Using Data Assimilation Methods of Prediction of Solar Activity

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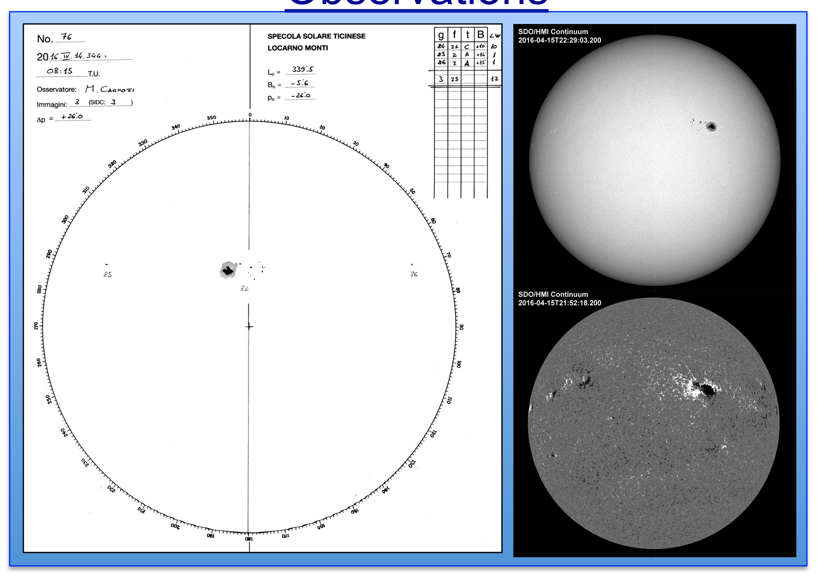
The variable solar magnetic activity known as the 11-year solar cycle has the longest history of solar observations. These cycles dramatically affect conditions in the heliosphere and the Earth's space environment. Our current understanding of the physical processes that make up global solar dynamics and the dynamo that generates the magnetic fields is sketchy, resulting in unrealistic descriptions in theoretical and numerical models of the solar cycles. The absence of long-term observations of solar interior dynamics and photospheric magnetic fields hinders development of accurate dynamo models and their calibration. In such situations, mathematical data assimilation methods provide an optimal approach for combining the available observational data and their uncertainties with theoretical models in order to estimate the state of the solar dynamo and predict future cycles. In this presentation, we will discuss the implementation and performance of an Ensemble Kalman Filter data assimilation method based on the Parker migratory dynamo model, complemented by the equation of magnetic helicity conservation and long-term sunspot data series. This approach has allowed us to reproduce the general properties of solar cycles and has already demonstrated a good predictive capability for the current cycle, 24. We will discuss further development of this approach, which includes a more sophisticated dynamo model, synoptic magnetogram data, and employs the DART Data Assimilation Research Testbed.

Components of the Solar Cycle Prediction Approach

Variations of solar activity are a result of complicated dynamo processes in the convection zone. We consider this phenomenon in the context of sunspot number variations, for which we have detailed observational data during the past 23 solar cycles. However, despite the known general properties of solar cycles, a reliable forecast of the 11-year sunspot number is still a problem. The main reasons for these forecasting uncertainties are imperfect dynamo models and deficiency of the necessary observational data.

Observations



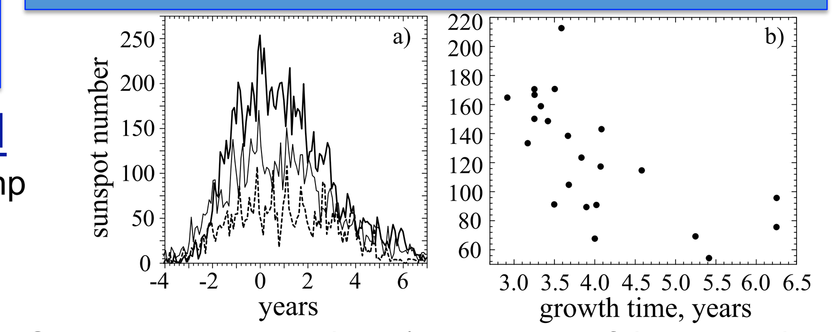
Dynamo model

Parker 1955, Kleeorin & Ruzmaikin, 1982
Kitiashvili & Kosovichev 2009, 2011

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

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

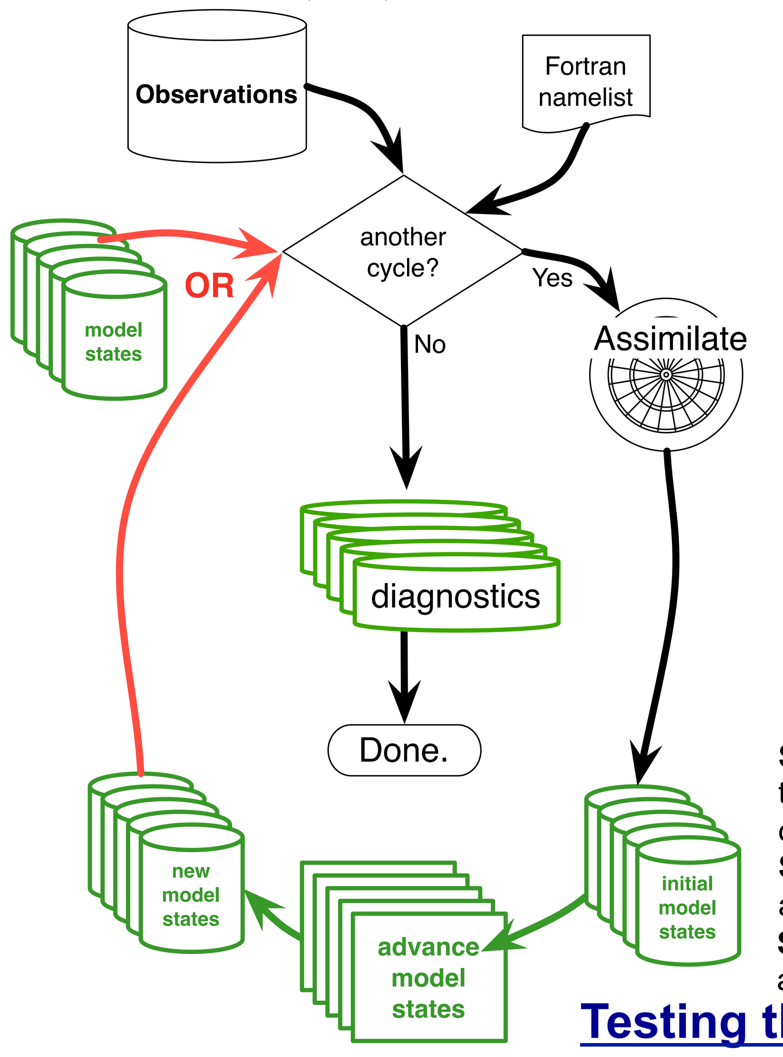
$$\frac{\partial \alpha_m}{\partial t} = \frac{\mu}{4\pi\rho}\left(\mathbf{B}\cdot(\nabla\times\mathbf{B}) - \frac{\alpha\mathbf{B}^2}{\eta}\right) - \frac{\alpha_m}{T_\alpha}$$



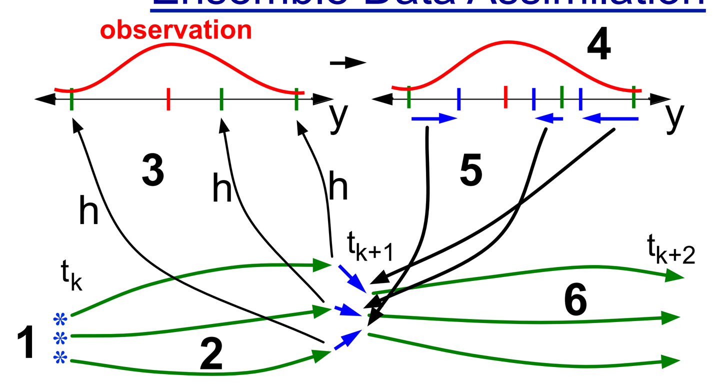
Sunspot cycle properties: a) asymmetry of the mean shape of solar cycles (dotted curve corresponds to Cycle 14, solid thick curve to Cycle 19, and thin line to Cycle 23), and b) relationship between the cycle growth time and the sunspot number maximum (Waldmeier's rule). The data are from the original sunspot number set.

Data Assimilation Research Testbed

http://www.image.ucar.edu/DAReS/DART/index.php
Anderson et al., 2009; Anderson & Collins 2007

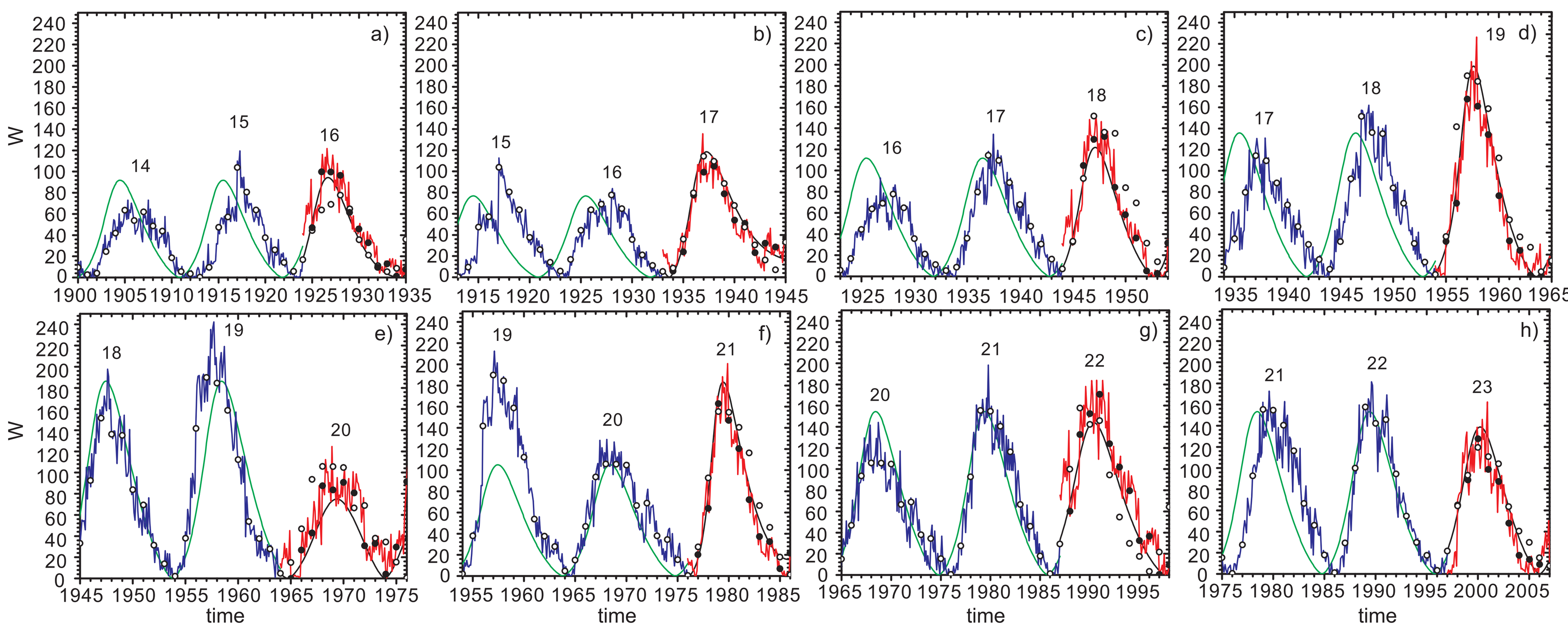


Ensemble Data Assimilation



Step 1: An ensemble size of 3 model states, after the previous assimilation step.
Step 2: Each model state is independently advanced in time.
Step 3: A forward operator (h) maps each model state to an expected observation value.
Step 4: Observation increments are computed based on the relationship between the observed value and expected error vs. the distribution of expected observation values.
Step 5: The increments are regressed onto the model states and the state values adjusted.
Step 6: Each model state is advanced in time and the cycle repeats until all observations are assimilated.

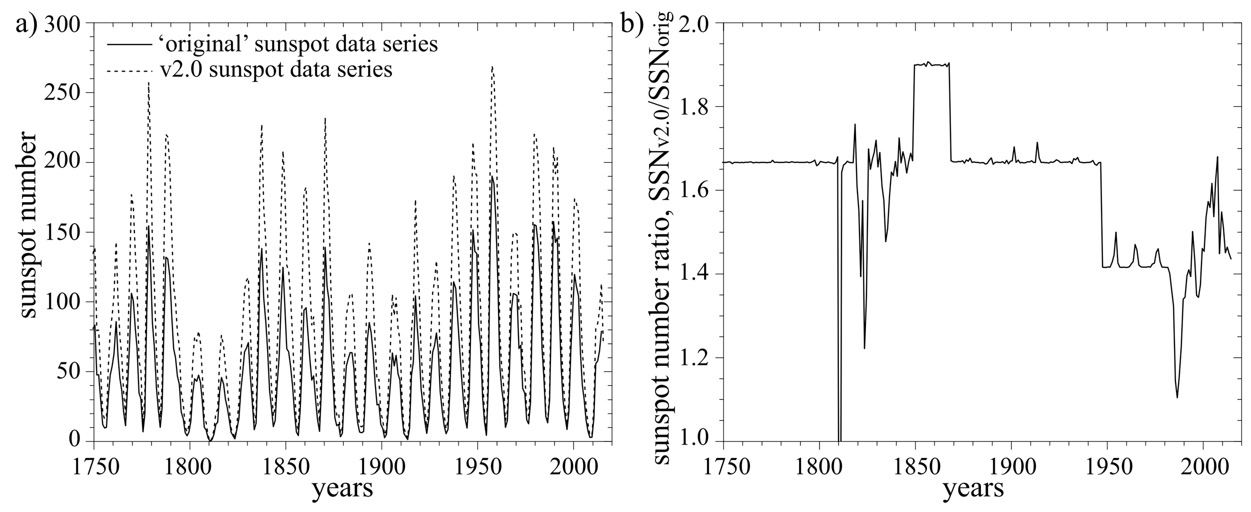
Testing the Prediction Capabilities



Testing the prediction capability for solar cycles 16-23. The green curves show the model reference solution. The blue curves show the best estimate of the sunspot number using the observational data (empty circles) and the model, for the previous cycles. The black curves show the model solution according to the initial conditions of the last measurement. The red curves show the prediction results.

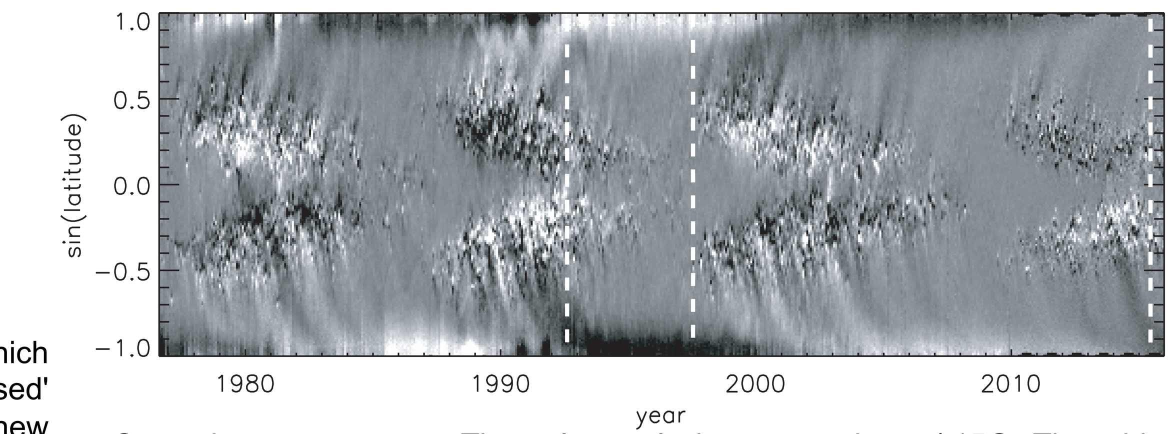
Preliminary Analysis of Prediction Solar Cycle 25 Uncertainties

To characterize the level of solar activity during systematic observations of sunspots, the relative sunspot number was introduced by Wolf (1850): **R = k(10g + n)**, where **k** is a correction factor, depending on observing conditions, **g** is the number of sunspot groups, and **n** is the number of individual sunspots.



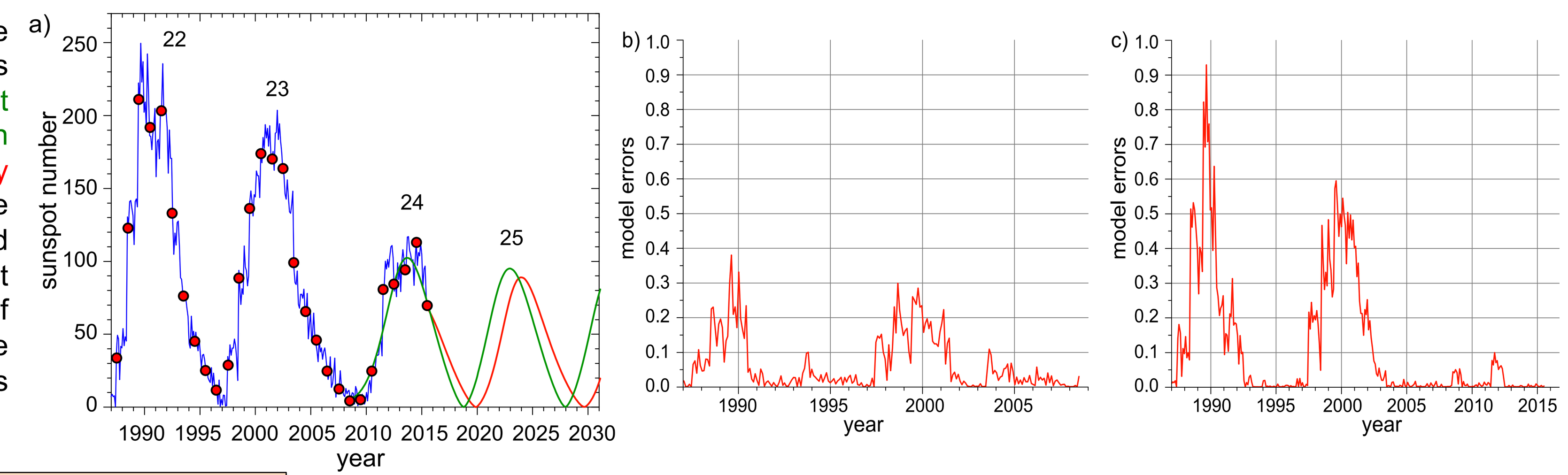
Comparison of the annual sunspot number series: the original (marked 'original' solid curve), which was used for the solar cycle 24 prediction by (Kitiashvili & Kosovichev 2008), and the 'revised' version (v2.0, Source: WDC-SILSO, Royal Observatory of Belgium, Brussels) by applying a new calibration to the historical and modern data sets (dotted curve, Clette et al. (2015) is shown in panel a). Panel b) shows the ratio of these data sets.

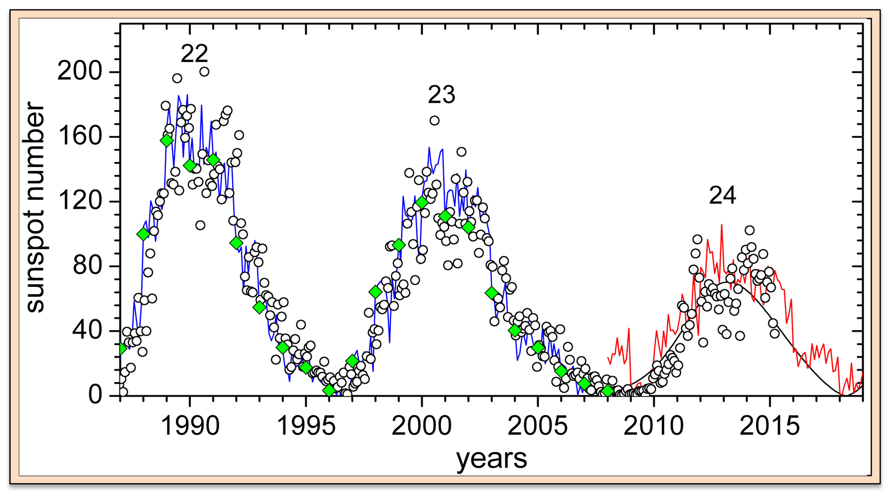
Previous experience and tests have shown that the EnKF procedure based on the dynamo model and sunspot number measurements has good predictive capabilities for estimating future solar activity in a time range from 7 - 8 years to a whole solar cycle. However, our attempts to make predictions for a period longer than one cycle often fail due to accumulation of errors. In this section, I consider in more detail the possibility of early forecasts of sunspot cycles and present an initial estimate for Cycle 25.



Synoptic magnetogram. The color scale is saturated at +/-15G. The white dashed lines indicate different moments of time: 1992, 1997 and 2015.

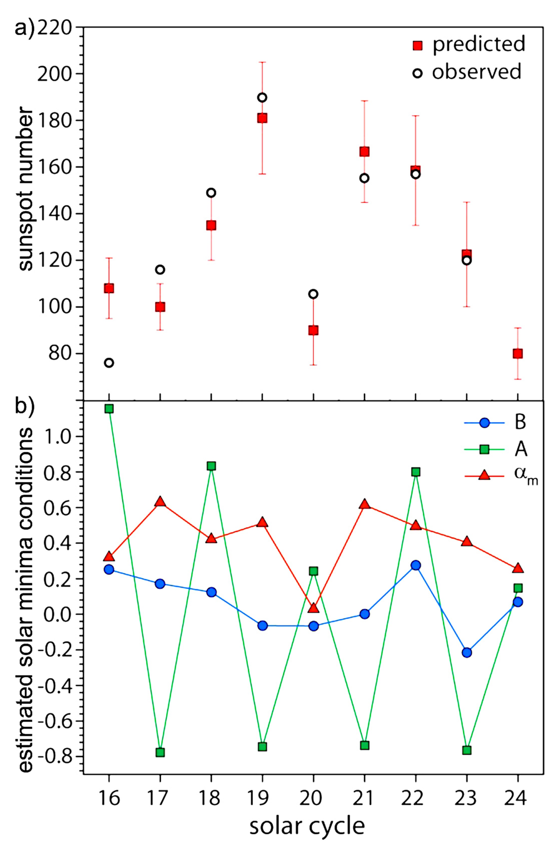
Early estimation of properties of Solar Cycle 25 for the sunspot number version 2.0. Panel a) shows two predictions for Cycle 25: 1) prediction obtained for observations that include the sunspot number data up to the solar minimum in 2008 (green curve); 2) prediction obtained using all currently available observations up to 2015 (red curve). Blue curve shows the best EnKF estimates of the previous cycles based on the dynamo model (4) and all available sunspot observation (red circles). Panel b) shows the model errors of toroidal magnetic field variations for the case using the observations made up to 2008. Panel c) shows these errors for the case when all available data (up to 2015) are used.





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).

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

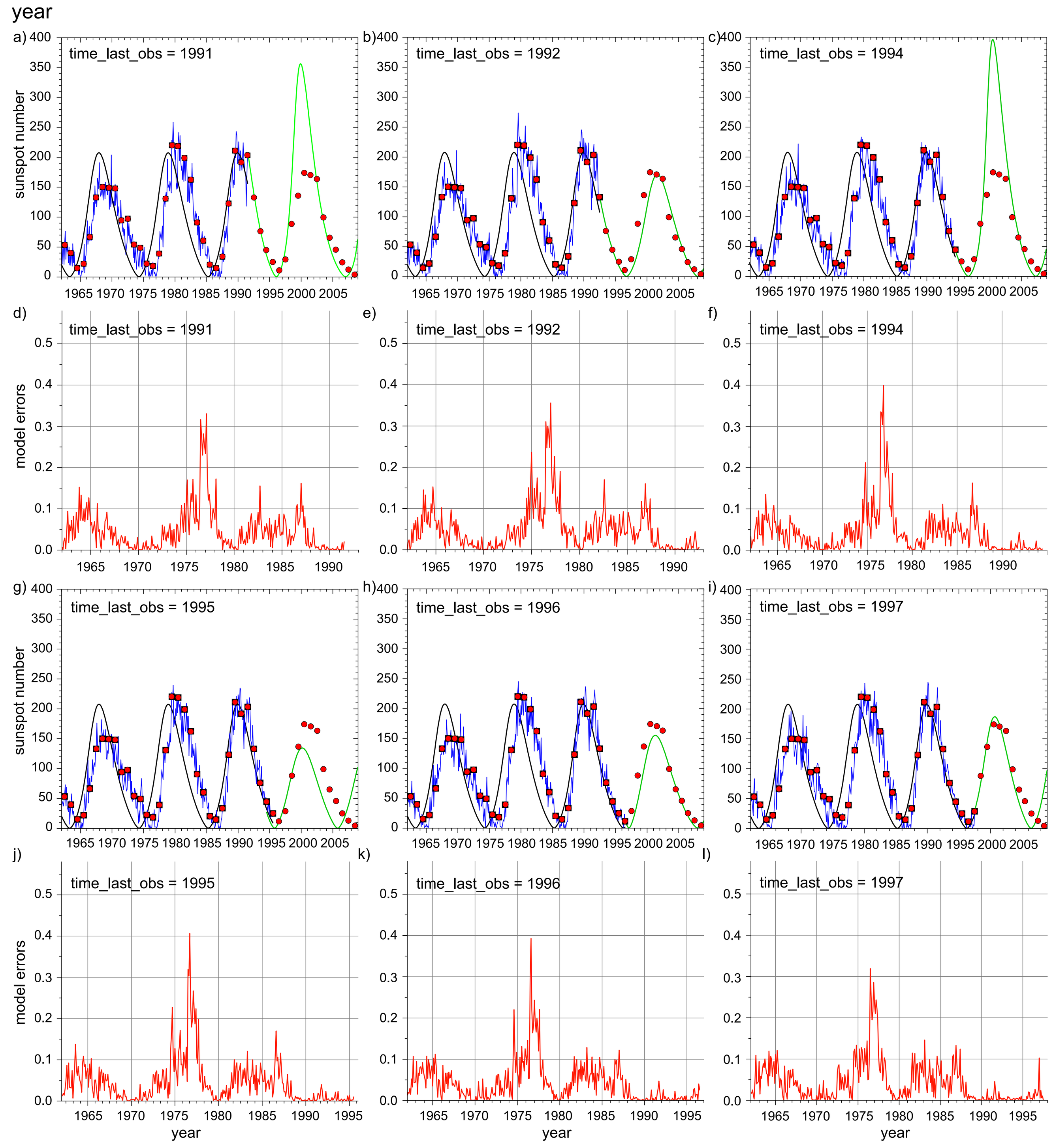


Toroidal magnetic field does not show a particular pattern and is close to zero.

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 strength of the polar magnetic field and the following sunspot number (Schatten 2005; Svalgaard et al, 2005)

Magnetic helicity shows significantly better correlation with future sunspot numbers, indicating that the magnetic helicity substantially decreases prior to weak sunspot cycles.



Simulated test predictions of Cycle 23 using the v2.0 annual sunspot number series. Panels *a-c* and *g-i* show Cycle 23 estimations (green curves) for the last observing times indicated in the figure panels. Black curves show the initial periodic solution obtained from the dynamo equations; red circles show the annual sunspot number. The blue curves show the best EnKF estimate of the model variations. Panels *d-f* and *j-l* show toroidal magnetic field errors of the model for each data assimilation case.

Conclusions

Prediction of solar cycles is one of most interesting problems closely linked to dynamo processes inside the Sun. Numerous earlier attempts to predict future solar cycles were mostly based on empirical relations derived from observations of previous cycles and provided a wide range of predicted strengths and durations of the cycles. 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 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.

The initial prediction of Cycle 25 shows that this cycle will start in about 2019 - 2020, reach the maximum in 2023 - 2024, and the mean sunspot number at the maximum will be ~90 (for the v2.0 sunspot number series) with an estimated error of ~15%. The test simulation runs for early cycle predictions have been performed and identified the following criteria for a successful prediction capability: a) the model errors relative to observations should be less than 20% for the last 10 years, and b) the prediction should be performed starting from a period when either the toroidal or poloidal field is dominant relative to the other. This corresponds to two moments of time: the polar field reversals shortly after the solar maxima (strong toroidal field and weak poloidal field) and during the solar minima (strongest poloidal and weak toroidal fields).

The next steps of this study are (1) transition from the sunspot number to physical quantities such as synoptic magnetograms and magnetic helicity and (2) using more advanced dynamo models that provide a better physical basis for development of a high-fidelity pipeline for solar activity predictions.

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