Polar Field Predictions
with A *Surface Flux Transport Model*

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Abstract

Surface Flux Transport Models study the spatio-temporal evolution of the magnetic field on the solar photosphere. Observational data driven SFT models can give a good estimate of the strength of polar fields. Since the polar field at the end of a cycle is known to be strongly correlated with the amplitude of the subsequent sunspot cycle, data driven SFT modelling of the polar field can extend the prediction window by a full cycle. Our aim is to develop a SFT model for prediction of polar flux and finally couple this with a dynamo model for extended solar cycle forecasts.

Introduction

The sunspots appearing on the solar surface is a distinct manifestation of magnetic nature of the Sun. It is believed that the dynamo mechanism inside the solar convection zone is responsible for sustaining the decadal sunspot cycle. The evolution of sunspots on the solar photosphere is governed by Babcock-Leighton *(BL)* mechanism. In this mechanism, magnetic flux associated with the sunspots gets diffused due to turbulent diffusion (caused by turbulent motion of super-granular convective cells) and drifts towards the pole with the help of meridional circulation. The advected flux accumulates at the pole and alters the polarity of the global solar magnetic field. This polarity reversal generally occurs during cycle maximum. The polar flux attains its peak value during cycle minimum.

It was shown in previous studies that polar flux generated at the end of a cycle plays an important role in determining the amplitude of subsequent cycle. This is the main motivation for developing a Surface Flux Transport *(SFT)* Model which captures the physics of BL mechanism acting on magnetic field and gives an estimation of the polar flux produced at the end of a cycle. Thus SFT models can be used as a tool for forecasting global solar activities.

Here we have presented the preliminary results obtained from our simulation of magnetic field evolution for the time period spanning from 1913 to 1987.

Surface Flux Transport Model

Basic equation

The evolution of photopheric magnetic field ($\vec{B}$) is governed by magnetic induction equation,

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B}) + \eta \nabla^2 \vec{B} \tag{1}$$

Here $\vec{v}$ represents the large scale velocities (both meridional circulation and differential rotation) responsible for advection of $\vec{B}$ and η is the magnetic diffusion. Since most of the surface (on $\theta - \phi$ plane) magnetic field is confined in the radial direction, we shall solve only the radial part of the field. The radial component $B_r(\theta, \phi, t)$ of the induction equation (Eq. 1) when expressed in spherical polar coordinates is ,

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

Here θ is co-latitude, ϕ is longitude, $R_\odot$ is the solar radius, $\omega(\theta)$ is the differential rotation on the solar surface, $v(\theta)$ is the meridional circulation, η_h is the effective diffusion coefficient and $S(\theta, \phi, t)$ is the source term describing the emergence of new sunspots. Since we are studying the evolution of B_r on the surface of a sphere, the code is developed using **spherical harmonics**.

Transport parameters

The meridional circulation on the solar surface carries magnetic field from lower latitudes to higher latitudes. To replicate the effect of this large scale flow we have used a velocity profile used by van Ballegooijen et al.(1998).

$$v(\lambda) = \begin{cases} -v_0 \sin(\pi\lambda/\lambda_0) & \text{if } |\lambda < \lambda_0| \\ 0 & \text{otherwise} \end{cases} \tag{3}$$

where λ is the latitude in degrees ($\lambda = \pi/2 - \theta$) and λ_0 is the latitude beyond which the circulation speed becomes zero. The maximum velocity v_0 lies between 10 to 20 ms^{-1}. In our code we have taken $\lambda_0 = 75^o$ and v_0 =15 ms^{-1}.

Another large scale flow on the solar surface is differential rotation. To include its effect in the code we have used the empirical profile given by Snodgrass(1983),

$$\omega(\theta) = 13.38 - 2.30\cos^2\theta - 1.62\cos^4\theta \tag{4}$$

where $\omega(\theta)$ has units in degrees per day. This profile is also validated by recent helioseismology observations.

The supergranular cells in the solar convection zone effectively diffuse the magnetic field on the solar surface. We have taken the value of the diffusion coefficient (η_h) as 250 km^{2}s^{-1}.

Numerical modeling parameters

Ideally one should consider all possible values of degree (l) of spherical harmonics. Instead of taking the whole range of values of l form 0 to ∞, we have considered l values varying from 0 to 63. $l = 63$ can spatially resolve elements which have size of the supergranular cells (roughly 30 Mm) on the solar photosphere. Our code is second order accurate in space and first oder accurate in time.

We have assumed that all sunspots appear on the photosphere as **b**ipolar **m**agnetic **r**egions (BMRs). The Royal Greenwich Observatory (RGO) and USAF/NOAA database provide information about timing, position (in latitude and longitude), area of sunspots. We have used these data to simulate the sunspot cycles over the period of 1913 to 1987. Tilt angles of the BMRs follow Joy's law with a cycle to cycle variation as suggested by Jiang et al. (2011a, A&A)

Results

We have studied the evolution of polar flux in both hemispheres for almost 70 years (from cycle 15 to cycle 21) and compared our results with the polar flux estimated from polar faculae observations done by A. Munoz-Jaramillo et al. (2012, ApJ). The Polar flux obtained from simulation is calculated by integrating the magnetic field present in the polar cap region (extended from 0 to 30 degree of latitude) in both hemispheres.

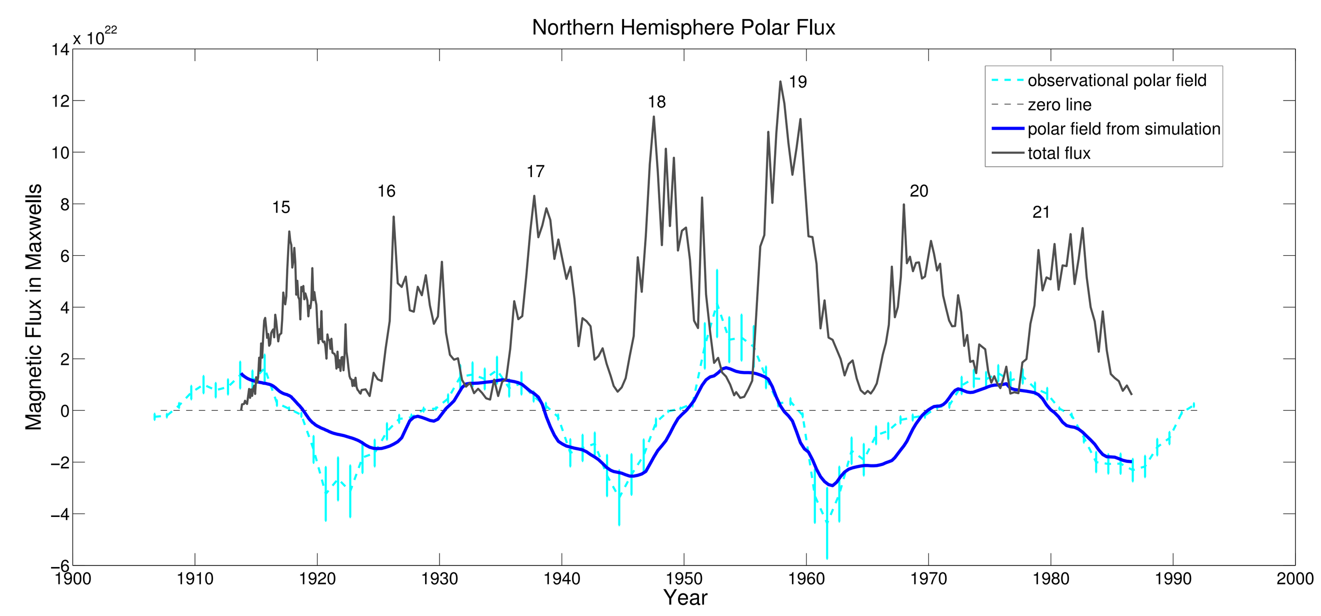

Figure 1: Evolution of polar flux in northern hemisphere during cycle 15 to cycle 21. Total flux shown in the above figure is scaled down by 15 for better representation.

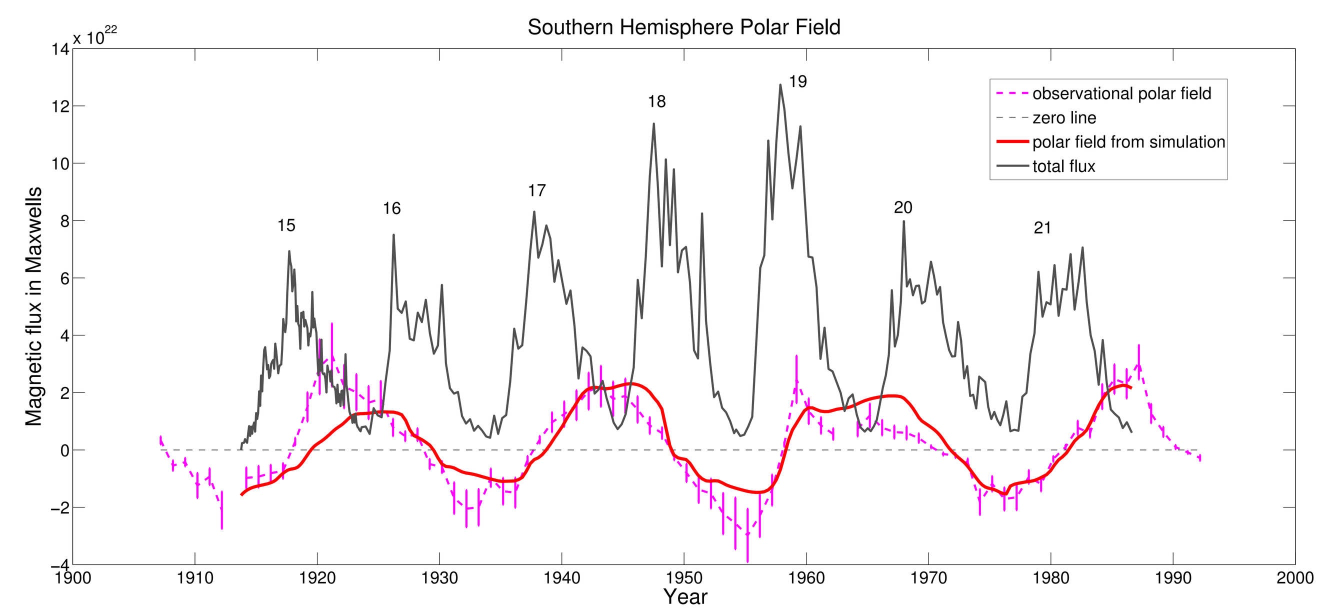

Figure 2: Evolution of polar flux in southern hemisphere during cycle 15 to cycle 21. Here also the total flux is scaled down by 15 for better representation.

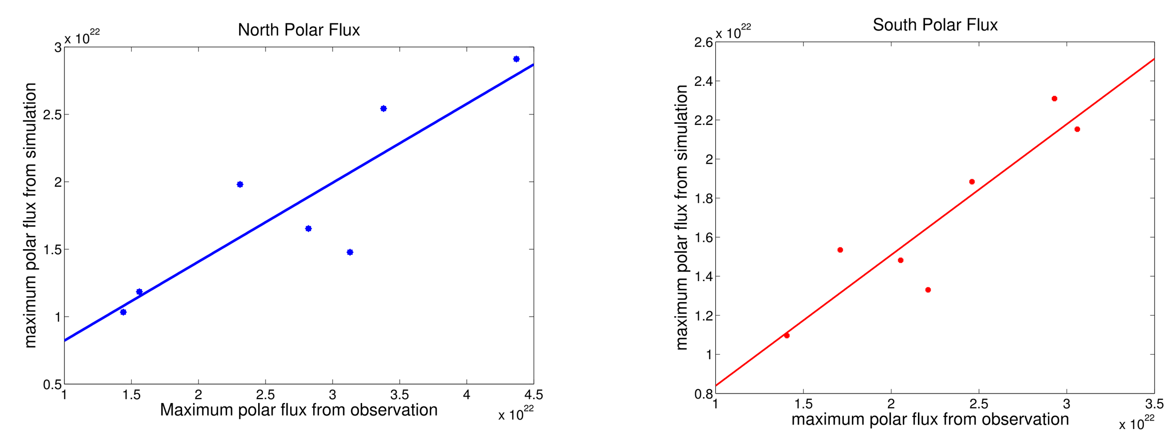

Figure 3: We have calculated values of Pearson linear correlation coefficients between the maximum polar flux obtained from observation and simulation for both hemispheres. For north polar flux the value of correlation is 0.87 and for south polar flux the value is 0.91 (with confidence level about 99 % for both hemispheres).

Comparing results from simulations with observations, we have found that the polar field reversal timing obtained from simulation matches well with the observation for most cycles. The magnitude of polar flux generated at the end of different cycles from our simulations lies well within the error range of observational data. We think whatever little difference exists between simulation and observation at the end of cycles is due to the lack of data at the beginning of cycle 15. This can be reduced by fine tuning the initial magnetic field configuration at the beginning of cycle 15.

Conclusions

The SFT model we have developed is successful in capturing the physics of the Sun's global photospheric magnetic field evolution.

Forthcoming Research

In our model we have considered meridional circulation to be time independent throughout all cycles. Introduction of time varying flow in the model relying on the recent observations of meridional circulation may improve the quality of the results. Our next goal is to study the evolution of photospheric magnetic with inclusion of time varying meridional circulation.

References

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