Global Evolution of Solar Magnetic Fields and Prediction of Solar Activity Cycles

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Prediction of solar activity cycles is challenging because the physical processes inside the Sun involve a broad range of multiscale dynamics that no model can reproduce, and the available observations are highly limited and cover mostly surface layers. Helioseismology makes it possible to probe solar dynamics in the convective zone, but variations in the differential rotation and meridional circulation are currently available for only two solar activity cycles. It has been demonstrated that sunspot observations, which cover over 400 years, can be used to calibrate the Parker-Kleiner-Ruzmaikin model and that the Ensemble Kalman Filter (EnKF) method can be used to link the model magnetic fields to sunspot observations to make reliable predictions of a following cycle. However, for more accurate predictions, it is necessary to use actual observations of the solar magnetic fields, which are available for only four solar cycles. This raises the question of how limitations in observational data and model uncertainties affect predictive capabilities and implies the need for the development of new forecast methodologies and validation criteria. In this presentation, I will discuss the influence of the limited number of available observations on the accuracy of EnKF estimates of solar cycle parameters.

Data Assimilation Methodology

Observations

Dynamo model

Kalman gain

\[ K = \frac{\alpha(C'_{\psi\psi})}{\alpha(C'_{\psi\psi}) + M'} \]

\[ \psi' = \psi + K((d - M\psi') - \text{corrected dynamo solution}) \]

Evolution of the toroidal and poloidal magnetic fields obtained from the synthetic magnetograms

Comparison of the best estimates of the sunspot number variations according to the annual sunspot numbers (blue curves), future observations (red curve), and monthly sunspot numbers.

Comparison of sunspot number predictions and estimated parameters at the solar minima

Conclusions

Prediction of solar cycles is one of most interesting problems closely linked to dynamo processes inside the Sun. The difficulty is due to our incomplete understanding of the physical mechanisms of the solar dynamo and also due to observational limitations that result in significant uncertainties in the initial conditions and model parameters. We have developed a relatively simple non-linear mean-field dynamo model, which nevertheless can describe the essential general properties of the cycles and the observed sunspot number series (such as Waldmeier's rule). Combined with the data assimilation approach, this model provides reasonable estimates for the strengths of following solar cycles. In particular, the prediction of Cycle 24 calculated and published in 2008 is holding quite well so far. It was found that the best periods for predicting future solar cycles are during the preceding solar minimum or solar maximum. This effect is explained by the fact these periods correspond to a solar dynamo state in which the primary magnetic field components, toroidal or poloidal, change their polarity.

In this work we use a data assimilation approach, widely used to predict weather conditions in the presence of uncertainties in observations and models. Using this technique, we have made a successful prediction of the current Solar Cycle 24 before it started. The prediction was made by using the sunspot number data as a proxy of the solar magnetic field. Our approach takes advantage of synoptic observations of magnetic field emerging on the solar surface to develop a more advanced and reliable forecasting method. For this work, we combined observations from NASA's space missions SOHO and SDO with ground-based data from the National Solar Observatory. The observational data are assimilated into our model, which is forced by a model description of the generation and evolution of the global magnetic field of the Sun. This Ensemble Kalman Filter data assimilation method works best for nonlinear systems and takes into account deviations of the model solution from observations.

Using the currently available observational data, predictions and prediction uncertainties have been calculated for Solar Cycle 25. The results based on both the sunspot number series and observed magnetic fields indicate that the upcoming Solar Maximum (Solar Cycle 25) is expected to be weaker than that of the current cycle (which near its end). The model results show that a deep extended solar activity minimum is expected in about 2020-2021, the maximum will occur in 2024-2025, and the mean sunspot number at the maximum will be about 30 for the v2.0 sunspot number series with an error estimate of ±15%. The maximum will likely have a double peak or show extended high activity over 2 to 3 years.

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