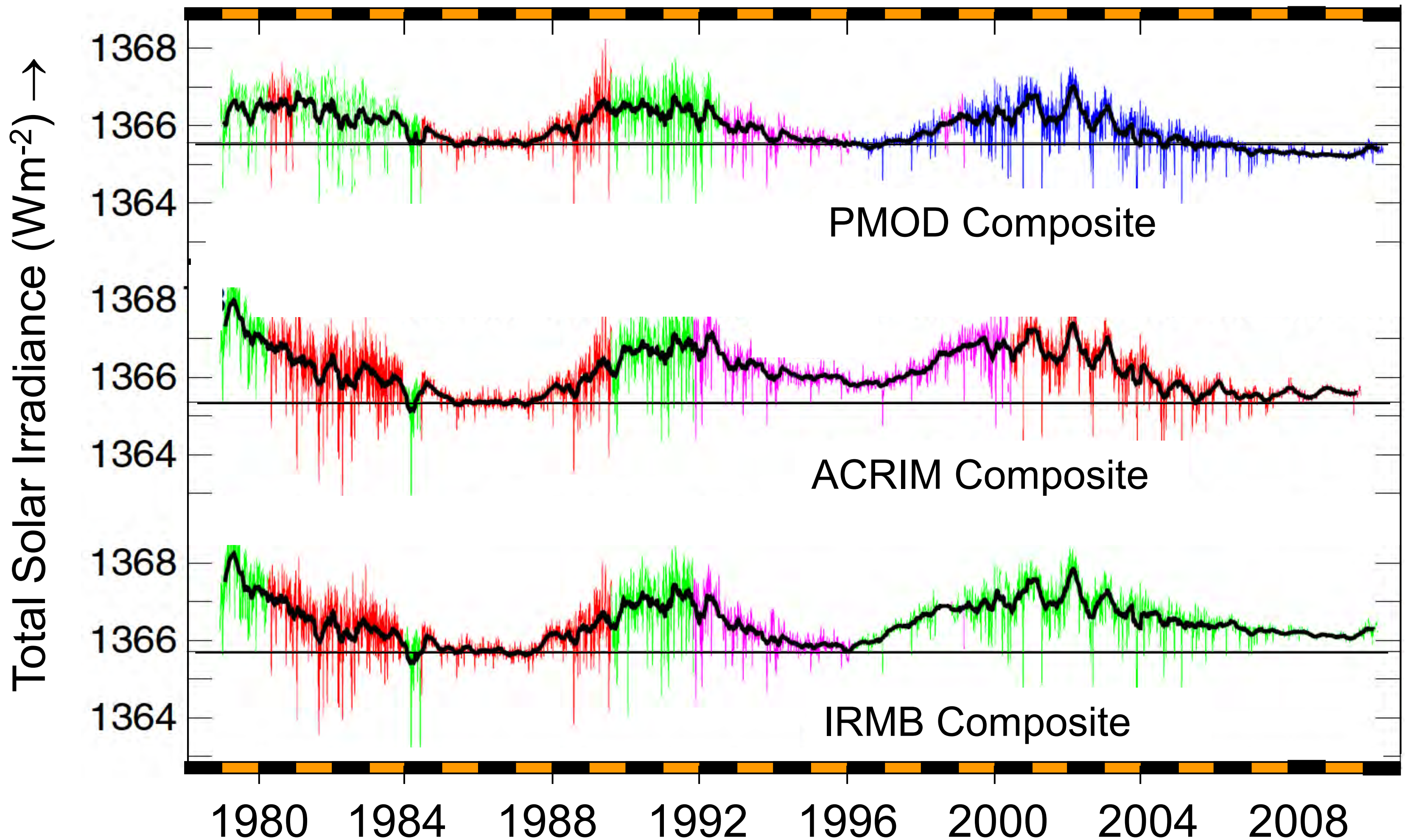
Solar Irradiance Composites

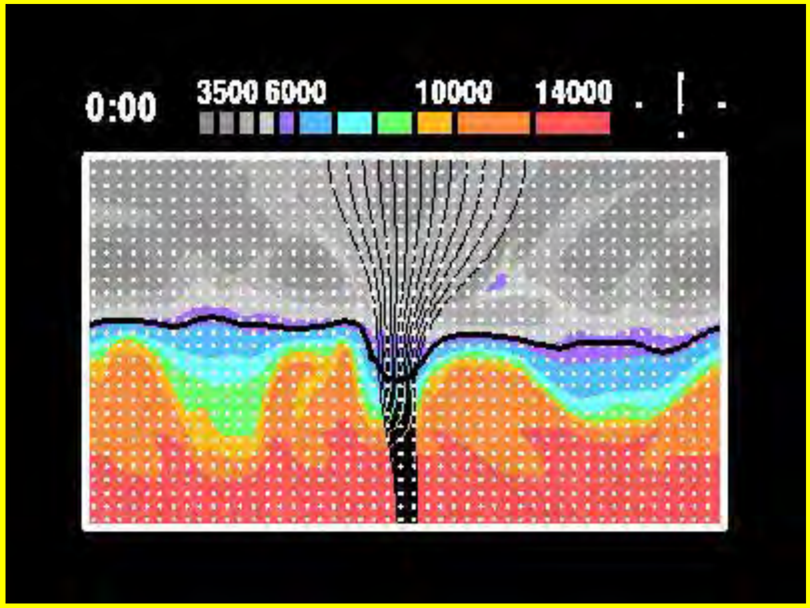
Errors and drifts corrected by intercalibration

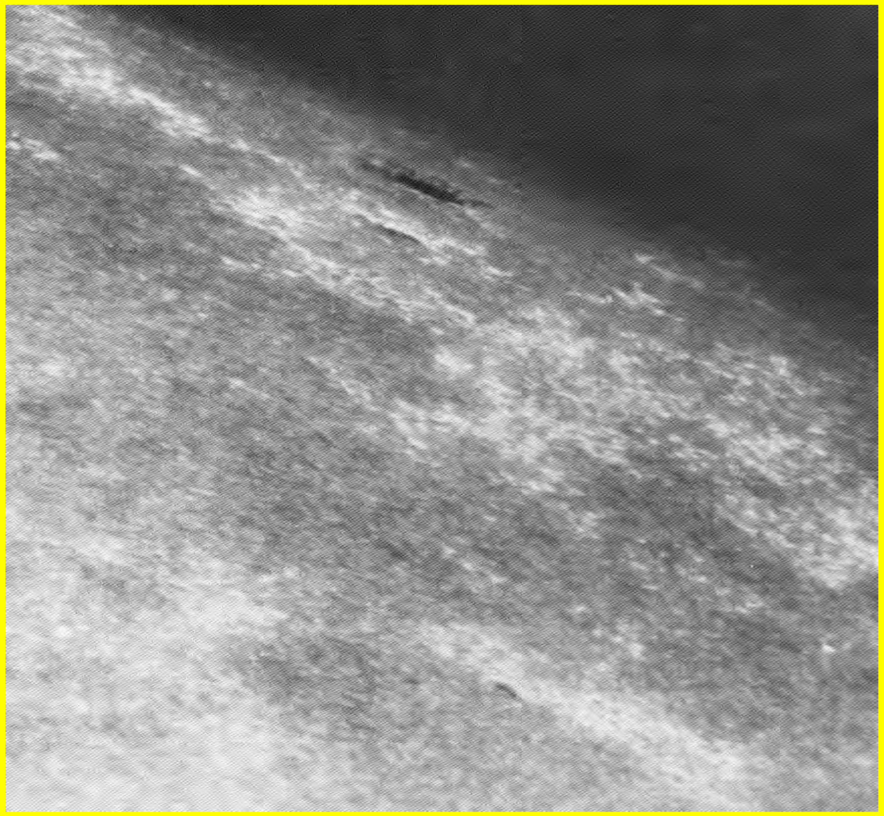


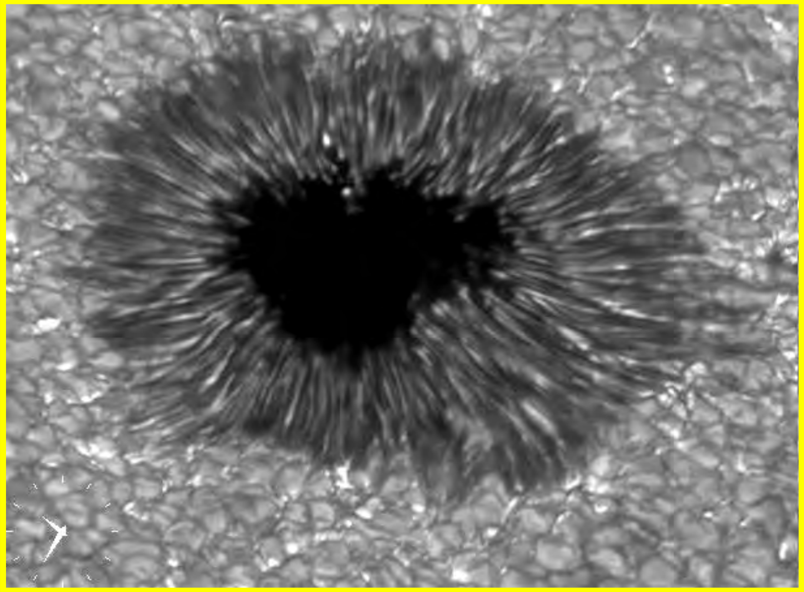


Total solar irradiance changes and magnetic field emergence

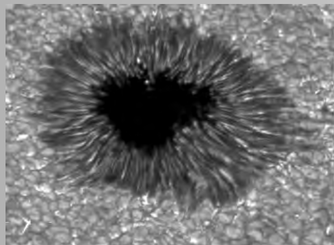
- Dark sunspots and bright faculae are where magnetic field threads the solar surface

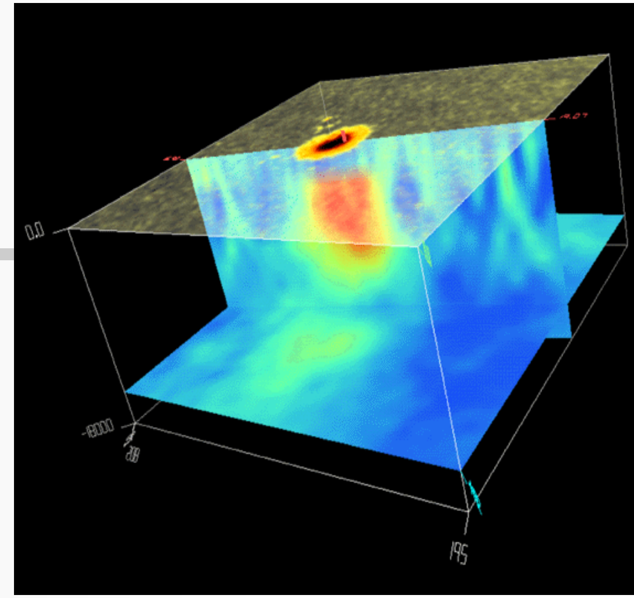


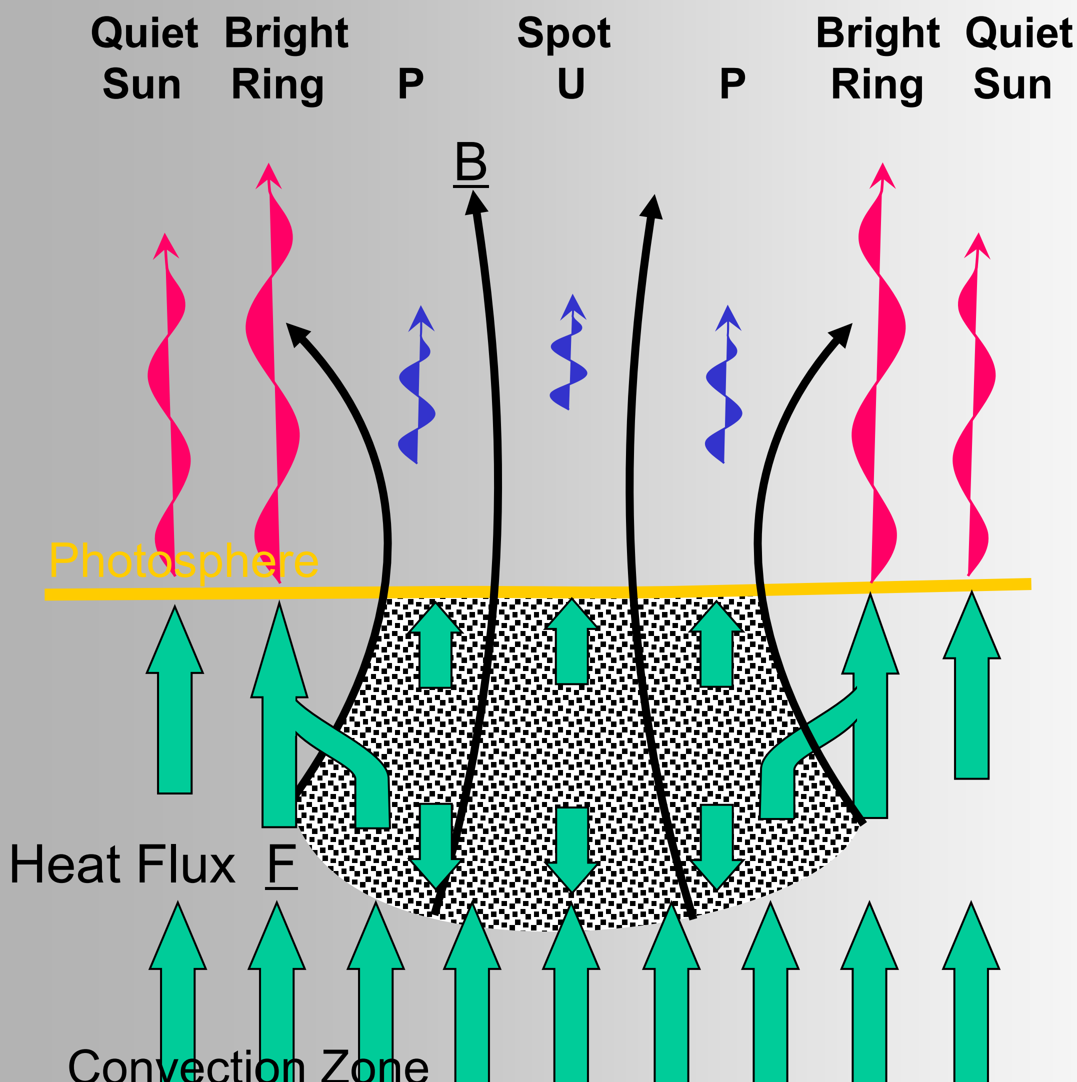




Sunspot Darkening

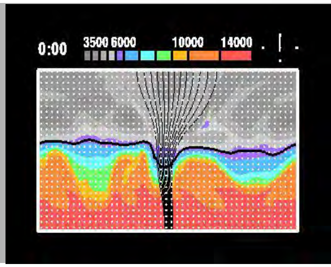






- Enhanced field B blocks upward heat flux F
- Gives temperatures:

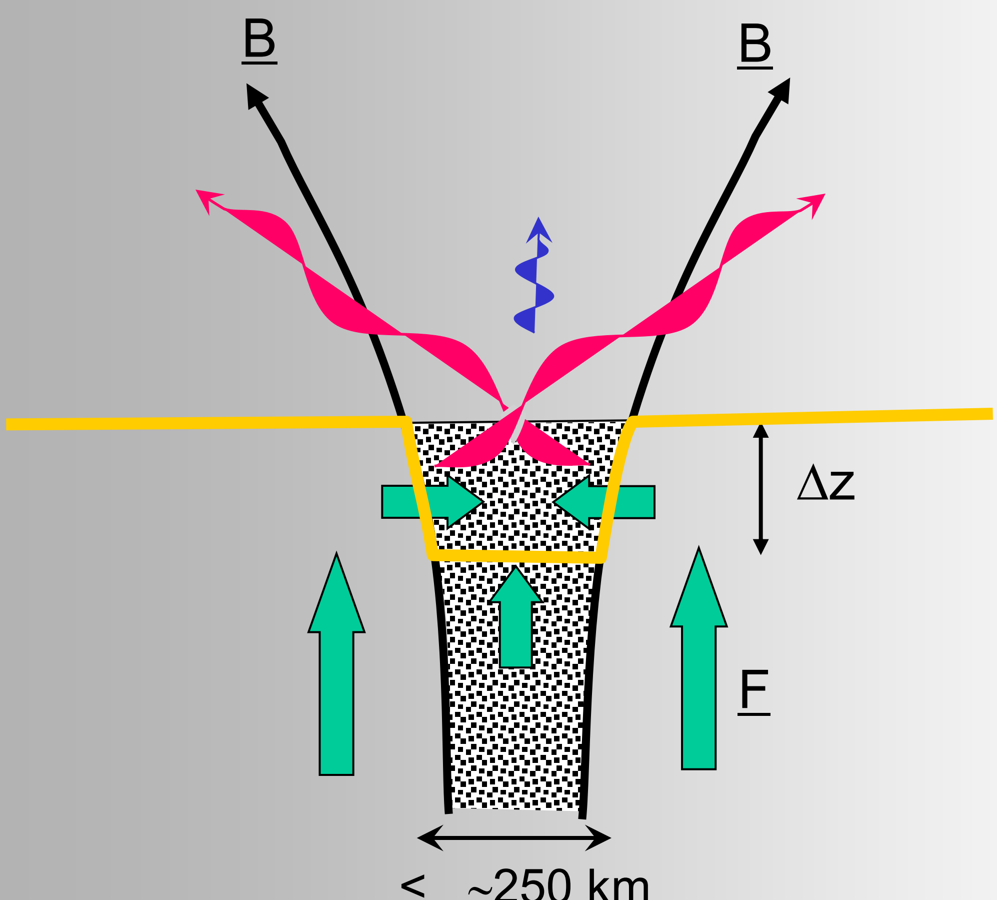
  Quiet Sun $T_{QS} \approx 6050K$
  Bright ring $T_{BR} \approx 6065K$
  Penumbra $T_P \approx 5680K$
  Umbra $T_U \approx 4240K$



Facular Brightening

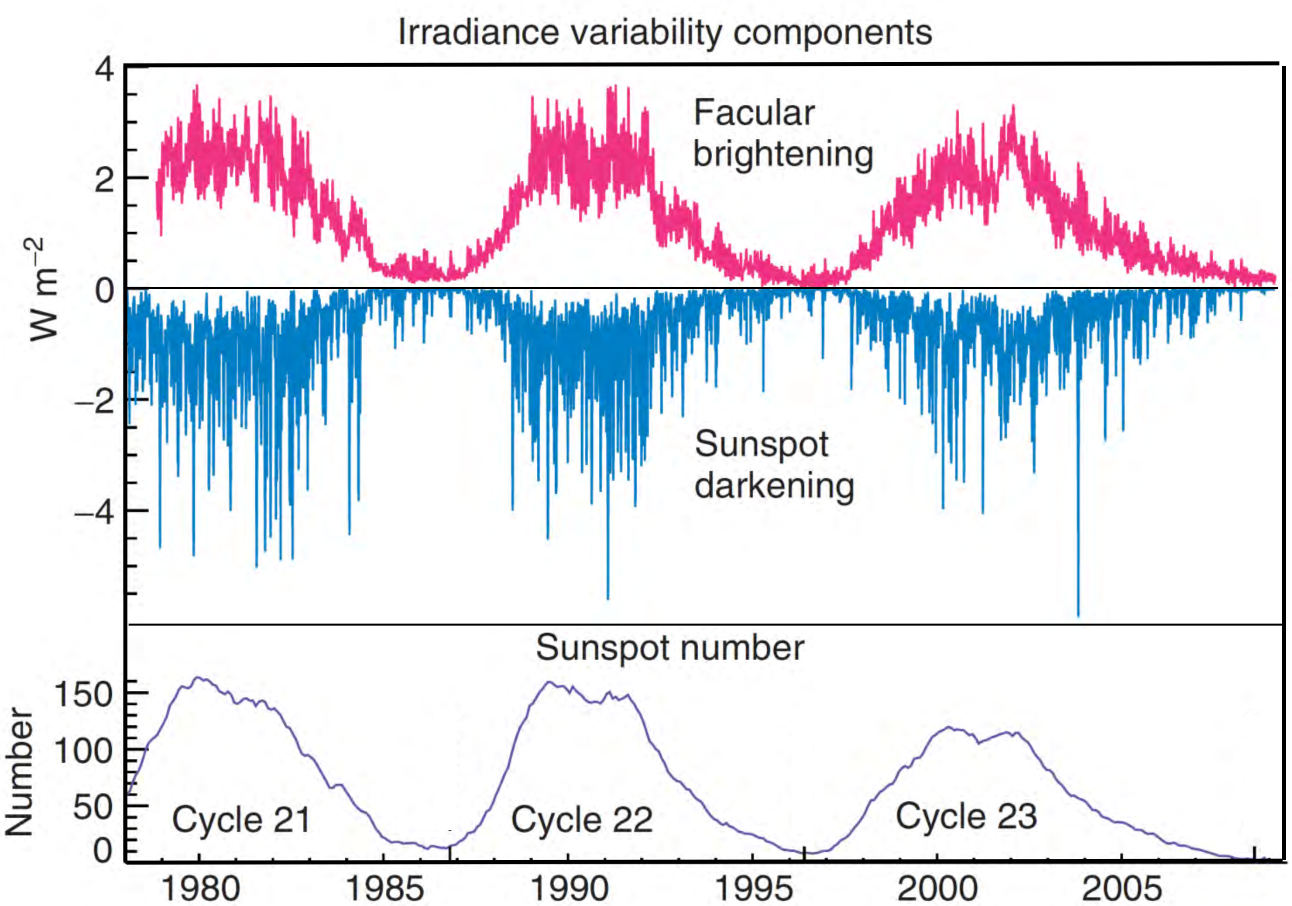
The Bright Wall Model

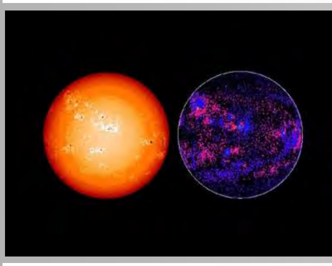
- Enhanced field raises magnetic pressure and depresses thermal pressure Nk_BT



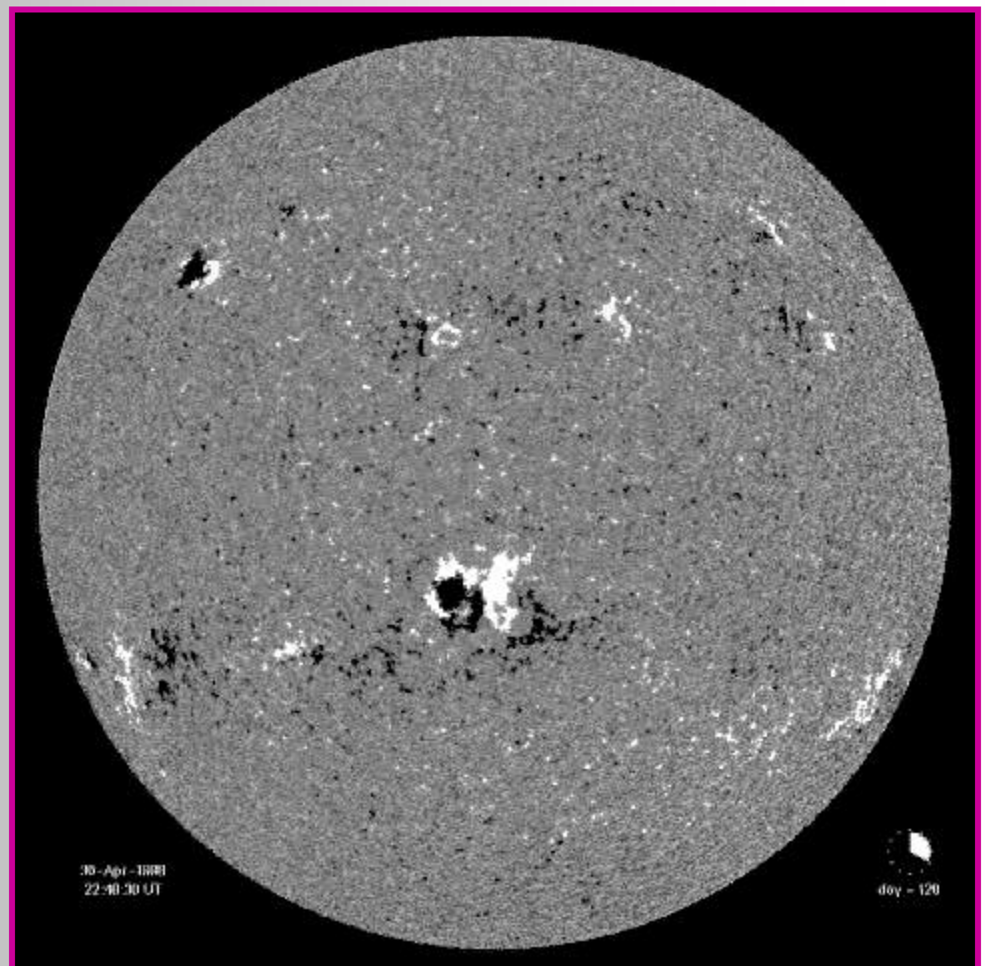
- flux tube small enough for radiation from walls to maintain internal temperature T
- N falls & the $\tau_O = 2/3$ contour is depressed by $\Delta z \approx 50$ km
- bright walls most visible at small μ for which $T_f \approx$ 6200 K

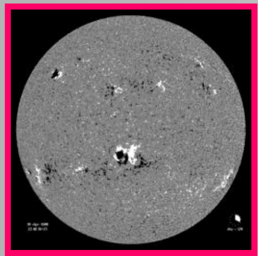
Sunspot Darkening & Facular Brightening





Photospheric magnetic field magnetogram data





3-component TSI model

using magnetogram data

- Use model contrasts of umbrae, penumbrae and faculae C_U, C_P, and C_F (>0 for brightenings) as a function of position on disc μ and wavelength λ (w.r.t quiet Sun, so $C_{QS}(\mu,\lambda) = 0$)

- Contrasts independent of time t – the time dependence is all due to that in the filling factors α which are functions of μ and t, but not λ.

- Every pixel in the magnetogram for time *t* that falls on the visible disc is then classified as either umbra, penumbra, facula or quiet Sun to derive α_U, α_P, α_F. Limb darkening function is $L_D(\mu,\lambda)$ and the quiet-Sun intensity (free of all magnetic features) of the disc centre is I_O

penumbrae

$$I_{TS}(\lambda,t = (\pi R_s^2 / R_1^2)\, I_O \int_0^1 L_D(\mu,\lambda)\, [\, \alpha_P(\mu,t)\{C_P(\mu,\lambda)+1\} +$$

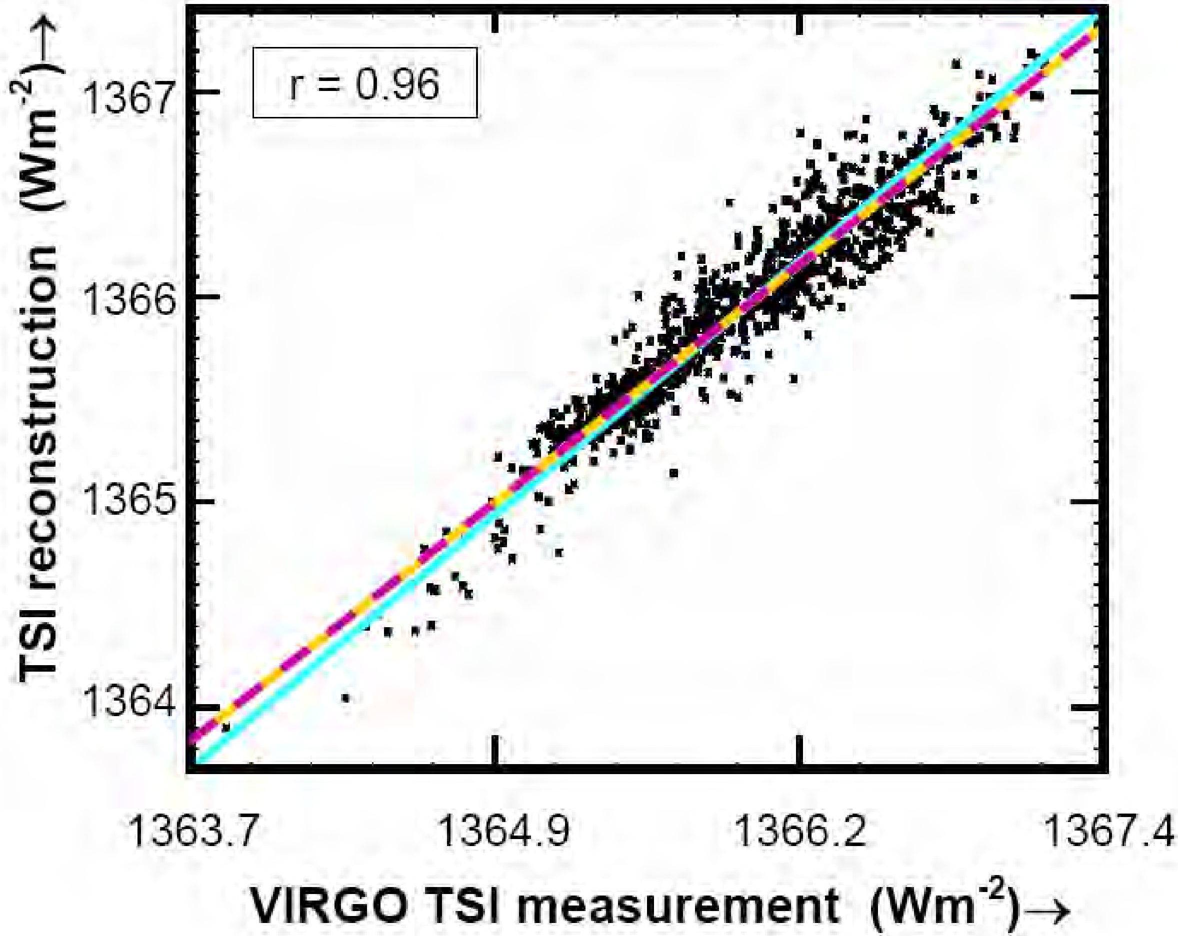
umbrae | faculae | quiet Sun

$$\alpha_U(\mu,t)\{C_U(\mu,\lambda)+1\} + \alpha_F(\mu,t)\{C_F(\mu,\lambda)+1\} + \{1-\alpha_P(\mu,t)-\alpha_U(\mu,t)-\alpha_P(\mu,t)\}\ ]\mu d\mu$$

4-component model

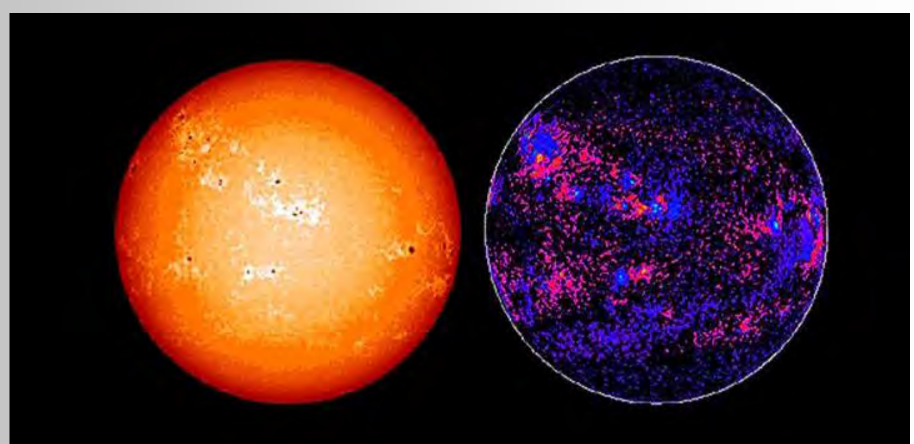
(Solanki et al., 2003)

- Total Solar Irradiance reconstructions using 4 component model ("SATIRE") with magnetograms for 1996-2002 from the MDI satellite, compared with SoHO TSI data



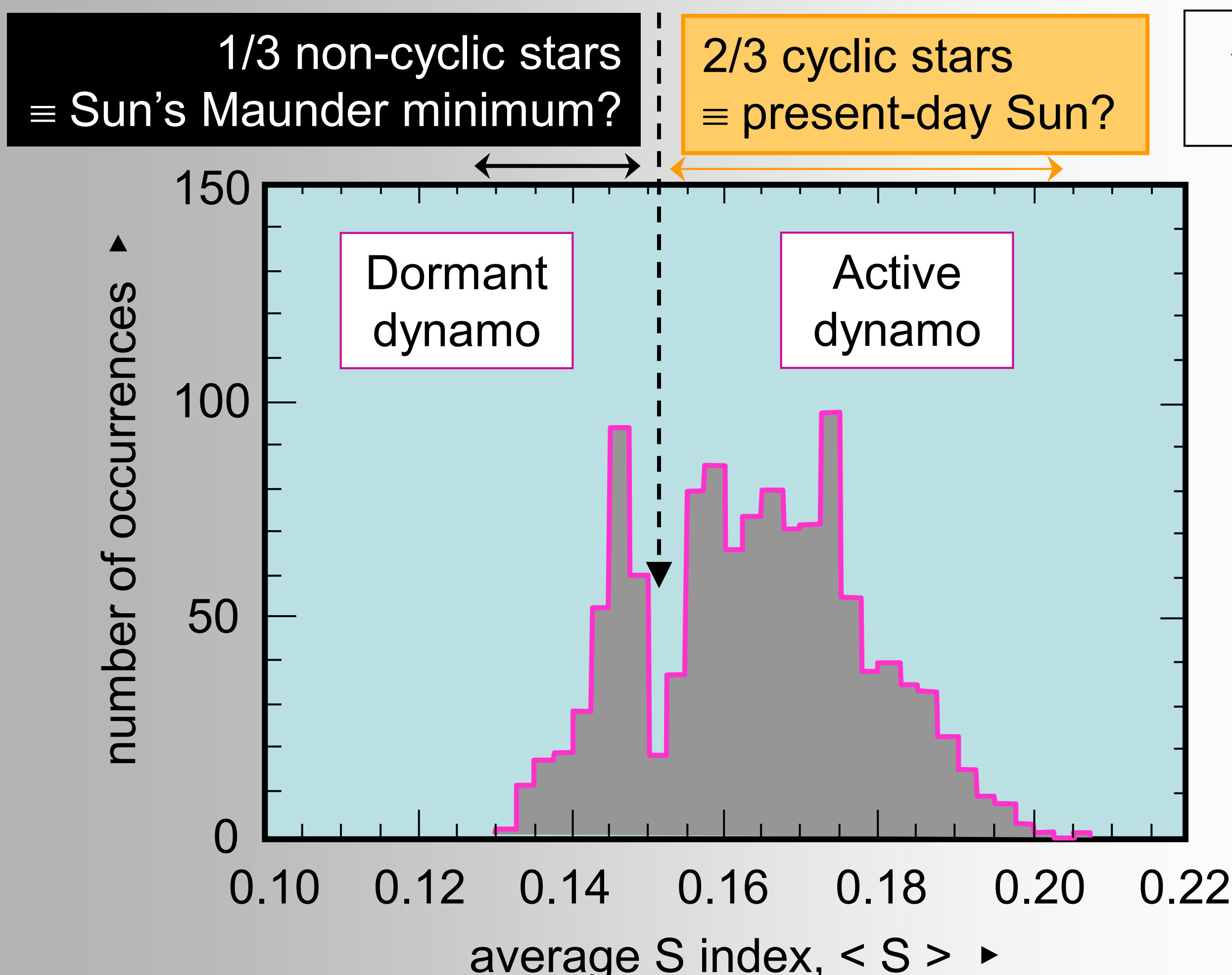
Stellar Analogues: The use of the S index

- S index is a measure of stellar flux in the Ca I H and K lines (chromospheric emissions associated with magnetic field threading the solar surface)
- related to facular brightening term in TSI by Lean et al. (1992)



Stellar Analogues:

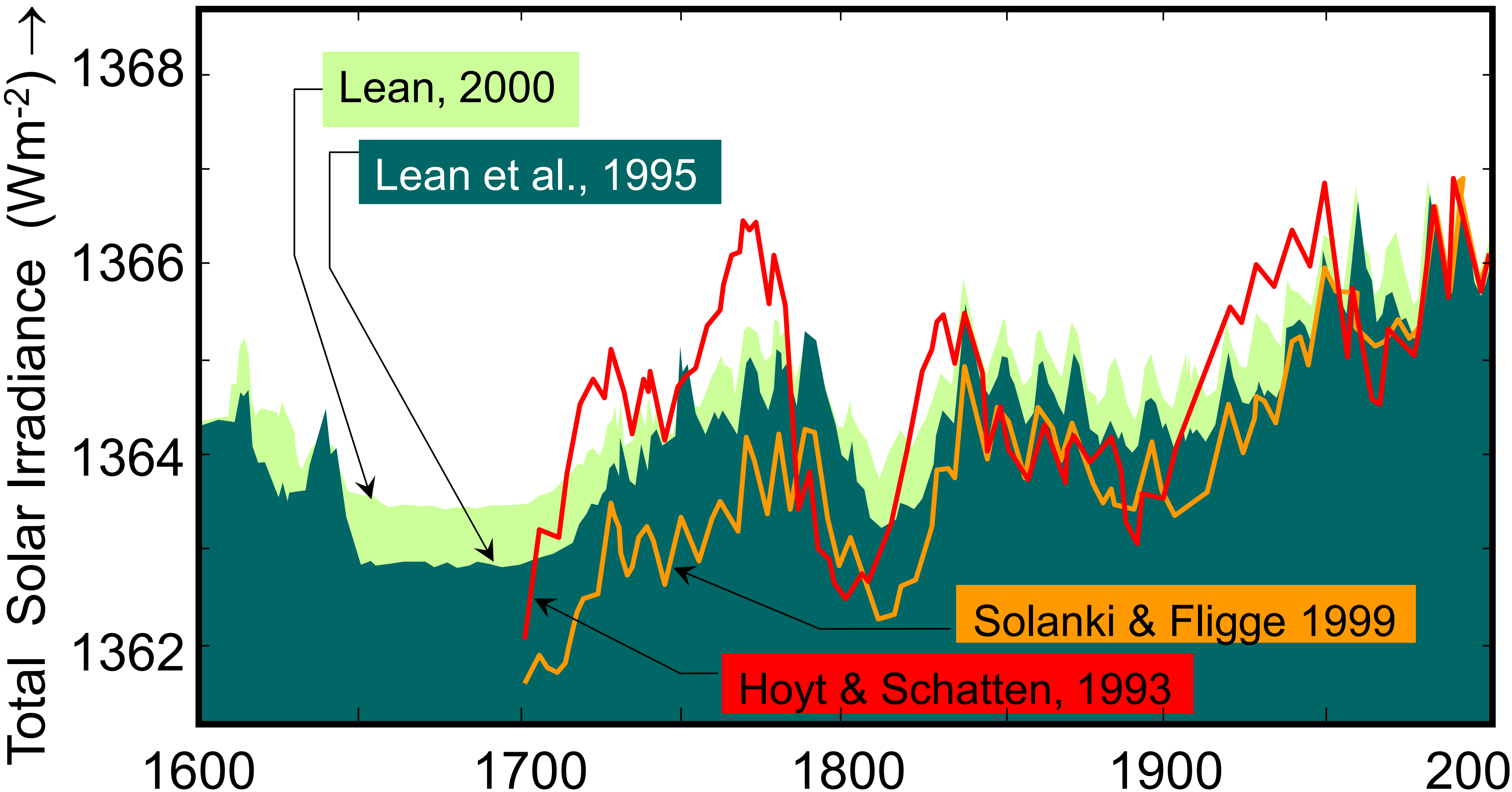
The distribution of S index values



← from 13 of the 74
(so a third is just 4)

- Baliunas & Jastrow (1990). Data from the Mt. Wilson survey of Sun-like stars.
- 74 "solar-type" stars with B - V colours in range 0.60–0.76 (0.95-1.10 M_S).

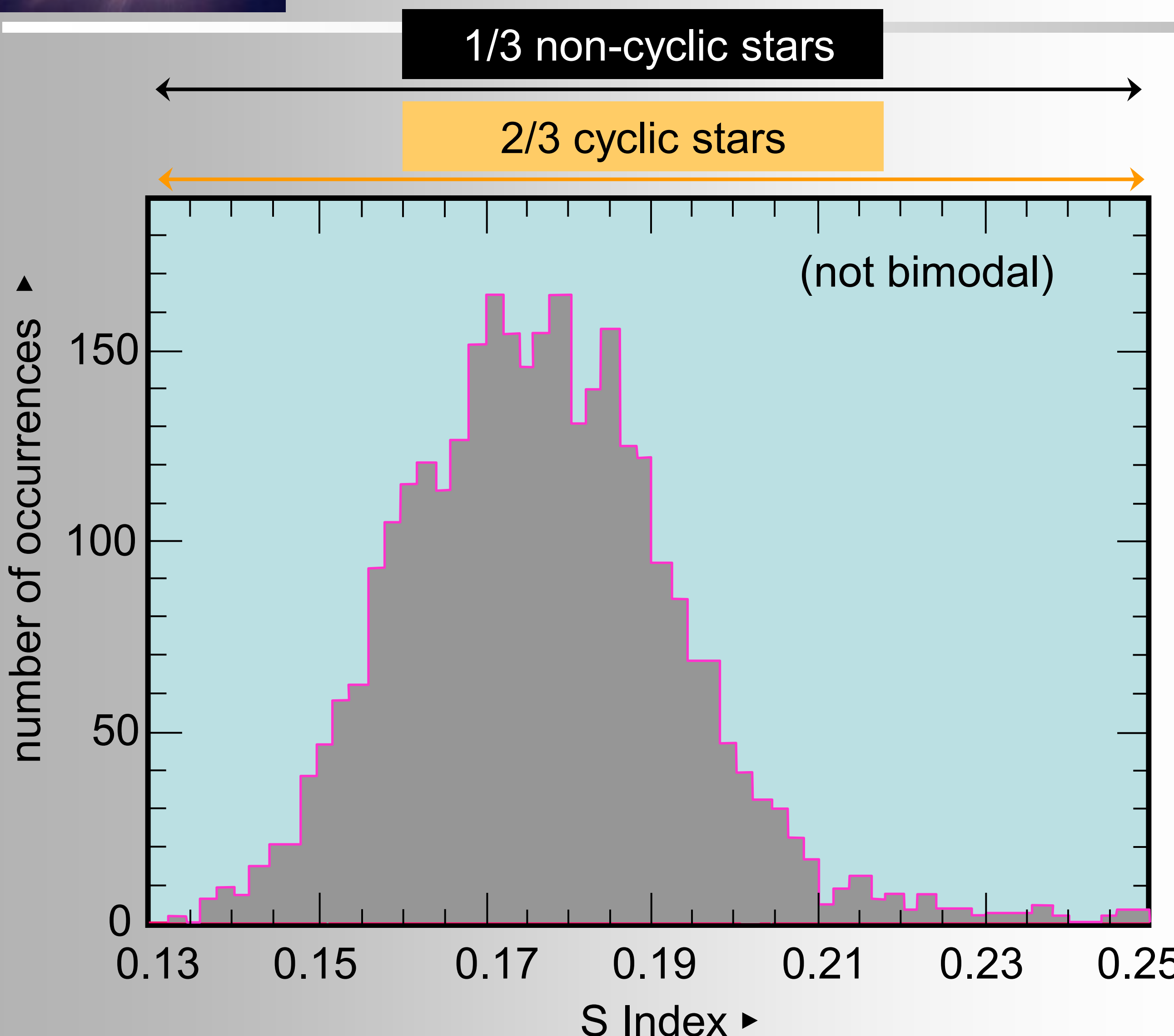
TSI Reconstructions



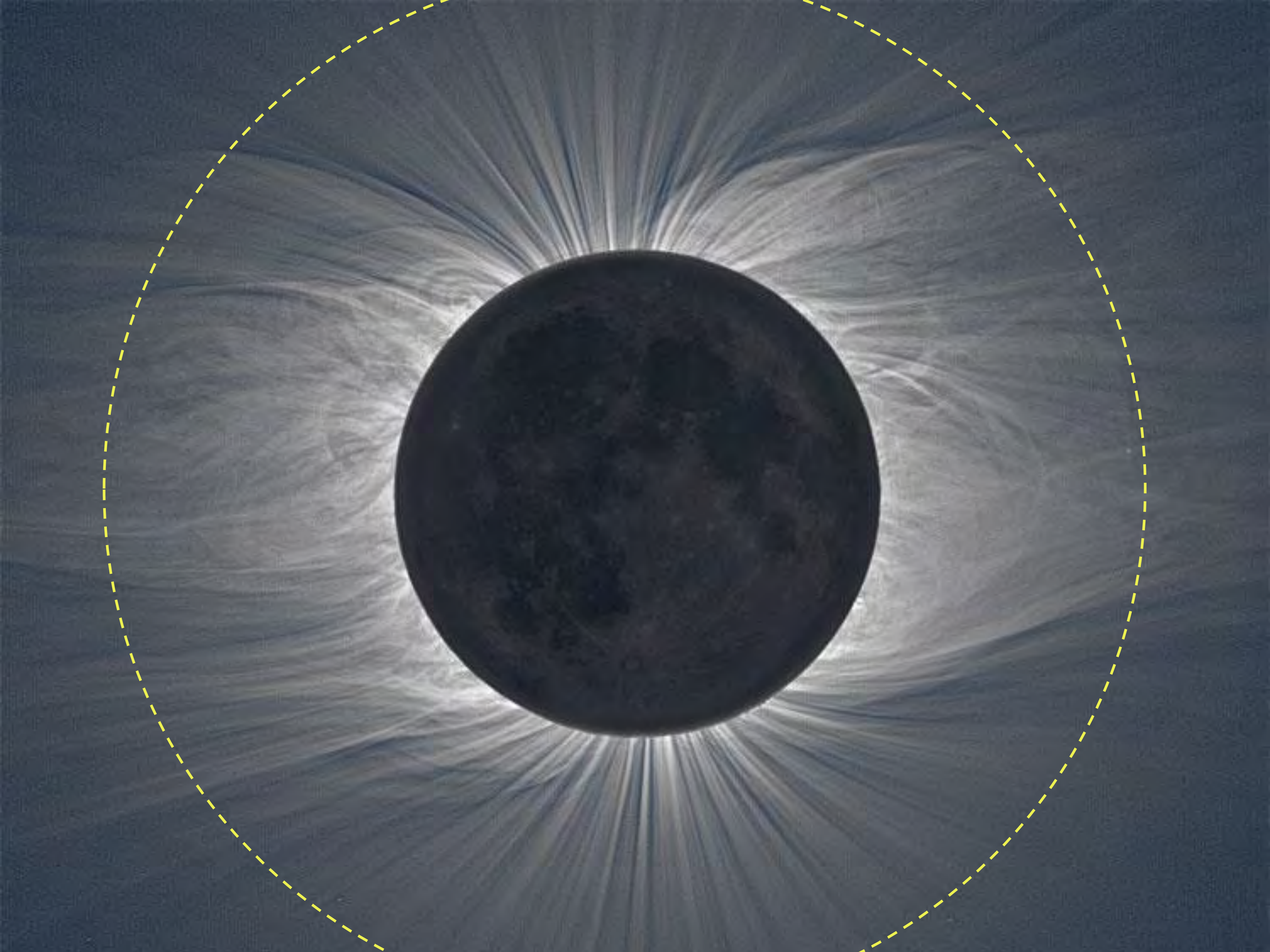
Hoyt and Schatten used solar cycle length, L, Lean et al. and Lean used a combination of sunspot number R and R_{11}, Solanki and Flkigge use a combination of R and L, Lockwood and

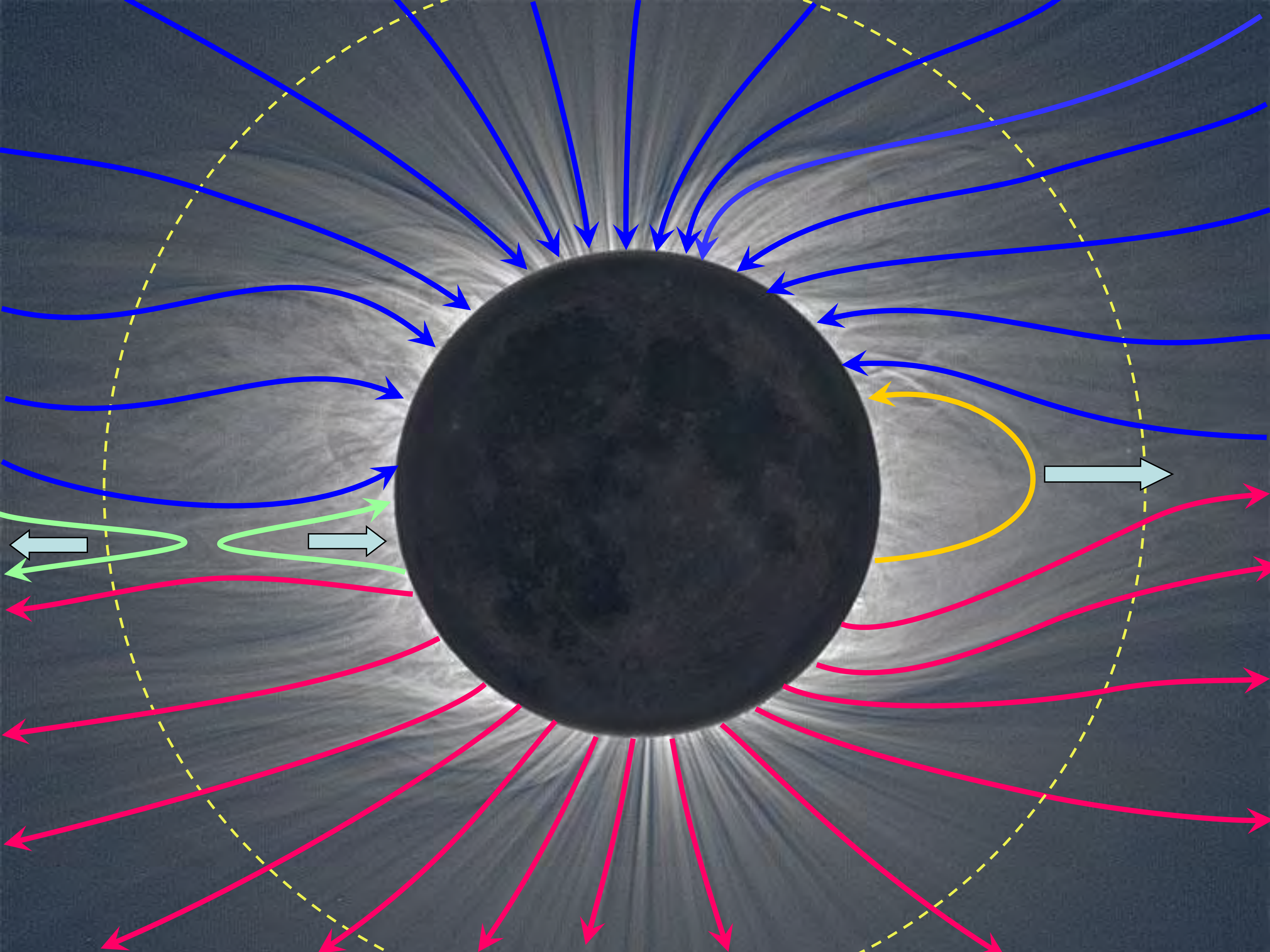
Stellar Analogues:

Recent re-evaluation of distribution



- Hall and Lockwood (2004) Lowell survey of 300 stars with colours in the same range as adopted by B&J (0.60≤ B-V ≤0.76)



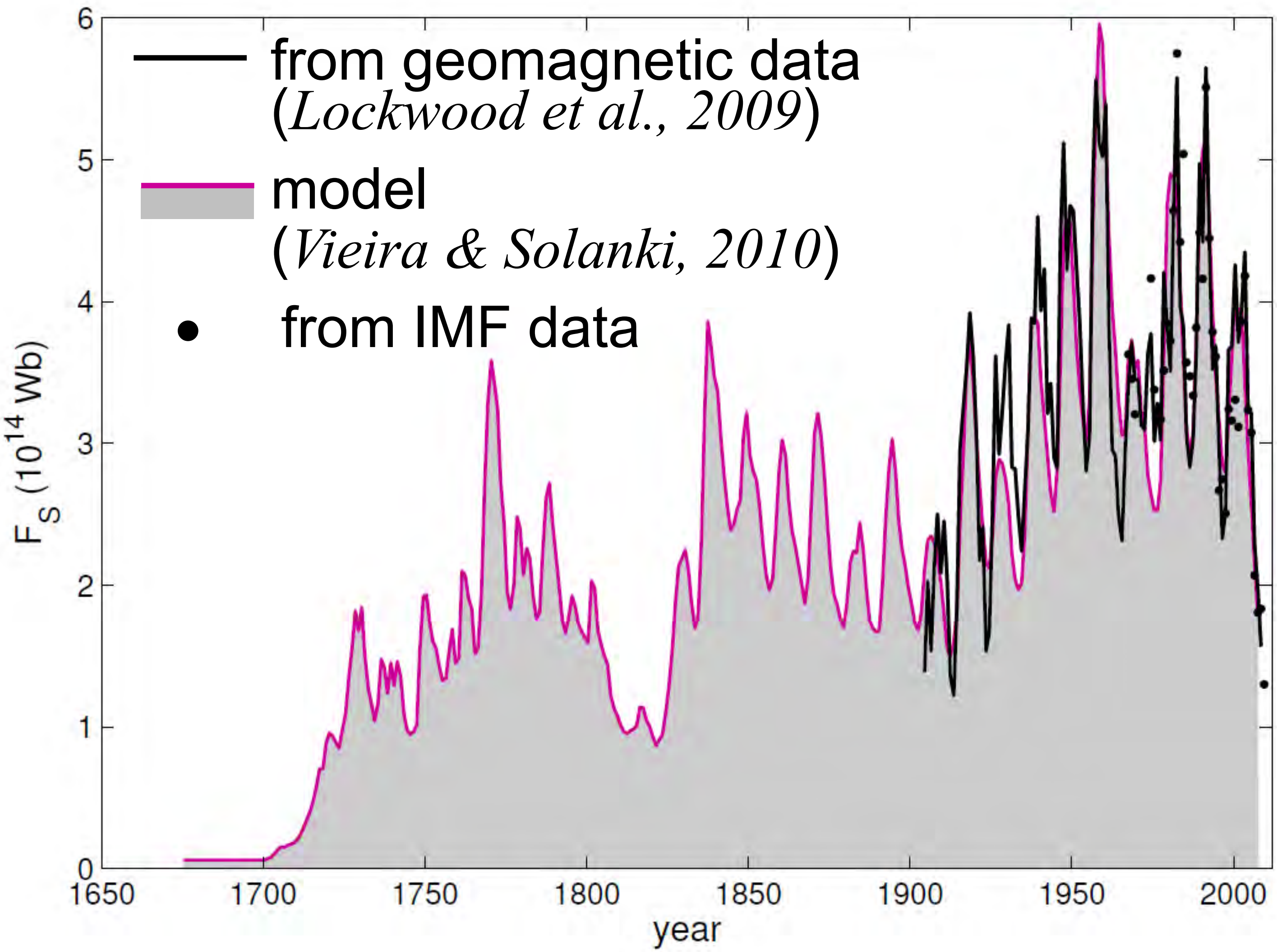


Analogy: the spacing of birds on a wire!

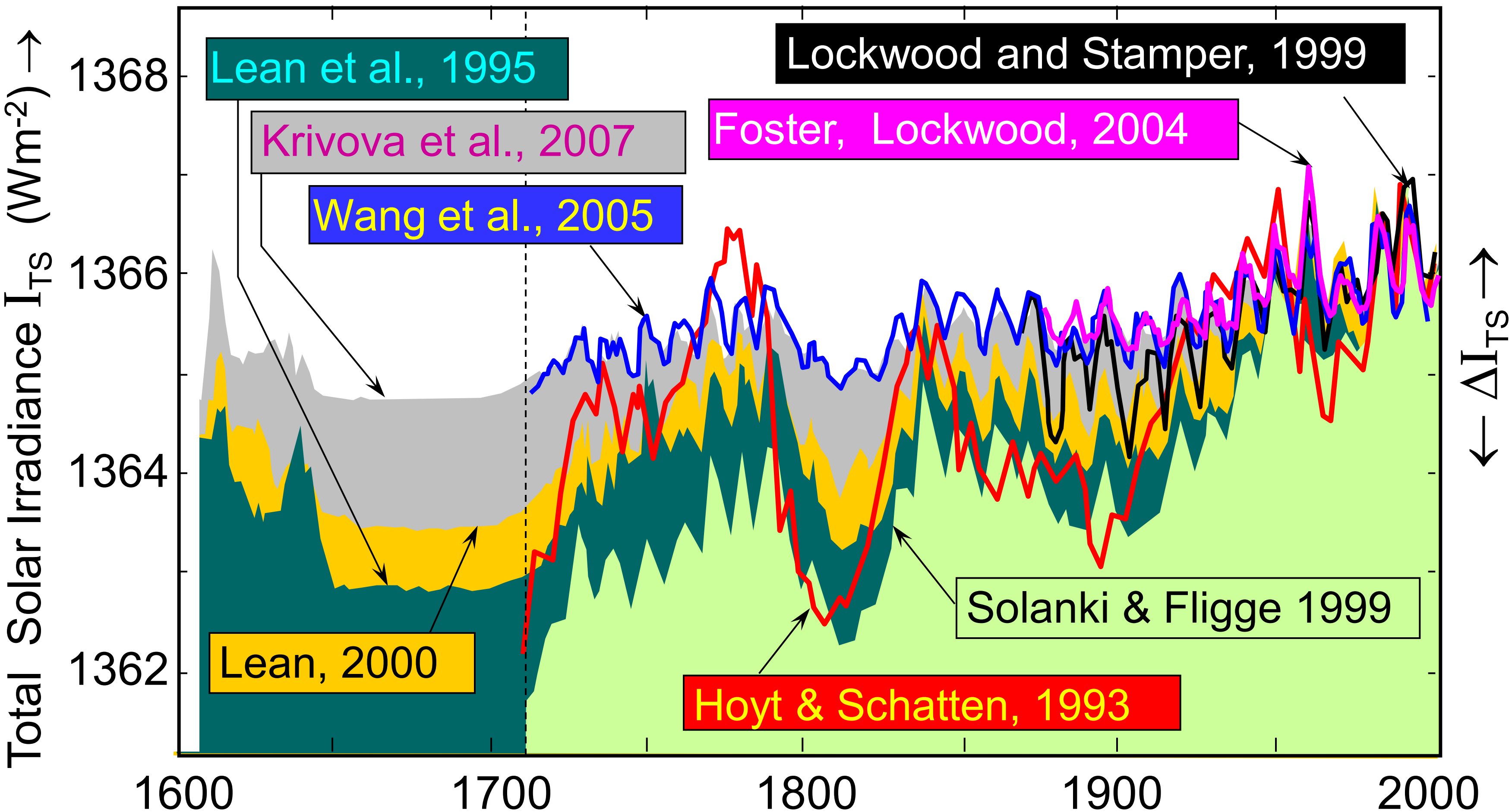
Open Solar Flux, F_S

(allowing for longitudinal structure in solar wind)

- use both range and hourly mean geomagnetic data
- model emergence from sunspot number with two time constants for decay of open flux



TSI Reconstructions



Most recent best estimates are $\Delta I_{TS} \approx 1\ Wm^{-2}$ since MM

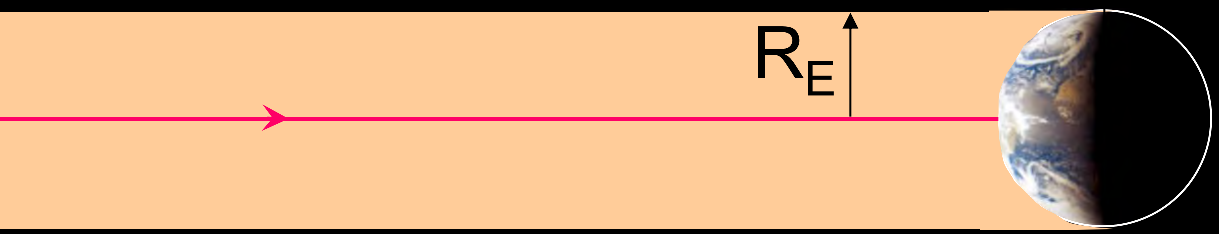
Outgoing Longwave (LW) Radiation

- infra-red (Longwave, LW) emmission = heat
- Earth is close to a "Blackbody" radiator of effective temperature T_E
- emitted power by unit area of Earth = σT_E^4 where σ is the Stefan – Boltzmann constant

- Define $T_E^4 = (1\text{-}g)T_S^4$, where g is the greenhouse term
- surface area of $4\pi R_E^2$, so total LW power ouput,

$$P_{out} = 4\pi R_E^2 \sigma T_E^4 = 4\pi R_E^2 \sigma (1 - g)T_S^4$$

Incoming short wave (SW) radiation



- power density in sunlight $= I_{TS}$ ($W\ m^{-2}$)
- called the "total solar irradiance" (TSI)
- the area of target presented by Earth $= \pi R_E^2$ (m^2) where R_E is the mean Earth radius
- of the incident power a fraction A is reflected back into space, where A is called Earth's "albedo"
- of the incident power a fraction (1-A) is not reflected back into space,
- Input SW Power $P_{in} = I_{TS}\, \pi R_E^2\, (1 - A)$

Terrestrial Energy Budget

Input SW Power $P_{in} = I_{TS}\,\pi R_E^2\,(1 - A)$

Output LW Power $P_{out} = 4\pi R_E^2\,\sigma\,T_E^4 = 4\pi R_E^2\,\sigma\,(1 - g)T_S^4$

σ = Stefan-Boltzmann constant
T_E = effective temperature of Earth / atmosphere $\approx$ 255K
T_S = surface temperature of Earth
g = normalised greenhouse effect

Also need to consider power q (per unit area) surface gives to sub-surface layers (particularly the deep oceans)

$$P_{in} = P_{out} + 4\pi R_E^2 q$$

$$\rightarrow \quad \boxed{I_{TS}(1 - A)/4 = \sigma\,(1 - g)T_S^4 + q}$$

Terrestrial Energy Budget

$$I_{TS}(1 - A)/4 - \sigma T_S^4 + \sigma\, g T_S^4 - q = 0$$

$$I_{TS}(1 - A)/4 - \sigma T_S^4 + G - q = 0$$

Differentiate w.r.t. time

$$\Delta T_S = [\Delta I_{TS}/4 - I_{TS}\Delta A/4 + \Delta G - \Delta q] / (4\sigma T_S^3)$$

σ = Stefan-Boltzmann constant

T_E = effective temperature of Earth / atmosphere ≈ 255K

T_S = surface temperature of Earth

g = normalised greenhouse effect, N.B., $g = G / (\sigma T_S^4)$

G = greenhouse radiative forcing (in Wm^{-2})

Gives the concept of "radiative forcing" where we can add together the changes in the powers per unit surface area due to different effects in the term in square brackets

A little greenhouse gas is a good thing!

$$T_S = \left[\frac{I_{TS}(1 - A) - 4q}{4\sigma\ (1 - g)} \right]^{1/4}$$

If no greenhouse gases, g = 0 and surface in equilibrium with oceans (q = 0):

$I_{TS} = 1366.5\ \mathrm{Wm^{-2}}$, Albedo, A = 1/3

$\sigma = 5.669 \times 10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$

(if $g = 0$ $T_E = T_S$)

Gives T_S = 251.8 K = -21.2 °C

TOO COLD FOR ALMOST ALL LIFEFORMS!

Terrestrial Energy Budget

$$T_S = \left[\frac{I_{TS}(1 - A) - 4q}{4\sigma(1 - g)} \right]^{1/4}$$

Typical values

I_{TS} = 1366.5 Wm^{-2} , Albedo, A = 1/3,

q = 1 Wm^{-2} *(Hansen et al., Science, 2005)*

σ = 5.669 × 10^{-8} W m^{-2} K^{-4}

T_E = effective temperature of Earth & its atmos. ≈ 253K

$g = 1 - (T_E / T_S)^4$

Above eqn. for g = 0.410 gives T_S = 286.9 K = 13.9 °C

Increase g to 0.416 (a 1.5% rise & ≈ the value or 2000)
gives T_S = 14.7 °C i.e. it gives a rise in T_s of ΔT_s = 0.8 °C

Terrestrial Energy Budget

Typical values from before:

- $g = 0.410$ gives $T_S = 286.9$ K (= 13.2 °C)

  corresponds to $G = g\,\sigma T_S^4 = 157.5$ Wm^{-2}

- Increasing g to 0.416 (≈ value for 2000) gives

  $T_S = 287.7$ K (= 14.7 °C)

  (the observed rise in T_s, $\Delta T_s = 0.8$ °C)

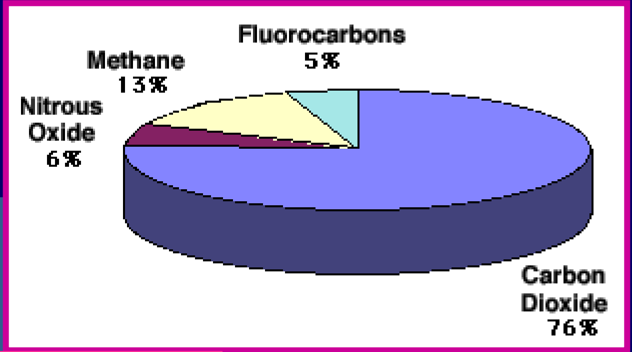
  corresponds to $G = g\,\sigma T_S^4 = 161.6$ Wm^{-2}

- Thus a radiative forcing anomaly of $\Delta G = 4.1$ Wm^{-2} gives a surface temperature rise $\Delta T_s = 0.8$ K

- The "climate sensitivity" = $\Delta T_s / \Delta G$

  ≈ 0.2 K W^{-1} m^{2}

Do greenhouse gases alone explain the observed warming?



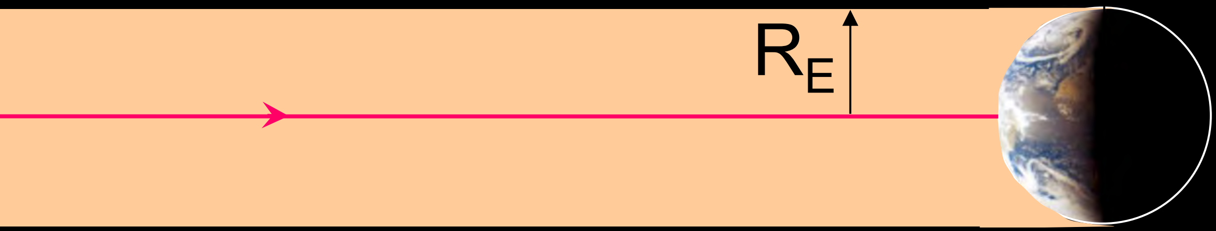
(from before) for 1900-2000:

- radiative forcing anomaly of $\Delta G = 4\ Wm^{-2}$ gives a surface temperature rise $\Delta T_s = 0.8$ K

	ppmv			$\delta G\ (Wm^{-2})$		$\Delta G\ (Wm^{-2})$
	1700	1900	2000	1900	2000	1900-2000
CO_2	278	295.2	362.5	0.3	1.4	1.1
NH_4	700	898	1800	0.2	0.5	0.3
Others				0.1	0.5	0.4
Total				0.6	2.4	1.8

- direct effects not enough: but there are feedback effects

Solar radiative forcing



- Input SW Power $P_{in} = I_{TS}\,\pi R_E^2\,(1 - A)$

- SW Power per unit surface area of earth

$P_{SW} = I_{TS}\,\pi R_E^2\,(1 - A) / (4\,\pi R_E^2) = I_{TS}\,(1 - A) / 4$

Solar radiative forcing = $\Delta P_{SW} = \Delta I_{TS}\,(1 - A) / 4$

Since pre-industrial times $\Delta I_{TS} \approx 1\ \mathrm{Wm^{-2}}$

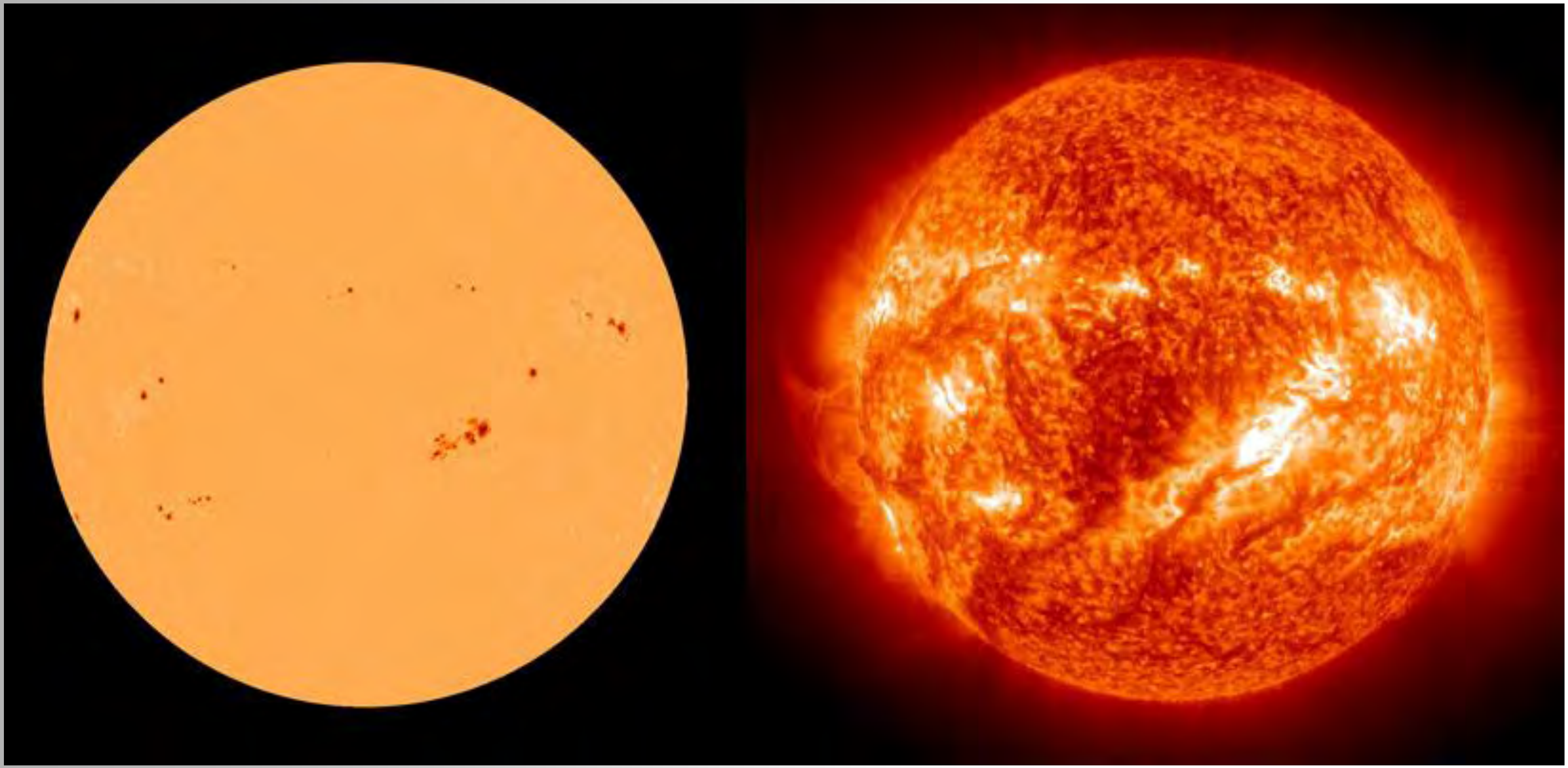
Gives $\Delta P_{SW} \approx 1/6 = 0.167\ \mathrm{Wm^{-2}}$ (for $A = 1/3$)

= a tenth of greenhouse gas radiative forcing $\approx 1.8\ \mathrm{Wm^{-2}}$

And remember total radiative forcing needed to explain GMAST rise (with feedbacks) = $\Delta G \approx 4\ \mathrm{Wm^{-2}} \approx 24\,\Delta P_{SW}$

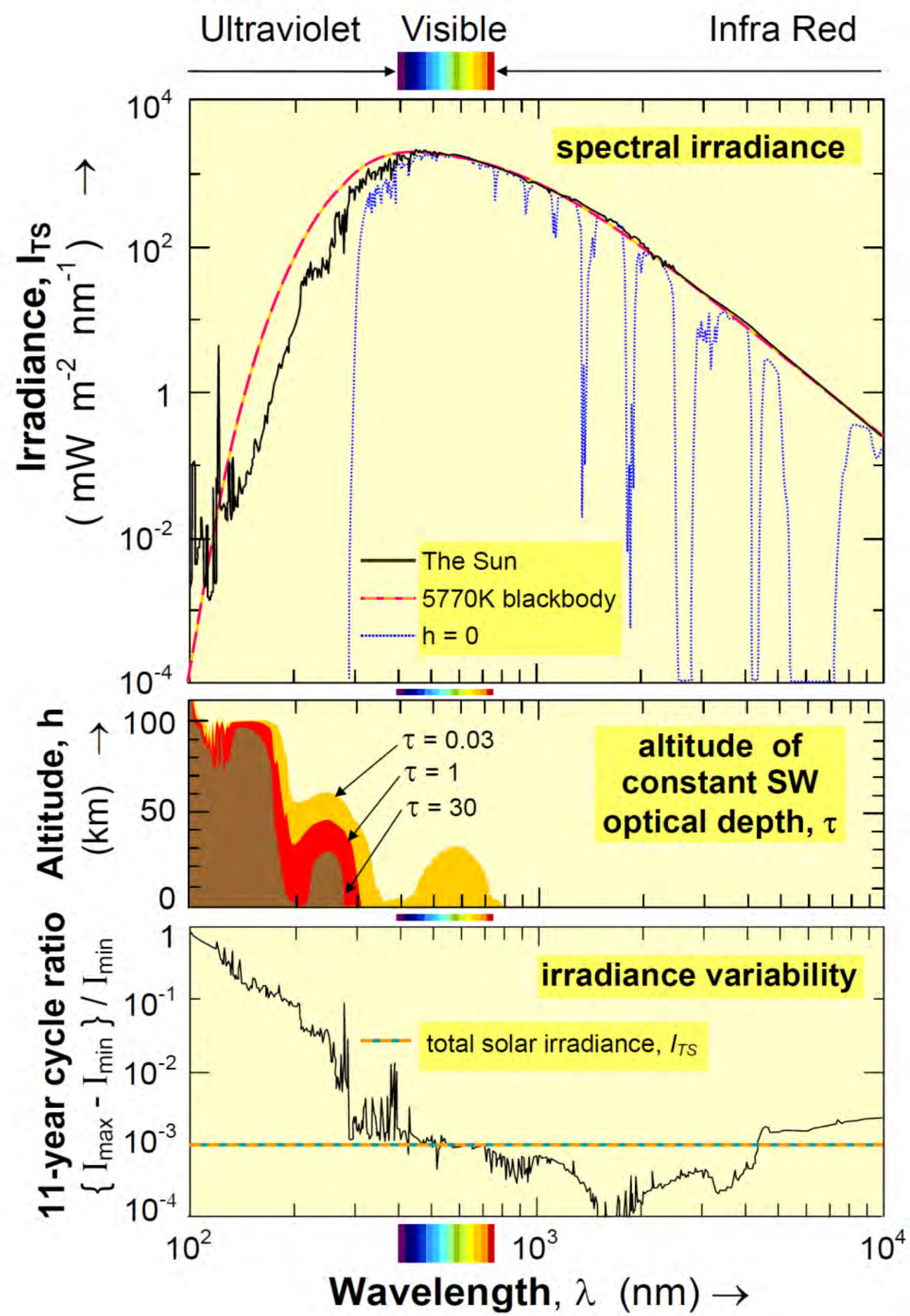
The sun seen is Visible and UV light

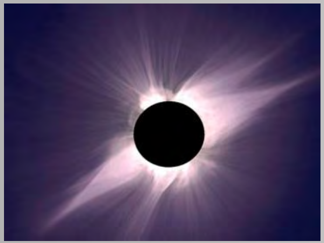
3rd February 2002



- white light, λ = 400-700 nm
- Ultraviolet, λ = 30.4 nm

- The Sun's e-m radiation spectrum
- Variability is low in parts of spectrum power is greatest
- Variability is highest in UV which is absorbed in the stratosphere

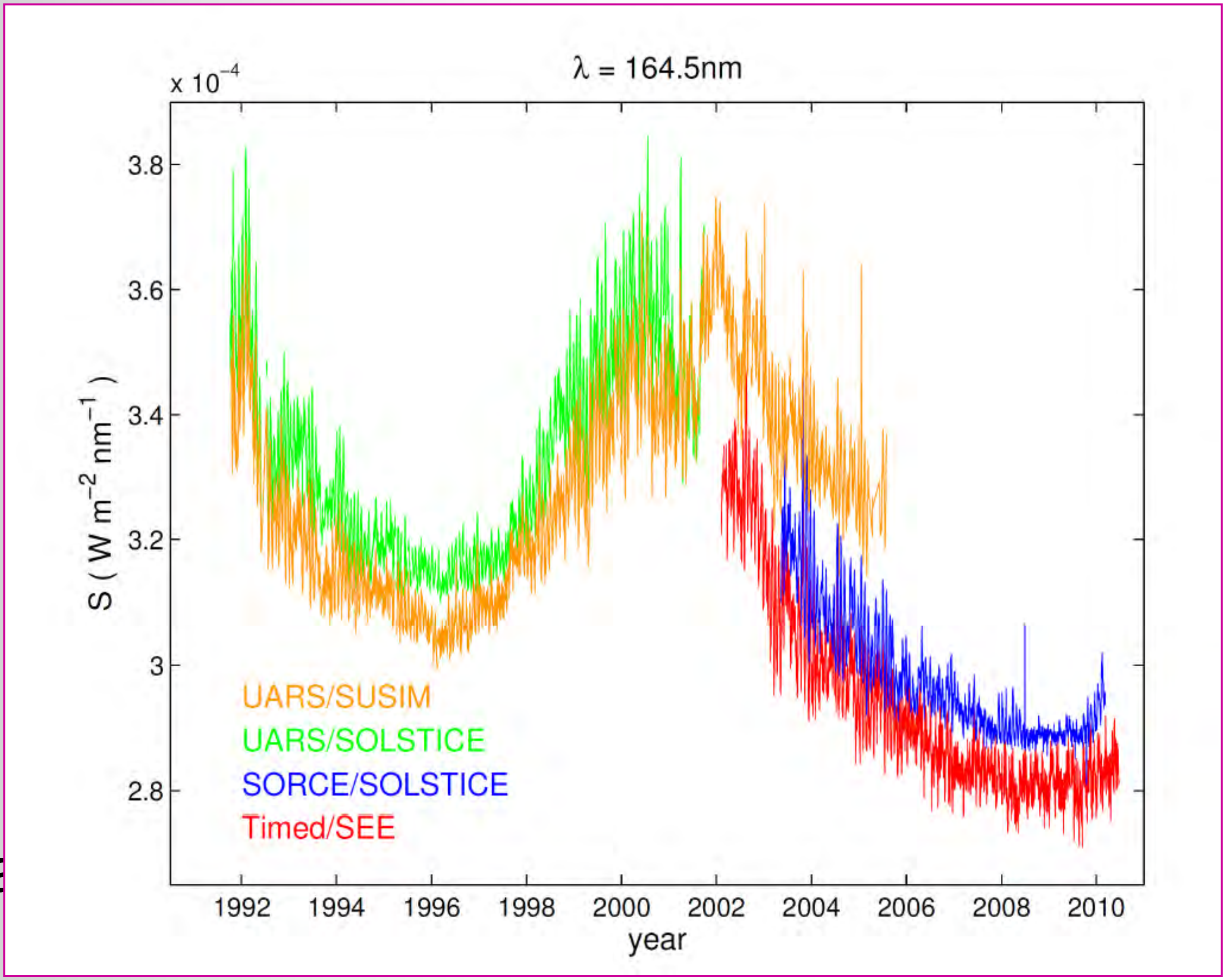




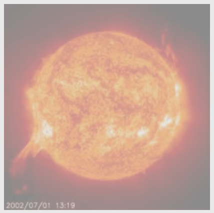
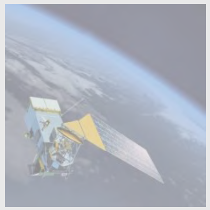
Solar UV data intercalibration

(Lockwood, JGR, 2011)

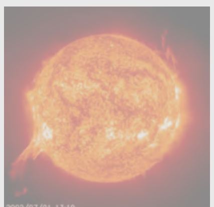
- e.g. λ = 164.5nm
- data from different satellite and instruments
- note the "SOLSTICE gap" between the end of UARS/SOLSTICE data and start of SORCE/SOLSTICE data.
- UARS/SUSIM data not reliable at λ>205nm



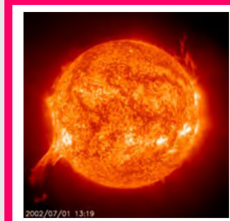
Solar Variability:
Effects on Climate?

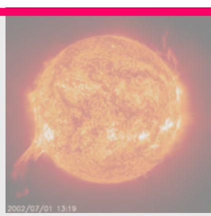
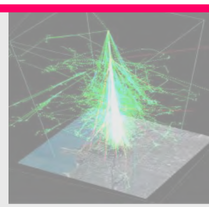
Solar Outputs

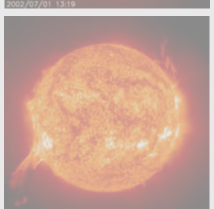
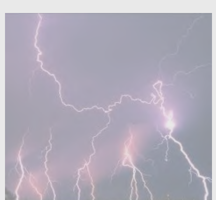
Solar Variability

Global Effects

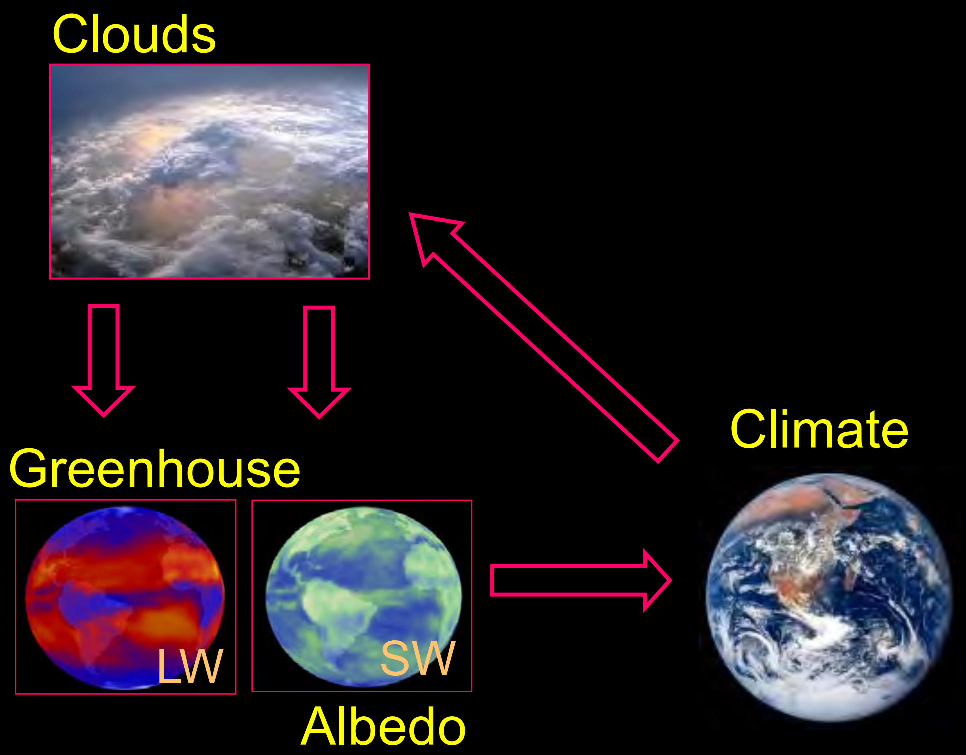
 

Regional & Seasonal Effects

The Future

Cosmic Rays & Clouds



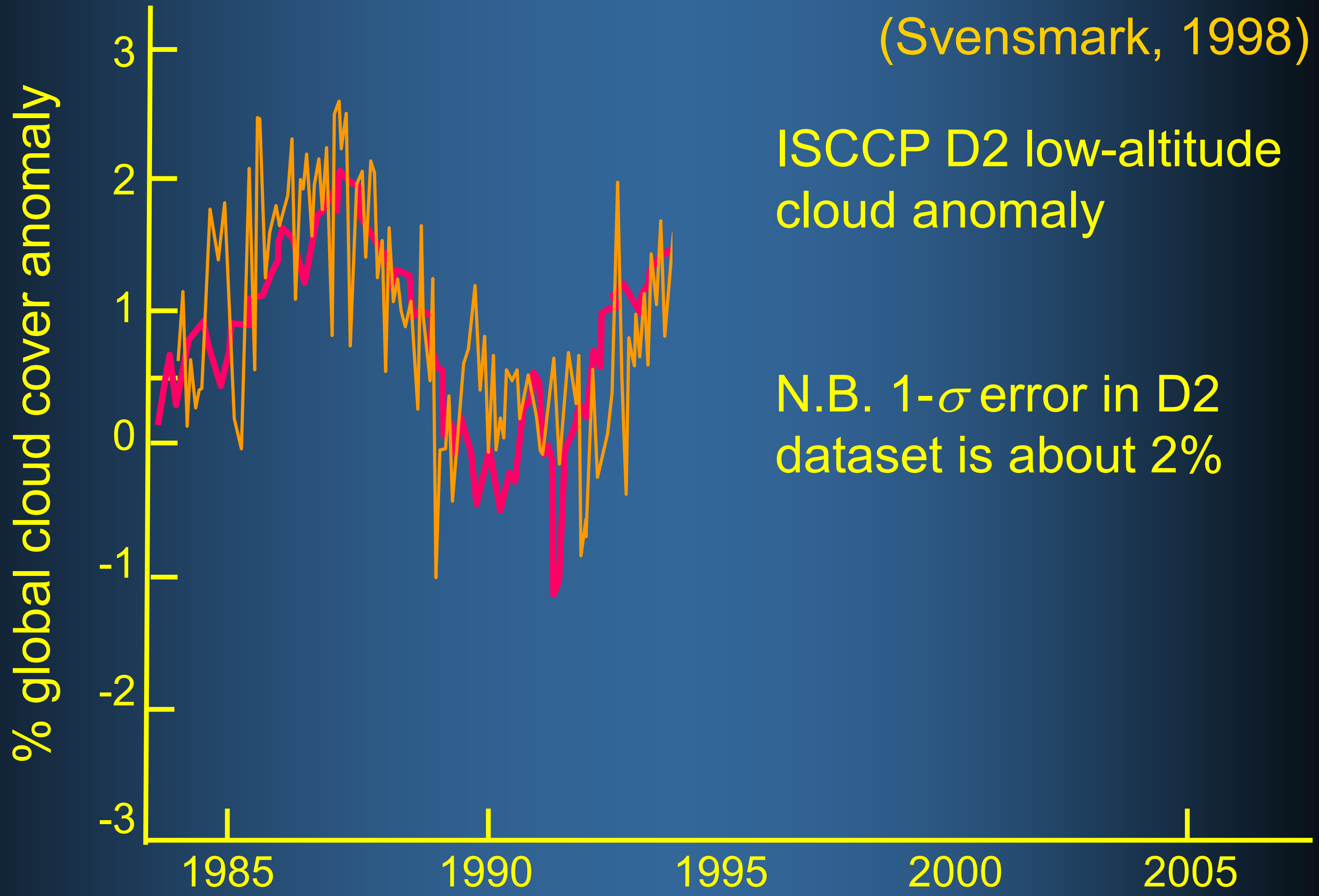
Low cloud: Albedo effect exceeds greenhouse trapping effect

High Cloud: greenhouse trapping effect exceeds albedo effect

GCR fluxes fell over 1900-1985 so to contribute to warming Earth, they would have to generate low altitude cloud (so reduced albedo exceeds reduced greenhouse trapping)

Global Cloud Cover Variation

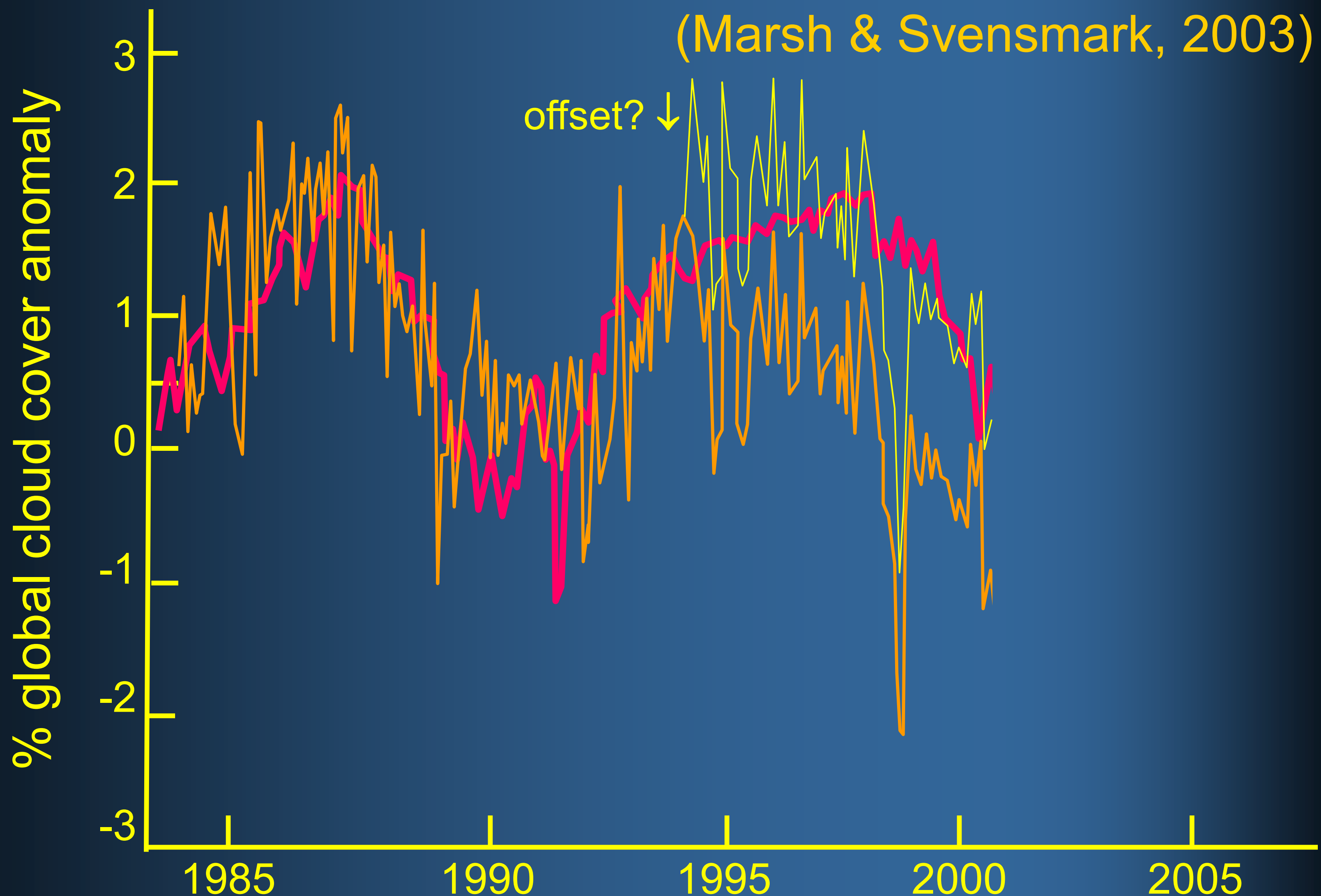
(Svensmark, 1998)



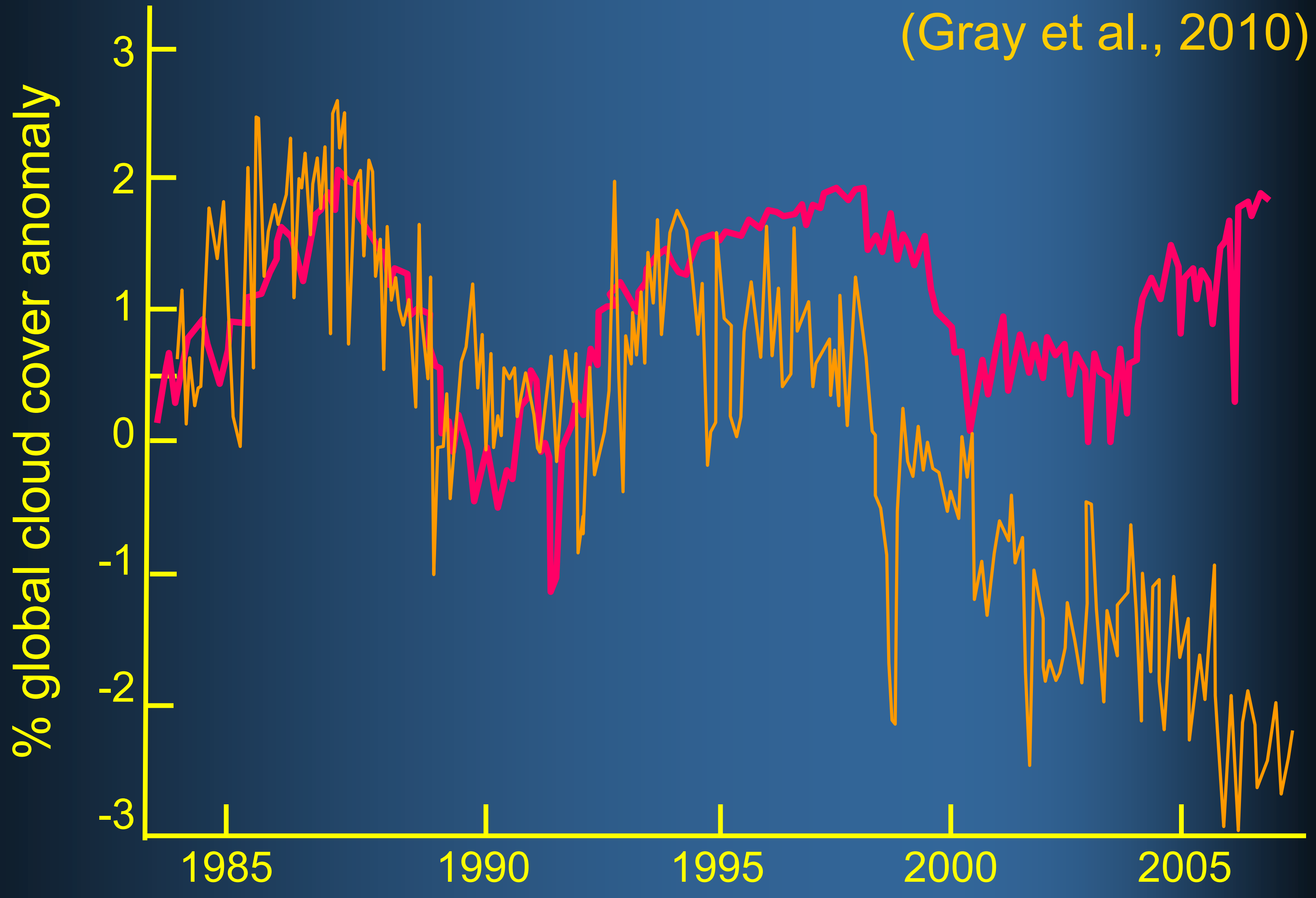
ISCCP D2 low-altitude cloud anomaly

N.B. 1-σ error in D2 dataset is about 2%

Global Cloud Cover Variation



Global Cloud Cover Variation



New Evidence: Diffuse Fraction (DF)

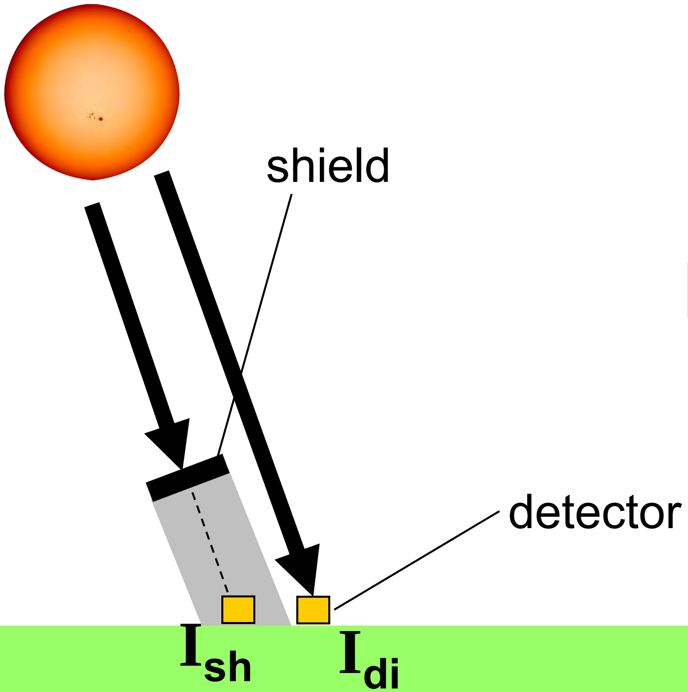
- Intensity in direct sunlight = I_{DI}
- Intensity in shade = I_{SH}
- Diffuse fraction, DF = I_{SH} / I_{DI}

- Measured at a number of sites since the 1950s

CLEAR SKY

$I_{SH} \approx 0$

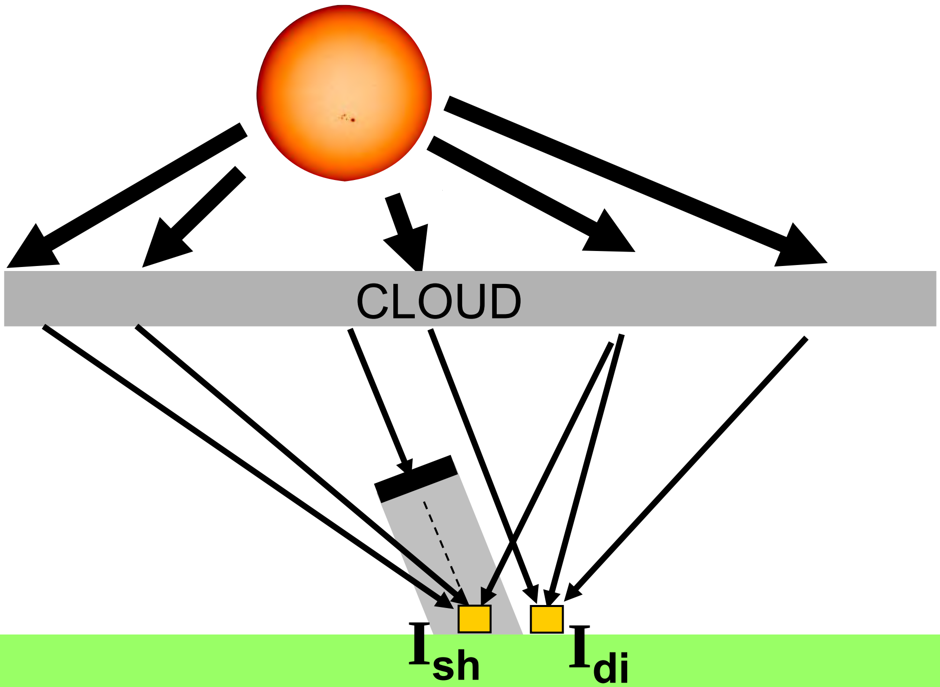
$DF = I_{SH} / I_{DI} \approx 0$



CLOUDY SKY (and/or aerosols)

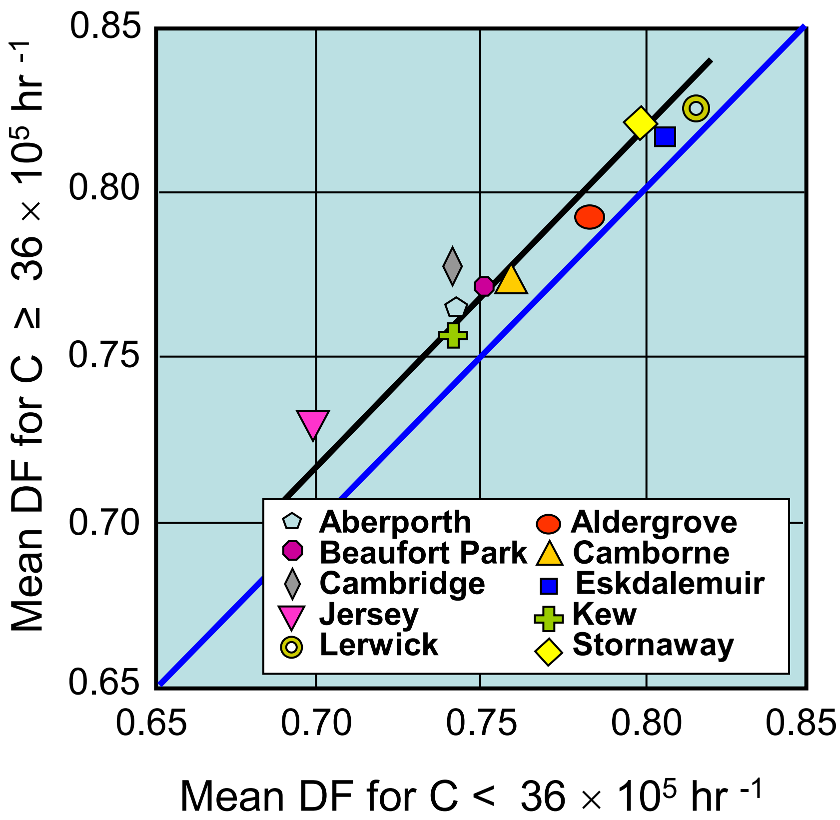
$I_{SH} \approx I_{DI}$

$DF = I_{SH} / I_{DI} \approx 1$



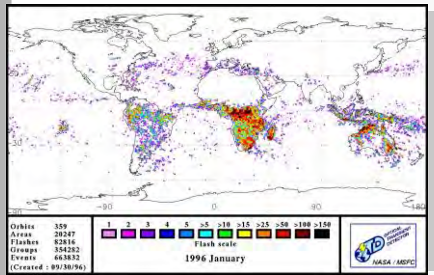
Global Cloud Cover Variation

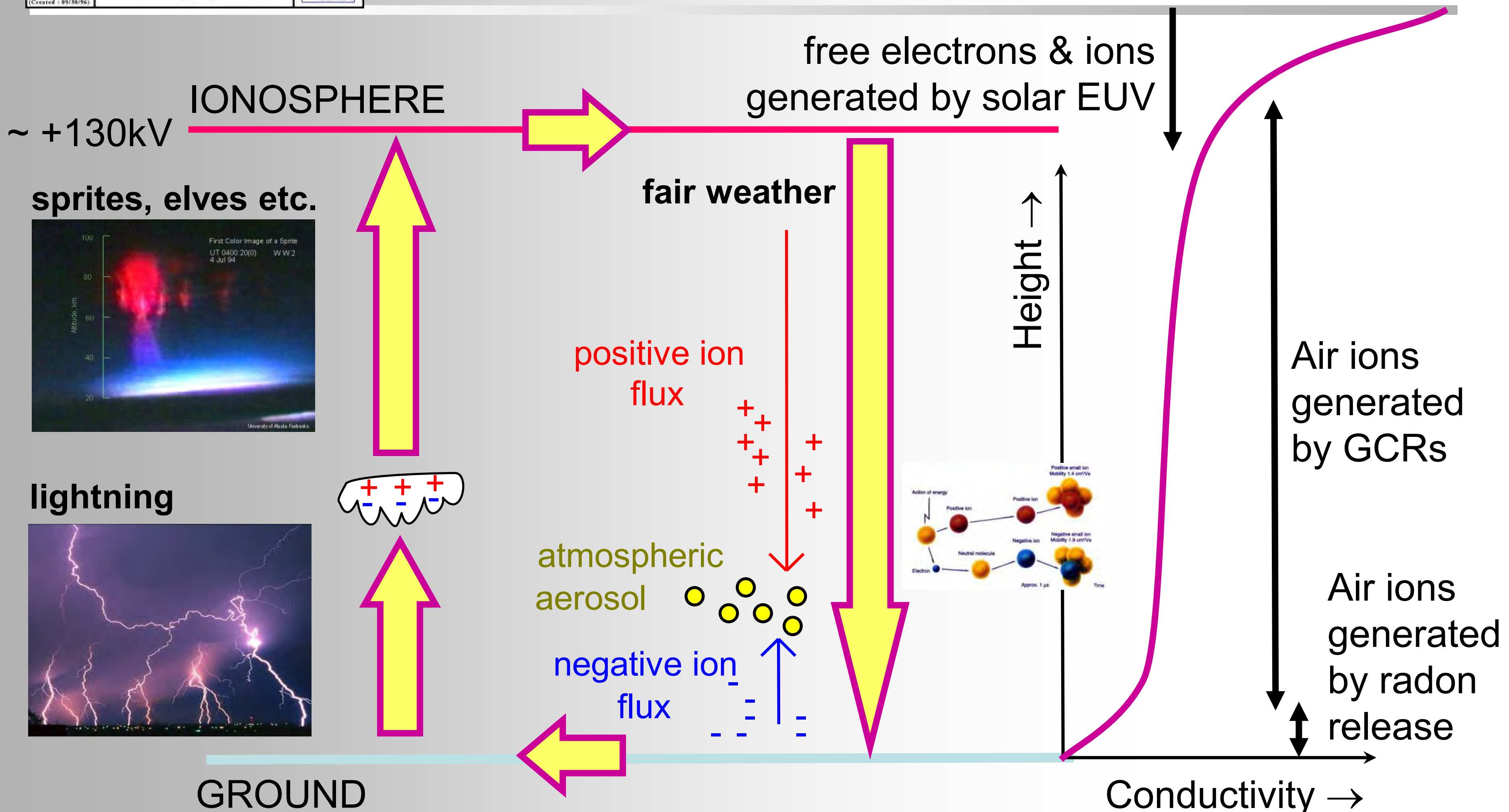
Harrison and Stephenson, Proc Roy. Soc (2006)

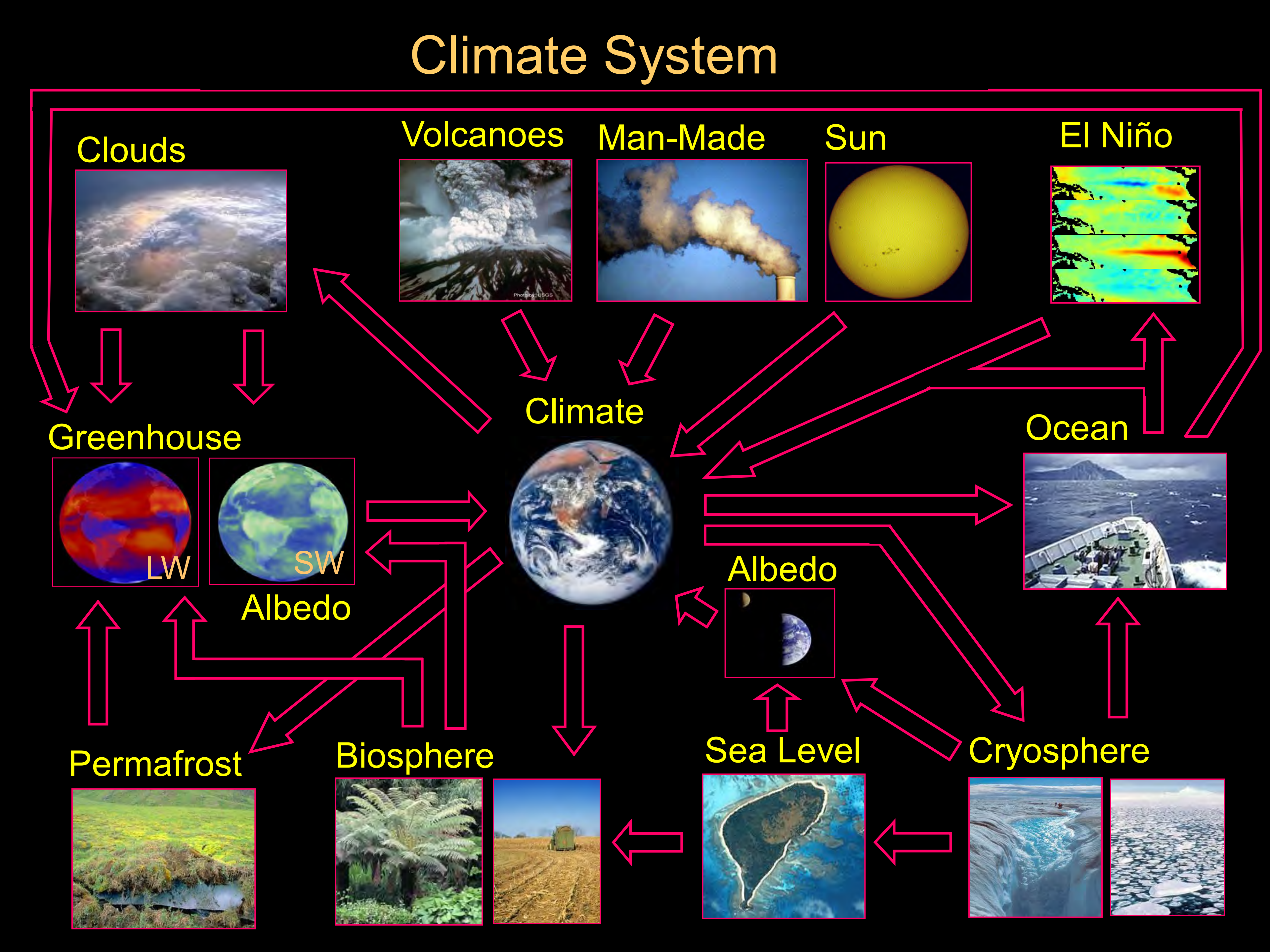


- Average DF for various stations in UK since 1950's
- Sorted according to the galactic cosmic ray flux (>3GeV) at Climax, C
- Mean DF for C > threshold consistently exceeds mean DF for C < threshold

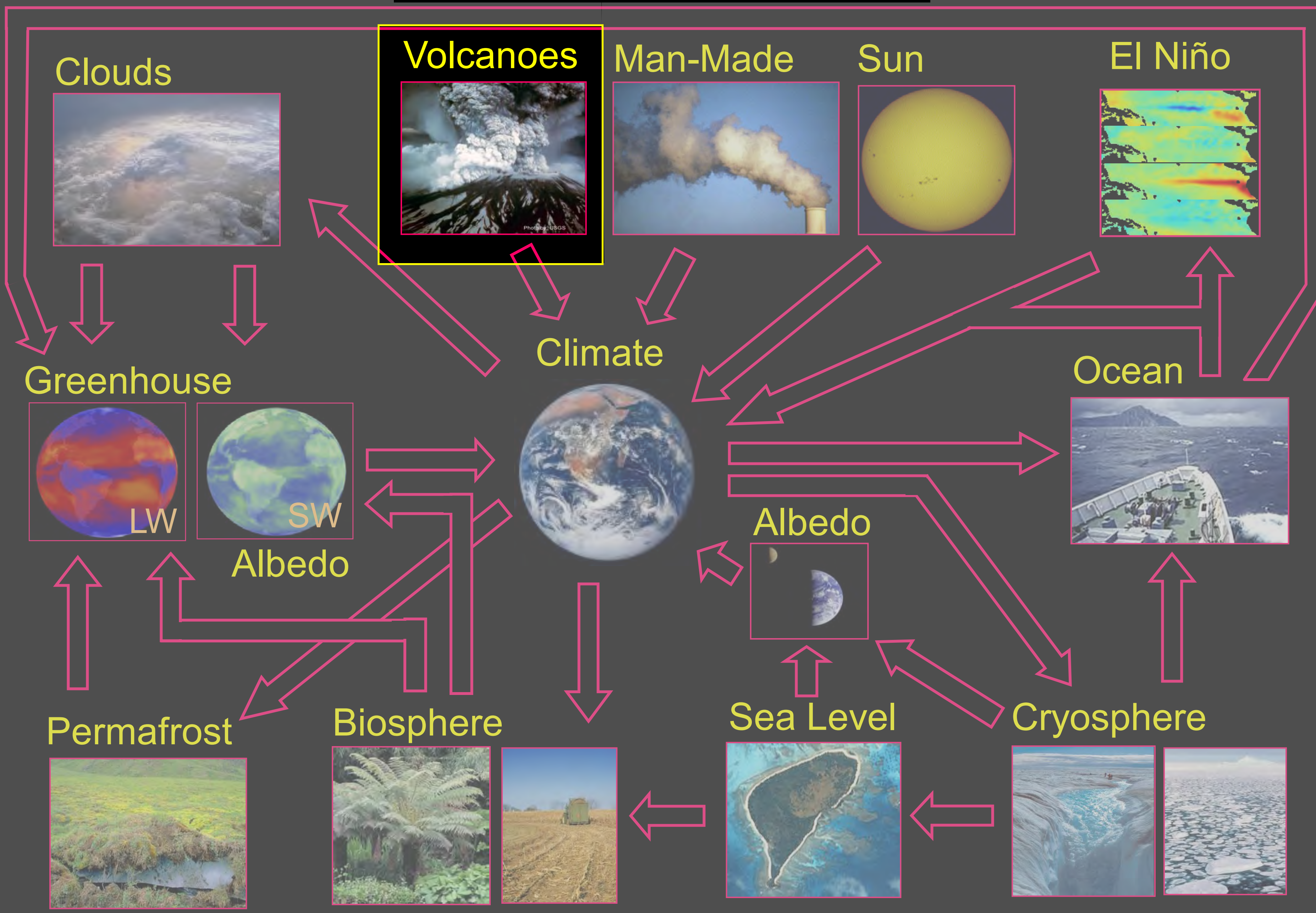
Global Electric Circuit



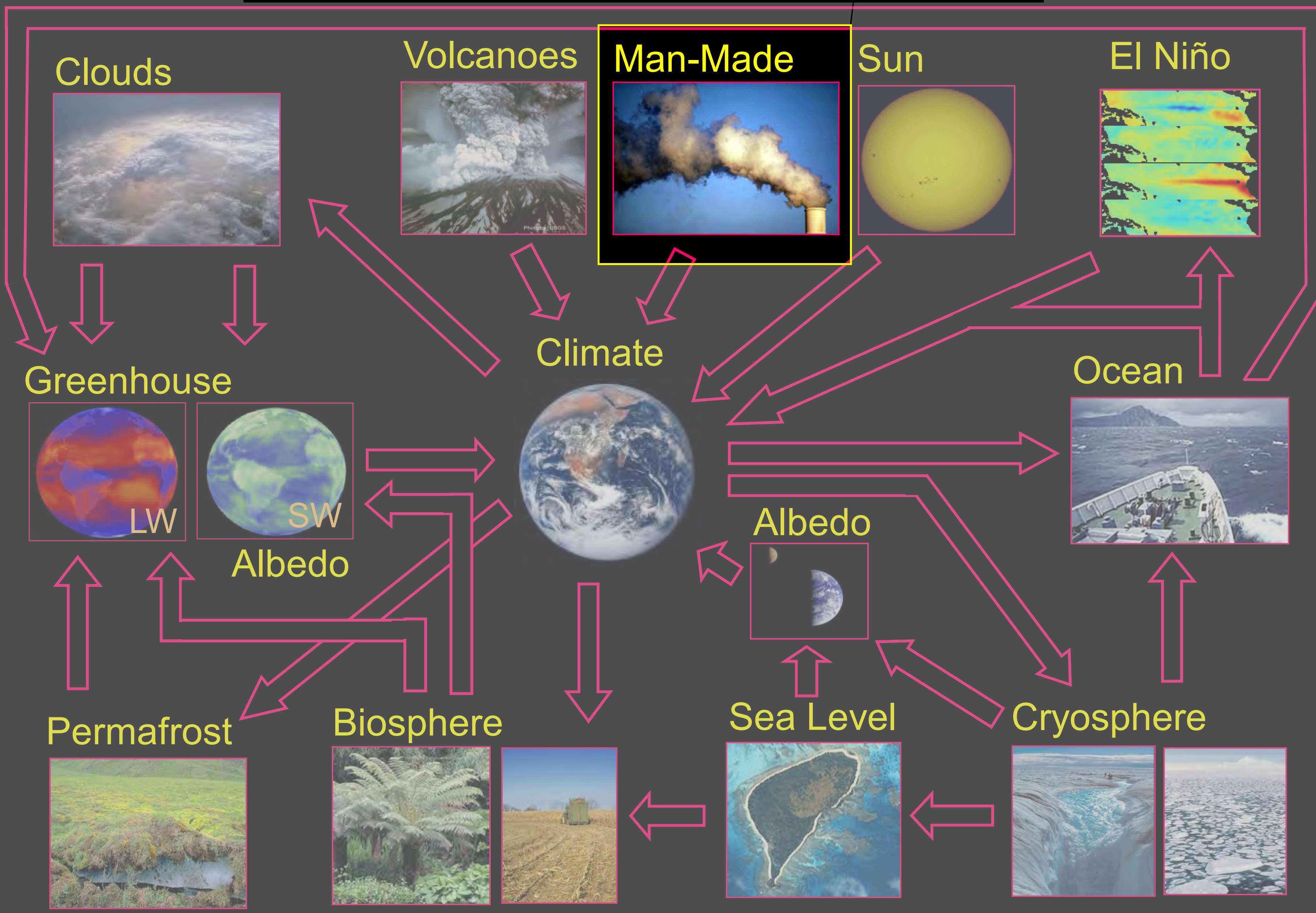



Climate System
Clouds
Volcanoes
Man-Made
Sun
El Niño
Climate
Greenhouse
LW
SW
Albedo
Ocean
Albedo
Permafrost
Biosphere
Sea Level
Cryosphere

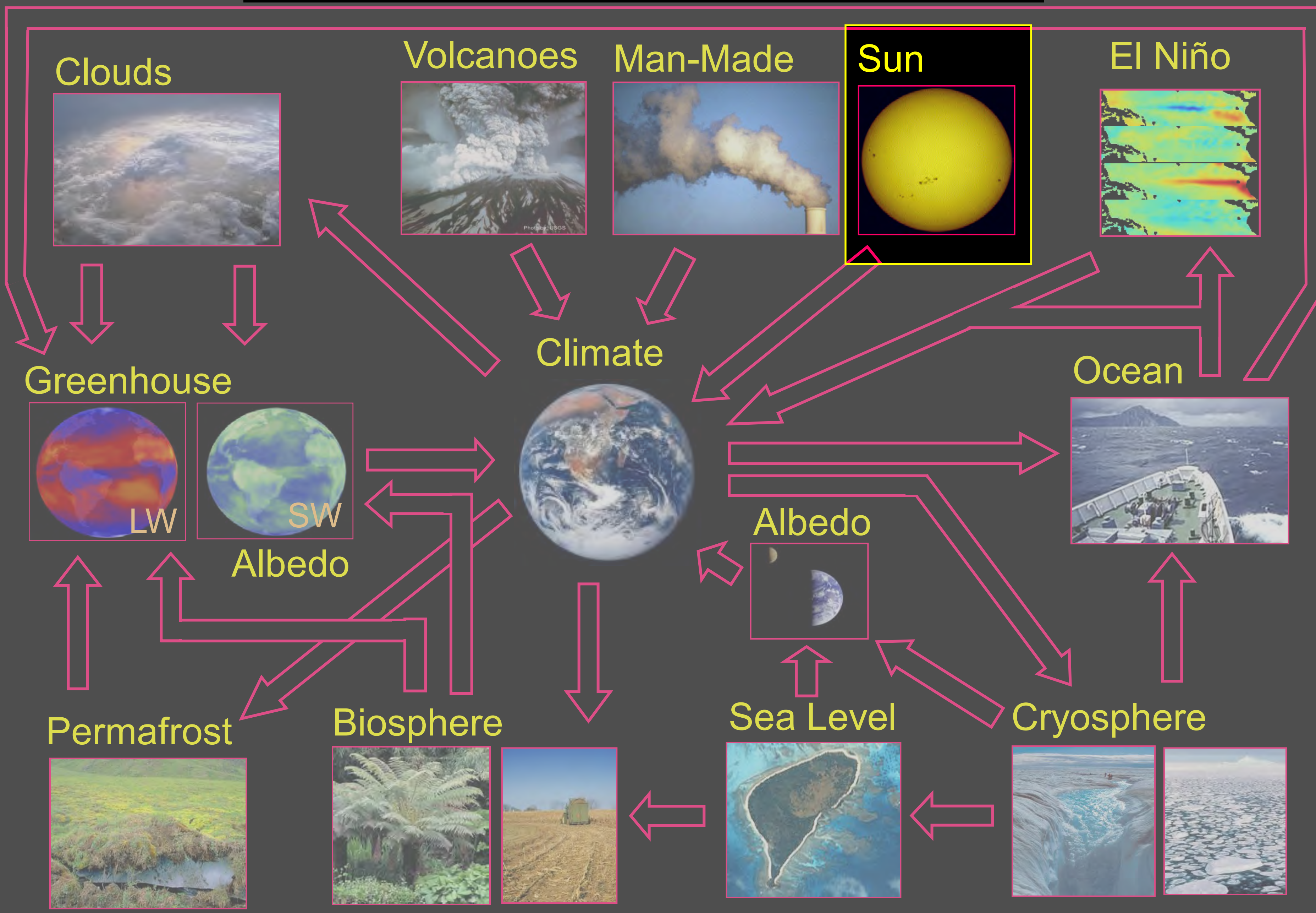
Geological Effects



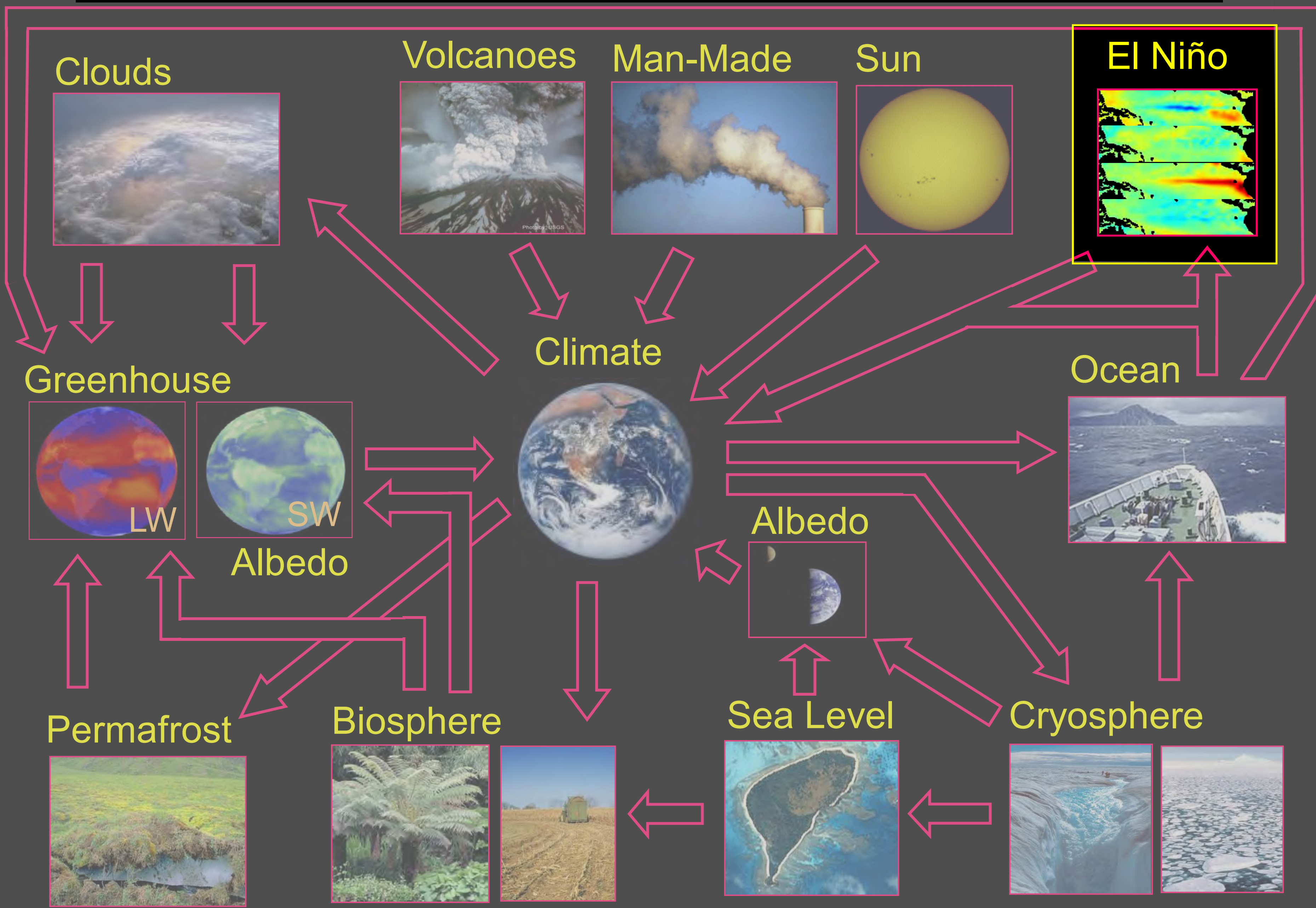
Anthropogenic Effects



Solar Influence



Short-Timescale Ocean Energy Exchange



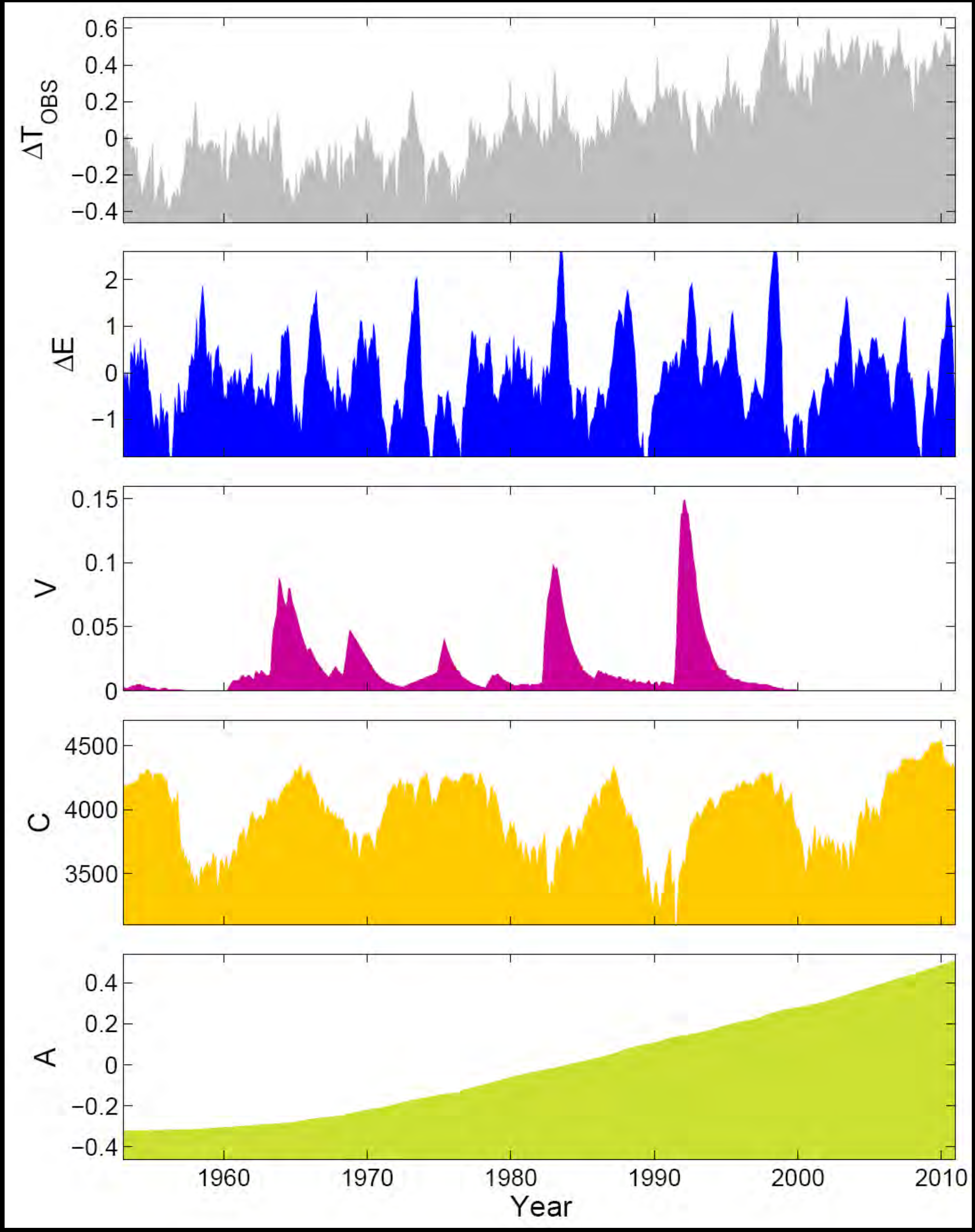
Observed Global Surface Air Temperature Anomaly, ΔT_{OBS}

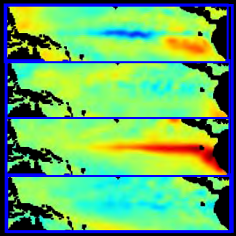
ENS0 N3.4 index Anomaly, ΔE

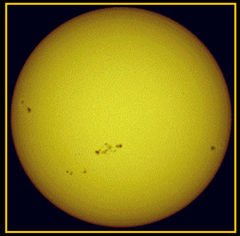
Mean Optical Depth (AOD) at 550 nm, V

Cosmic Ray Counts at Climax, C

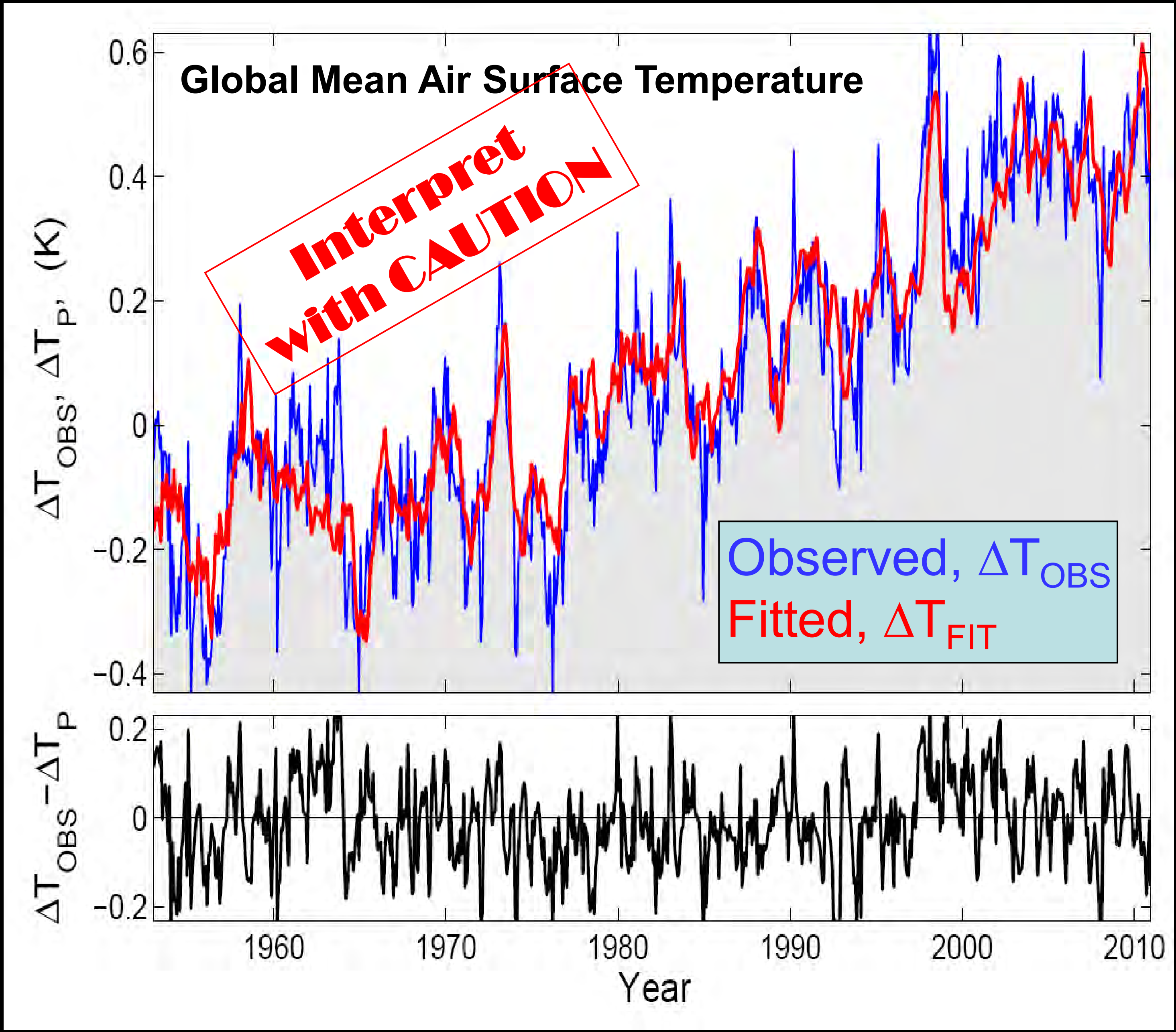
Anthropogenic forcing, A, (greenhouse gases, aerosols,& land use change)







- fit to observed GMAST anomaly obtained using the Nelder-Mead simplex (direct search) method



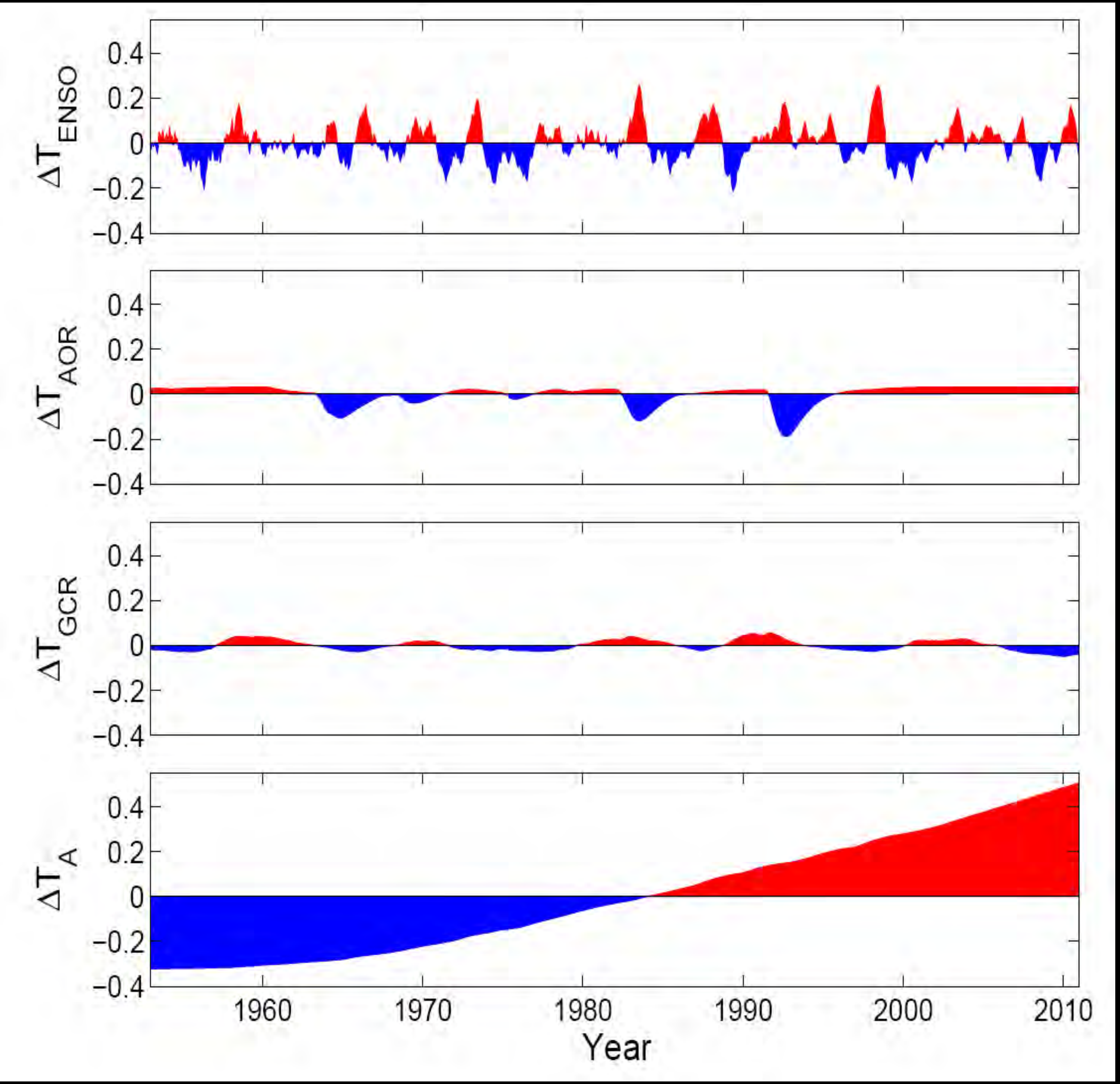
(Lockwood, 2008)

- when a fit has too many degrees of freedom
- can start to fit to the noise in the training subset, which is not robust throughout the data (fit has no predictive power)
- recognised pitfall when quasi-chaotic behaviours give large internal noise such as in climate science[1] and population growth[2]
- often not recognised in space physics where systems tend to be somewhat more deterministic with lower internal variability.

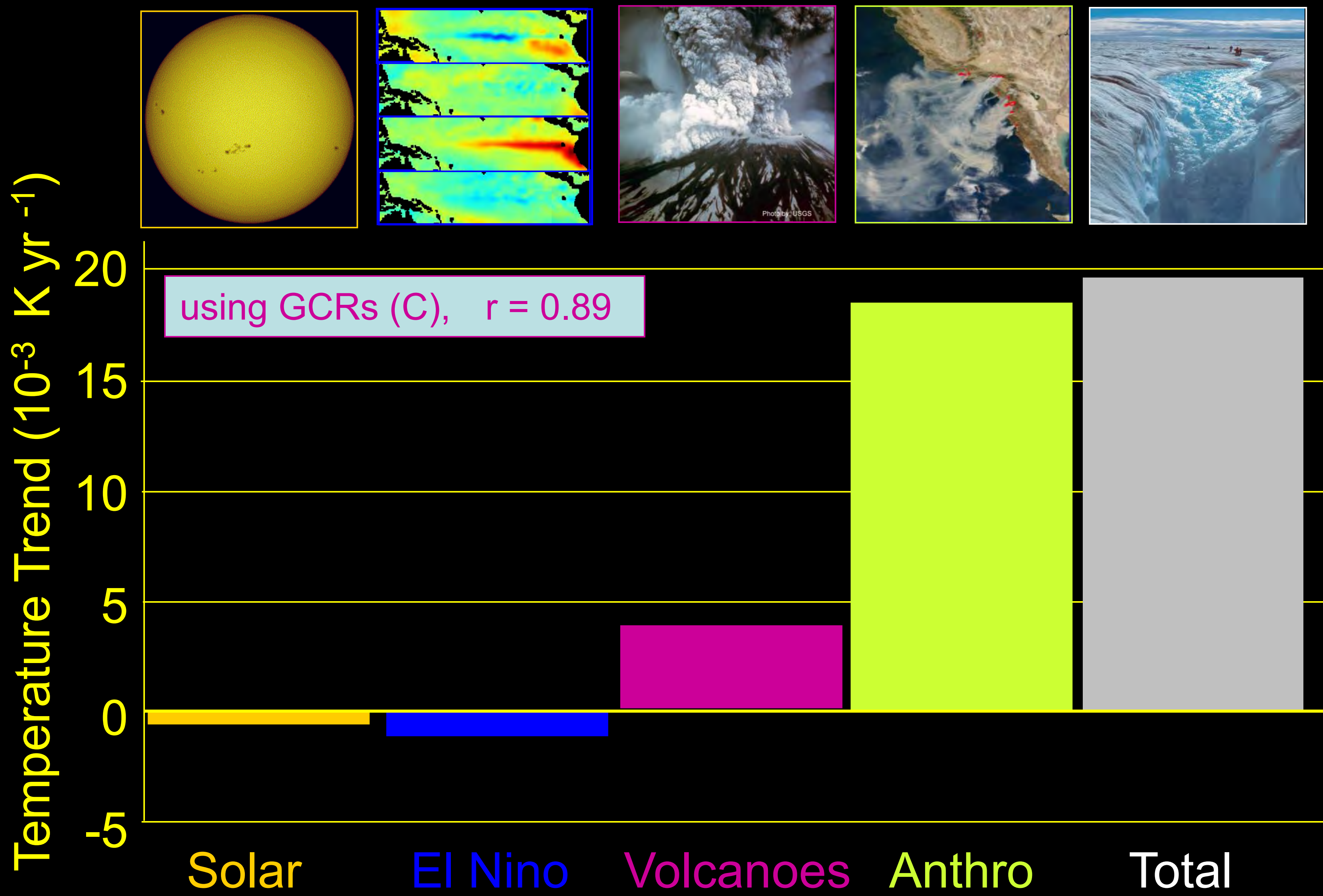
[1] e.g. Knutti et al. (2006) *J. Climate*, DOI: 10.1175/JCLI3865.1

[2] e.g. Knape and de Valpine (2011) *Proc. Roy. Soc. London B*, DOI: 10.1098/rspb.2010.1333

- Weighted contributions to best fit variation, T_p (uses Climax GCR counts to quantify solar effect)



(updated from Lockwood, 2008)

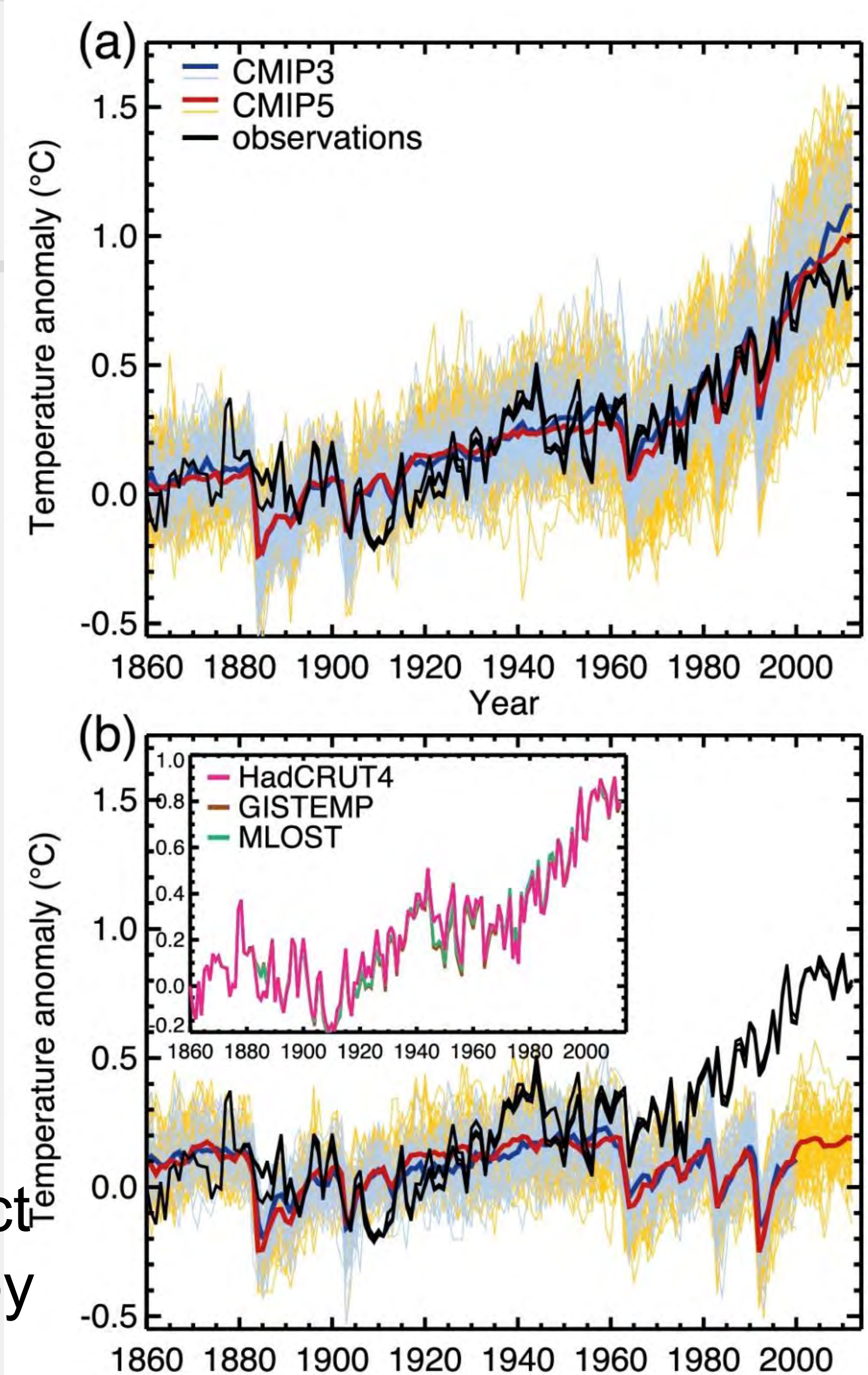


1987-present

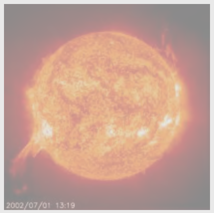
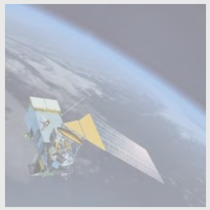
(Lockwood, 2008)

Detection-Attribution

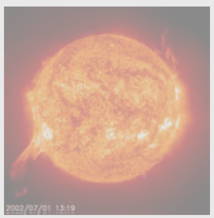
- Use models to avoid over-fitting problem
- The idea is that models, started from slightly different initial conditions, can reproduce the internal variability of the climate system
- Produce an ensemble of many model runs for set inputs and then compare mean or median with observations
- Runs with no anthropogenic effect differ from observed GMAST rise by more than the internal noise level



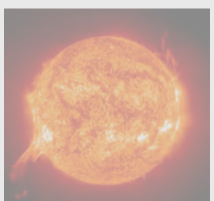
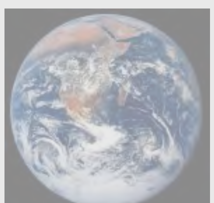
Solar Variability: Effects on Climate?

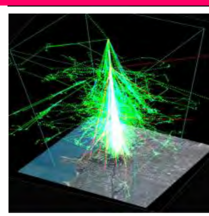
Solar Outputs



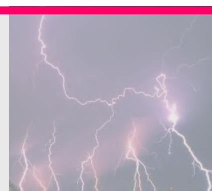

Solar Variability

Global Effects

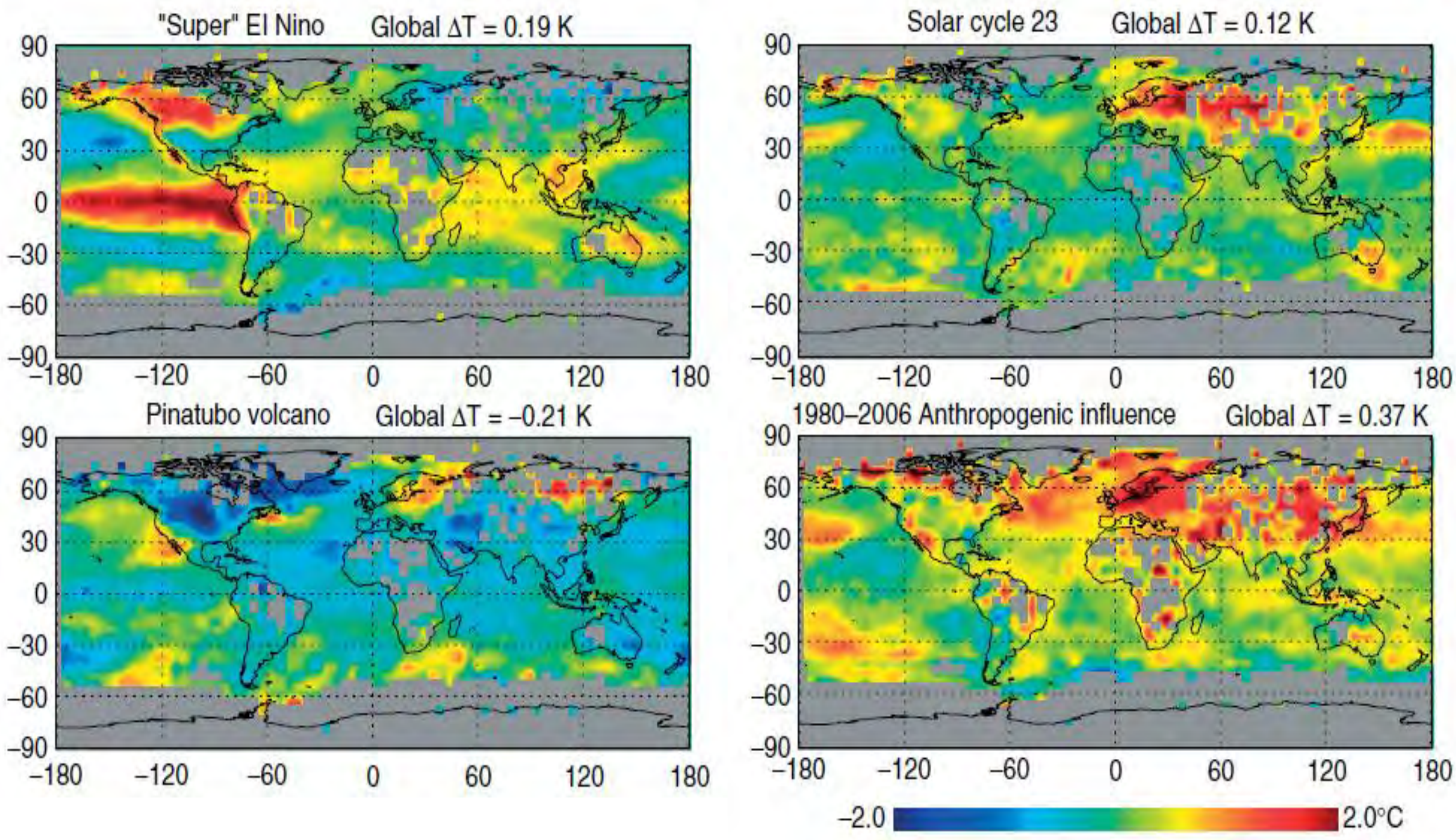
Regional & Seasonal Effects

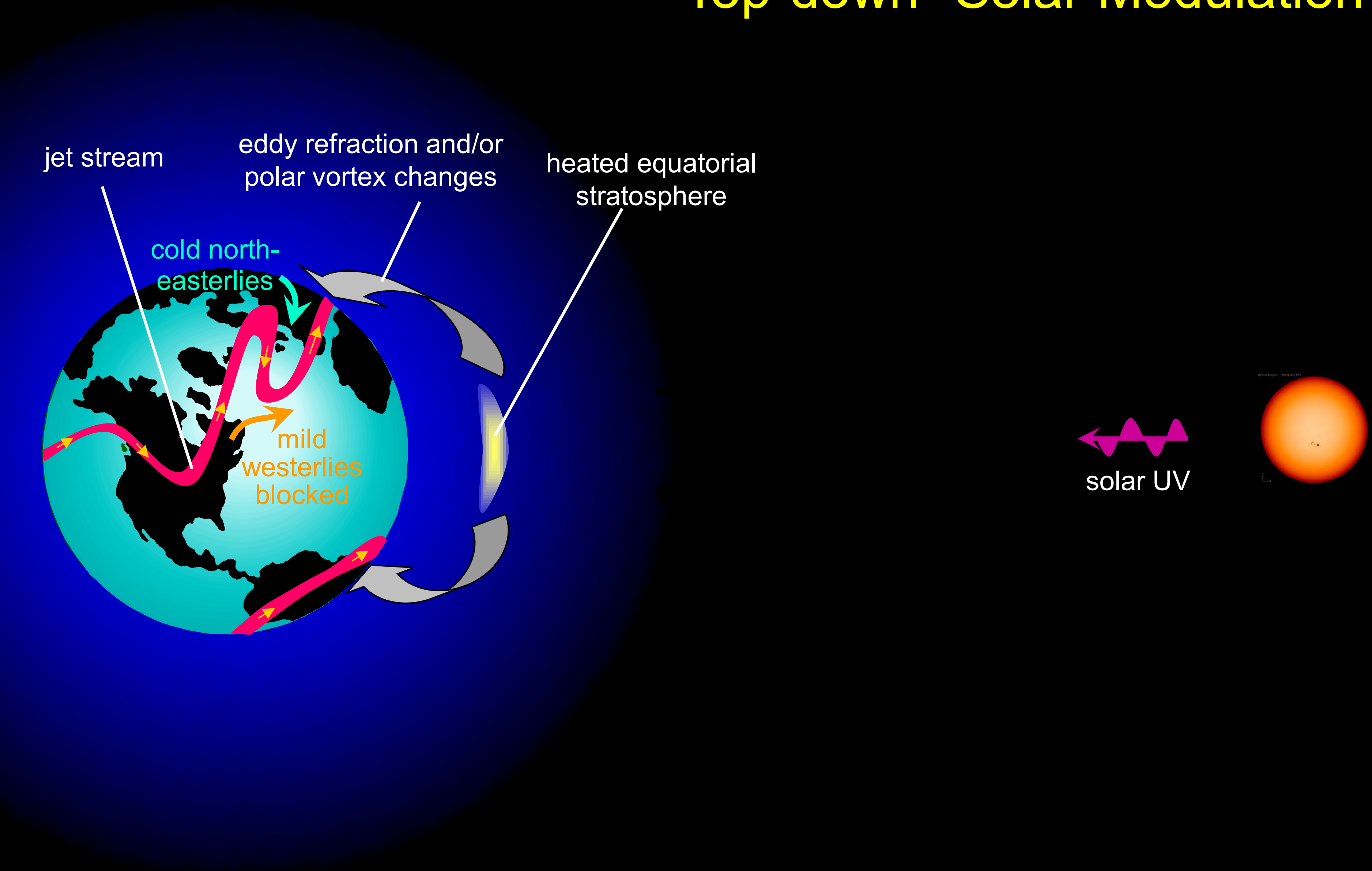
The Future

Regional Analysis

(Lean and Rind, 2008)



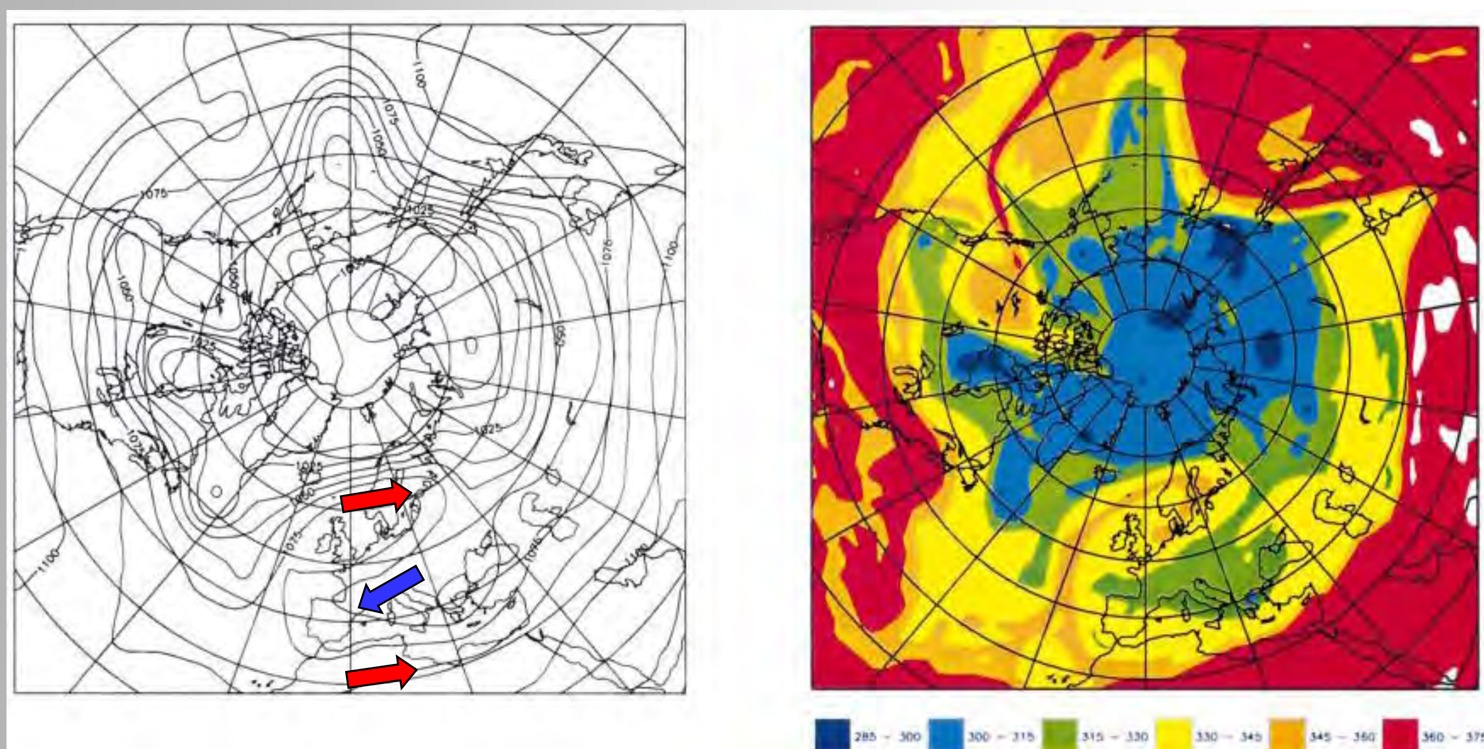
“Top-down” Solar Modulation



Atlantic blocking events

(Plelly and Hoskins, 2003)

- blocking events are large long-lived anticyclones which disrupt easterly flow of storms, bifurcating the jet stream and, in winter, causing cold winds from the east over Europe



Example at 12UT, 21 Sept, 1998: on the potential vorticity PV=2 surface
(a) 250-hPa geopotential height (b) potential temperature θ (K)

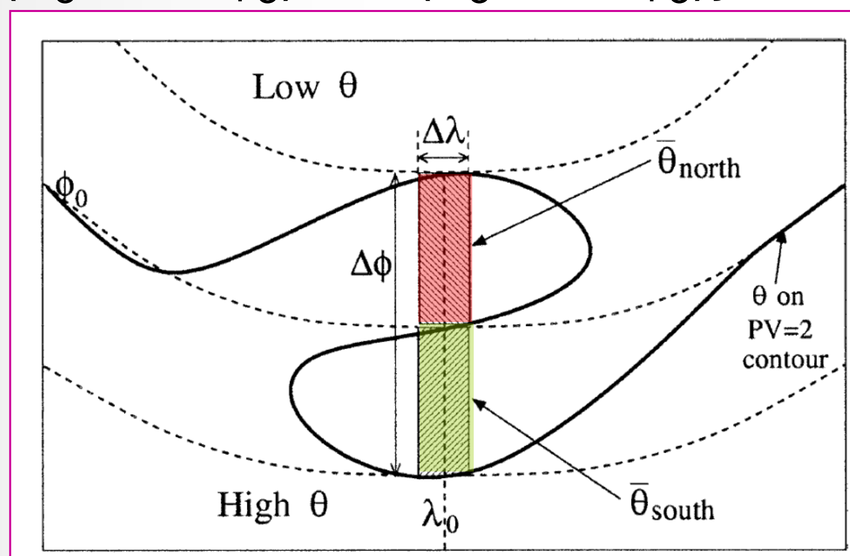
Blocking Intensity Indices

- *Lejenäs and Økland (1983)* required a region of easterly winds and used $Z(\lambda, \phi_o+\Delta\phi/2)-Z(\lambda, \phi_o-\Delta\phi/2)$ where Z is a constant height geopotential, λ is the longitude and ϕ the latitude

- *Barriopedro et al. (2006,2008)* used $BI = 100\times \{[Z(\lambda_o, \phi_o)/RC]-1\}$ where $RC = \{Z(\lambda_o+\Delta\lambda, \phi_o) - Z(\lambda_o-\Delta\lambda, \phi_o)\} / 2$

- *Pelly and Hoskins (2006,2008)* used mean potential temperature θ in the red and green areas of the plot B =

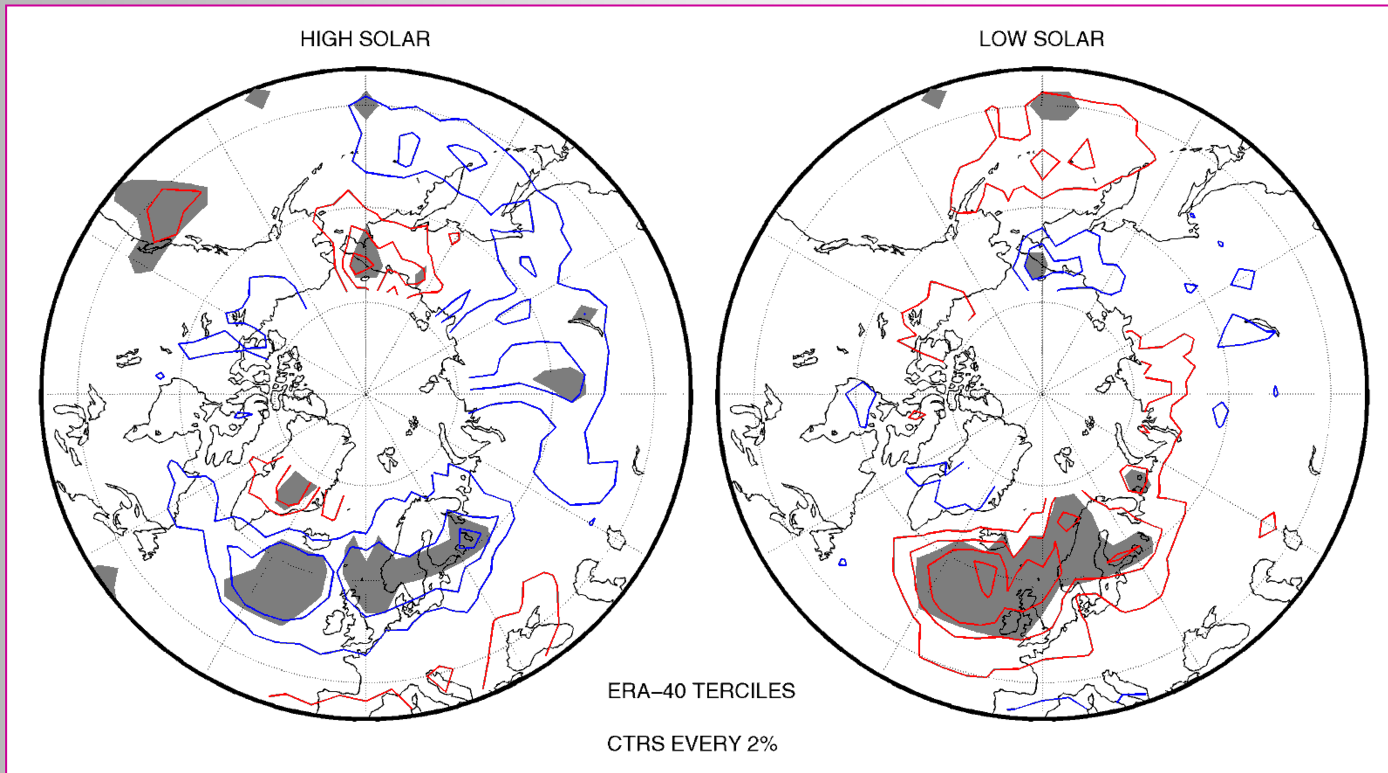
$$(2/\Delta\phi) \int_{\phi_o}^{\phi_o+\Delta\phi/2} \theta \, d\phi - (2/\Delta\phi) \int_{\phi_o-\Delta\phi/2}^{\phi_o} \theta \, d\phi$$



ERA-40 Analysis of Blocking Index

(change of terciles relative to whole set)

(Woollings et al, GRL.,2010)



- sorted using open solar flux F_S

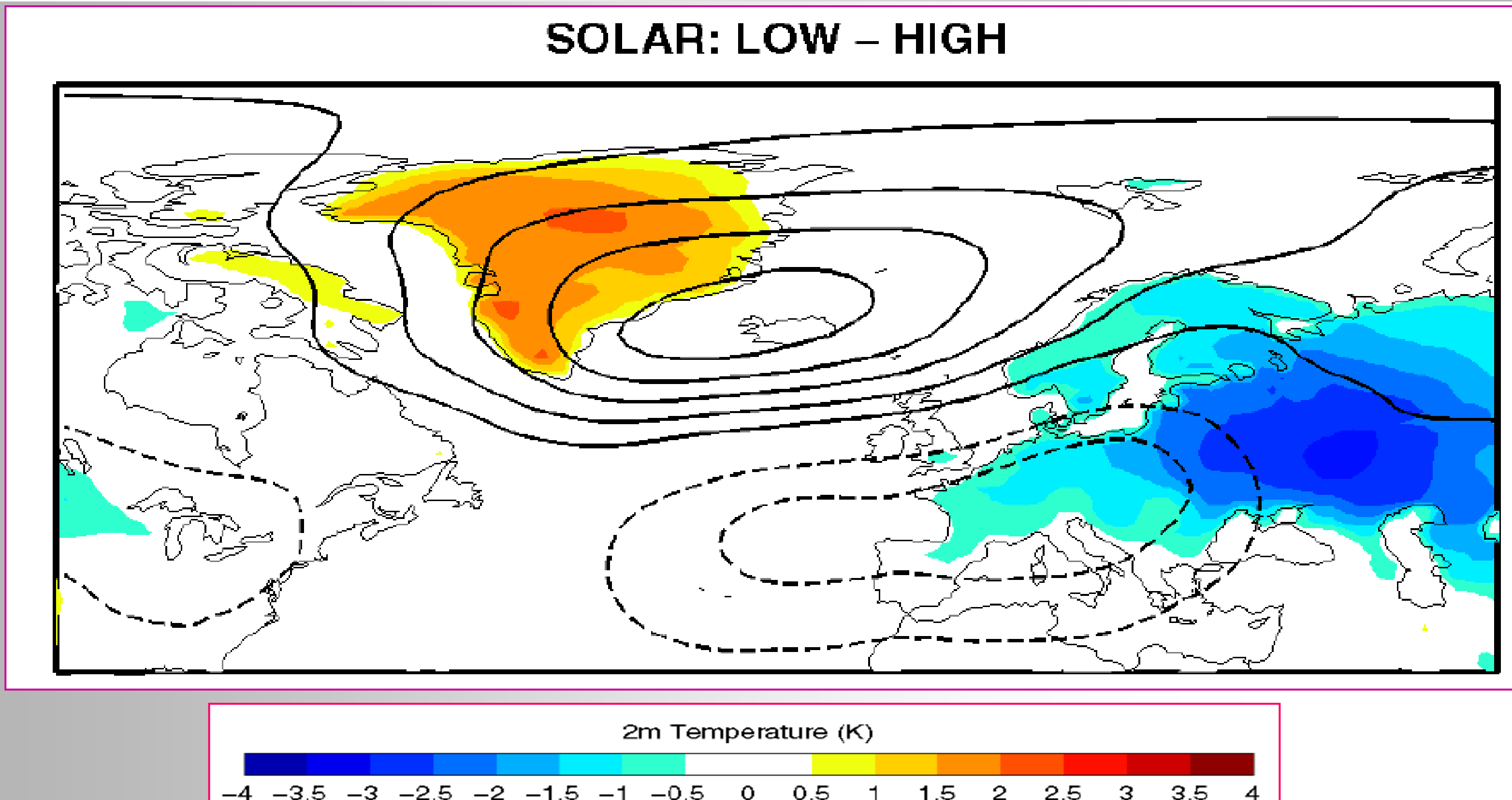
High/Low solar activity gives reduced/enhanced (up to 8%) blocking over east Atlantic and Europe (symmetric effect)

Consistent and localised effect

Grey area shows significance from Monte-Carlo technique > 95%

ERA-40 Analysis of DJF temperatures & circulation (difference of high and low tercile subsets)

(Woollings et al, GRL.,2010; see also Barriopedro et al., JGR, 2008)



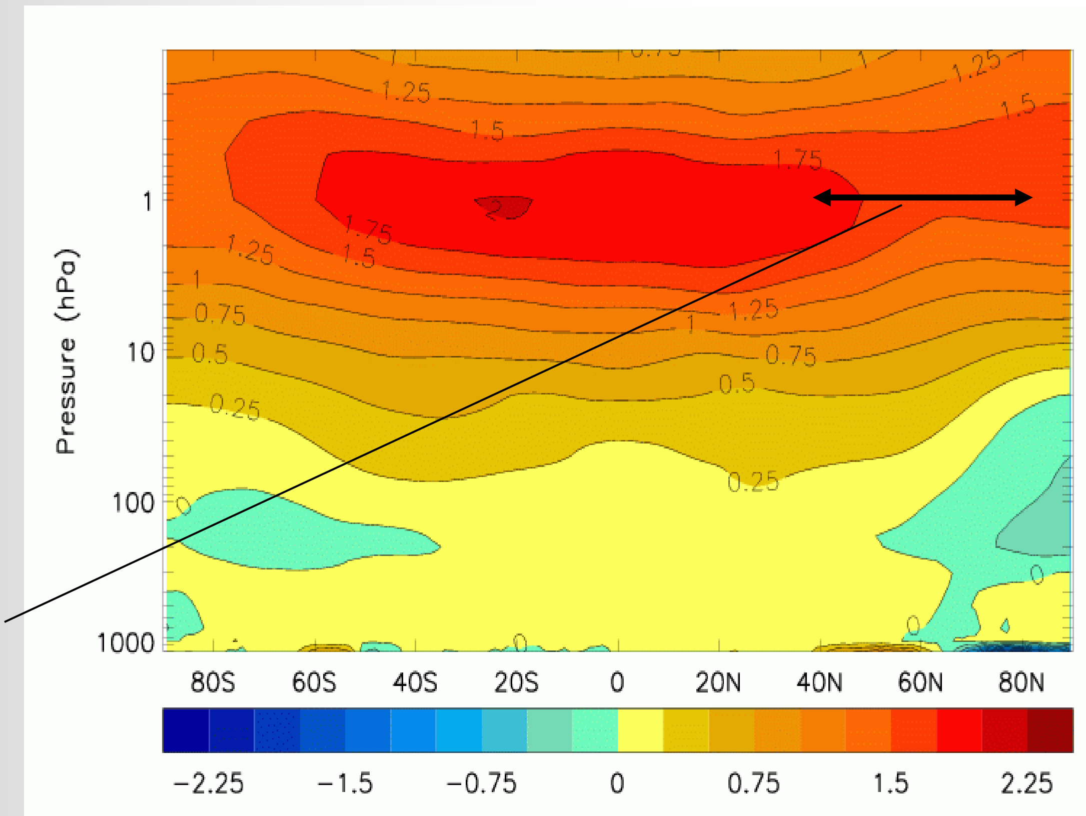
- sorted using open solar flux F_S

Low solar activity gives lower surface temperatures in central England
Effect much stronger in central Europe
Analysis shows a distinct system to NAO

Modelled solar maximum-solar minimum temperatures

(Ineson et al, Nature Geosci., 2011)

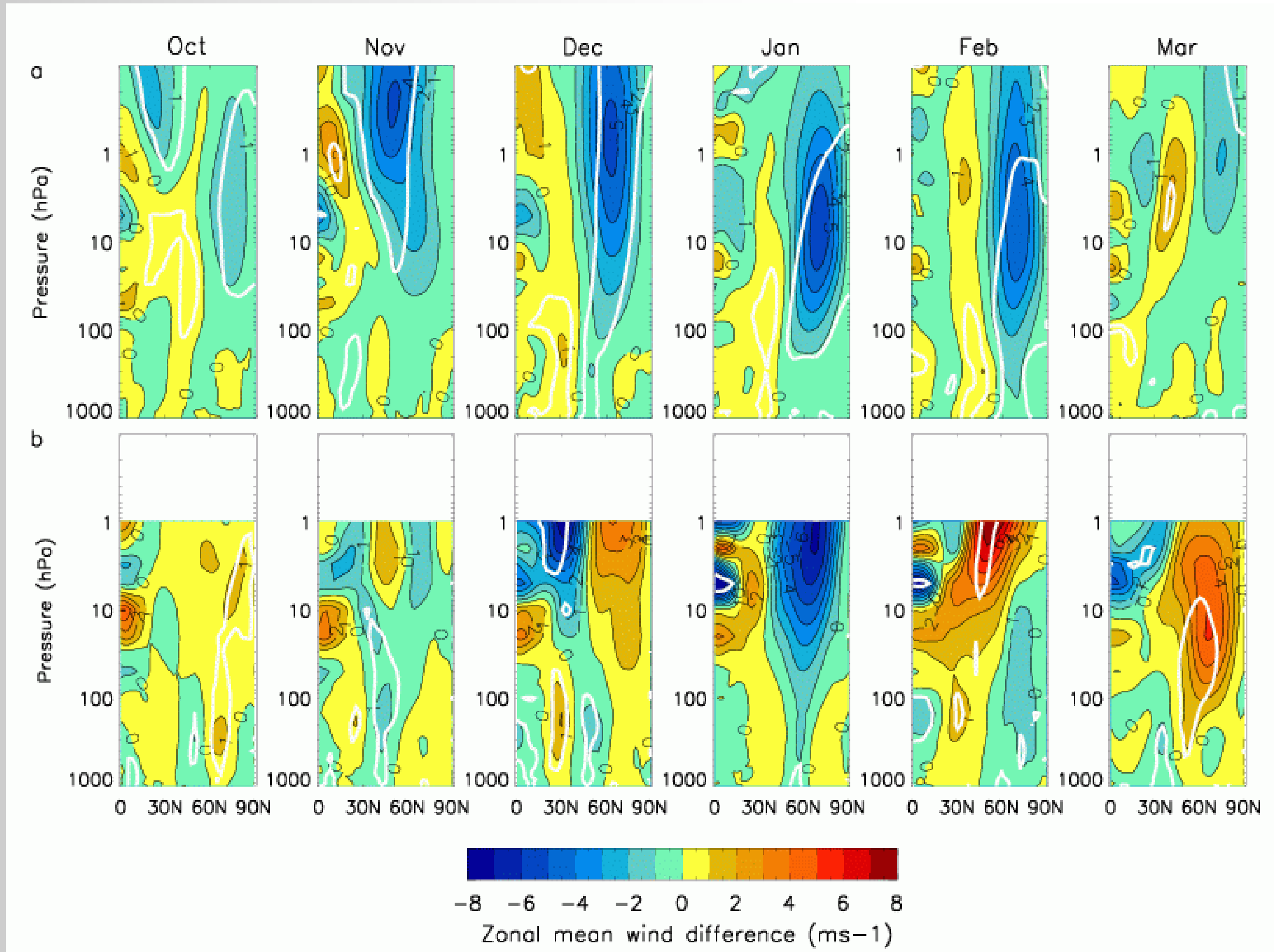
- Heating effect only (no [O_3] change)
- HADGEM3rev1.1 GCM, 85 atmos and 42 ocean levels.
- Uses the SORCE max-min UV spectrum $S_S(\lambda)$
- Increased meridional temperature gradient →increase in westerly flow



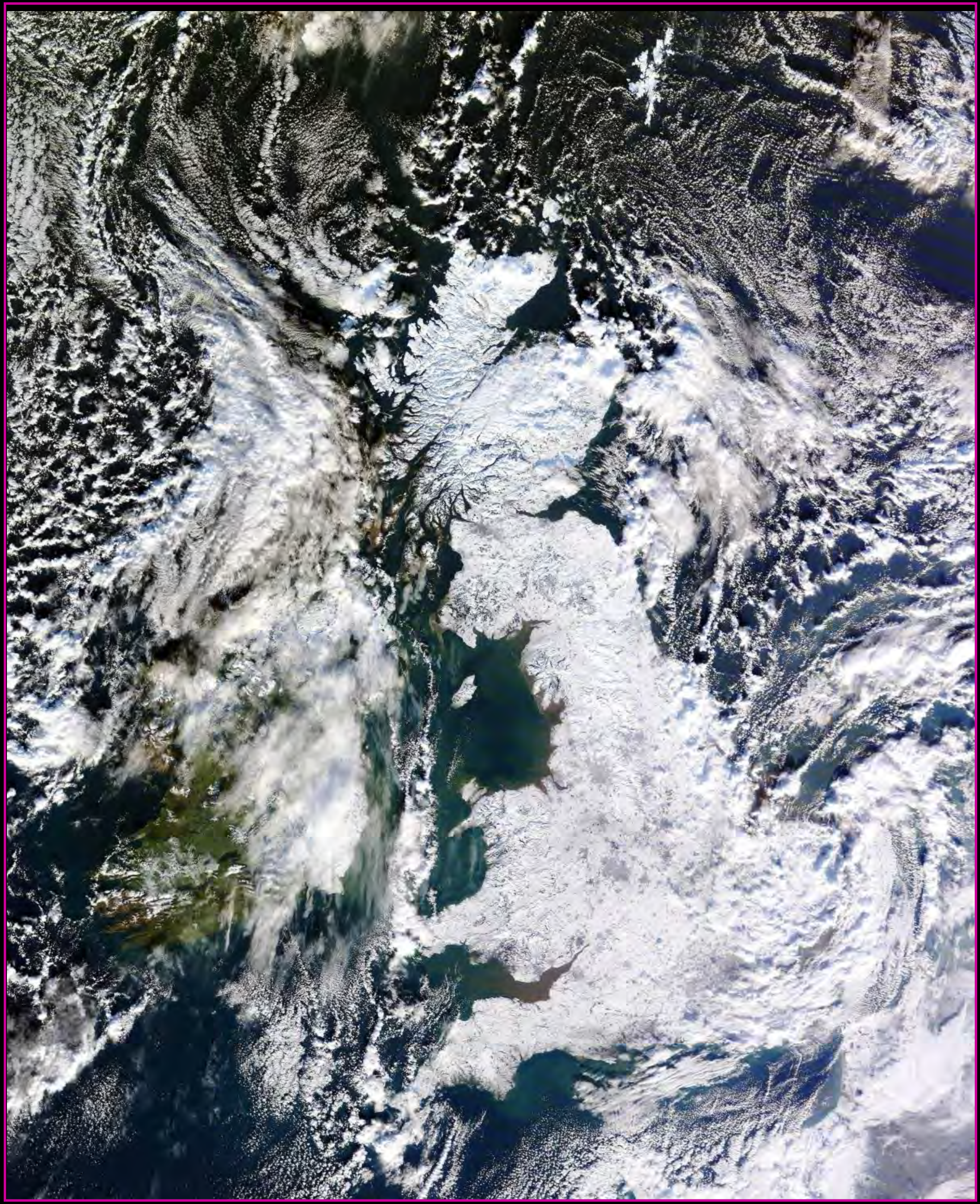
Modelled solar maximum-solar minimum zonal wind speed

(Ineson et al, Nature Geosci., 2011)

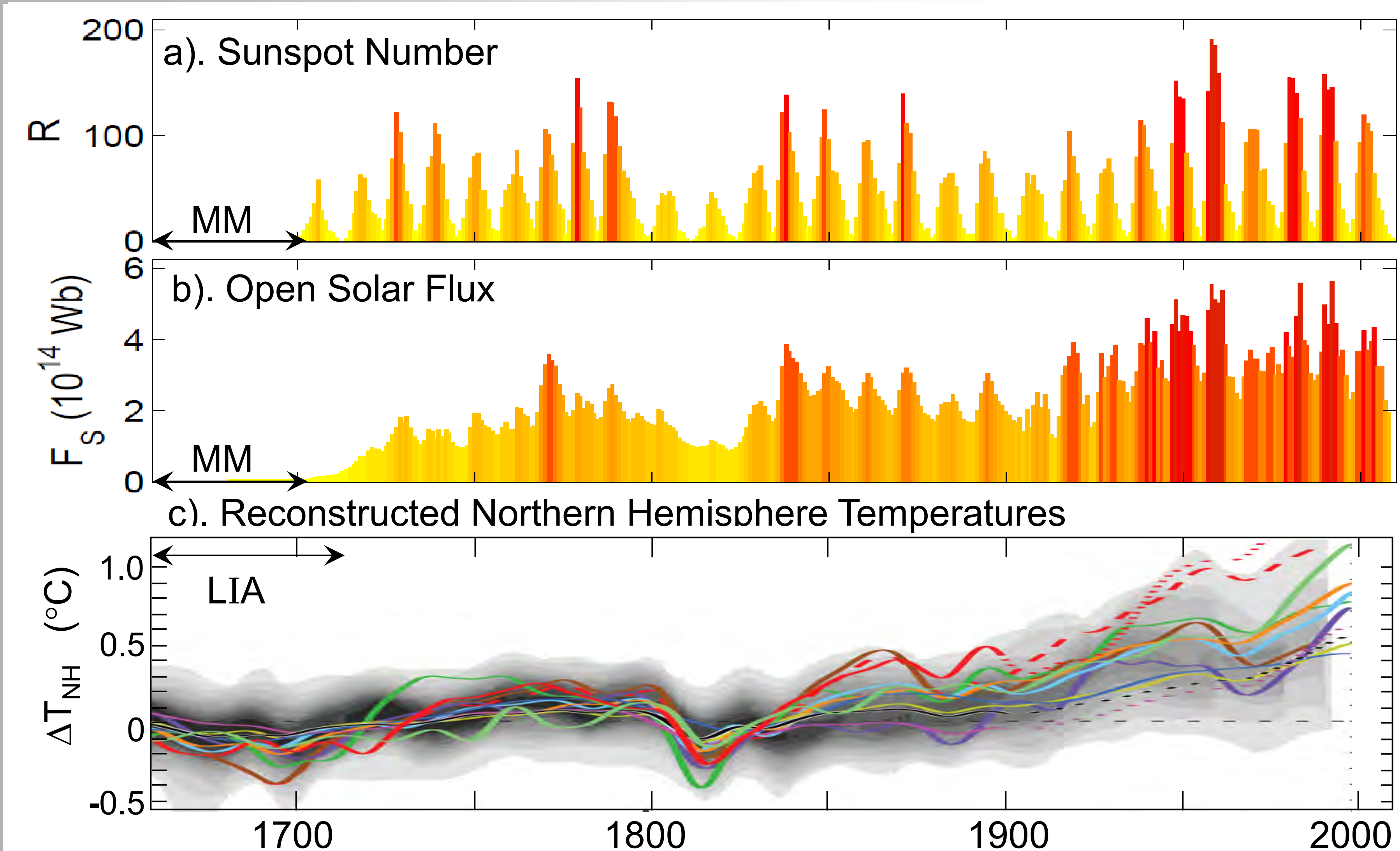
- Modelled downward and northward propagation of easterly wind anomaly (by Eliassen-Palm flux divergence)
- seen in ERA40+ data
- c.f. Kodera and Kuroda, 2002; Matthes et al.,2006



January 2010



Maunder Minimum & the "Little Ice Age"



January 1683

A Frost Fair on the Thames in London. The river froze in central London relatively frequently during the Maunder Minimum of sunspot activity

“An exact and lively mapp … with an alphabetical explanation of the most remarkable figures”

“An exact and lively mapp … with an alphabetical explanation of the most remarkable figures”

H. The Musick Booth

“An exact and lively mapp … with an alphabetical explanation of the most remarkable figures”

I. The Printing Booth

“An exact and lively mapp … with an alphabetical explanation of the most remarkable figures”

E. The Roast Beefe Booth

"An exact and lively mapp … with an alphabetical explanation of the most remarkable figures"

N. The Boat drawne with a Hors

“An exact and lively mapp … with an alphabetical explanation of the most remarkable figures”

Q. The Bull Baiting

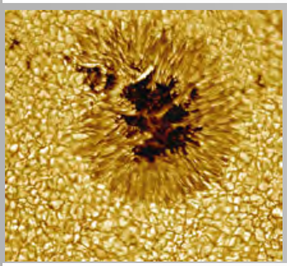
"An exact and lively mapp … with an alphabetical explanation of the most remarkable figures"

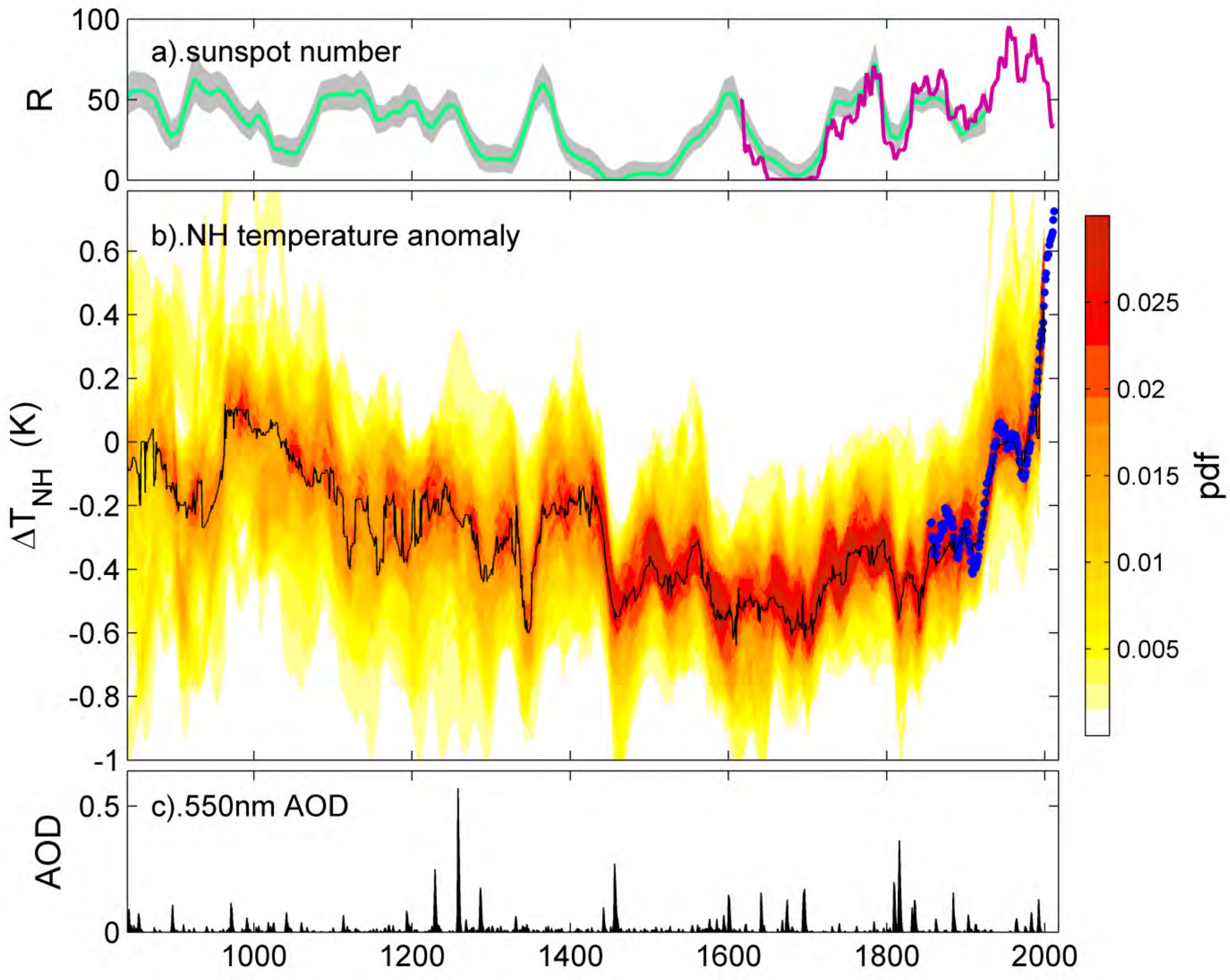
C. The Tory Booth

"An exact and lively mapp … with an alphabetical explanation of the most remarkable figures"

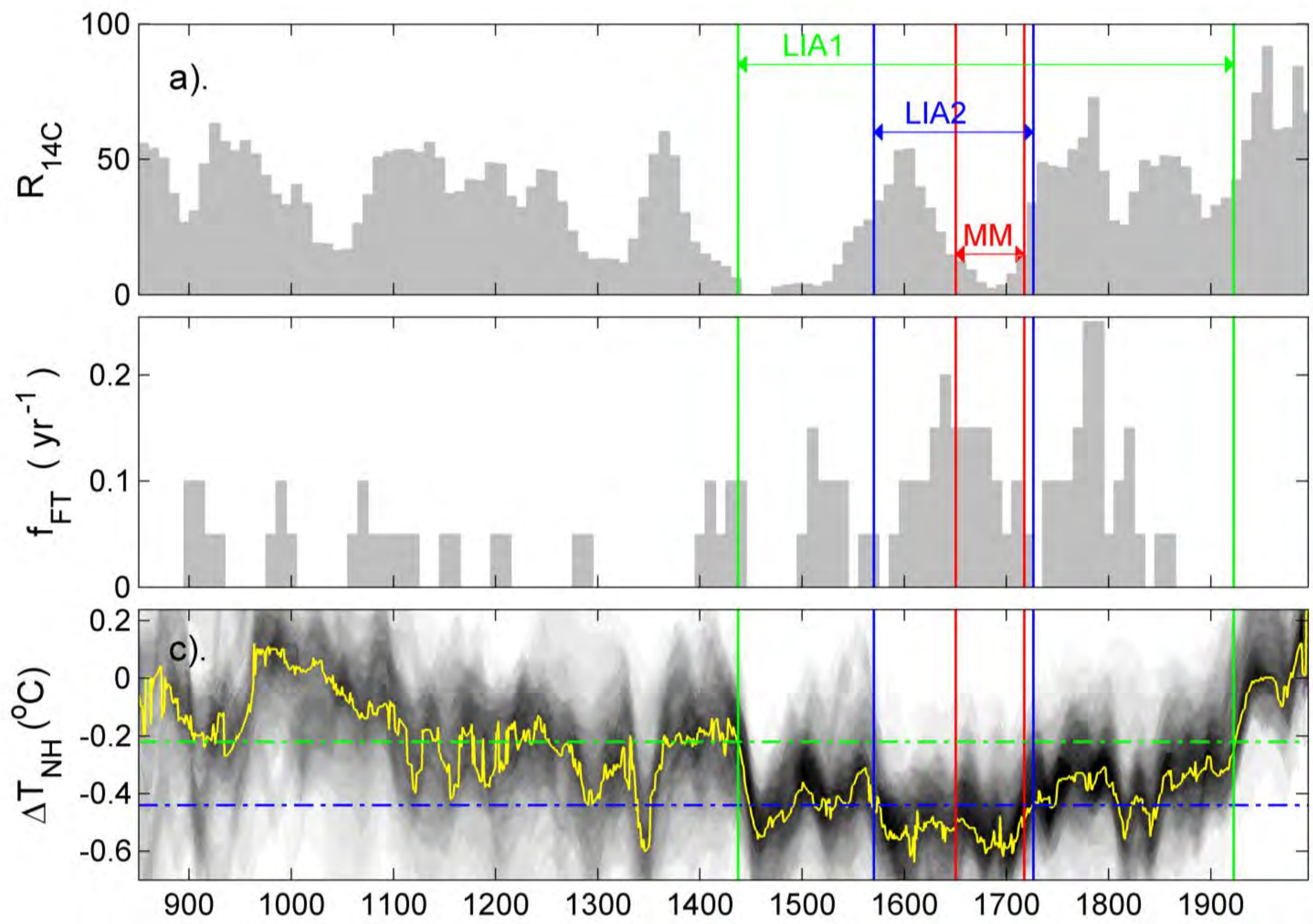
Z. London Bridge

Maunder Minimum & the "Little Ice Age"

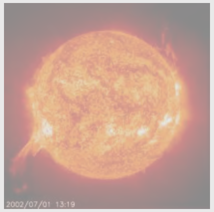
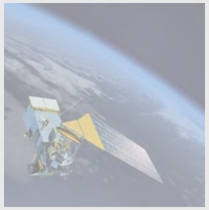




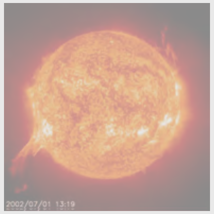
Maunder Minimum & the "Little Ice Age"



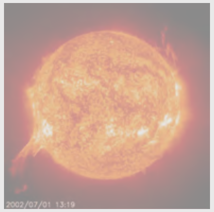
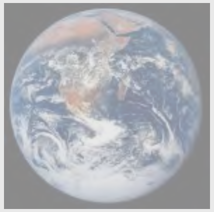
Solar Variability:
Effects on Climate?

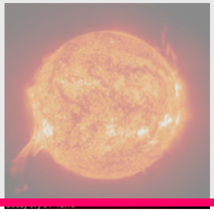
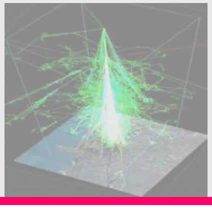
Solar Outputs




Solar Variability

Global Effects

Regional & Seasonal Effects


The Future

Predictions for the future

"It is not important to predict the future, but it is important to be prepared for it"

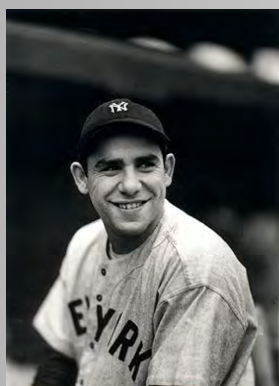
Pericles,
Athenian orator, statesman and general
c. 495 – 429 BC

"It is not important to know the future, but to shape it"

Antoine de Saint Exupéry,
French writer and aviator
1900 - 1944

"Prediction is very hard — especially when it's about the future"

Niels Bohr
Danish Physicist
1885 – 1962



"Never make predictions — especially about the future"

Lawrence Peter ("Yogi") Berra
American Baseball Player, coach and author
1925 –

Who also said *"I never said half the things I really said."*

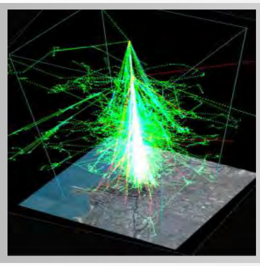
"It ain't over 'till it's over"

"When you come to a fork in the road, take it."

"It's like déjà vu all over again"

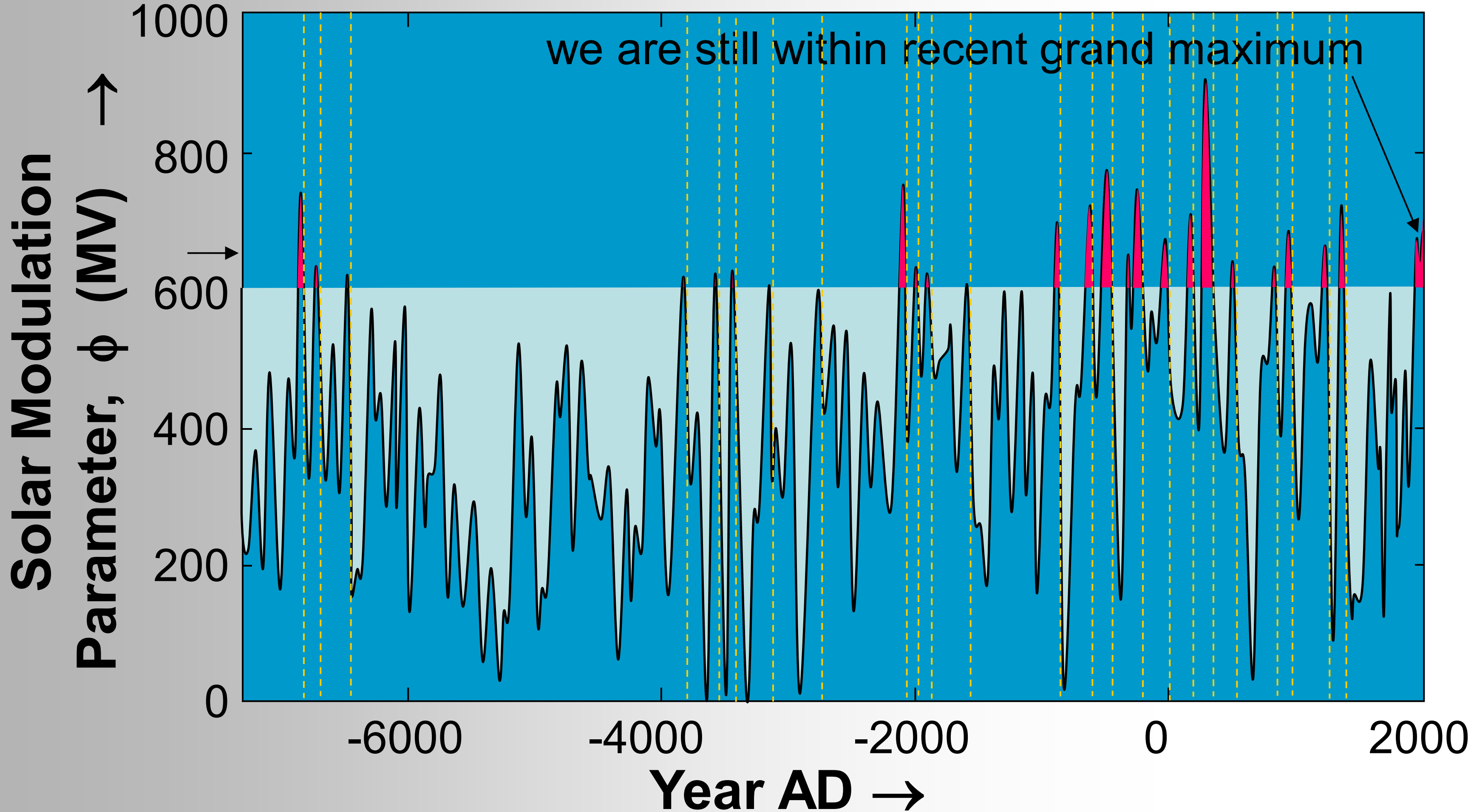
"Always go to other peoples' funerals, otherwise they won't come to yours."

"I don't have nightmares about my team – you've got to be able to sleep before you can have nightmares"



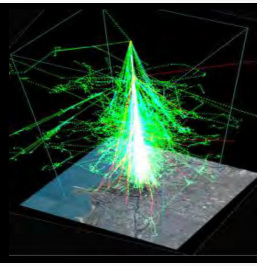
Millennial Variation

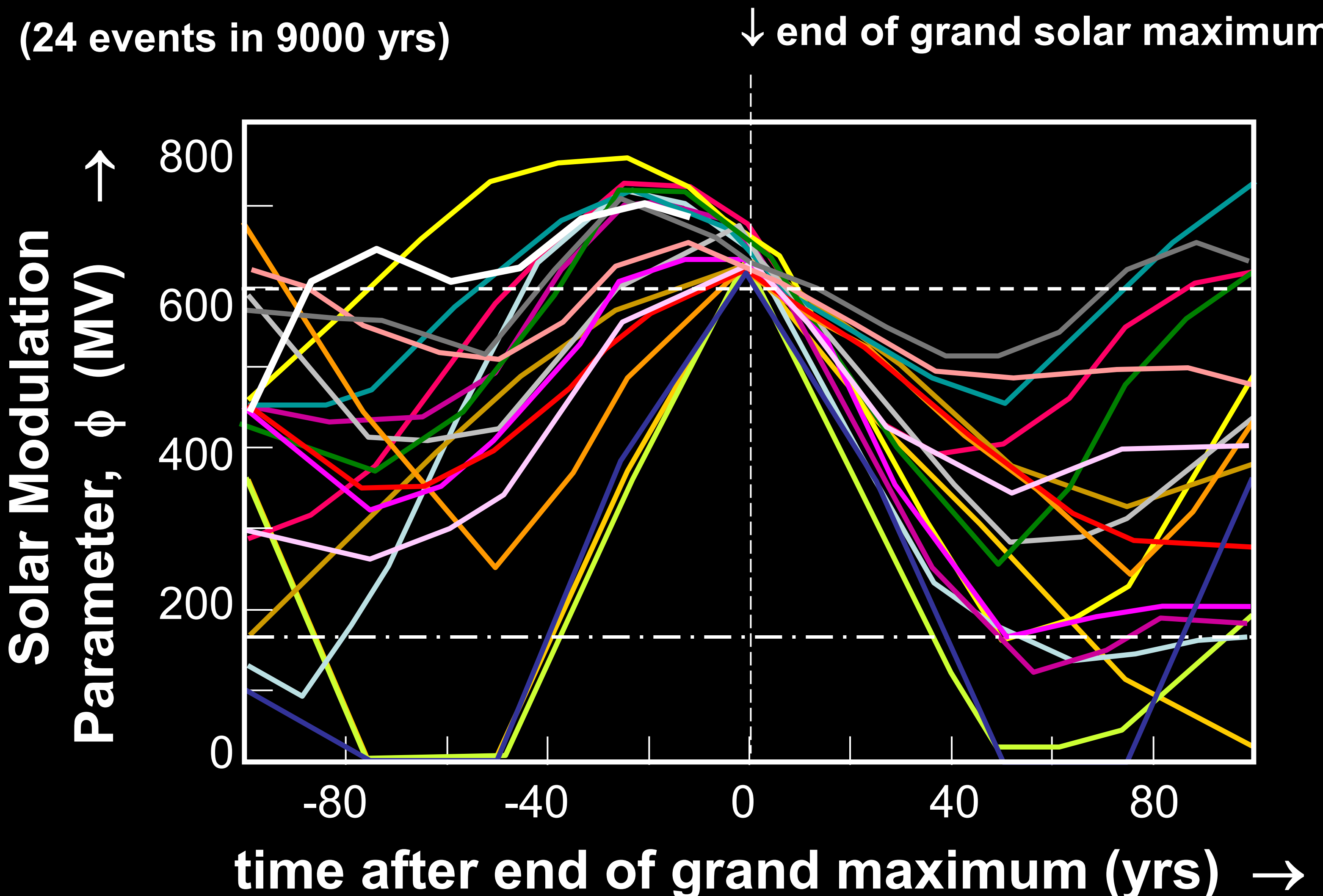
ϕ composite (25-year means) from cosmogenic isotopes by Steinhilber et al. (2008)

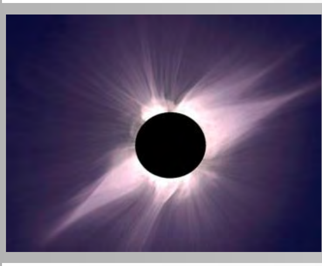


composite from Solanki et al., 2004; Vonmoos et al., 2006 & Muscheler et al., 2007

Superposed epoch study of the end of grand maxima



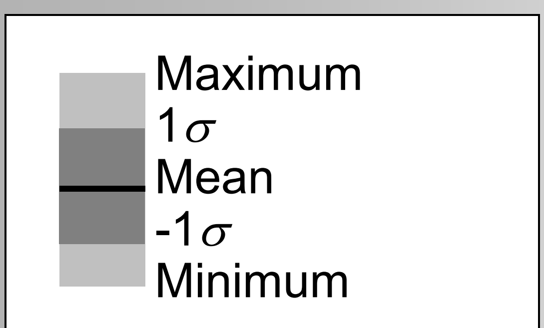


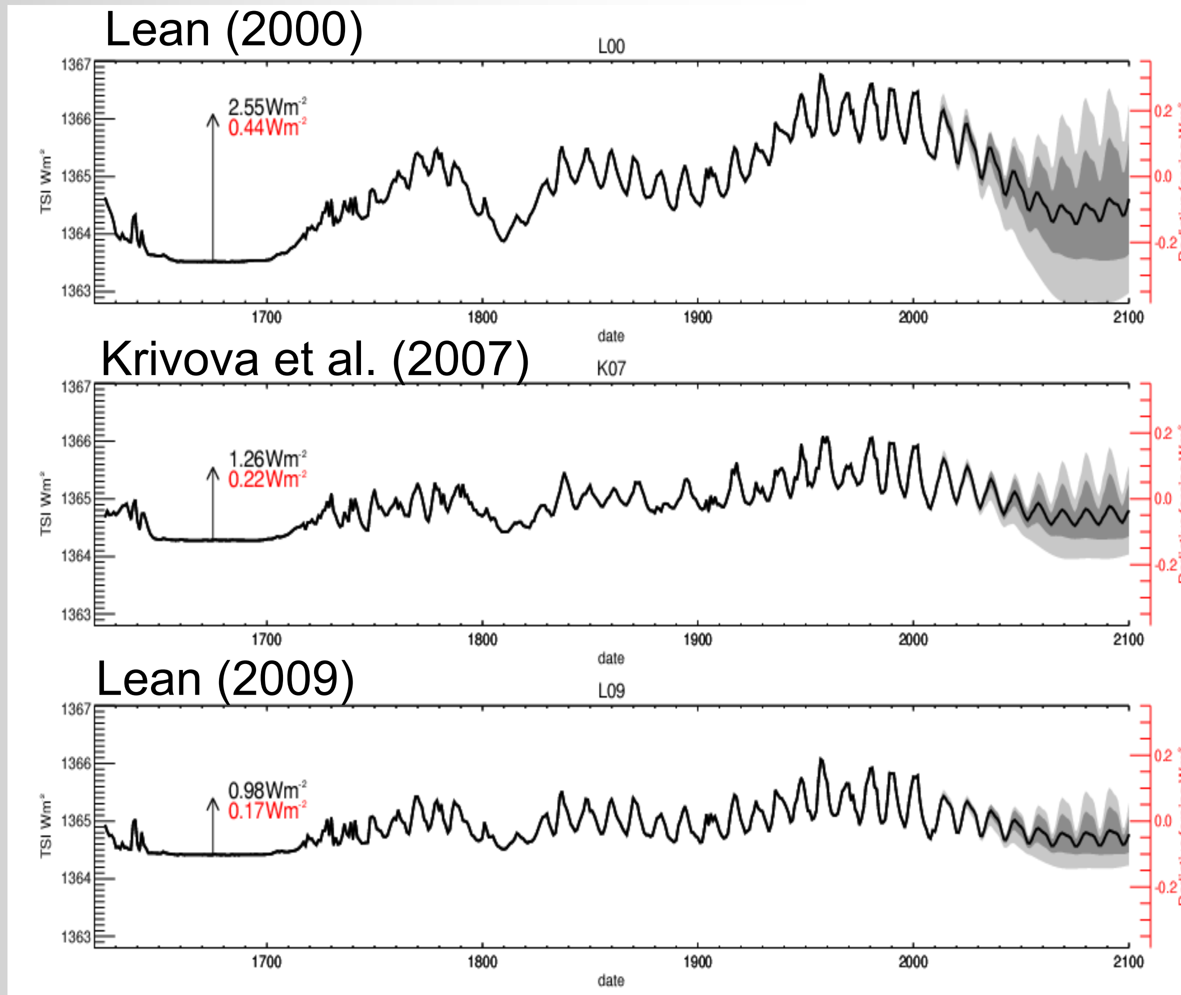


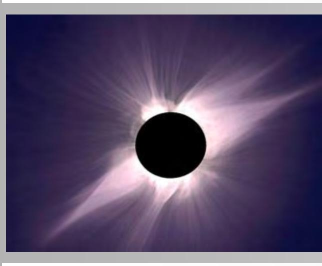
Future TSI Variation?

(Jones, Lockwood and Stott, JGR 2011)

- using the relationship of TSI and GCRs
- & relationship between solar cycle amplitude and the mean



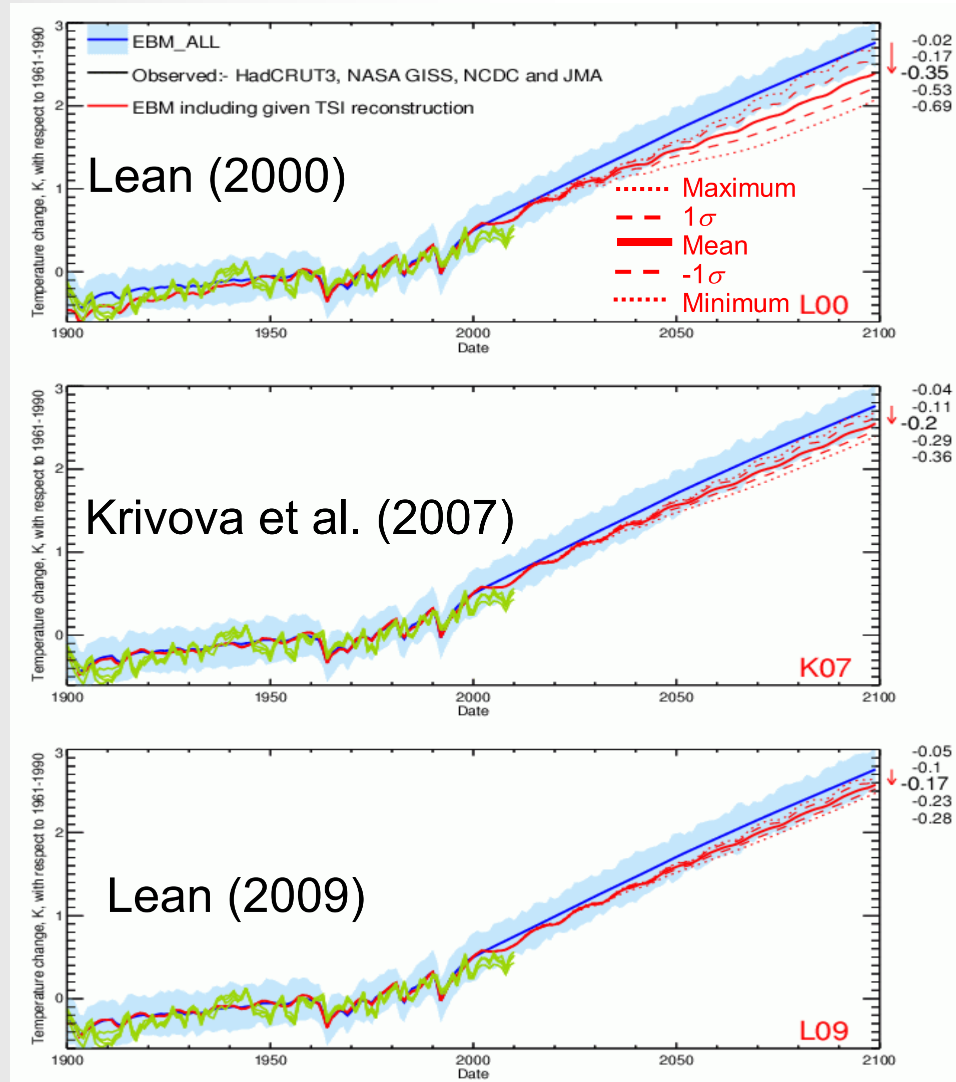




GMAST Predictions – EBM tuned to HadCM3

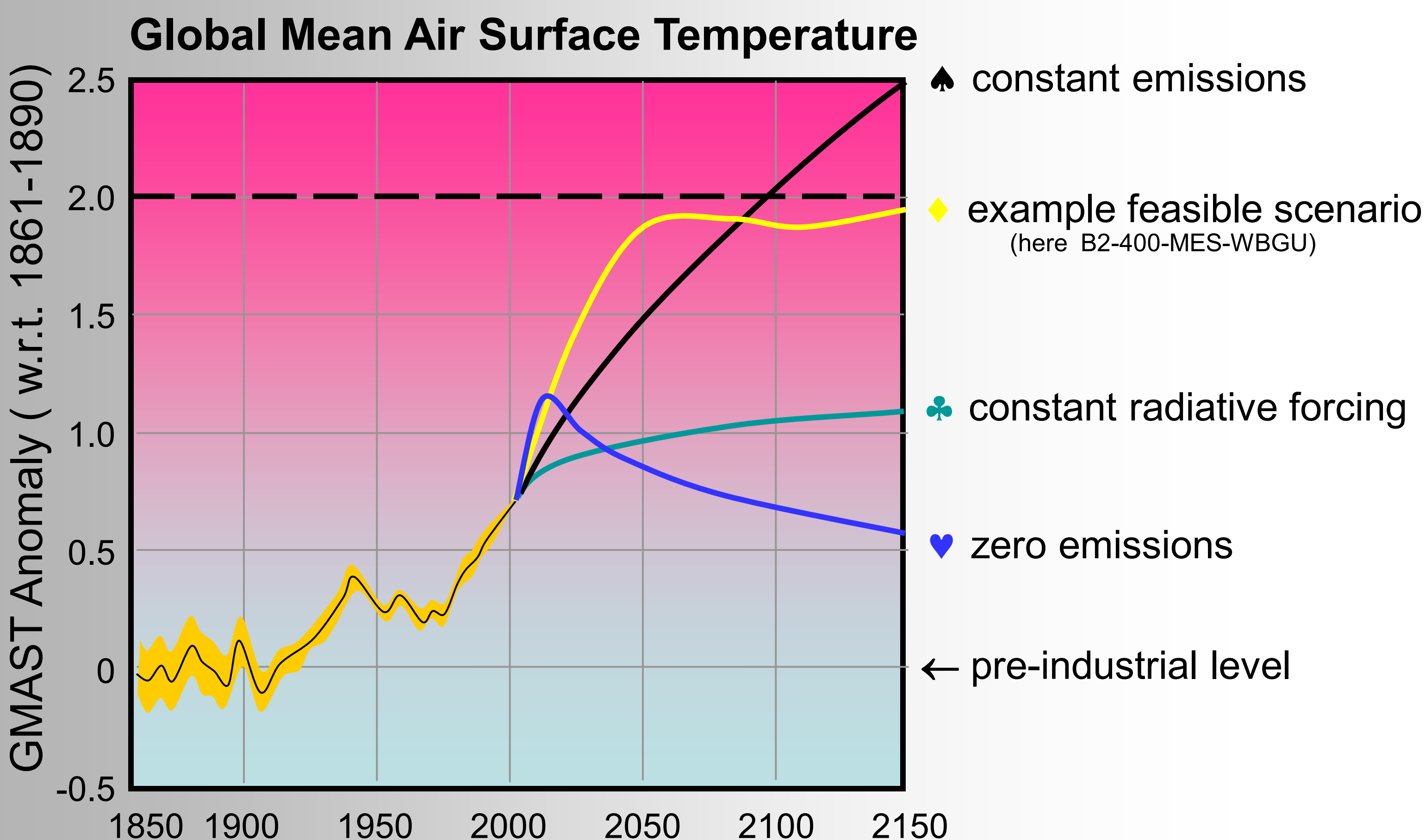
(*Jones, Lockwood and Stott, JGR in press, 2011)*

- use B2 SRES emissions scenario
- no future volcanic forcing
- solar responses have been scaled to match a maximum possible solar cycle amplitude of 0.1K.



Temperature Commitment

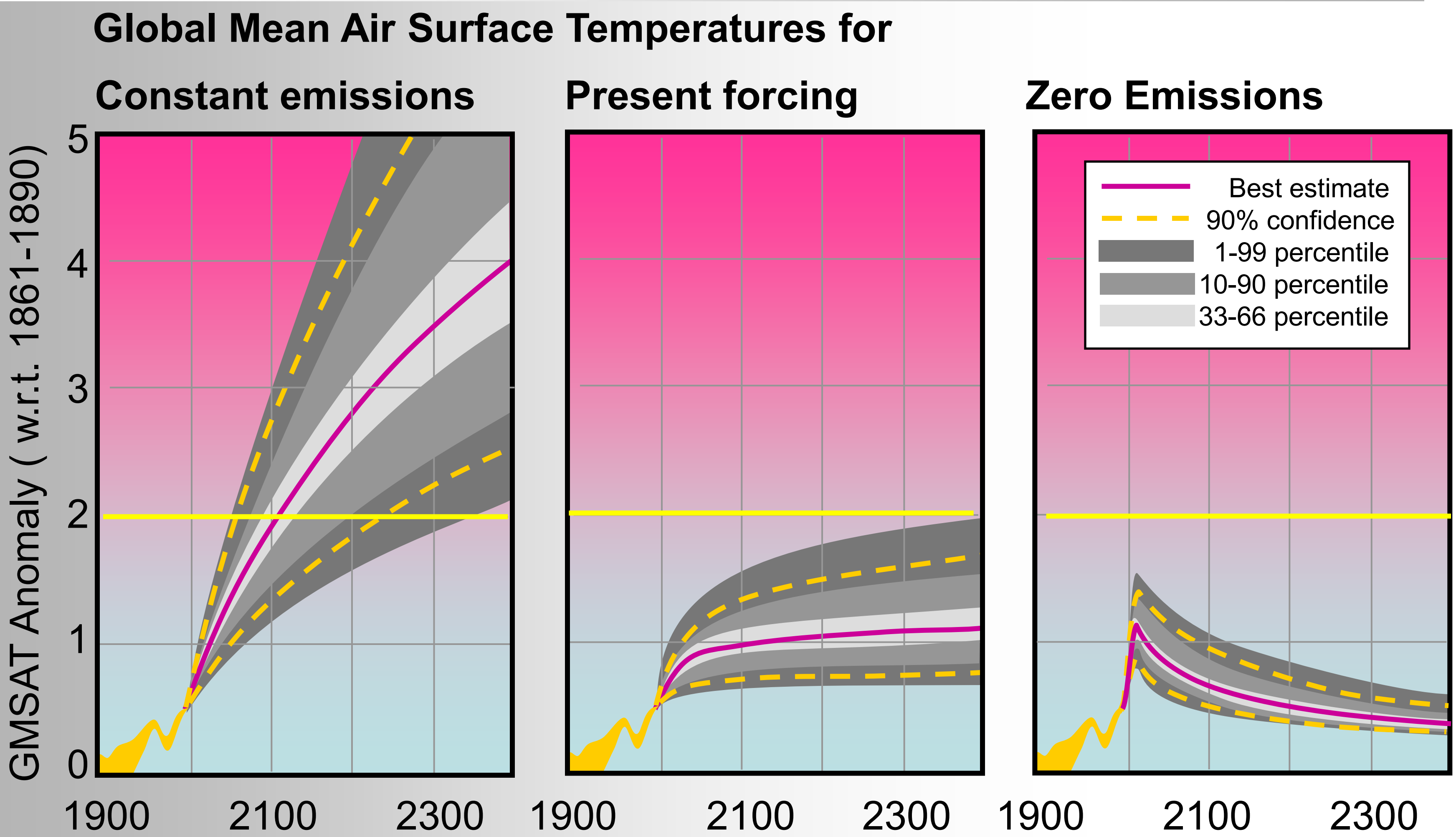
Climate Sensitivity 2.8° C



(Hare & Meinshausen, 2006)

Handling Uncertainty

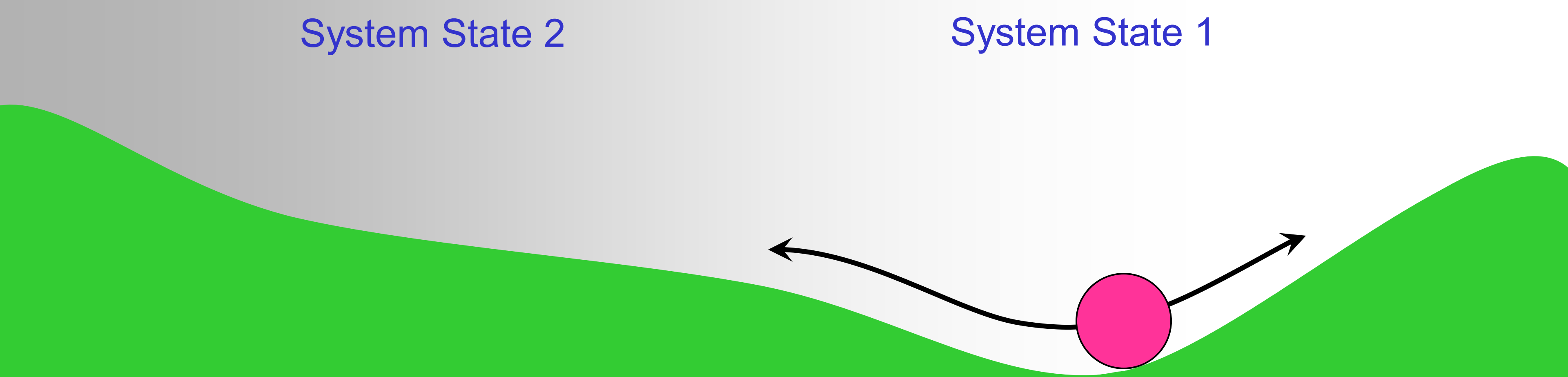
- For IPCC lognormal pdf of climate sensitivity



(Hare & Meinshausen, 2006)

Tipping Points

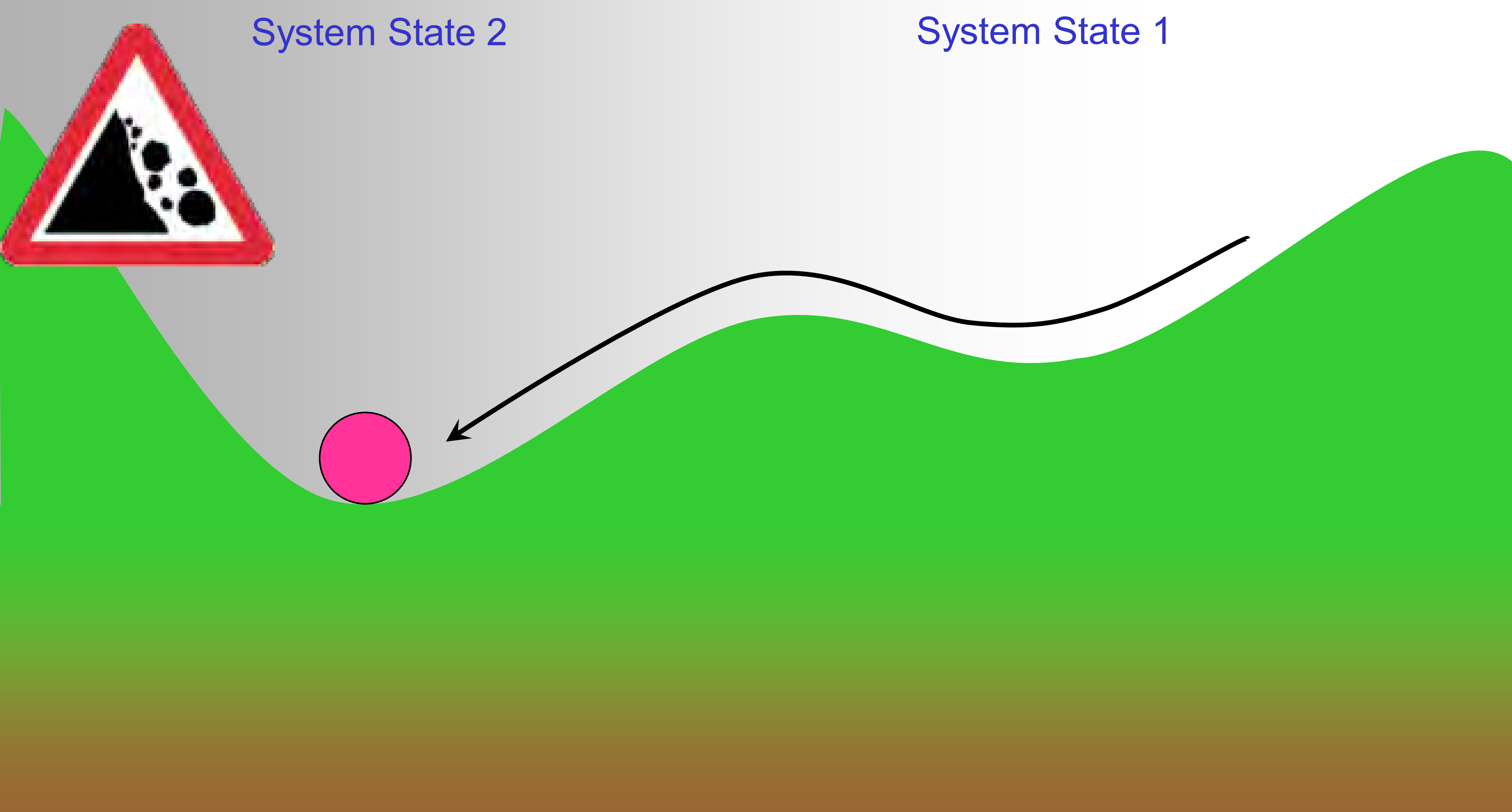
(Lenton et al., 2007)



Not necessarily irreversible ….

Tipping Points

(Lenton et al., 2007)



Tipping Points

(Lenton et al., 2007)

System State 2

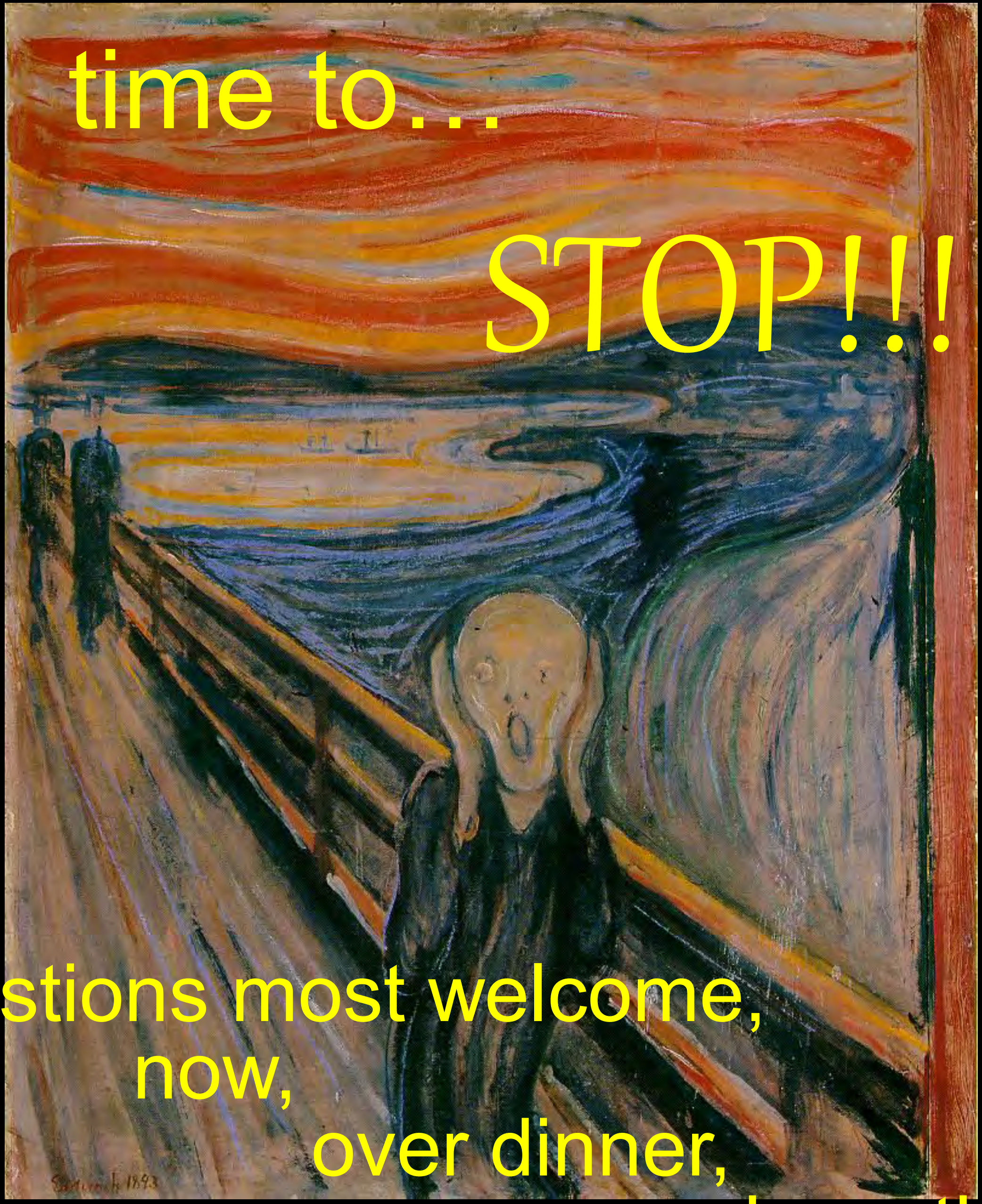
System State 1

Potential tipping points between climate states are:

- Atlantic themohaline circulation disruption
- Indian monsoon chaotic multistability
- West African monsson latitude shift
- Change in ENSO frequency and/or amplitude
- West Antarctic ice sheet instability
- Changes in Antarctic bottom water formation
- Arctic sea ice loss
- Greenland ice sheet melting
- Boreal forest dieback
- Loss of permafrost and tundra
- Sahara greening
- Amazon rainforest dieback

time to…

STOP!!!



but questions most welcome,
now,
over dinner,
or down the pub after