Application of Synoptic Magnetograms for Prediction of Solar Activity Using Ensemble Kalman Filter

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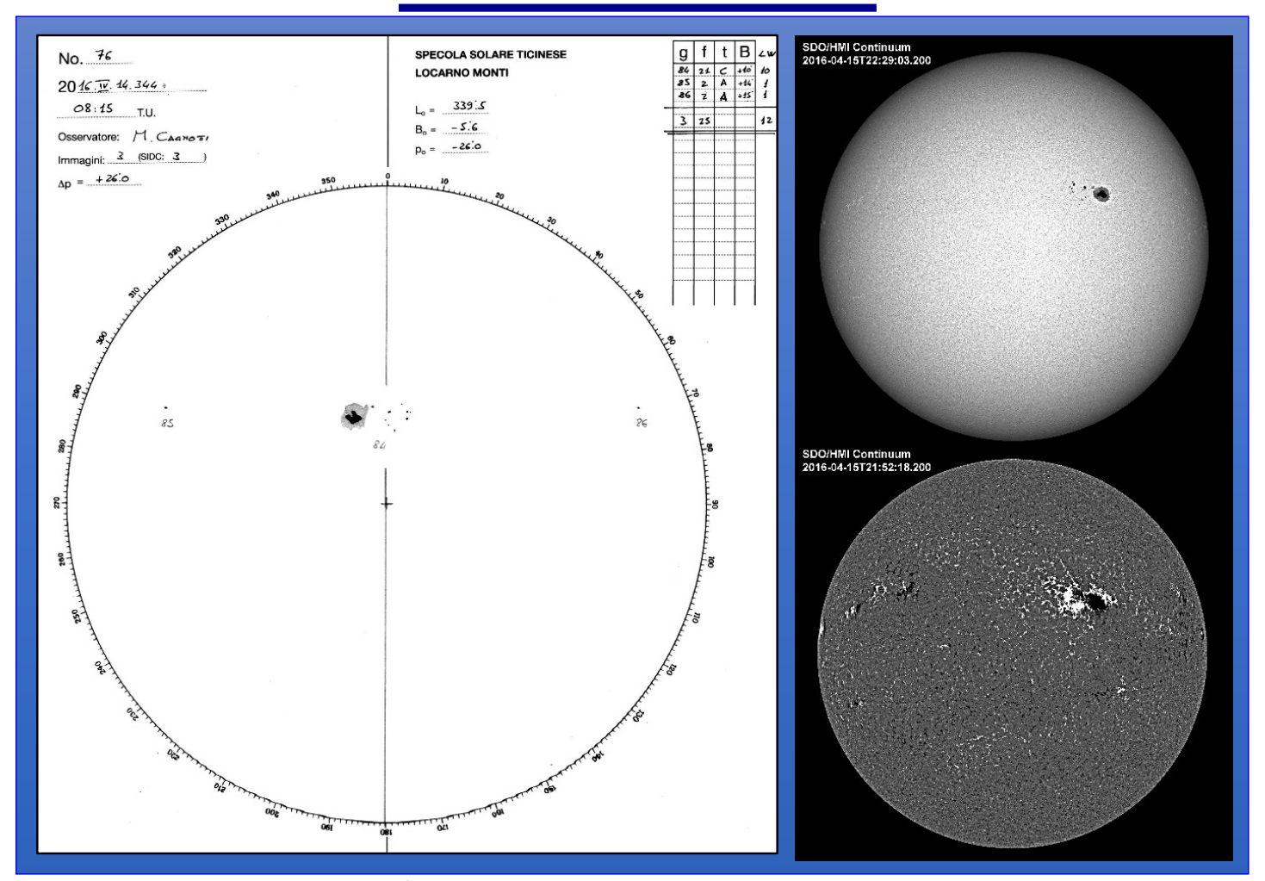
Solar activity predictions using the data assimilation approach have demonstrated great potential to build reliable long-term forecasts of solar activity. In particular, it has been shown that the Ensemble Kalman Filter (EnKF) method applied to a non-linear dynamo model is capable of predicting solar activity up to one sunspot cycle ahead in time, as well as estimating the properties of the next cycle a few years before it begins. These developments assume an empirical relationship between the mean toroidal magnetic field flux and the sunspot number. Estimated from the sunspot number series, variations of the toroidal field have been used to assimilate the data into the Parker-Kleeorin-Ruzmakin (PKR) dynamo model by applying the EnKF method. The dynamo model describes the evolution of the toroidal and poloidal components of the magnetic field and the magnetic helicity. Full-disk magnetograms provide more accurate and complete input data by constraining both the toroidal and poloidal global field components, but these data are available only for the last four solar cycles. In this presentation, using the available magnetogram data, we discuss development of the methodology and forecast quality criteria (including forecast uncertainties and sources of errors). We demonstrate the influence of limited time series observations on the accuracy of solar activity predictions. We present EnKF predictions of the upcoming Solar Cycle 25 based on both the sunspot number series and observed magnetic fields and discuss the uncertainties and potential of the data assimilation approach.

Data Assimilation Methodology

Observations



Dynamo model

Parker 1955, Kleeorin & Ruzmaikin, 1982, Kleeorin et al., 1995, Kitiashvili & Kosovichev 2009, 2011

$$\frac{\partial A}{\partial t} = \alpha B + \eta \nabla^2 A \qquad \alpha_k = -(\tau/3)\langle \mathbf{u}(\nabla\times\mathbf{u})\rangle$$

$$\frac{\partial B}{\partial t} = G\frac{\partial A}{\partial z} + \eta\nabla^2 B \qquad \alpha_m = (\tau/12\pi\rho)\langle \mathbf{h}(\nabla\times\mathbf{h})\rangle$$

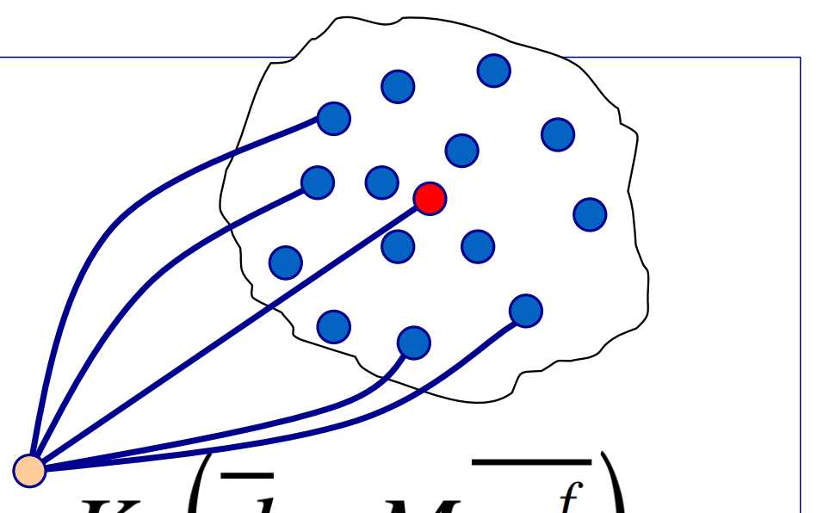
$$\alpha = \alpha_k + \alpha_m$$

$$\frac{\partial \alpha_m}{\partial t} = \frac{\mu}{4\pi\rho}\left(\mathbf{B}\cdot(\nabla\times\mathbf{B}) - \frac{\alpha\mathbf{B}^2}{\eta}\right) - \frac{\alpha_m}{T_\alpha}$$

$$\underbrace{d_j = \psi^t + \varepsilon_j \qquad j = 1,\ldots,N \qquad d\psi = G(\psi)dt + h(\psi)dq}$$

Kalman gain

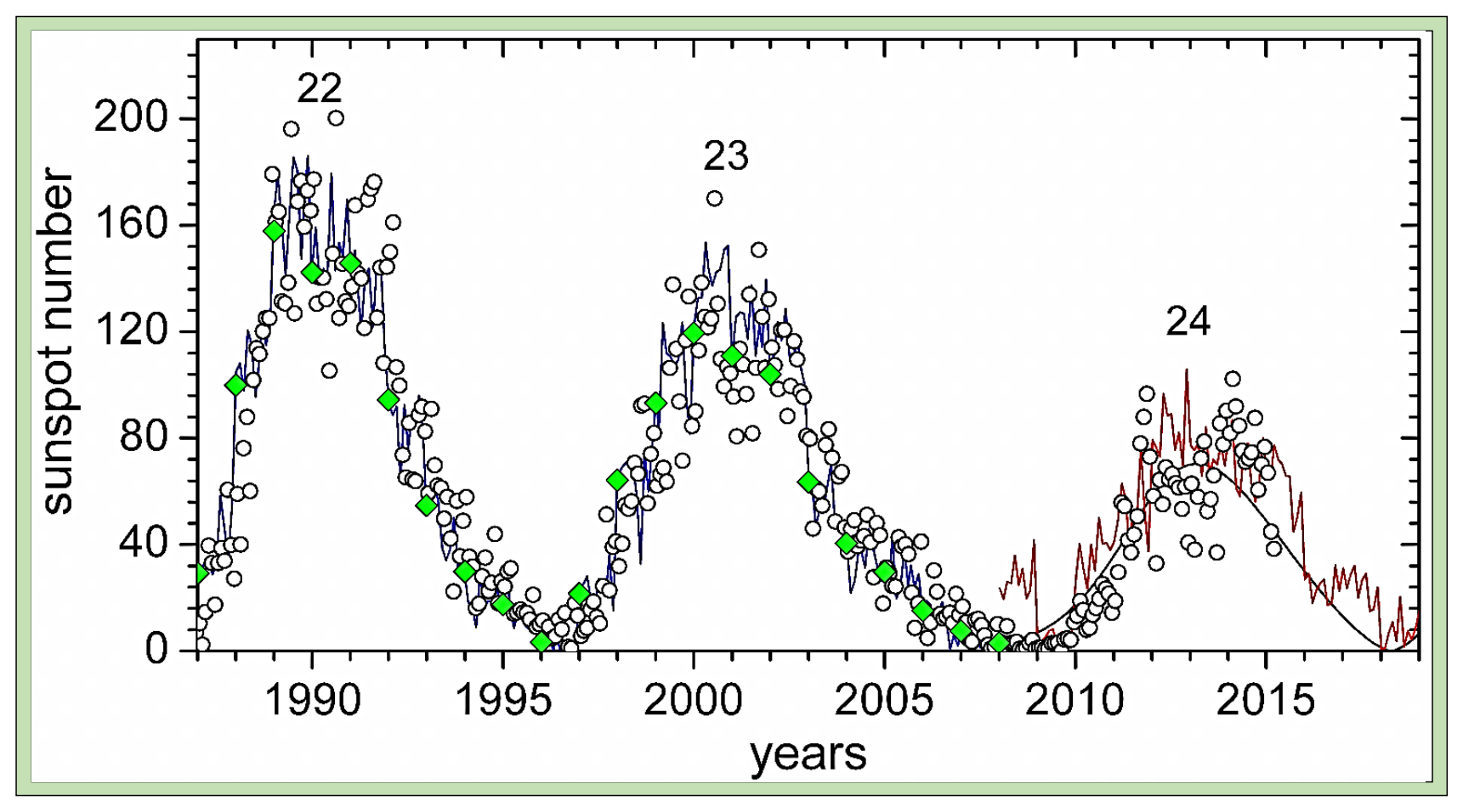
$$K_e = \frac{\left(C^e_{\psi\psi}\right)^f M^T}{M\left(C^e_{\psi\psi}\right)^f M^T + C^e_{\varepsilon\varepsilon}}$$



$$\psi^a_j = \psi^f_j + K_e\left(d_j - M\psi^f_j\right) \qquad \overline{\psi^a} = \overline{\psi^f} + K_e\left(\overline{d} - M\overline{\psi^f}\right)$$

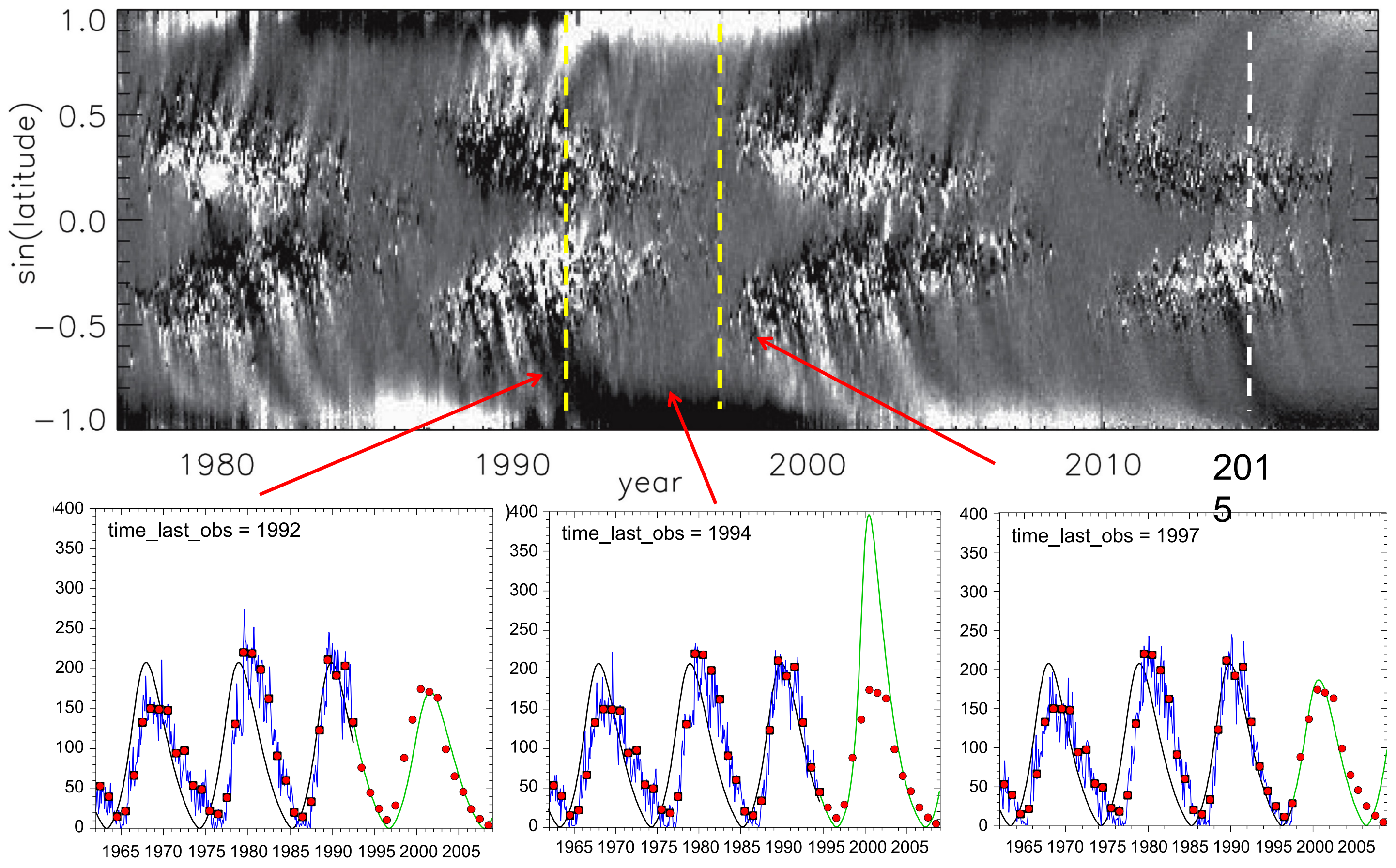
$$\psi^a_j - \overline{\psi^a} = (I - K_e M)\left(\psi^f_j - \overline{\psi^f}\right) + K_e\left(d_j - \overline{d}\right)$$

$$\left(C^e_{\psi\psi}\right)^a = \overline{\left(\psi^a_j - \overline{\psi^a}\right)\left(\psi^a_j - \overline{\psi^a}\right)^T} = (I - K_e M)\left(C^e_{\psi\psi}\right)^f$$

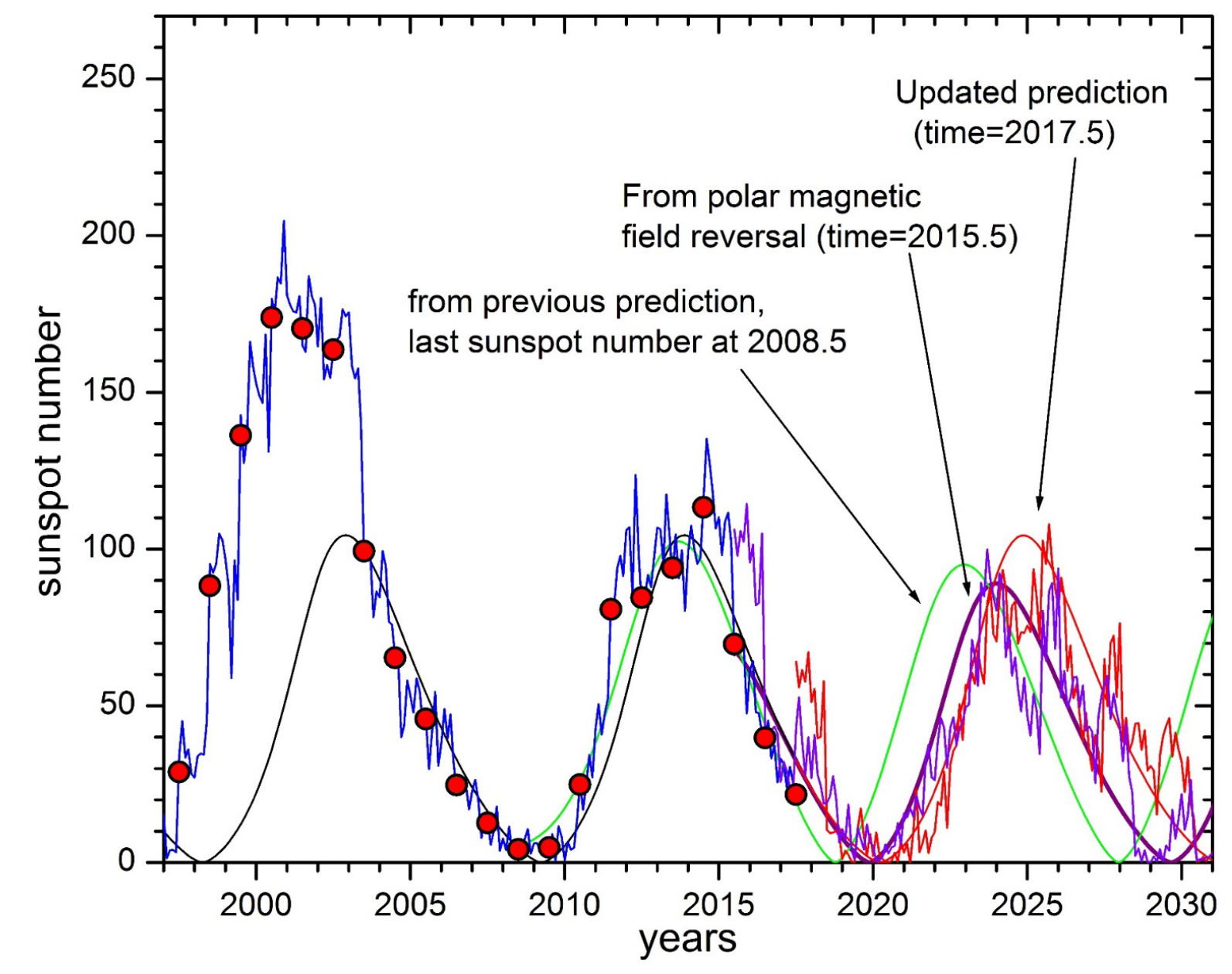


Comparison of the sunspot number prediction for Solar Cycle 24 (red curve, Kitiashvili & Kosovichev, 2008) and actual observations of monthly sunspot number. The blue curve shows the corrected dynamo solution according to annual sunspot number (green diamonds).

Synoptic magnetogram. The color scale is saturated at +/-15G. The yellow dashed lines indicate different moments of time: 1992 and 2015.

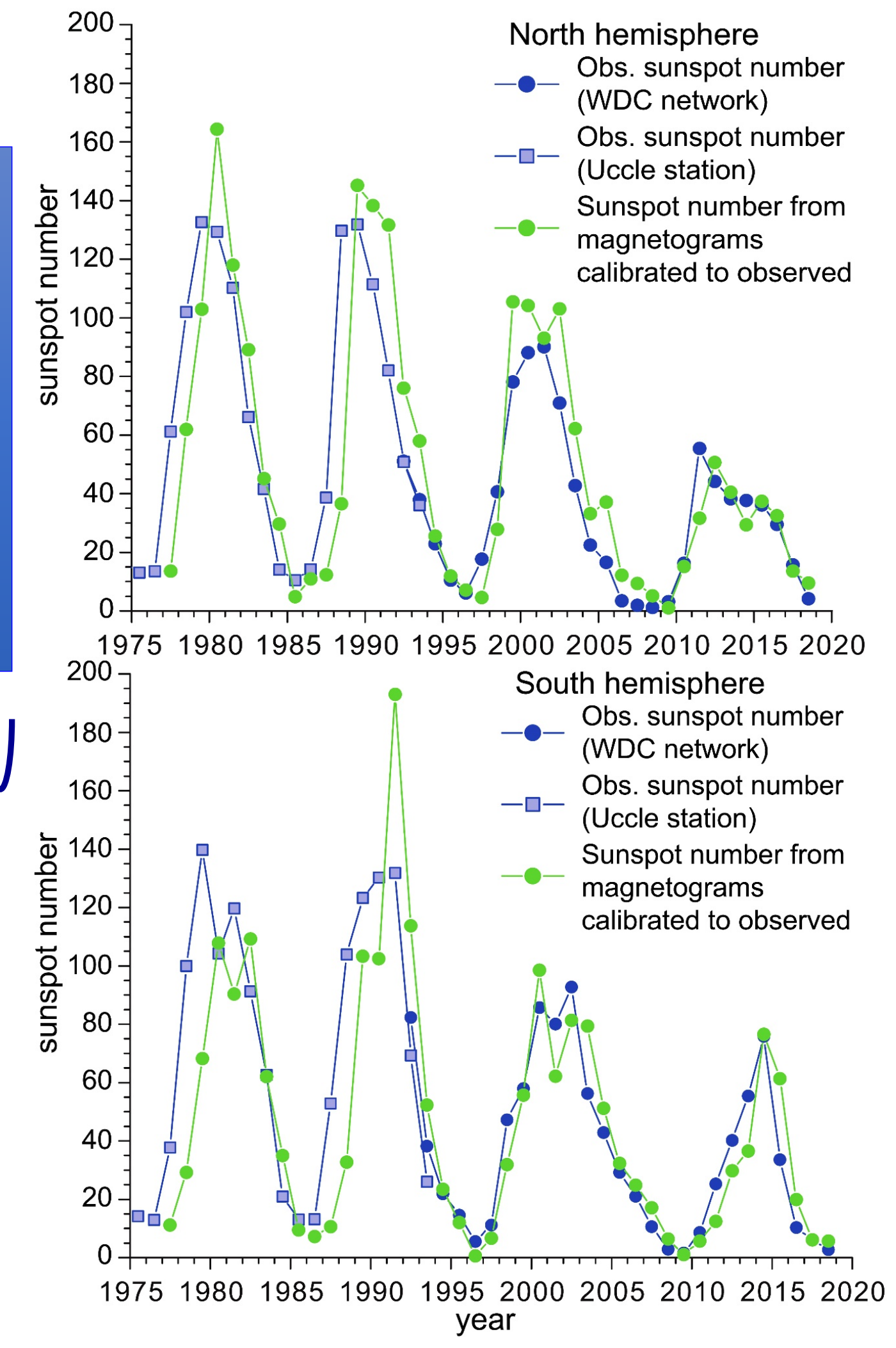


Uncertainties in Prediction of Solar Cycle 25

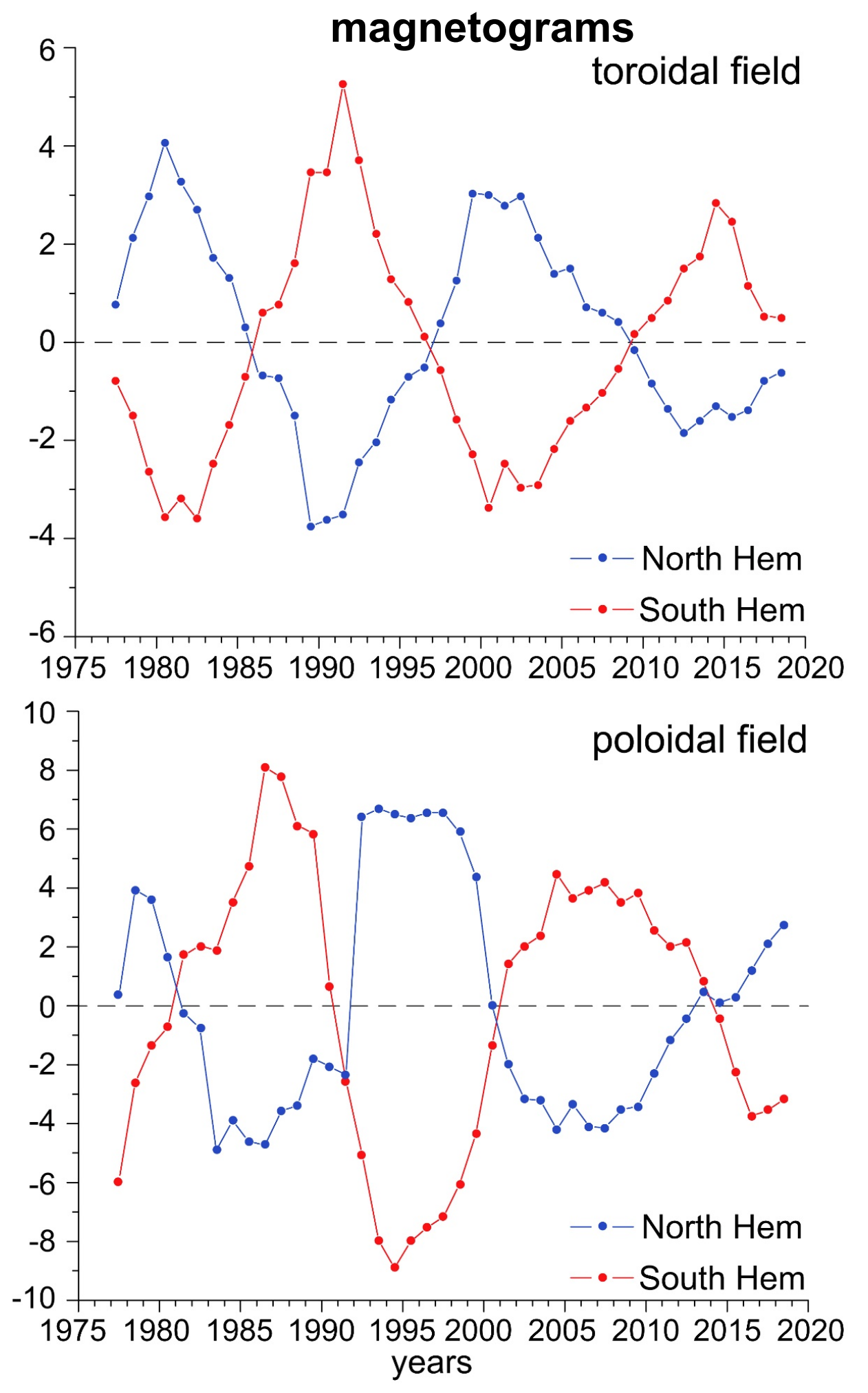


Early estimation of properties of Solar Cycle 25 (for sunspot number version 2.0) shows 1) prediction obtained for observations which include the sunspot number data up to the solar minimum in 2008 (green curve); 2) prediction obtained for the last observation during the polar magnetic field reversal (purple/violet); 3) prediction obtained using all currently available observations up to 2017 (red curve). Blue curve shows the best EnKF estimates of the previous cycles based on the dynamo model (4) and all available sunspot observations (red circles).

Comparison of hemispheric sunspot numbers, observed and inferred from magnetograms

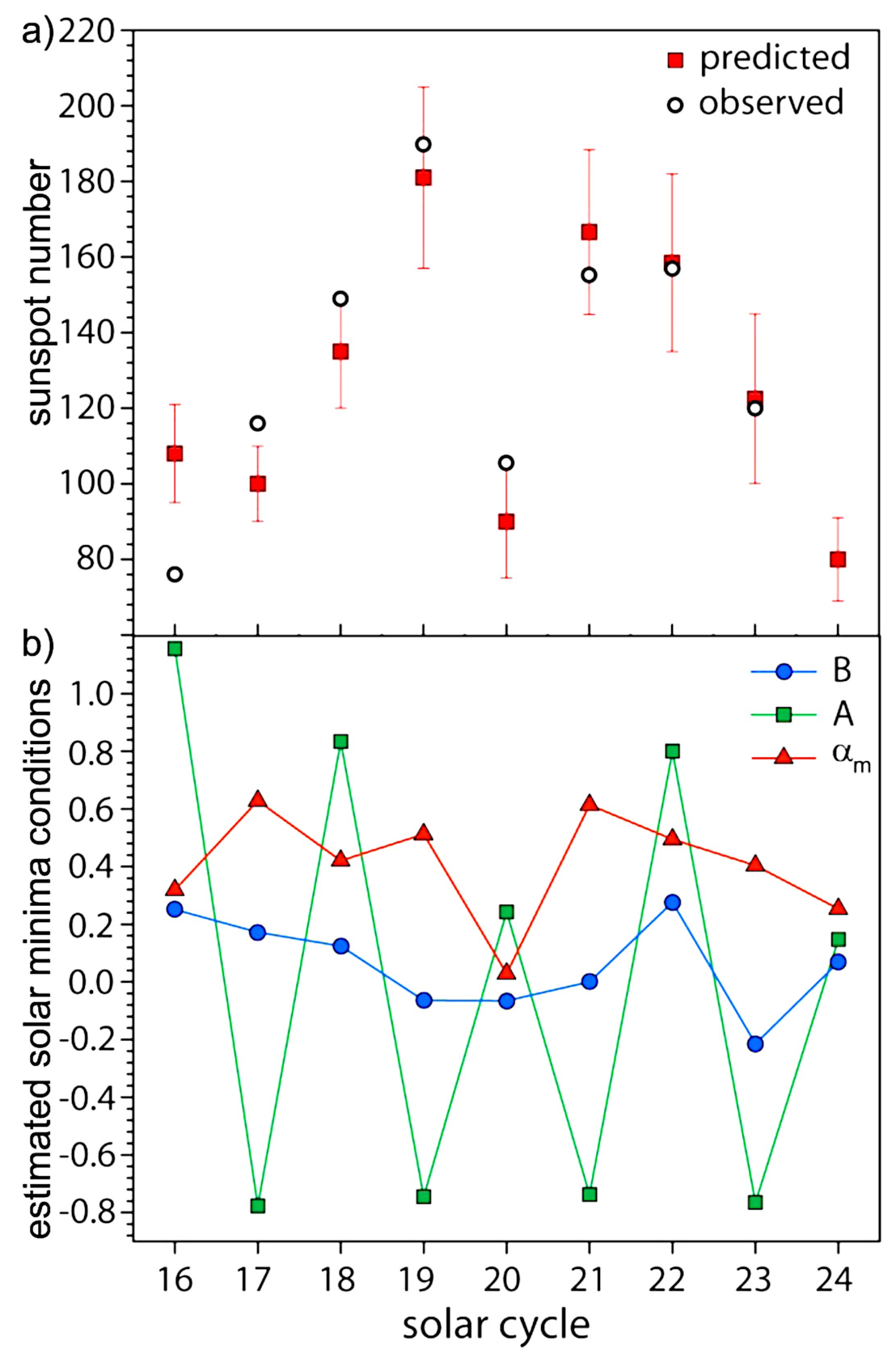


Evolution of the toroidal and poloidal magnetic fields obtained from the synoptic magnetograms



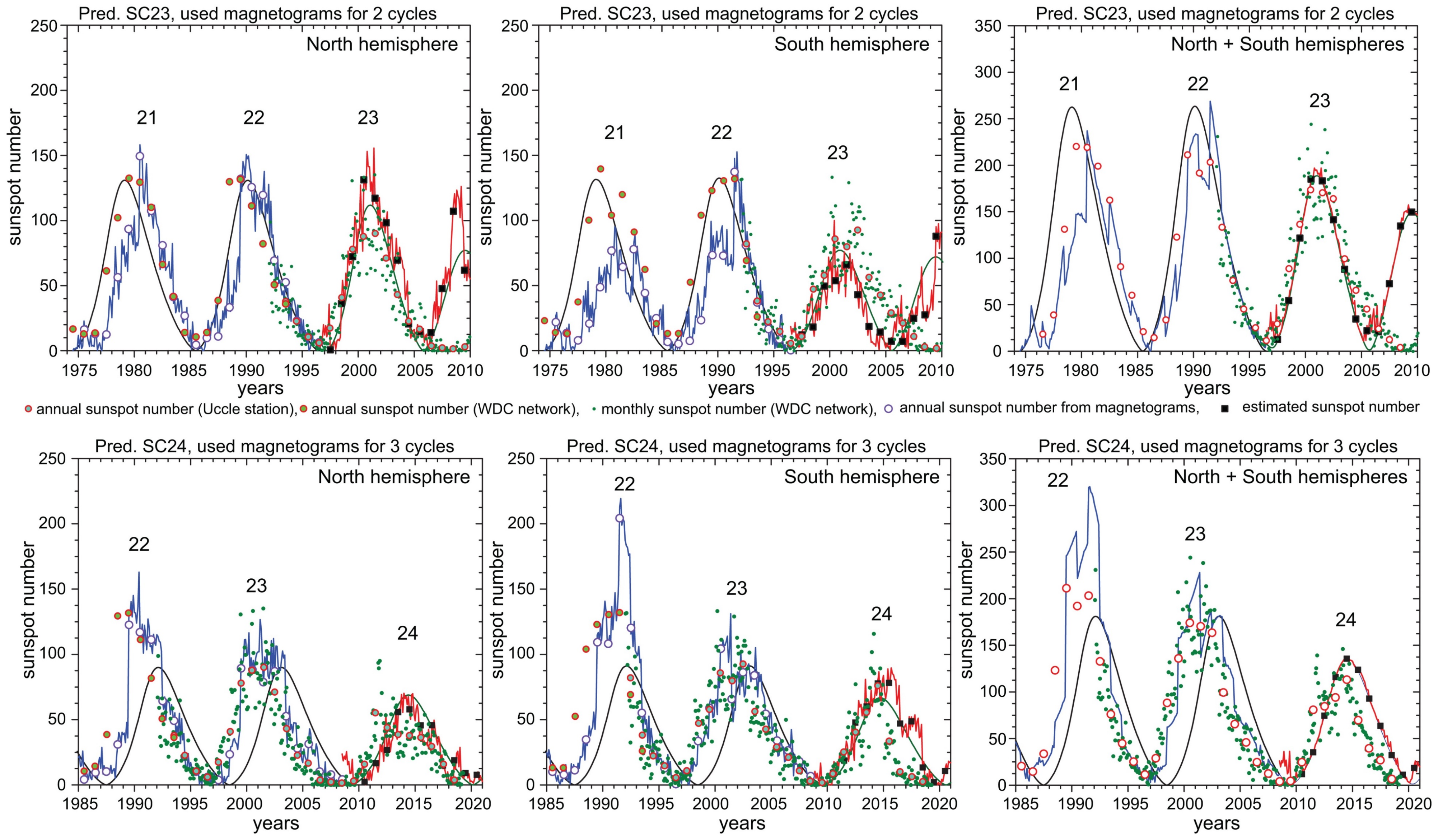
Results of magnetic field decomposition into toroidal and poloidal field components from the observed radial field synoptic magnetograms.

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

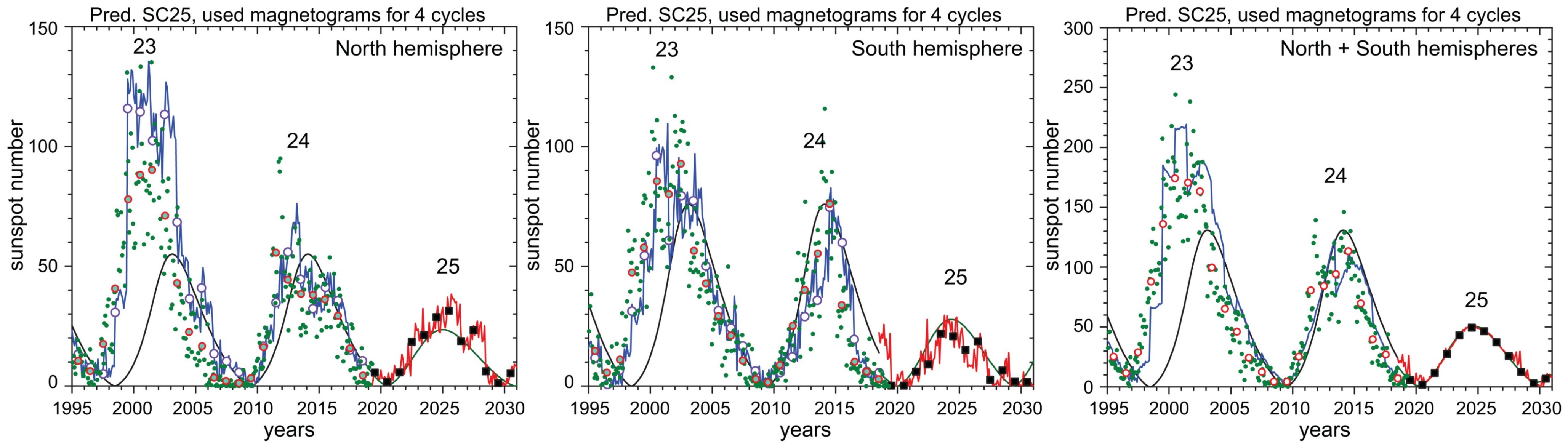


The large-scale magnetic helicity shows significantly better correlation with future sunspot numbers; in particular, the magnetic helicity substantially decreases prior to weak sunspot cycles.

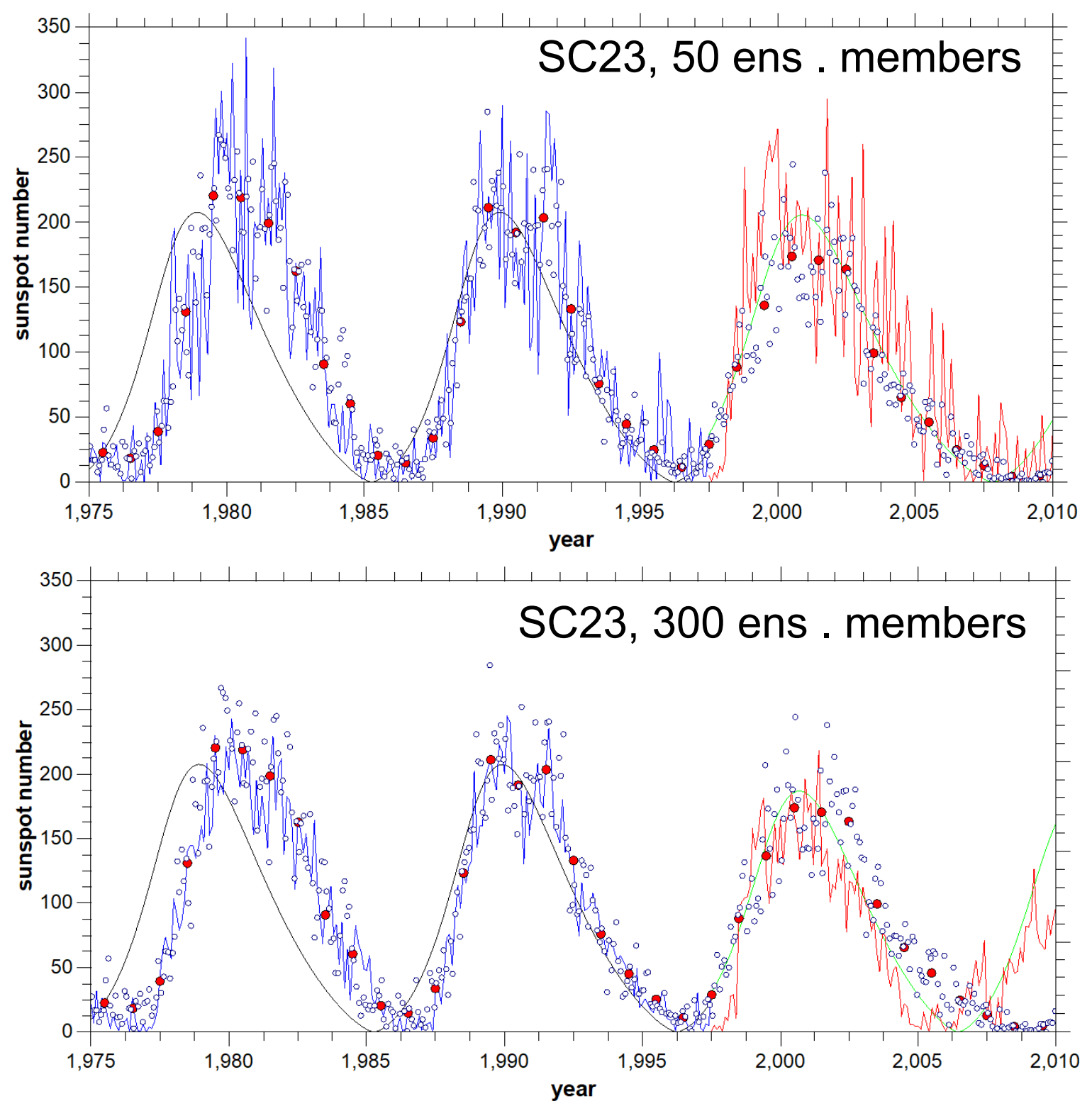
Test 'Prediction' of Solar Cycles 23 and 24 for the North and South hemispheres using the reconstructed toroidal and poloidal magnetic field components



Solar Cycle 25 prediction



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



Toroidal magnetic field does not show a particular pattern and is close to zero.

Vector-potential of the poloidal field changes sign corresponding to the polar field reversal. The amplitude at the start of Cycles 20 and 24 is substantially lower than during other minima.

This may correspond to the well-known correlation between the polar magnetic field strength and the following sunspot-number maximum (Schatten 2005; Svalgaard et al, 2005).

References

Evensen G. Data Assimilation. Springer. 2007
Kitiashvili I.N. 2016. ApJ 831, article id. 15
Kitiashvili I. N., Kosovichev A. G. 2008. ApJ 688, L49-L52.
Kitiashvili I.N., Kosovichev A.G. 2009. Geophys. Astrophys. Fluid Dyn. 103, 53-68.
Kitiashvili, I.N., Kosovichev, A.G. 2011. Lecture Notes in Physics, Vol. 832, p121.
Kleeorin N.I., Ruzmaikin A.A. 1982. Magnetohydrodynamics, 18, 116.
Kleeorin N., Rogachevskii I., Ruzmaikin A. 1995. A&A 297, 159-167.
Schatten K. 2005. J. Geophys. Res. Letter, 32, 21106.
Svalgaard L., Cliver E.W., Kamide Y. 2005. ASP Conf. Series, 346, 401.

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 strength of the 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 new approach takes advantage of synoptic observations of magnetic field emerging on the surface of the Sun 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 a non-linear dynamo model which provides a theoretical 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 2019-2021, the maximum will occur in 2024 - 2025, and the maximum sunspot number at the maximum will be about 50 (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 – 2.5-years.

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