Prediction of Sunspot Cycle 25

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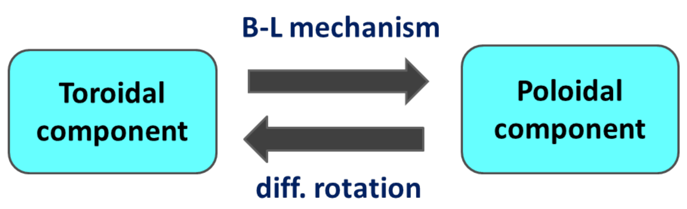
Highlights: Century-scale observational data-driven simulations of solar magnetic field are utilised to predict sunspot cycle 25 – ***for the first time***

Abstract

Solar magnetic activity strongly influences the space weather condition in heliosphere at different time scales: on the one hand, via short-lived but high energetic events such as solar flares, coronal mass ejections, geomagnetic storms and on the other, by modulating the overall heliospheric magnetic and particulate flux output on decadal timescale. As space weather studies have gradually gained impetus predicting the strength of future solar cycle has become an important yet challenging scientific objective. The intrinsic stochastic nature of the solar convection zone limits the predictability up to one cycle. Physics-based predictions can be achieved by utilizing solar dynamo models with precise knowledge of the poloidal magnetic field at cycle minimum. Here we present a methodology to extend the predictive time window by first using a Surface Flux Transport (SFT) simulations to generate the probable poloidal field at cycle 24 minimum and eventually implementing this in a dynamo model to predict the strength and peak timing of solar cycle 25.

Introduction

The magnetic cycle of the Sun is understood to originate from a magnetohydrodynamic dynamo mechanism[1] involving complex interactions between plasma flows and magnetic field within the solar convection zone, resulting in a systematic cyclic interchange between the two components of the magnetic field (the toroidal, B_T and the poloidal, B_P) with a periodicity of 22 years. Differential rotation in the solar interior stretches B_P in the azimuthal (ϕ) direction – generating and amplifying B_T, which eventually rises through the solar convection zone due to magnetic buoyancy and emerge on the solar surface as sunspots with latitude-dependent tilt angle (decided by the Coriolis force). Dispersal of the magnetic field associated with these tilted sunspots in presence of large-scale plasma flows and magnetic diffusion regenerates B_P through a complex process – also known as the Babcock-Leighton *(B-L)* mechanism[2]. In short,



The B-L mechanism also leads to reversal (at solar maximum) and build-up of the solar polar field which reaches eventually its maximum amplitude at solar minimum. Thus, while the decadal-scale sunspot cycle is a manifestation of the time-varying toroidal component (B_T), evolution of the poloidal component (B_P) is captured in the time series of the polar magnetic field measured on the solar surface.

The polar field at solar minimum is found to be the best precursor for predicting the amplitude of the subsequent cycle which is nothing but an outcome of the working principles of solar dynamo. However, reliable prediction using a dynamo model is only possible if polar field (or B_P) during cycle minimum is known – restricting the prediction range within half a solar cycle ($\sim$ 5 years). In this work, we use a methodology to extend the time window for prediction further by first utilizing a ***Surface Flux Transport*** (**SFT**) model to predict the polar field at the minimum and subsequent using this to drive a solar ***Dynamo*** model to predict the next cycle toroidal field which in turn decides the sunspot cycle amplitude.

We have developed a data-driven SFT model to simulate surface magnetic field dynamics over last century (1913 – 2016) and extract the poloidal field information from this model at every solar minimum and assimilate them into a solar dynamo model to reproduce the century-scale evolution of the sunspot forming toroidal field component. This combined SFT-dynamo setup is further utilized to predict the amplitude, shape, and timing of solar cycle 25.

Computational Models

Surface Flux Transport (SFT) Model

The SFT model, developed by imbibing the fundamental elements of the BL-mechanism, replicates the dynamics of surface magnetic field which is governed by the magnetic induction equation. Since the surface magnetic field is primarily in the radial direction, we solve only the radial component, $B_r(\theta, \phi, t)$ of the induction equation which can be expressed in spherical polar coordinates as,

$$\frac{\partial B_r}{\partial t} = -\omega(\theta)\frac{\partial B_r}{\partial \phi} - \frac{1}{R_\odot \sin\theta}\frac{\partial}{\partial\theta}\Big(v(\theta)B_r\sin\theta\Big) + \frac{\eta_h}{R_\odot^2}\left[\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\Big(\sin\theta\frac{\partial B_r}{\partial\theta}\Big) + \frac{1}{\sin^2\theta}\frac{\partial^2 B_r}{\partial^2\phi}\right] + S(\theta,\phi,t)$$

Where θ and ϕ represent co-latitude and longitude, respectively. $R_\odot$ is the solar radius. $\omega(\theta)$ and $v(\theta)$ correspond to the differential rotation and meridional circulation on solar surface which are modeled using latitude-dependent functions[3,4] obtained from analyzing observational data. For magnetic diffusivity, η_h, we assume a constant amplitude of 250 km^{2}s^{-1}. The source term, $S(\theta, \phi, t)$, represents emergence of new sunspots on the solar surface.

Source of Sunspot Data

We utilize observational data (for a period spanning from 1913 to September 2016) obtained from the sunspot database of the **Royal Greenwich Observatory (RGO)** and **USAF/NOAA** where we assume all sunspots appearing on the solar surface are **b**ipolar **m**agnetic **r**egions (BMRs) with tilt angles decided by a modified Joy's law[5]. Beyond September 2016, we model the declining phase of cycle 24 (i.e., the last 3.25 years) by using 110 synthetic sunspot input profiles[6] with statistical properties similar to those of the already observed spots during solar cycle 24.

Solar Dynamo Model

We use a 2D kinematic axisymmetric solar dynamo model[7] which includes both B-L mechanism and mean field α- effect for generation of B_P from B_T. In a continuous century-scale dynamo simulation we regularly assimilate the surface magnetic field maps obtained from the SFT simulation at every solar minimum (for cycles 16–23). The dynamo model also mimics the eruption of sunspots and provides a proxy (B^{Dyn}) for the toroidal magnetic field at the base of the convection zone, quantification of which can be used to reproduce past solar cycles. The century-scale dynamo simulation is then forward run in a predictive mode to simulate solar cycle 25 by utilizing predicted surface magnetic map at cycle 24 minimum.

Published as: Bhowmik & Nandy, Nature Communications 9, 5209 (2018)

Funding: CEFIPRA-IFCAR grant, NASA Heliophysics Grand Challenge grant, MHRD, Govt. of India

Results

Longitudinally averaged radial magnetic field $B_r(R_\odot, \lambda, \phi, t)$ obtained from the SFT simulation is plotted as a function of latitude and time covering sunspot cycle 15 to the currently on-going cycle 24 to generate the magnetic butterfly diagram.

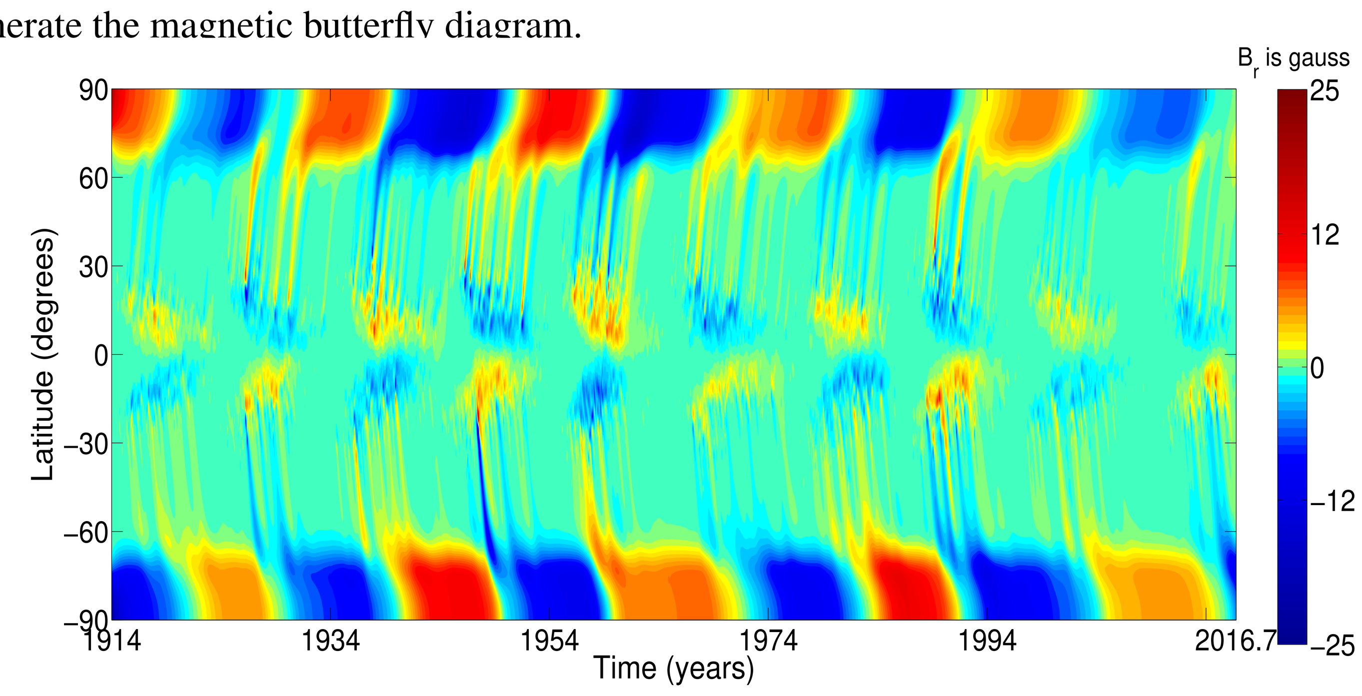


Figure 1: **Evolution of the surface magnetic field during the last 100 years.**

We further compare the time evolution of polar flux calculated from our SFT simulations with those obtained from polar faculae observations during the last 100 years[8]. A linear correlation analysis between the simulated averaged (over two hemispheres) polar flux and the observed one during solar minima gives Pearson correlation coefficient of 0.88.

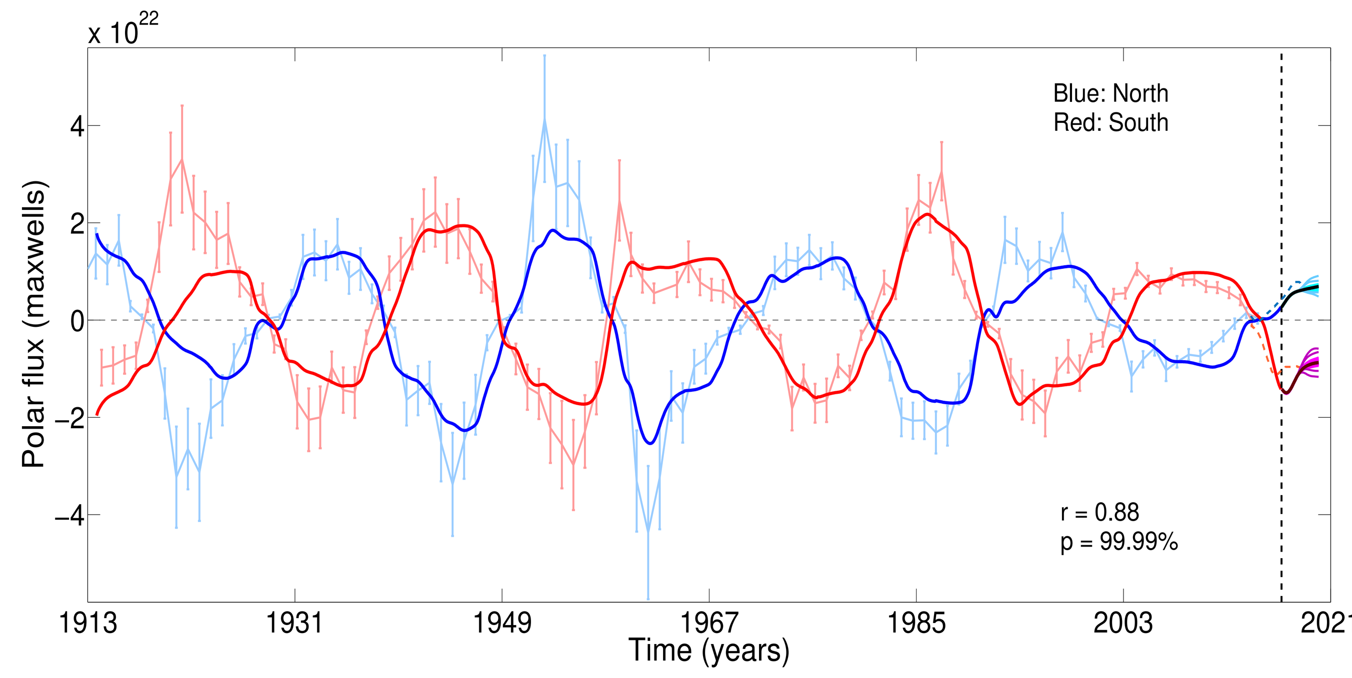


Figure 2: **Data-driven simulation of solar surface polar flux.** The light blue (and light red) curve with error bars represents the polar flux estimated from polar faculae observations in the northern (and the southern) hemisphere, whereas the solid blue (and red) curve shows the polar flux obtained from our simulation. The dashed blue (and dashed red) curve beyond 2014.5 represents the polar flux obtained from WSO polar field observations for the northern (and the southern) hemisphere. The set of light and dark cyan and magenta curves beyond September 2016 (vertical dashed line) depict predicted polar fluxes (up to 2020) from ensemble runs with several synthetic input profiles. The black and dark red curves represent the polar field prediction associated with a standard predictive run.

Finally, we assimilate surface maps obtained from the SFT simulations at every solar minimum (starting from cycle 16 minimum until the end of solar cycle 24) in the poloidal magnetic field component in a century-scale continuous dynamo simulation. A linear correlation analysis between the peak of $B^{Dyn}(t)$ and maxima of observed unsigned magnetic flux associated with sunspots during the past eight solar cycles gives Pearson correlation coefficient of 0.87. We note that at no point in our century-scale simulations is any individual scaling done to the amplitude of any single cycle, or any model driving parameters is fine-tuned.

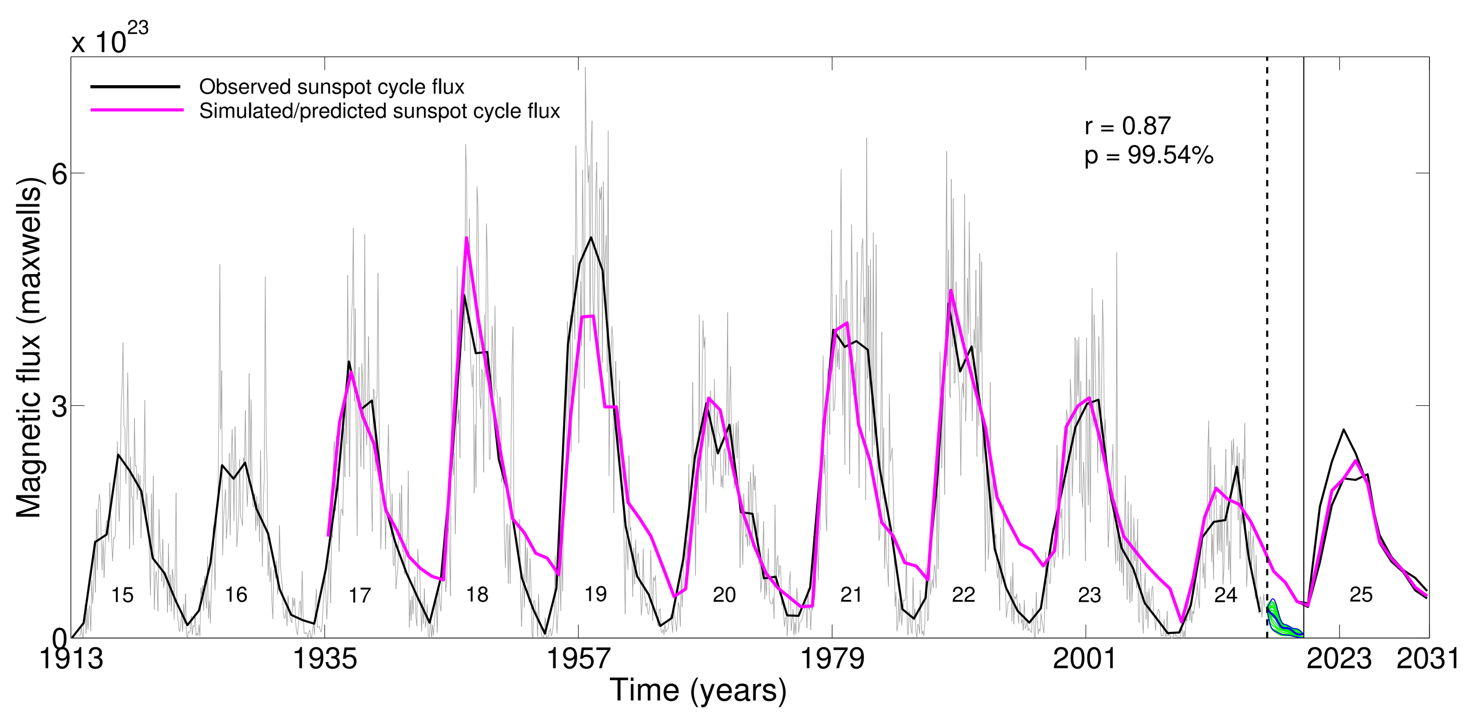


Figure 3: **Prediction of sunspot cycle 25.** Solar dynamo simulated sunspot cycles (magenta curve) compared with the observed sunspot cycle (unsigned magnetic flux; black curve), where both quantities are yearly averaged. The light gray curve in the background represents monthly averaged unsigned sunspot flux. The blue and set of green curves between the vertical black dashed and solid lines depict flux associated with the synthetic profiles used in the SFT model as plausible realizations of the descending phase of cycle 24. The magenta curve beyond the solid-black vertical line depicts the predicted shape and strength of sunspot cycle 25, and the set of two black curves beyond the solid-black vertical line represent the strongest and the weakest magnetic cycles (that is the range of our ensemble forecast) based on our diverse predictive dynamo runs.

Conclusions

- Prediction window for solar cycles can be extended to a decade allowing for advanced space weather assessment and preparedness.
- During solar cycle 25 the maximum magnetic flux (annual averaged) will be 2.29×10^{23} maxwells (with a predicted range: (2.11–2.69)$\times10^{23}$ maxwells) peaking around 2024($\pm$1) – indicating an overall weak solar cycle similar or slightly stronger than the current cycle 24.
- The corresponding prediction for the yearly mean sunspot number at the maximum of cycle 25 is 118 with a predicted range of 109–139.
- Solar cycle 25 is likely to alter the multi-cycle weakening trend observed in the last 40 years of solar activity.

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