Solar Irradiance Variability Over the Last 9000 Years

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Introduction

- Total (TSI) and spectral (SSI) Solar Irradiance: directly measured from space since 1978 - too short to assess solar influences on climate.
- Irradiance changes are primarily driven by the balance between dark sunspots and bright faculae and network (Krivova et al., 2003).
- While sunspot numbers (SN) have been recorded for over 400 years, data on small-scale bright features in the past are missing.
- Modern observations show that the emergence rate of magnetic features follows a single power-law distribution over a broad range of scales (Thornton & Parnell, 2011).
  → This was used by Krivova et al. (2021) to estimate the emergence rate of small-scale bright features directly from SN.

We use this approach to reconstruct solar irradiance variations over the past 9000 years.

Irradiance reconstruction

The model solves ordinary differential equations to simulate the evolution of surface magnetic flux (Solanki 2000, 2002).
This flux is used as input to the SATIRE-T (Spectral And Total Irradiance REconstruction for Telescopic data, developed at MPS) model to reconstruct TSI (Krivova et al., 2010).
We perform 2 reconstructions:

- Using directly observed SN covering the last 400 years (ISNv2, Clette et al., 2023), see Fig.1.
- Using the SN derived from cosmogenic isotope data (composite of ^{14}C and ^{10}Be) covering the past 9000 years (Wu et al., 2018).

As the SN from cosmogenic isotopes has a decadal cadence, we apply the following steps to resolve solar cycles before reconstructing irradiance:

- We produce synthetic data by taking the observed SN, splitting it into decades, and producing the decadally averaged SN (see Fig.2).
- Decadal averaging is repeated 10 times by shifting the start of the averaging period by one year.
- We derive empirical relations linking decadal SN averages to: SN at cycle maximum, SN at cycle minimum, length of the previous cycle, and the rise time (see Fig.3).
- These relationships are then applied to the decadal SN from cosmogenic isotope composites (Wu et al. 2018a) to resolve individual cycles.

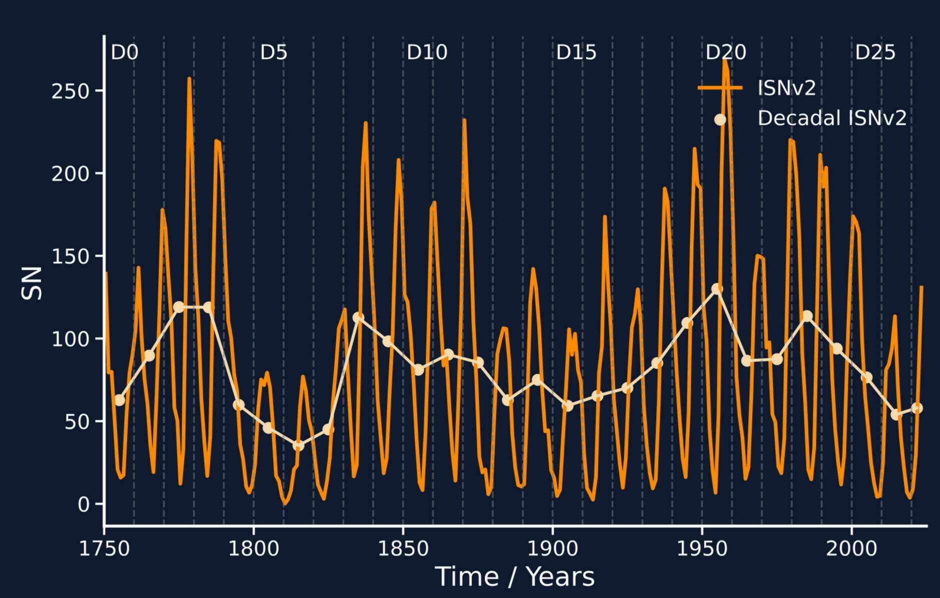

Fig. 2 Annually (orange) and decadally (dots connected by the yellow curve) observed SN (ISNv2 Clette et al., 2023).

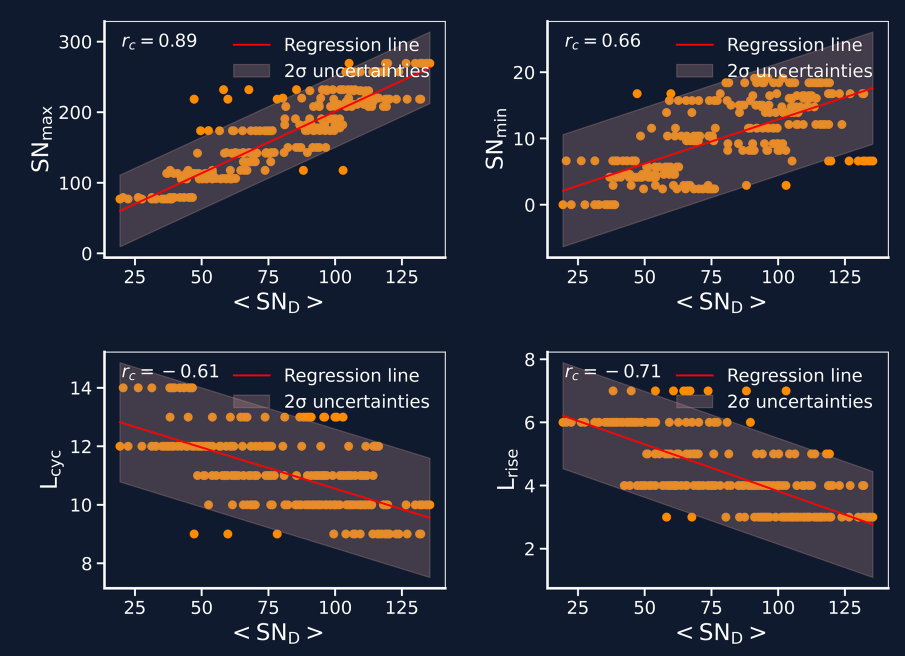

Fig. 3 Relationships between the decadally averaged sunspot numbers and four solar cycle parameters: SN at cycle maximum, SN at minimum, the length of the previous cycle, and the risetime. The shaded area represents the 2σ uncertainty range.

TSI reconstruction from the telescopic data

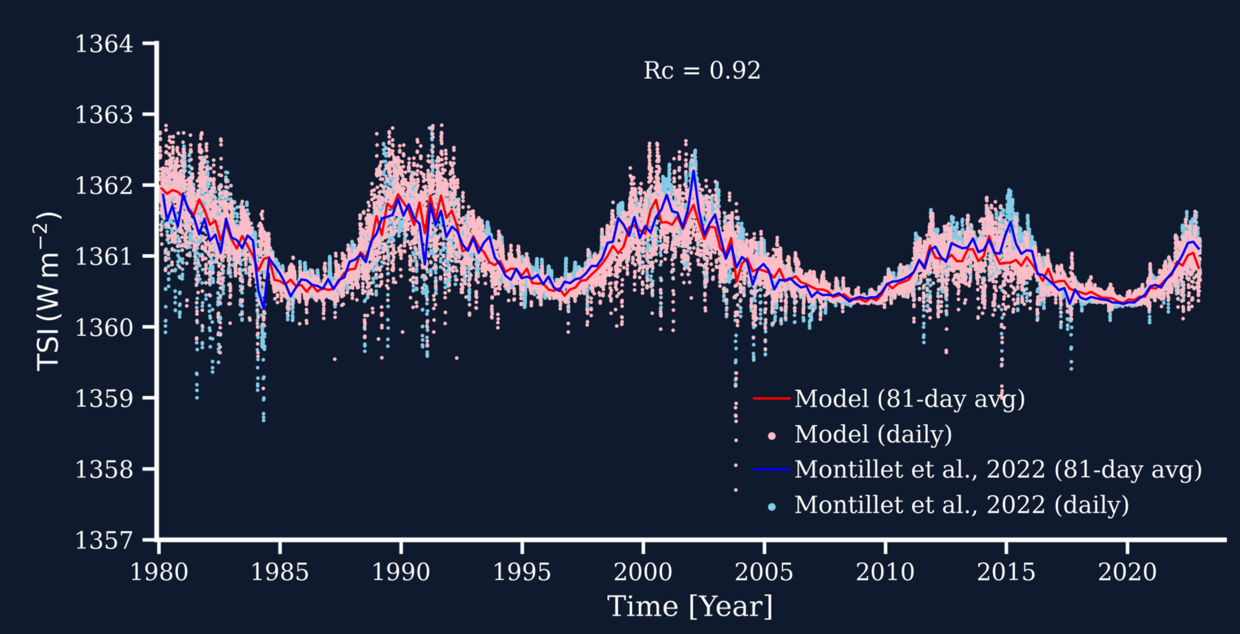

Fig. 1 TSI reconstructed from observed SN (ISNv2): daily values (pink) and 81-day moving average (red). Daily TSI measurements from Montillet et al. (2022, light blue dots), and the 81-day moving average (blue curve). The correlation coefficient between the model and the observations is Rc = 0.92.

TSI reconstruction for the past 9000 years

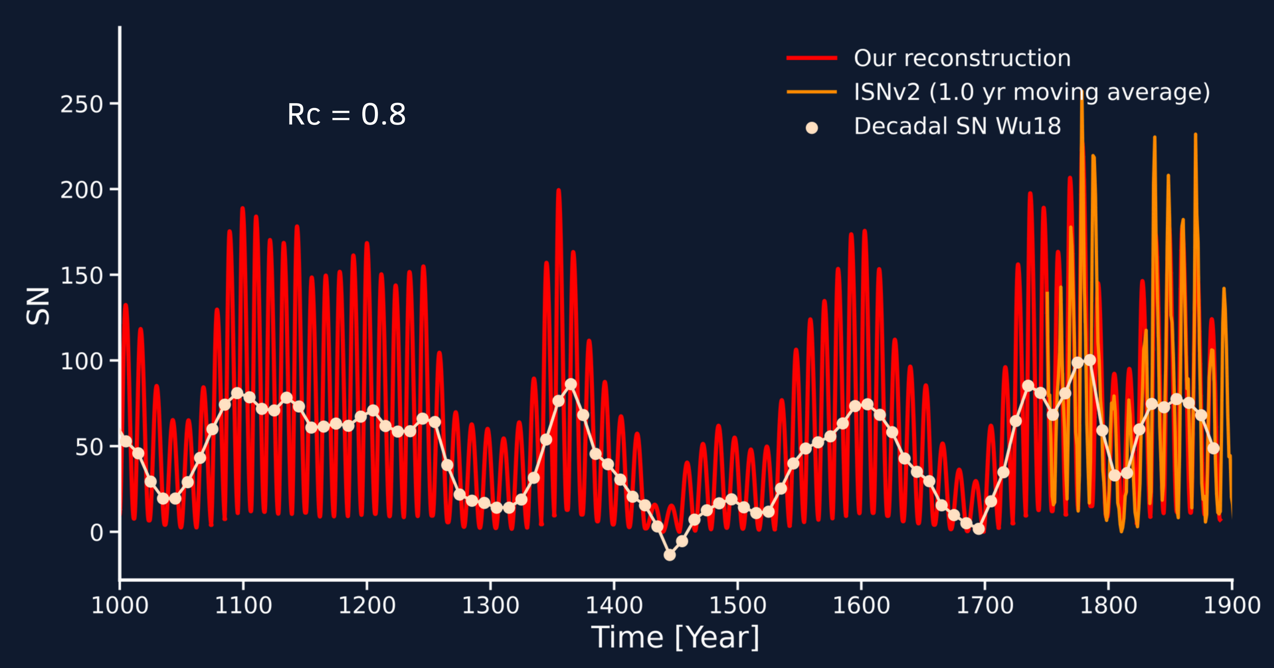

Fig. 4 Annual SN reconstructed from the decadal cosmogenic isotope composite (red). The decadal SN from the cosmogenic isotope composite (Wu et al., 2018a, light orange dots). The observed SN with a one-year average (orange). The reconstructed annual SN and observed SN have a correlation of Rc = 0.8 over the overlapping period.

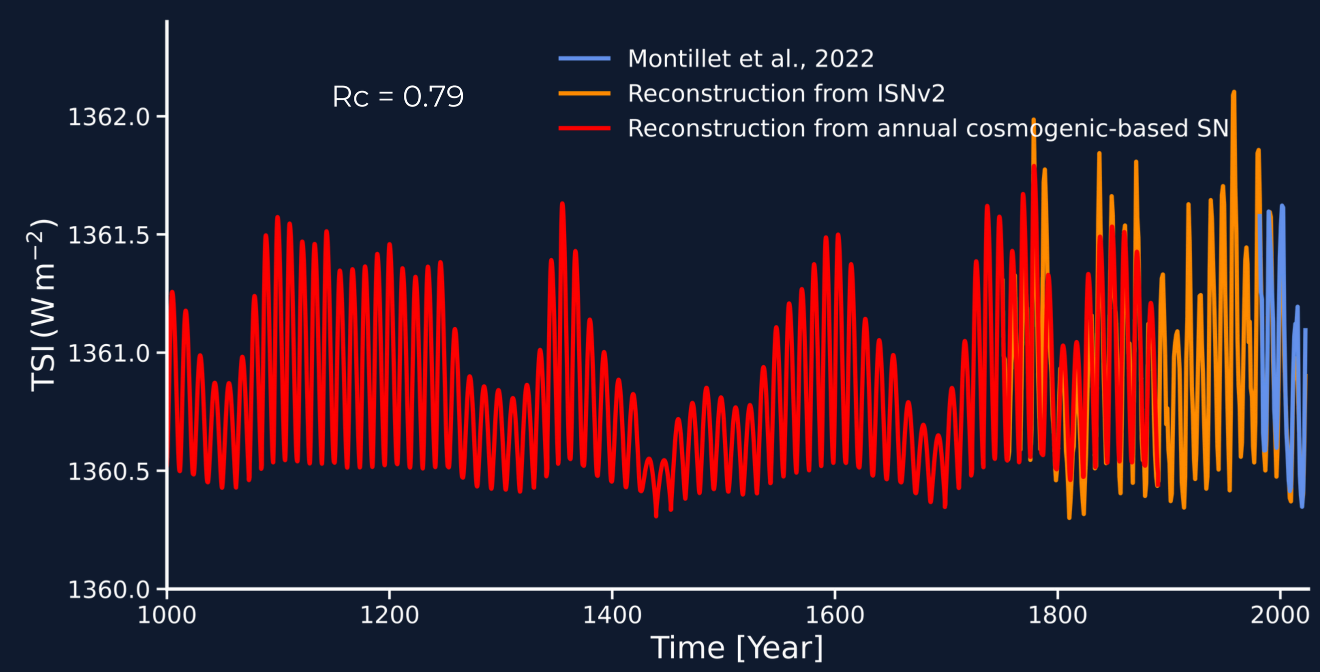

Fig. 5 TSI reconstructed from: SN derived from cosmogenic isotopes (annual resolution, red), from telescopic SN (annually averaged orange), and the TSI composite by Montillet et al. (2022, blue). The TSI reconstructed from the cosmogenic-based SN and from ISNv2 align with Rc = 0.79.

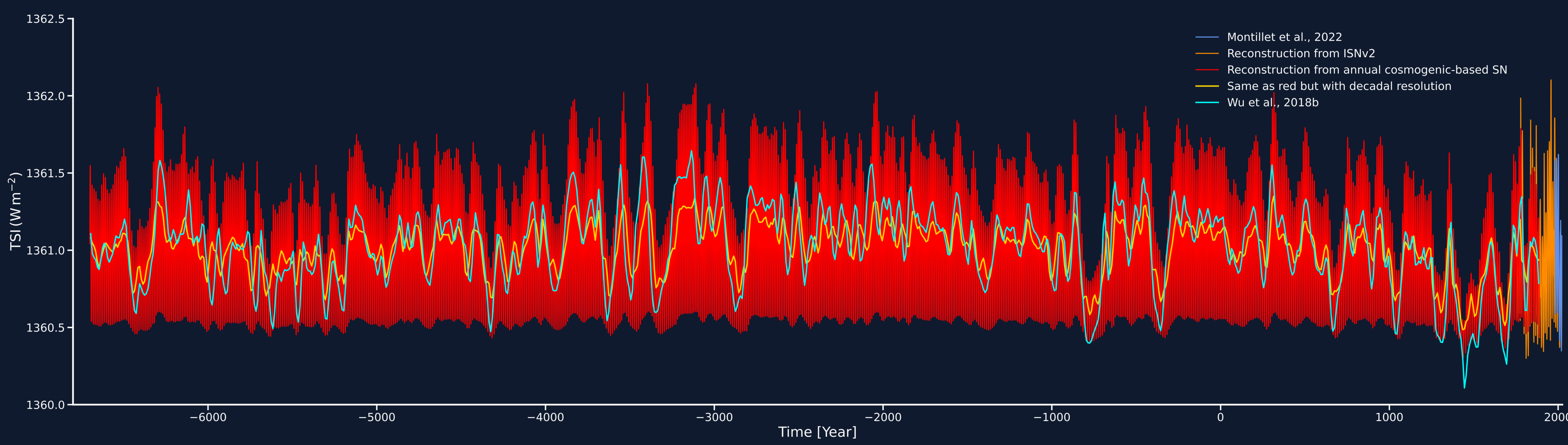

Fig. 6 The total solar irradiance reconstructed from the cosmogenic isotope data for the past 9000 years with annual resolution (red) and decadal resolution (yellow). Decadal TSI reconstruction from cosmogenic isotope data from Wu et al. 2018b (cyan). Our annual TSI reconstruction from the telescopic data (orange). Annual TSI measurements from Montillet et al. (2022, blue).

Summary

- **We use the updated SATIRE-T model to reconstruct Total Solar Irradiance (TSI) from direct sunspot observations over the last 400 years (Fig.1).**
  → We find excellent agreement (Rc = 0.92) with observed TSI (Montillet et al., 2022).
- **To extend the reconstruction over the past 9000 years from the decadal cosmogenic isotope composite (Wu et al. 2018):**
  - **We derive statistical relationships between the decadally averaged SN and solar cycle parameters (e.g., SN at max, SN at min, rise time, cycle length, Fig. 2).**
  - **We reconstructed annual SN and found a good agreement (Rc = 0.79) with the observed sunspot number ISNv2 (Fig. 4).**
  - **We used these reconstructed annual SNs, resolving the solar cycle, as input to the SATIRE-T model to compute annual TSI over nine millennia (Fig. 5, 6).**
- **TSI reconstructed from cosmogenic isotope data agrees well with the TSI reconstructed from telescopic data, with a correlation coefficient of (Rc = 0.79) over the overlapping period.**

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