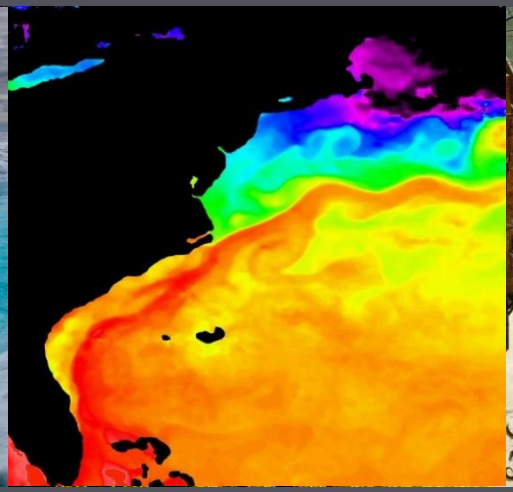
Department of Meteorology

University of Reading

Mike Lockwood





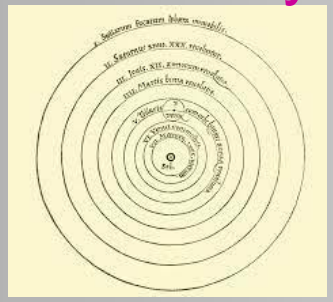

Solar influences on global and regional climate change: science, people & politics

STFC Summer School

21st September 2023, St Andrews University (remote talk)

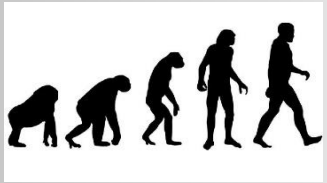
Attacks on the age of reason: 4 stories of disinformation, denial and cognitive dissonance*

Astronomy



- solar-centric solar system (1543)
- the church
- moon landings
- flat Earth

Biology

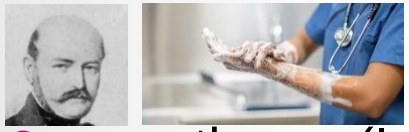


- evolution (1858)
- the church
- creationism

- slave trade lobby

- racism

Medical science



- germ theory (Ignaz Semmelweis,1880)

(1950)

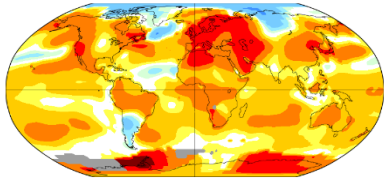
- smoking & cancer

- tobacco lobby
- smoking c.d.*
- HIV denial

- anti-vax

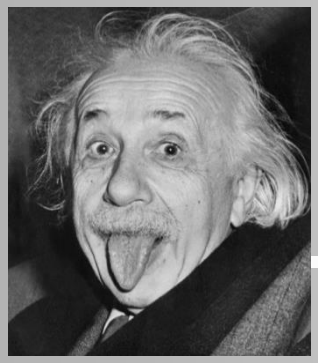
Climate science

- CO_2 warming (Eunice Foote, 1856)



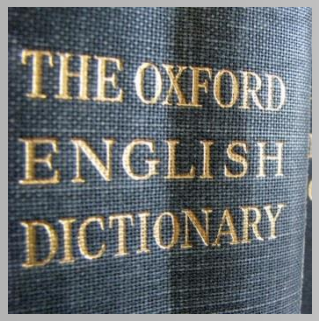
- Numerical modelling (1970-2000)

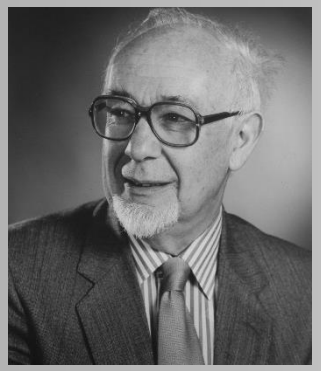
- fossil fuel lobby
- ?



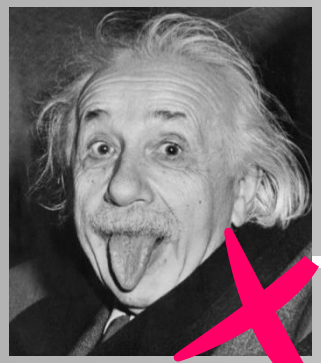
Science

saɪəns
(noun)



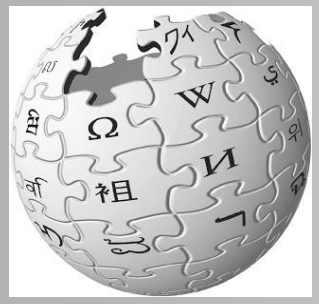


- Cambridge Dictionary: “(knowledge from) the careful study of the structure & behaviour of the physical world, especially by watching, measuring, and doing experiments, and the development of theories to describe the results of these activities”
- Wikipedia: “(from Latin *scientia*, meaning knowledge) 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): “**consensus**, is the touchstone of reliable science”



Science Consensus

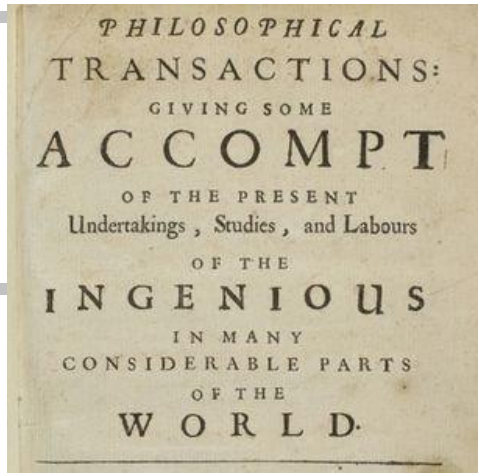
sʌɪəns kən ˈsɛnsəs
(compound noun)



- 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”

The solar science community at the STEREO-3/SOHO-22 Workshop: “Three Eyes on the Sun: Multi-spacecraft studies of the corona and impacts on the heliosphere” Bournemouth, UK April/May 2009

How we arrive at a scientific consensus: peer review


PHILOSOPHICAL
TRANSACTIONS:
GIVING SOME
ACCOMPT
OF THE PRESENT
Undertakings, Studies, and Labours
OF THE
INGENIOUS
IN MANY
CONSIDERABLE PARTS
OF THE
WORLD.

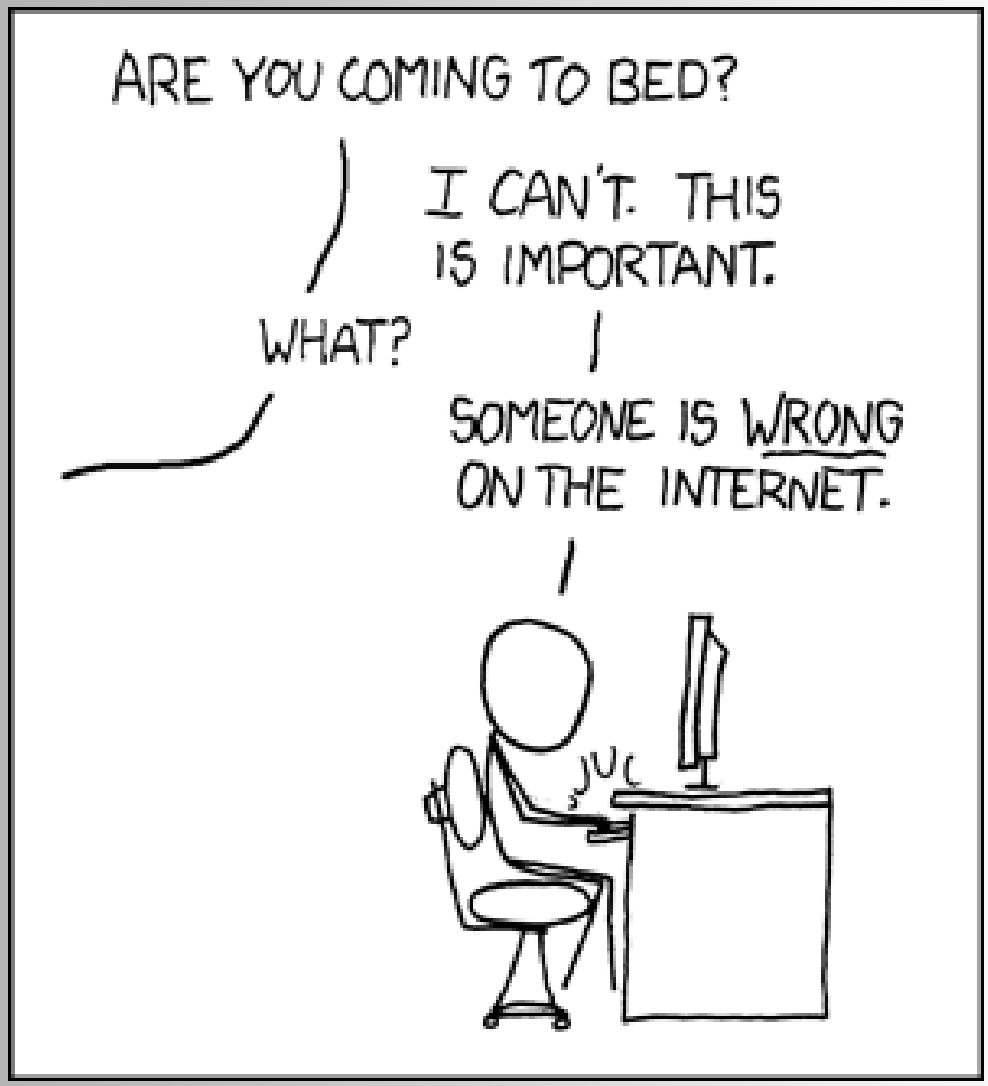
- Peer review is Britain's single greatest contribution to science - bar none!

- first introduced in 1665 by German immigrant, Henry (formerly Heinrich) Oldenburg, founding Editor of the world's oldest scientific journal: *Philosophical Transactions of the Royal Society*

- formal peer-review procedures as we know them today, developed from his ideas by Sir Francis Bacon & applied to *Medical Essays and Observations* published by the Royal Society of Edinburgh in 1731.

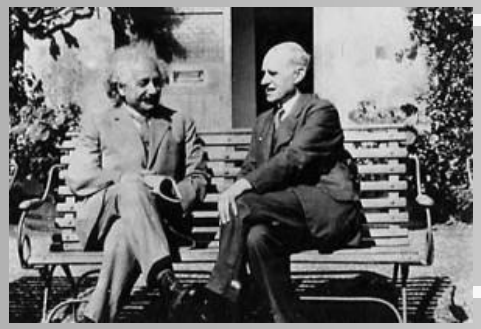
- It is how science expunges "fake news"

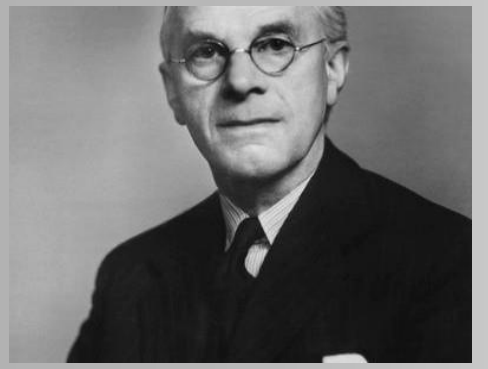
Peer review avoids the information “wild west” we now have on the internet



- As famously observed by xkcd (Randall Munroe)

“Duty Calls”
1st December 2011





Scientific Consensus at work: Einstein's relativity & GPS

- Scientific objections started to fall away after Eddington's 1919 eclipse observations, consistent with general relativity (GR).
- Denounced as "*Jüdische Physik*" by e.g.1921 Berlin Philharmonic Hall event & by newspapers
- Herbert Dingle (spectroscopist). From 1939 Nature letter to his death in 1978, he tried to publish articles about why Einstein's special relativity (SR) was wrong. His 1972 book talked of a conspiracy by the "physics establishment". Still widely cited – but only on the internet
- Sat-Nav: GPS (designed 1972, first launch 1978) use corrections for both SR and GR on its satellite clocks. 1ns timing error → 30cm position error, Without SR and GR error grows at 2km and 13 km per day, respectively!

Consensus matters.

Ways of dismissing what we don't want to hear, #1: "MRDA"

"Well he would [say that], wouldn't he"

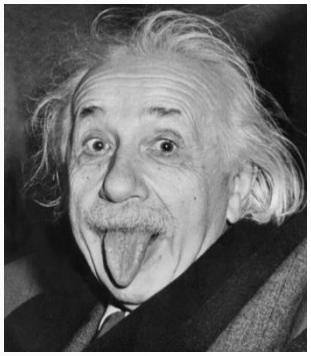
Mandy Rice-Davies
(Old Bailey,1963)

An aphorism frequently applied to marginalise scientists and to allow scientific findings to be ignored

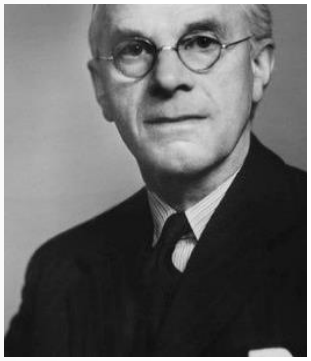
Internet Slang:
"MRDA" =
"Mandy Rice Davis Applies"

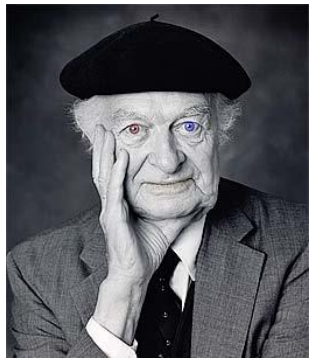
Two things that Mandy almost certainly never knew about scientists

- 1. What every scientist lives for is to become famous for being right

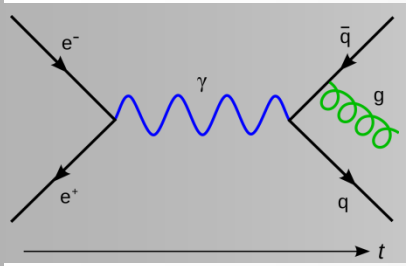


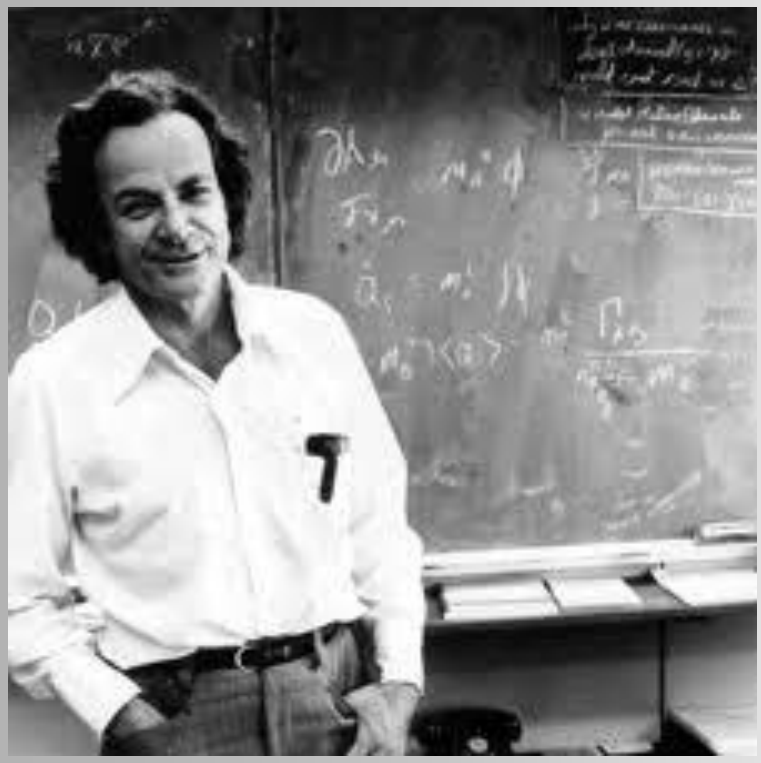
- 2. What every scientist dreads is to become notorious for being wrong





Right: Albert Einstein – Nobel prize for Brownian motion. Devised special and General relativity
Right: Linus Pauling – Nobel prizes for Chemical bond and Peace Prize for nuclear disarmament studies and campaign. Founded fields of quantum chemistry and molecular biology
Wrong: Herbert Dingle – vocal opponent of special relativity
Wrong: Linus Pauling – in later life made unfounded claims about medical efficacy of Vitamin C



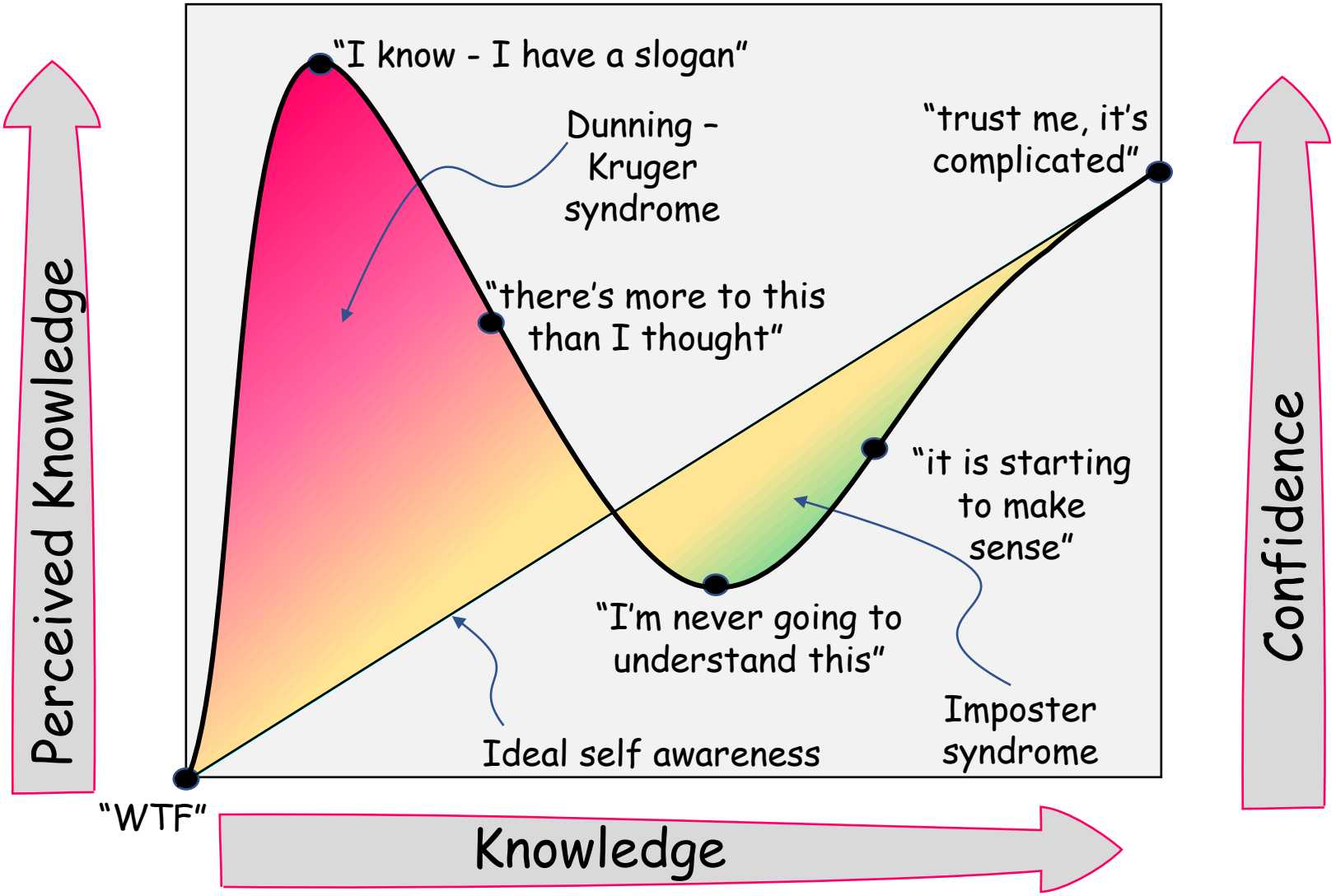


"The first principle is that you must not fool yourself and yourself is the easiest person to fool"

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

Richard P. Feynman
(1918-1988)

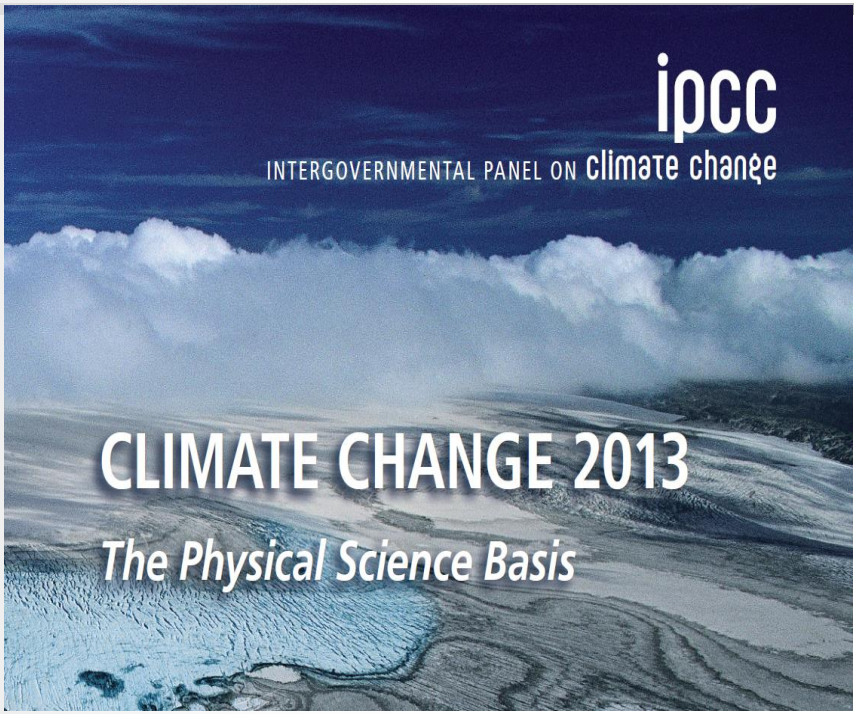
The Dunning-Kruger syndrome



Kruger, J., and D. Dunning (1999) Unskilled and Unaware of It: How Difficulties in Recognizing One's Own Incompetence Lead to Inflated Self-Assessments, Journal of Personality and Social Psychology. 77 (6), 1121–1134, doi:10.1037/0022-3514.77.6.1121.

Do we know that there is a scientific consensus on climate change?

✓ Yes



- IPCC **NOT** a “closed club”
- The IPCC report **IS** the global community of climate scientists’ consensus view of the science
- Open & transparent peer review: all drafts published; 850 lead authors (from nominations by governments & NGOs); >6000 contributing authors;140,000 reviews from >2000 self-nominated expert reviewers LA, CA and ER from >80 nations; all unpaid.
- The IPCC **IS** inclusive – reports cite alternative views.

Climate change: there IS an overwhelming scientific consensus

OPEN ACCESS

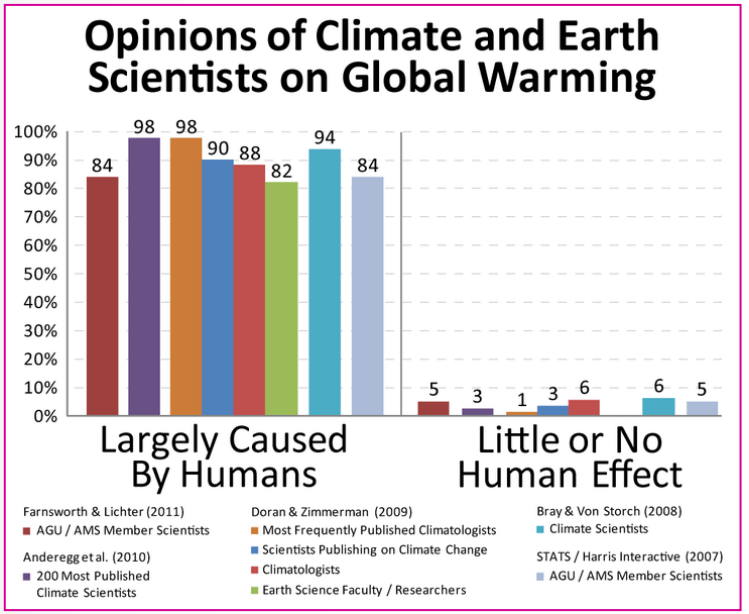
IOP PUBLISHING — ENVIRONMENTAL RESEARCH LETTERS

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

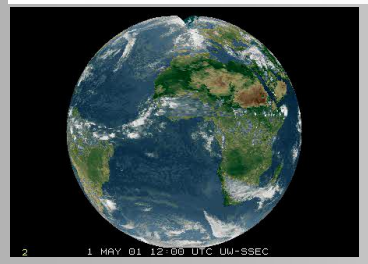
Quantifying the consensus on anthropogenic global warming in the scientific literature

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



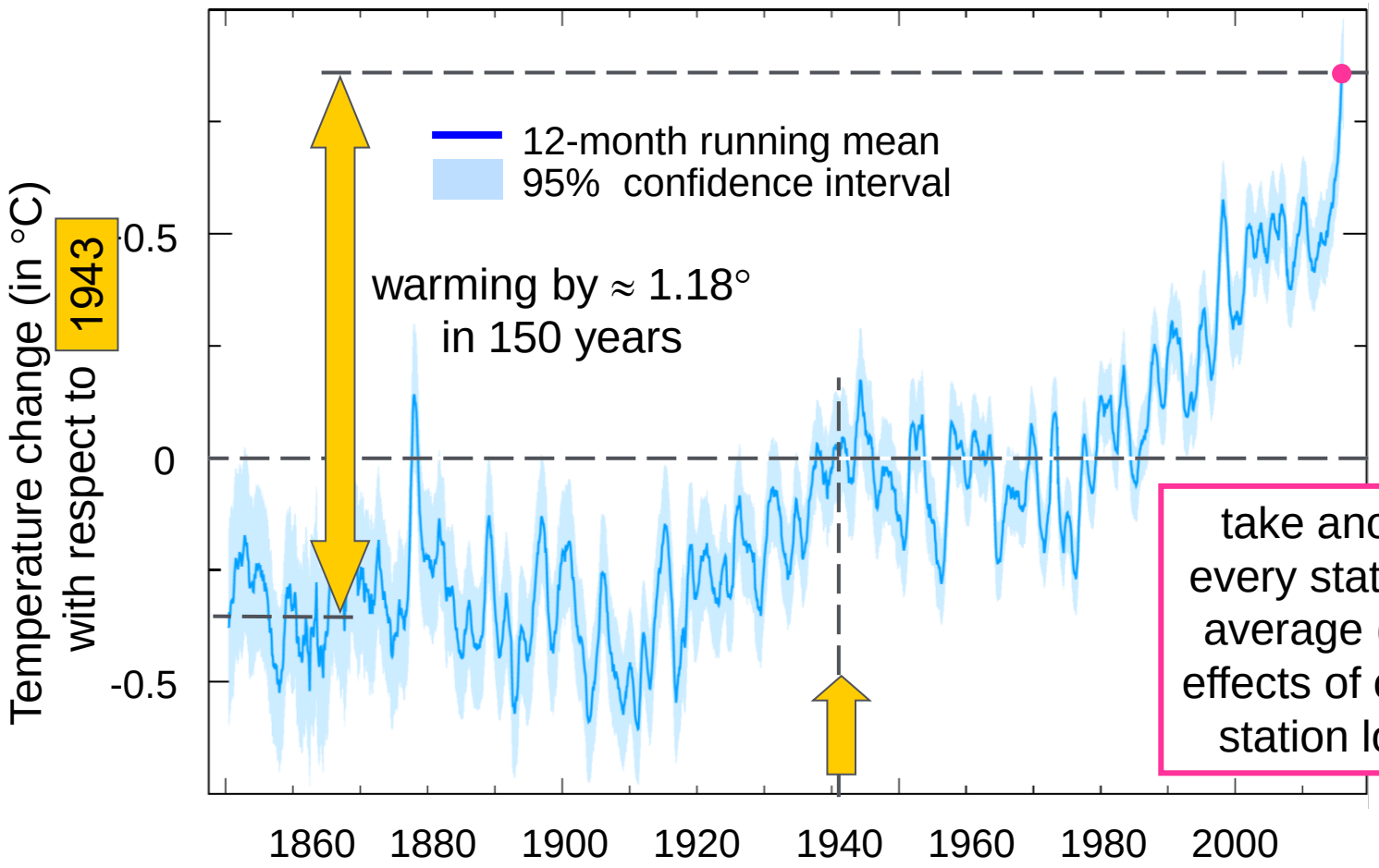
↑ Survey of all papers published 1991-2011 using keywords "climate change" and "global warming" (11944 of them)
97% of papers offering an opinion on climate change agreed that human activities are causing global warming



Is the Earth Warming?

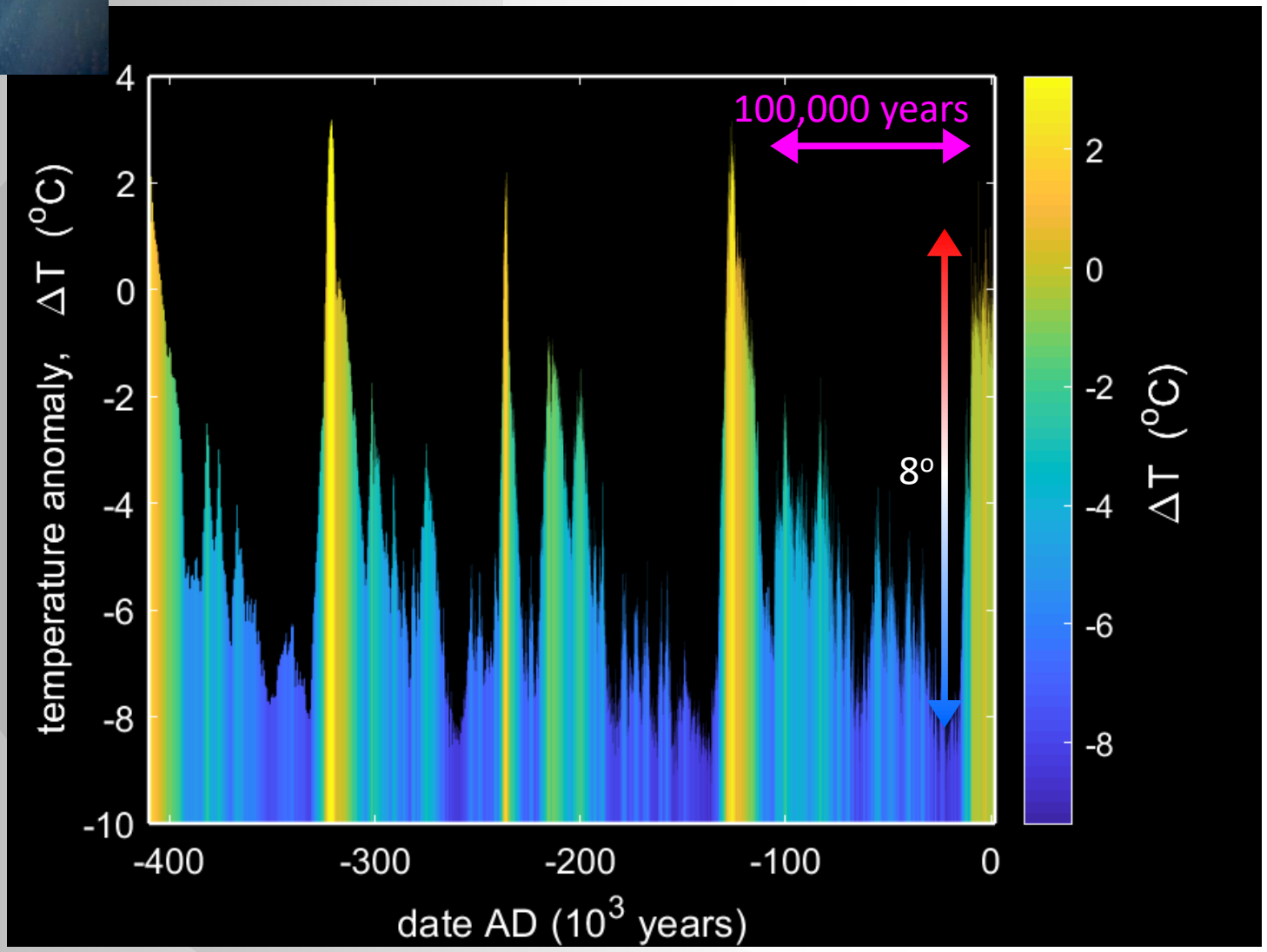
✓Yes

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



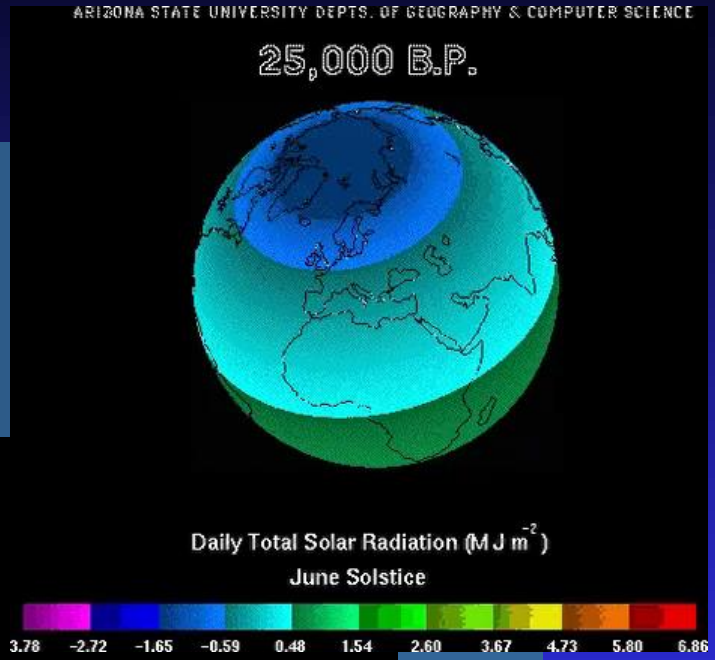
take anomaly for every station & then average (limits the effects of changes in station locations)

Real Ice Ages and Warm Interglacials

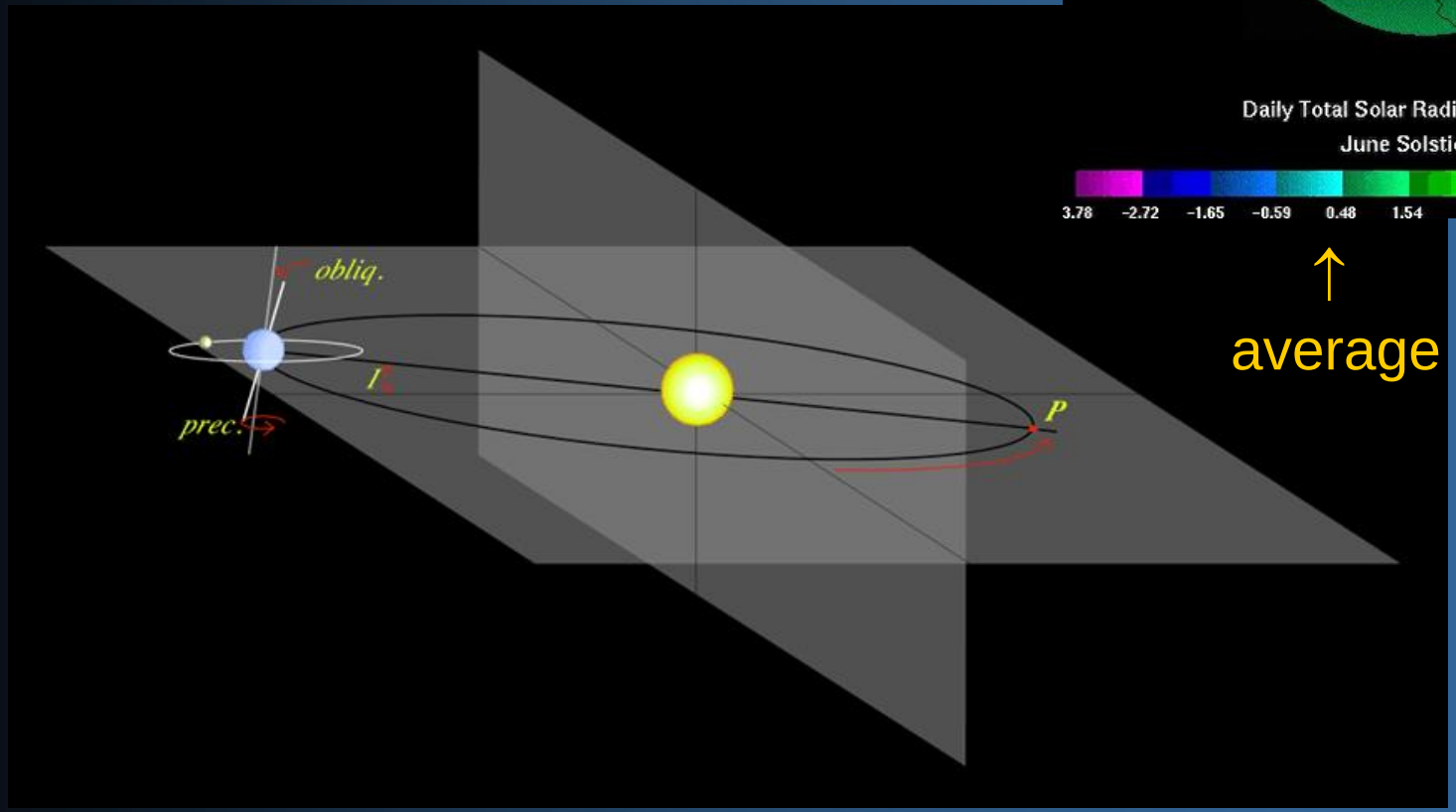


Milankovitch Cycles

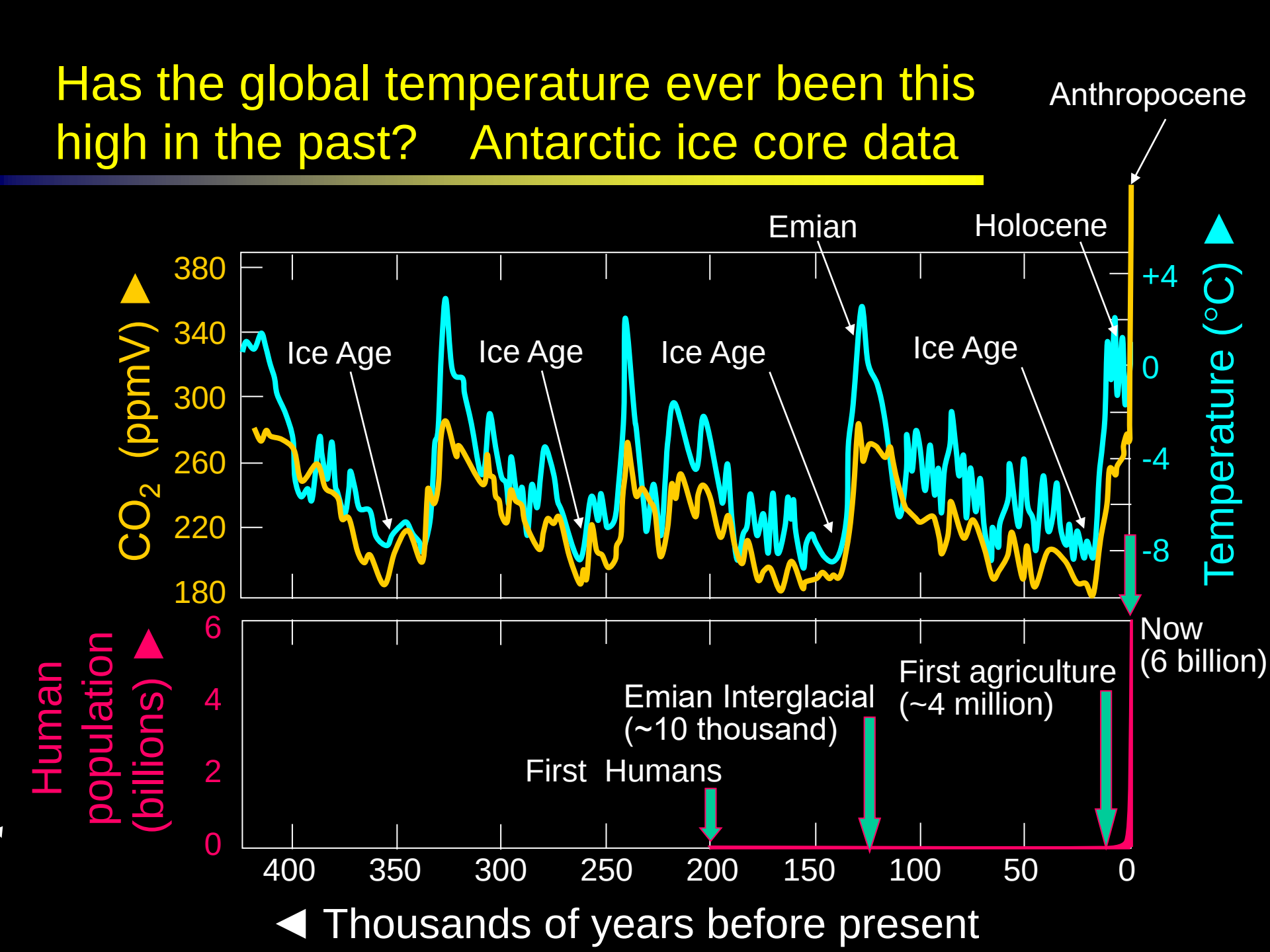
- cycles in Earth's orbit eccentricity
- precession of the equinoxes
- cycles in Earth's axial tilt (obliquity)



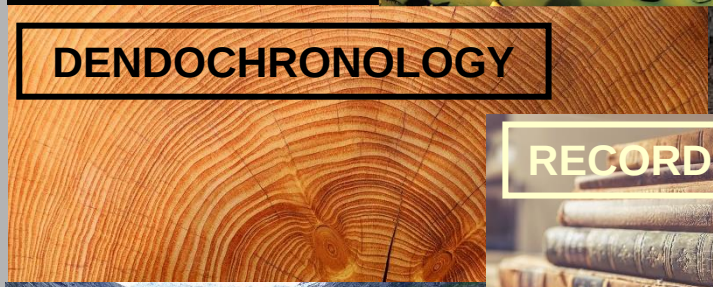
↑ average insolation

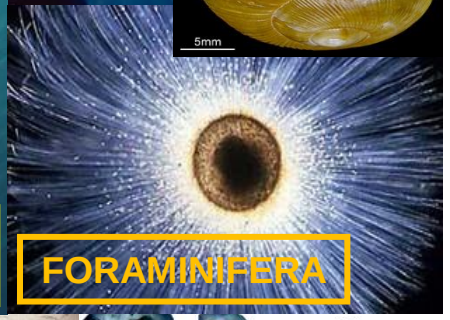


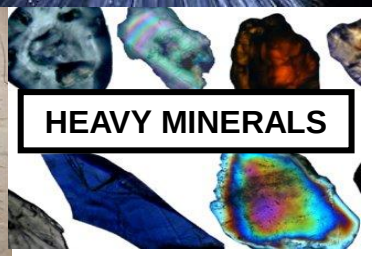
Has the global temperature ever been this high in the past? Antarctic ice core data



Reconstructing past temperatures, including



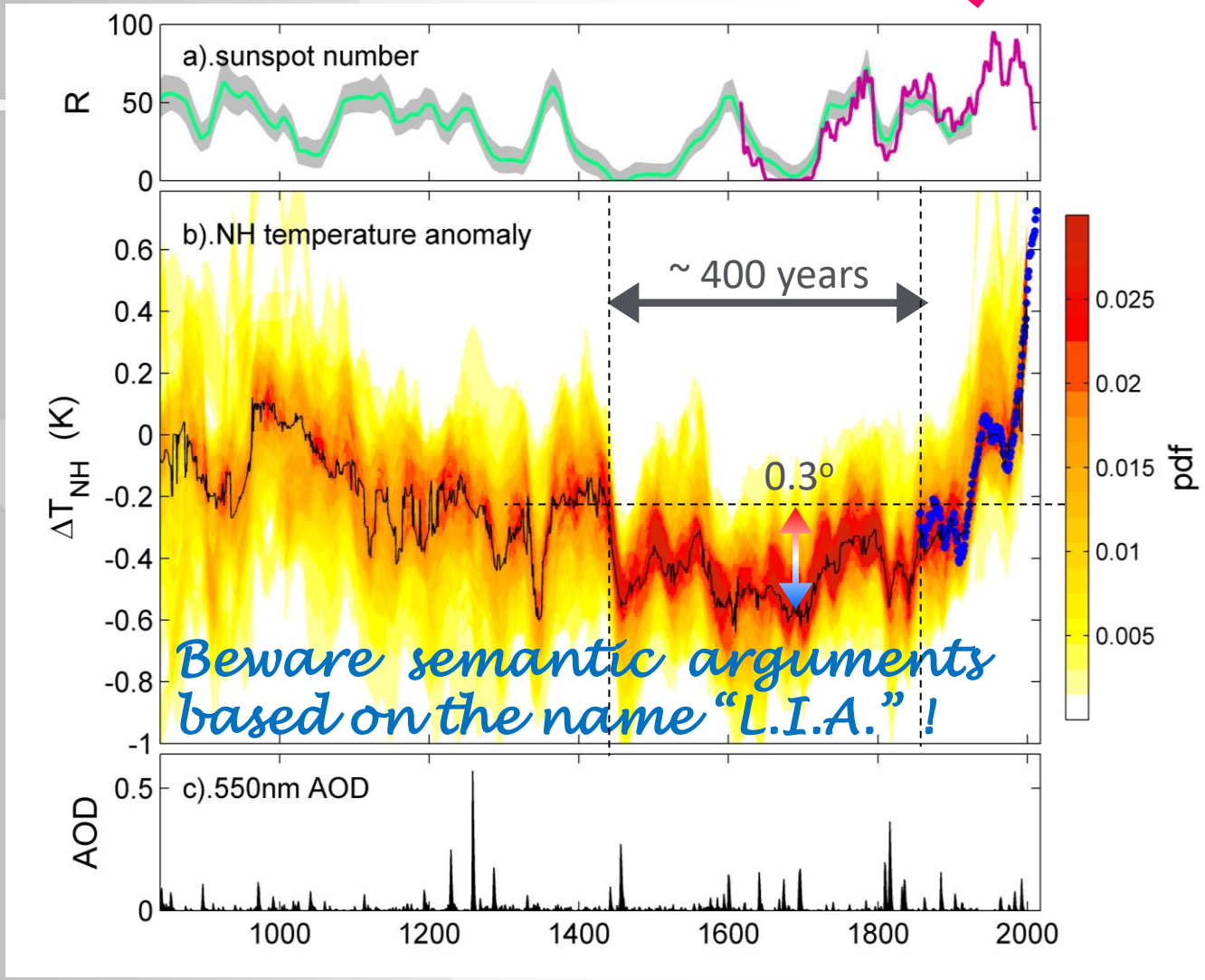




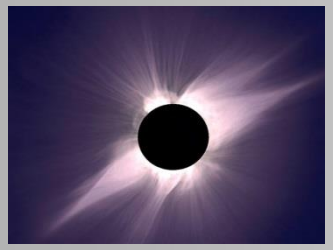
Was it a "Little Ice Age"

No

- Northern hemisphere temperature anomaly, ΔT_{NH} reconstruction
- Based on data from boreholes, corals, sclerosponges, ice cores, insect numbers, instrumental data, pollens, lake levels, loess (wind-blown silt), glacier extents, plant macrofossils, diatoms, molluscs, foraminifera, dinoflagellates, ostracods, heavy minerals, grain-size, trace elements in speleothems, dendrochronology & historical records (recorded freeze/thaw dates, harvest yields & dates, etc.)

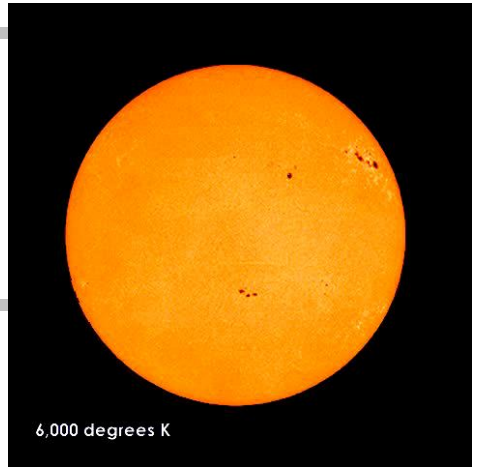


- *Masson-Delmotte, V., and 16 other authors (2013) doi:10.1594/PANGAEA.828636.*



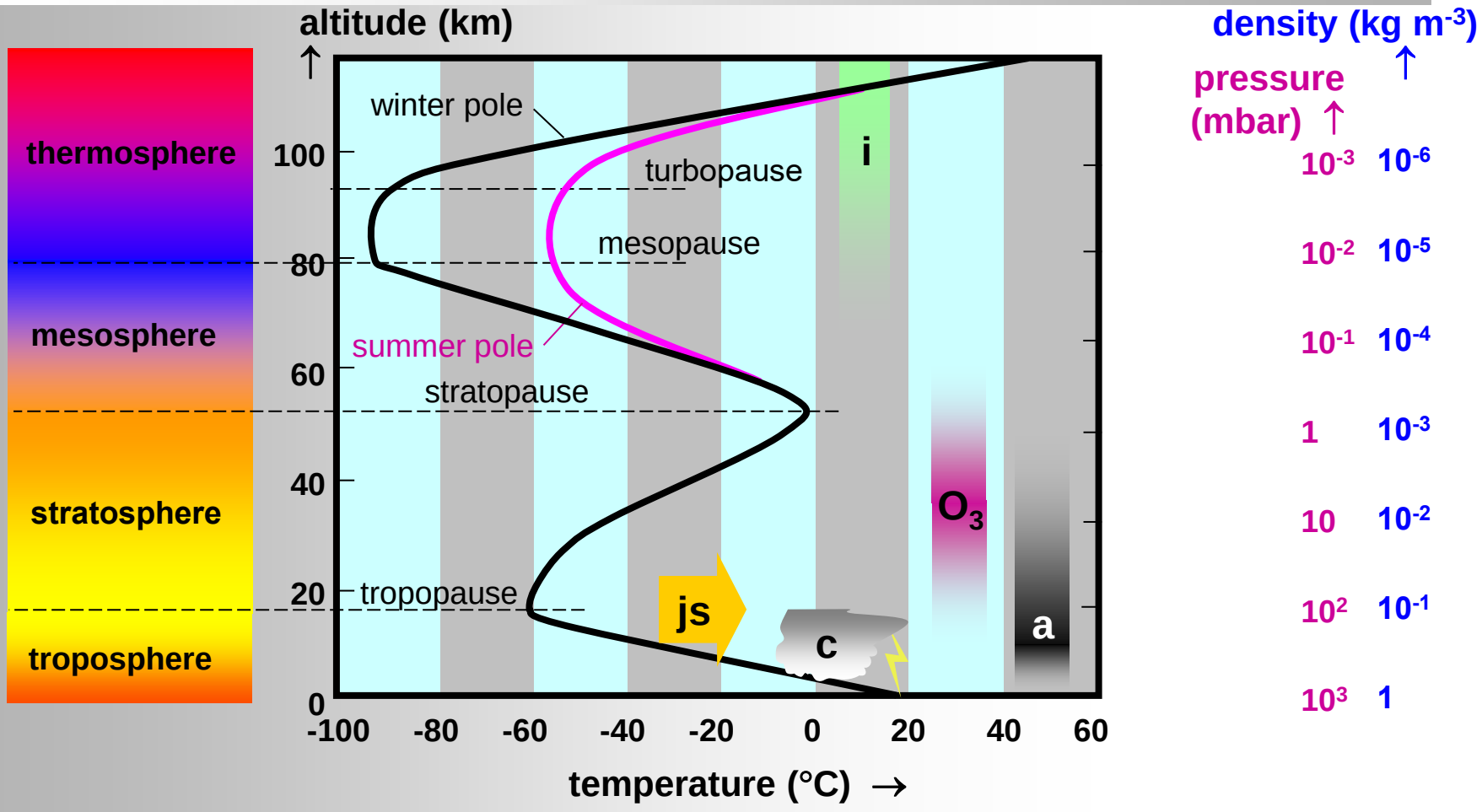
Solar Outputs

(% modulation over the solar cycle)



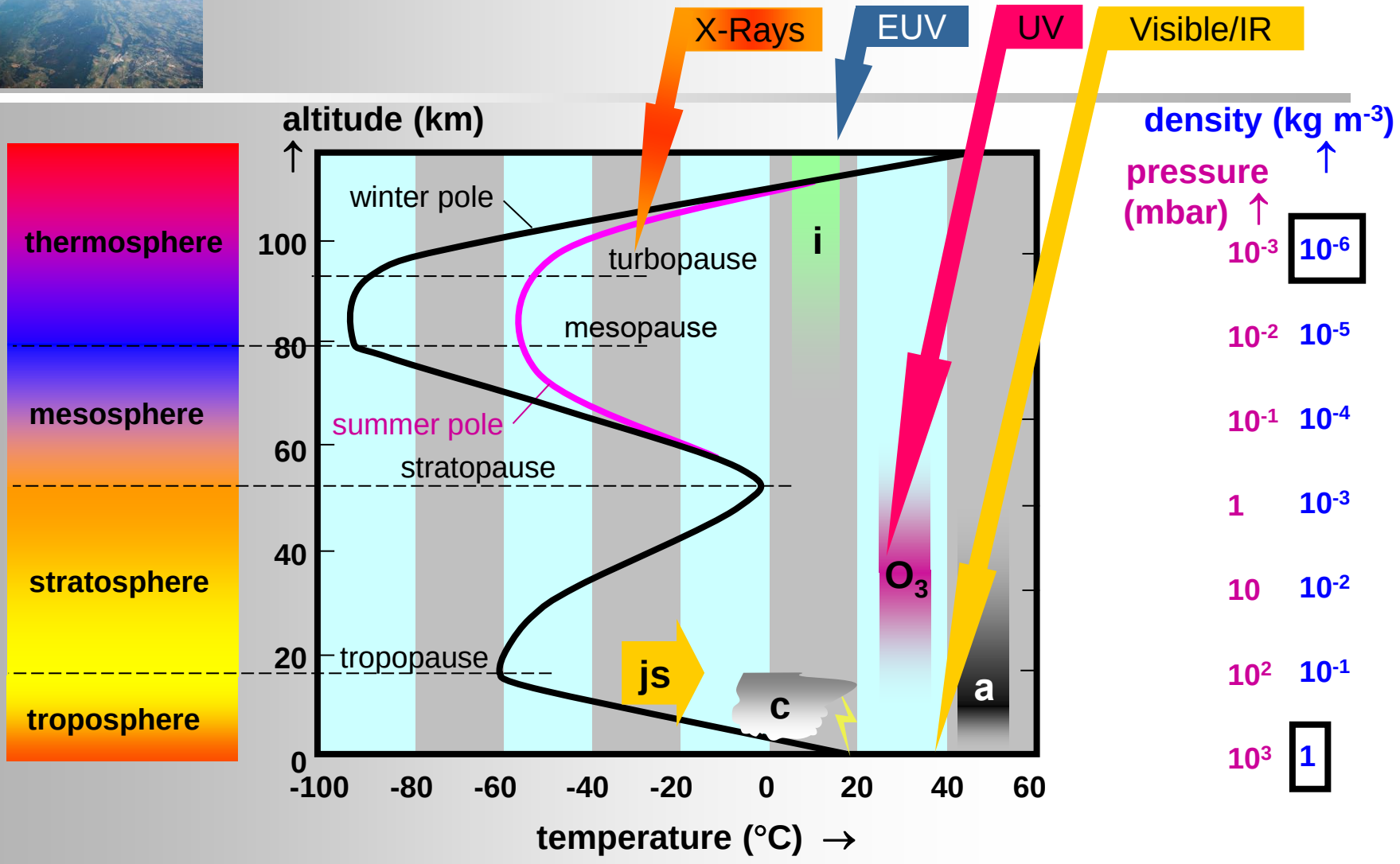
Visible/IR	weakly modulated (~0.1%) by magnetic field in photosphere
UV	modulated (~1%) by magnetic fields threading the lowest solar atmosphere (chromosphere)
EUV	strongly modulated (~50%) by magnetic fields in the solar atmosphere (corona)
X-Rays	fully dependent on (modulated ~90%) by magnetic fields 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
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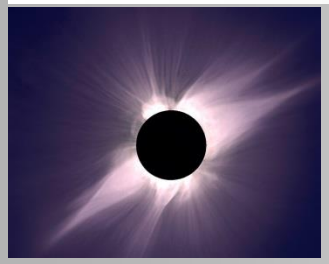
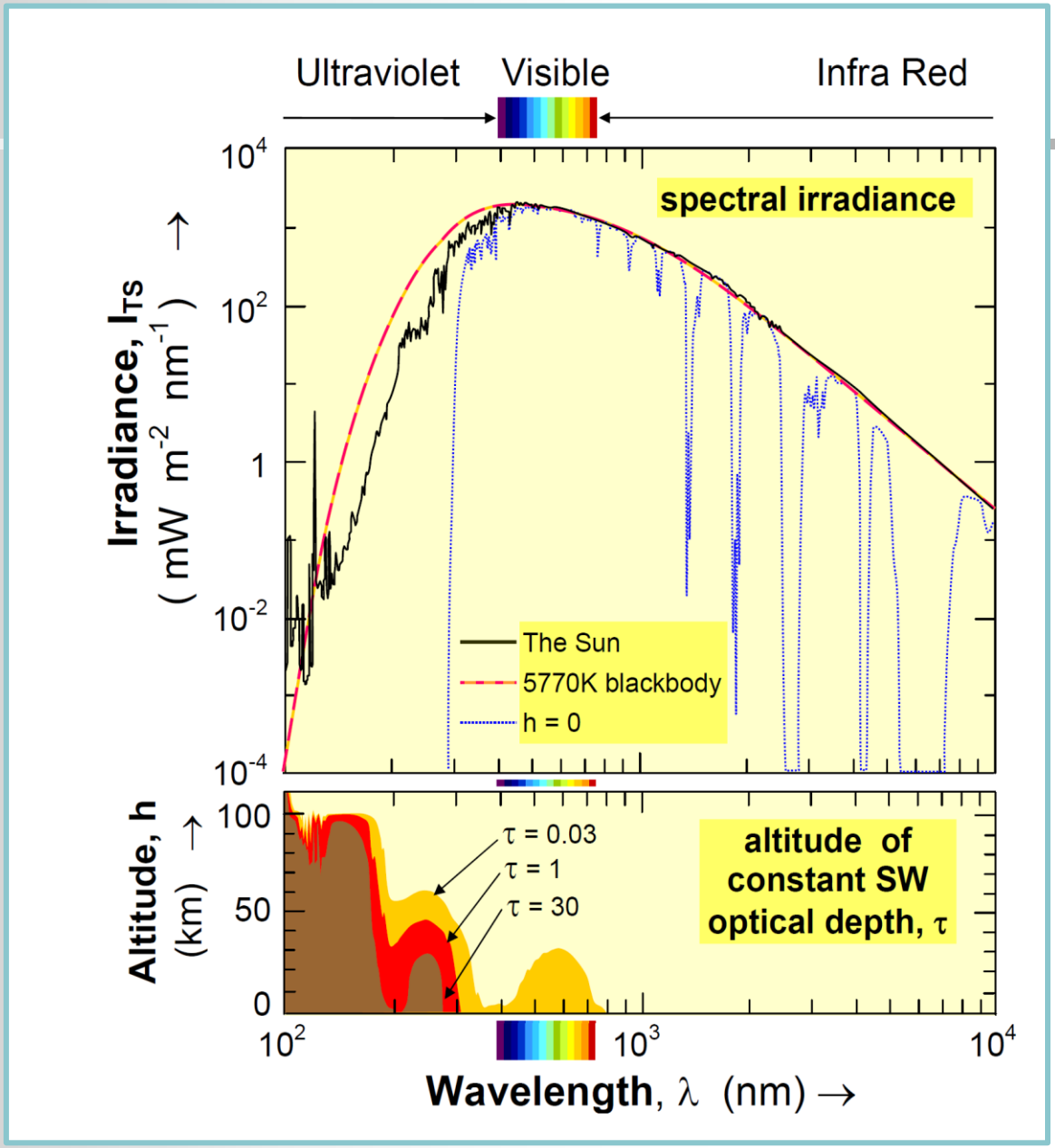
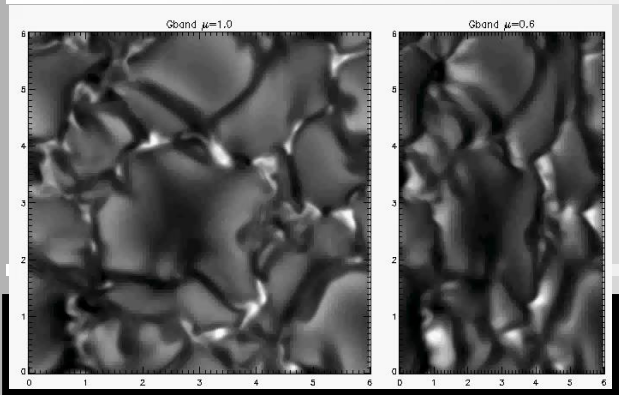


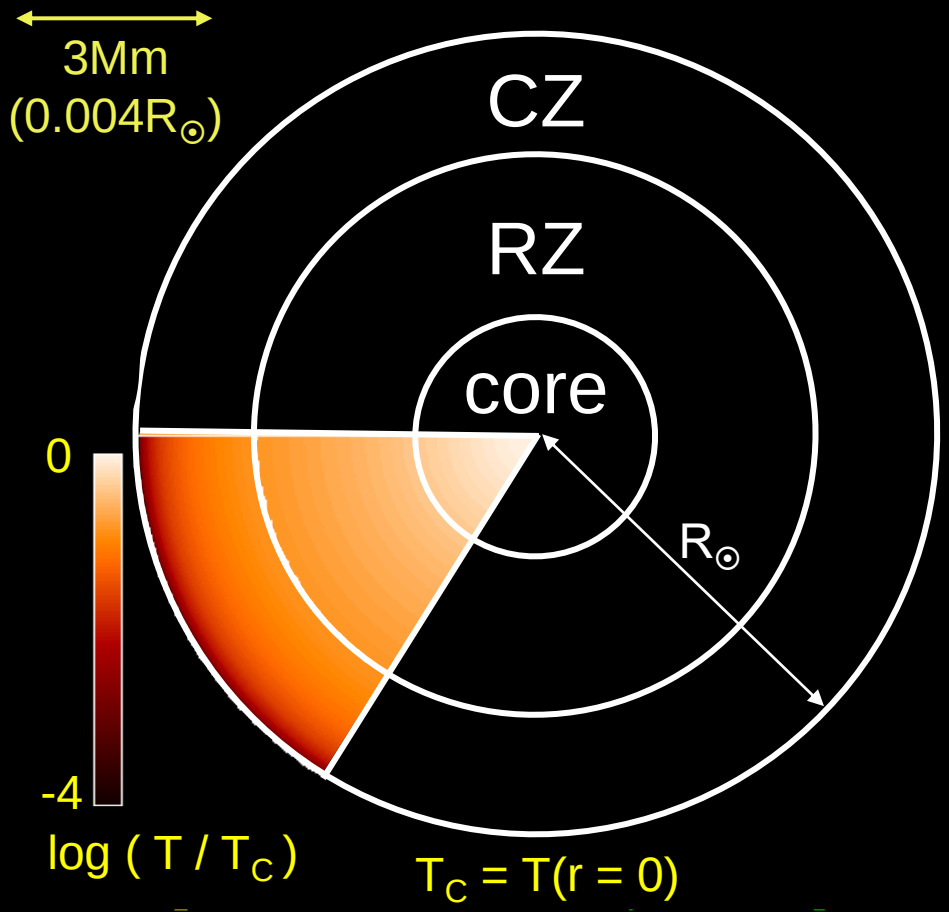
The Sun's e-m radiation spectrum

- 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 $1- \exp(t/\tau) = 0.001$

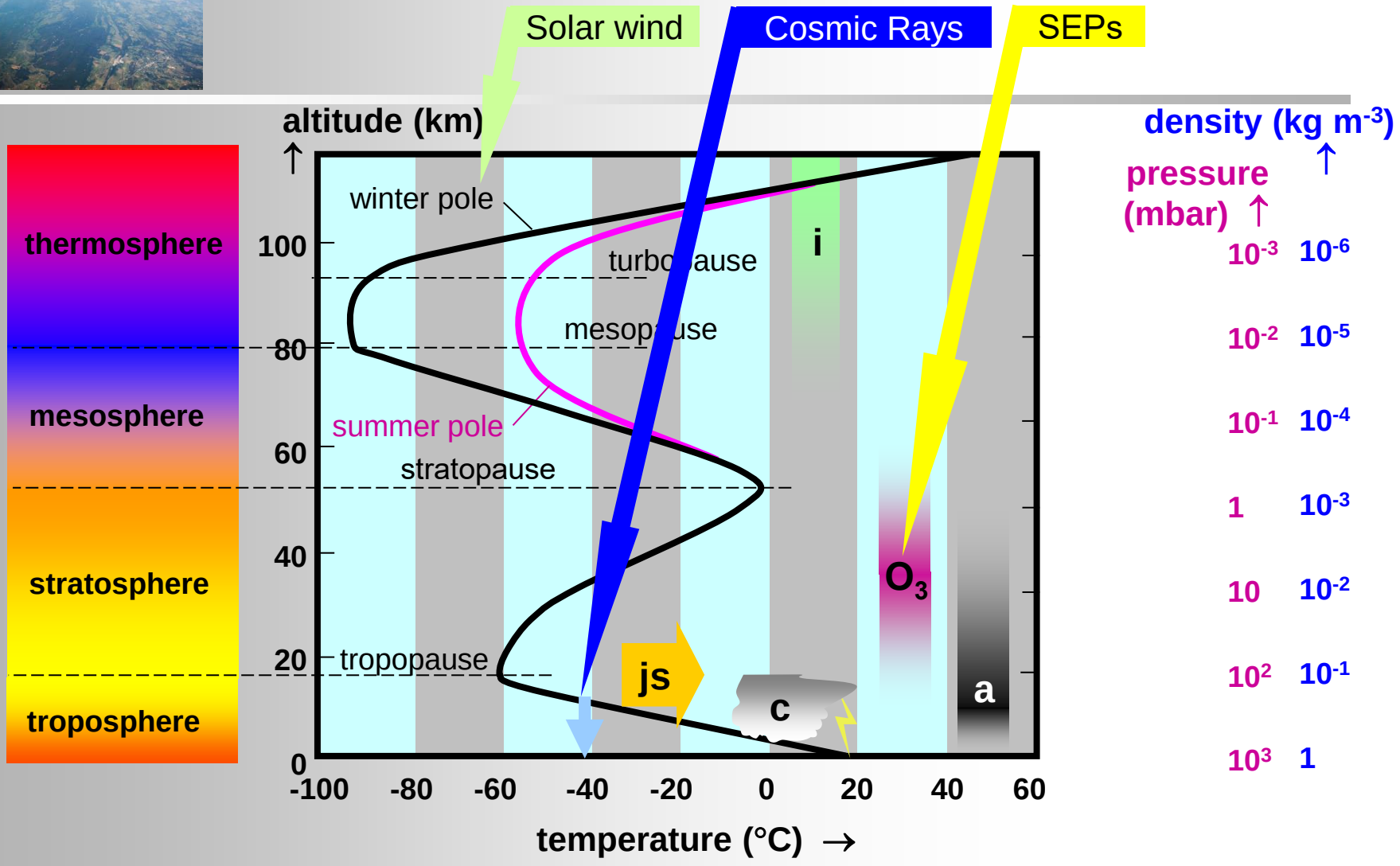
$F = \varepsilon\sigma T_{sun}^4$ so that

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

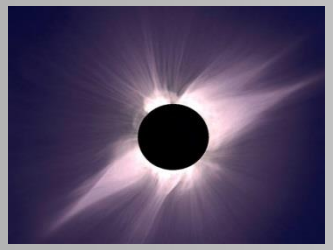
$= 0.999^4 = 0.996$

i.e. F changes by just 0.4%

Corpuscular solar inputs



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

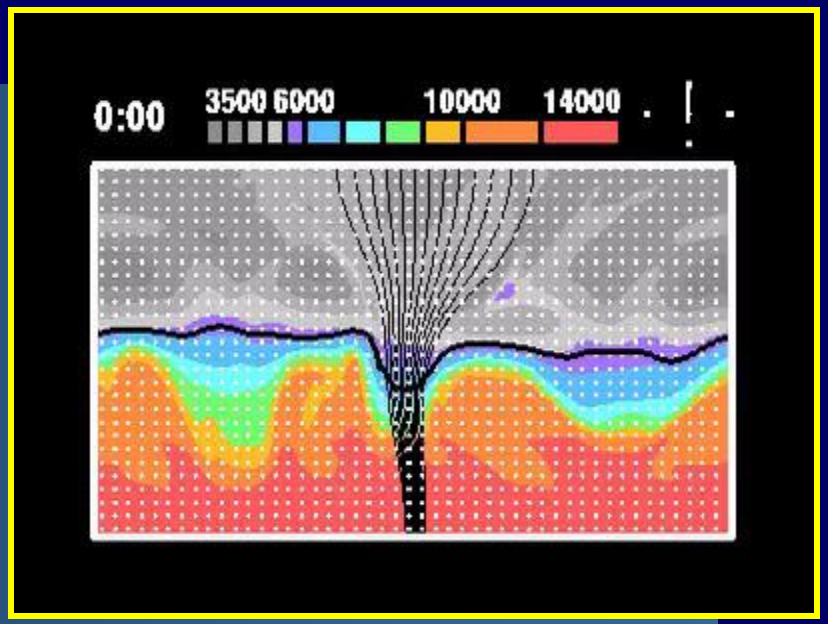


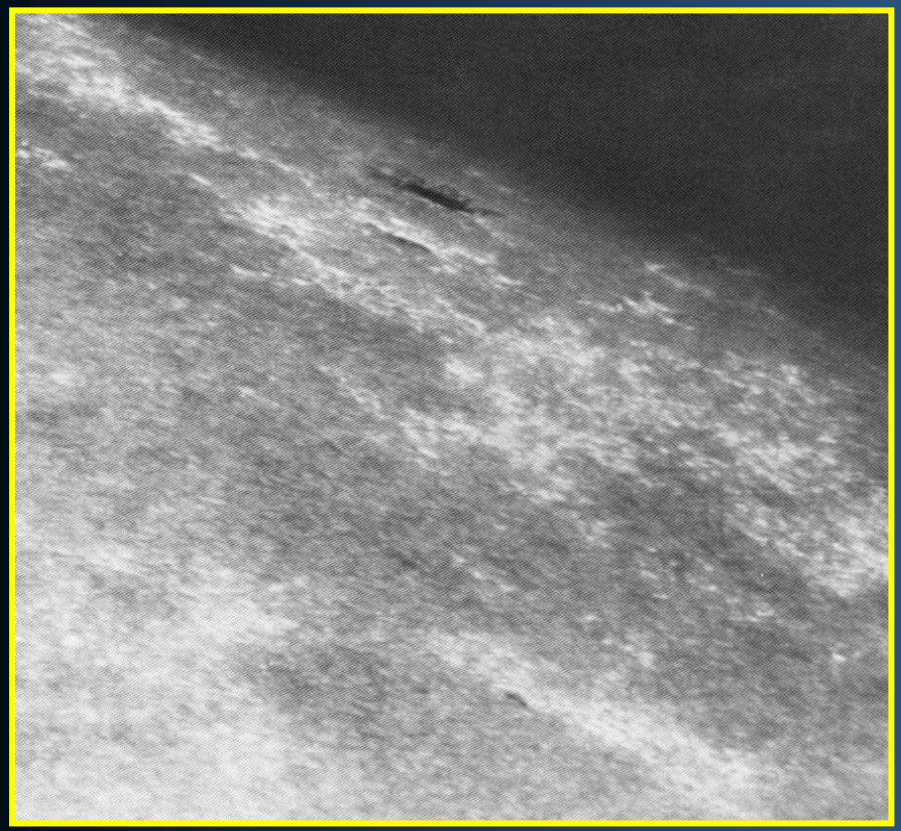
Solar Output Signals in Troposphere

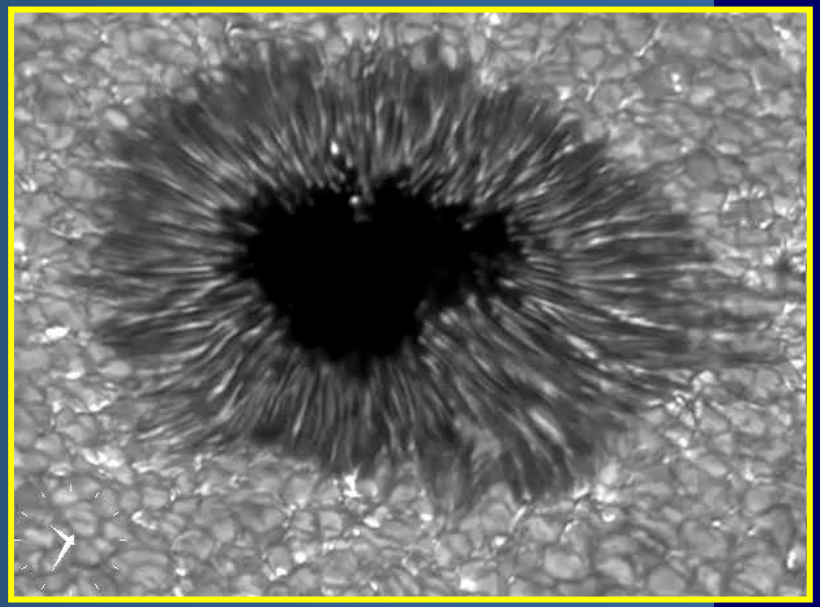
Visible/IR	at most, very small “bottom up” signals reported in troposphere
UV	clear heating effects in statosphere (ozone layer) – may have subtle “top down” effects on troposphere
EUV	dominates thermosphere, no evidence nor credible mechanism for coupling to the troposphere
X-Rays	major effects in thermosphere, 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

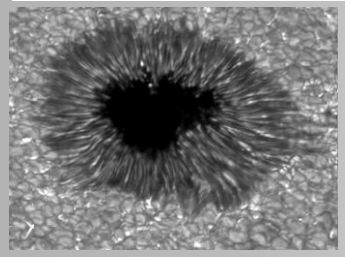
Total solar irradiance changes and magnetic field emergence

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

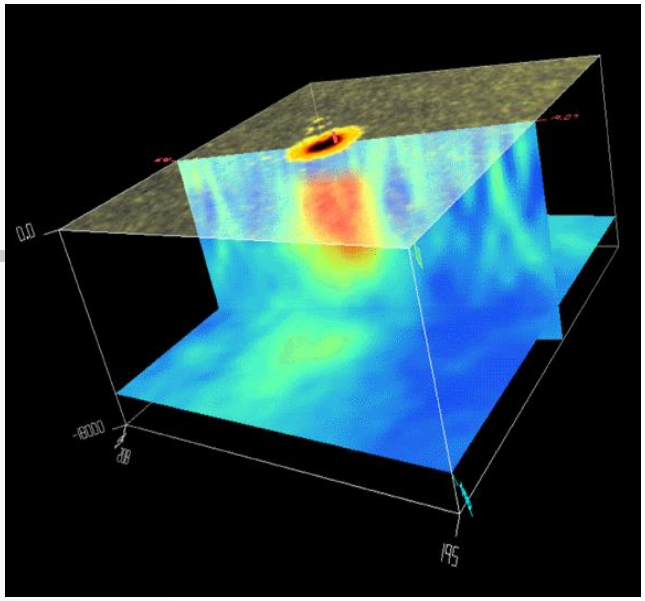


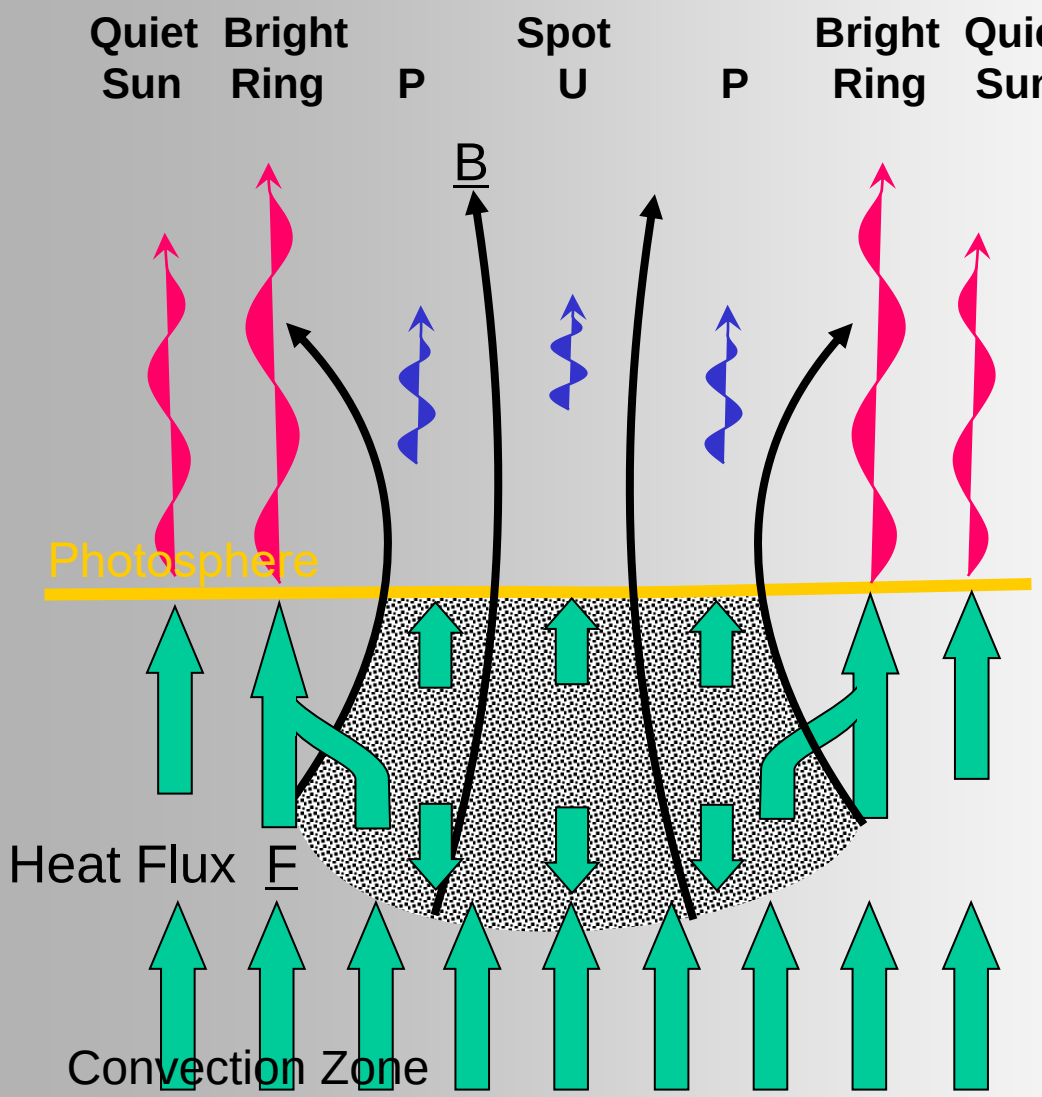






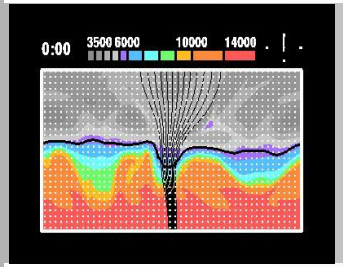
Sunspot Darkening





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

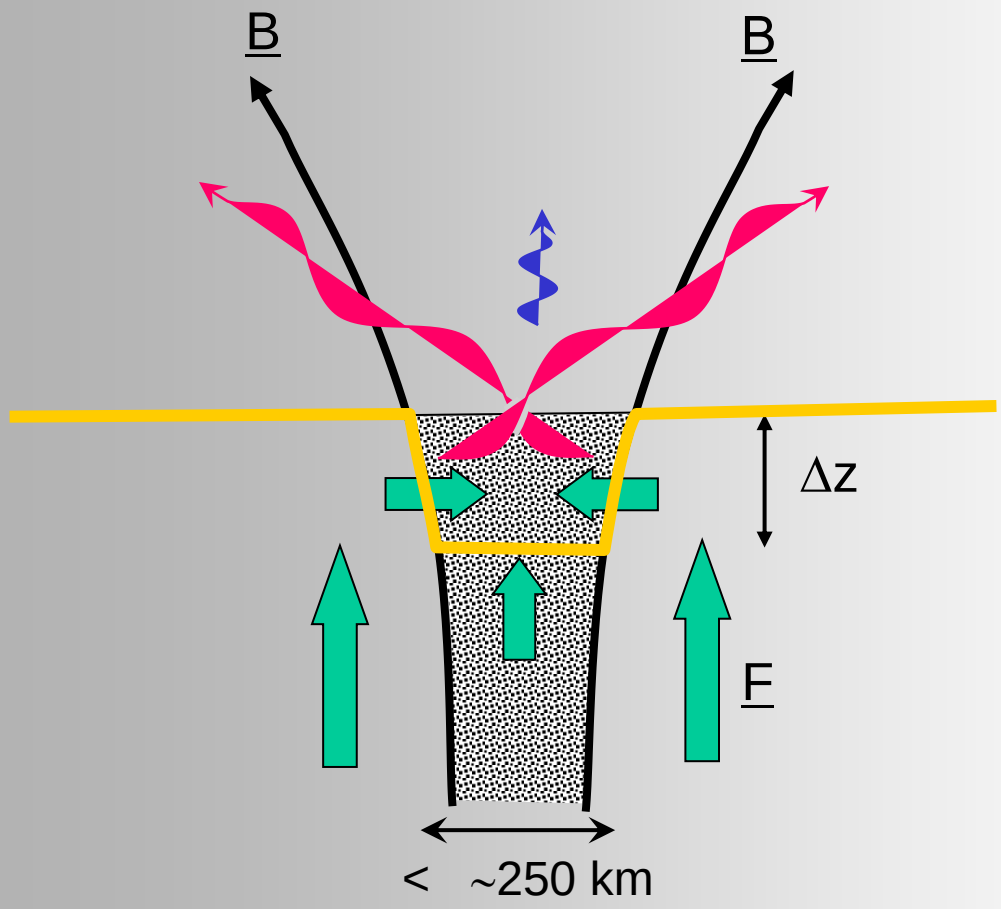
  Quiet Sun $T_{QS} \approx 6050K$
  Bright ring $T_{BR} \approx 6065K$
  Penumbra $T_P \approx 5680K$
  Umbra $T_U \approx 4240K$



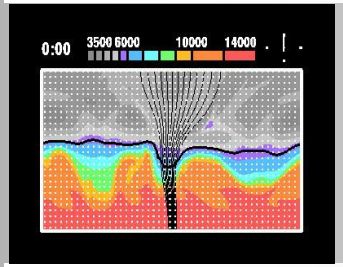
Facular Brightening

The Bright Wall Model

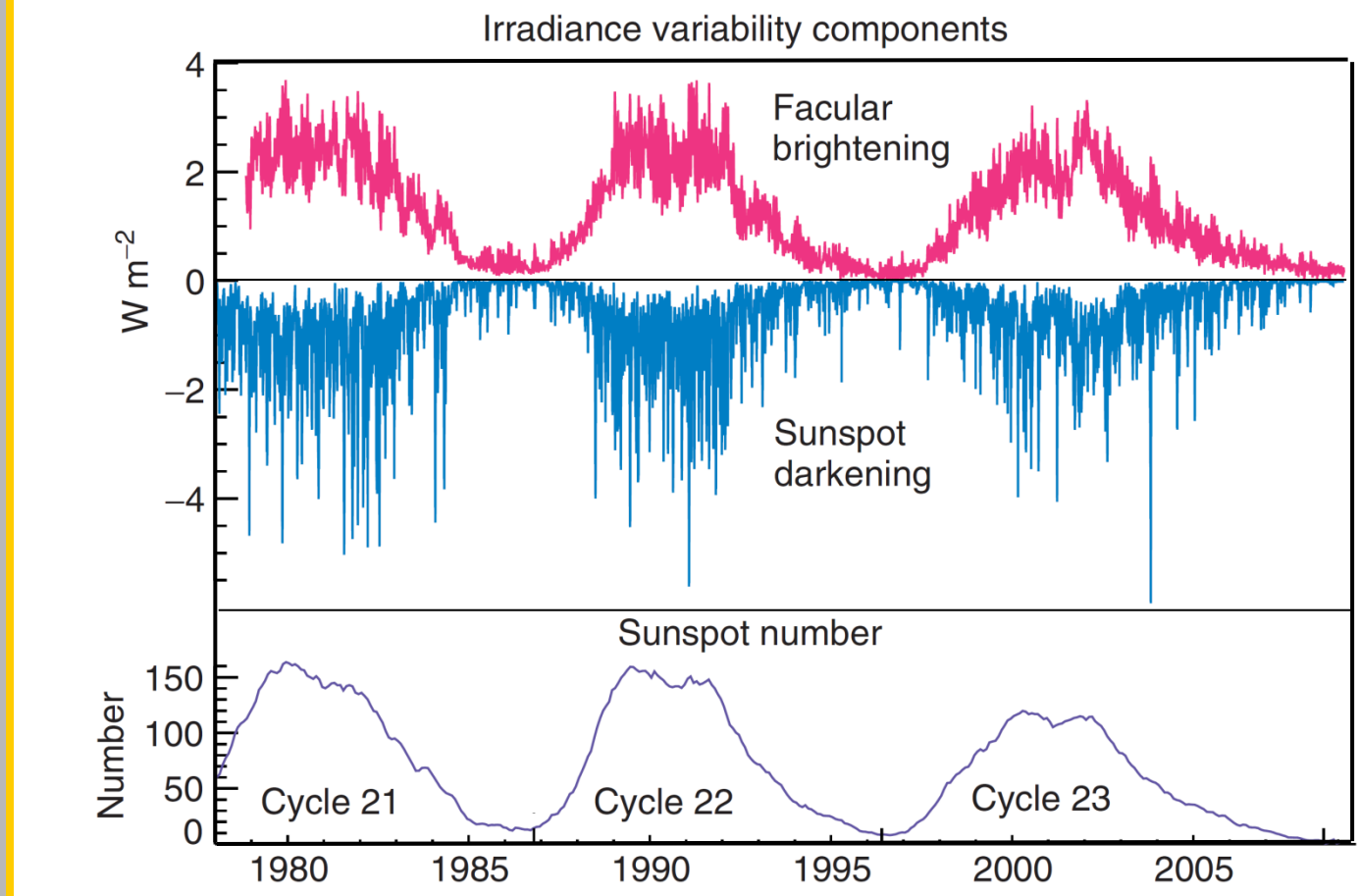
- Enhanced field raises magnetic pressure and depresses thermal pressure Nk_BT

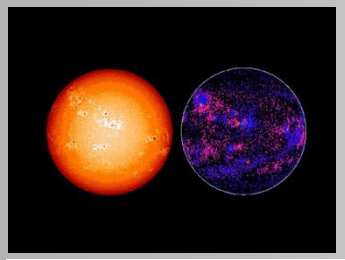


- flux tube small enough for radiation from walls to maintain internal temperature T
- N falls & the τ_O = 2/3 contour is depressed by $\Delta z \approx 50$ km
- bright walls most visible at small μ for which $T_f \approx$ 6200 K

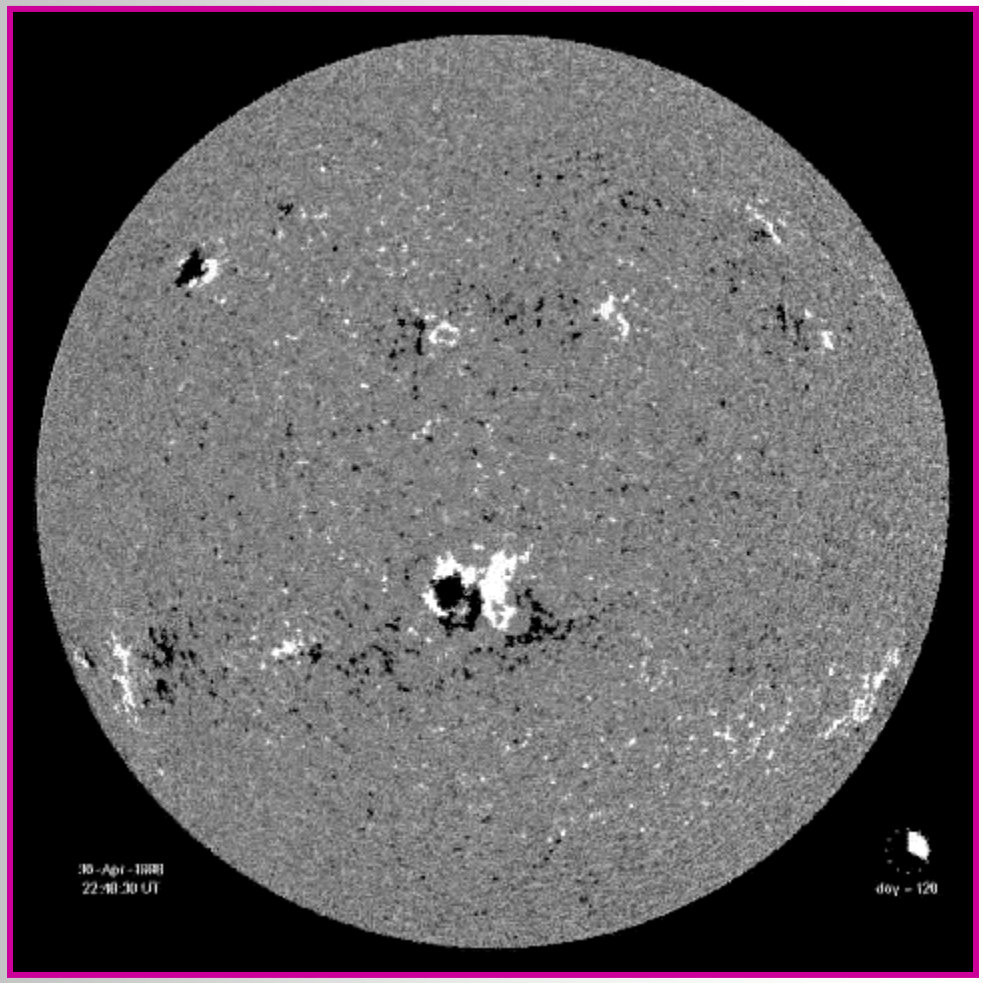


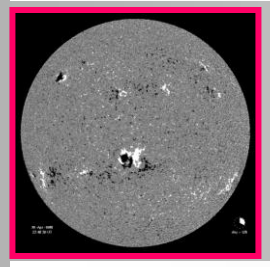
Sunspot Darkening & Facular Brightening





Photospheric magnetic field magnetogram data





3-component TSI model

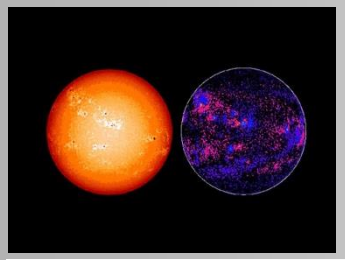
using magnetogram data

- 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

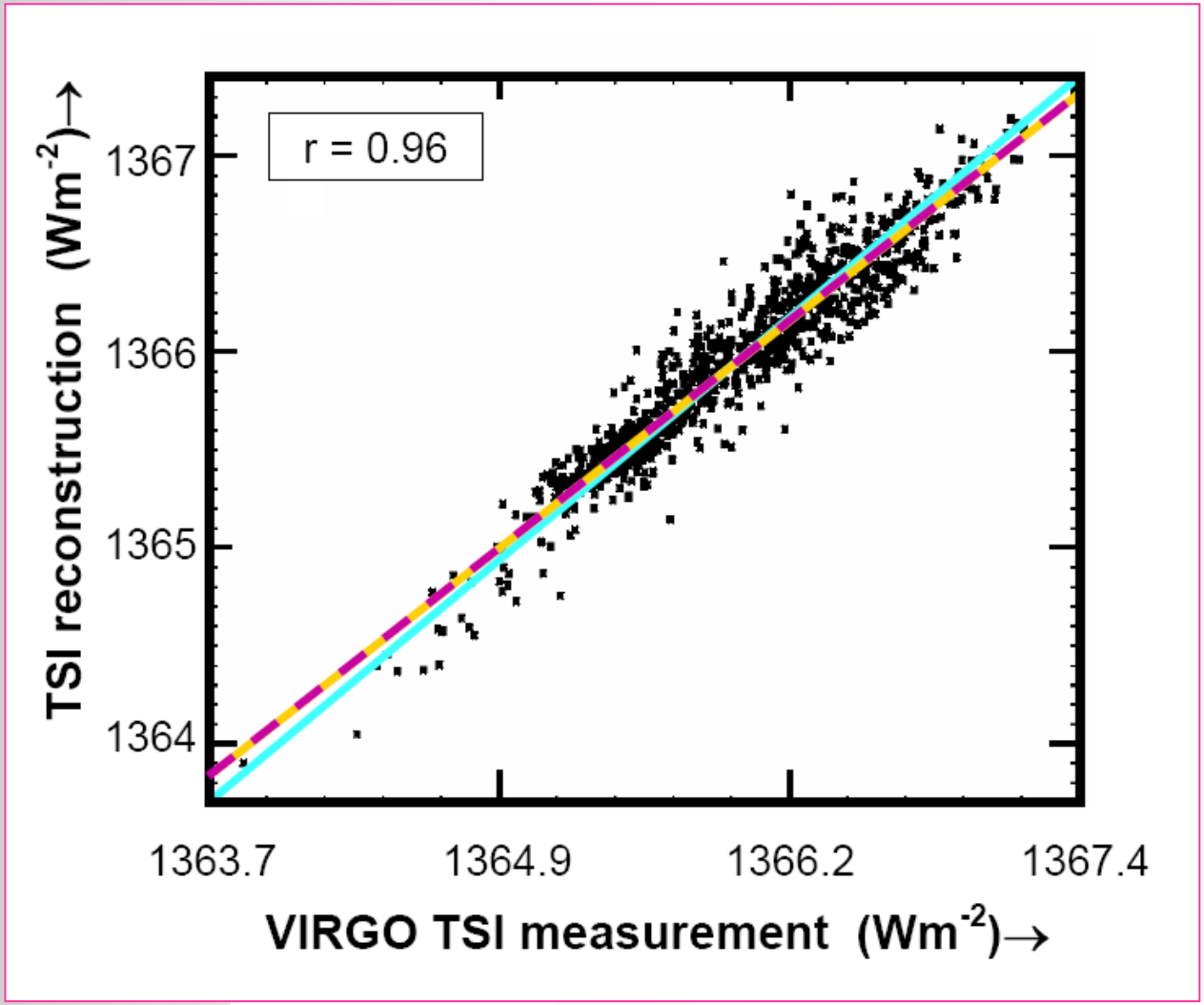
$$I_{TS}(\lambda,t = (\pi R_s^2 / R_1^2)\, I_O \int_0^1 L_D(\mu,\lambda)\, [\, \underbrace{\alpha_P(\mu,t)\{C_P(\mu,\lambda)+1\}}_{\text{penumbrae}} + \underbrace{\alpha_U(\mu,t)\{C_U(\mu,\lambda)+1\}}_{\text{umbrae}} + \underbrace{\alpha_F(\mu,t)\{C_F(\mu,\lambda)+1\}}_{\text{faculae}} + \underbrace{\{1-\alpha_P(\mu,t)-\alpha_U(\mu,t)-\alpha_P(\mu,t)\}}_{\text{quiet Sun}}\,]\mu d\mu$$



4-component model

(Solanki et al., 2003)

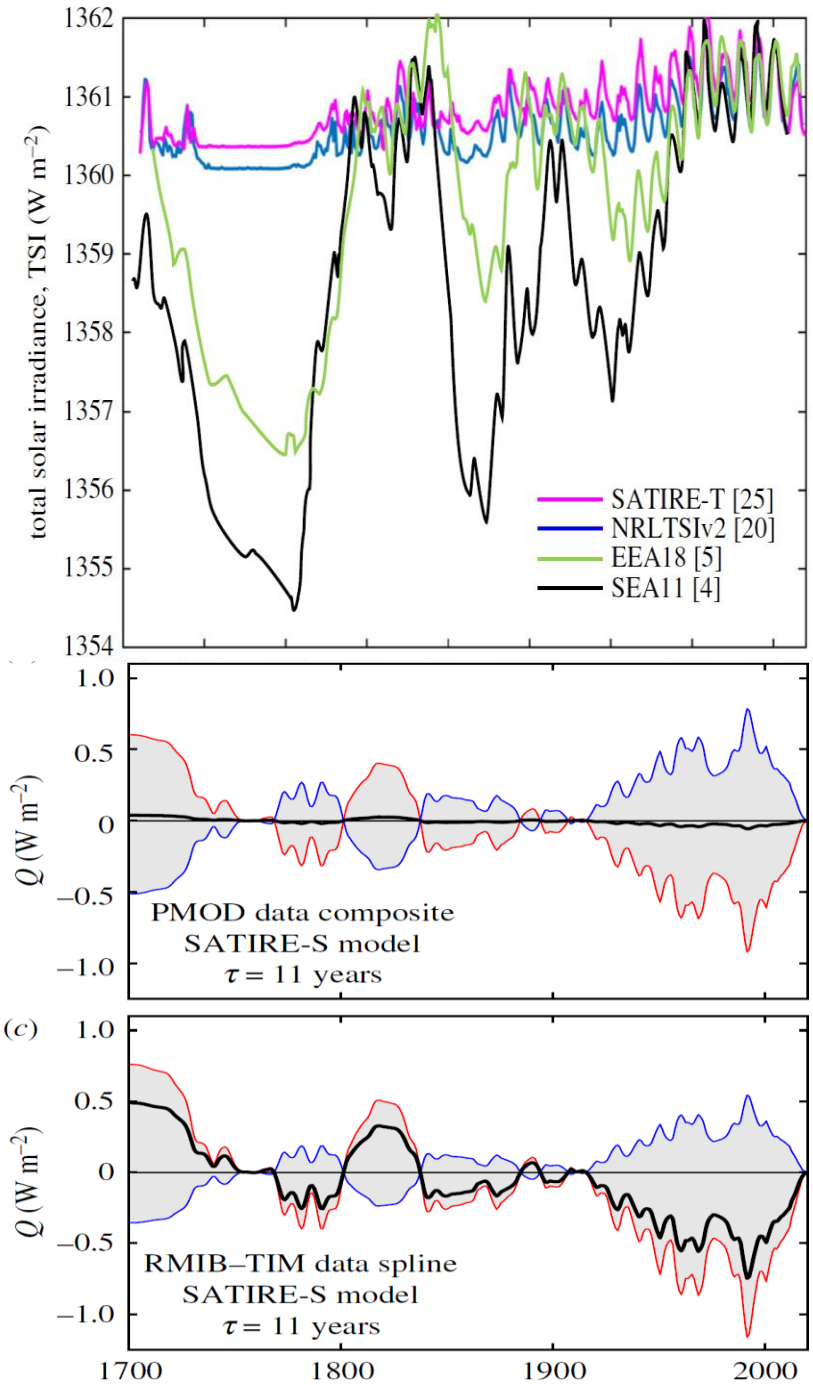
- Total Solar Irradiance reconstructions using 4 component model (“SATIRE”) with magnetograms for 1996-2002 from the MDI satellite, compared with SoHO TSI data

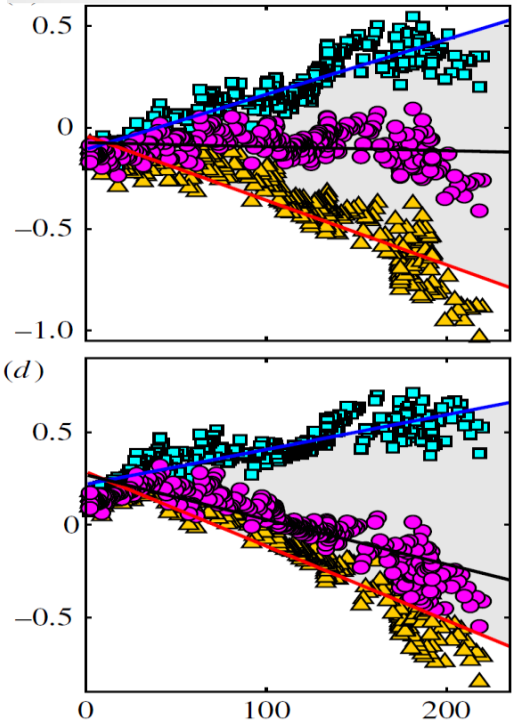


Models of long-term TSI variation

(Lockwood and Ball, 2020)

- SATIRE-T and NRLTSIv2 use sunspot number and 4 component model – have very little drift in TSI of quiet Sun Q
- EEA18 & SEA11 have v. large drift in Q based on cosmogenic isotope data





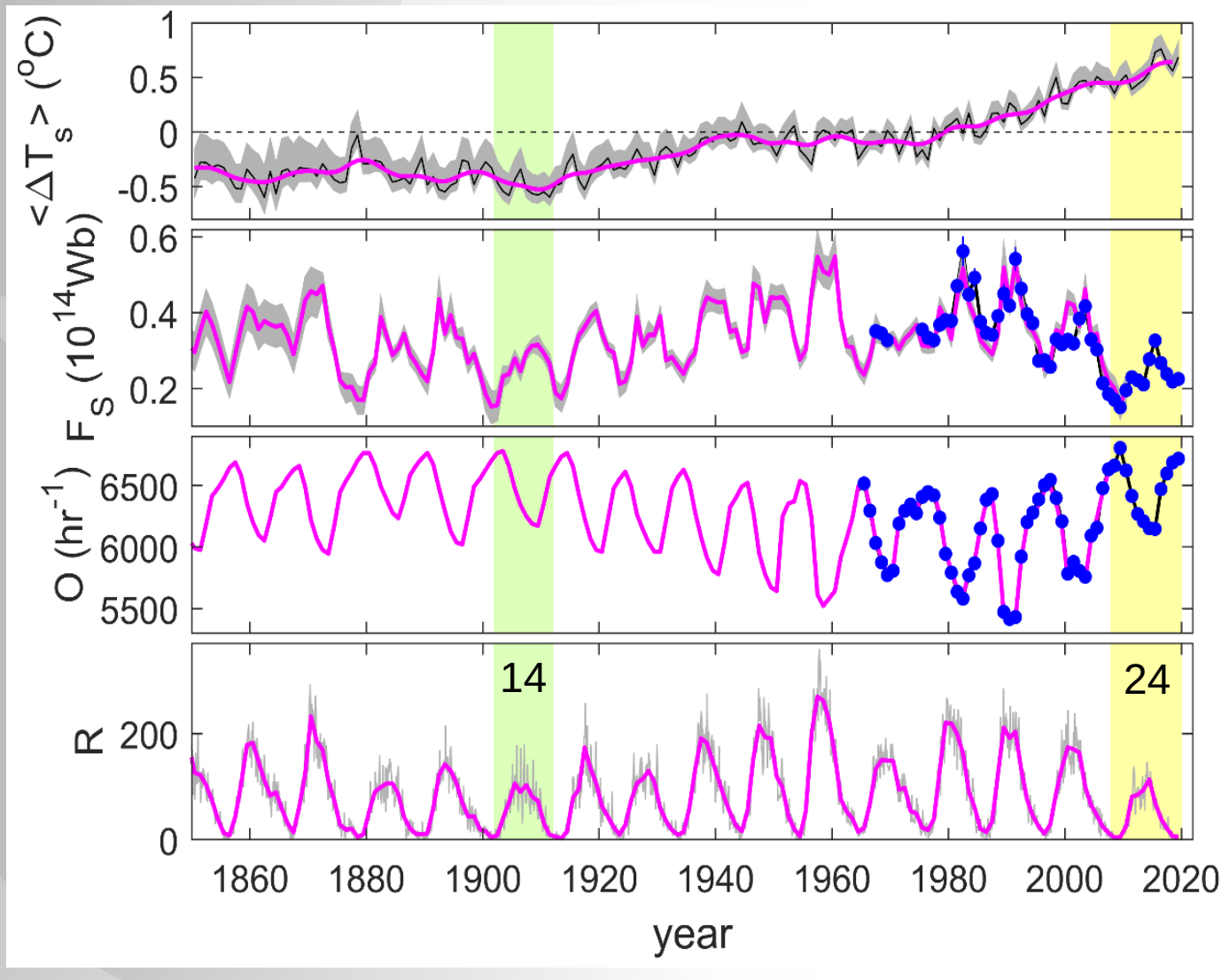
- L&B20 looked at how EEA18 and SEA|11 derived Q and showed drift in Q depends on assumed stability of TSI data
- Within that uncertainty drift in Q may even be in opposite sense to that found by EEA18 and SEA11

Is solar activity the cause?

solar cycle #24 very similar to #14

✗ Globally: No

- HadCRUT4 global mean air surface temperature anomaly *(Morice et al.,2012)*
- Open Solar Flux *(Lockwood et al.,2012)*
- Galactic Cosmic Ray Counts (at Oulu station) *(Usoskin et al., 2002)*
- Sunspot number *(Clette et al., 2018)*



Is the Greenhouse Effect real? ✓Yes

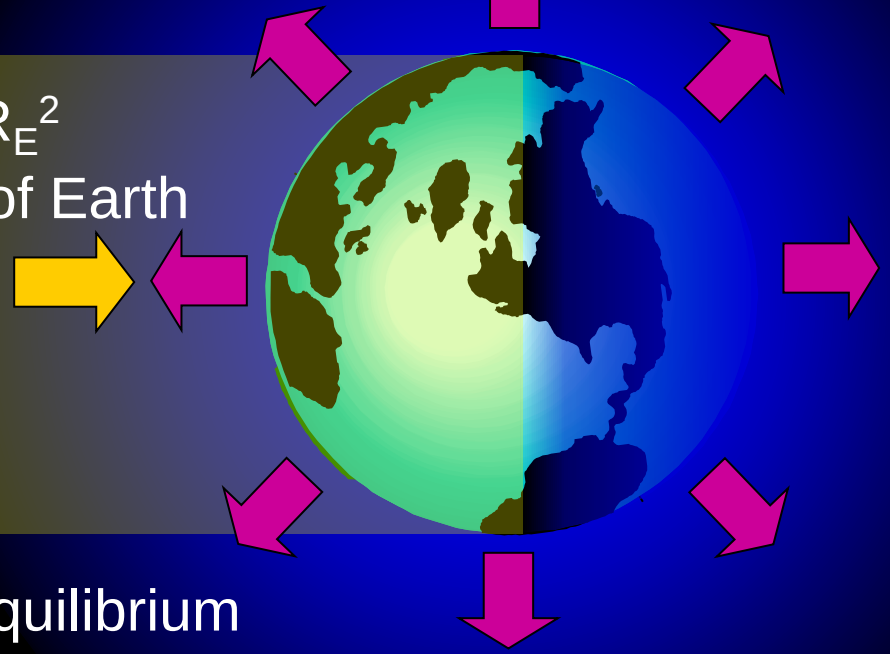
- area Earth presents to Sun is πR_E^2

  power input per unit surface area of Earth

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

  R_E = a mean Earth radius

  A = Earth's albedo ≈ 1/3



- Earth heats up to give radiative equilibrium

  $P_{IN} = I_{TS}(1\text{-}A)/4 = P_{OUT}$

- If no greenhouse effect, by Stefan-Boltzmann law, $P_{OUT} = \sigma T_s^4$
- so mean surface temperature would be $T_s = \{I_{TS}(1\text{-}A)/(4\ \sigma\}^{1/4}$
- gives $T_s = -21°C$ (*Fourier, 1822*)
- coldest permanently inhabited place on Earth is Oymyakon (Оймяко́н) in east Siberia, where the annual mean temperature is $T_s = -16°C$

Does CO_2 contribute to the Greenhouse effect ✓Yes

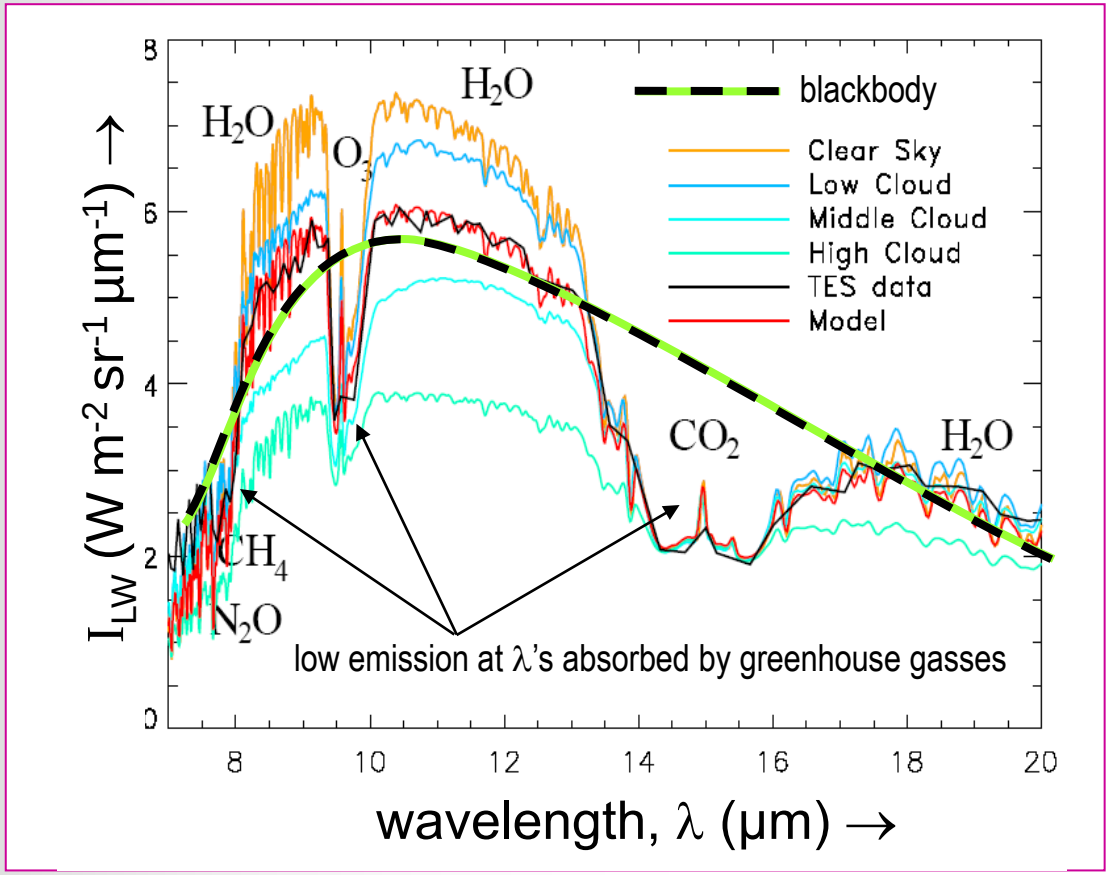
↑ 24 hours leaving Earth: looking back from Mars Global Surveyor

OLR (IR) observations of Earth from Mars Global Surveyor (in black) →

The model is the appropriate mix of Earth "scene" types (in red) →

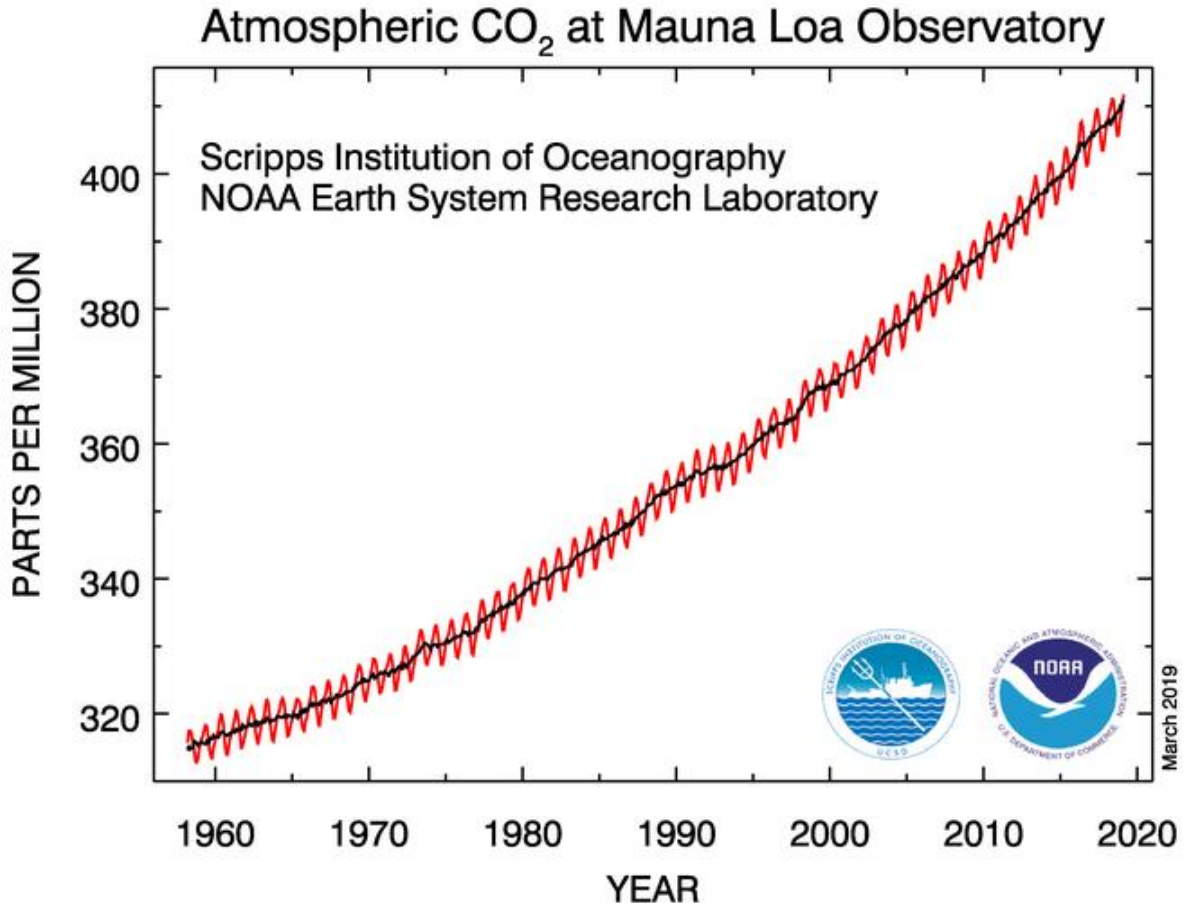
Spectrum of outgoing longwave (infra red)

(Note that low cloud emits more than high cloud because it is warmer)



Have atmospheric CO_2 levels risen?

✓Yes



- Ice cores show the pre-industrial level was 270 ppm

Is the CO_2 rise man-made?

^{13}C and the carbon cycle

*** ("isotopic fractionisation")**

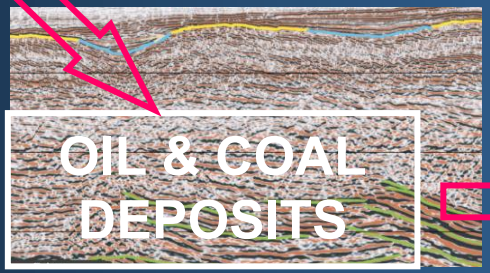
$[^{13}CO_2]$ / $[^{12}CO_2]$ decreases with anthropogenic rise in $[CO_2]$

^{12}C is taken up 2% more than ^{13}C by plants and trees*

TROPOSPHERE

OCEANS

BIOMASS



OIL & COAL DEPOSITS

reduced $[^{13}C]$ / $[^{12}C]$

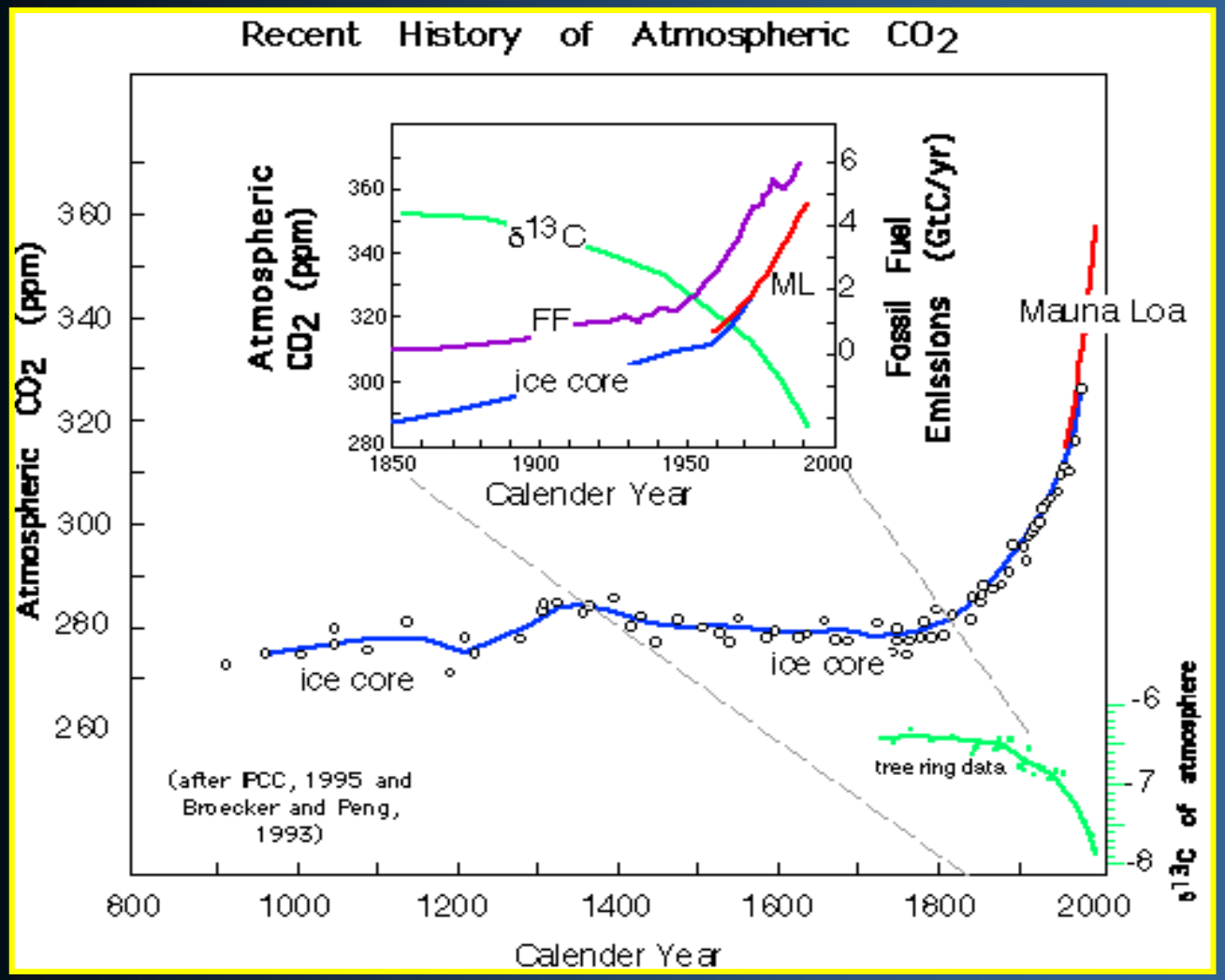
reduced $[^{13}CO_2]$ / $[^{12}CO_2]$

FOSSIL FUEL EXTRACTION & BURNING

Is the CO_2 rise man-made?

✓Yes

The "2nd Suess Effect": dilution of $^{13}CO_2$ by burning of fossil fuels & biomass



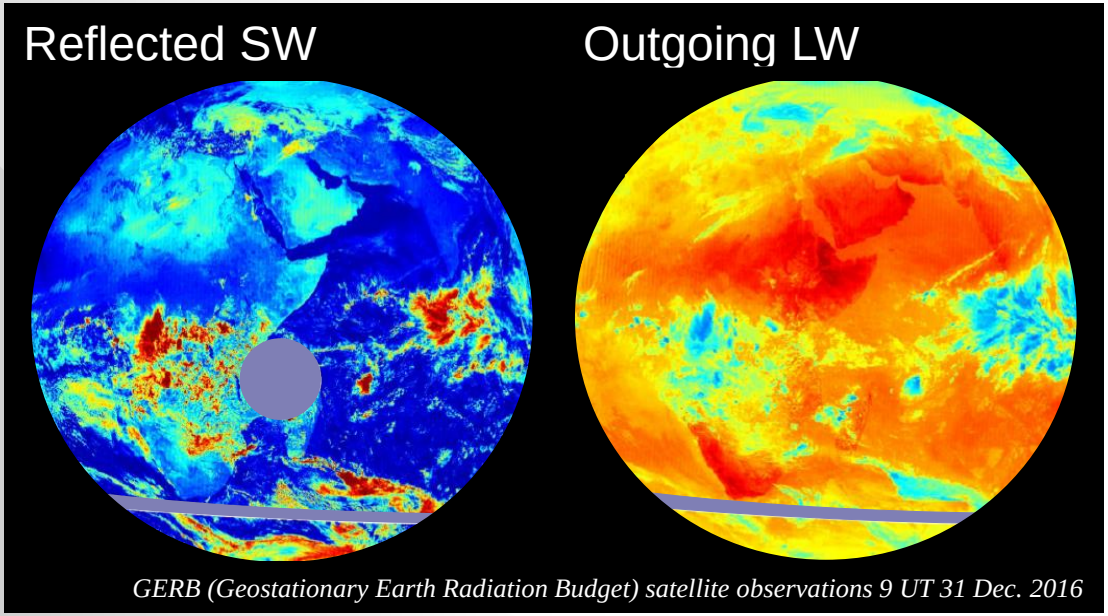
- green line shows $\delta^{13}C$, related to the fraction of ^{13}C in CO_2 which has declined exponentially as estimated fossil fuel use (FF) and atmospheric CO_2 has risen

Does more CO_2 add to the Greenhouse effect?

two mutually exclusive arguments have been used:

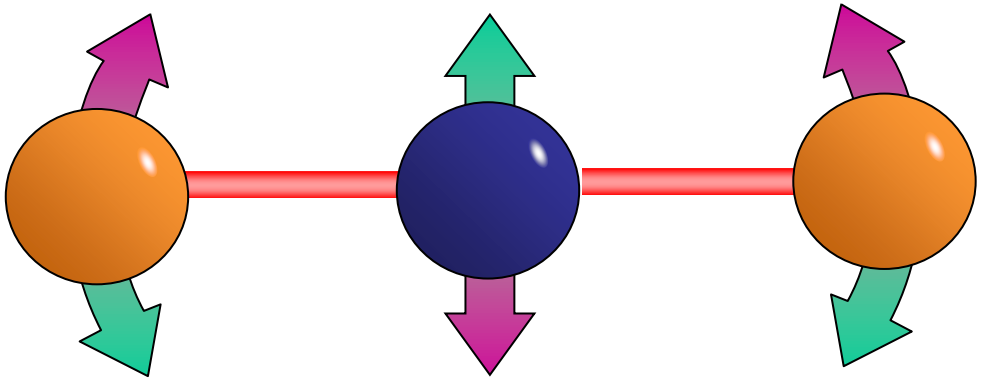
- A. CO_2 does not absorb infrared (longwave) radiation
- B. CO_2 is so good at absorbing infrared (longwave) radiation that adding more does not cause any further absorption (the absorption lines are argued to be “saturated”)

- *we have known A is wrong since John Tyndall’s measurements published in 1860*
- *B. demonstrates a failure in understanding how the greenhouse effect actually works (as first described by Svante Arrhenius in 1896)*

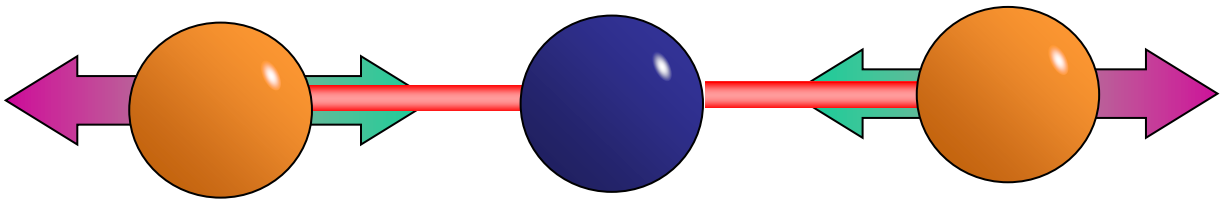


GERB (Geostationary Earth Radiation Budget) satellite observations 9 UT 31 Dec. 2016

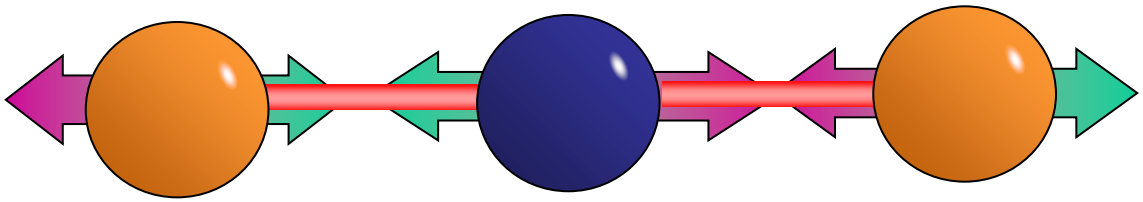
CO_2



(a) Bending mode



(b) symmetric stretch



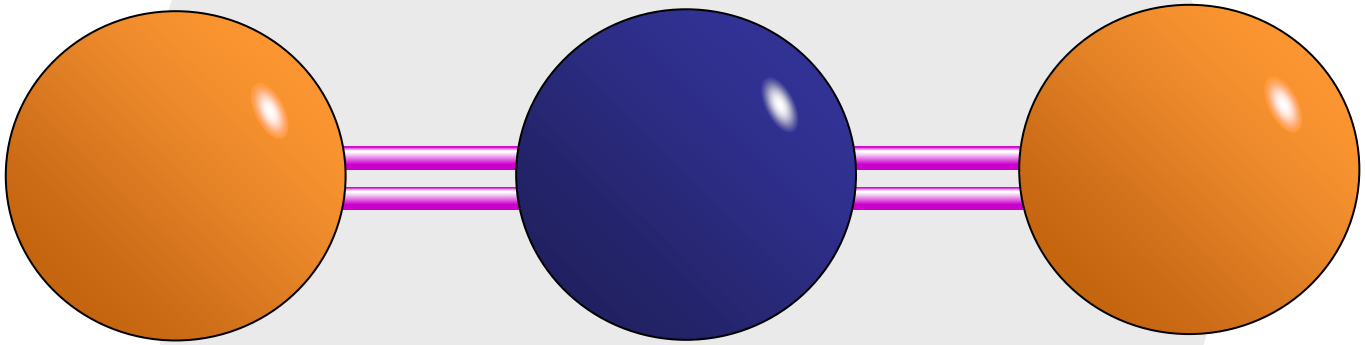
(c) asymmetric stretch

Carbon

Oxygen

a CO_2 molecule

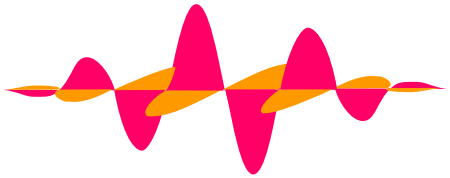
(a simple, linear, triatomic molecule)



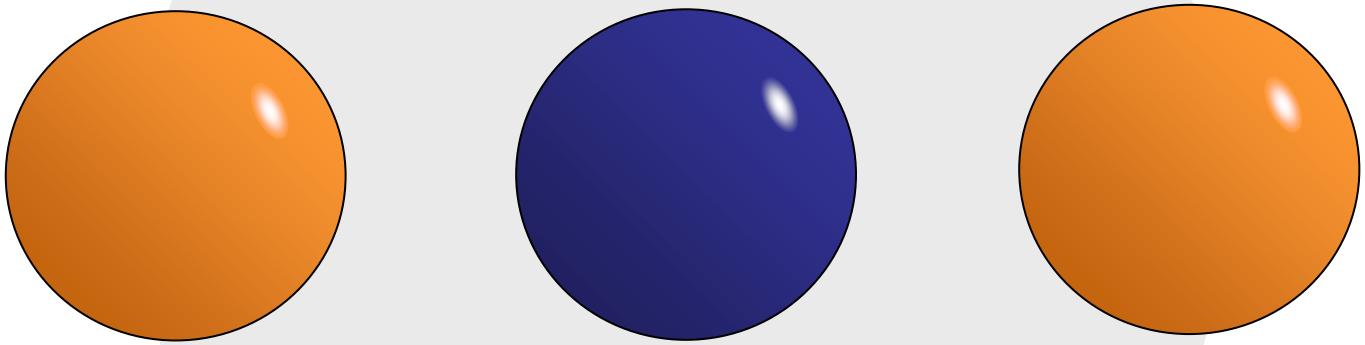
Carbon

Oxygen

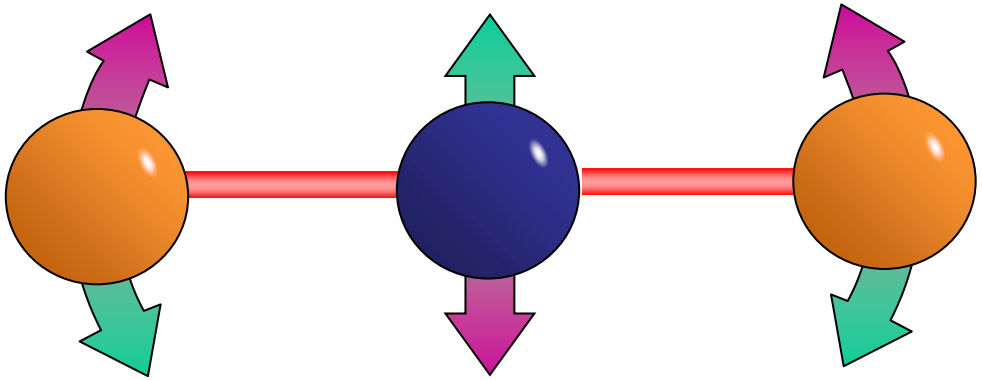
SW Photon



a CO_2 molecule



CO_2



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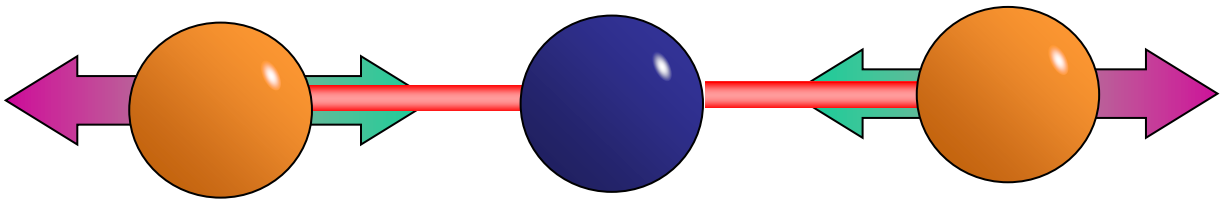
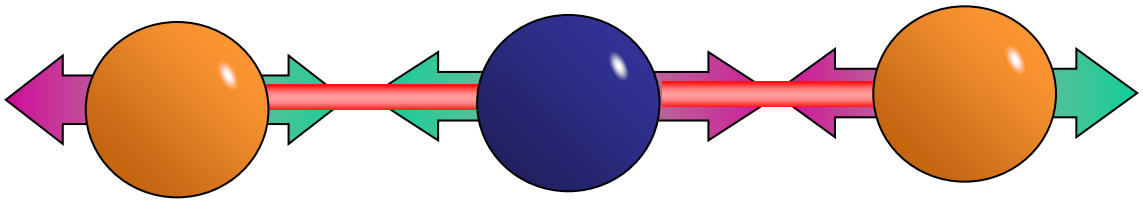


(b) symmetric stretch

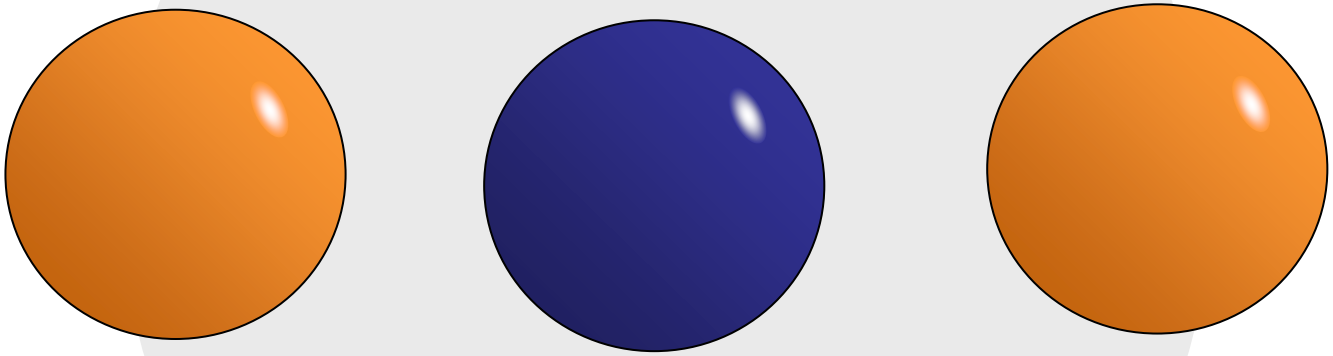


(c) asymmetric stretch

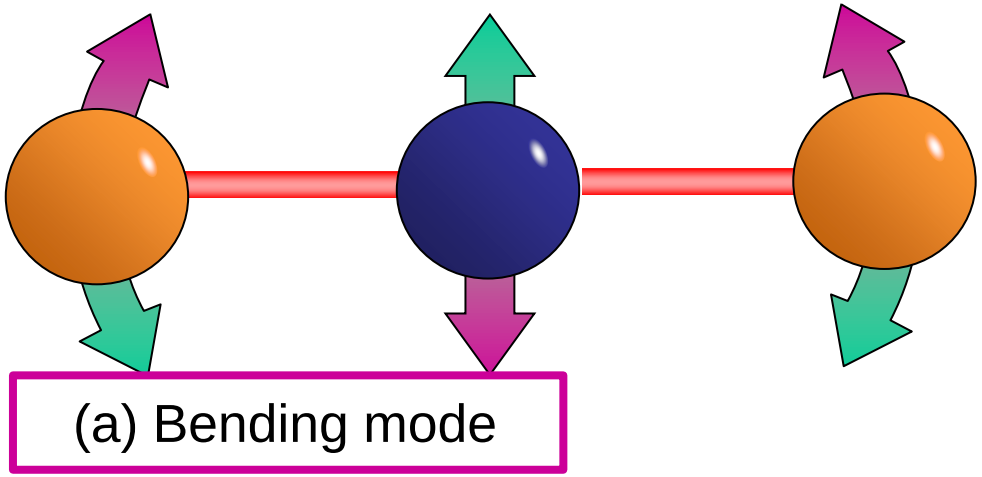
Carbon

Oxygen

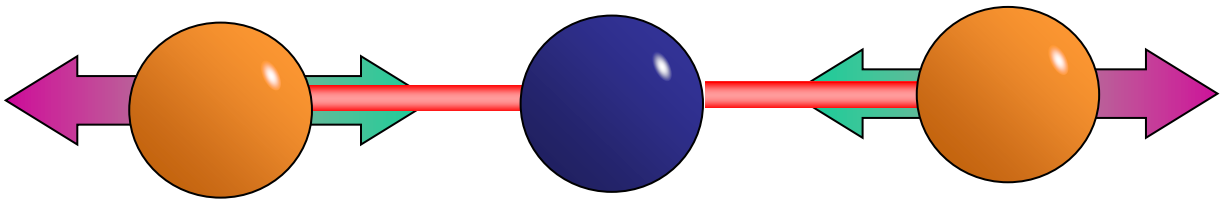
a CO_2 molecule



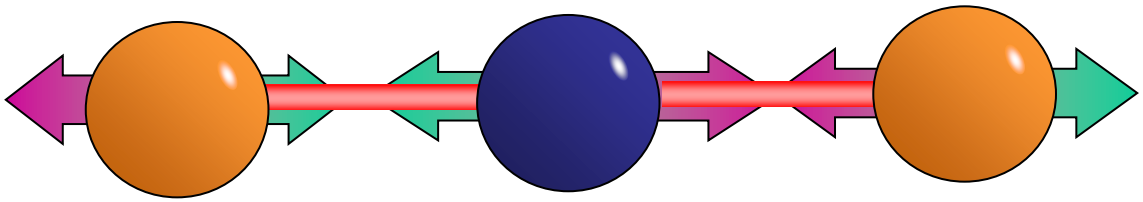
CO_2



(a) Bending mode

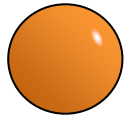


(b) symmetric stretch



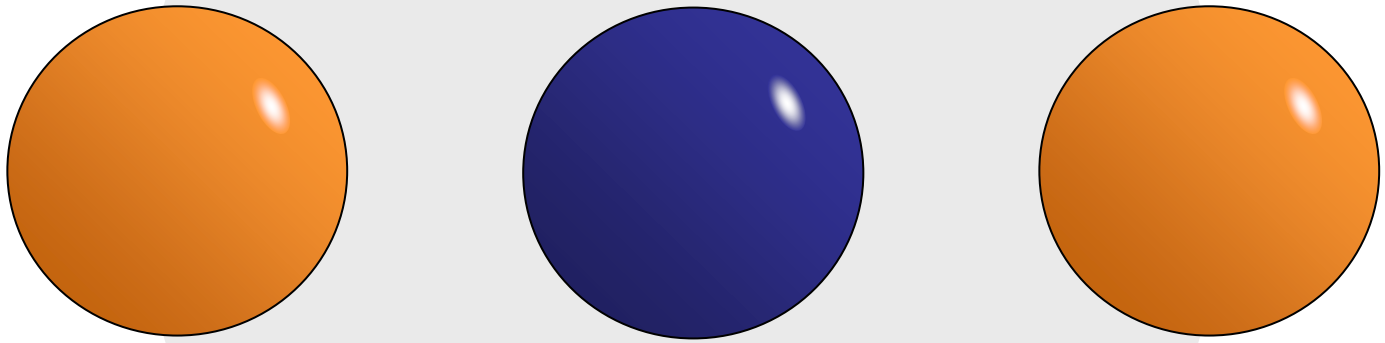
(c) asymmetric stretch

Carbon



Oxygen

a CO_2 molecule

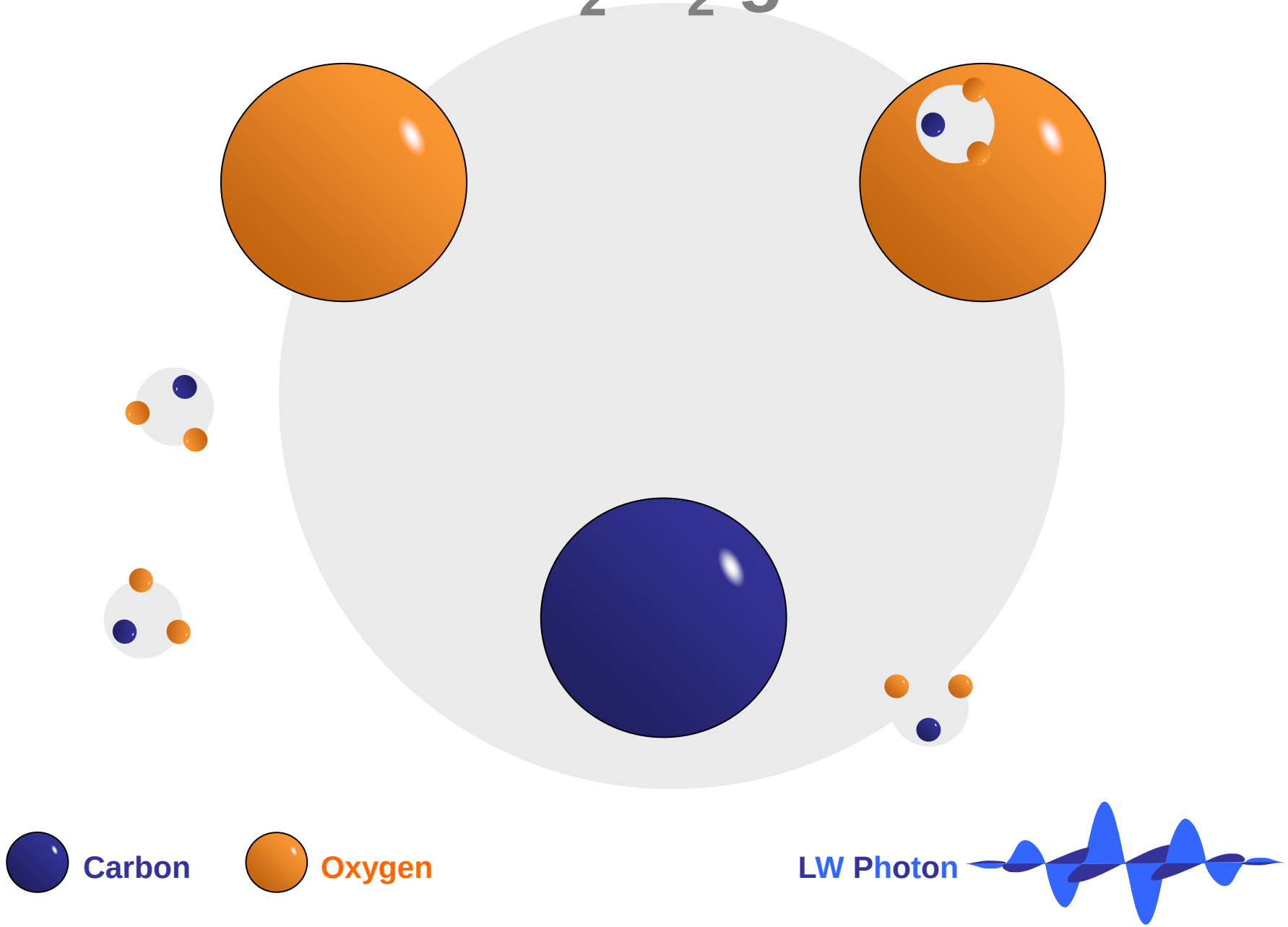


Carbon

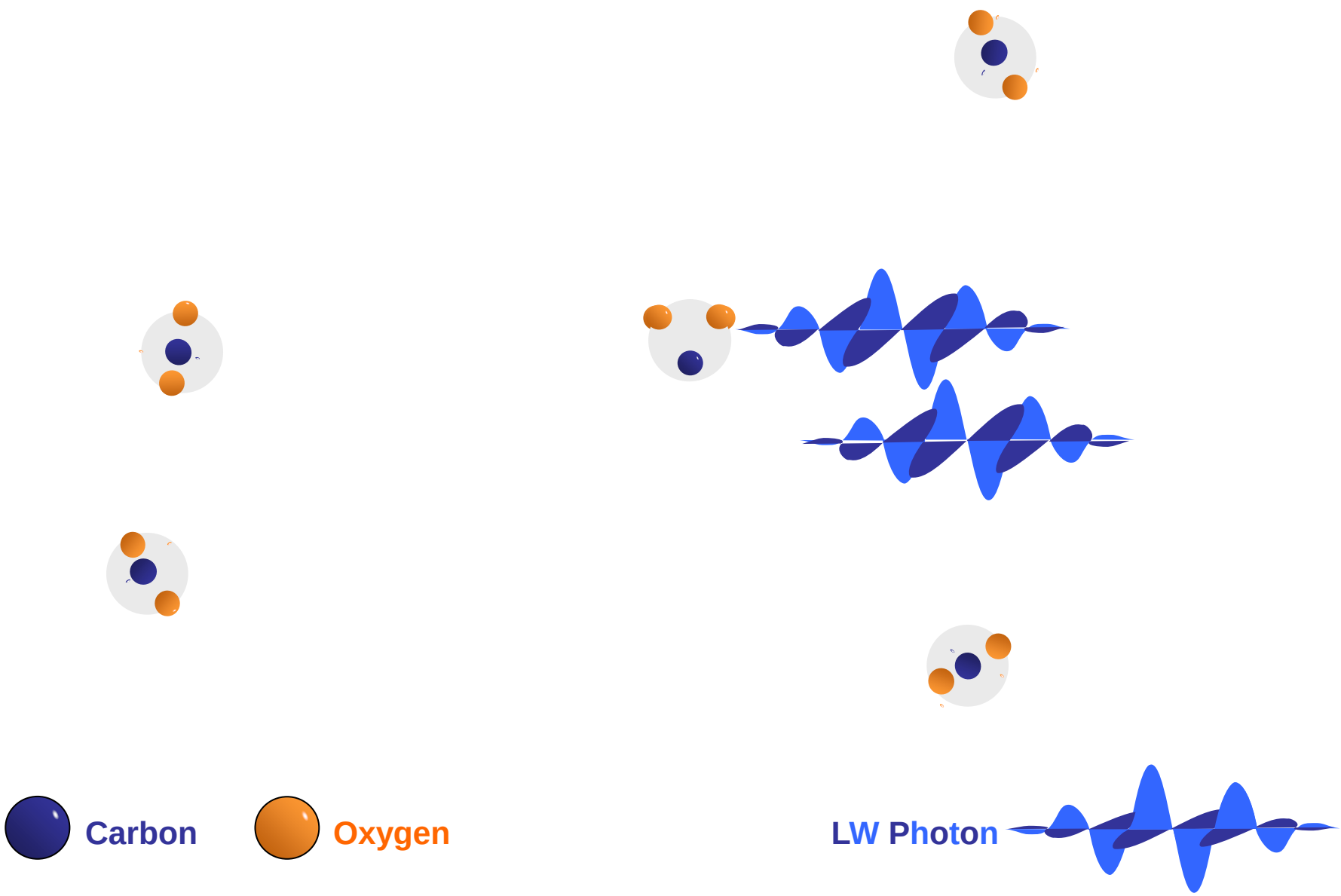
Oxygen

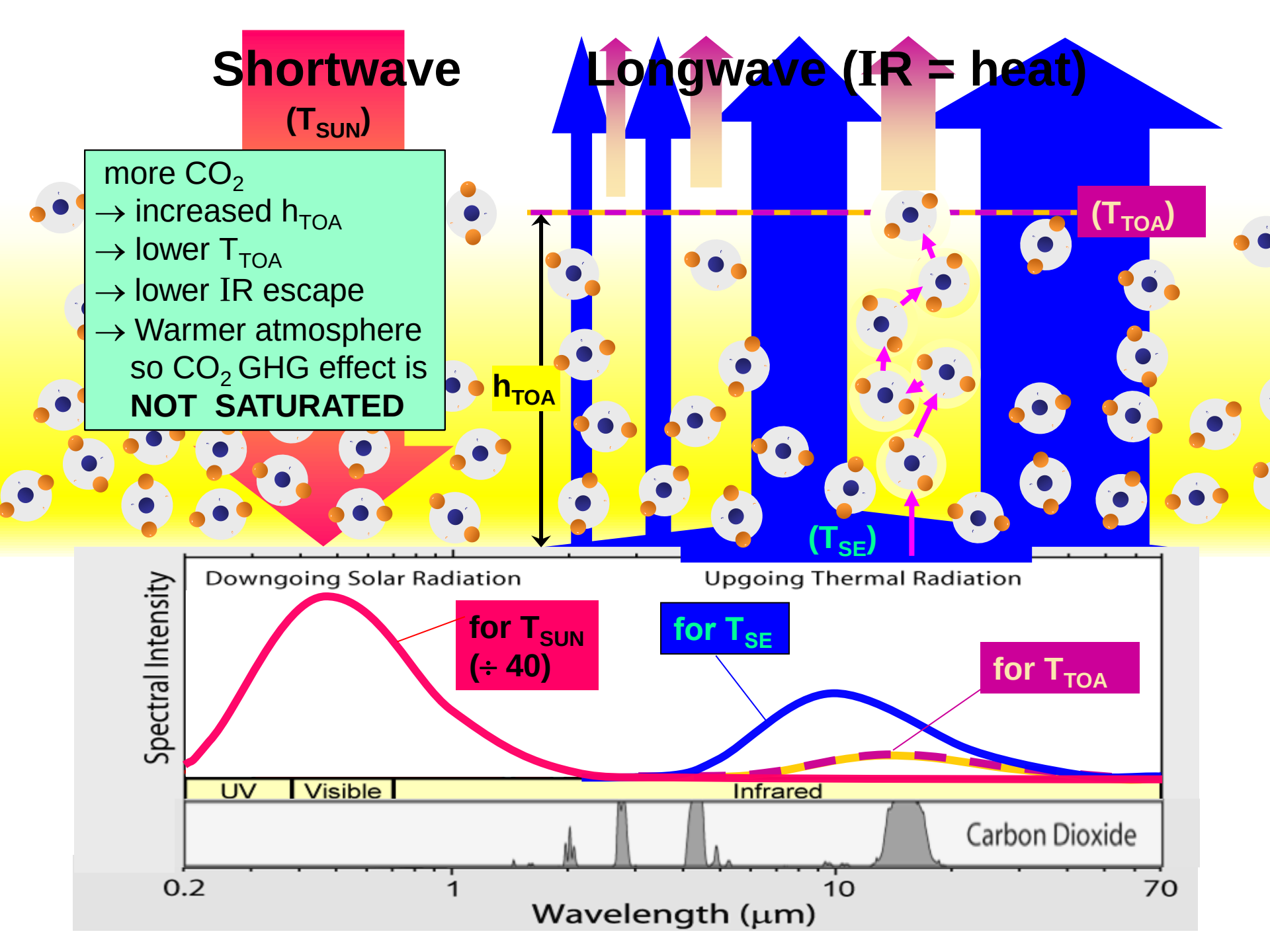
LW Photon

a CO_2 Molecule



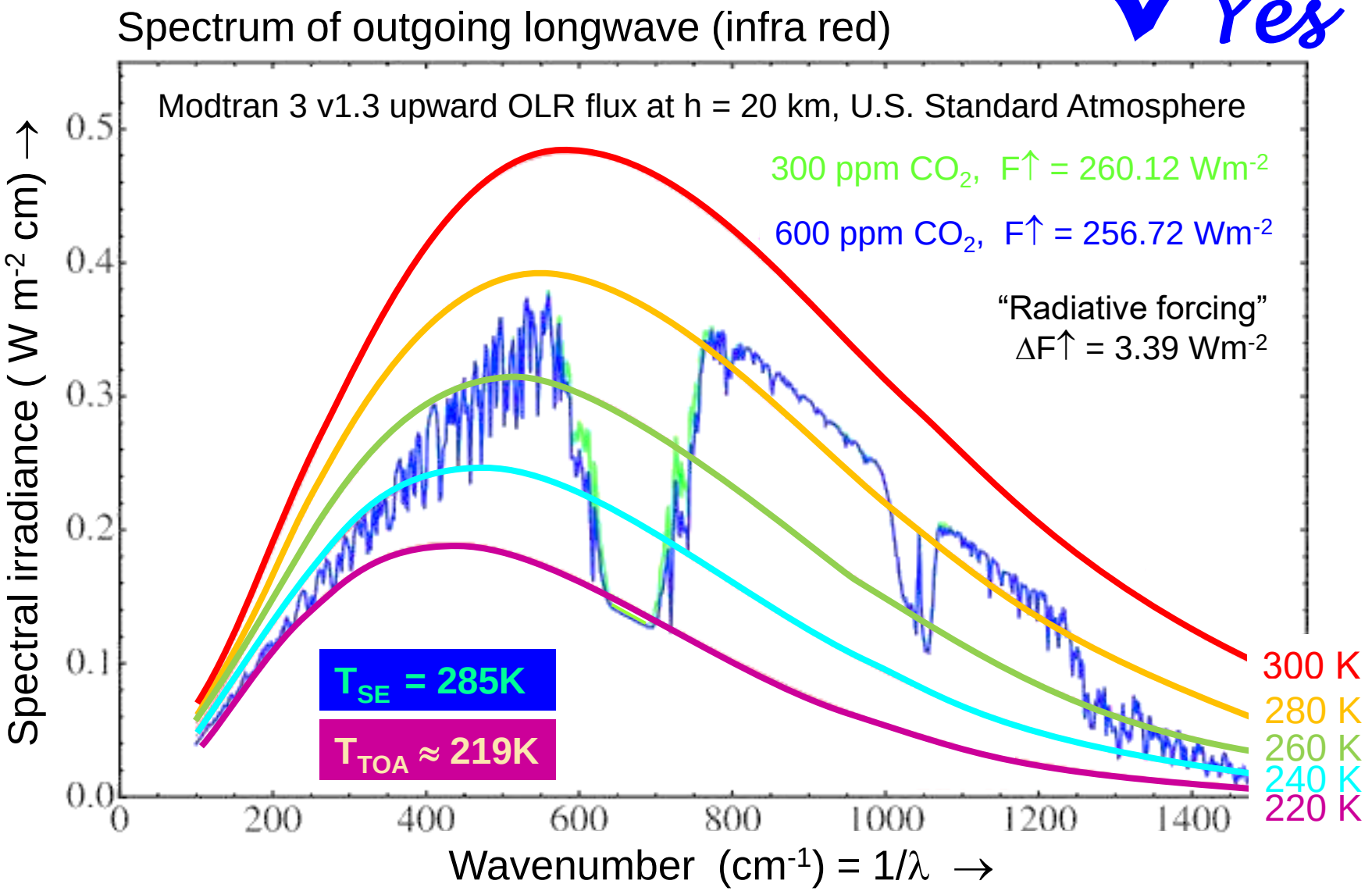
a CO_2 gas




Shortwave
(T_{SUN})
Longwave (IR = heat)
more CO_2
→ increased h_{TOA}
→ lower T_{TOA}
→ lower IR escape
→ Warmer atmosphere
so CO_2 GHG effect is
NOT SATURATED
h_{TOA}
(T_{TOA})
(T_{SE})
Downgoing Solar Radiation
Upgoing Thermal Radiation
Spectral Intensity
for T_{SUN}
(÷ 40)
for T_{SE}
for T_{TOA}
UV
Visible
Infrared
Carbon Dioxide
0.2
1
10
70
Wavelength (μm)

Does more CO_2 add to the Greenhouse effect

✓ Yes

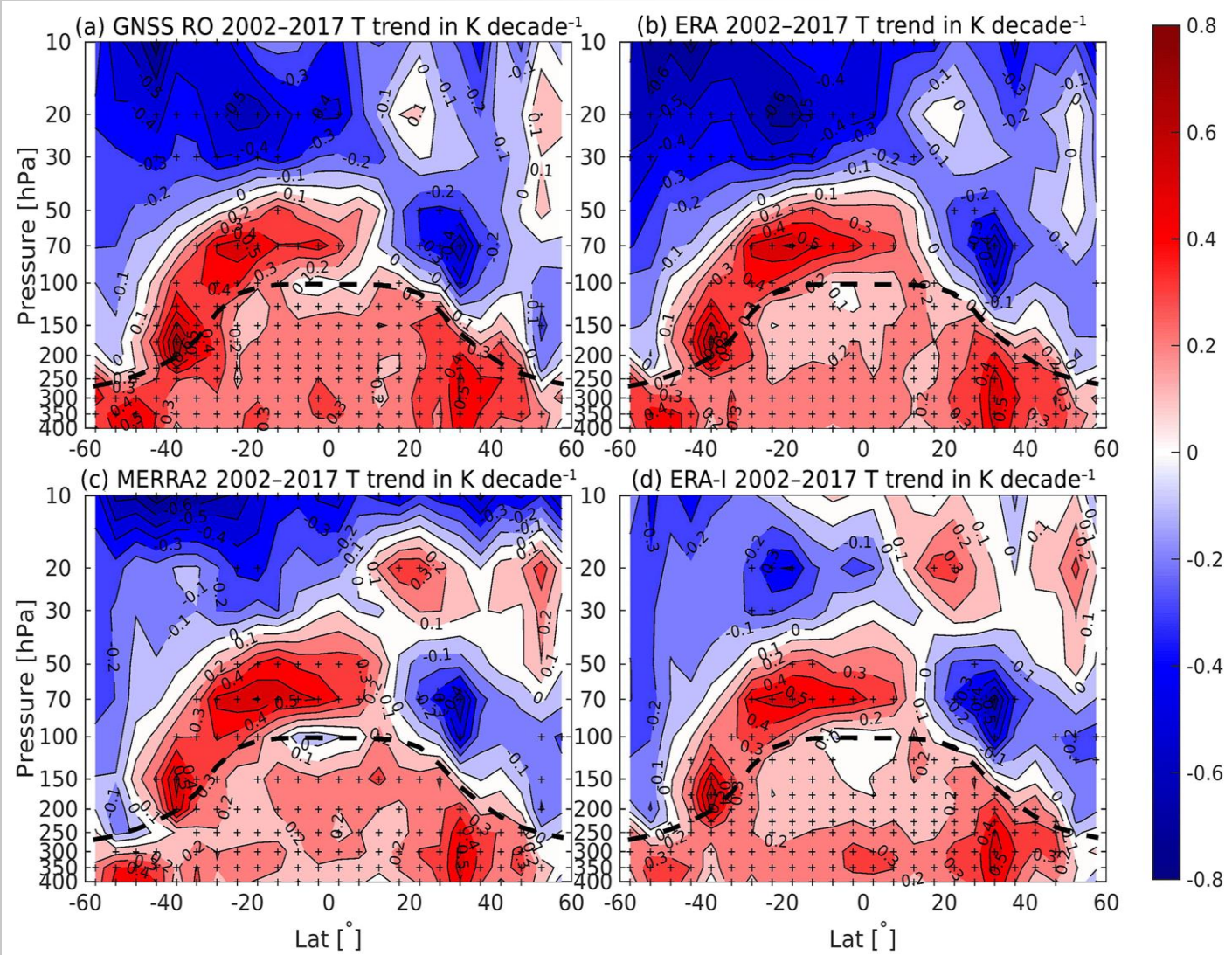


Is solar irradiance the main cause?

The stratosphere is cooling and not warming

No

- Temperature trends in troposphere and stratosphere in K decade^{-1} based on GNSS RO, ERA5, MERRA2, and ERA-I for 2002-2017.
- + marks the significant area at 95 % level.

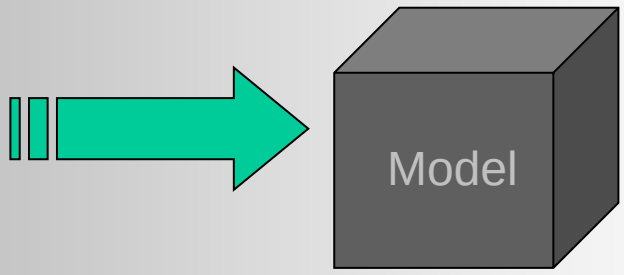


Is the global temperature rise consistent with the CO_2 rise?

Yes but …

Ada, Countess of Lovelace (1815-1852) the first computer programmer and the first human to understand the concept of numerical modelling

Feedback effects mean that we need numerical climate 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 make rational and objective and inclusive selections **and not cherrypick**)

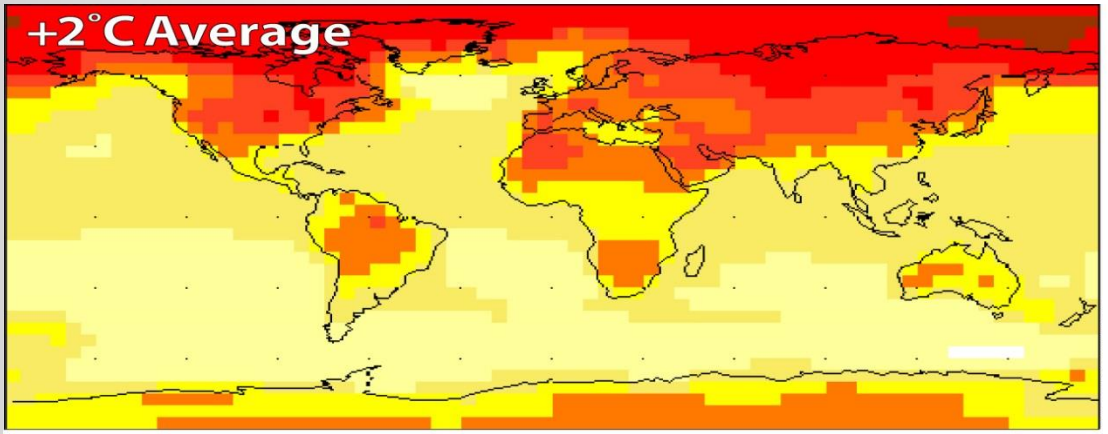
"Prediction is very hard — especially when it's about the future"

Niels Bohr
Danish Physicist
1885 – 1962

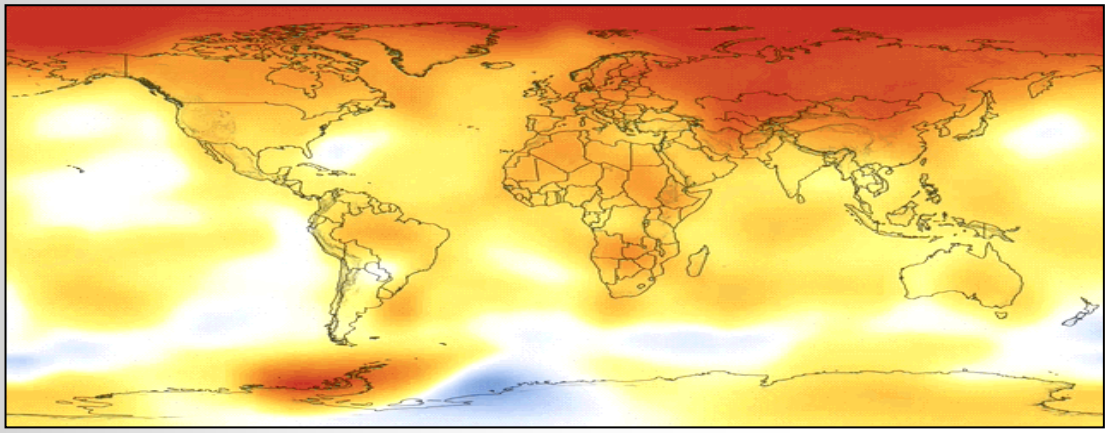
Map of Air Surface Temperature rise predicted in 1988

Hansen, J., et al. (1988) J. geophys. Res. 93, D8, 9341-9364, doi: 10.1029/JD093iD08p09341

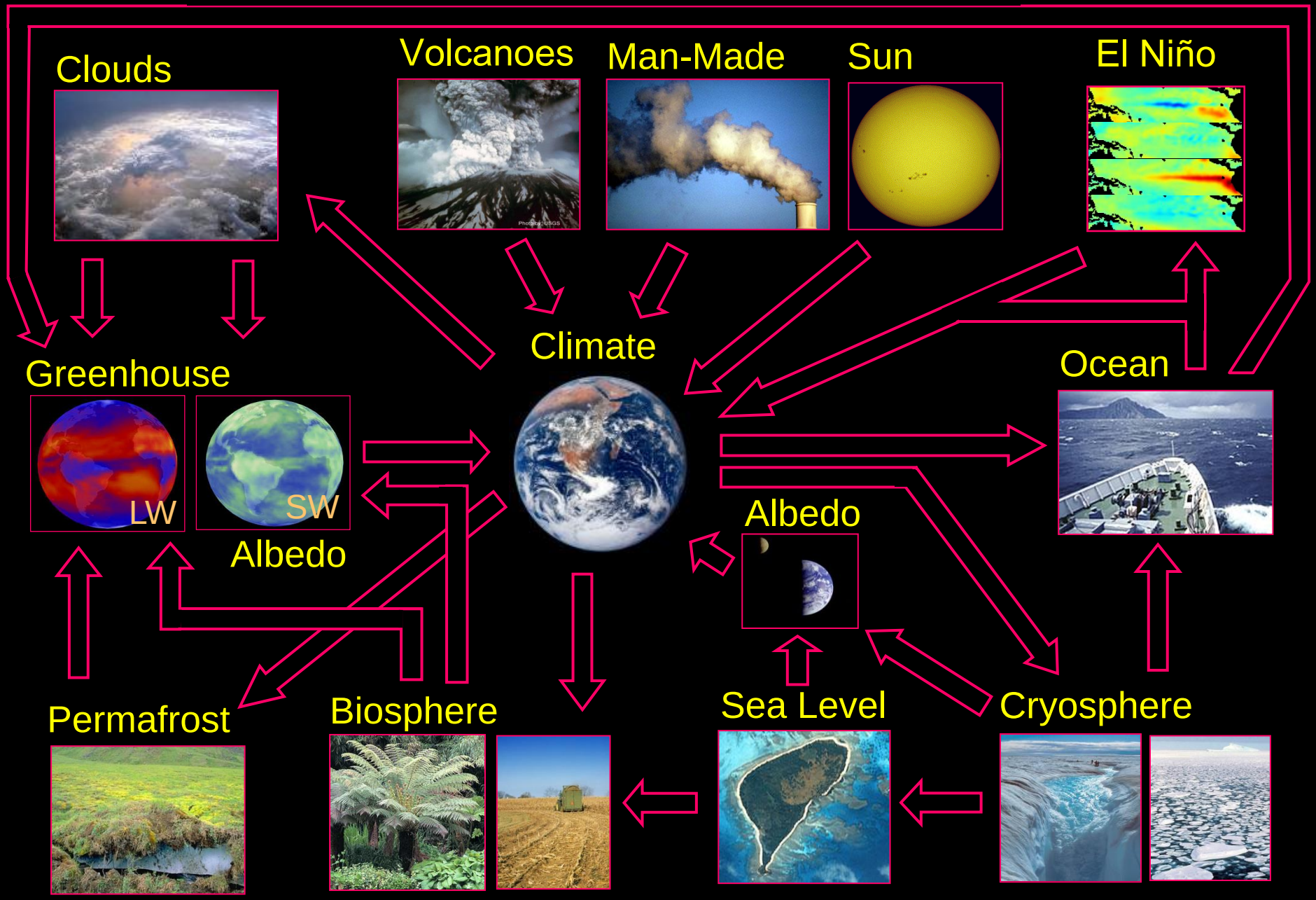
MODELLED AST MAP – for a GMAST rise of ΔT_S = +2ºC



OBSERVED AST MAP – NASA/GISS data for 1888-2008 (for which measured GMAST rise ≈ 1.1°C)



Climate System



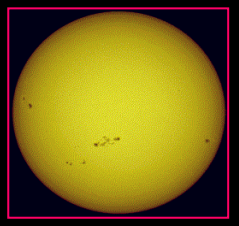
Are Climate Feedbacks Positive?

Clouds

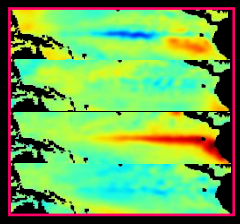
Volcanoes

Man-Made

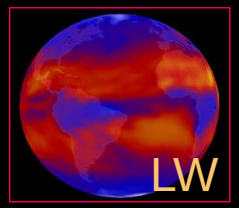
Sun

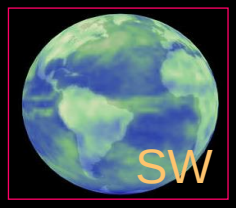


El Niño



Greenhouse





Albedo

Climate

Ocean

Albedo

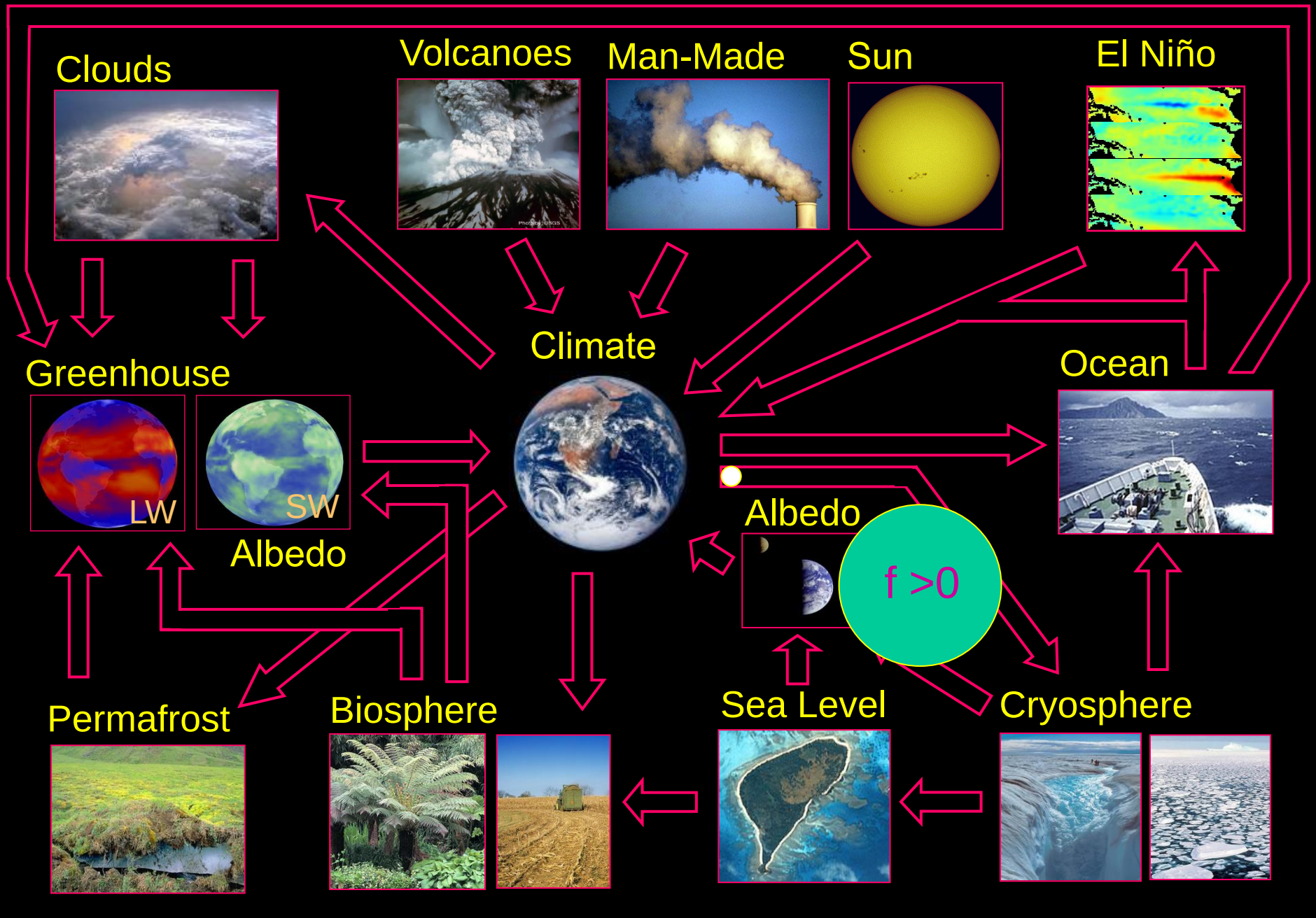
Permafrost

Biosphere

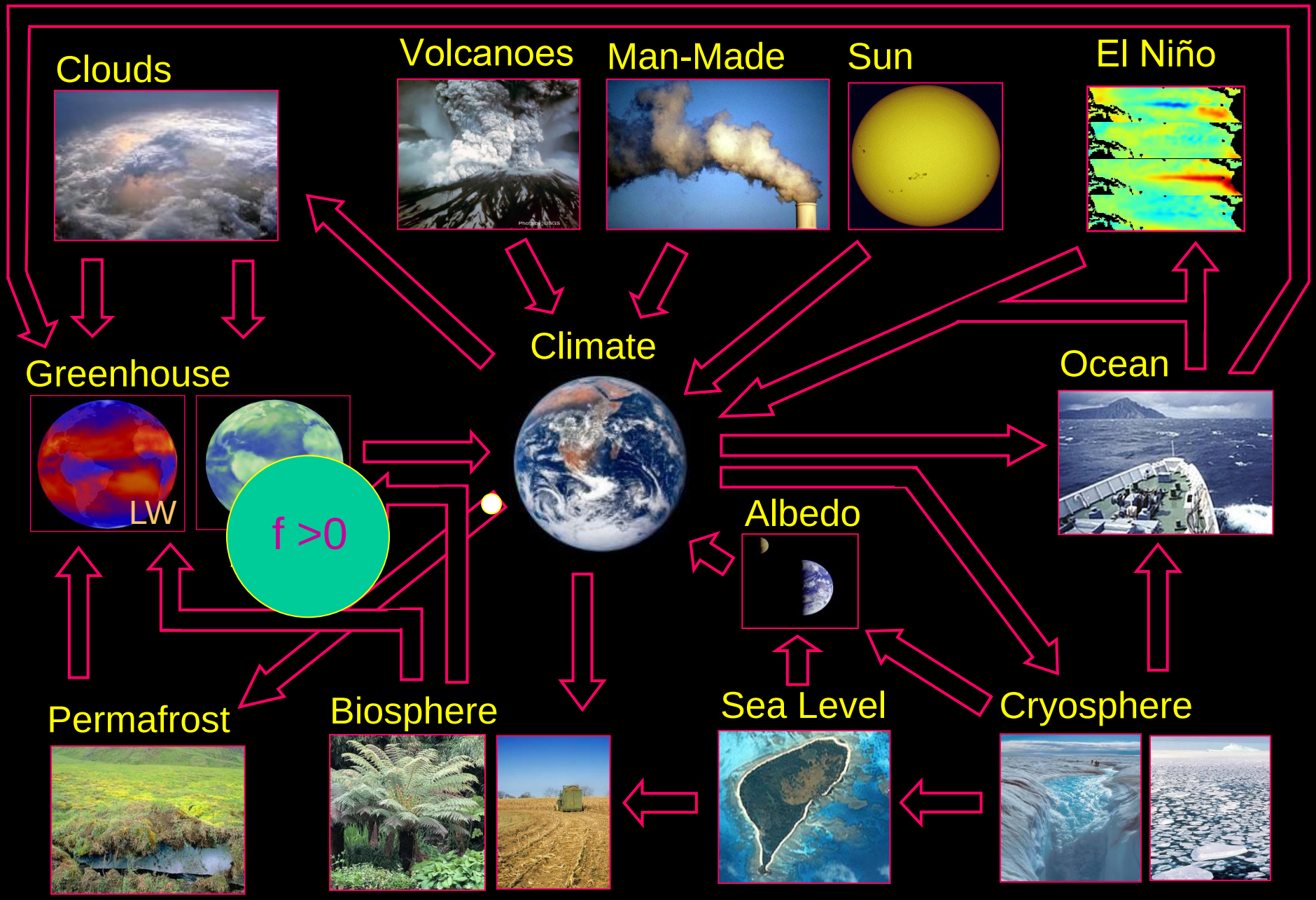
Sea Level

Cryosphere

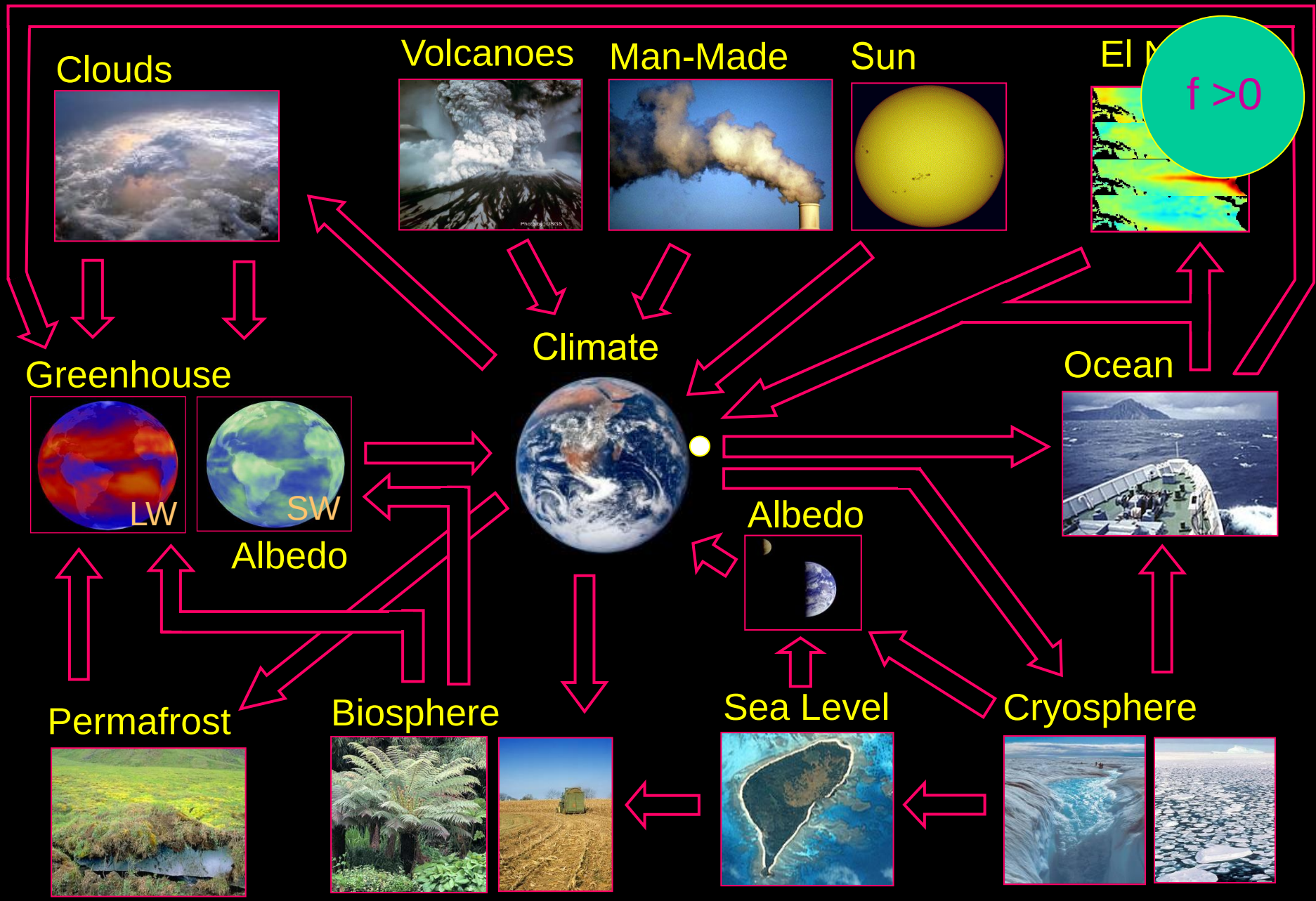
Climate Feedbacks: Loss of Sea and Land Ice



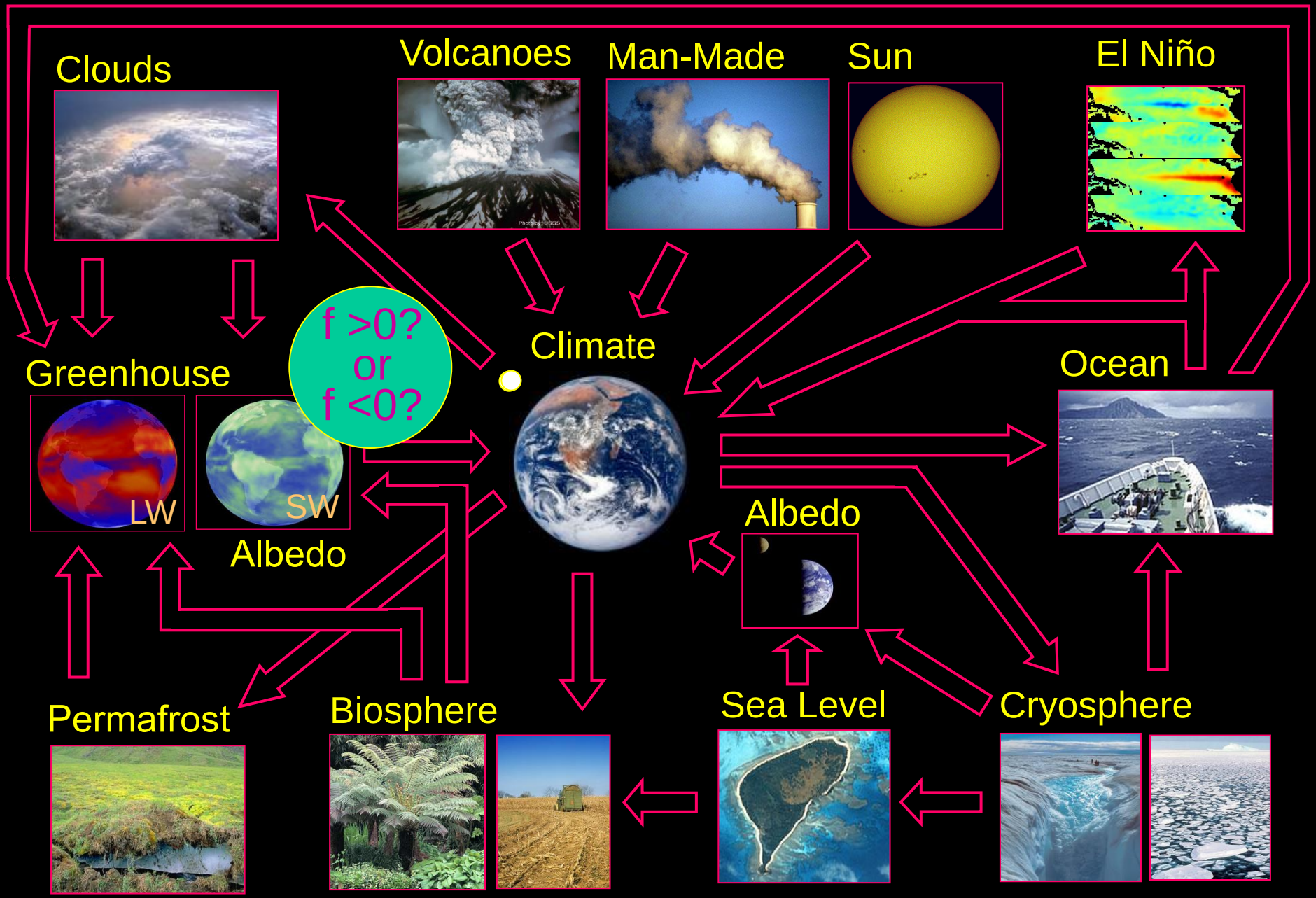
Climate Feedbacks: Melting Permafrost



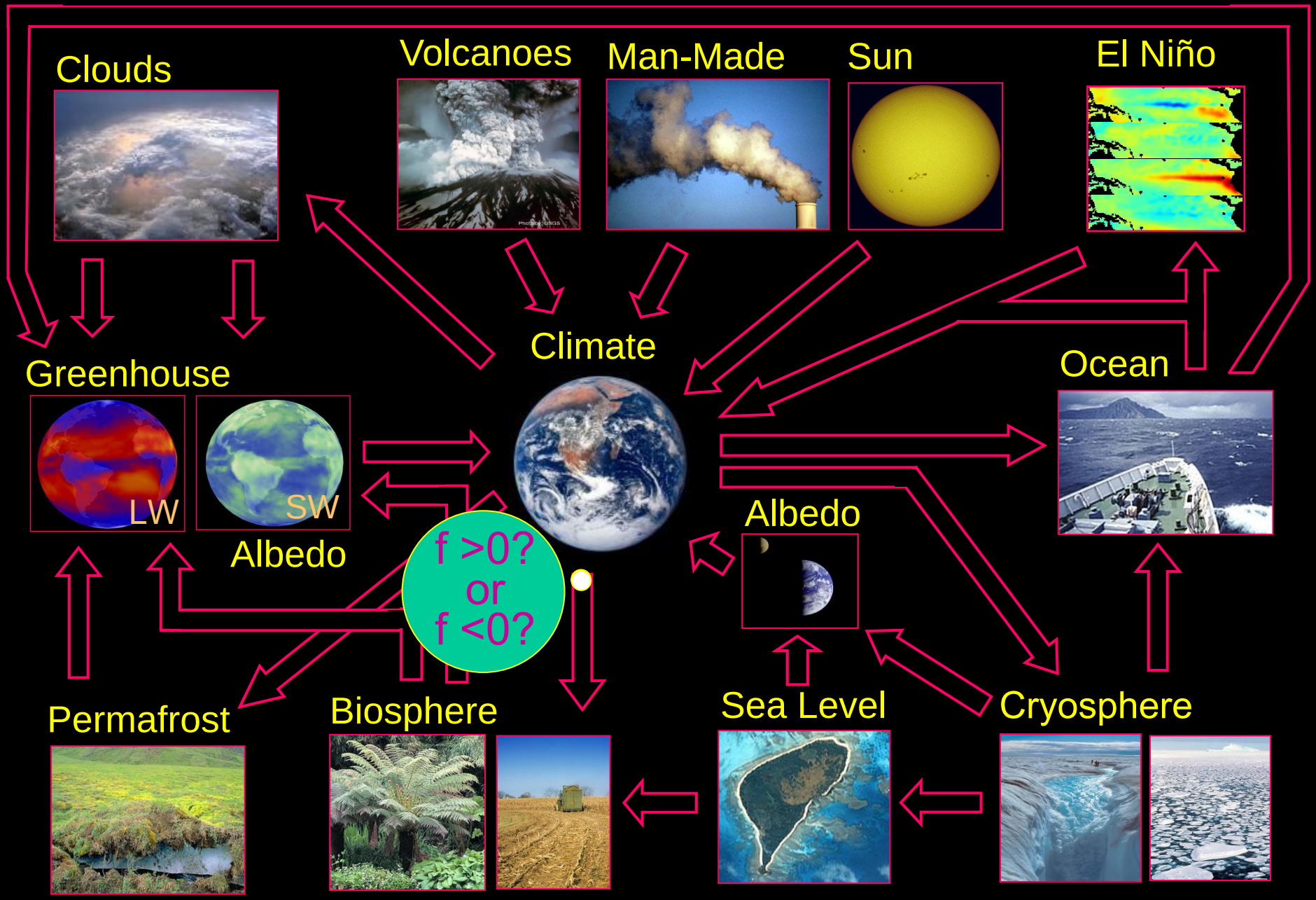
Climate Feedbacks: Warming Oceans



Climate Feedbacks: Clouds



Climate Feedbacks: Biosphere Response



Net f >0 ?

Effects vary with timescale

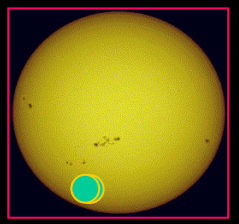
But models say yes

Clouds

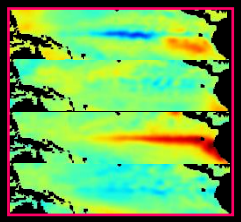
Volcanoes

Man-Made

Sun

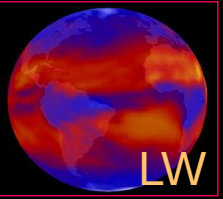


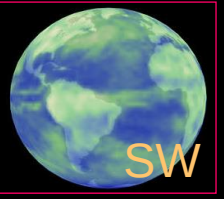
El Niño



Climate

Greenhouse





Albedo

Ocean

Albedo

Permafrost

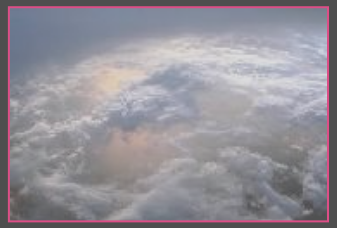
Biosphere

Sea Level

Cryosphere

Geological Effects

Clouds

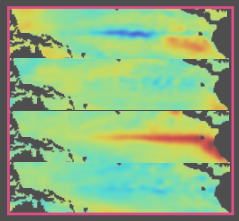


Volcanoes

Man-Made

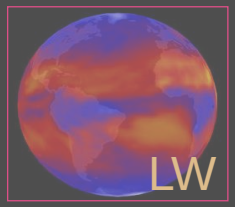
Sun

El Niño



Climate

Greenhouse



Albedo

Ocean

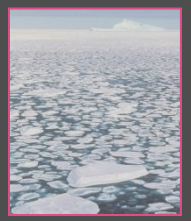
Albedo

Permafrost

Biosphere

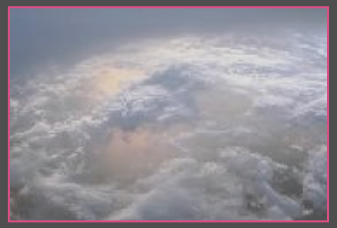
Sea Level

Cryosphere



Anthropogenic Effects

Clouds

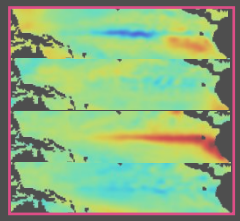


Volcanoes

Man-Made

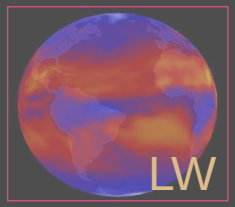
Sun

El Niño



Climate

Greenhouse



Albedo

Ocean

Albedo

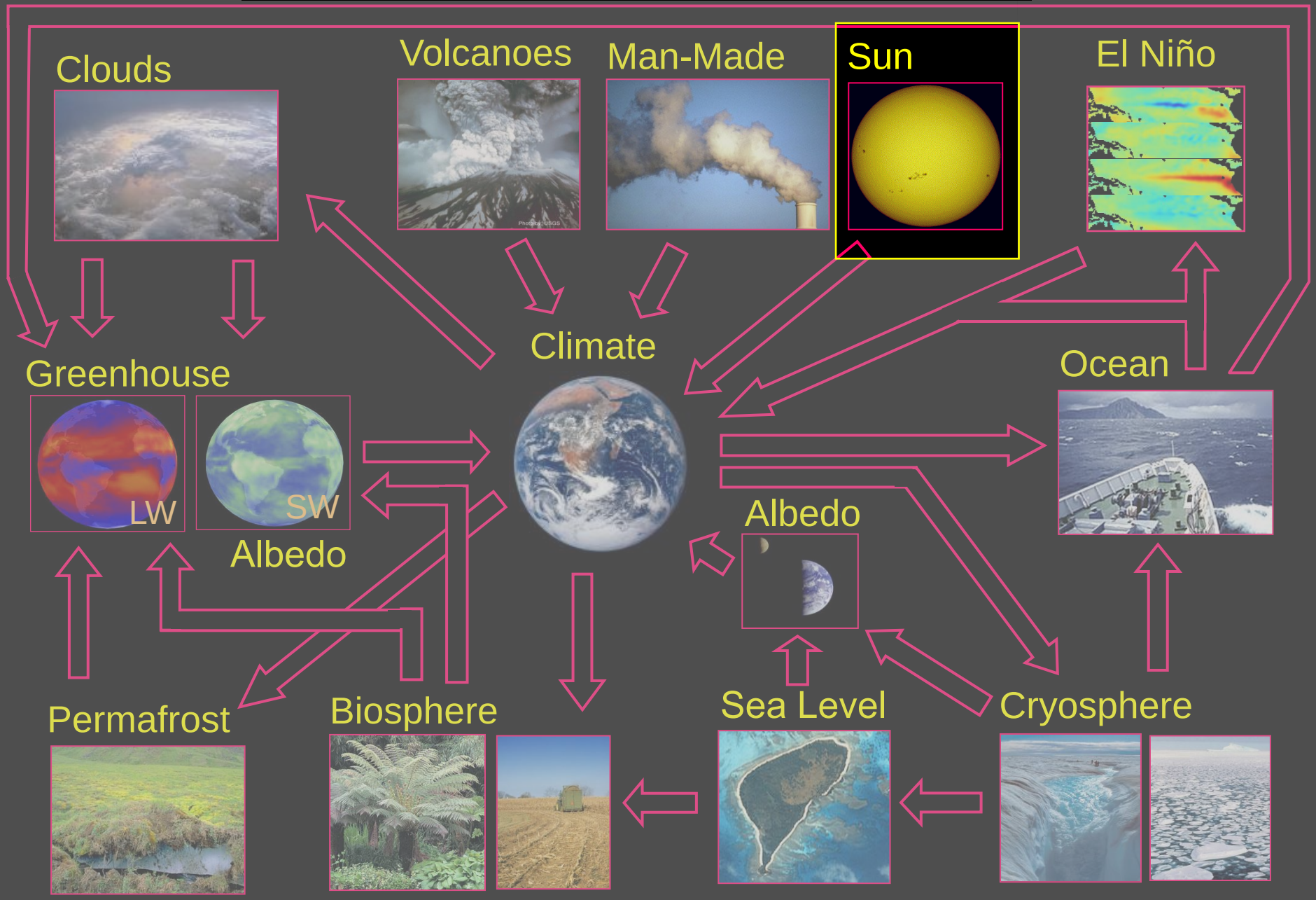
Permafrost

Biosphere

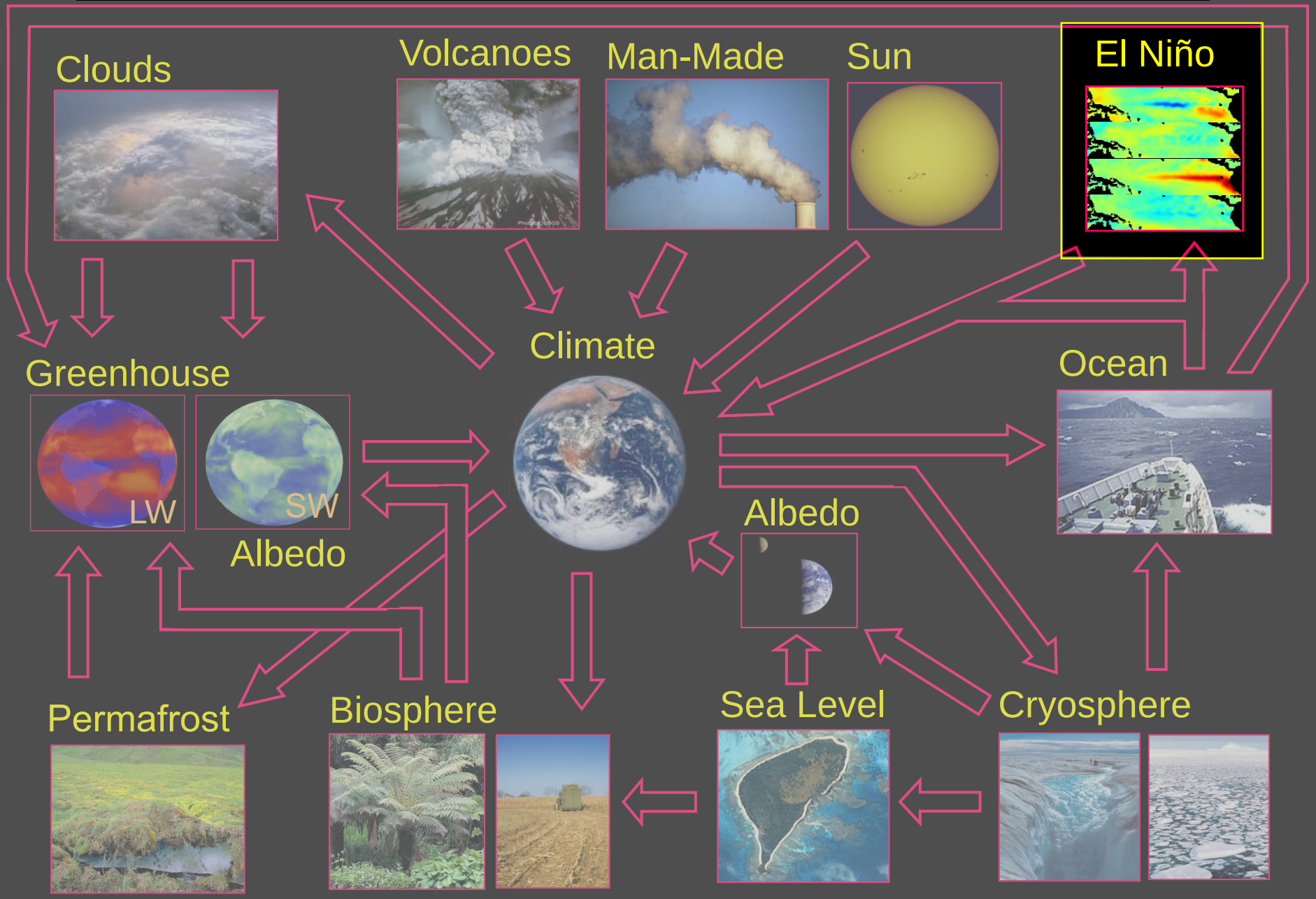
Sea Level

Cryosphere

Solar Influence



Short-Timescale Ocean Energy Exchange



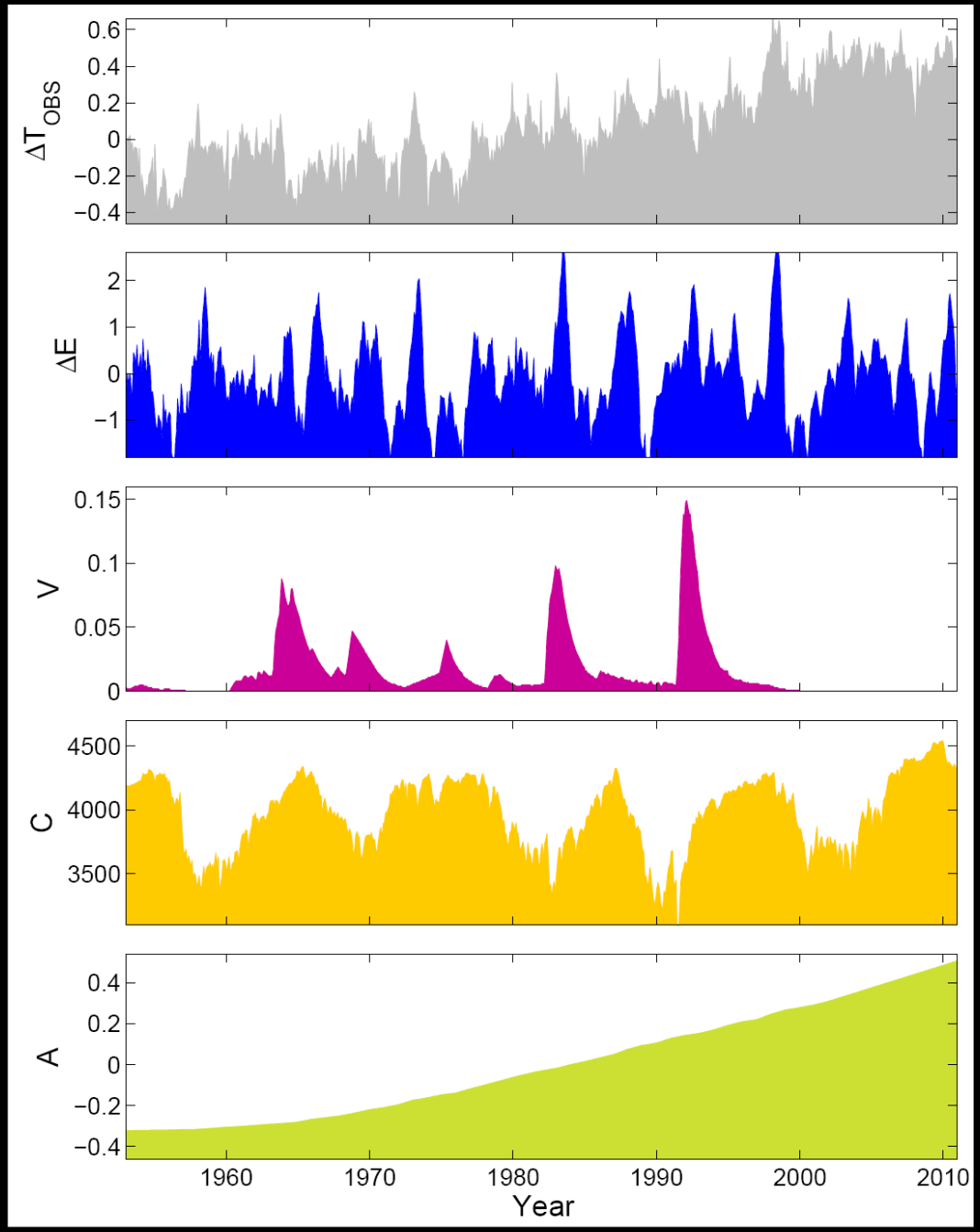
Observed Global Surface Air Temperature Anomaly, ΔT_{OBS}

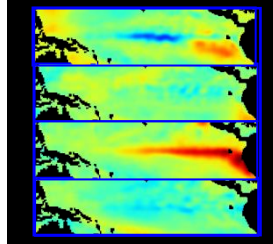
ENS0 N3.4 index Anomaly, ΔE

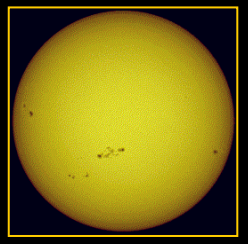
Mean Optical Depth (AOD) at 550 nm, V

Cosmic Ray Counts at Climax, C

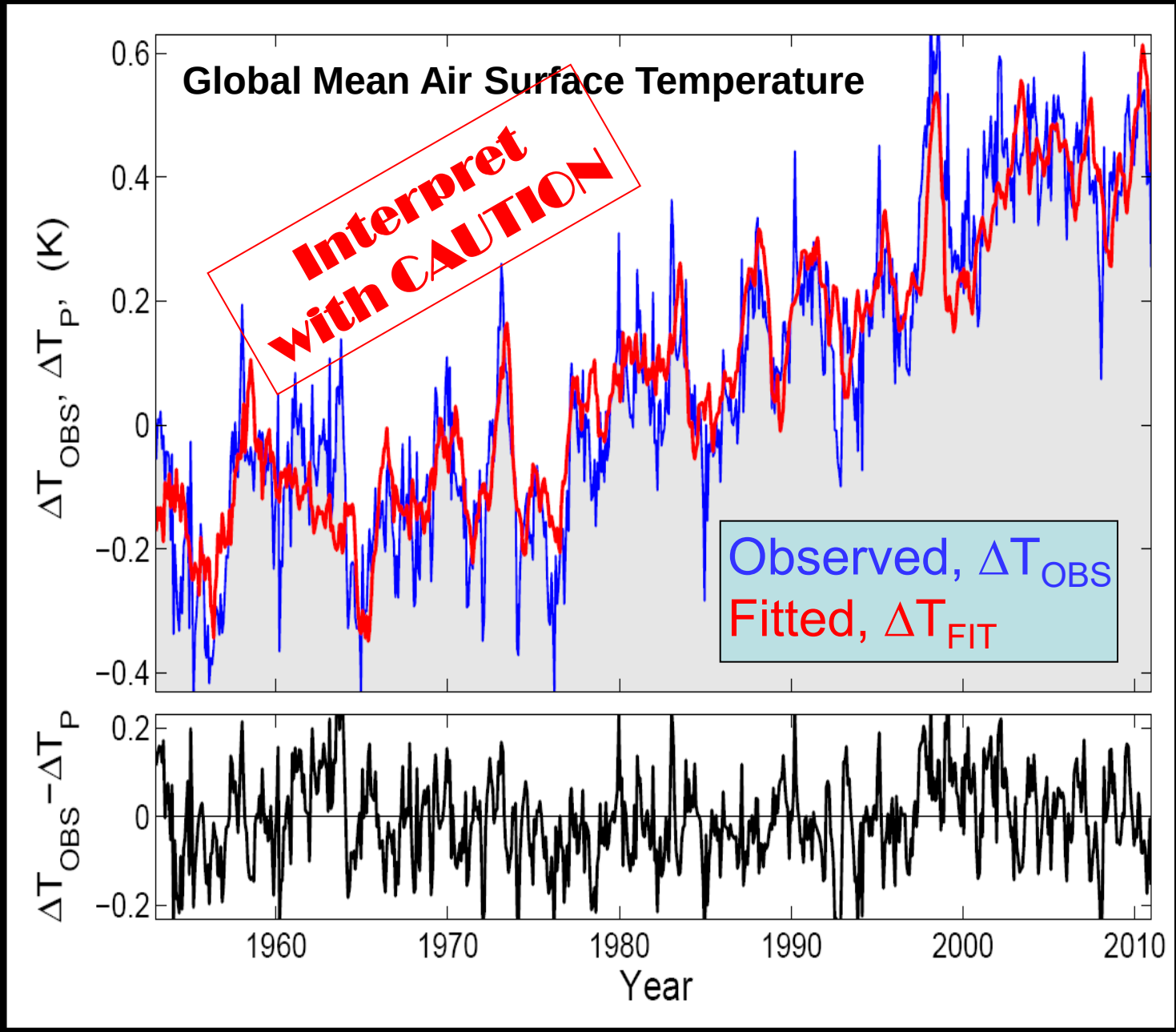
Anthropogenic forcing, A, (greenhouse gases, aerosols,& land use change)





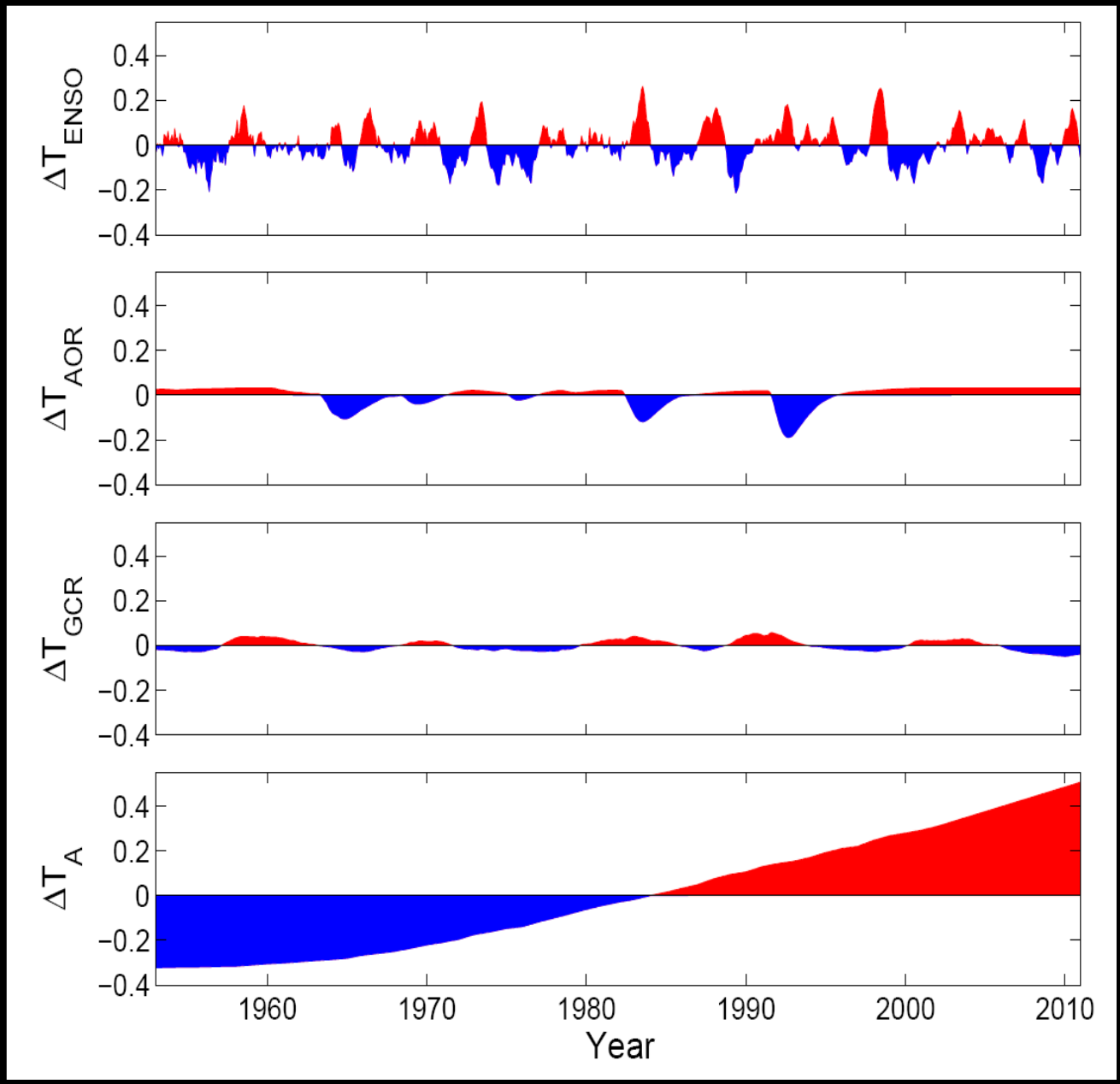


- fit to observed GMAST anomaly obtained using the Nelder-Mead simplex (direct search) method

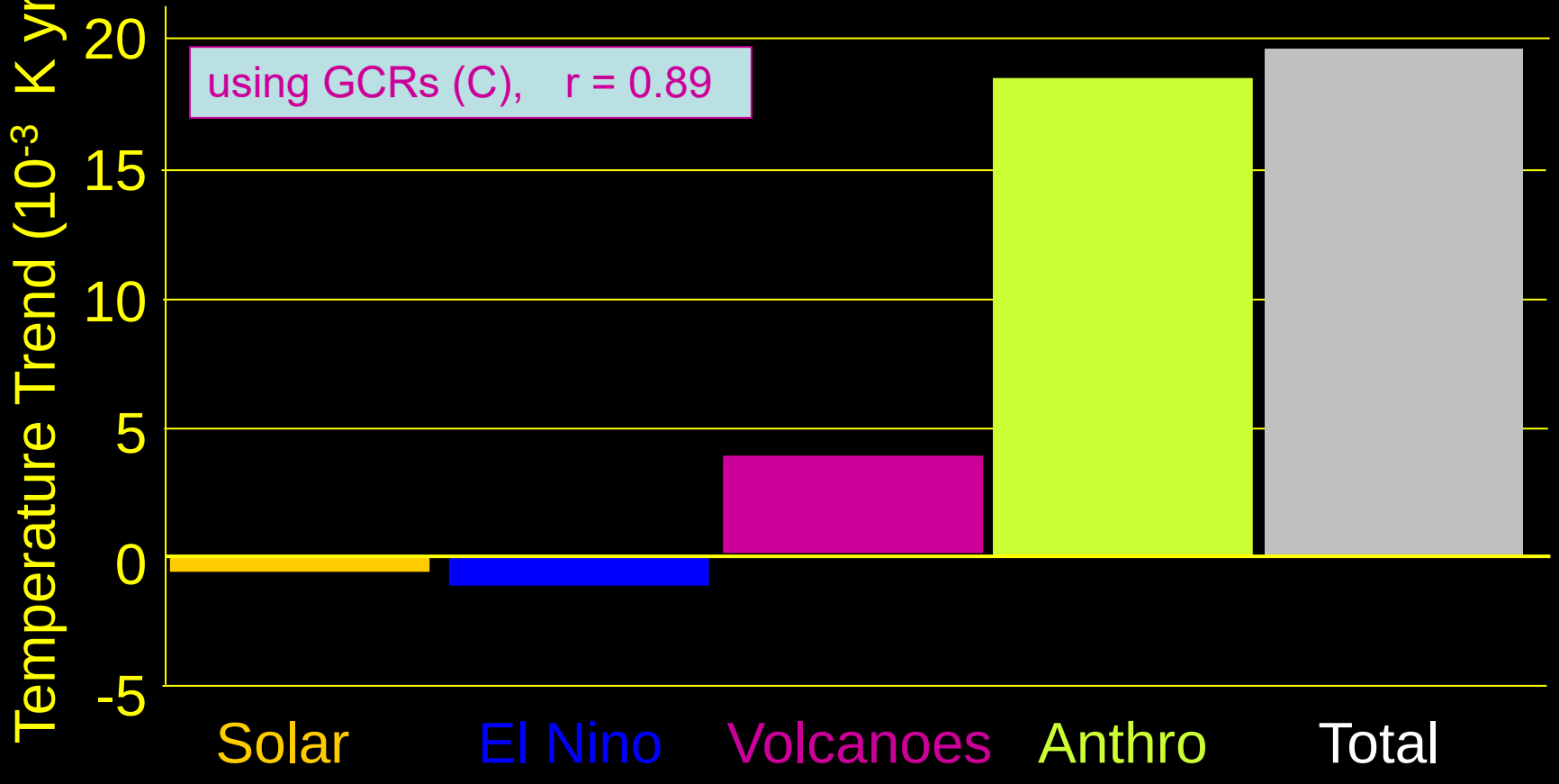


(Lockwood, 2008)

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



(updated from Lockwood, 2008)



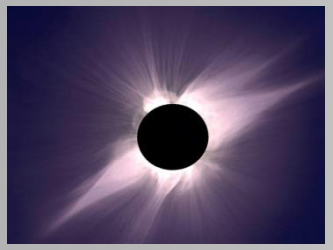
1987-present

(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.

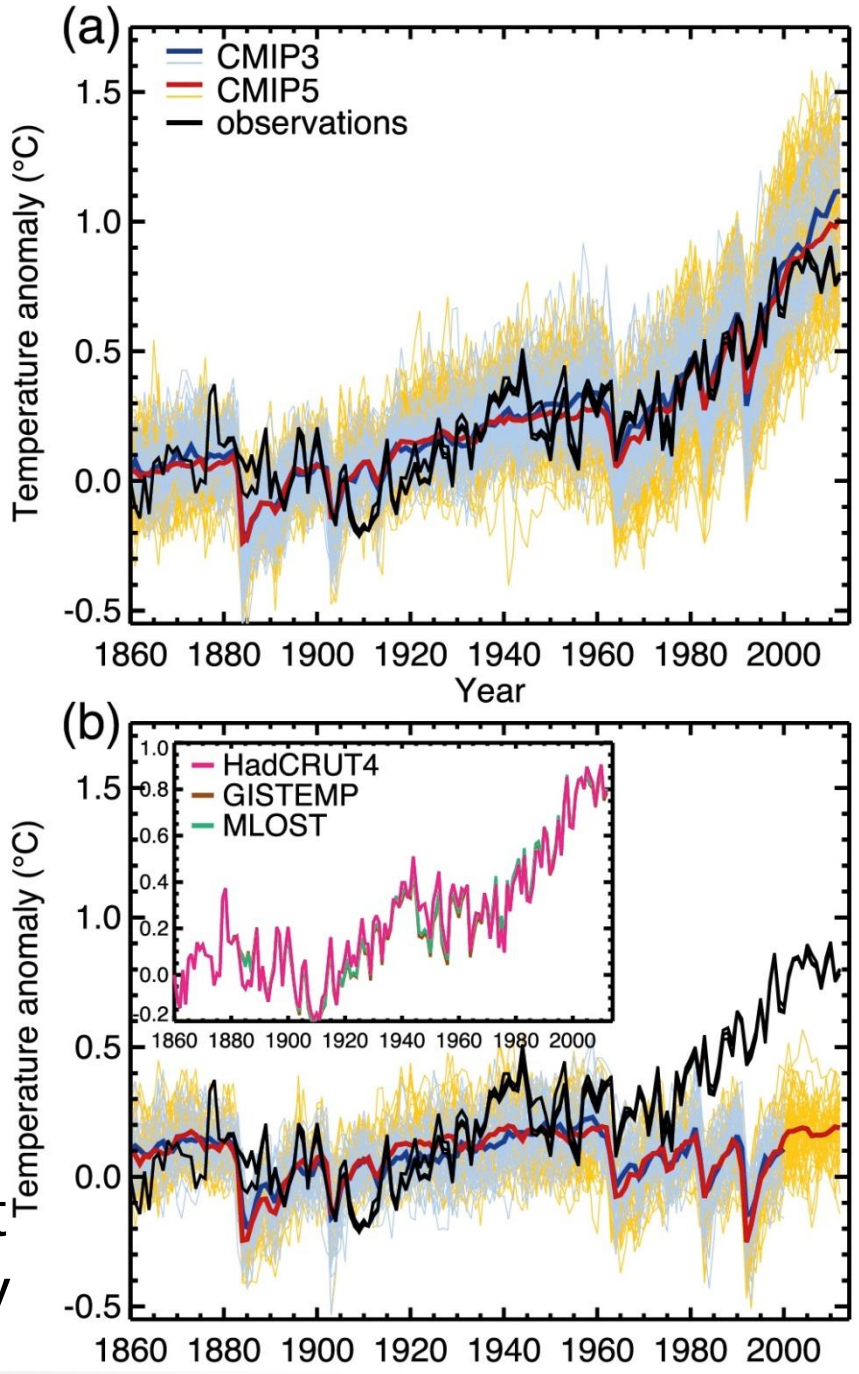
[1] e.g. Knutti et al. (2006) *J. Climate*, DOI: 10.1175/JCLI3865.1

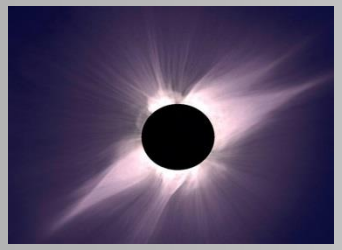
[2] e.g. Knape and de Valpine (2011) *Proc. Roy. Soc. London B,* DOI: 10.1098/rspb.2010.1333



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

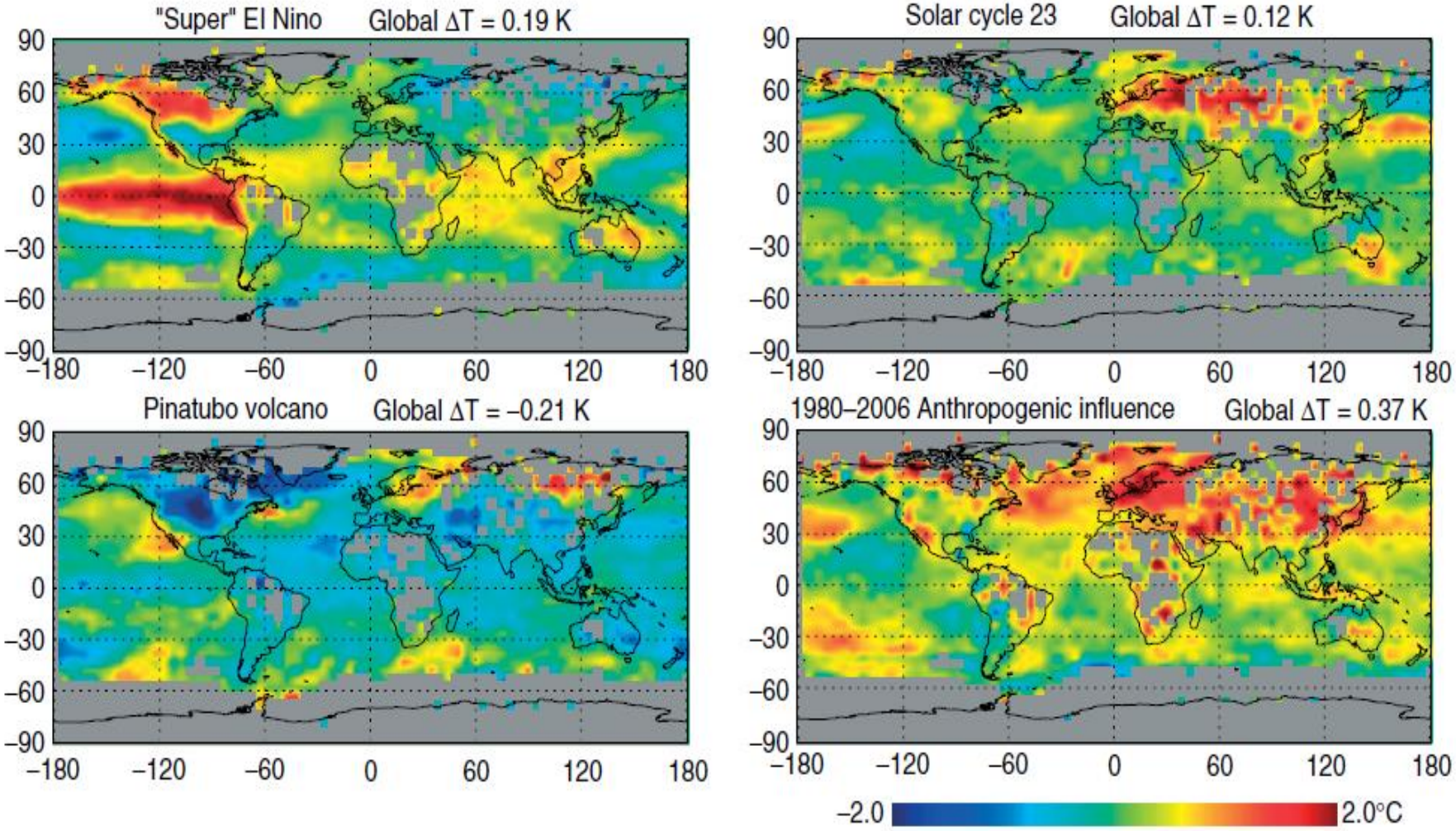




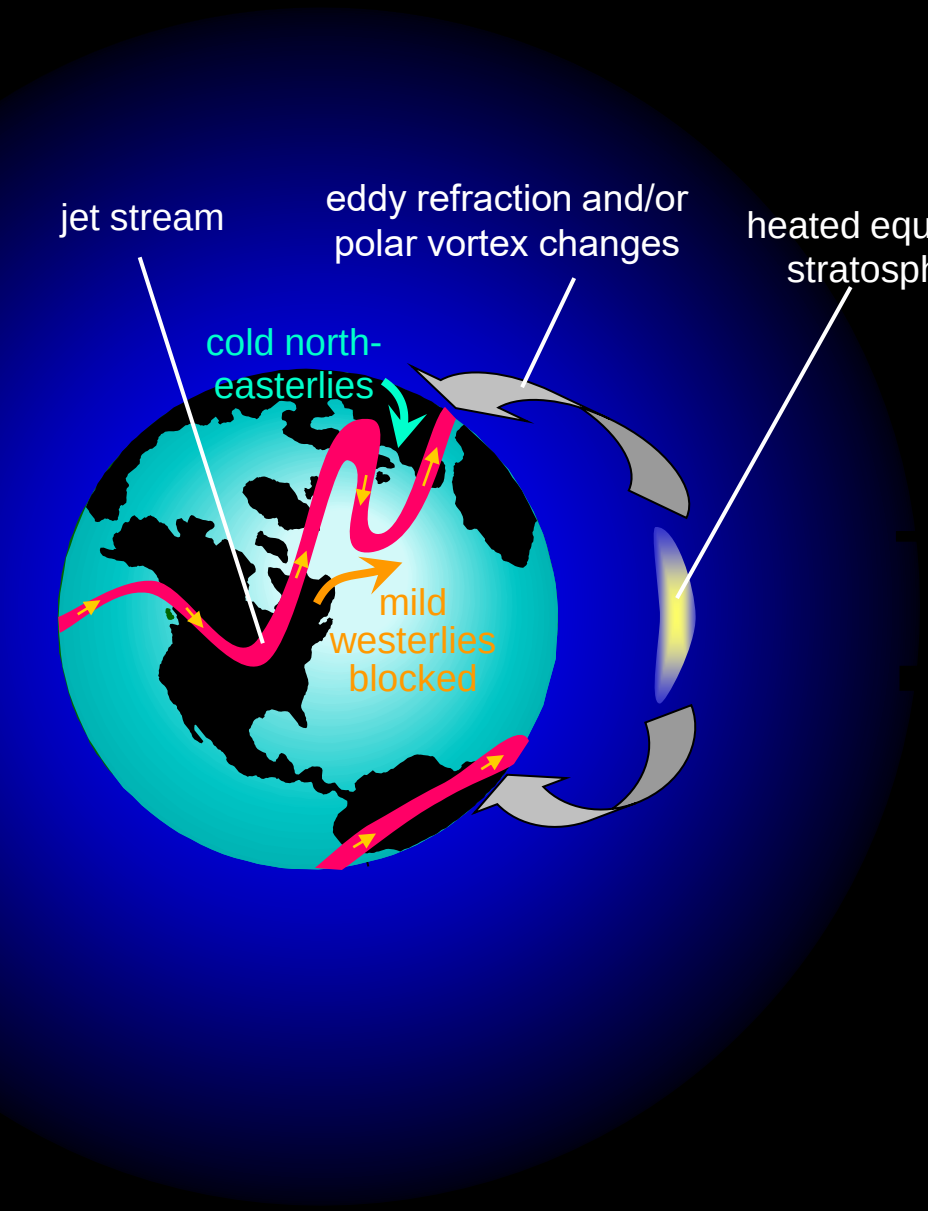
But …..Regional Analysis ?

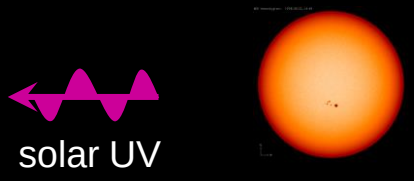
(Lean and Rind, 2008)

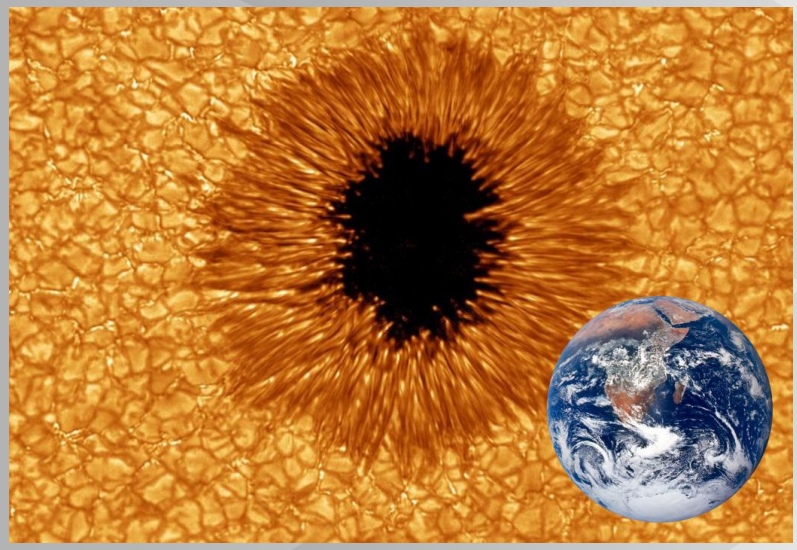
interesting !



“Top-down” Solar Modulation







Sun and climate: key questions

University of Reading

Do solar outputs vary?

Yes ✓

Do we know how they have varied over the last 150 years? ✗

Not really – we have models with assumptions

Do we know how solar outputs affect Earth's atmosphere? ✓

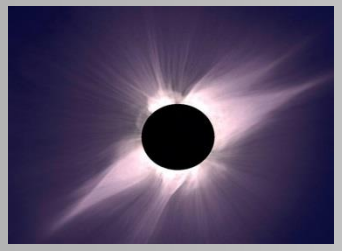
Mainly Yes – unsure about energetic particles

Is there evidence the Sun has played a role in climate? ✗ ✓

Global climate : no – regional climate : yes

Is there evidence for anthropgenic global warming? ✓

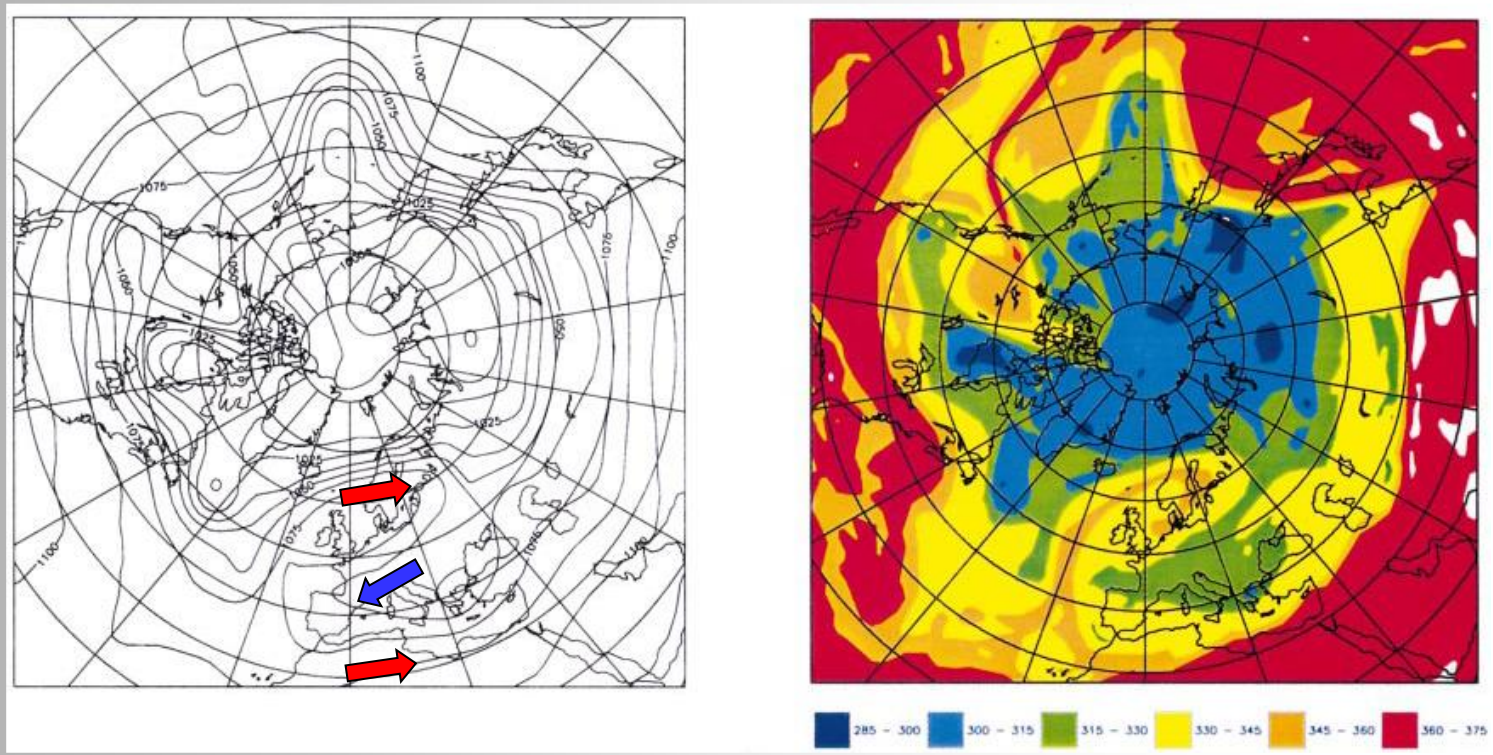
overwhelmingly Yes



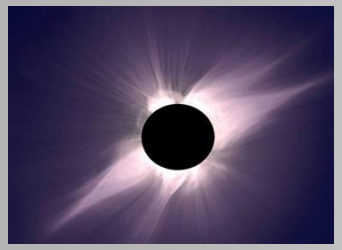
Atlantic blocking events

(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

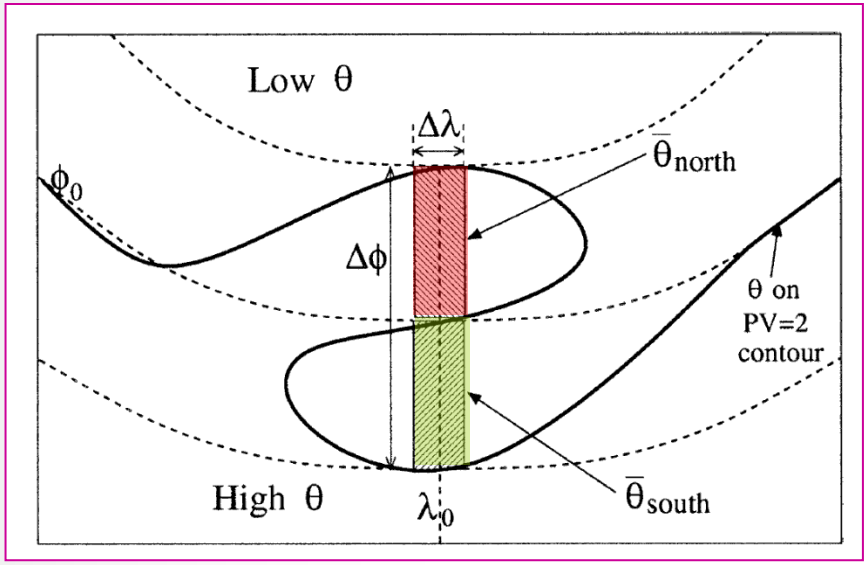


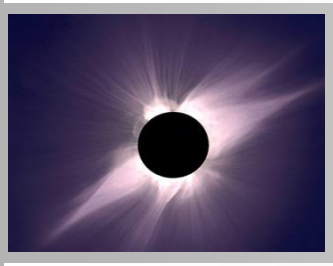
Example at 12UT, 21 Sept, 1998: on the potential vorticity PV=2 surface
(a) 250-hPa geopotential height (b) potential temperature θ (K)



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

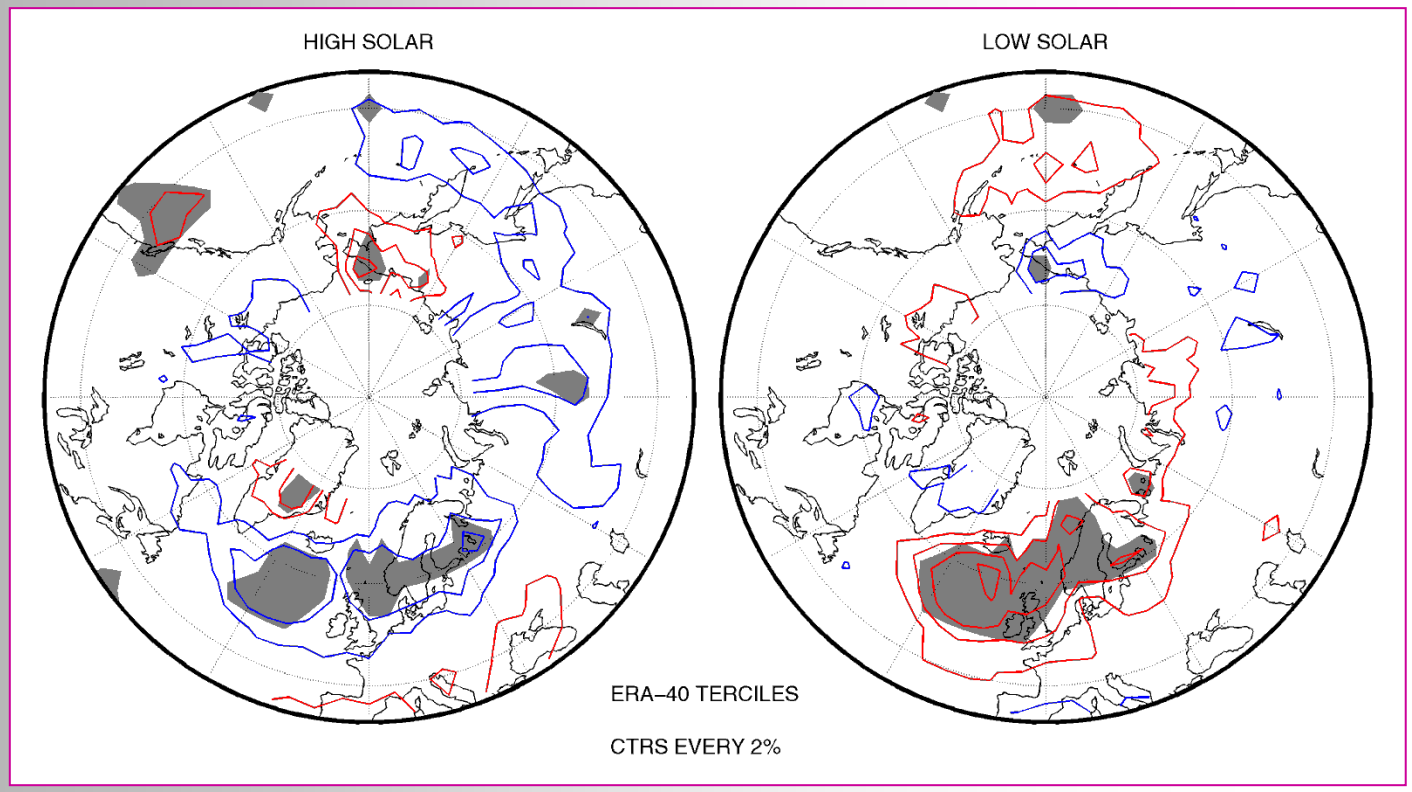




ERA-40 Analysis of Blocking Index

(change of terciles relative to whole set)

(Woollings et al, GRL.,2010)

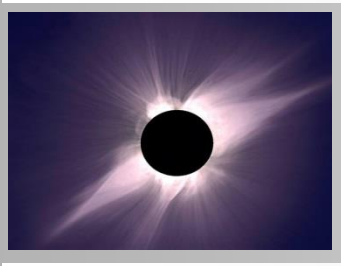


- sorted using open solar flux F_S

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

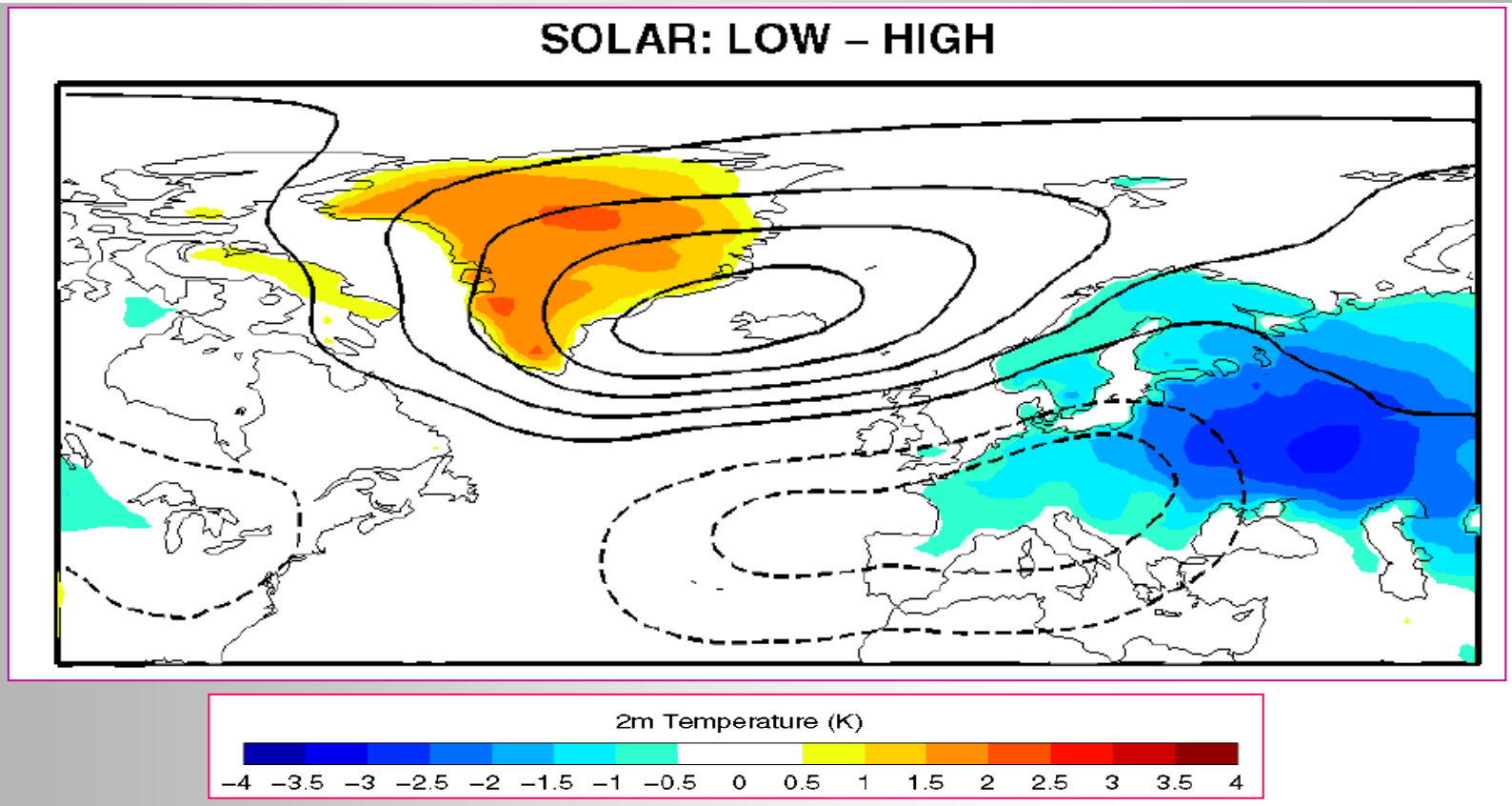
Consistent and localised effect

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



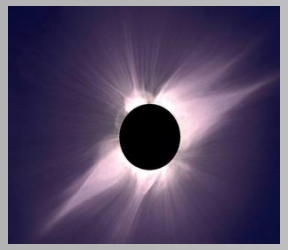
ERA-40 Analysis of DJF temperatures & circulation (difference of high and low tercile subsets)

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



- sorted using open solar flux F_S

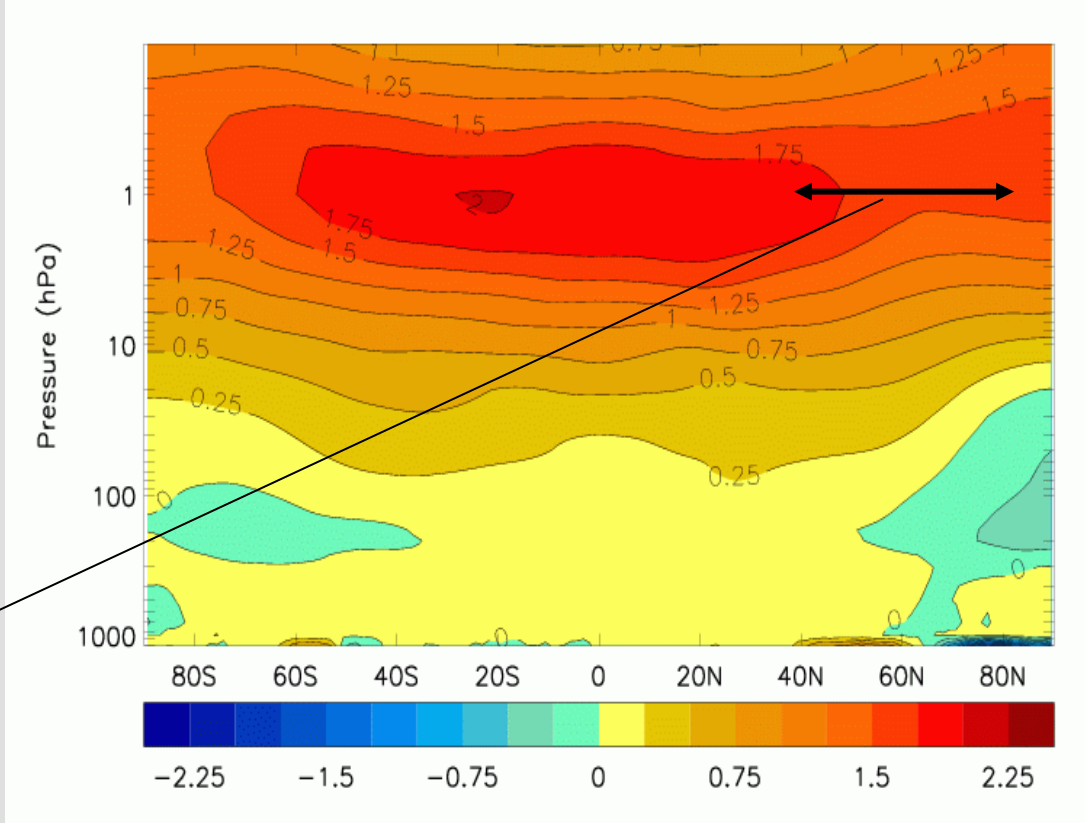
Low solar activity gives lower surface temperatures in central England
Effect much stronger in central Europe
Analysis shows a distinct system to NAO

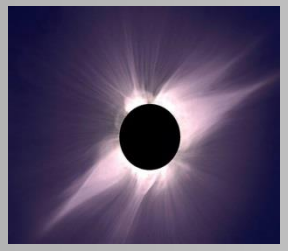


Modelled solar maximum-solar minimum temperatures

(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 $\rightarrow$increase in westerly flow

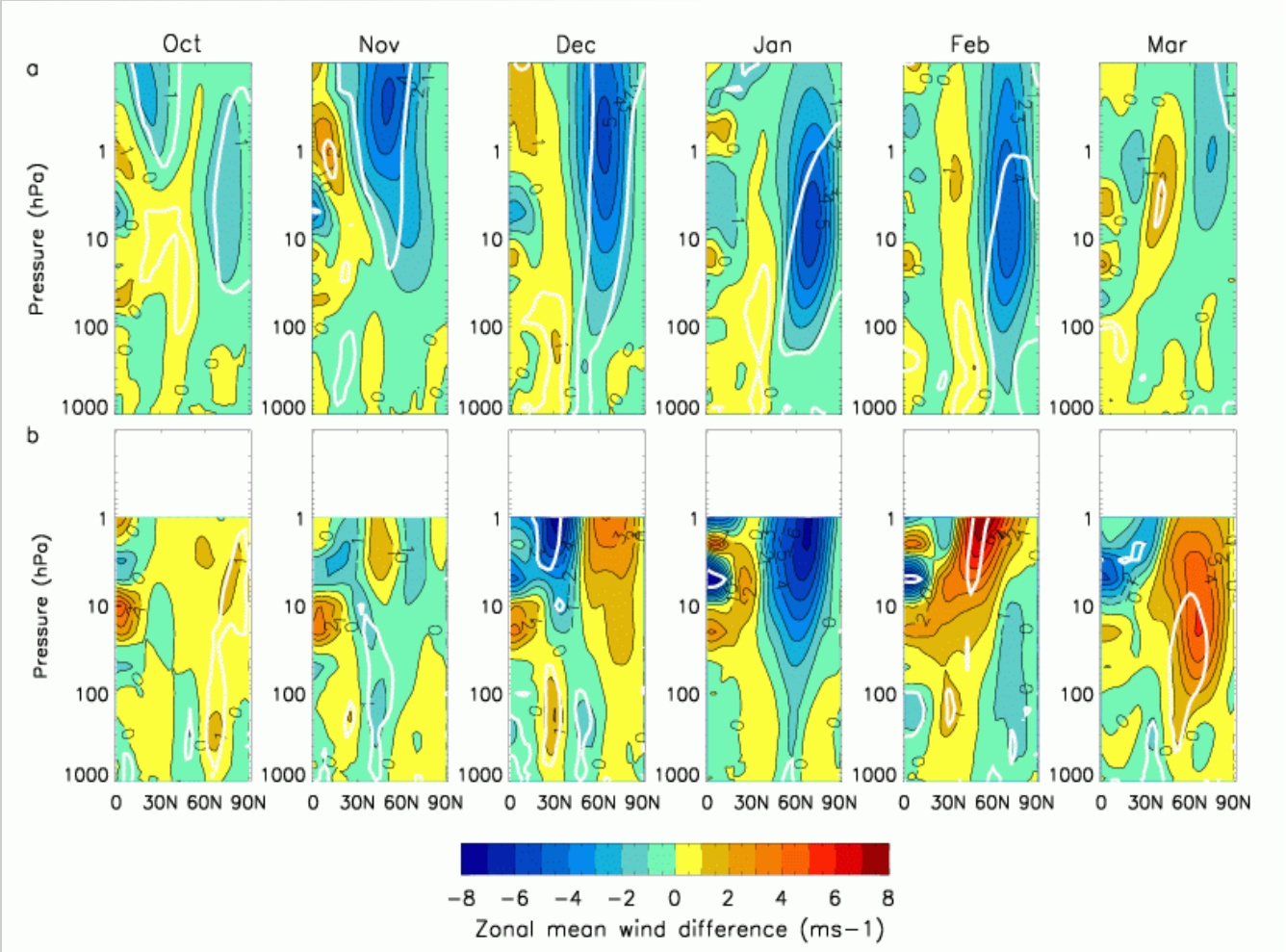




Modelled solar maximum-solar minimum zonal wind speed

(Ineson et al, Nature Geosci., 2011)

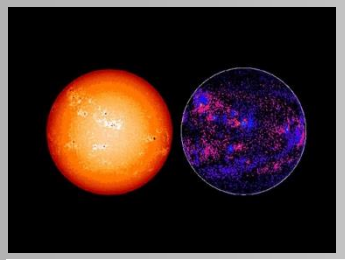
- Modelled downward and northward propagation of easterly wind anomaly (by Eliassen-Palm flux divergence)
- seen in ERA40+ data
- c.f. Kodera and Kuroda, 2002; Matthes et al.,2006



In summary

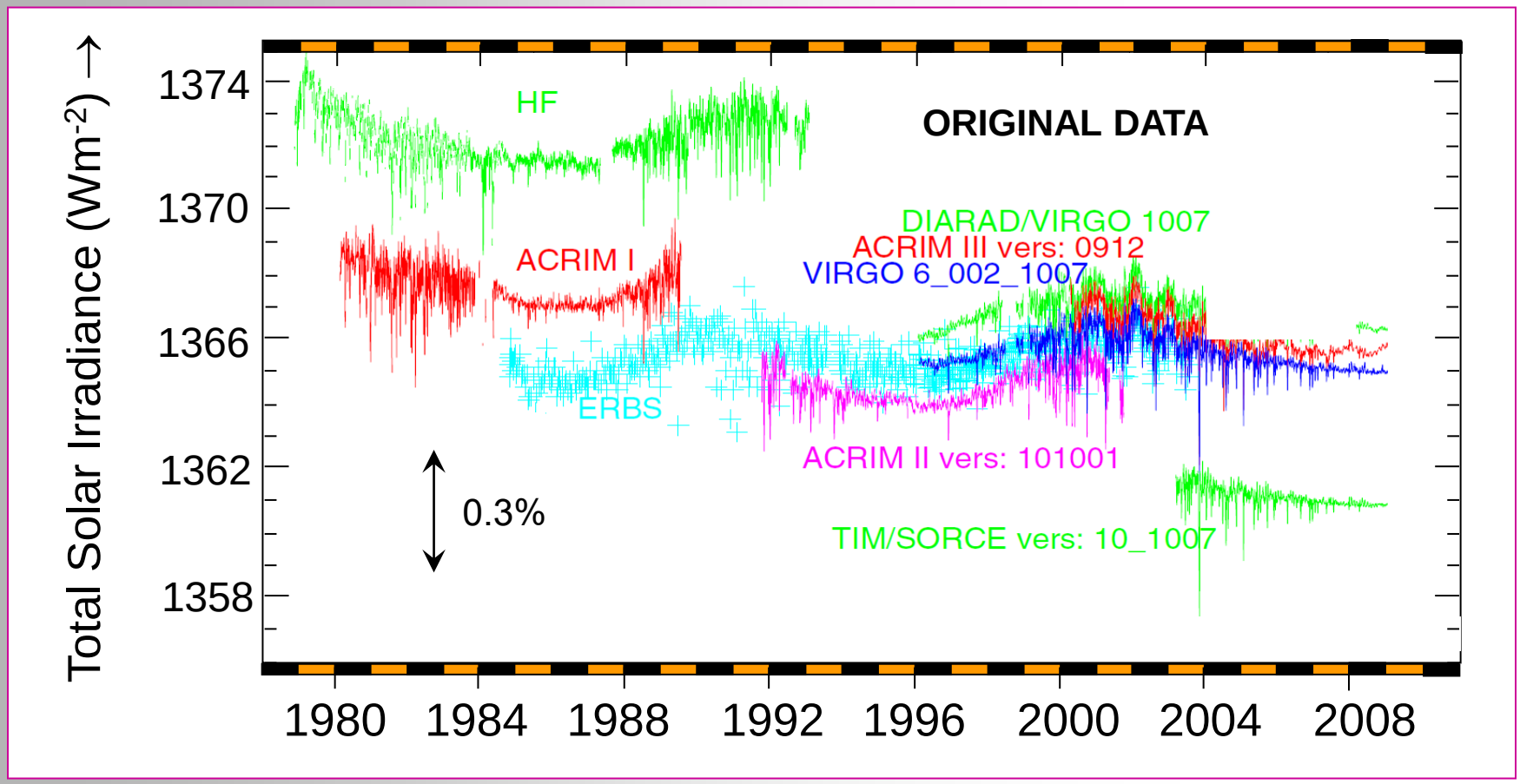
- consensus arrived at through peer review is how science makes progress
- is there consensus that CO_2 is the main driver of climate change? ☑ *yes*
- is the greenhouse effect real? ☑ *yes (good job too!)*
- has the global mean surface air temperature risen? ☑ *yes*
- has CO_2 in the atmosphere risen? ☑ *yes*
- does the extra CO_2 come from fossil fuel burning? ☑ *yes*
- is the CO_2 effect "saturated"? ☒ *no !!!*
- are the ice sheets melting? ☑ *yes*
- are sea levels rising ☑ *yes*
- is the stratosphere cooling? ☑ *yes*
- is total solar irradiance variability a viable explanation? ☒ *no*
- is solar activity a major contributor globally? ☒ *it doesn't fit the data*
- …and for regional climate? ☐ *some evidence, e.g. European winters*
- are the oceans warming (and acidifying)? ☑ *yes*
- are the deep oceans warming? ☐ *don't know yet*
- does deep ocean warming matter? ☑ *for sea level rise*
- do we know what it all will mean for global circulation patterns? ☒ *not yet*

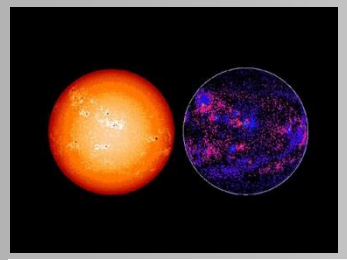
Thank you for listening!



Total Solar Irradiance Observations

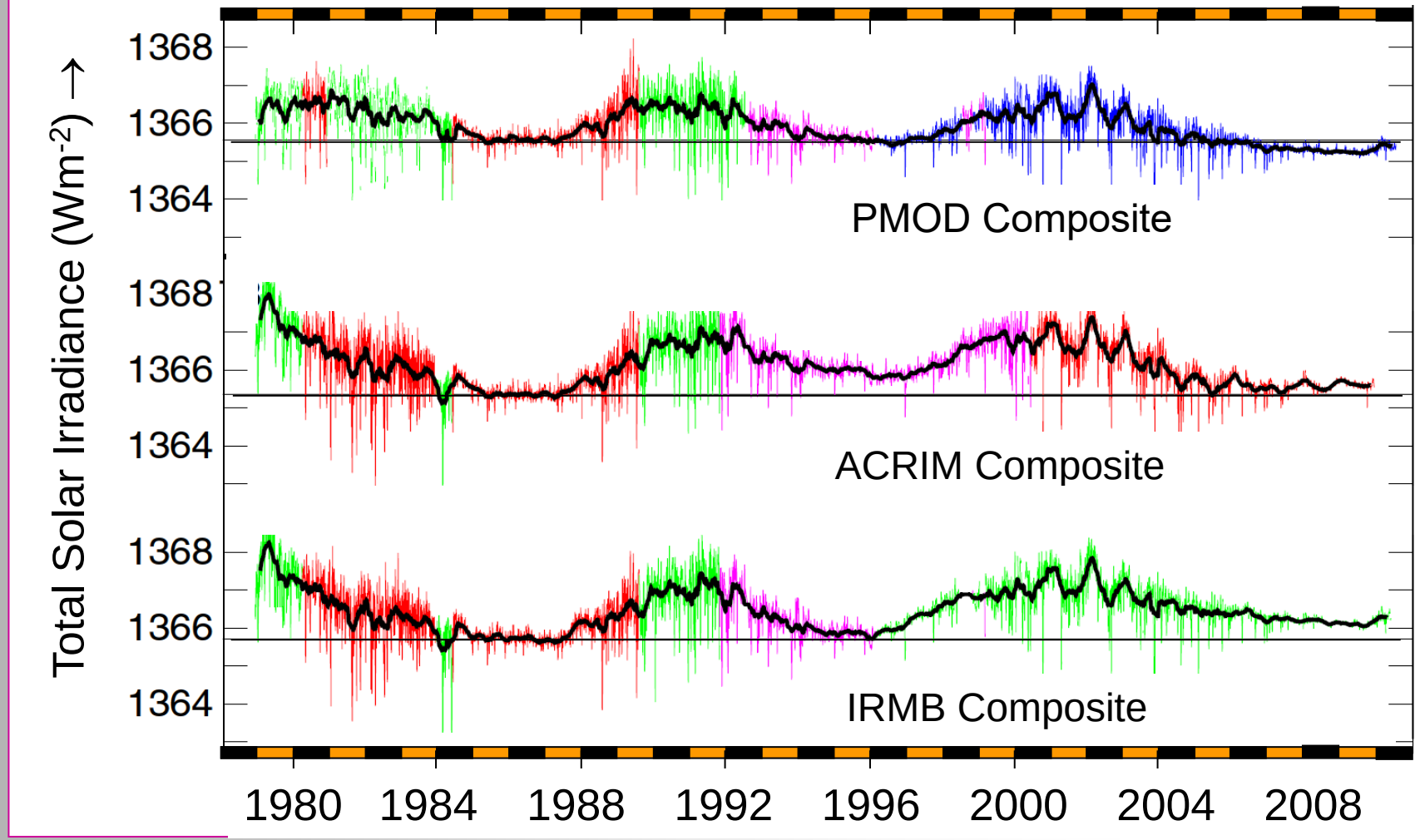
Systematic errors and drifts due to instrument degradation

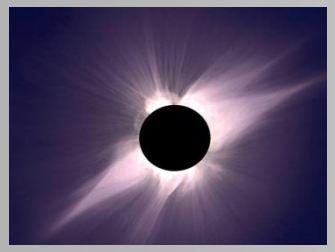




Solar Irradiance Composites

Errors and drifts corrected by intercalibration



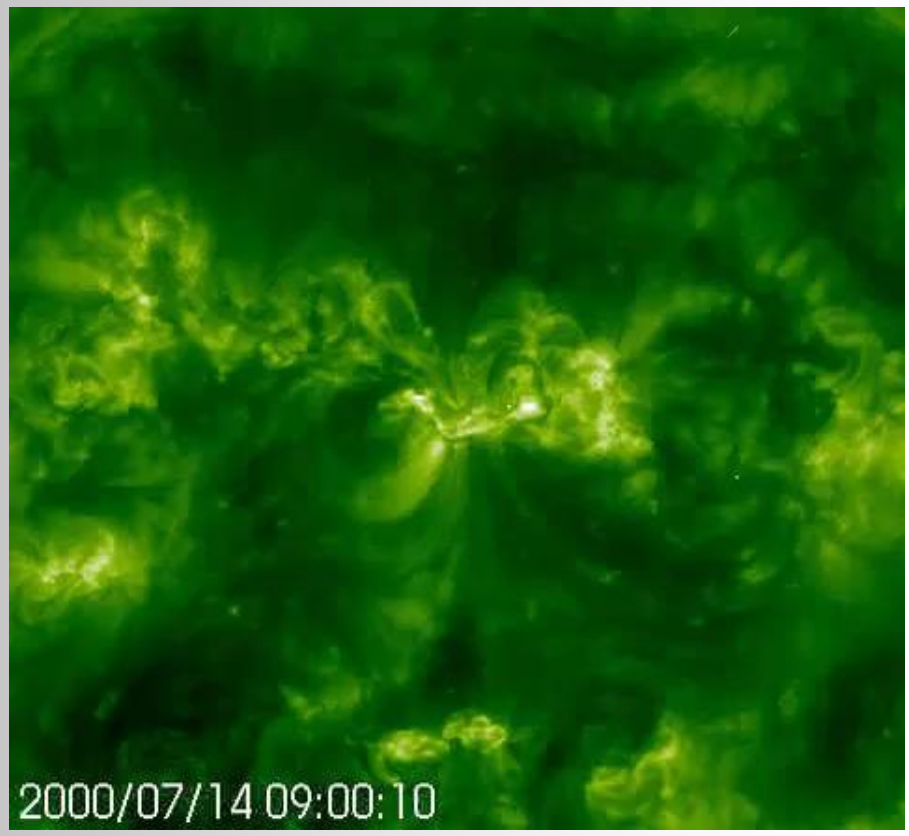


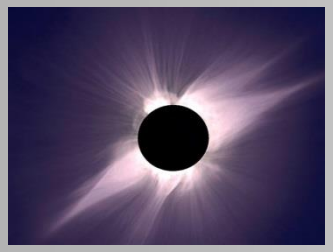
The Bastille Day Storm

Flare and SEPs

Solar Terrestrial Physics
Summer School

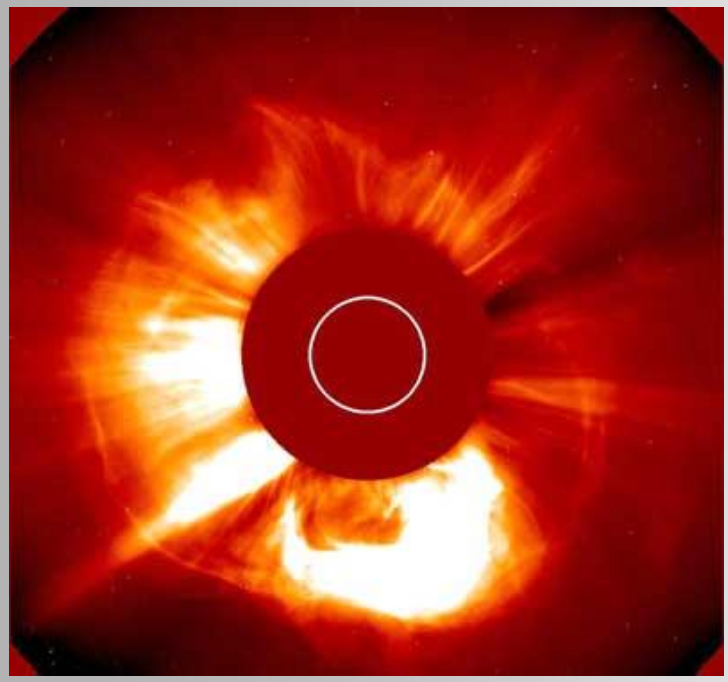
- CME hit Earth on 14th July 2000
- Start of the Story: the associated flare

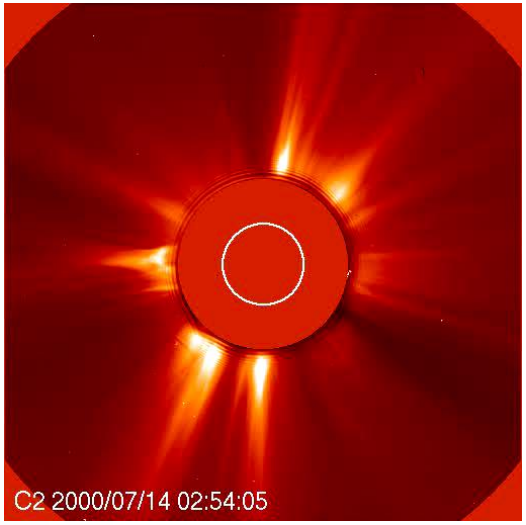




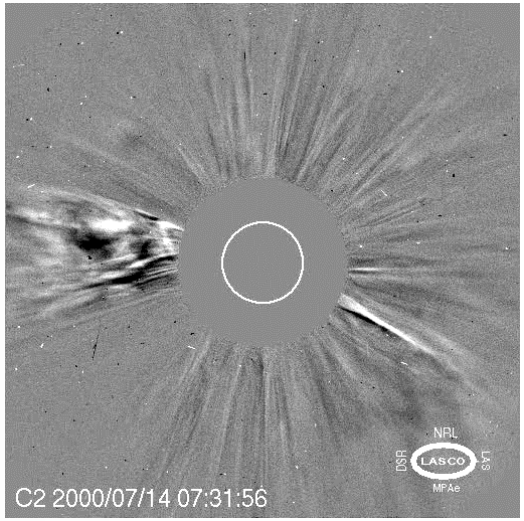
The Bastille Day Storm CME

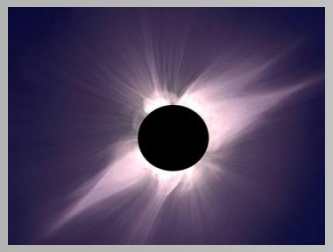
seen by SoHO/Lasco C2 and C3 Coronographs





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

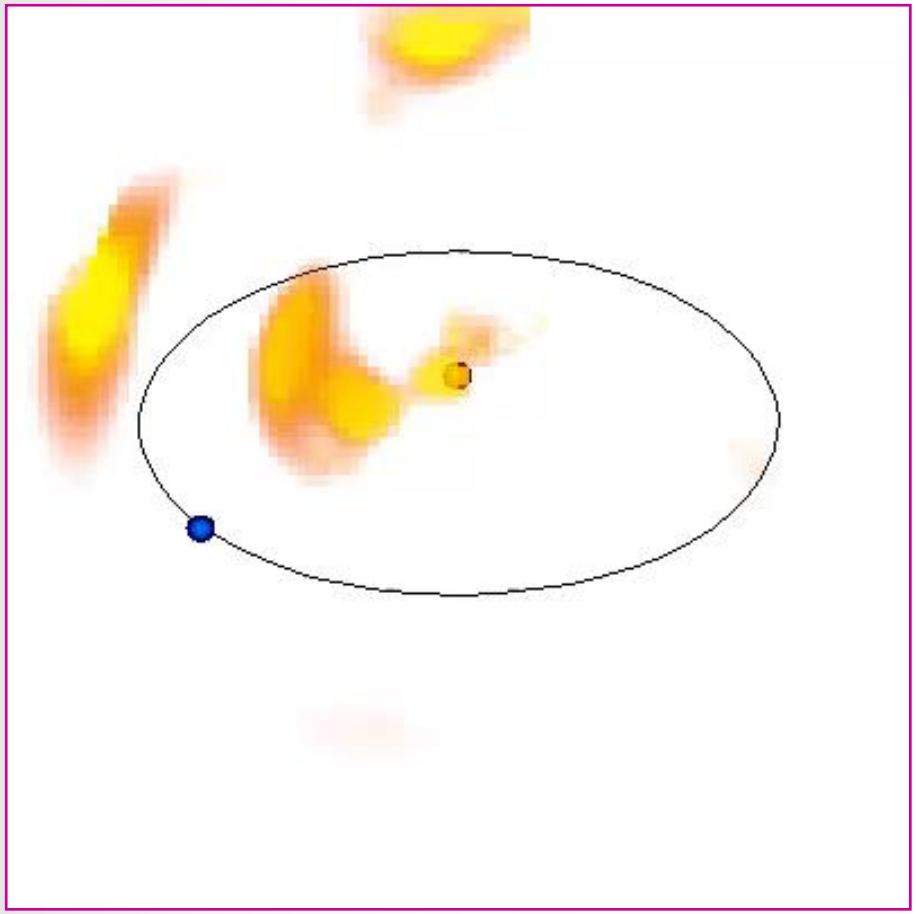


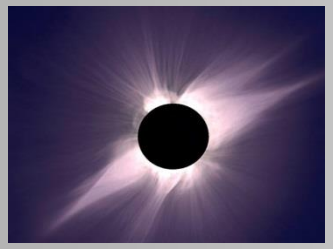


The Bastille Day Storm

CMEs seen by IPS

- Tomographic reconstruction from interplanetary scintillations



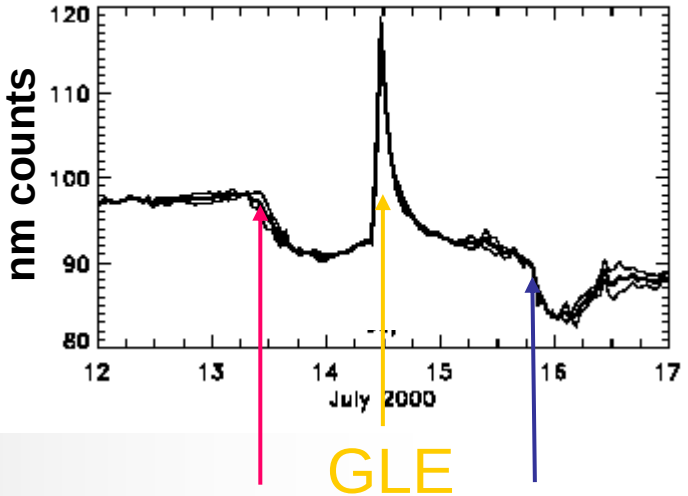


The Bastille Day Storm

GCRs and SEPs

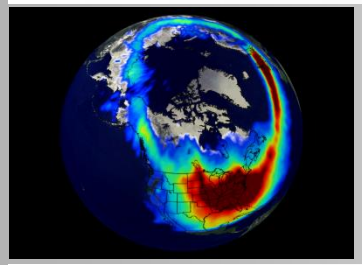
- Ground-level enhancement (GLE) of solar energetic particles seen between Forbush decreases of galactic cosmic rays caused by shielding by the two CMEs
- Here seen at stations in both poles (McMurdo and Thule)

Neutron Monitor counts



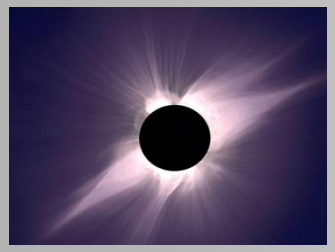
Forbush decrease caused by 1st CME

Forbush decrease caused by CME associated with GLE



The Bastille Day Storm

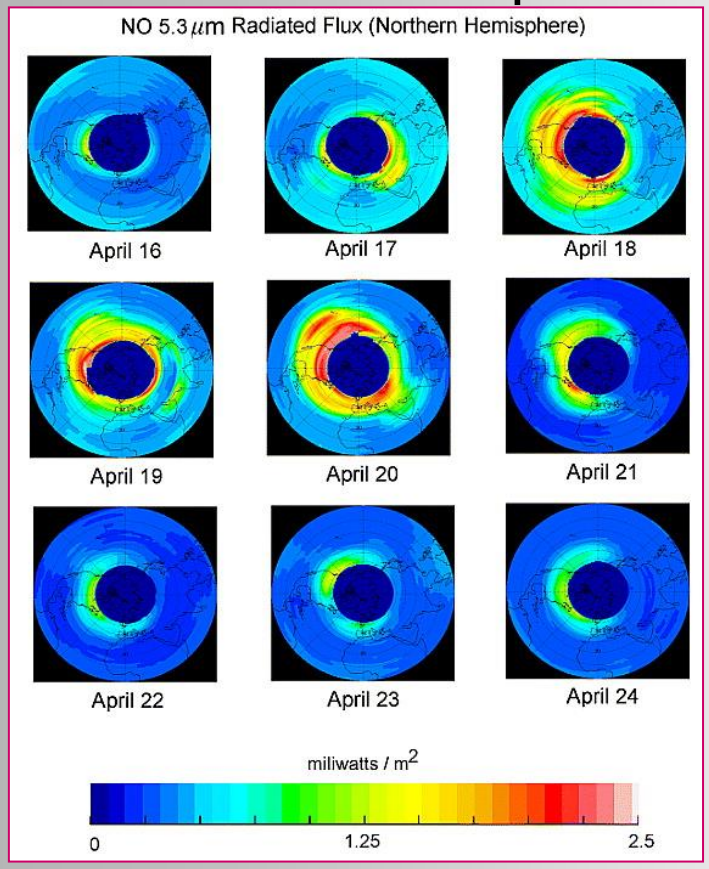
SEP Proton Aurora – seen by Image FUV-SI12



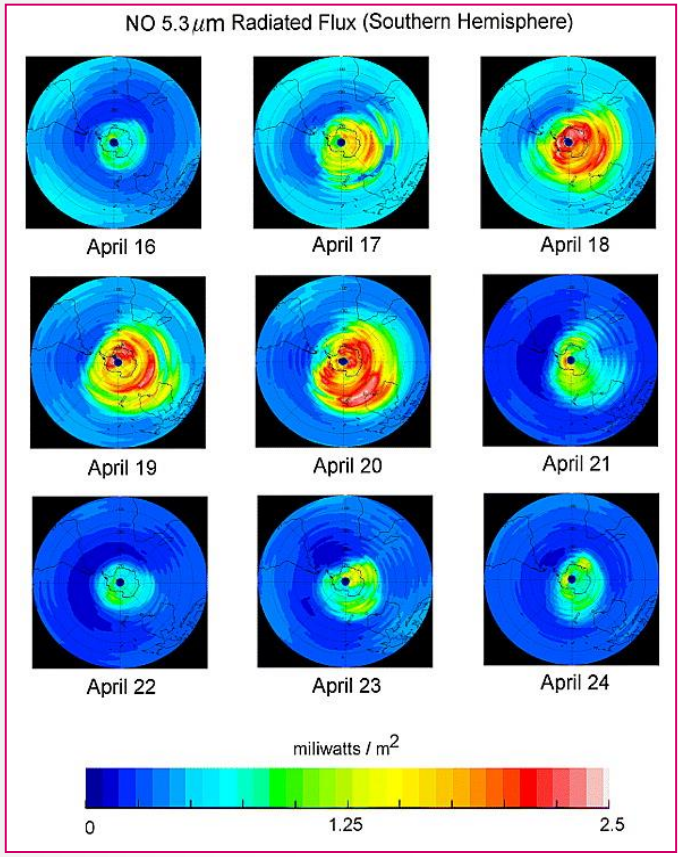
Polar Cap NO

From SEP event of April 2002

- Northern hemisphere



- Southern hemisphere



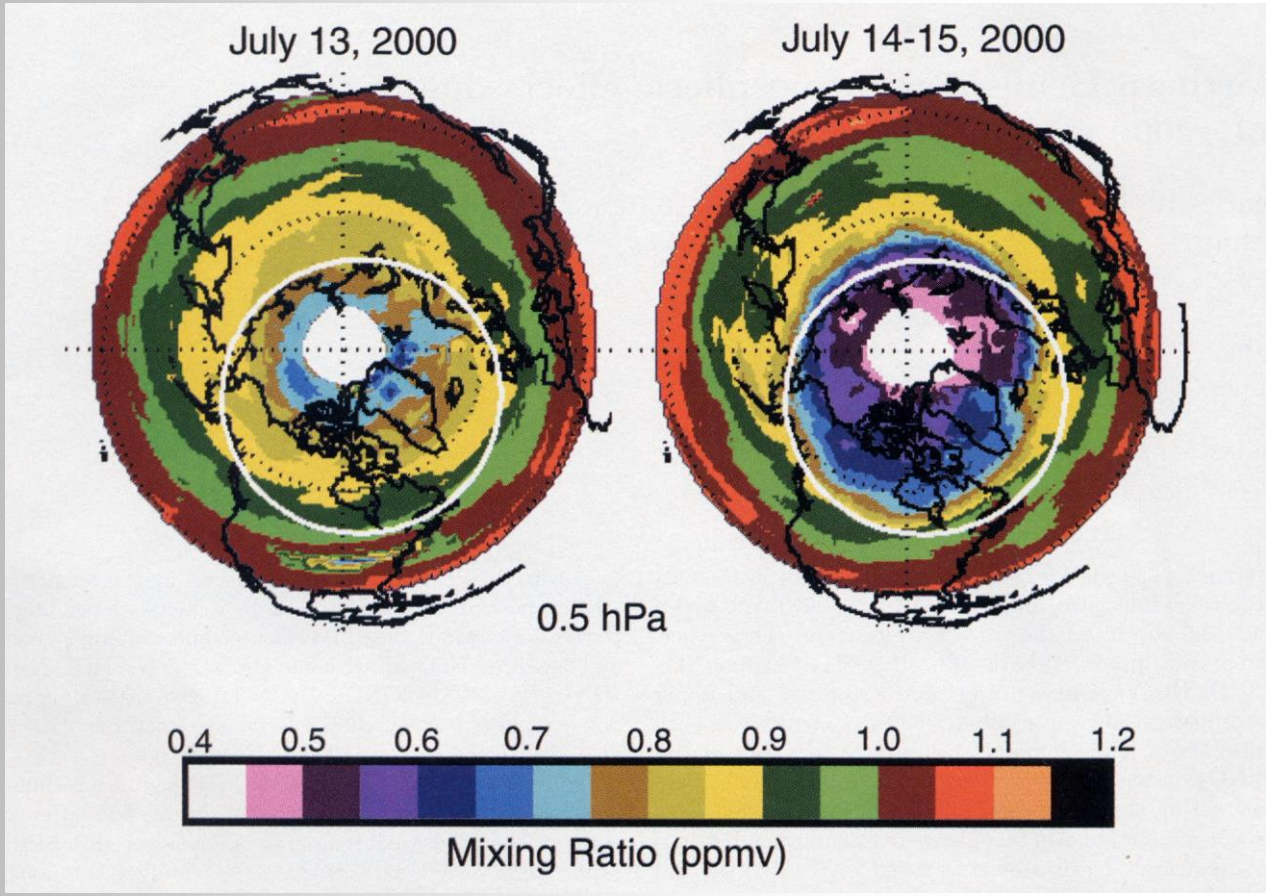
TIMED observations of 5.3 μm NO radiative fluxes (Wm^2)

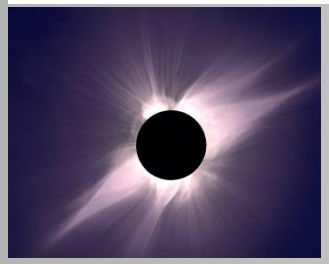
(Mlynczak et al., 2003)

The Bastille Day Storm

Ozone Depletion (TOMS)

Storm Event – SEP Ozone Depletion

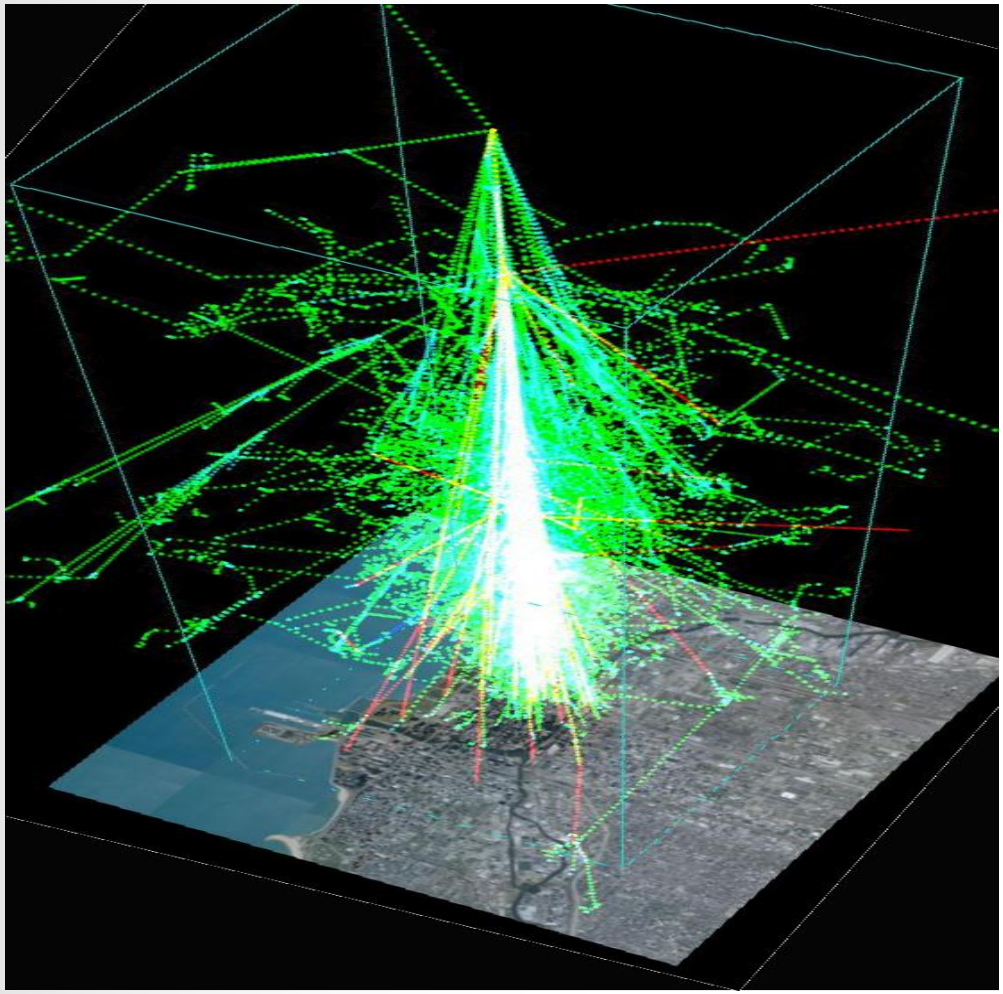




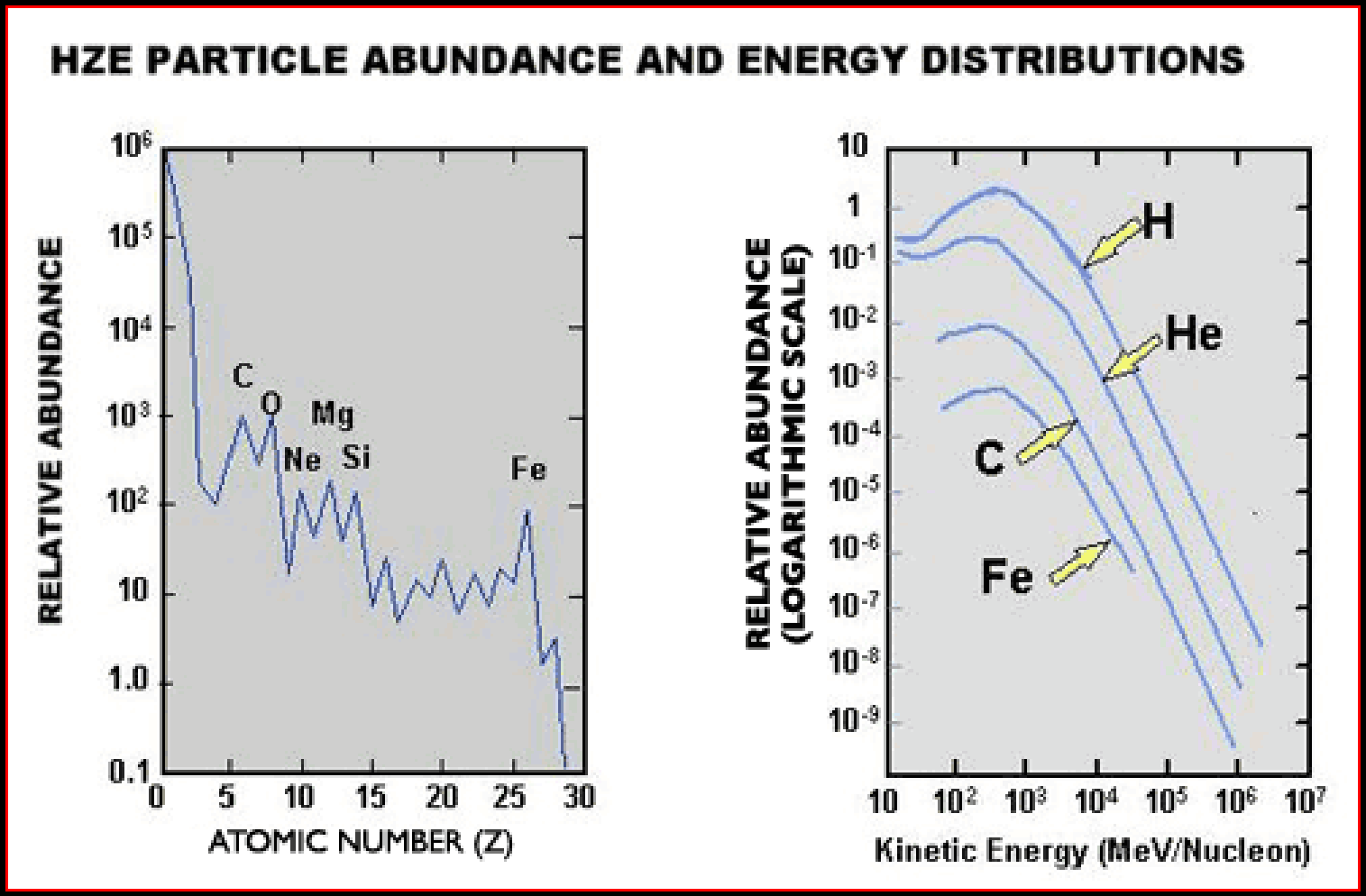
Energetic Particles

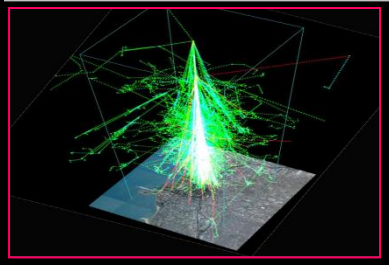
Galactic Cosmic Rays

- 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



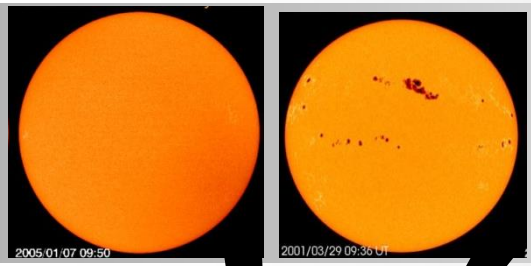
Galactic Cosmic Ray Spectra





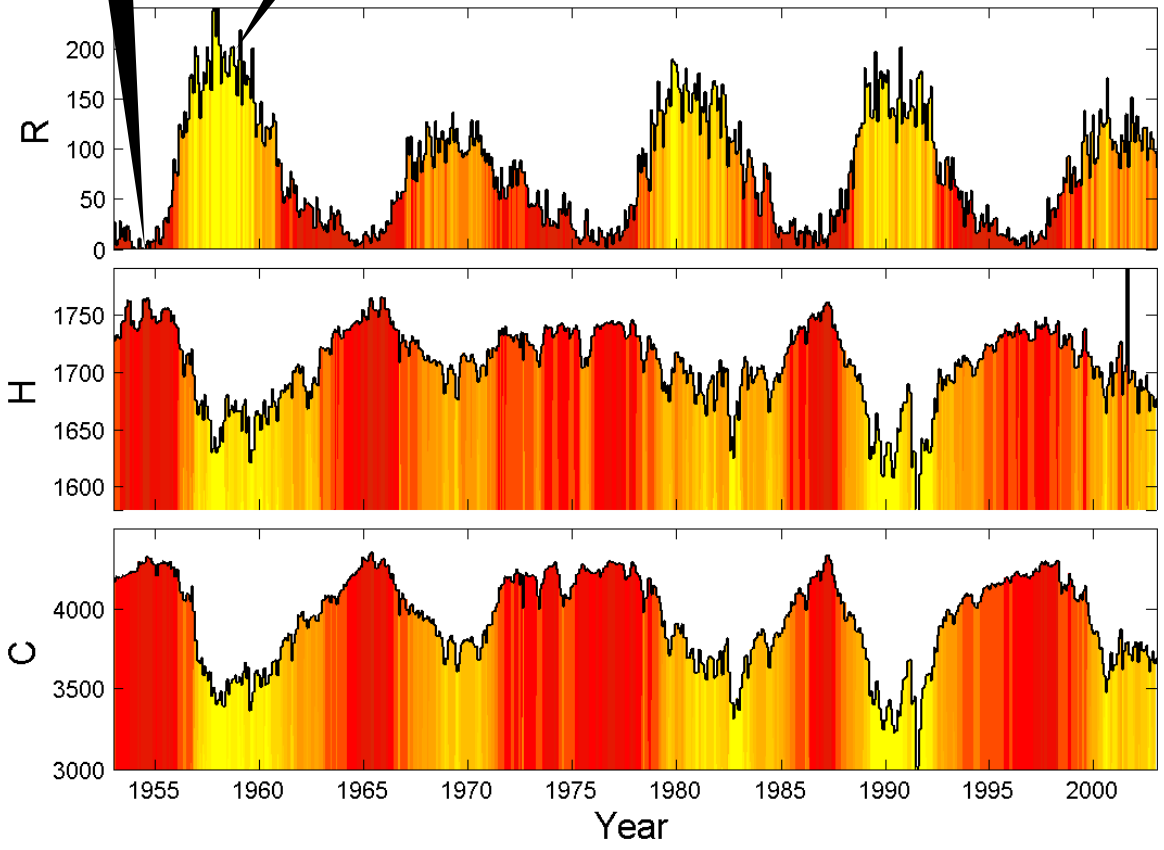
Galactic Cosmic Rays

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

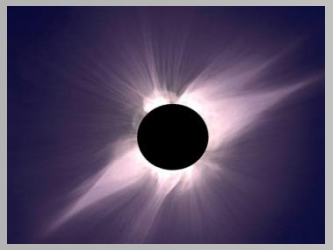
Anticorrelation with sunspot numbers



Sunspot Number

Huancauyo – Hawaii neutron monitor counts (>13GV)

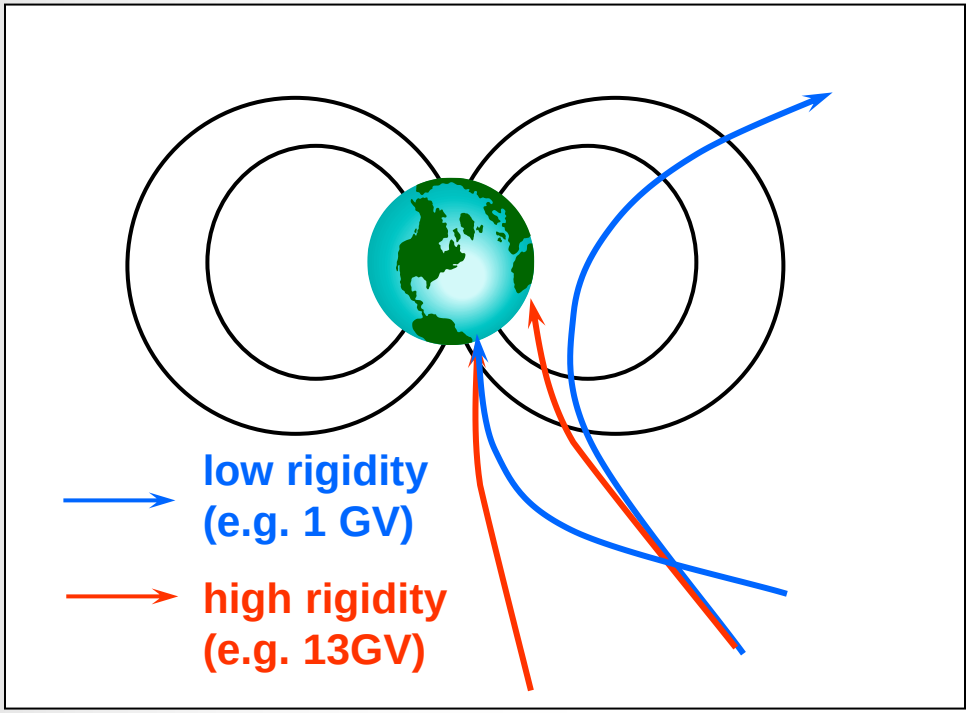
Climax neutron monitor counts (>3GV)



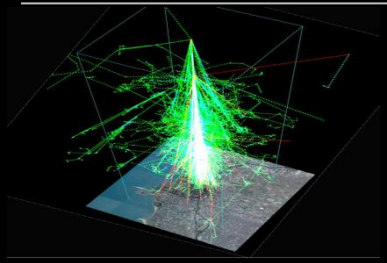
Geomagnetic Shielding of GCRs

(Cut-off rigidity)

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



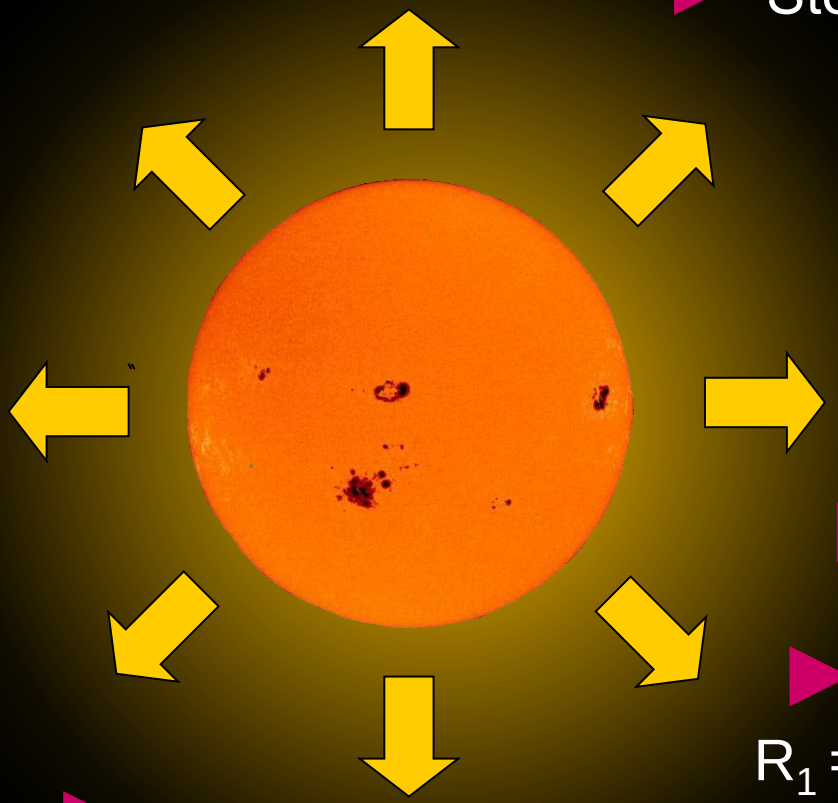
- minimum rigidity that can be seen at a magnetic latitude called the “rigidity cut-off” (e.g.) for Hawaii and Huancayo $\approx$ 13GV for Climax (Boulder) $\approx$ 3GV
- At highest latitudes rigidity cut-off set by atmosphere at $\approx$ 1GV



Galactic Cosmic Rays

Neutrons and muons produced in the atmosphere when bombarded with GCRs seen in a cloud chamber on the ground

Solar power input to climate



- Stefan-Boltzmann law

$$P / A = \sigma T^4$$

- Tyndall, 1864 : experiment;
  Stefan, 1879 : empirical fit to his data;
  Boltzmann,1884: thermodynamics;
  Max Planck: 1901 showed why
  $\sigma = 5.670 \times 10^{-8}\ W\ m^{-1}\ K^{-4}$
- $R_\odot$= radius of Sun, $A = 4\pi R_\odot^2$
  solar surface temperature, T = 5770K
- Sun radiates total power $P=4\pi R_\odot^2 \sigma T^4$

R_1 = Sun-Earth distance

- power per unit area at Earth $I_{TS}=4\pi R_\odot^2 \sigma T^4 /(4\pi R_1^2) = 1364\ Wm^{-2}$

"total solar irradiance", TSI & measured to be $1366\ Wm^{-2} \pm 3\ Wm^{-2}$

- TSI varies because of sunspots and "faculae" but only by 0.1%

TSI variation so small because outer part of sun ("convection zone") is so massive: TSI drop would be negligible even 100 years after a complete turning off of the heat source for the convection zone!!!