Magnetic Origins of Solar Irradiance Variations

Dibyendu Nandy[1](PI), Dora Preminger[2] (CoI) and Piet Martens[3] (Co-I)

Outline

- Scientific motivation
- Description of research
- Progress made
- Team Profile

Science Investigations: Overview

1. Relationship between AR magnetic properties and irradiance

2. Effect of AR evolution on solar irradiance

3. Modeling of spectral and total irradiance

Magnetic Properties of Active Regions and Solar Irradiance

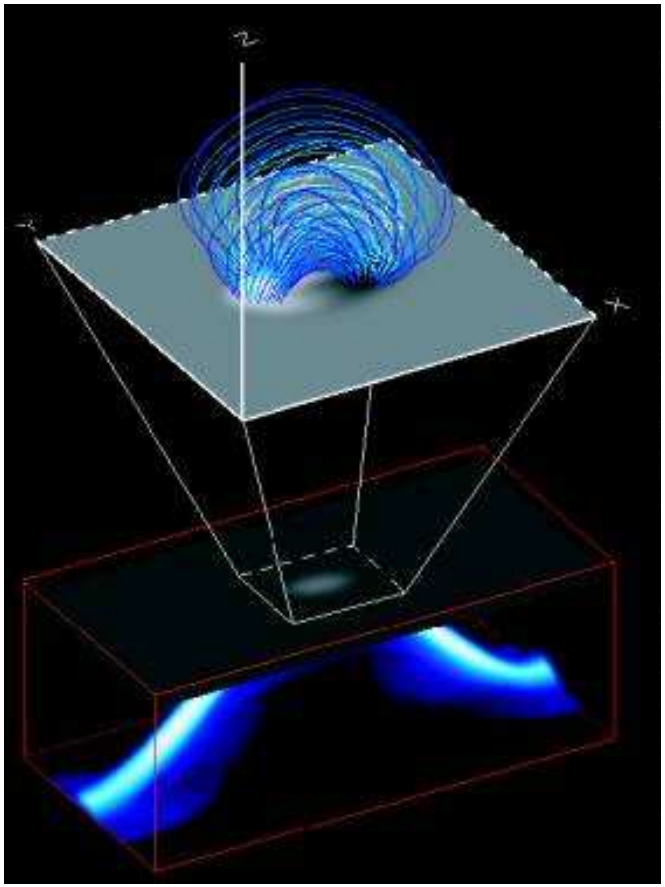
- Aim: Constrain first-principle-based models of AR irradiance
- Relevant timescales ~ seconds, minutes, days
- Physical processes: Energy storage and release, reconnection
- Method: Compare AR magnetic parameters to irradiance indices

Relevant AR parameters:

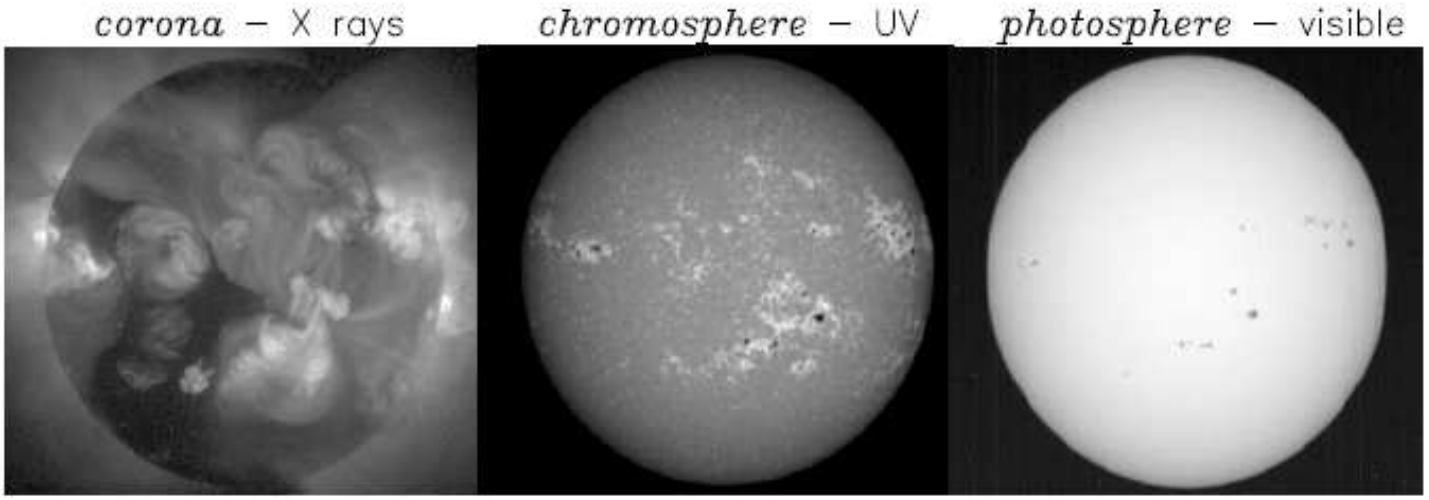
- B: Average field strength
- A: Area
- Φ: Flux
- L: Coronal loop length ($\pi d/2$)
- q: Field line twist (density)

Notes:

- Magnetic energy density ~ $B^2/8\pi$
- Twisted (non-potential) flux systems store excess energy – drives plasma relaxation (Nandy et al. 2003)



Magnetic Properties of Active Regions and Solar Irradiance



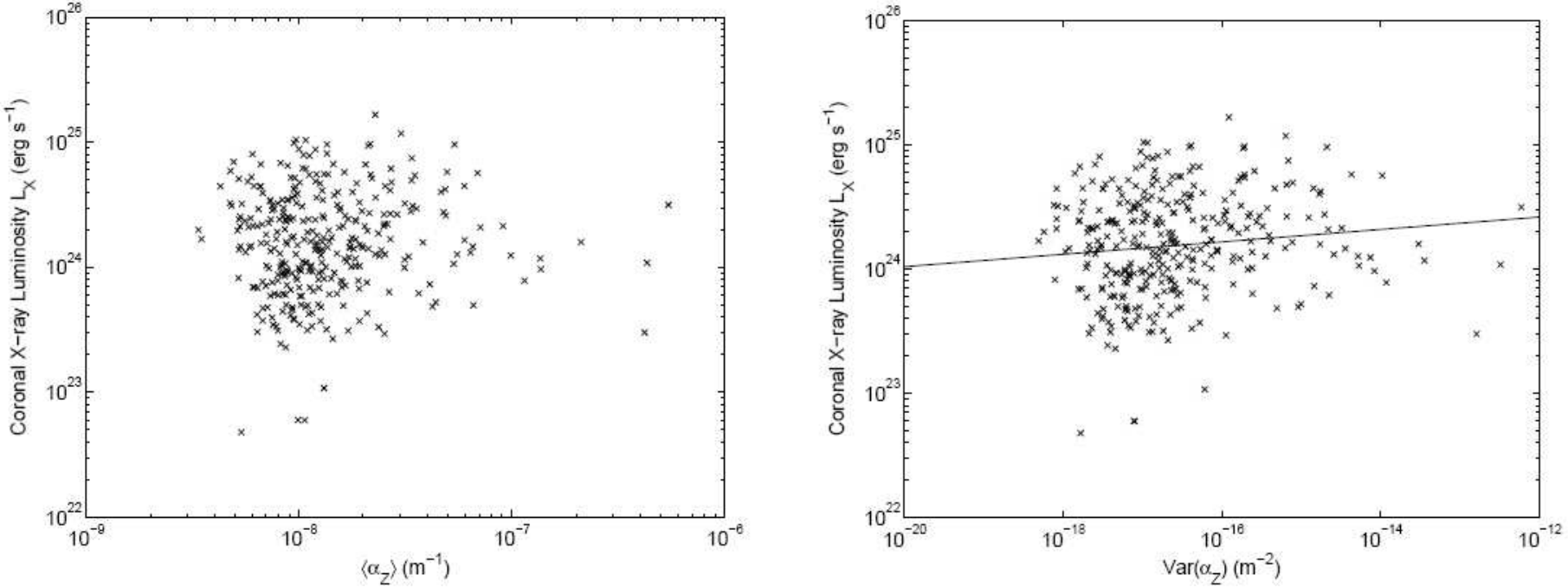
Irradiance Measures (partial…, intend to cover photosphere to Corona)

- Total Solar Irradiance
- CaK
- Mgii
- He1083
- Lyα
- UV
- EUV
- X-ray
- …???

Magnetic Properties of Active Regions and Solar Irradiance

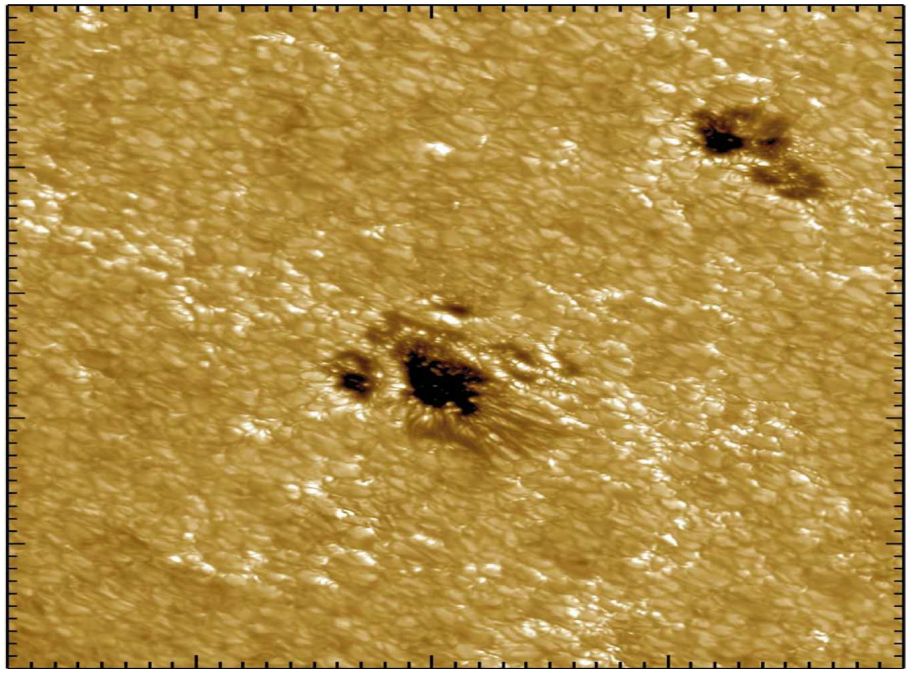
Progress

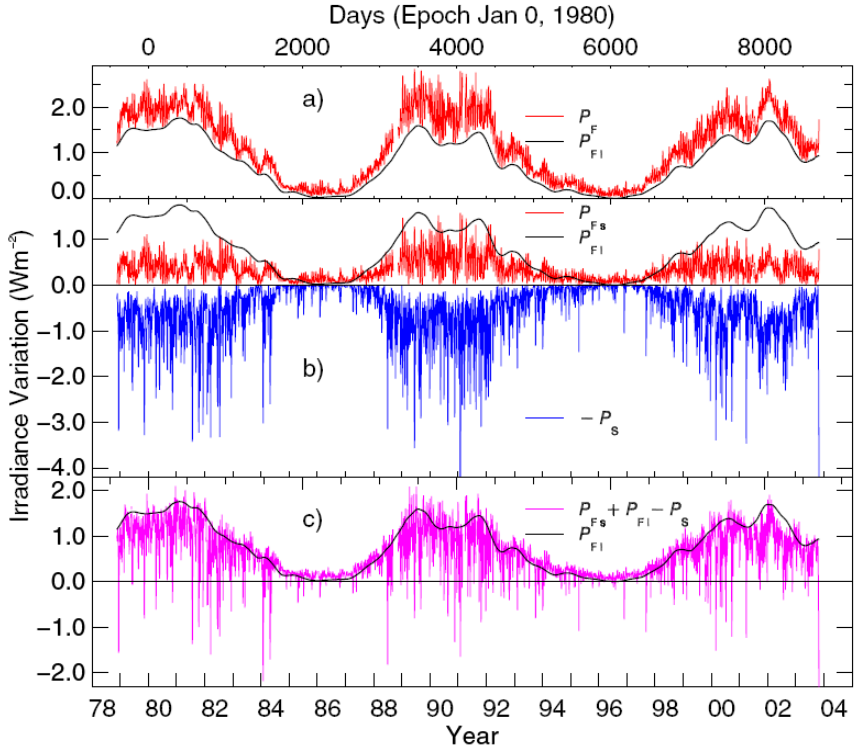
- Used Haleakala Stokes Polarimeter vector magnetogram data
- Reduced to generate relevant magnetic parameters
- Database contains more than 1000 ARs spanning 1988-2002
- Future : Comparison of magnetic parameters to irradiance measures



(X-ray Luminosity versus twist, Nandy 2008, see also Fisher et al. 1998)

Effect of AR Evolution on Solar Irradiance





(Left: Faculae and spot observed by Swedish Solar Telescope, Tickmarks: 1.34 arcsec)
(Right: TSI model, Sunspot darkening and facular brightening, Frohlich & Lean 2004)

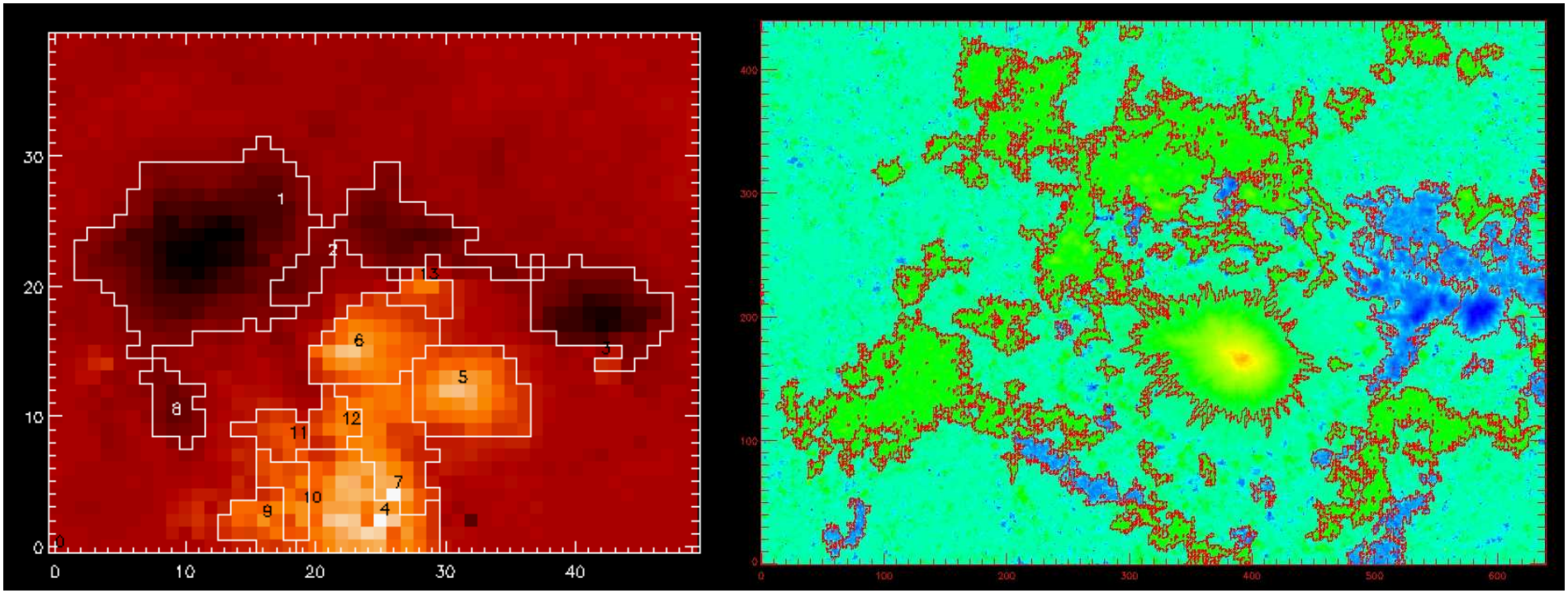
- Aim: Understand flux redistribution between spot and faculae
- Relevant timescales ~ days to solar rotation
- Physical processes: AR decay and flux fragmentation
- Method: Use magnetogram partitioning algorithm to follow evolution

Effect of AR Evolution on Solar Irradiance

Development of Magnetogram Partitioning Algorithm

- Downhill gradient based tessellation (Schrijver et al. 1997)
- Identifies fragments based on tessellation threshold (specified based on noise considerations)
- Global maximum chosen as first fragment and subsequent local maxima as different fragments
- Subsequent merging based on saddle-point, area and flux thresholds

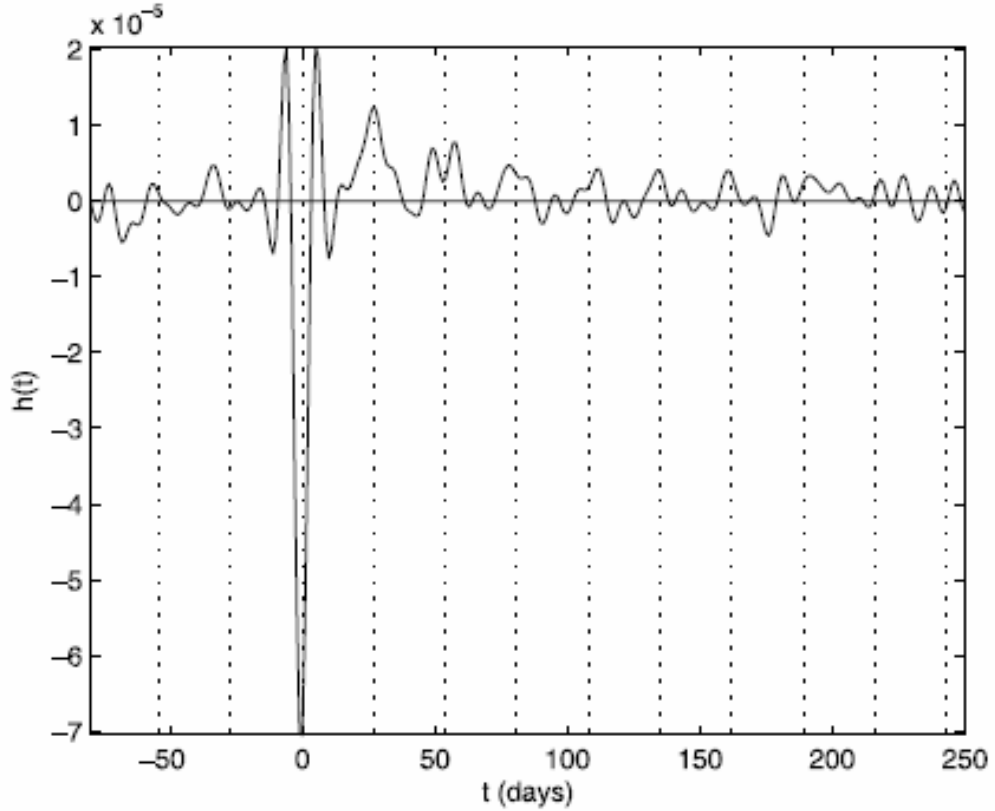
Effect of AR Evolution on Solar Irradiance



- Left: HSP AR 6615 observed by HSP
  Resolution: 5.6 x 5.6 arc-sec

- Right: AR 10940 observed by Hinode/SOT
  Resolution: 0.3 x 0.32 arc-sec
  Faculae identification now possible

Effect of AR Evolution on Solar Irradiance



(FIR function for TSI and sunspot area, Preminger & Walton 2005)

- Dip in TSI from sunspot appearance gives way to positive contribution within a solar rotational timescale
- Future: Partitioning algorithm will be used to study this evolution
- Progress: Partitioning code has already been developed

Modeling Total and Spectral Solar Irradiance

Aim: Build empirical models to constrain theoretical AR models
Method: Assimilate observational constraints through statistical analysis

Active Region Model (Time-Independent)

- Use observed relationship between magnetic parameters and measures of irradiance, and partial correlation analysis to constrain the parameters (c,d,e,f) in:

$$\Delta X \sim B^c \times A^d \times L^e \times q^f$$

- This kind of empirical relationship will constrain first-principle based AR loop heating models, e.g., pursued by others (Klimchuk et al…)

Modeling Total and Spectral Solar Irradiance

(Implicitly) Time-Dependent Models

- Use observations to construct Finite Impulse Response (FIR) functions

Suppose that X varies from its minimum level by an amount:

$$\Delta X = X(t) - X_{min}$$

Assuming that the index X varies in response to a physical impulse, say AR parameter A, this response can be modeled through a convolution using a FIR – $h_x(t)$

$$\Delta X(t) = A(t) \times h_x(t)$$

- This approach can be used to model long-term irradiance variations

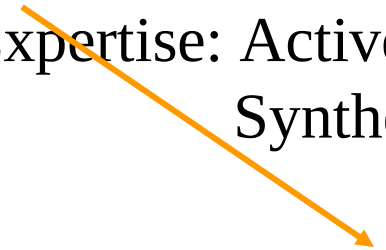
- Progress: Dora is going to talk about this…

Team Profile

Dibyendu Nandi (PI, Montana State University)
Relevant Expertise: Vector magnetic field observations and reduction
Statistical analysis and theoretical modeling

Dora Preminger (Co-I, San Fernando Observatory, CSUN)
Relevant Expertise: Spectral and total irradiance analysis and modeling

Piet Martens (Co-I, Harvard Smithsonian Center for Astrophysics)
Relevant Expertise: Active region loop modeling
Synthesis of observations and theory



LWS Focus Team: Modulation of Cosmic Rays, Sun-Climate Link…

"The goal is to identify and characterize the respective solar-driven processes that simultaneously, but by distinctly different processes, modulate both solar radiative output and heliospheric structure, composition and hence the flux of galactic cosmic rays."

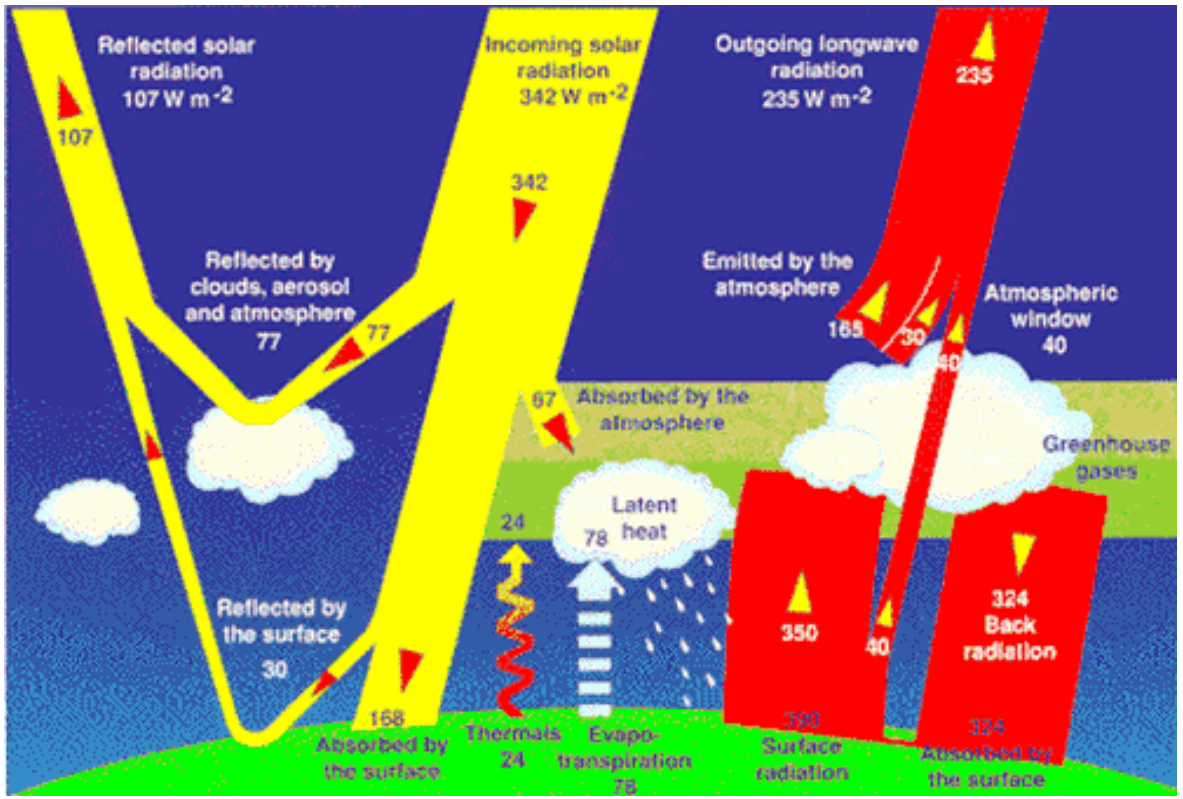
Additional Slides and Work (To be discussed if time permits…)

A Comparative Study of Net Solar Forcing and Global Temperature Changes Since 1600 AD

Dibyendu Nandy[1], Sarah Joy[2] and Piet Martens[3]

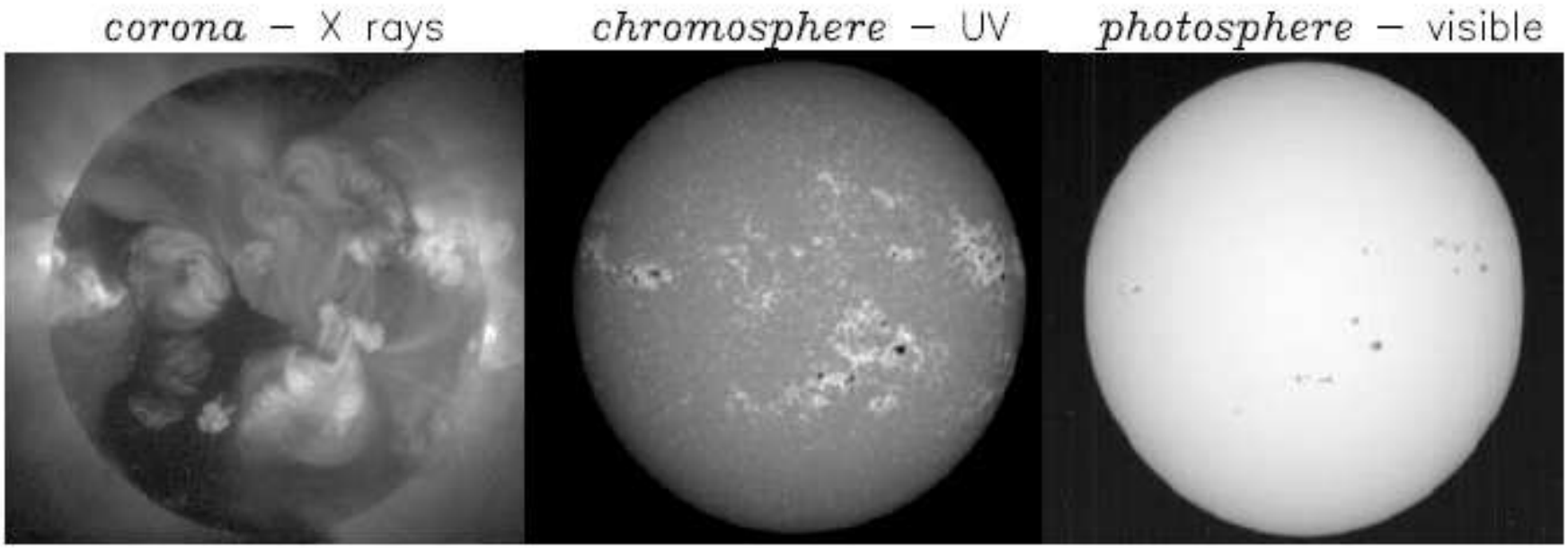
[1]Montana State University, USA
[2]University of Florida, USA
[3]Harvard-Smithsonian Center for Astrophysics, USA

The Sun—Climate Link



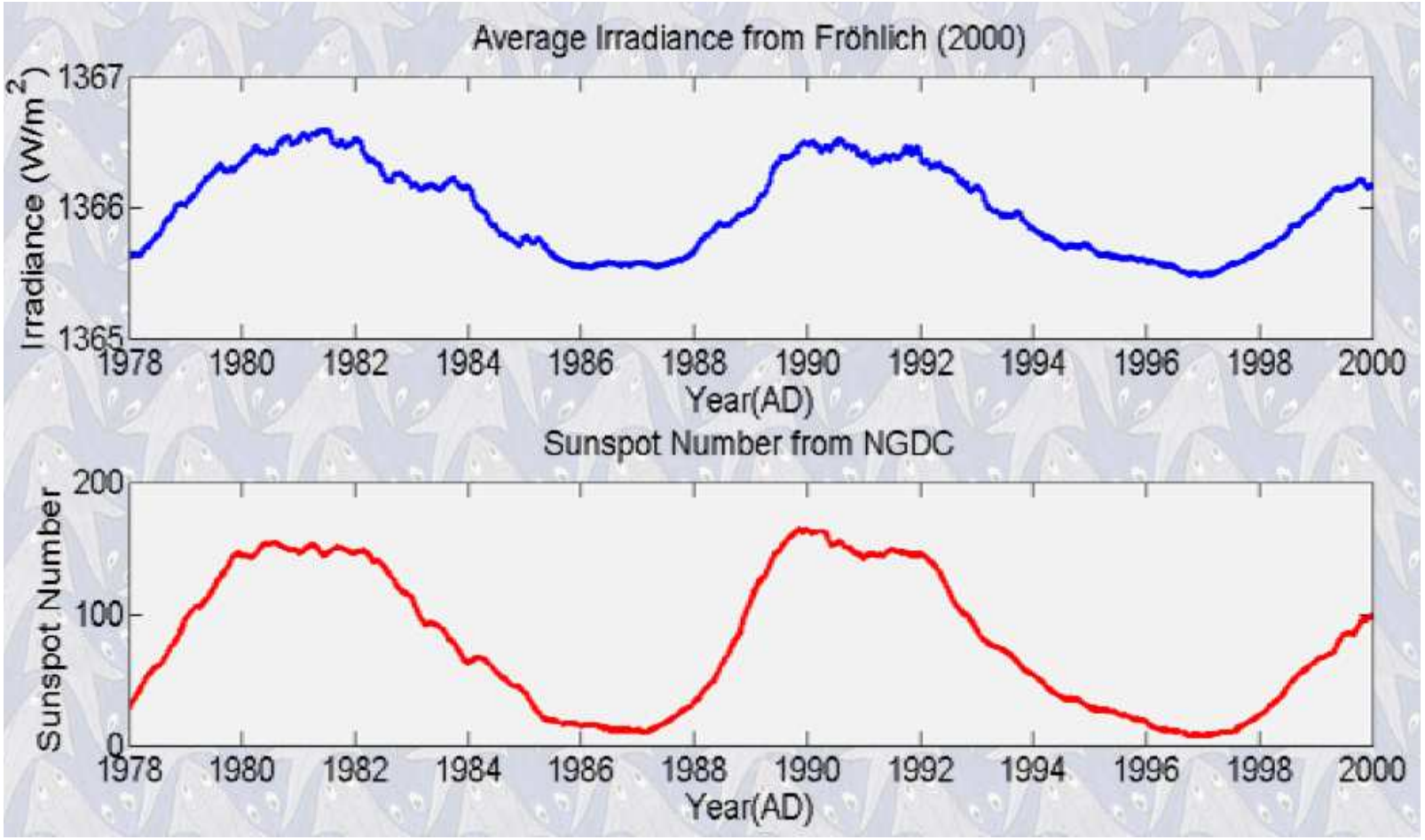
- The Sun radiates in different wavelengths: X-Rays, UV, Visible…
- This radiation is modulated by solar magnetic activity
- Solar activity also modulates galactic Cosmic Ray (CR) flux
- These may be the physical means through which solar forcing occurs
- Motivation: Study link between this solar forcing and global climate

Physical Basis of Solar Forcing: The Total Solar Irradiance – TSI



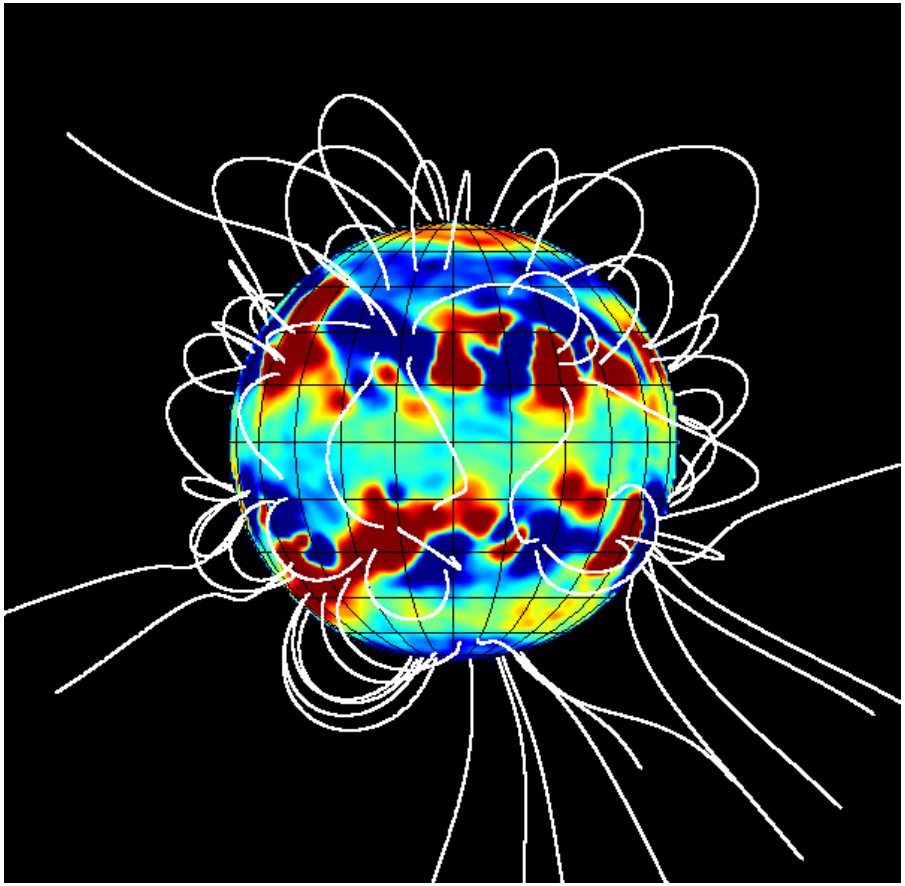
- TSI: Spectrally integrated total solar radiation
- Average value of 1366 W/m^2
- TSI is the primary radiative energy input into the Earth system

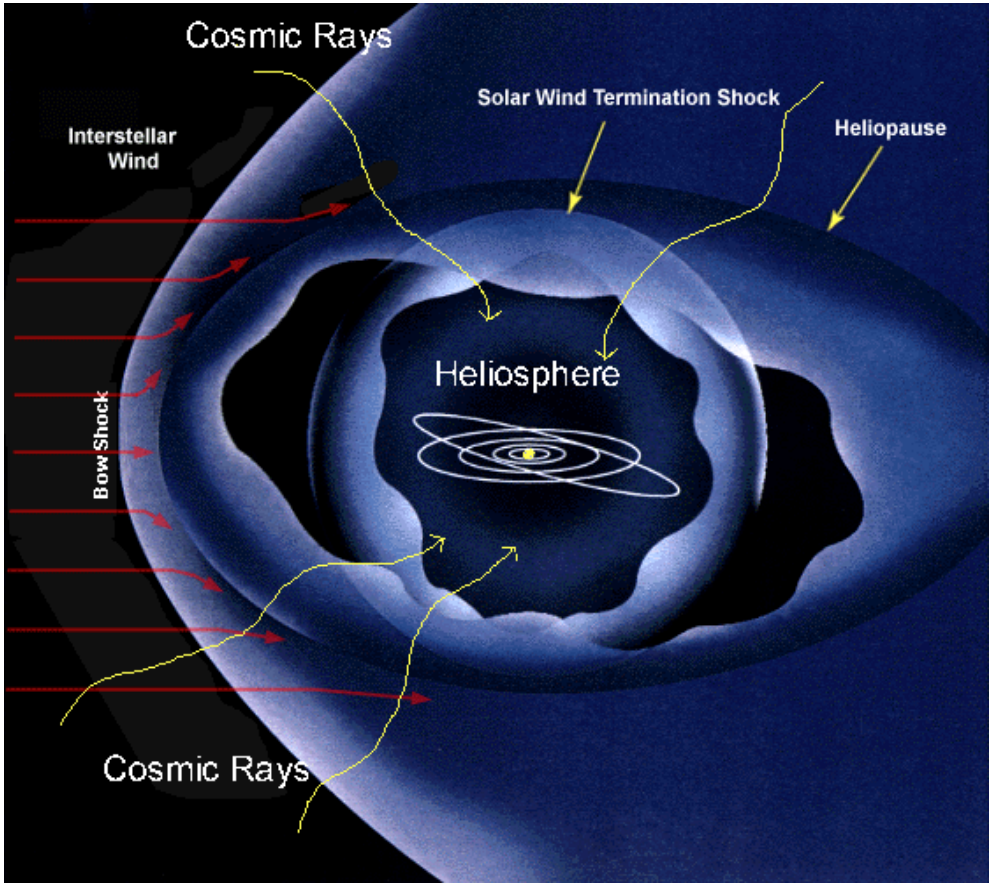
Variability of the Total Solar Irradiance – TSI



- TSI is modulated and varies (in phase) with solar magnetic activity
- Therefore it provides a link between solar variability and climate
- TSI observations exist only from 1978

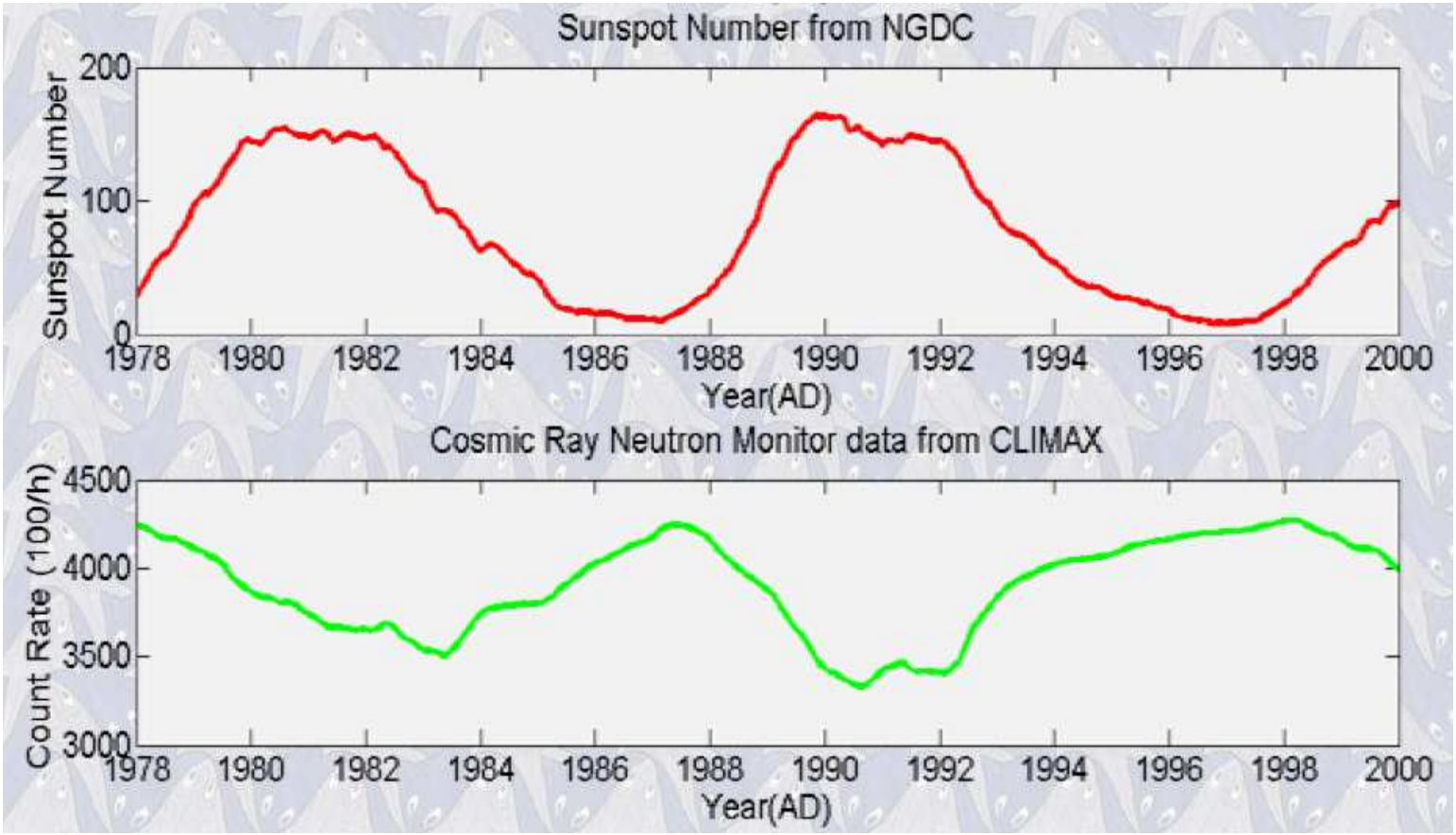
Physical Basis of Solar Forcing: Modulation of Cosmic Rays





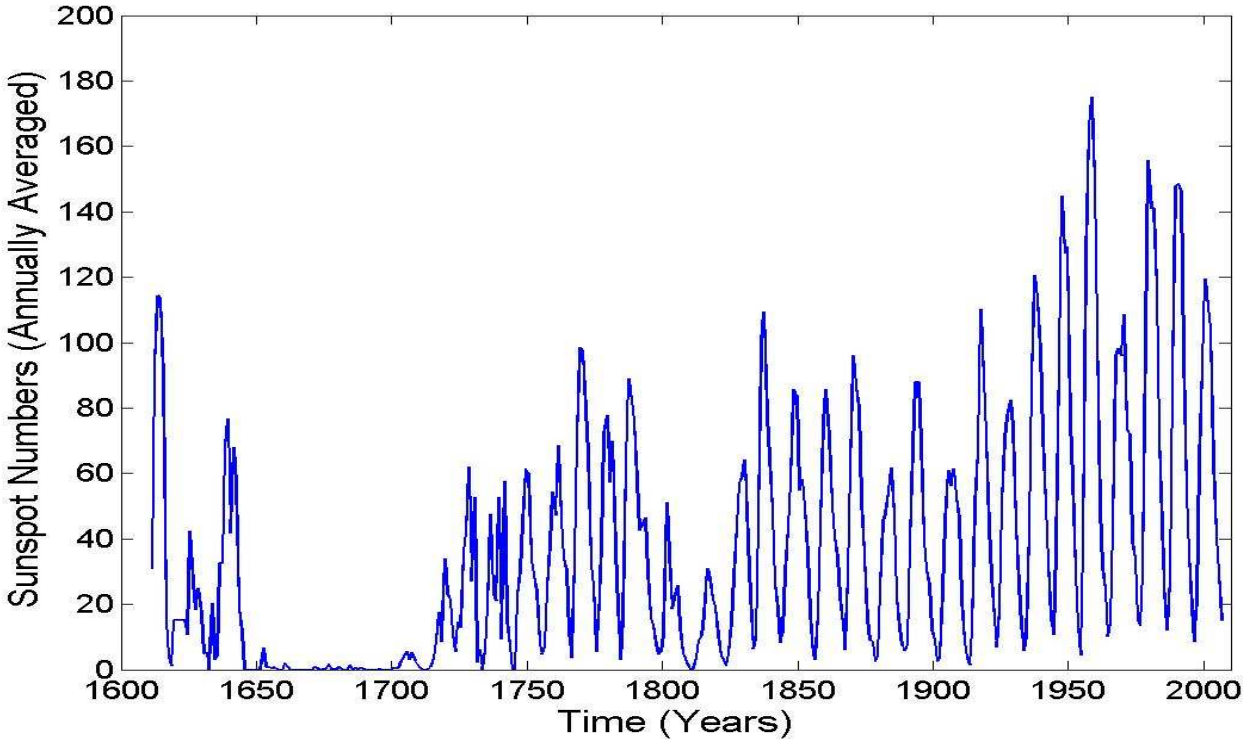
- Sunspots contribute to the evolution of the solar open magnetic flux
- The solar open flux defines the heliosphere
- The magnetic flux in the heliosphere modulates cosmic rays

Solar Modulation of Cosmic Rays



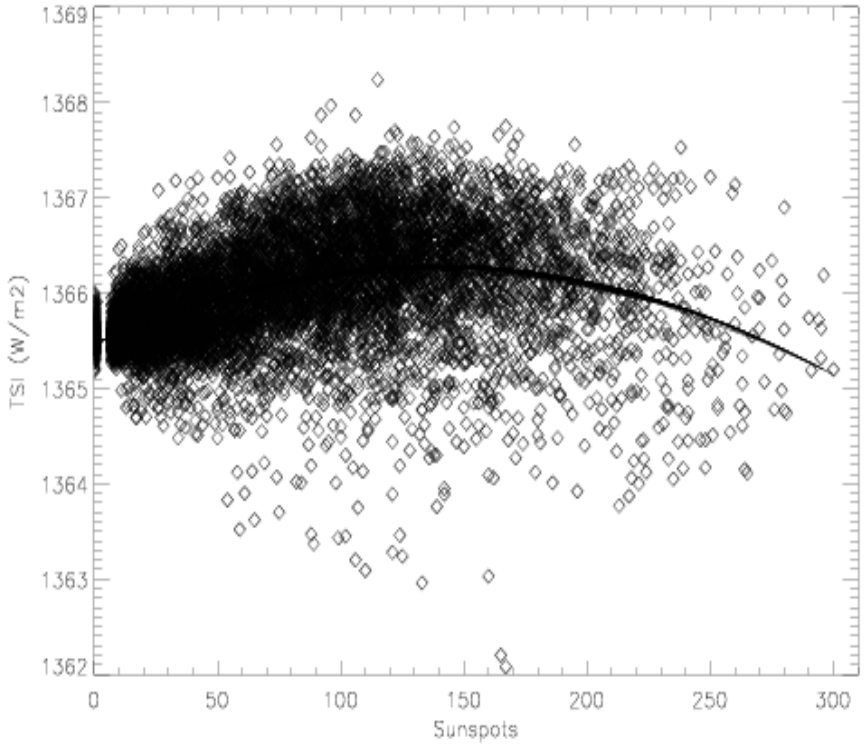
- Solar activity modulates cosmic rays (in anti-phase)
- Cosmic rays may affect climate by seeding clouds (Svensmark 1998)
- Hypothesis controversial (Carslaw, Harrison & Kirkby 2002)
- CR flux observations exist only from 1951

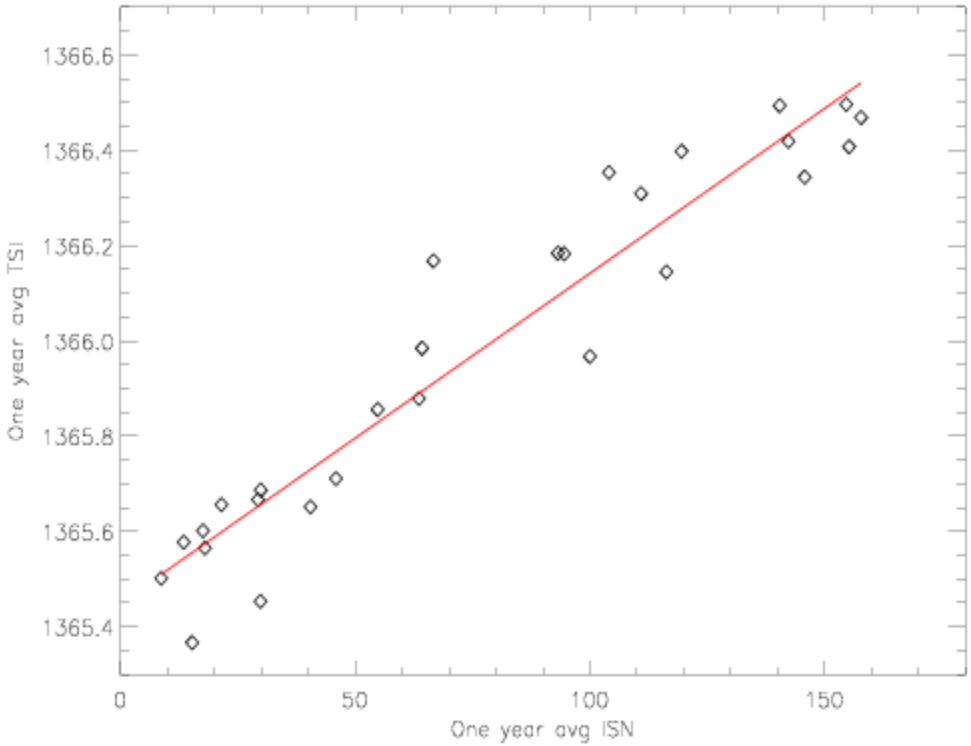
Methodology: Reconstruction based on Sunspot Numbers



- Reconstruct TSI and CR variation going back to 1600 AD
- Use simplistic empirical models of observed relationships, based on co-temporal TSI, CR flux and sunspot number (SN) data
- Calculate net solar forcing by making some assumptions regarding the radiative equivalent of CR variability and adding this to TSI variability
- Compare net solar forcing to global climate records over same period

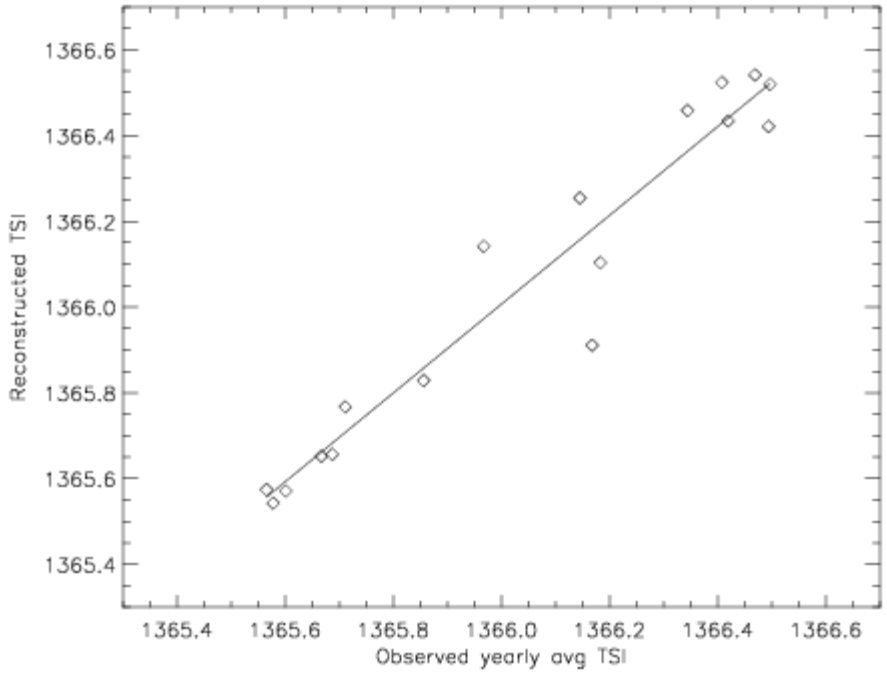
TSI Modeling

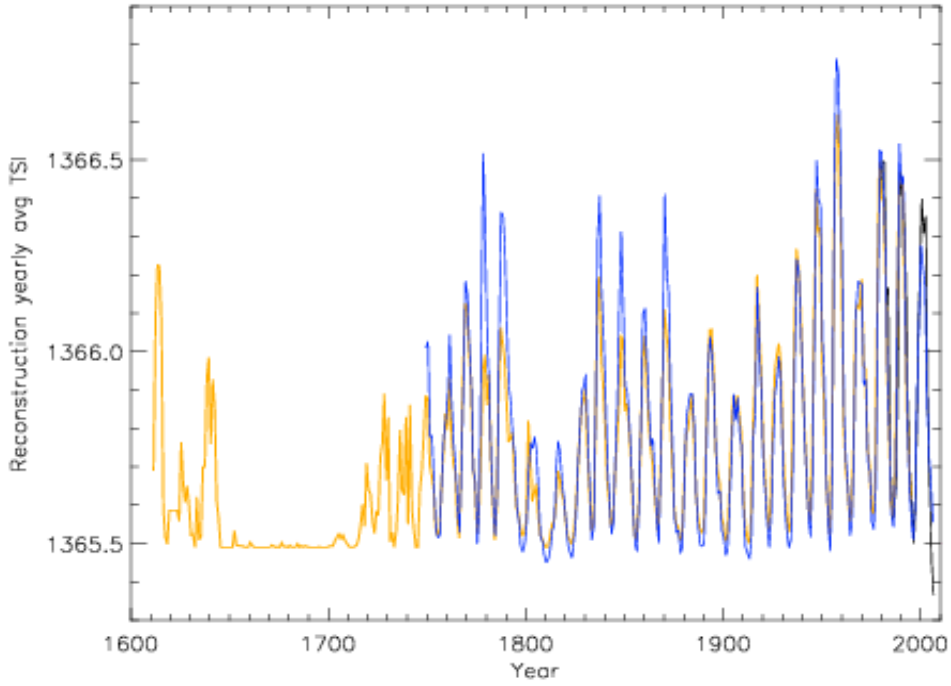




- Left: Observed daily TSI (PMOD composite) versus SN
- Right: Annually averaged TSI versus SN
  Linear correlation coefficient = 0.96
- On long-term averaging, the relationship seems to be fairly linear

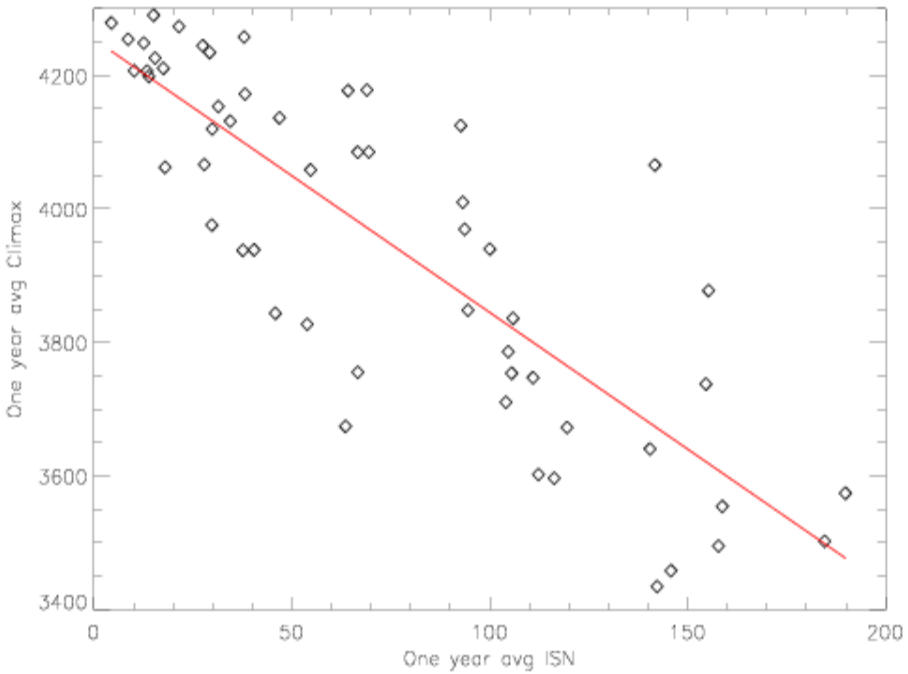
TSI Variability Reconstructions

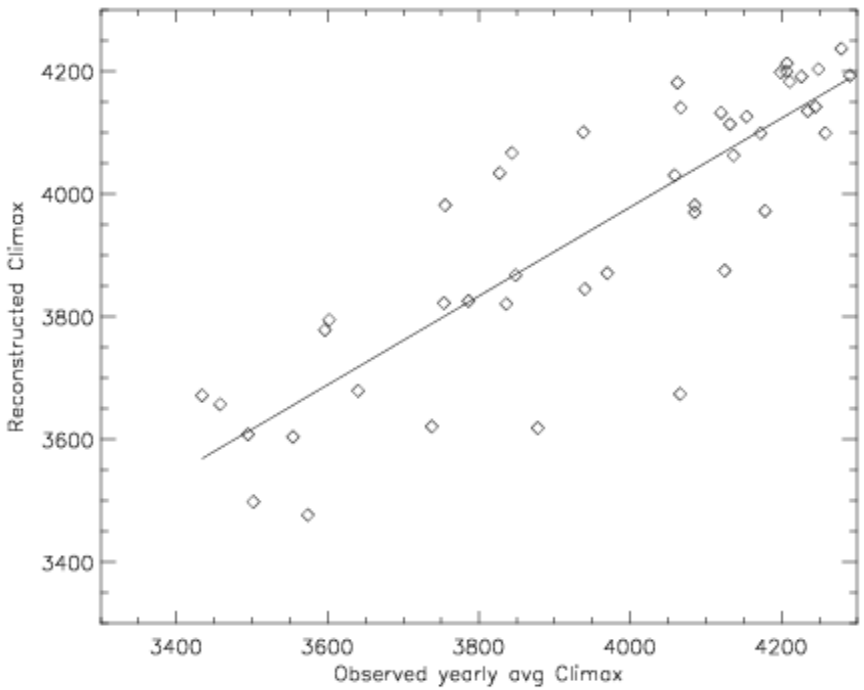




- Left: Reconstructed versus Observed TSI (linear correlation = 0.97)
- Right: Reconstructed TSI time-series based on GSN (orange), ISN (blue), and observed (black)
- Good agreement between reconstructed and observed time-series

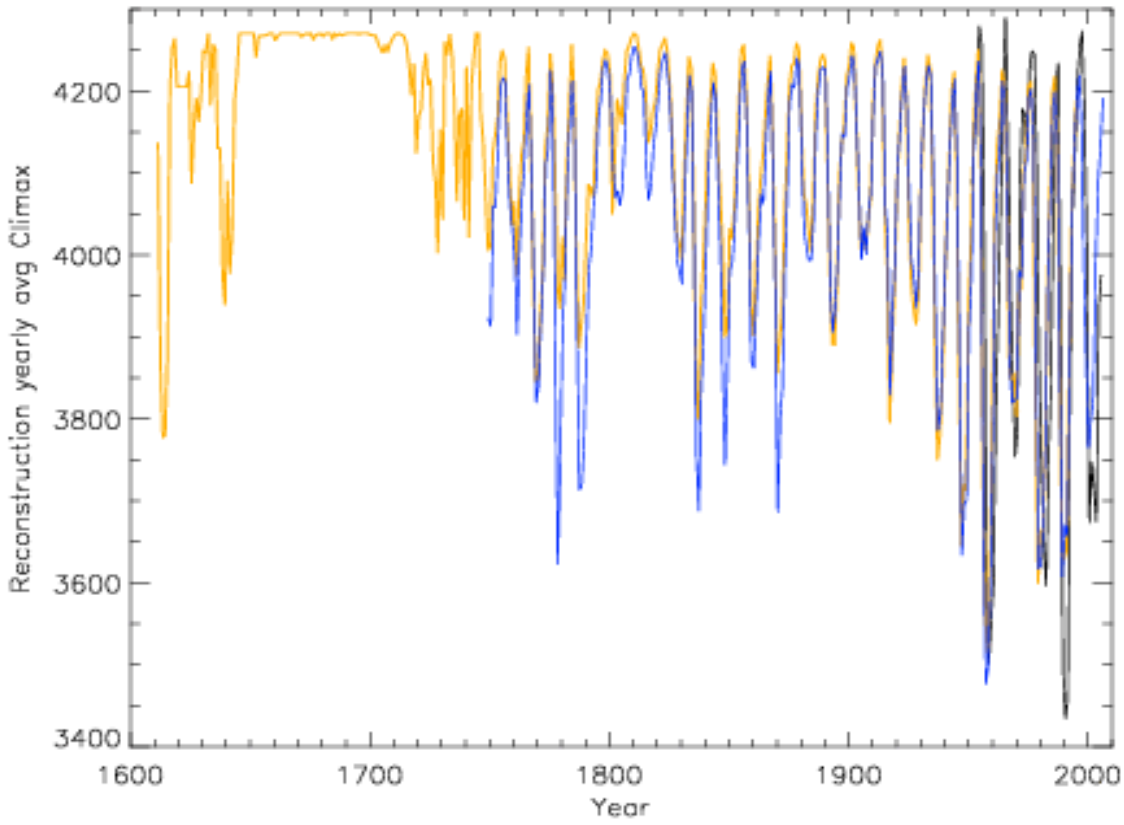
Cosmic Ray Flux Modeling





- Left: CR flux (CLIMAX neutron monitor) versus SN (annually averaged data), Linear correlation = – 0.83
- Right: Reconstructed versus observed CR flux
  Linear correlation coefficient = 0.85
- Significant scatter in the fit, nonetheless correlation still significant

Cosmic Ray Flux variability Reconstructions

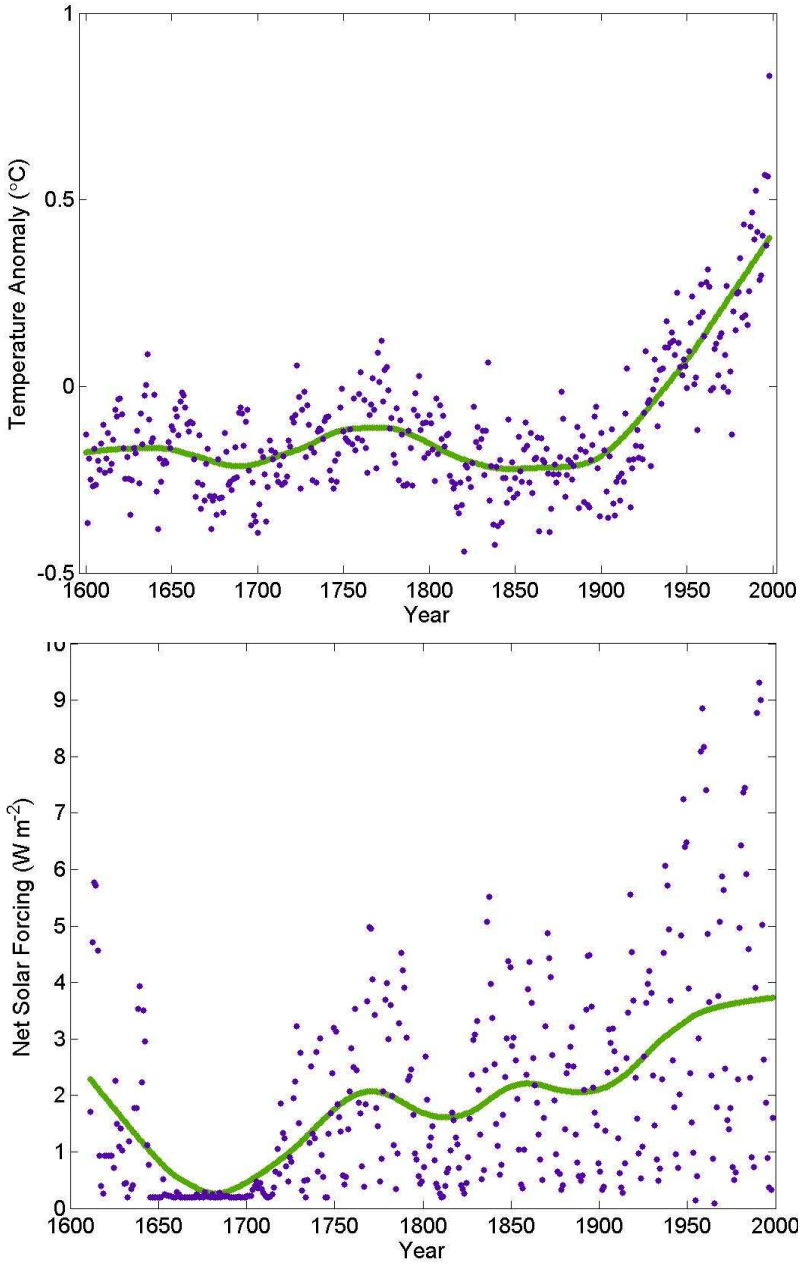


- Reconstructed CR flux time-series based on GSN (orange), ISN (blue), and observed (black)
- Fair agreement: Comparative amplitudes of maxima and minima preserved, although exact matching is not recovered

Estimating the Net Solar Radiative Forcing

- We want to estimate the net solar forcing based on TSI and CR flux
- For this we first assign the Maunder minimum level as the basal level
- Subsequently, we estimate the radiative forcing due to TSI relative to this basal level
- Svensmark (1998) claims that a 1% change in CR flux is equivalent to a change in radiative forcing of 0.42 W/m^2
- We assume that this is the case, and estimate the radiative forcing due to CR flux variations relative to its basal level (the working hypothesis is that more cosmic rays = more clouds = more incident energy reflected away = less net energy input into the Earth system)
- Finally, we add the radiative forcing due to both TSI and CR flux variability to calculate the net solar forcing

Net Solar Forcing versus Global Temperature Changes Since 1600 AD



Comments: Net Solar Forcing and Global Temperature Changes

- Global temperature anomaly is based on Mann et al. (1998)
- Both the temperature and solar forcing data has been smoothed with a locally weighted scatter plot smoothing using a linear least square fitting method to highlight the long-term trends (green curves)
- We note that simplistic co-temporal correlations between solar forcing and global temperature records are not necessarily evident, even before the pre-industrial era
- It seems that changes in solar forcing have an effect with a certain time delay in the global temperature record (note the relative positions of peaks and troughs)
- Note that the post 1800 AD enhancement in solar forcing did not reflect much in the temperature record (which actually kept fairly low)
- This may be due to the Tambora volcanic eruption in Indonesia in 1815 AD; volcanic eruptions are thought to result in global cooling
- In the 20th century, although solar forcing did increase, it is tending to flatten out. However, the global temperature curve continues to rise

Conclusions

- This simplistic analysis taught us the Sun-Climate link is not simple
- Co-temporal correlations are not easy to find between solar forcing and global temperature changes; often the latter lags the former
- We should take into account the cooling effect of volcanic eruptions as this may play a role in disentangling the Sun-Climate link
- Solar forcing did rise in the 20th Century, but it seems to have stopped doing so (that is, if you believe in the smoothing); however, the global temperature rise has not slowed down

Acknowledgements

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