Including ephemeral regions in surface flux transport simulations and solar irradiance reconstructions

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Abstract

Time-series of historical solar irradiance variations is an important input to climate models. An extension of the record of direct irradiance measurements available since 1978 to earlier times is only possible with the help of models. For this, we need to know the evolution of the surface magnetic field. The longest record of direct observations of solar activity is the sunspot number covering the last four centuries. However, it has the shortcoming that it only allows tracing the evolution of the large-scale active regions (ARs) harbouring sunspots, while the evolution of small-scale ephemeral regions (ERs) is heavily uncertain. At the same time, ERs play an important role in driving the long-term irradiance variations. We use a new model of the ERs emergence based on recent solar observations, where the emergence of all magnetic regions is described by a single power-law distribution with an exponent varying with solar activity, as represented by the sunspot number. The evolution of the magnetic field with time is simulated with a surface flux transport model (SFTM). The computed total magnetic flux is in good agreement with observations. The simulated magnetic field maps can be used for future TSI reconstructions.

Introduction

The Sun's total radiative energy flux at the mean distance from the Sun of 1 AU per unit area is called the total solar irradiance (TSI). TSI is a crucial input to climate models, yet measurement exist only since 1978. Longer TSI timeseries can be reconstructed from proxies of solar activity, based on the knowledge that the variation of TSI is driven by magnetic features on the solar surface, such as sunspots and faculae. The mostly used proxy is the sunsport number (SN), as it is the longest directly observed record of magnetic activity on the Sun. Missed by the SN records is the contribution of ephemeral region (ERs), short-lived bipolar magnetic regions (BMRs) that are too weak to form sunspots. Due to the high number of emerging ERs per day, even during solar minimum, they play an important role for the long-term TSI variability. Existing models either do not account for their evolution at all or link them linearly to active regions (ARs). We aim to model the evolution of ERs more realistically by including them as input into a surface flux transport model (SFTM) and reconstruct the evolution of the solar magnetic flux and TSI.

Emergence rate

We describe the emergence of all BMRs by a single powerlaw-size distribution (Krivova et al. 2021), based on the observations by Thornton & Parnell (2011).

$$\frac{\mathrm{d}N}{\mathrm{d}\phi} = \frac{n_0}{\phi_0}\left(\frac{\phi}{\phi_0}\right)^m , \qquad (1)$$

where ϕ is the magnetic flux of the region, $\phi_0 = 10^{16}$ Mx is the flux of the smallest features in the observations and $n_0 = 3.14 \times 10^{-14}$ cm^{-2} day^{-1}. The exponent m varies with the sunspot number and is fixed by comparison to the observations of Harvey that ARs change by a factor of 8 between solar activity minimum and maximum while ERs only change by a factor of 2.

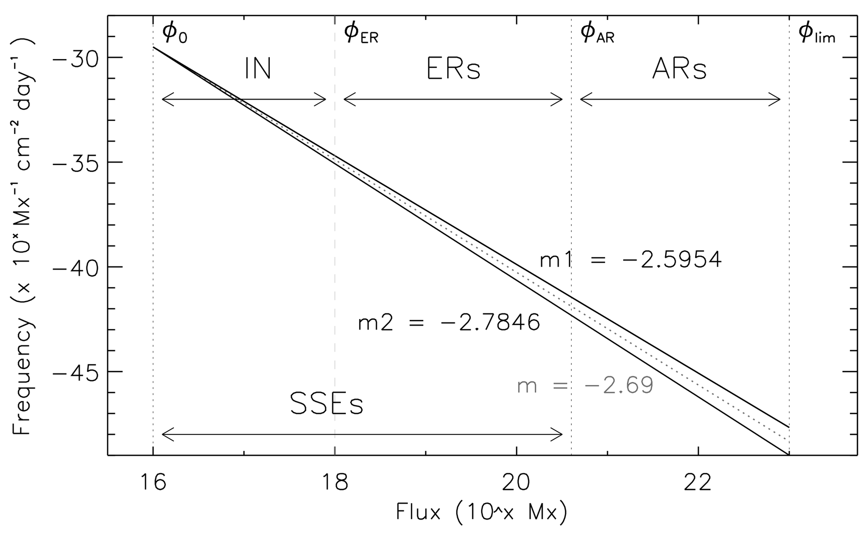

Figure 1: Frequency of emergence vs. the unsigned flux of an emergence event (see Eq. (1) following Thornton & Parnell 2011). ϕ_0, $\phi_{\rm ER}$, $\phi_{\rm AR}$ and $\phi_{\rm limit}$ represent the limit below which the local dynamo flux dominates, the minimum ephemeral region flux, the minimum active region flux, and the upper limit of the active region flux, respectively. The horizontal arrows mark the flux ranges corresponding to the internetwork (IN), ephemeral regions (ERs), active regions (ARs), and Small-Scale Emergences (SSEs). The SSE range includes IN fields and ERs. The slope m of the distribution was derived by Thornton & Parnell (2011) by fitting various observations at different activity levels. Slopes m_1 and m_2 represent the corresponding distributions at maximum and minimum of solar activity levels for cycle 21, respectively.

Tilt angle and latitude

Next, we model the emergence latitudes λ and tilt angles a_n of the distribution. For ARs, we use the empirical relationships by Jiang et al. (2011) and Jiao et al. (2021). The latitude distribution depends on strength of the solar cycle S_N (maximum of the 13-month running mean), as well as the phase within the solar cycle. The tilt angle depends on the square root of the emergence latitude as well as the cycle strength.
We model the standard deviations of ERs in agreement with observations by Harvey (1993). For the tilt scatter of ARs we follow the observations by Schunker et al. (2020) and the latitude scatter is taken again from Jiang et al. (2011). We use the magnetic flux limits of ERs and ARs from Krivova et al. (2021) to fit a relationship of the standard deviation with region size; see Fig. 2

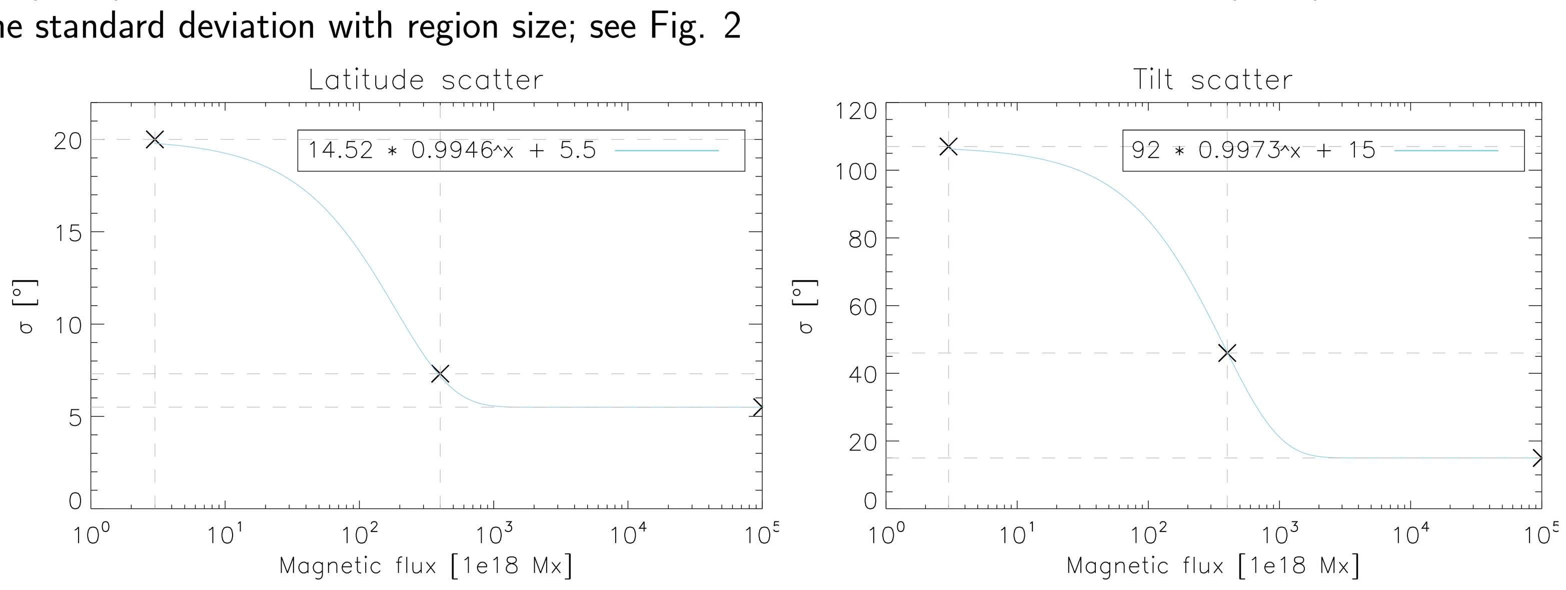

Figure 2: Left panel: Standard deviation of the emergence latitude depending on the magnetic flux of the region.
Right panel: Standard deviation of the tilt angle depending on the magnetic flux of the region.

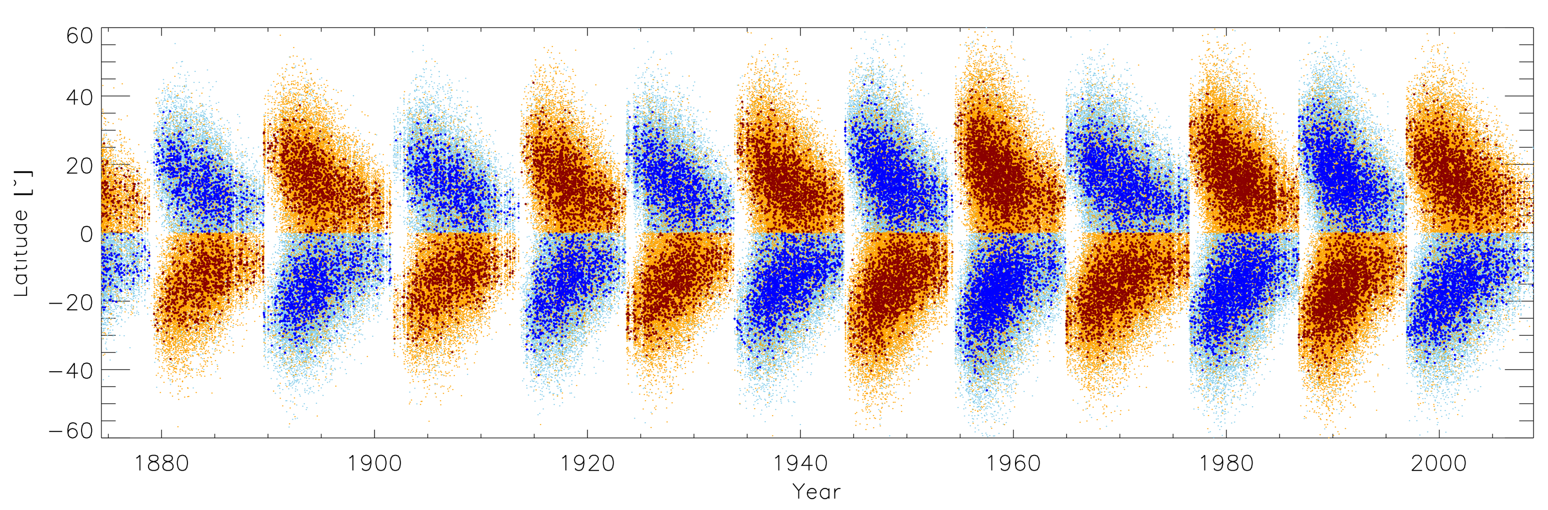

Figure 3: Simulated butterfly diagram using the mean emergence latitude and tilt angle distributions by Jiang et al. (2011) as well as the standard deviations from the fits in Fig. 2. Large, dark dots are large ARs forming sunspot, while small dots are small BMRs without spots.

Surface Flux Transport Model

A Surface Flux Transport Model (SFTM) simulates the evolution of the solar surface magnetic field through the effects of differential rotation, meridional flow and diffusion. New magnetic flux in form of BMRs is added through the source function. The shape of BMRs in the SFTM is given by the following equation adapted from van Ballegooijen et al. (1998) and depends on the angular separation $\Delta\beta$ between the two Gaussian-like magnetic polarity patches.

$$B^{\pm}(\theta,\phi) = B_{\rm amp} \exp\left\{\frac{2(1-\cos(\beta_{\pm}(\theta,\phi)))}{\beta^2_{\rm init}}\right\}. \qquad (2)$$

where $\beta_{\rm init} = 0.4\Delta\beta$ is the initial width of the polarity patch. $B_{\rm amp}$ is the maximum amplitude of the BMR. The angular separation determines the lifetime of a BMRs. A relationship between $\Delta\beta$ and initial magnetic flux of the region $\phi_{\rm BMR}$ is obtained by matching the SFTM lifetimes of the BMRs with the observed lifetimes derived from Thornton & Parnell (2011); Parnell et al. (2009):

$$\Delta\beta[^\circ] = 5.40 \times 10^{-11}\left(\phi_{\rm BMR} \times \frac{250}{B_{\rm amp}[\mathrm{G}]}\right)^{1/2} \qquad (3)$$

We find a good agreement for $B_{\rm amp} = 1300$G.

Total magnetic flux

Two populations of BMRs are tested in the SFTM in order to reconstruct the total magnetic flux. The first one includes large active regions forming sunspots (LAR) and the second includes all active regions with lifetimes $\geq$ 1 day, which is the current timestep of the SFTM. To the simulation output, we add the contribution by small-scale-emergences (SSEs, including ERs) using a set of ordinary differential equations following Krivova et al. (2021). We find that the total magnetic flux is in good agreement with observations from ground-based observatories, especially for the SAR run.

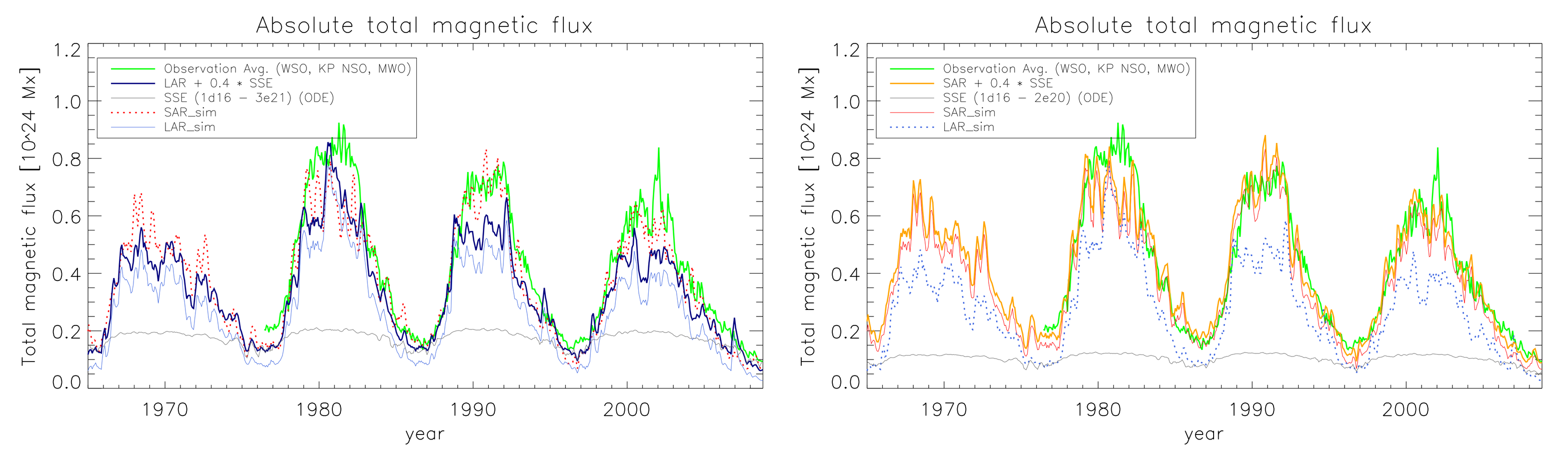

Figure 4: Total magnetic flux obtained from the simulated magnetograms. To the simulation output, we add the contribution of small scale regions not included in the SFTM from the model by Krivova et al. (2011) calculated from a set of ordinary differential equations. The results are compared to the average total magnetic flux from observations. Left panel: The first run (LAR) only includes large active regions that would feature sunspots ($\geq 3 \times 10^{2}1$Mx). Right panel: The second run (SAR) includes small active regions ($\geq 2 \times 10^{0}1$Mx) with lifetimes $\geq$ 1 day.

Conclusions

- Most models of solar irradiance and magnetic flux evolution on centennial time scales rely on sunspot observations.
- Sunspot data do not feature ER, but they are important for secular TSI changes.
- To overcome this, we follow the approach by Krivova et al. (2021) and use a single powerlaw distribution (Thornton & Parnell 2011) to describe emergence of regions of different sizes.
- The spatial distribution of the BMRs follows empirical relationships in agreement with observations.
- The total magnetic flux is in good agreement with observations.
- Next steps: Inclusion of even smaller regions into the SFTM.
- Reconstruct TSI from simulated magnetograms.

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