Millennium scale reconstruction of SSI/TSI with CHRONOS model

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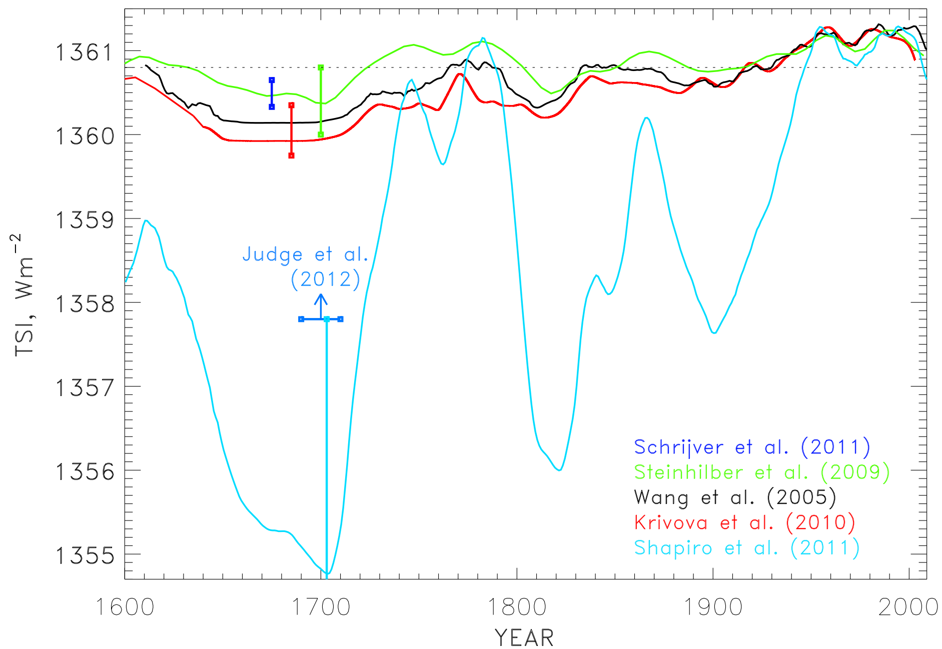
Motivation:

SSI reconstruction by Shapiro et al. (2011)



1. Address criticism (e.g., Judge et al., 2012; Ermolli et al., 2014)
2. Improve Shapiro et al. (2011, SSR11) approaches in the representation of decadal scale SSI variability.

Model CHRONOS

CHRONOS (Code for the High ResolutiOn recoNstructiOn of Solar spectral irradiance):

CHRONOS = NESSY + filling factors + quiet Sun

- Radiation code for the SSI calculations

SSR11: COSI using homogeneous distribution (full disk approach)

CHRONOS: NESSY (Tagirov et al., 2016), using activity belts for spots and plages.

- Calculation of the filling factors

SSR11: Linear relation to SSN for spots and plages.

CHRONOS: Linear/nonlinear relation to SSN for umbra/penumbra and plages.

- Calculation of the quiet Sun irradiance

SSR11: Model A from Fontenla et al. (1999); SMP from (McCracken et al., 2004)

CHRONOS: Model B; SMP from (Steinhilber et al., 2009)

SSI calculations

$$I(\lambda,t) = I_{qs}(\lambda,t) + \alpha_f(t) \times (I_f(\lambda)-I_c(\lambda)) + \alpha_{su}(t)\times(I_{su}(\lambda)-I_c(\lambda)) + \alpha_{sp}(t)\times(I_{sp}(\lambda)-I_c(\lambda))$$

t – time (the year);

I(λ,t) or I(λ) – spectral solar irradiance (calculated with NESSI)

qs – the quietest Sun (new model "B")

f – plage or facula (model "P" from Fontenla et al., 1999)

su – sunsport umbra

sp – sunspot penumbra

c – present day quiet sun (model C from Fontenla et al., 1999)

α – filling factors (calculated from SSN)

QS irradiance calculations (long-term evolution)

$$I_{qs}(\lambda,t) = I_c(\lambda) + (I_b(\lambda) - I_c(\lambda))\,(\Phi_{1996} - \Phi(t)) / (\Phi_{1996} - \Phi_{min})$$

t – time (the year);

I(λ,t) – spectral solar irradiance

qs – quiet Sun

c – atmospheric structure model 'C'

b – atmospheric structure model 'B' for minimal solar activity

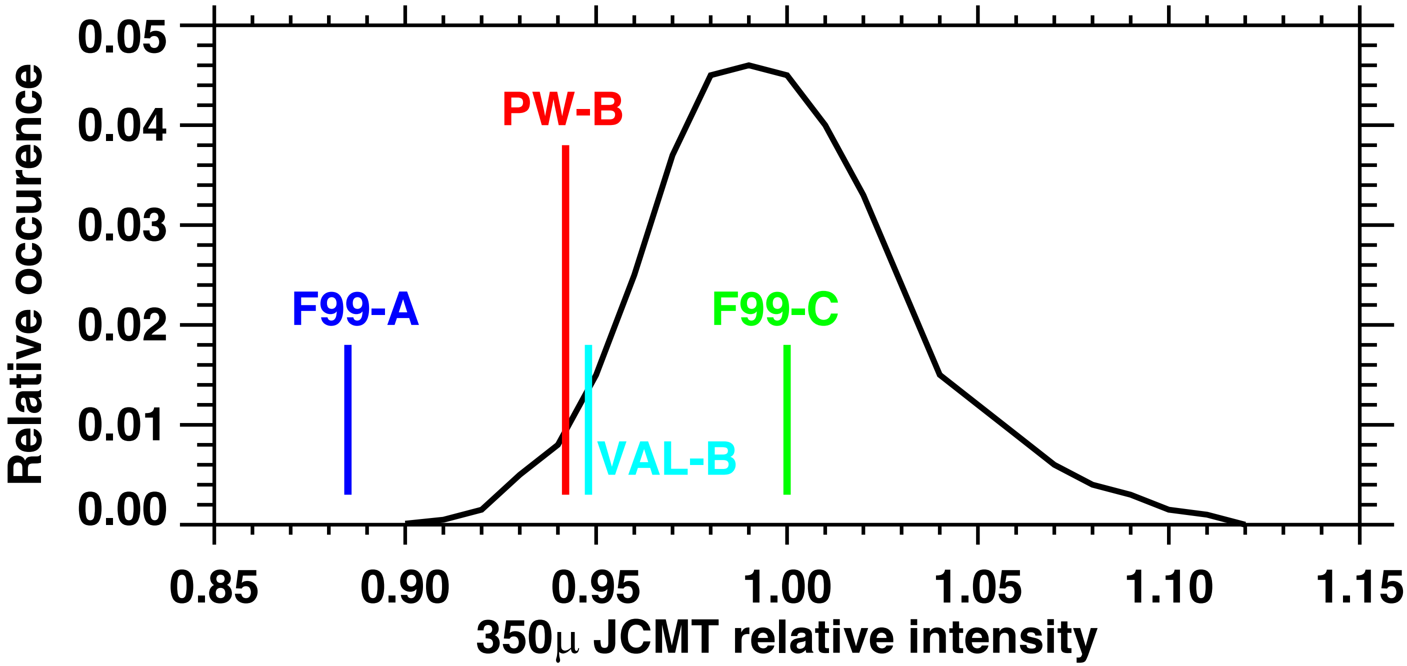
Φ (t) – time dependent solar modulation potential (SMP)

Φ_{1996} *– SMP for the present state of the Sun*

Φ_{min} *– smallest SMP for the time period 7000 BP - 2015*

Judge et al. (2012):

SSR11: Judge et al. (2012) noted that model A (from Fontenla et al., 1999) for the Quietest Sun is too cold

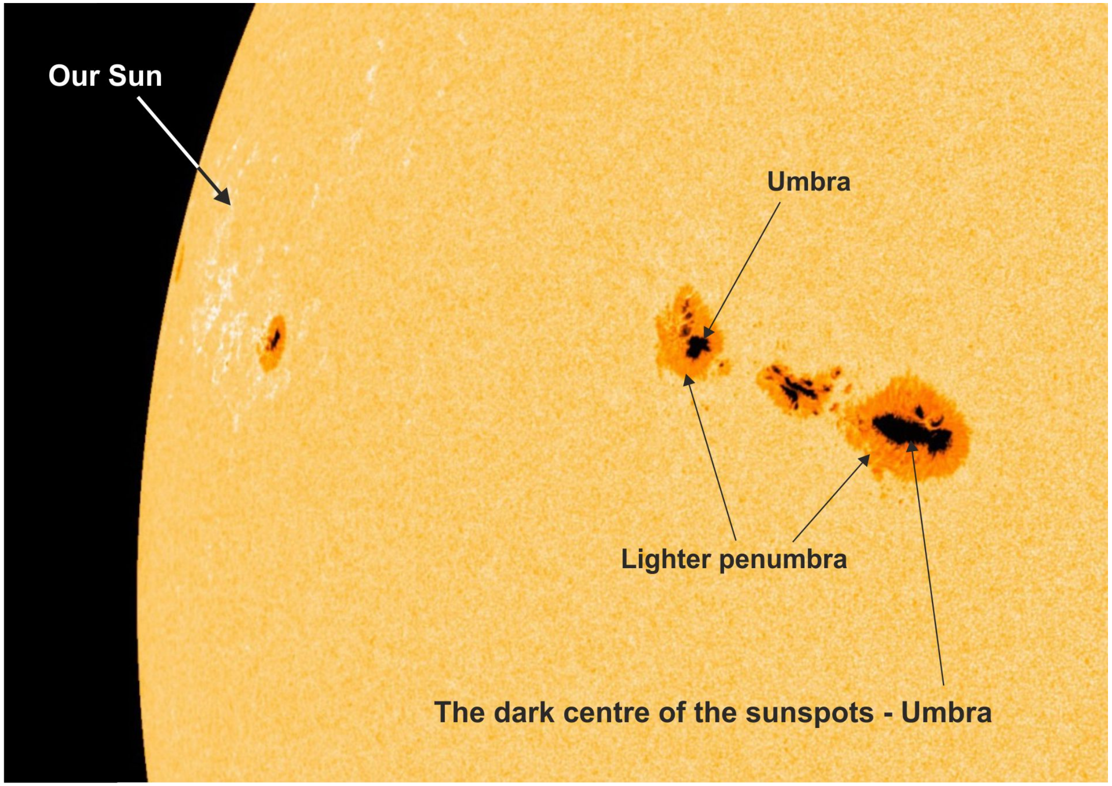


The distribution functions of relative intensities of quiet Sun regions at 350 μm observed with the James Clerk Maxwell telescope by Lindsey et al. (1995) and evaluated by Judge et al. (2012). The relative intensity 1.00 corresponds to the median of the frequency distribution. Model F99-C is representing the present day quiet Sun and its intensity is set to unity. The fluxes of model F99-A and of model B of the present work (PW-B) are indicated relative to the 350 mm flux of F99-C. The location of model VAL-B is placed as given by Judge et al. (2012).

CHRONOS: we use model B to represent the Quietest Sun

Ermolli et al., 2013

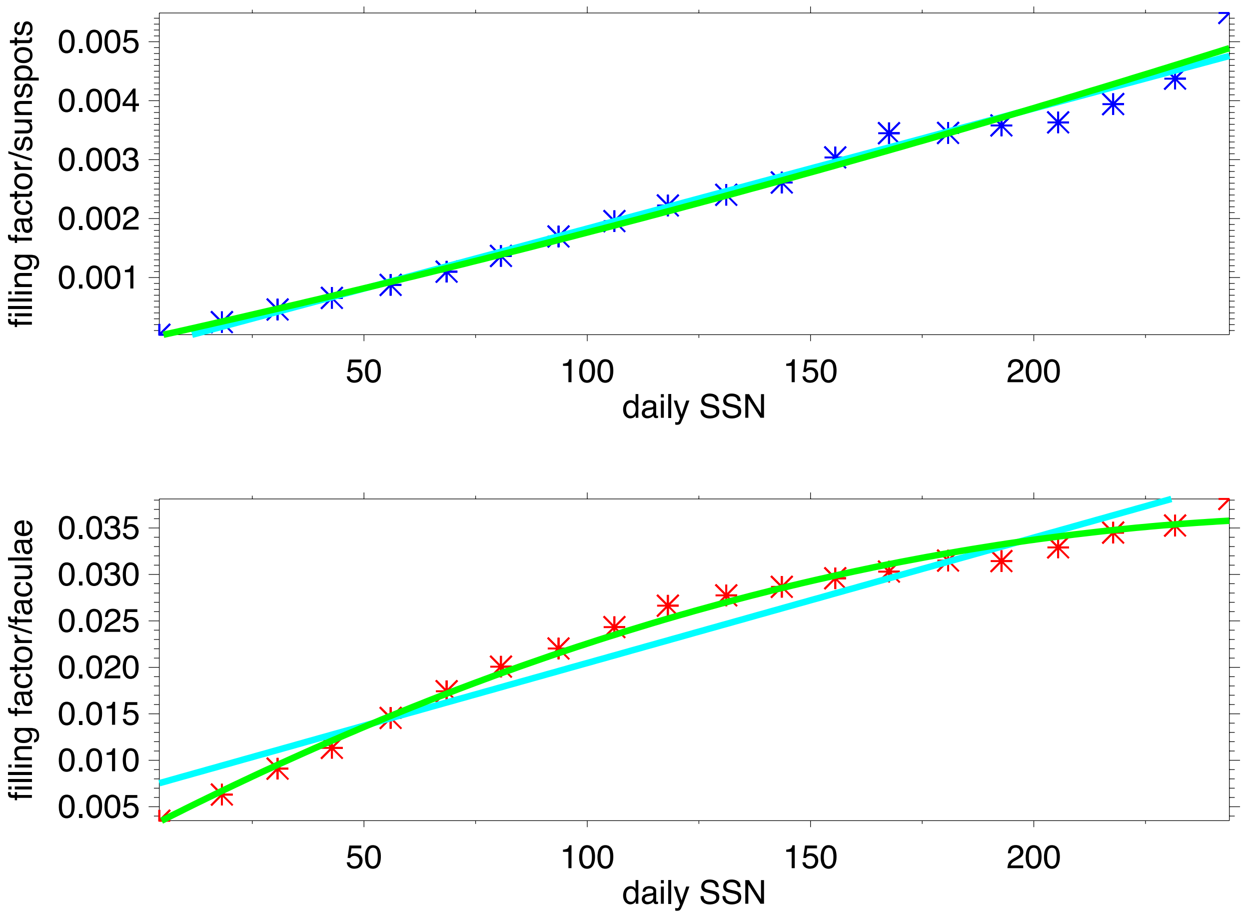
SSR11: They do not distinguish between umbra and penumbra



CHRONOS:: we have introduced spectra for umbra and penumbra separately

Calculations of the filling factors

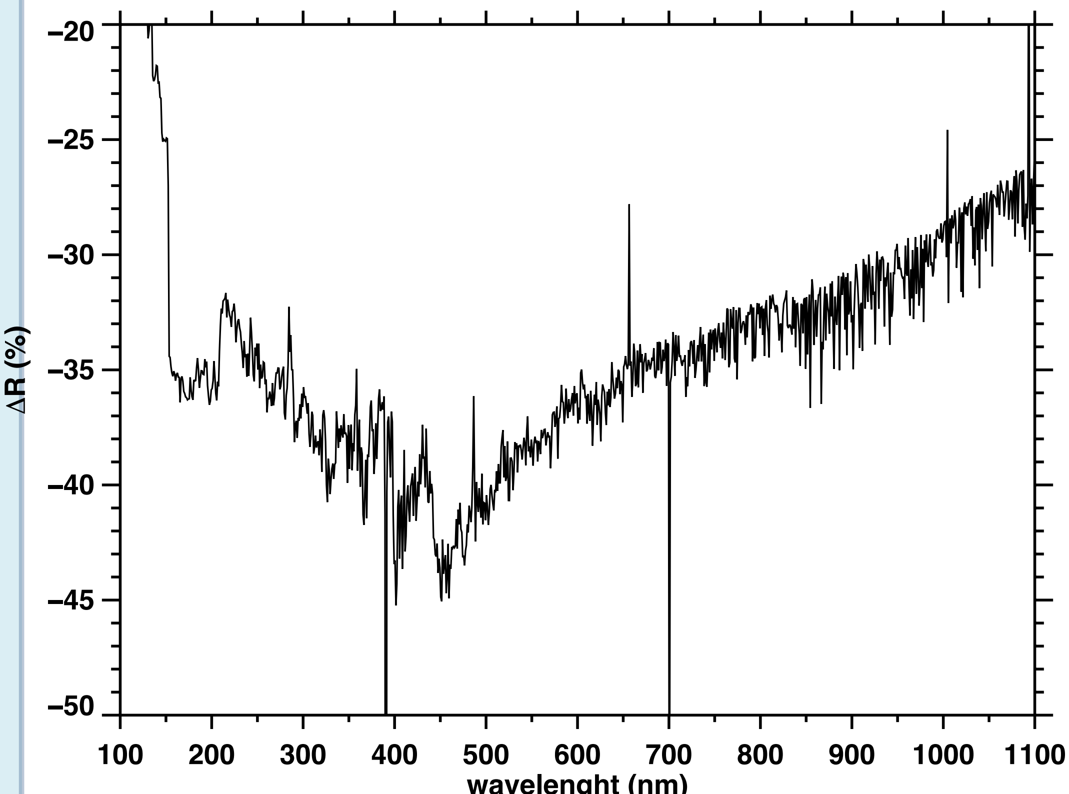
SSR11: Linear relation to SSN for spots and plages.

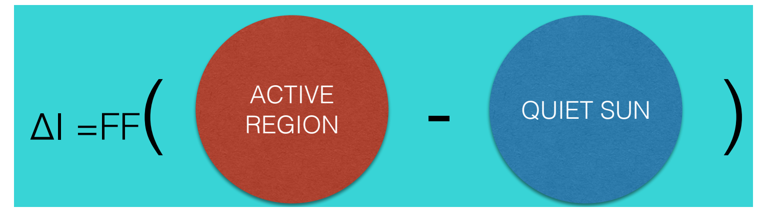


CHRONOS: Linear/nonlinear relation to SSN for umbra/penumbra and plages.

Activity belts for the irradiance calculations

SSR11: homogeneous distribution (full disk approach)



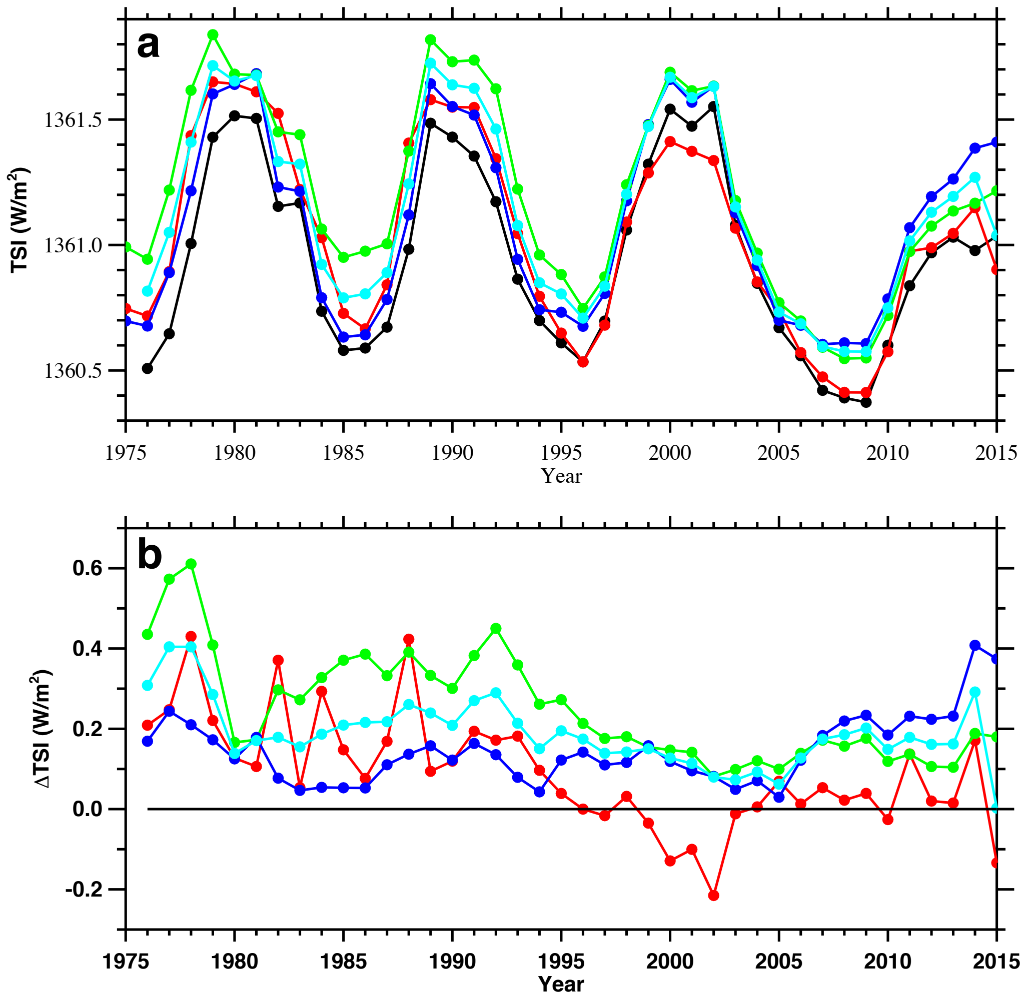


Relative deviation of the facular contribution to the brightening of the Sun (I_{FAC}-I_{QS}) calculated using activity belt approach from full disk model.

CHRONOS: activity belts for spots and plages.

New reconstruction of TSI and SSI covering period of time 6000 BCE – 2015 CE

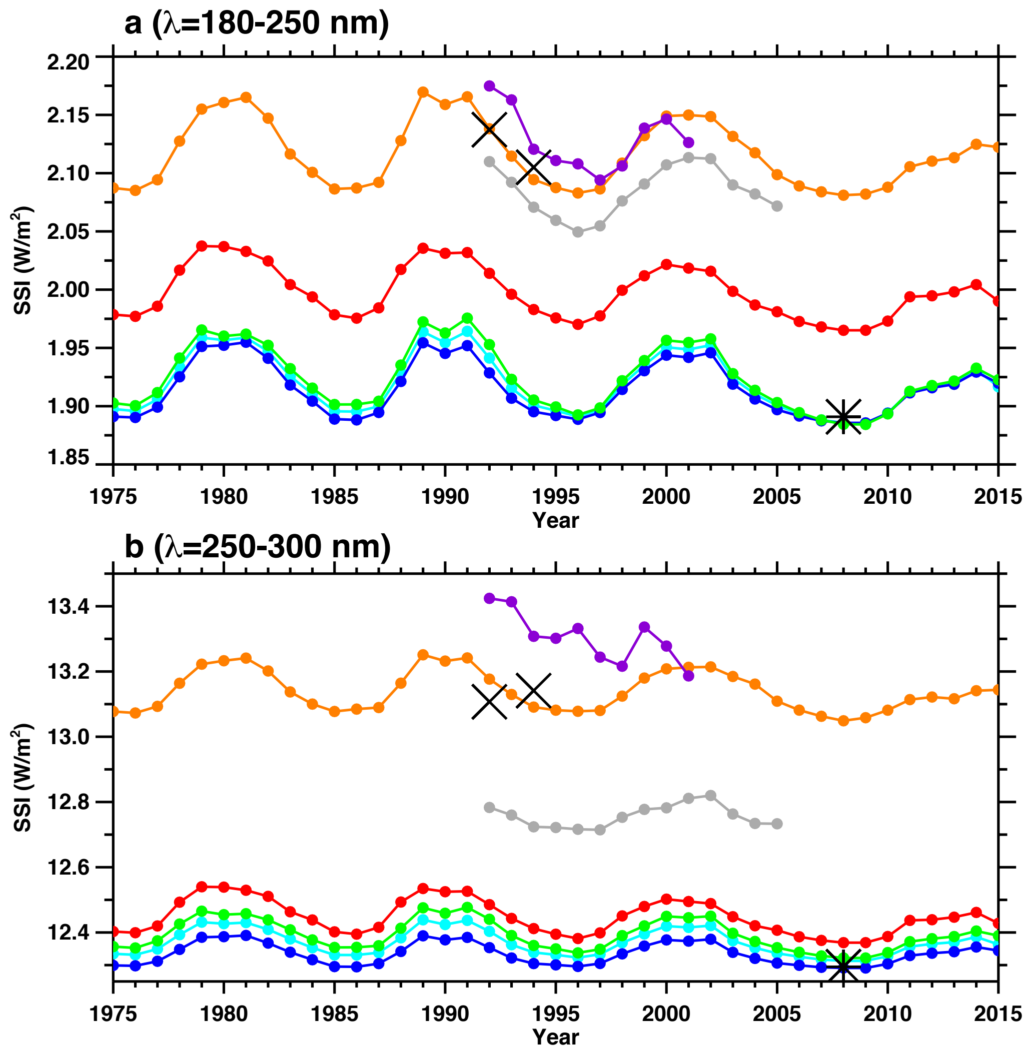
Decadal scale total solar irradiance variability



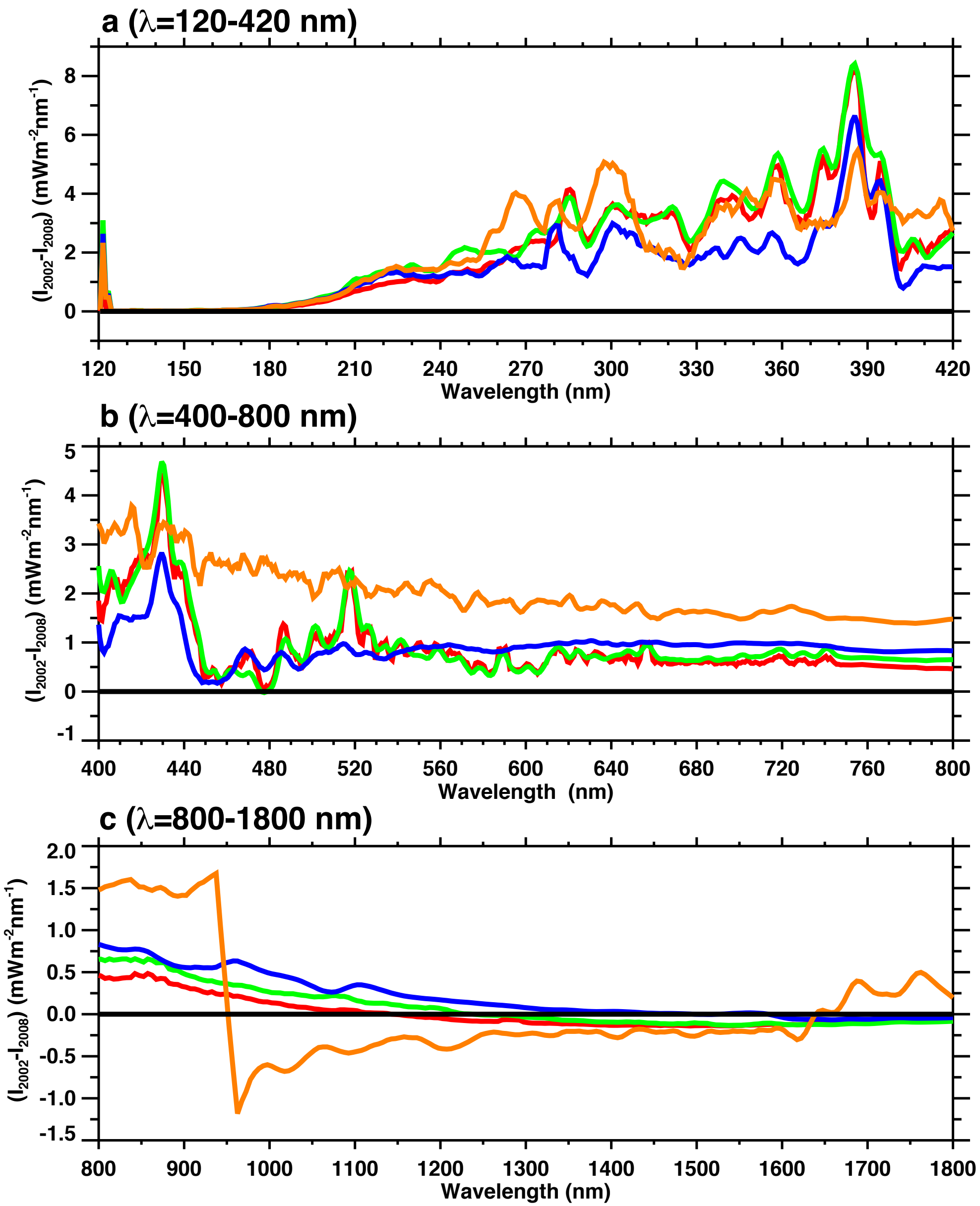
a) Total solar irradiance (TSI, W/m²) evolution calculated using **CHRONOS** in comparison with the **PMOD** composite, the **SATIRE**, the NRL models and solar irradiance prepared for the CMIP-6 project.

b) The deviation of TSI (W/m²) calculated using the **CHRONOS**, the **SATIRE**, the **NRL** models and solar irradiance prepared for the CMIP-6 project from the **PMOD** composite.

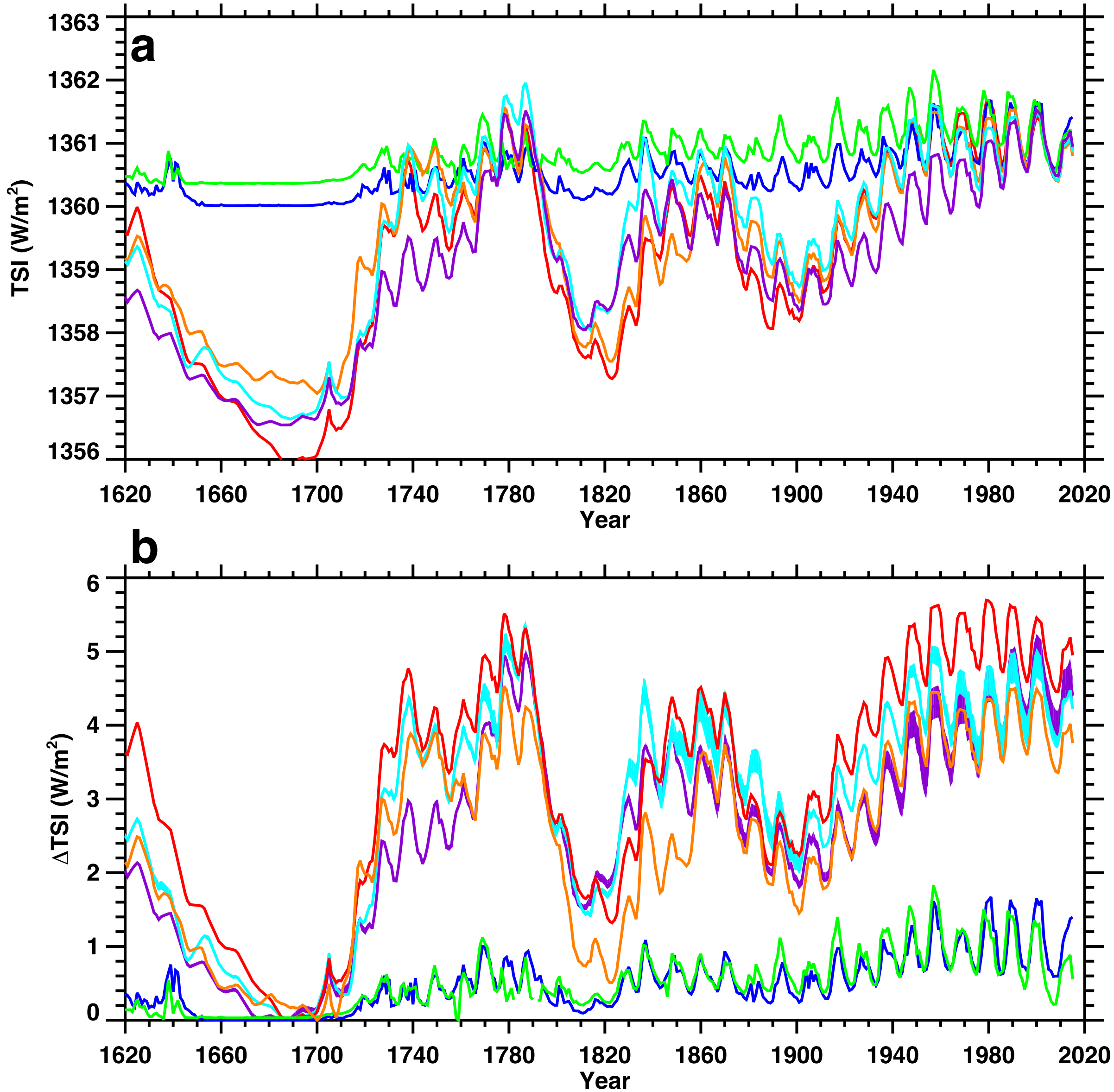
Decadal scale spectral solar irradiance variability



Solar irradiance (W/m²) evolution calculated using **CHRONOS** in comparison with **SATIRE**, **NRL**, **CMIP-6**, **UARS SUSIM** and **SOLSTICE**, **SOLID** composite. The data from the reference spectral measurements in 1992, 1994 (ATLAS missions) and 2008 (WHI misison) are shown by crosses and asterisk. Panels a and b show the results for the wavelengths intervals 180-250 nm and 250-300 nm respectively.

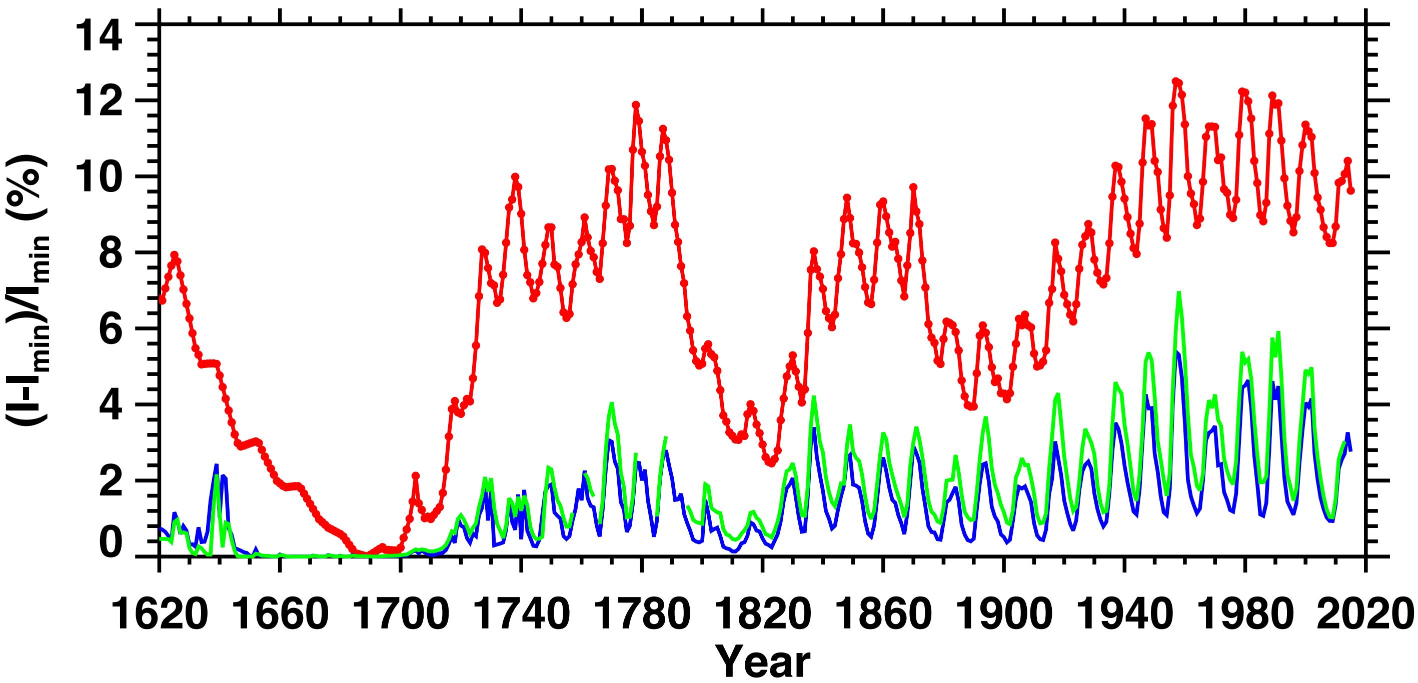


*Spectral solar irradiance (mWm^{-2}nm^{-1}) difference between years 2002 and 2008 from **CHRONOS** in comparison with **SATIRE**, **NRL**, and **SOLID** composite. The original time series were smoothed using 5 nm window for better visibility.*

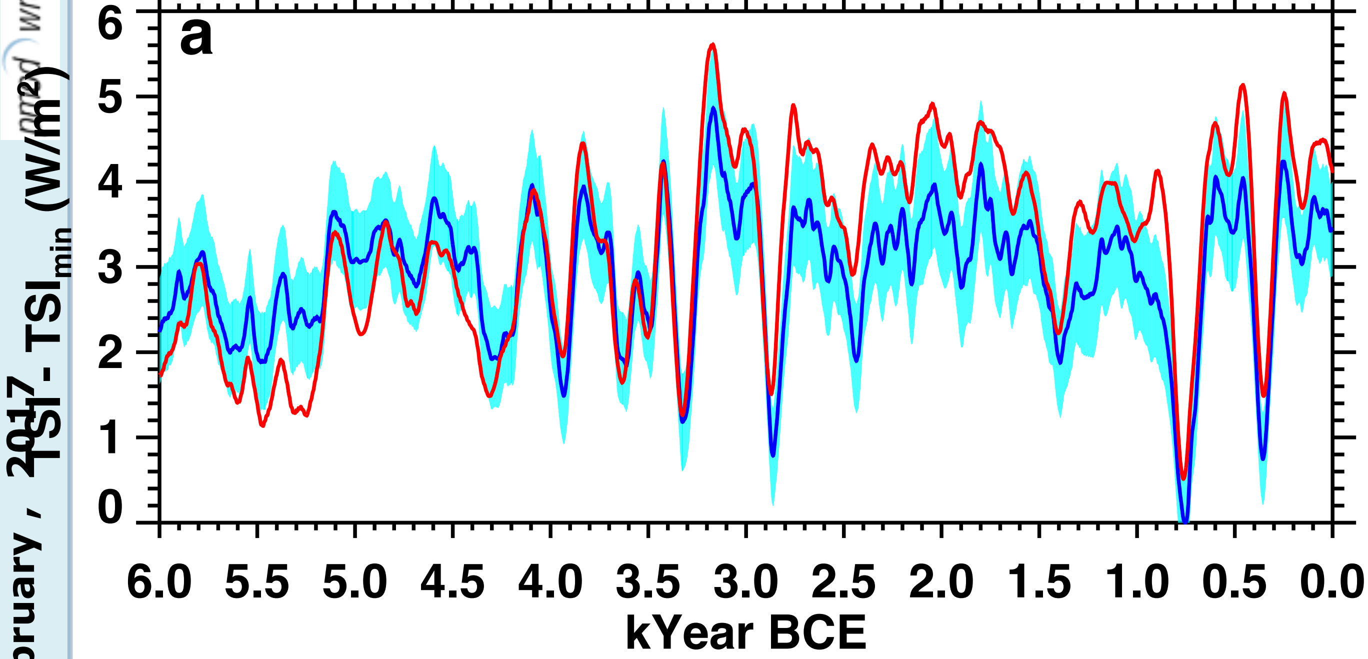


a) Total solar irradiance (TSI, W/m^2) evolution calculated using **CHRONOS** with McCracken, (2007, **orange**), McCracken, 2017, **red**), Usoskin (2016**,** **light blue**) and Muscheler (2016, violet) solar modulation potentials in comparison with the **SATIRE**, the **NRL** .

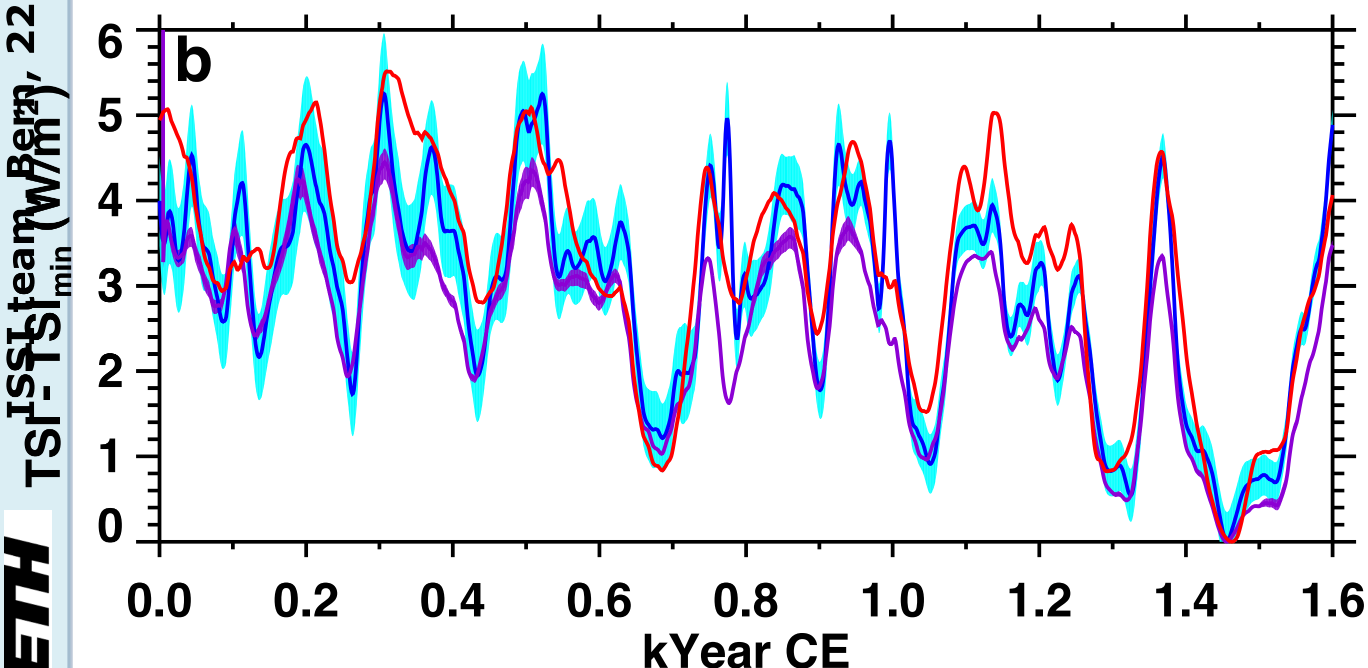
b) The deviation of TSI (W/m^2) from the minimal values for the same models.



Relative deviation of SSI integrated over 180-250 nm from its minimum value (%) from ***CHRONOS*** *in comparison with* ***SATIRE*** *and* ***NRL*** *.*



a) *The deviation of TSI (W/m^2) from the minimal values from 6000 years BCE calculated with CHRONOS using solar modulation potentials of* McCracken, (2017, **red**), Usoskin (2016, **light blue**) and Muscheler (2016, violet) . *The time series were smoothed using 100 years window.*



b) *The same but for the period 0-2000 years CE. The time series were smoothed using 11 years window.*

Conclusions

1. The new reconstruction of TSI and SSI using Code for the High ResolutiOn recoNstructiOn of Solar spectral irradiance (CHRONOS) covers the period 6000 BC 2015 AC

2. The improvements provide better agreement with the observed solar irradiance variability on decadal time scale. We demonstrate that the performance of our model with simplified treatment of the solar active regions is similar to the existing more complicated models.

3. Using the updated model and proxy data we show that the magnitude of the multi-centennial solar forcing is 25-40% smaller in comparison to SSR11. This smaller-than-expected decrease of the amplitude results from compensating effects of the application of the new basic solar structure model and the new solar modulation potential data.

4. In agreement with Judge et al. (2012) the substitution of basic model A used in SSR11 by model B reduces the amplitude of solar forcing from SSR11 by a factor of about two, but the application of the new updated solar modulation potential time series enhanced the forcing leading to up to 4.5 W/m^2 TSI increase from Maunder to present day minimum in 2008.

5. The magnitude of TSI and SSI increase on multi-centennial time scale exceeds the estimates published by other groups rendering the question about the magnitude of solar forcing open.