Solar Total and Spectral Irradiance Reconstruction Over the Last 9000 Years

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Solar Irradiance

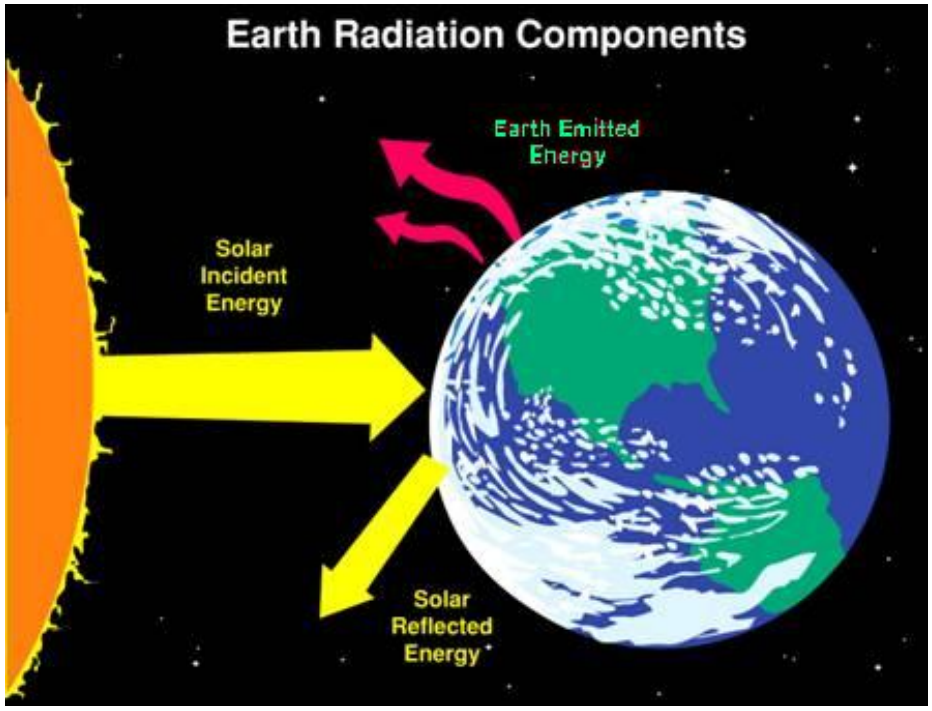


Figure 1: Solar irradiance

- TSI is $\sim$ 1360 Wm^{-2} with variability $\sim$ 0.1%
- UV/SSI contribute $>$ 50% TSI variability
- Effect of SSI on Earth's climate through top-down & bottom-up mechanisms (heights, wavelengths dependent)

Why model solar irradiance

- Continuous observations only cover four decades

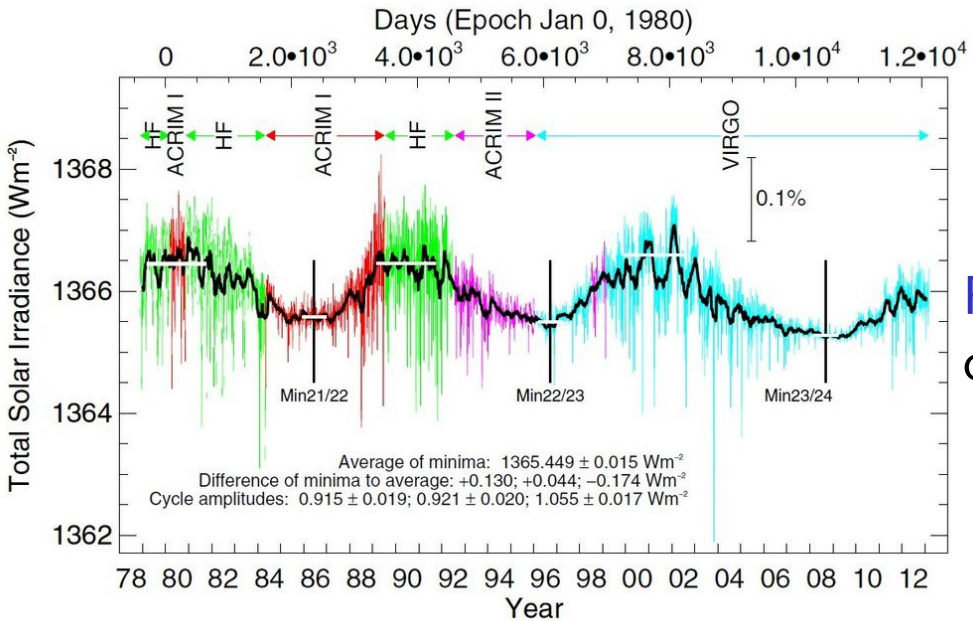


Figure 2: TSI PMOD composite

- Connection between solar variability & solar surface magnetism
- Various models use different indices/proxies of solar magnetic activity to reconstruct solar irradiance in the past

Spectral And Total Irradiance REconstruction

- Solar variability $>$ 1 day caused by surface magnetism
- Solar surface composed by Faculae(f), Network(n), Umbra(u), Penumbra(p), Quiet Sun(q)
- Surface coverage α of component f,n,u,p,q
- Intensity spectra I of component f,n,u,p,q from radiation transfer code + model atmosphere (spectrum spans 115 - 160000 nm)

Solar spectrum at any given time

$$F(\lambda, t) = \alpha_q(t) I_q(\lambda) + \alpha_u(t) I_u(\lambda) + \alpha_p(t) I_p(\lambda) + \alpha_f(t) I_f(\lambda) + \alpha_n(t) I_n(\lambda)$$

Spectral **A**nd **T**otal **I**rradiance **RE**construction

- SATIRE-Satellite : Continuum Images & Magnetograms (back to 1974; Ball et al. 2014; Yeo et al. 2014, 2015)
- SATIRE-Telescope : Group sunspot number (back to 1610; Krivova et al. 2007, 2010)
- SATIRE-Telescope v.2 : Synthesis sunspot number & simulated magnetograms (SFTM) (back to 1700; Dasi-Espuig 2014, 2015)
- SATIRE-Millennia : Cosmogenic isotopes ^{14}C & ^{10}Be (prior to 1610; Vieira et al. 2011)

Other models

SRPM; back to cycle 23 [Fontenla et al. 1999]

NRLSSI; back to 1610 [Lean et al. 2001, Coddington et al. 2015]

Millennial TSI through linear correlation; [Steinhilber 2009, Shapiro et al. 2011]

SATIRE-T

- Coupled ODEs
  describing evolution of magnetic fields
- Free parameters
  describing relations between magnetic components, timescales of components

$$\frac{d\phi_{act}}{dt} = \varepsilon_{act} - \frac{\phi_{act}}{\tau^0_{act}} - \frac{\phi_{act}}{\tau^s_{act}} - \frac{\phi_{act}}{\tau^r_{act}}$$

$$\frac{d\phi_{eph}}{dt} = \varepsilon_{eph} - \frac{\phi_{eph}}{\tau^0_{eph}} - \frac{\phi_{eph}}{\tau^s_{eph}}$$

$$\frac{d\phi^r_{open}}{dt} = \frac{\phi_{act}}{\tau^r_{act}} - \frac{\phi^r_{open}}{\tau^r_{open}}$$

$$\frac{d\phi^s_{open}}{dt} = \frac{\phi_{act}}{\tau^s_{act}} + \frac{\phi_{eph}}{\tau^s_{eph}} - \frac{\phi^s_{open}}{\tau^s_{open}}$$

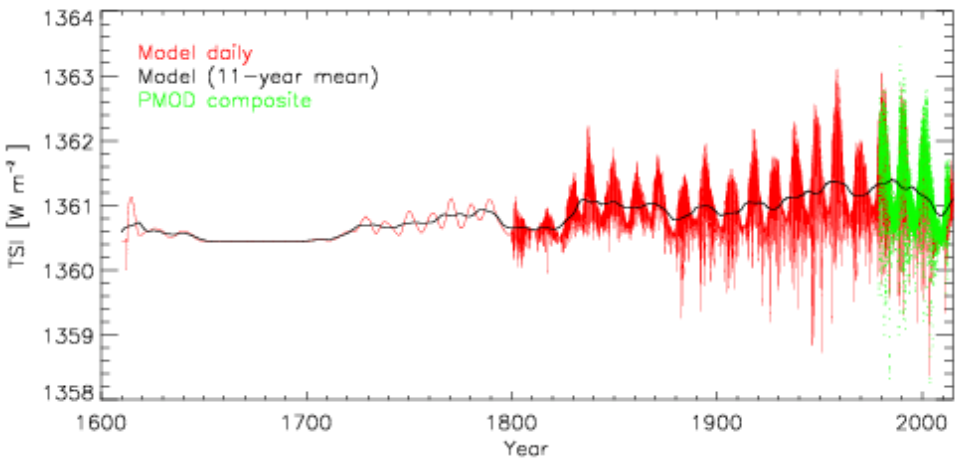


Figure 3: TSI reconstruction

SATIRE-M

1. Proxies: Cosmogenic isotope concentration in natural archives

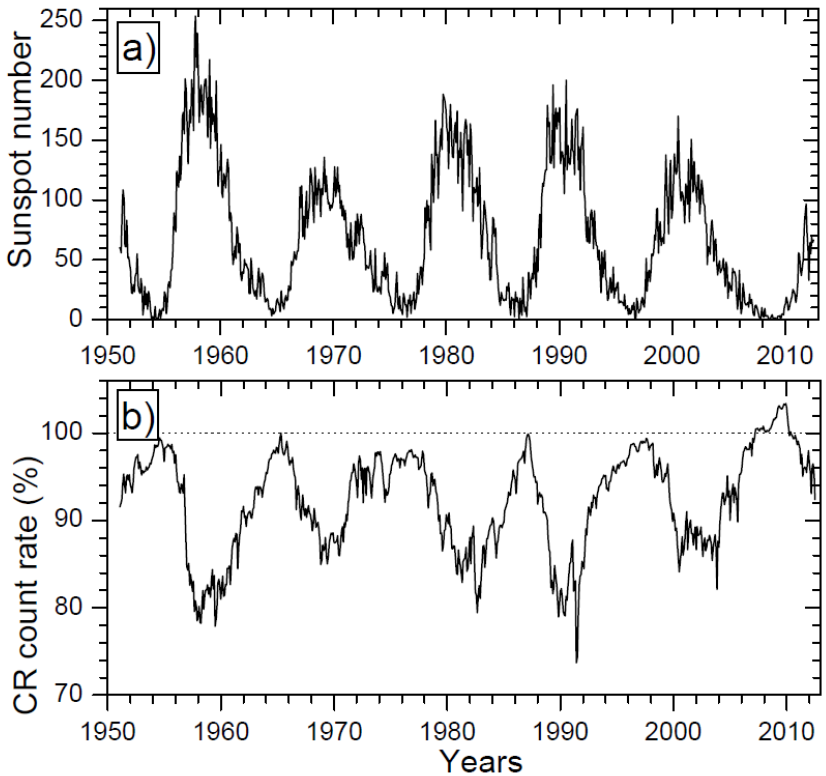
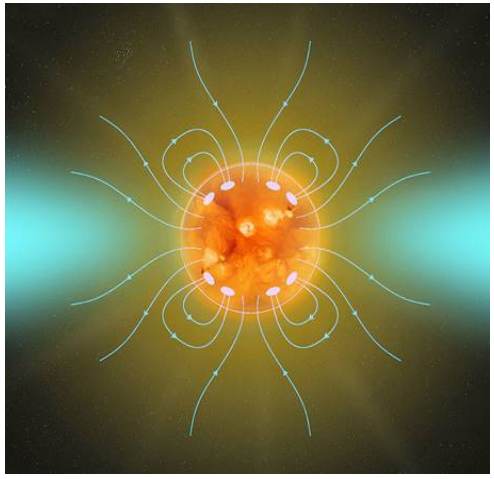
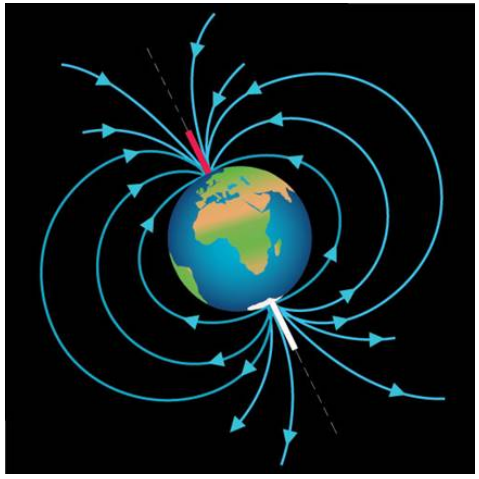
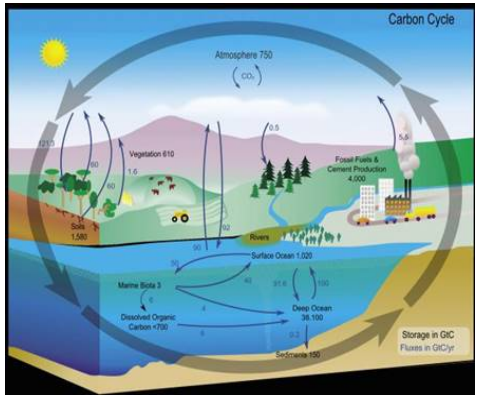
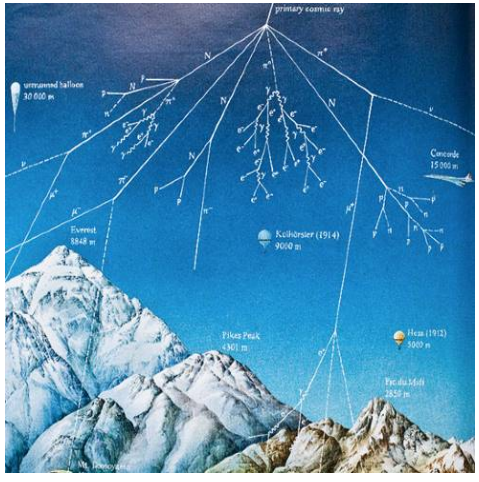


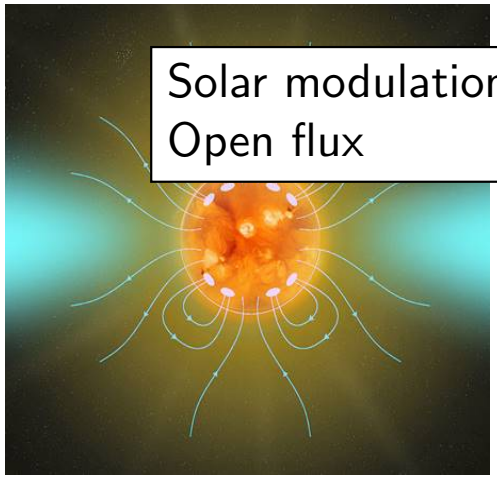
Figure 4: Solar activity vs. cosmic ray flux



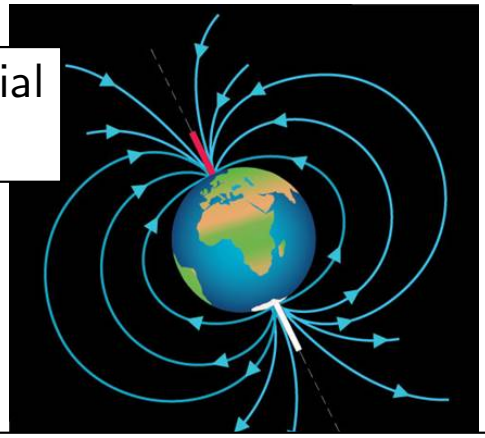



Carbon Cycle
Atmosphere 750
Vegetation 610
Soils 1,580
Rivers
Fossil Fuels & Cement Production 4,000
Surface Ocean 1,020
Marine Biota 3
Dissolved Organic Carbon +700
Deep Ocean 38,100
Sediments 150
Storage in GtC
Fluxes in GtC/yr

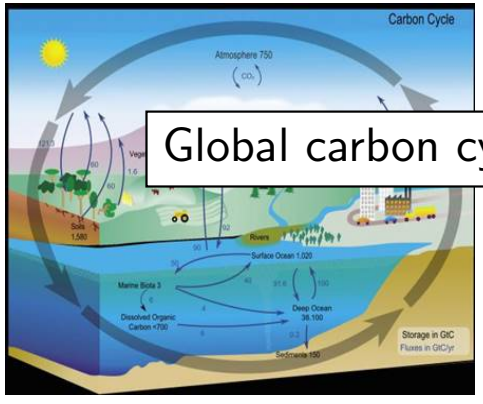

primary cosmic ray
unmanned balloon
30 000 m
Concorde
15 200 m
Everest
8848 m
Kulhörsier (1914)
9000 m
Pikes Peak
4301 m
Hess (1912)
5000 m
Pic du Midi
2858 m

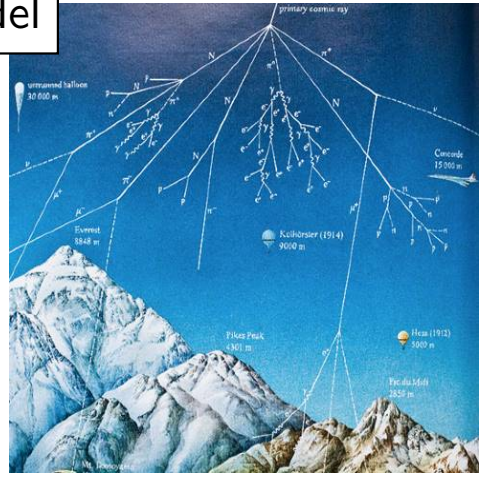


Solar modulation potential
Open flux

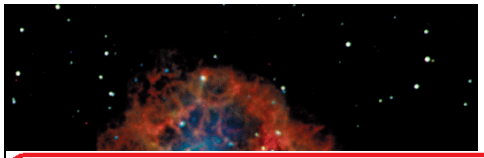


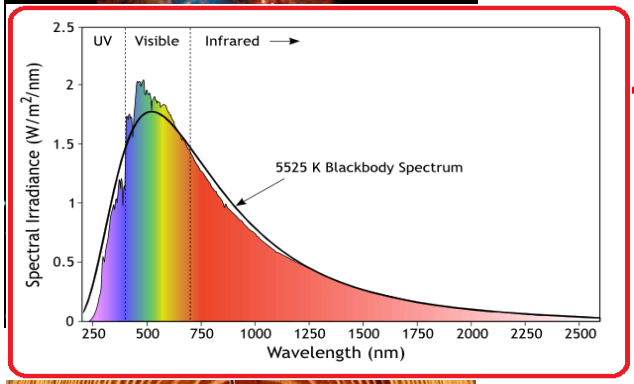
Geomagnetic field model

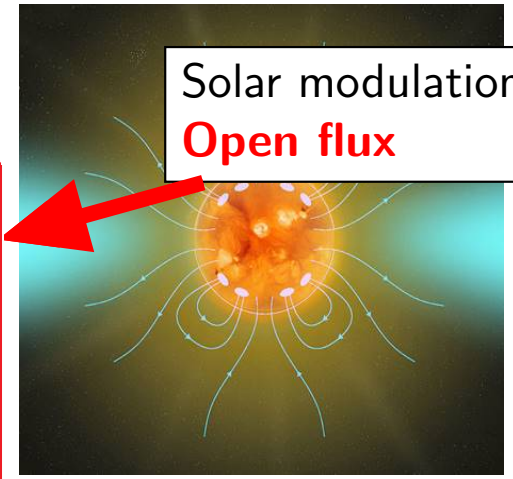




Regional precipitation model

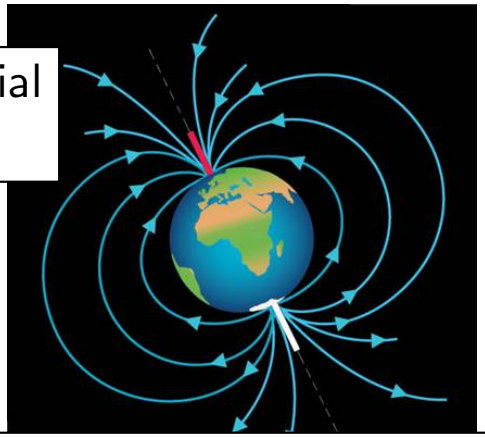




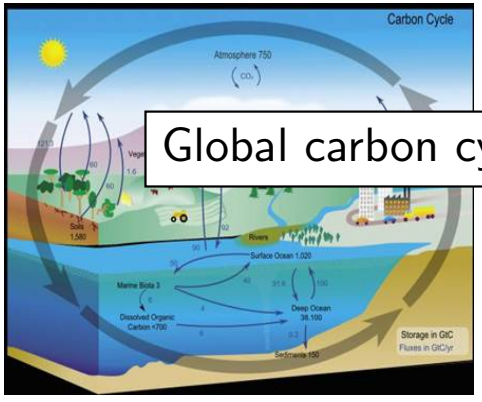


Solar modulation potential

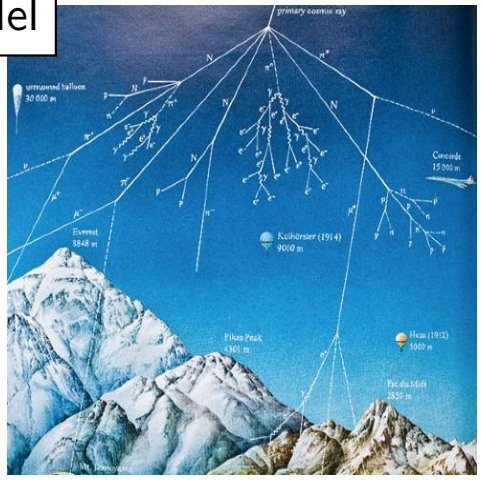
Open flux

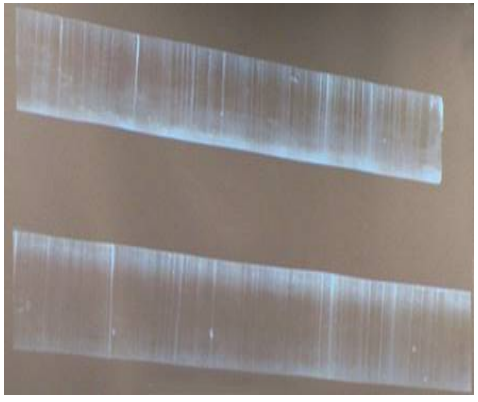


Geomagnetic field model



Global carbon cycle model





Regional precipitation model

SATIRE-M

1. Proxies: Cosmogenic isotope concentration in natural archives
2. Decadal average of SATIRE-T ODEs
3. Constrained parameters from SATIRE-T

$$< R_g >_j = a < \phi_{open} >_j + b < \phi_{open} >_{j+1}$$

R_g (decadal) + each component's I = millennial SSI reconstruction

Coefficients a & b are constrained from SATIRE-T

First SSI reconstruction with physics-based model

Summary

- SATIRE-M is so far the only physics-based model reconstructs TSI/SSI on millennial timescale.
- TSI has about 0.1% variability and UV/SSI (200-400 nm) contributes 51.8% variability on millennial timescale.
- The relations between cosmogenic isotope abundances and TSI/SSI are non-linear. Linear assumption is not realistic.