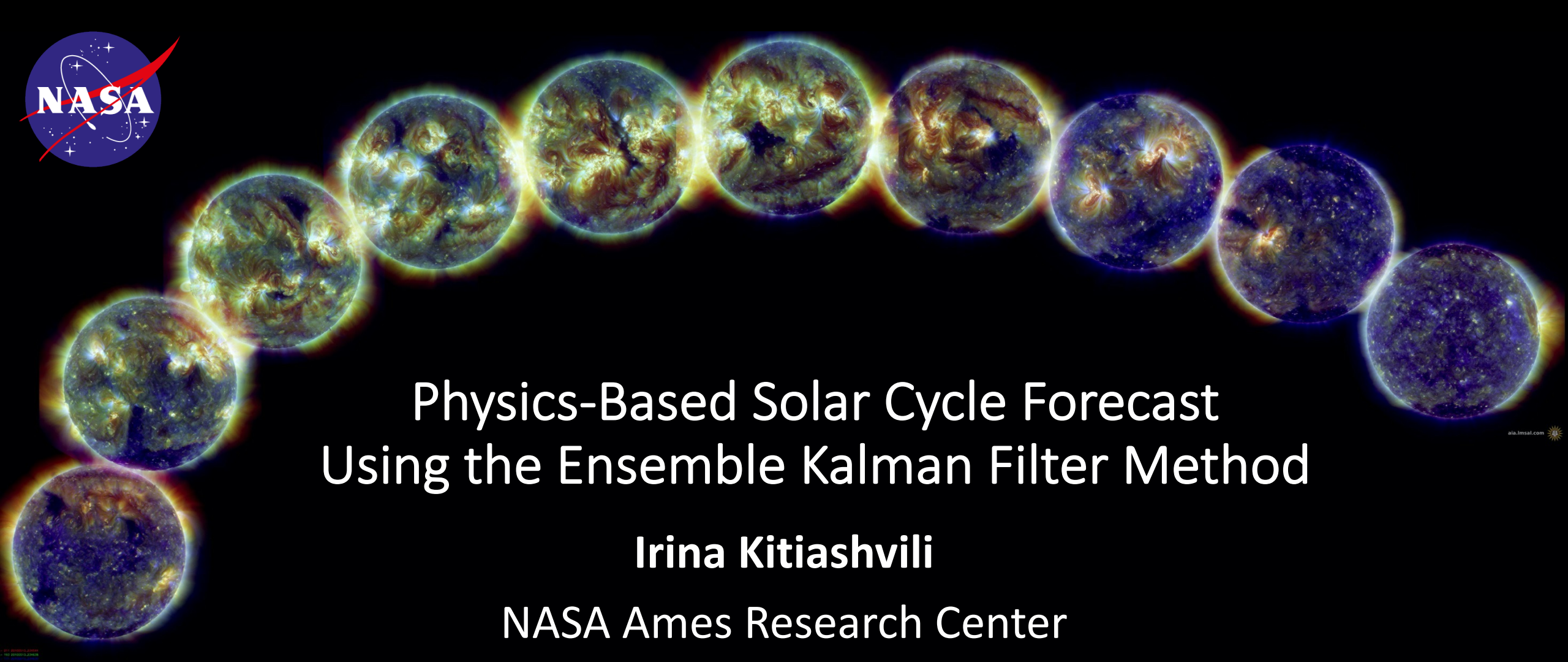


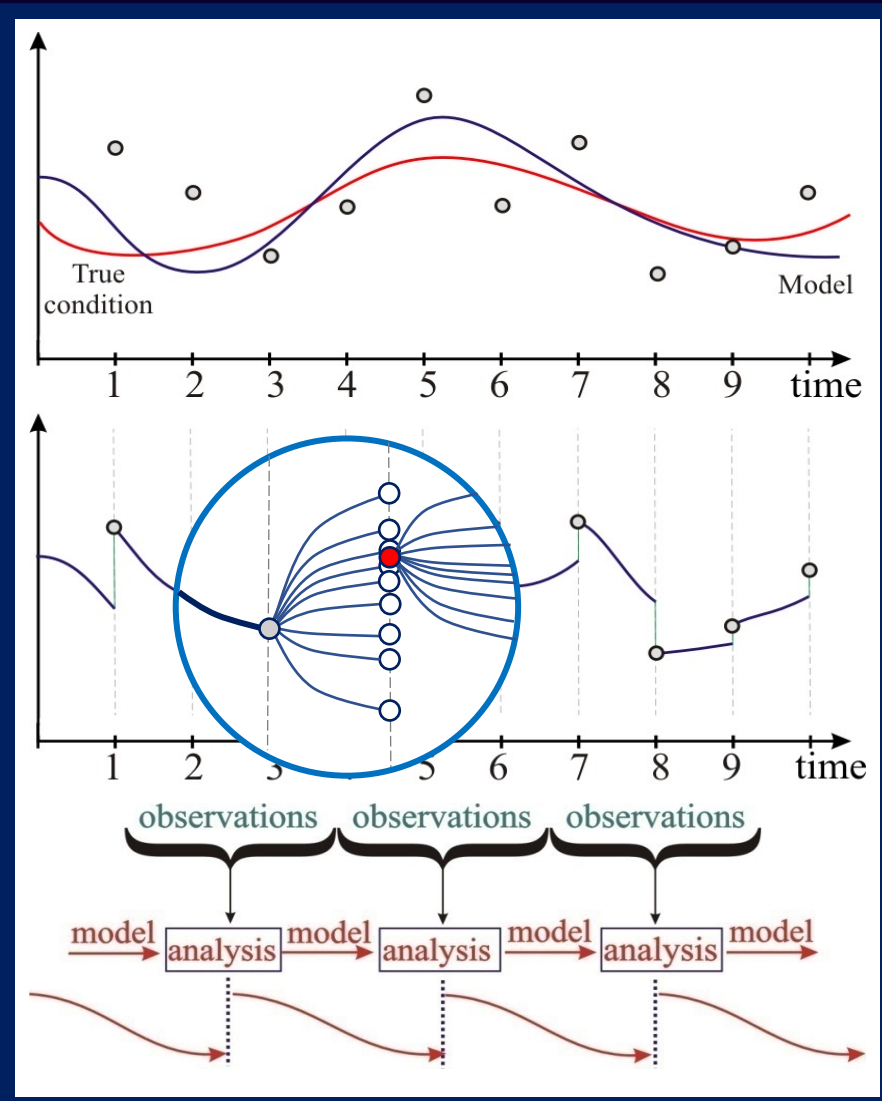


Physics-Based Solar Cycle Forecast Using the Ensemble Kalman Filter Method

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Data Assimilation 101: Ensemble Kalman Filter



Observational data include errors, and a model constructed on their basis is characterized by some approximations; therefore, a prediction of the next set of observations will diverge from the real data.

$$d_j = M\psi^t + \varepsilon_j \text{ observations}$$

$$\frac{d\psi^t}{dt} = f(\psi^t, t) + q \text{ model}$$

$$\psi_j^f = M\psi^t + p_j^f \text{ forecast}$$

$$\psi_j^a = \psi_j^f + K(d_j - M\psi_j^f) \text{ Best estimate of a state}$$

$$K = (C_{\psi\psi}^e)^f M^T \left(M (C_{\psi\psi}^e)^f M^T + C_{\varepsilon\varepsilon}^e \right)^{-1} \text{ Kalman gain}$$

Methods of data assimilation allow us, with the help of the already constructed model and observational data, to determine the initial state that is in agreement with a new set of observations and to obtain a forecast of future observations and to estimate their errors.

Parker-Kleorin-Ruzmaikin (PKR) Dynamo Model

$$\begin{aligned}\frac{\partial A}{\partial t} &= \alpha B + \eta \nabla^2 A \\ \frac{\partial B}{\partial t} &= G \frac{\partial A}{\partial z} + \eta \nabla^2 B\end{aligned}$$

Parker's classic dynamo model gives only non-chaotic oscillatory solutions, even in nonlinear cases, and therefore cannot explain the observed variations of the sunspot number in solar cycles. To create chaotic variations of the magnetic field it is necessary to add to the model a third equation describing variations of the magnetic helicity and its interaction with the large-scale magnetic field.

+

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

(Kleorin & Ruzmaikin, 1982; Kleorin et al., 1995)

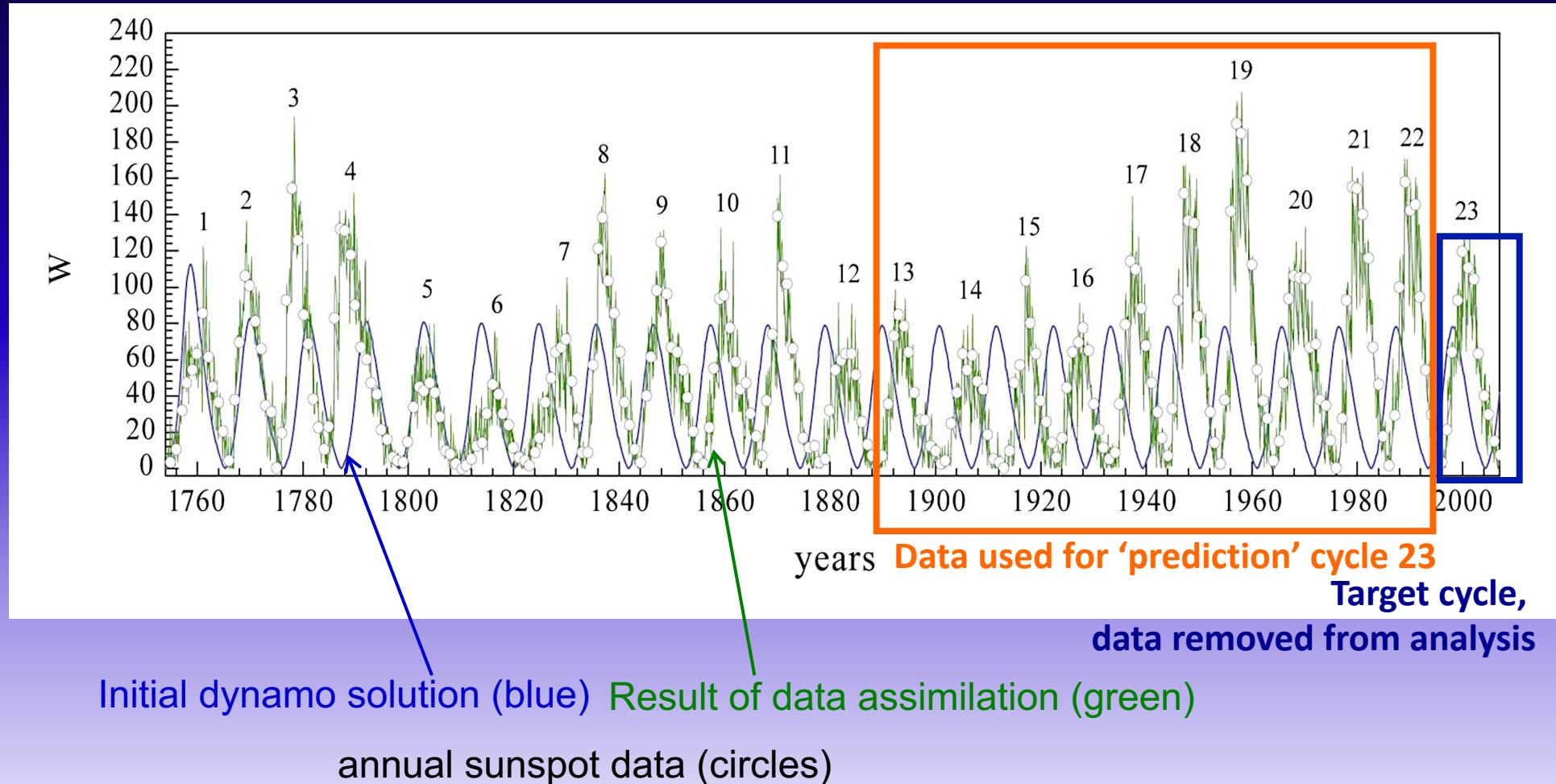
$$\alpha = \alpha_k + \alpha_m$$

$$\alpha_k = -(\tau / 3) \langle \mathbf{u} (\nabla \times \mathbf{u}) \rangle$$

$$\alpha_m = (\tau / 12\pi\rho) \langle \mathbf{h} (\nabla \times \mathbf{h}) \rangle$$

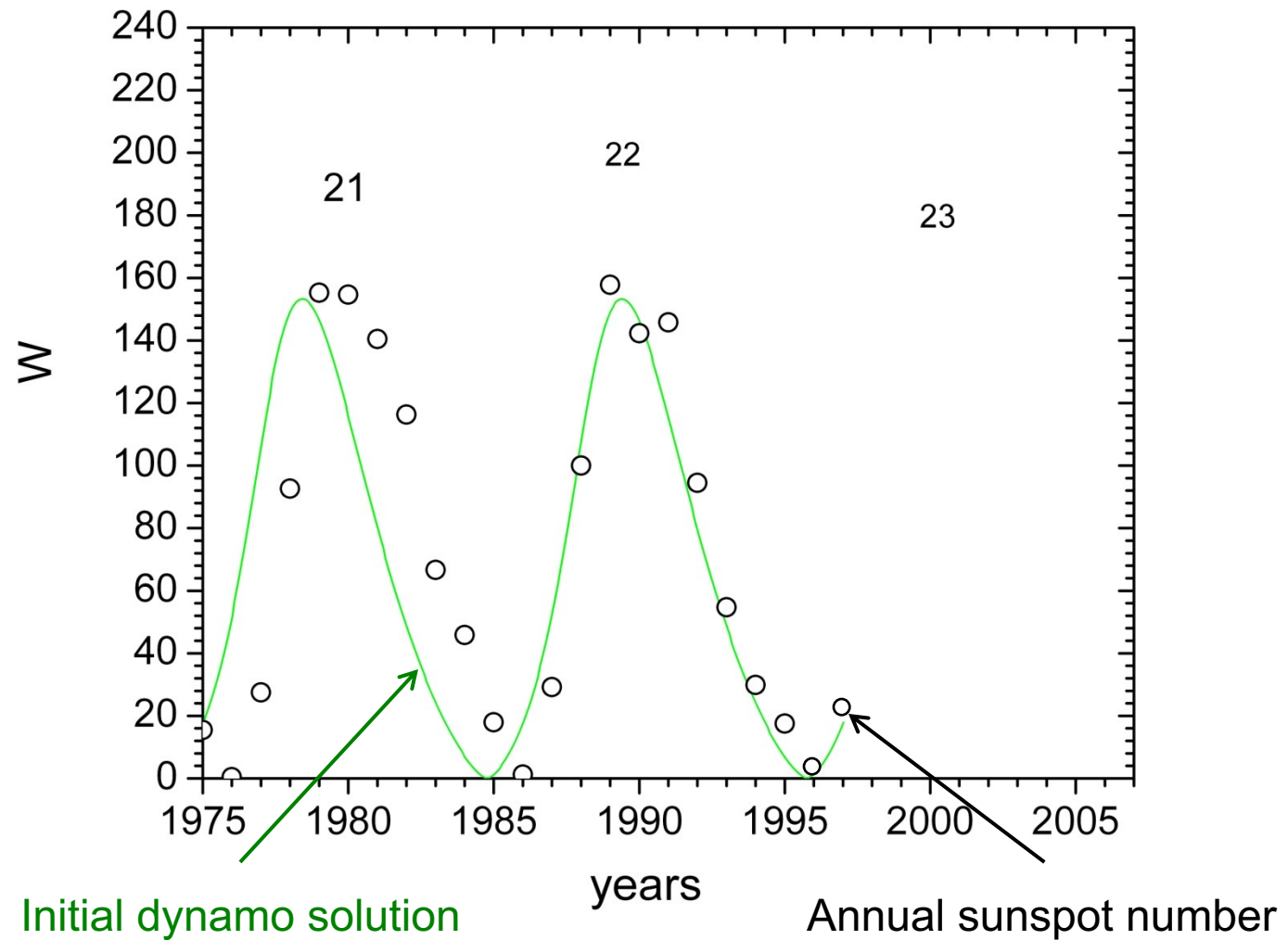
G is the large-scale radial shear; u is turbulent velocity; h is turbulent magnetic field; α_k and α_m are the kinetic and magnetic helicities; $\mu \approx 0.1$; ρ is the density; k is wave number; η and η_m are the turbulent and molecular magnetic diffusivities; T_α is characteristic time

Assimilation for the known obs. data

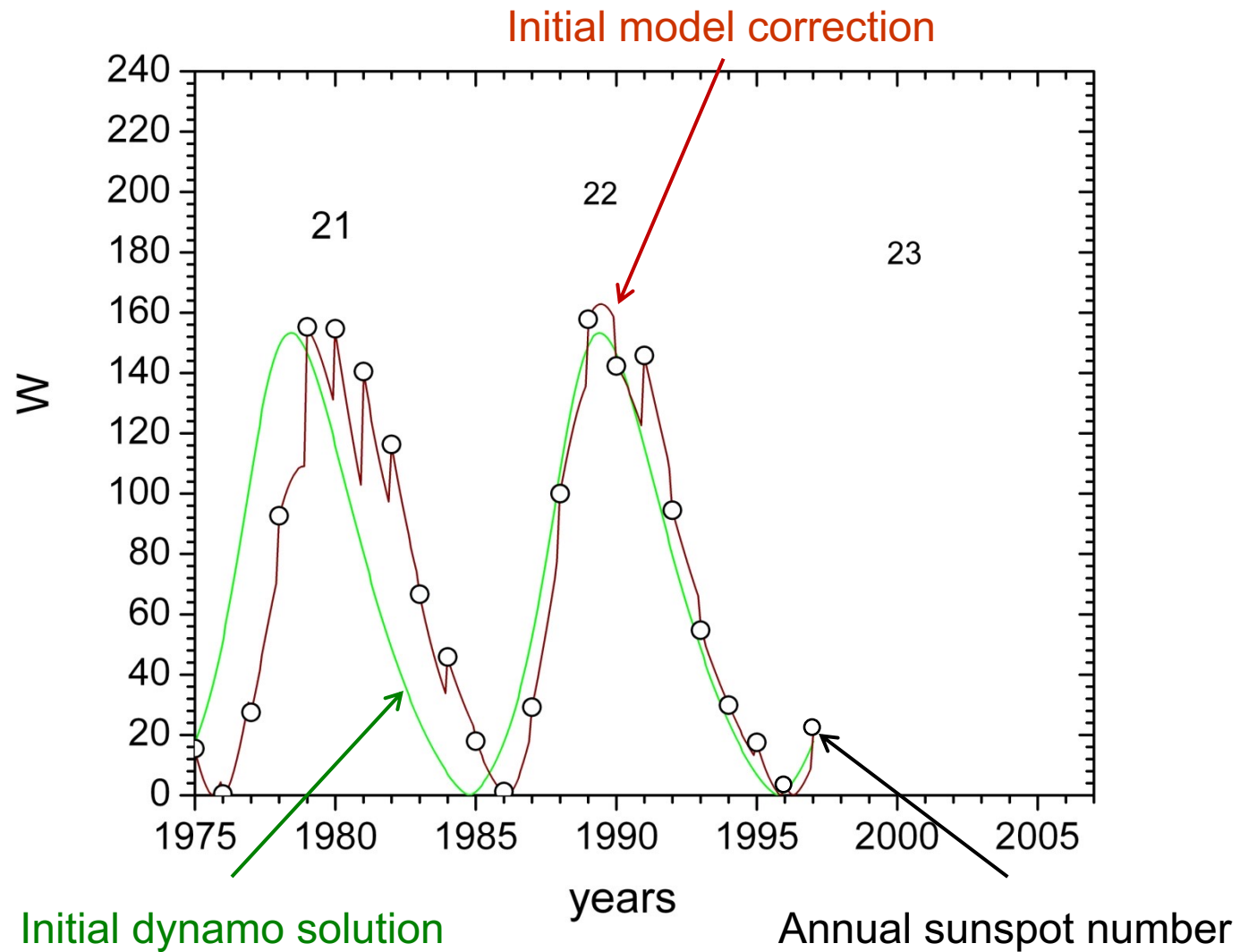


(Kitiashvili and Kosovichev 2008)

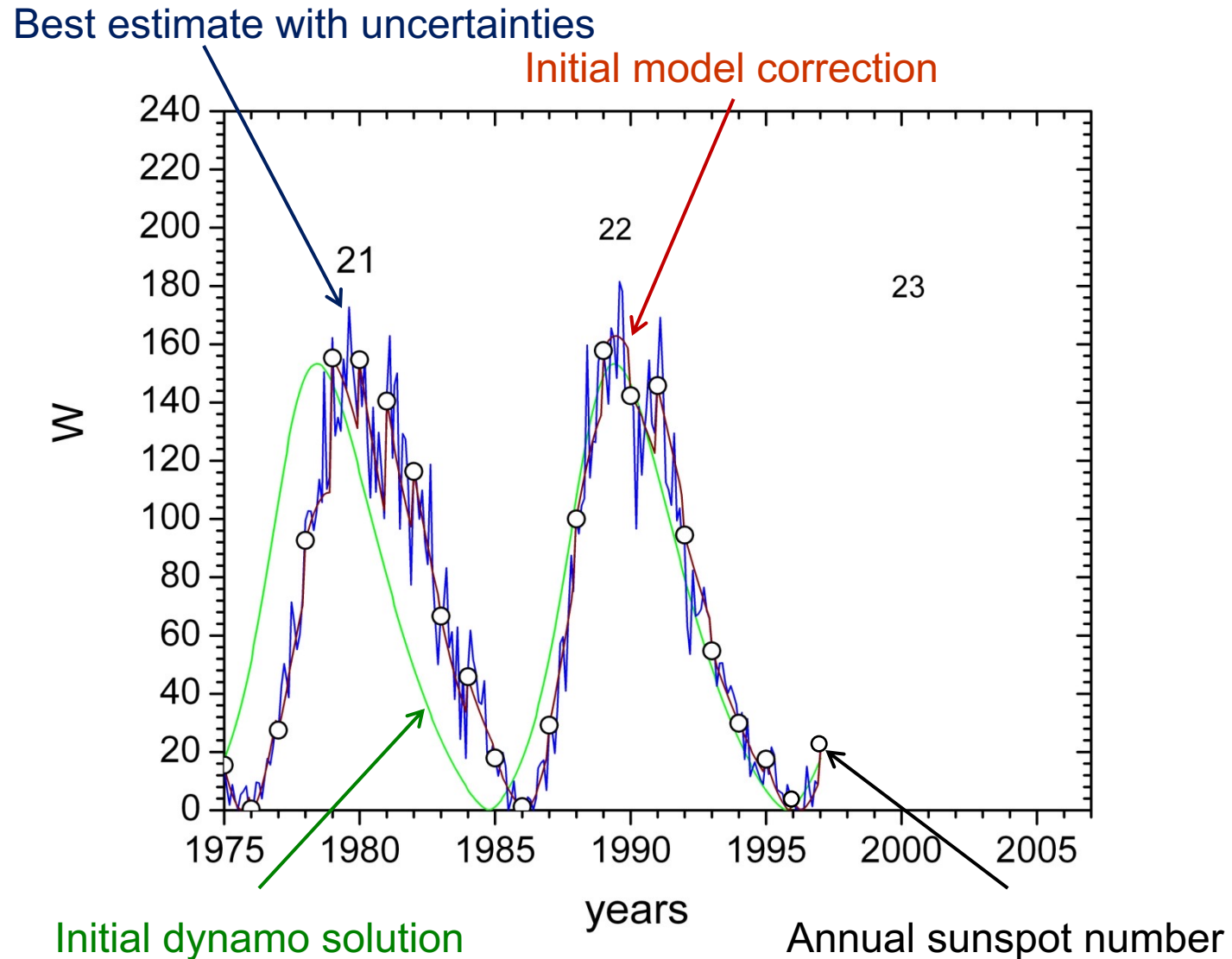
Test example: Prediction of cycle 23



Test example: Prediction of cycle 23

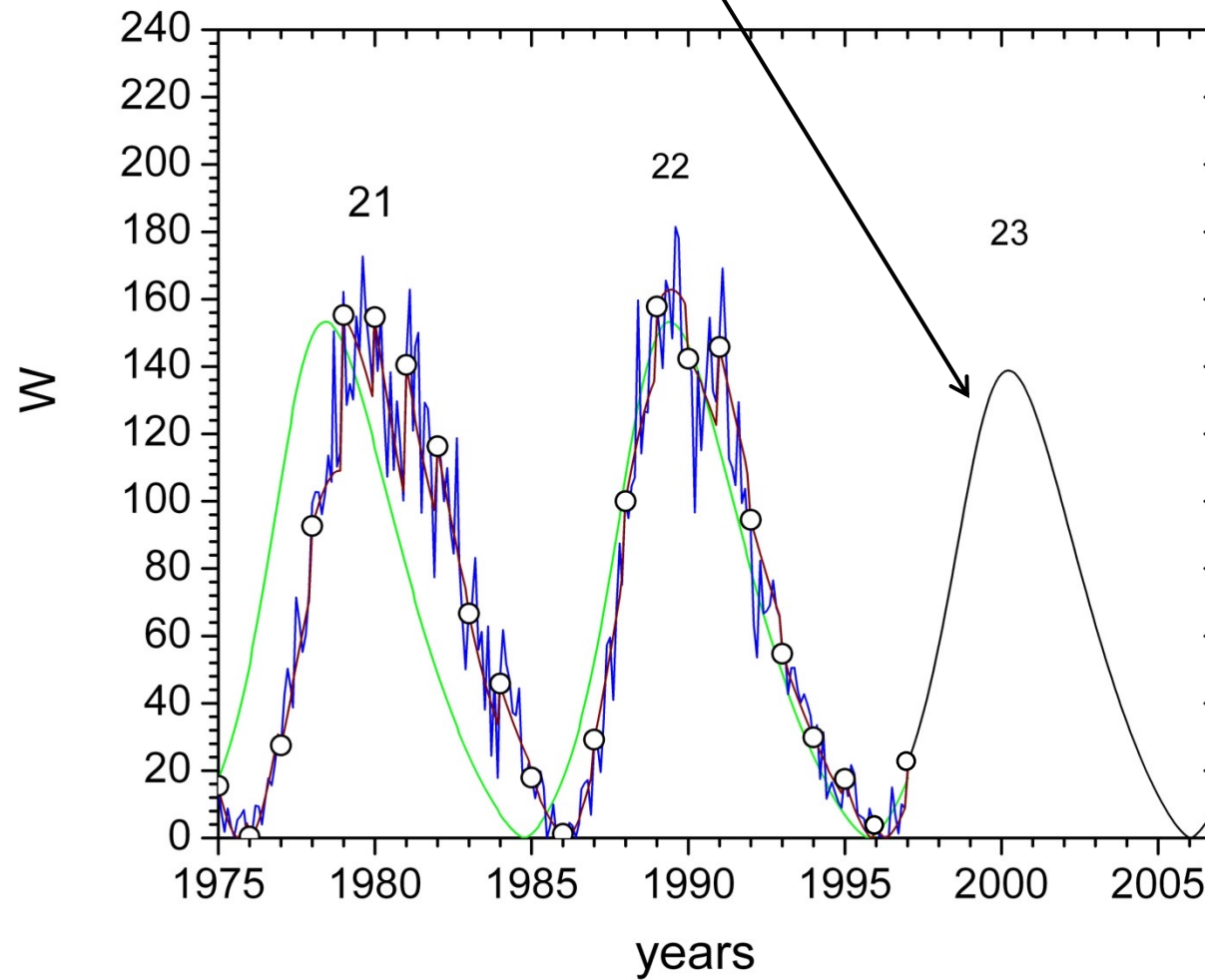


Test example: Prediction of cycle 23



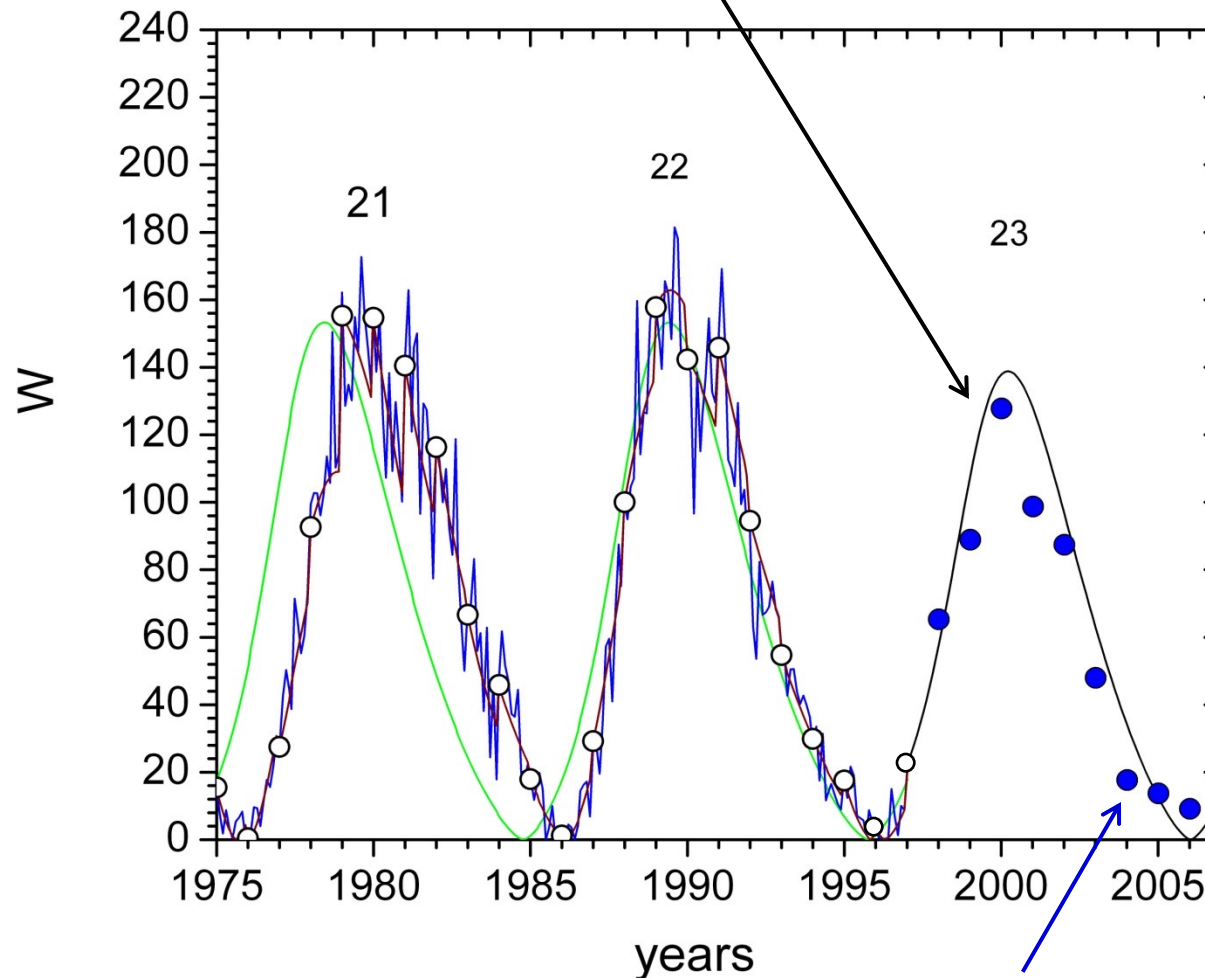
Test example: Prediction of cycle 23

Dynamo solution for cycle 23 with new initial conditions



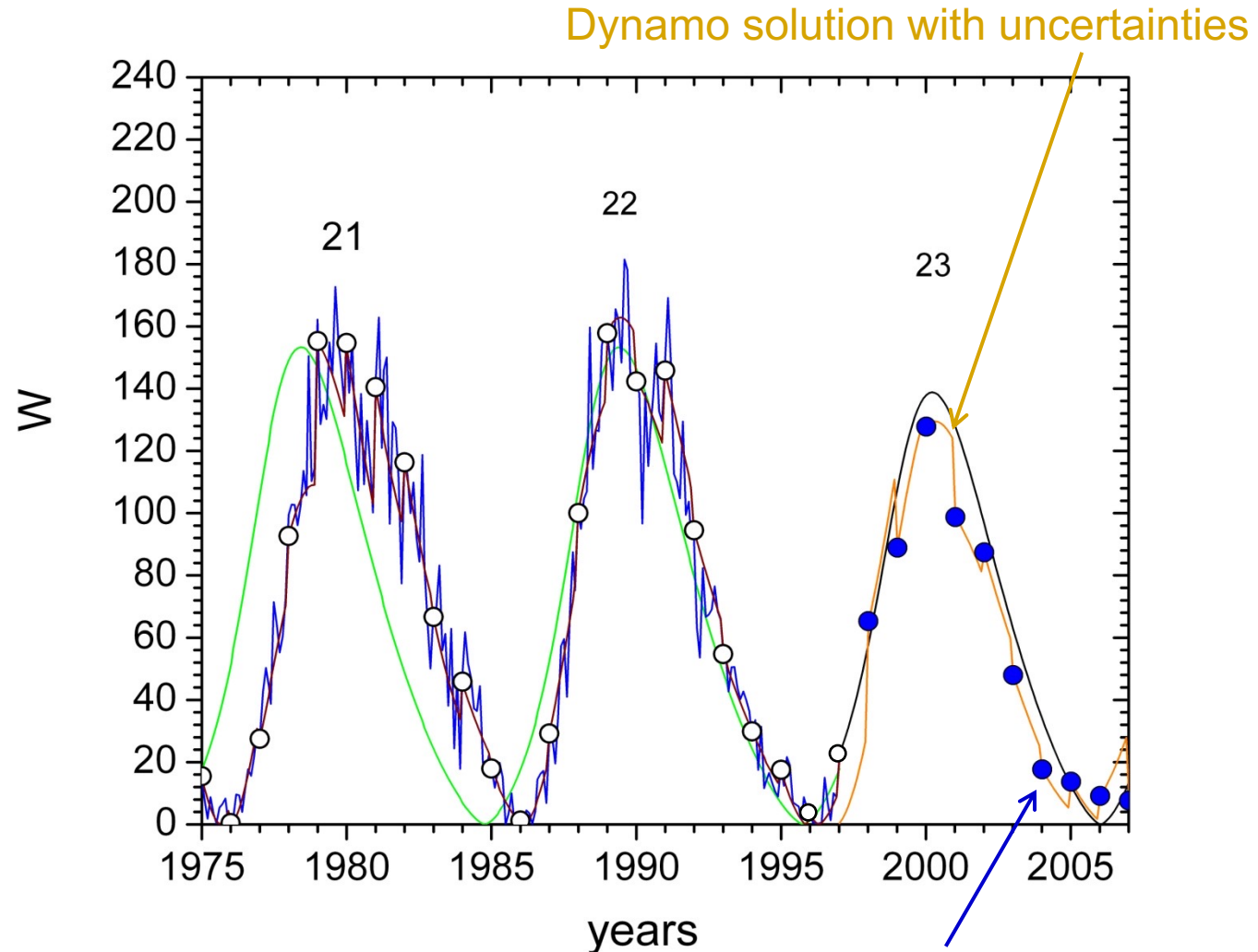
Test example: Prediction of cycle 23

Dynamo solution for cycle 23 with new initial conditions



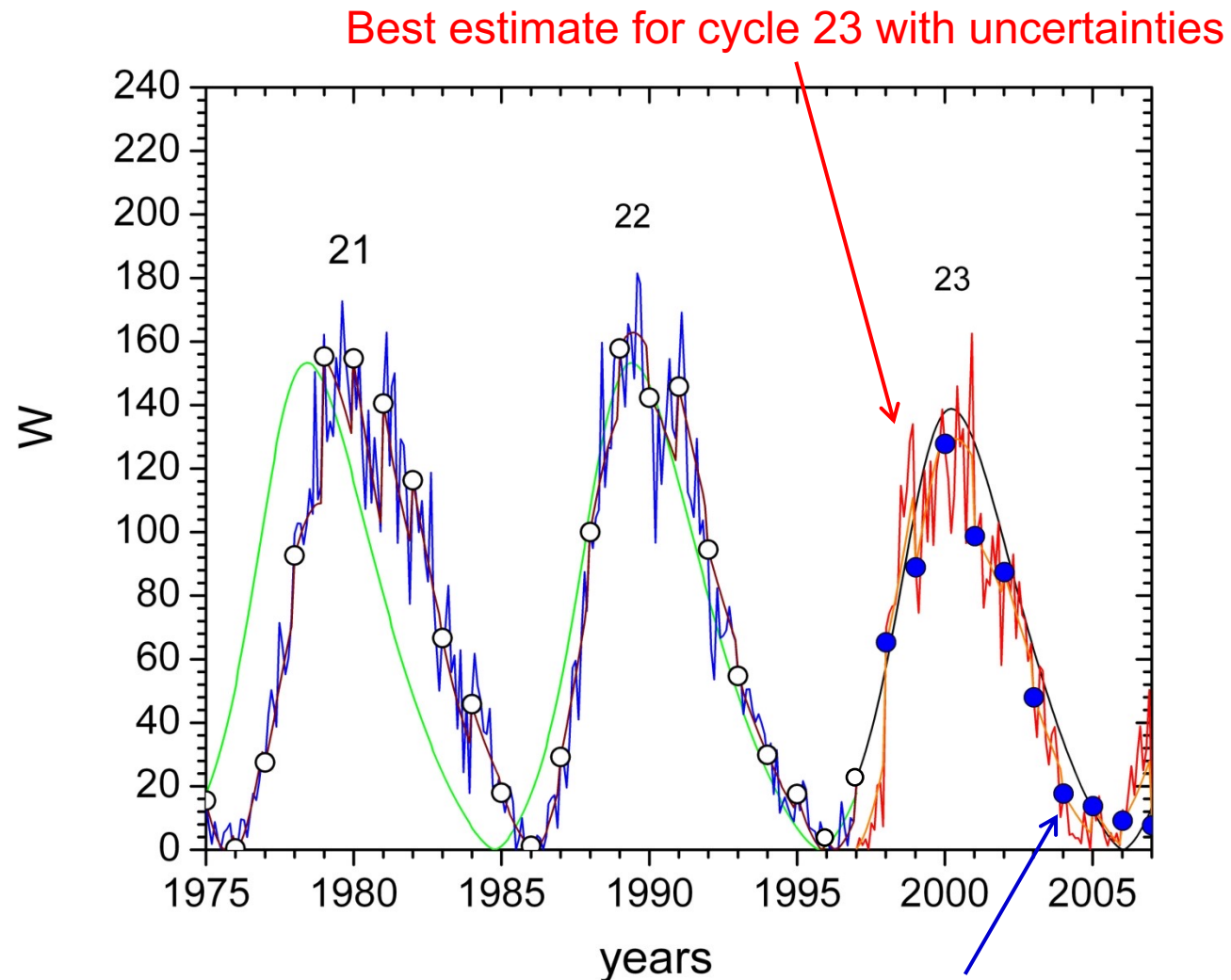
Sunspot number data generated from the dynamo model and uncertainties estimated from previously observed cycles

Test example: Prediction of cycle 23



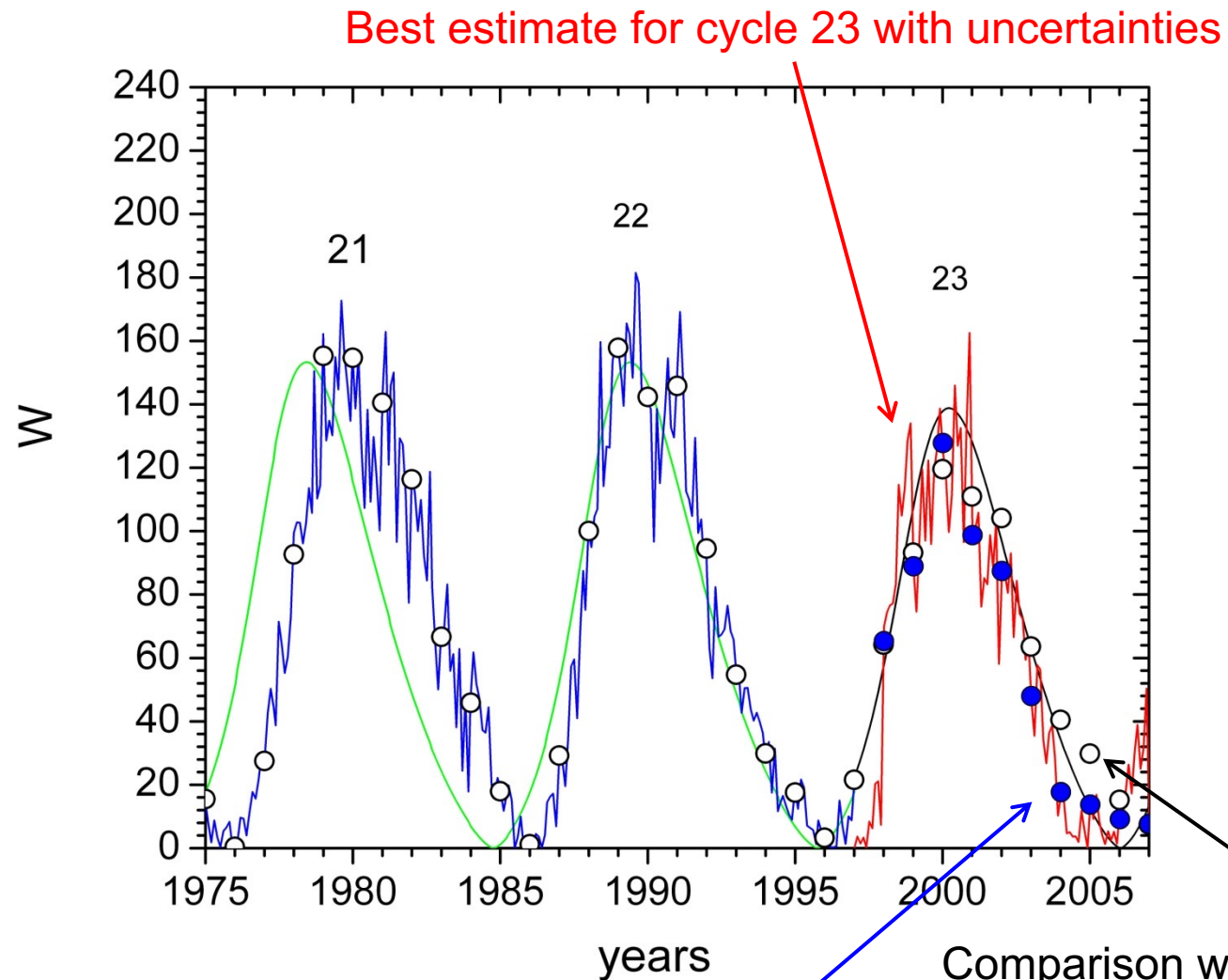
Sunspot number data generated from dynamo and uncertainties known from modeling previous cycles

Test example: Prediction of cycle 23



Sunspot number data generated from the dynamo model and uncertainties estimated from previously observed cycles

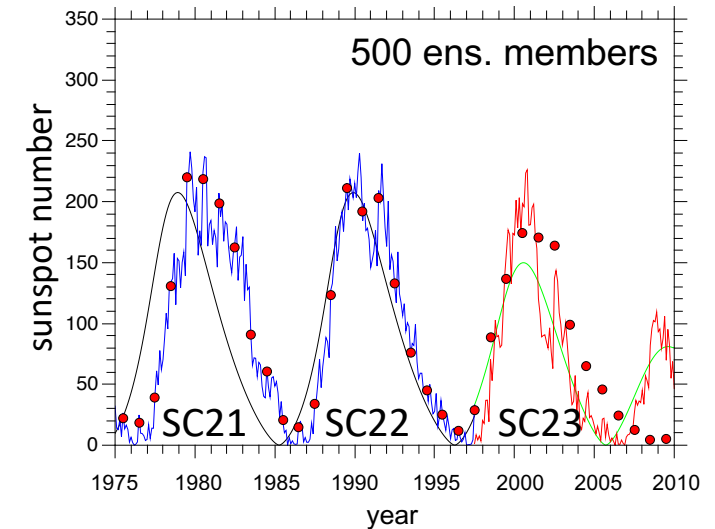
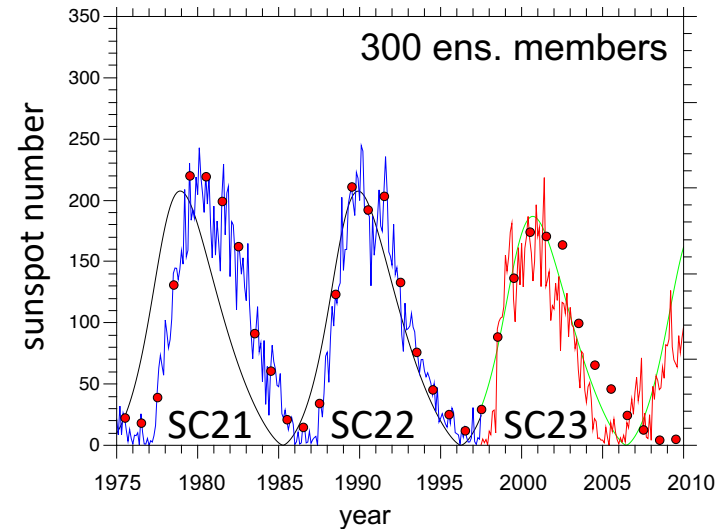
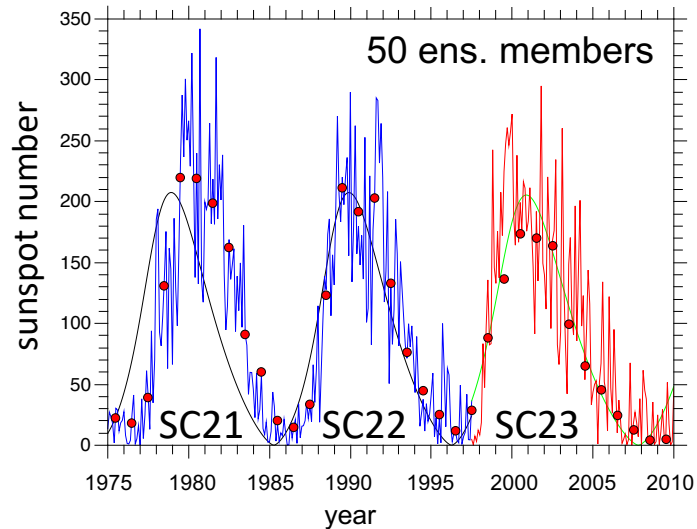
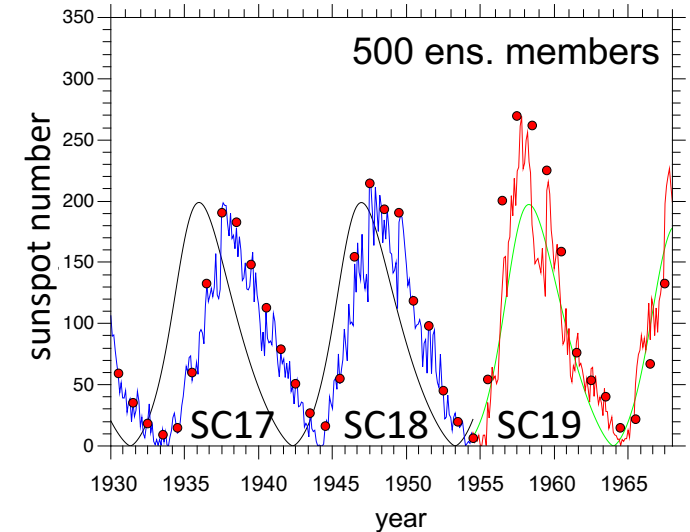
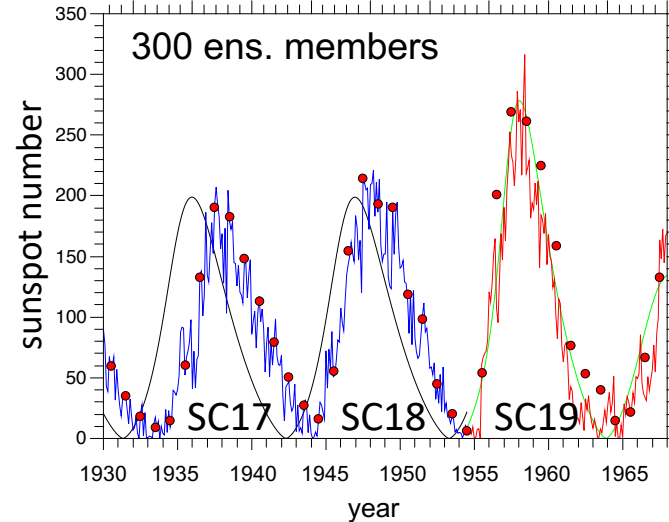
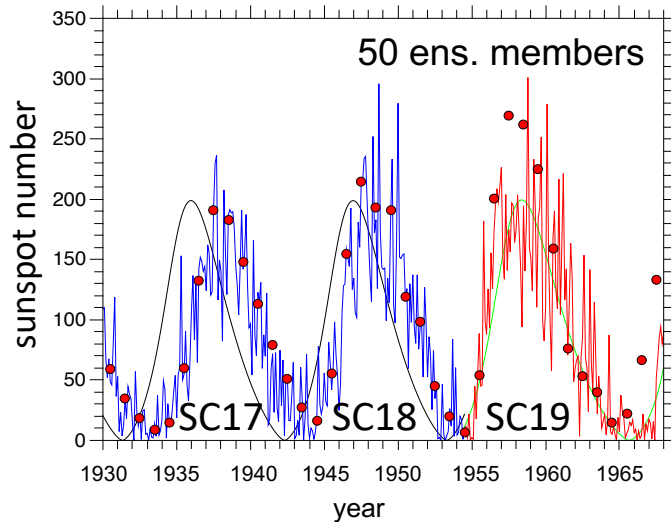
Test example: Prediction of 23



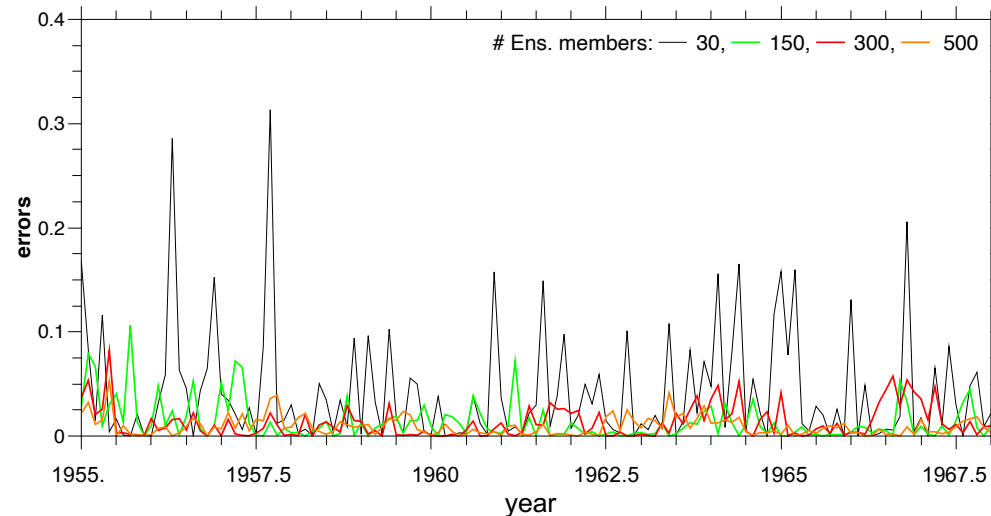
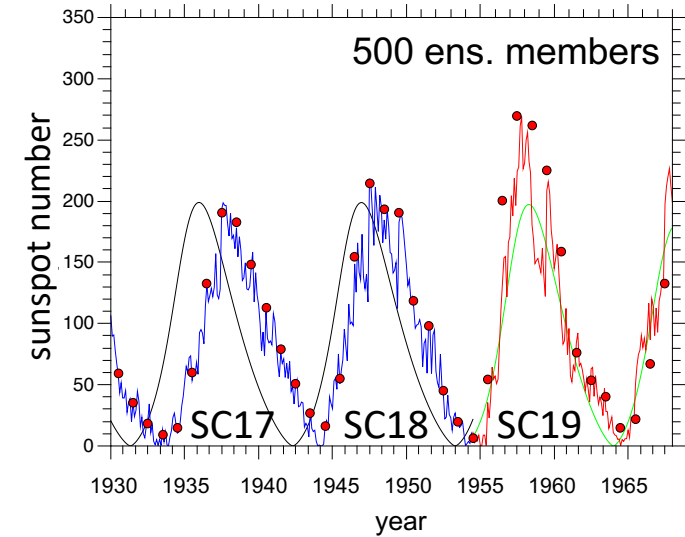
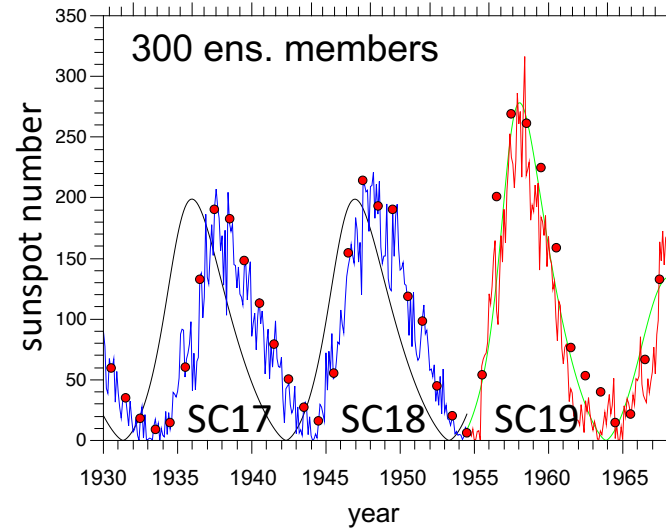
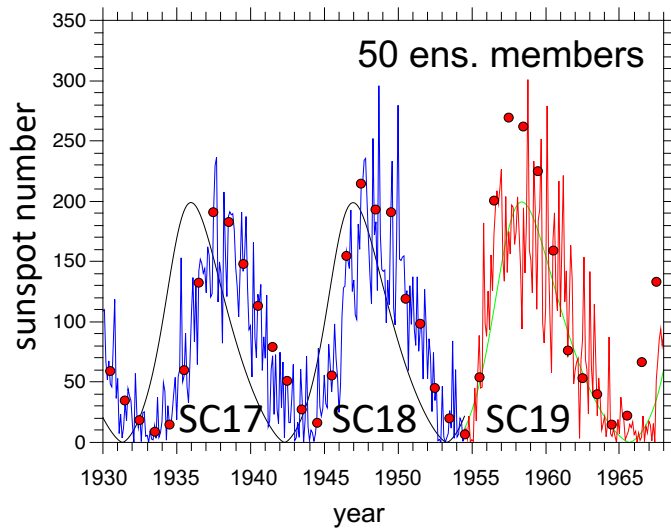
Sunspot number data generated from dynamo and uncertainties known from modeling previous cycles

Comparison with the actual sunspot number data

Effect of the Ensemble Kalman Filter Parameters on Predictive Capabilities of Solar Cycles

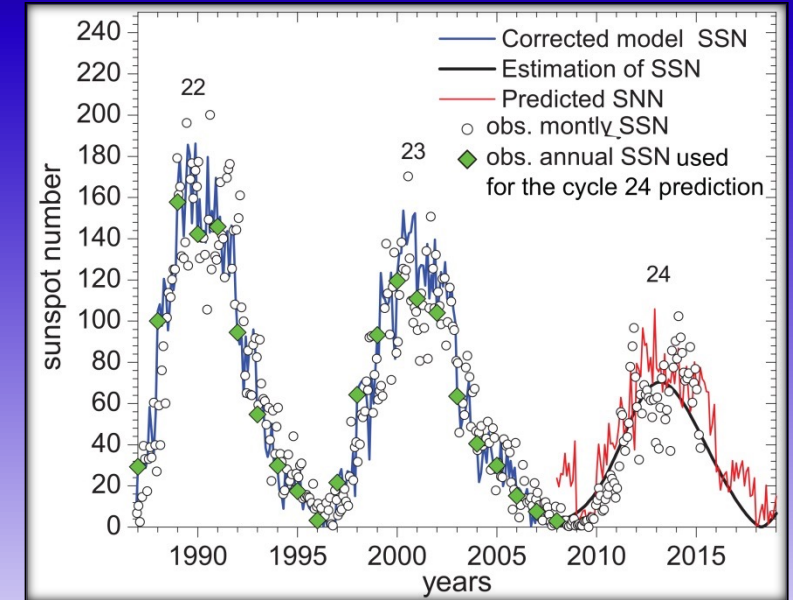
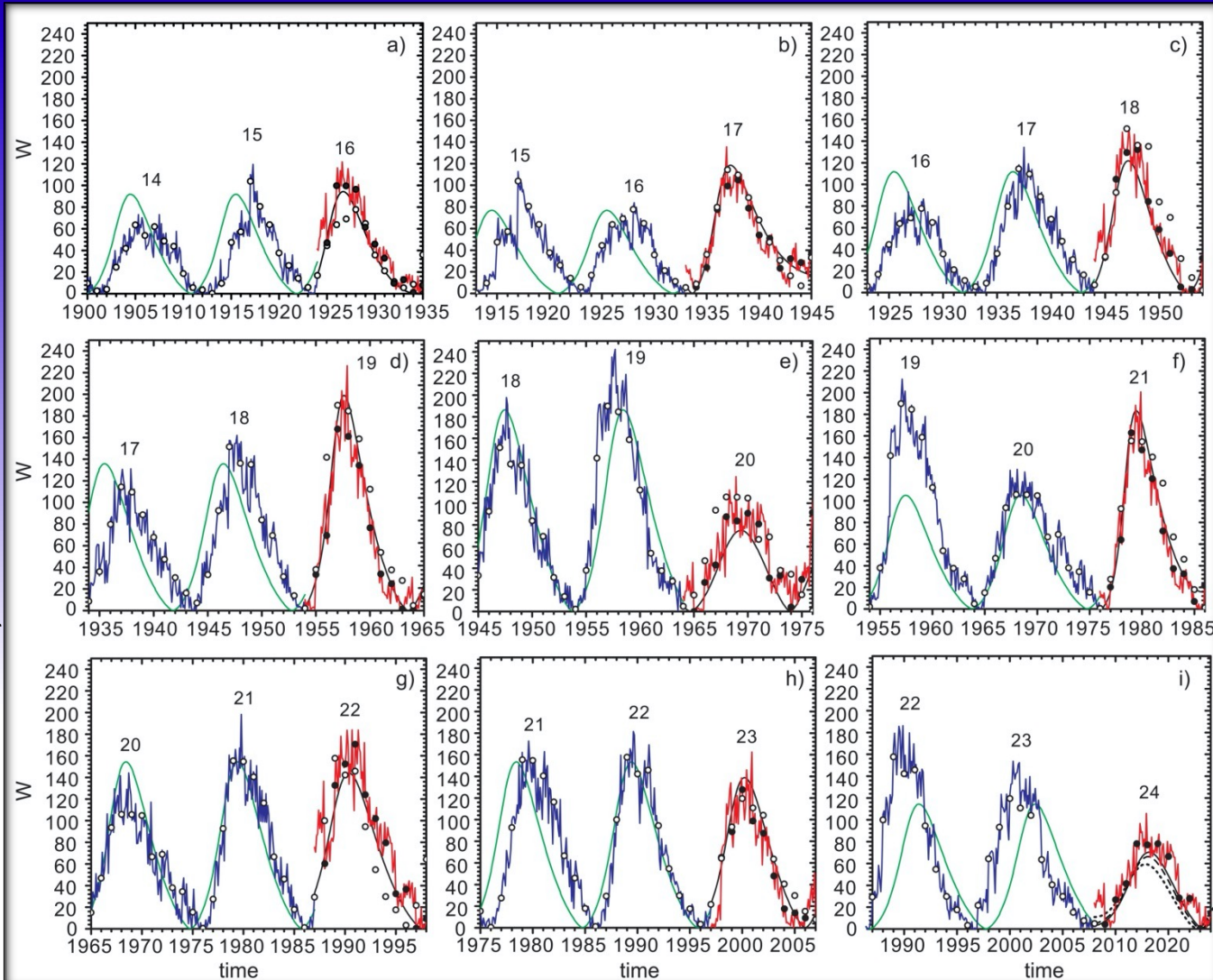


Effect of the Ensemble Kalman Filter Parameters on Predictive Capabilities of Solar Cycles



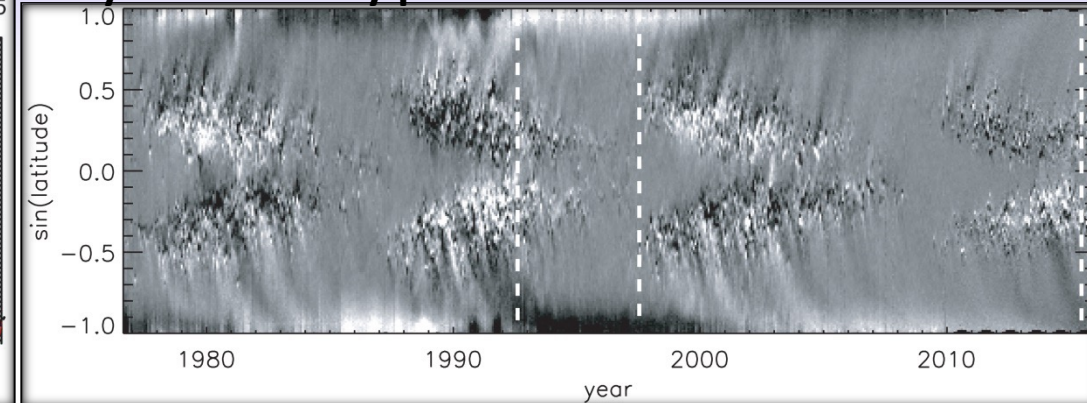
For synthetic
observations
during prediction
of Solar Cycle 19

Forecast of solar activity with long sunspot number time-series



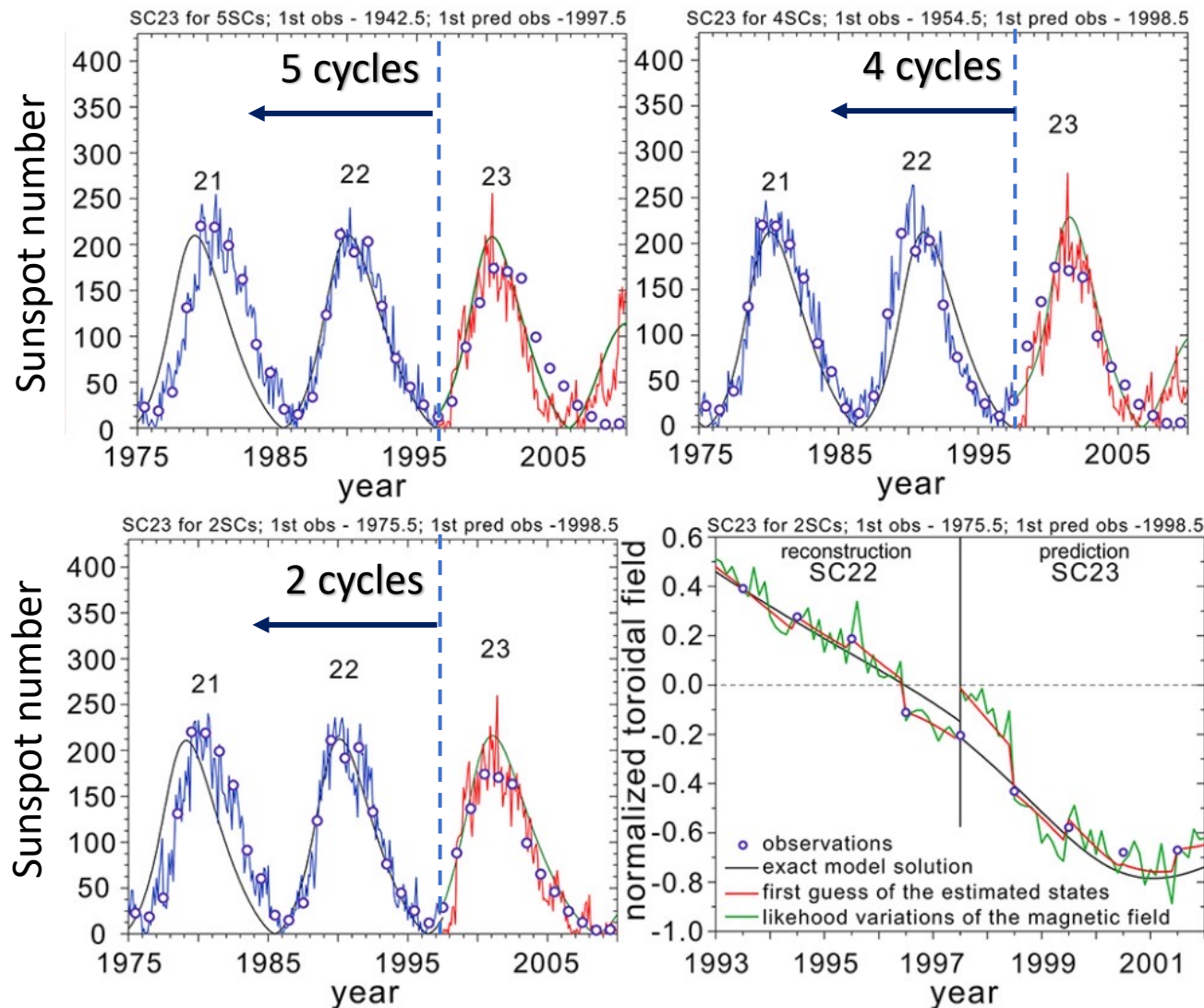
Kitiashvili, 2016

Early solar activity prediction



Kitiashvili & Kosovichev, 2008

Forecast of solar activity with **short** sunspot number time-series

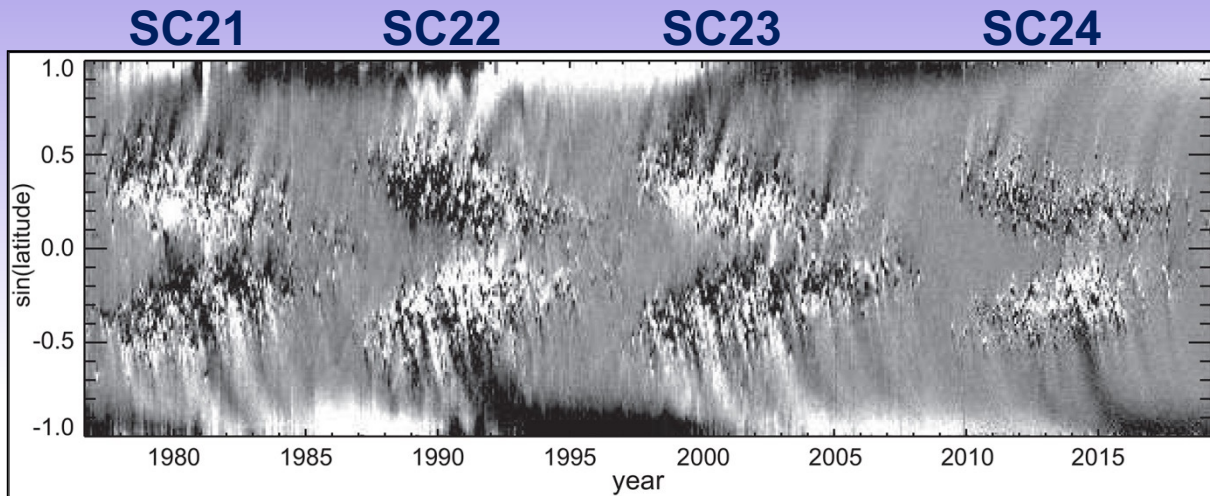


Criteria to identify an accurate model prediction:

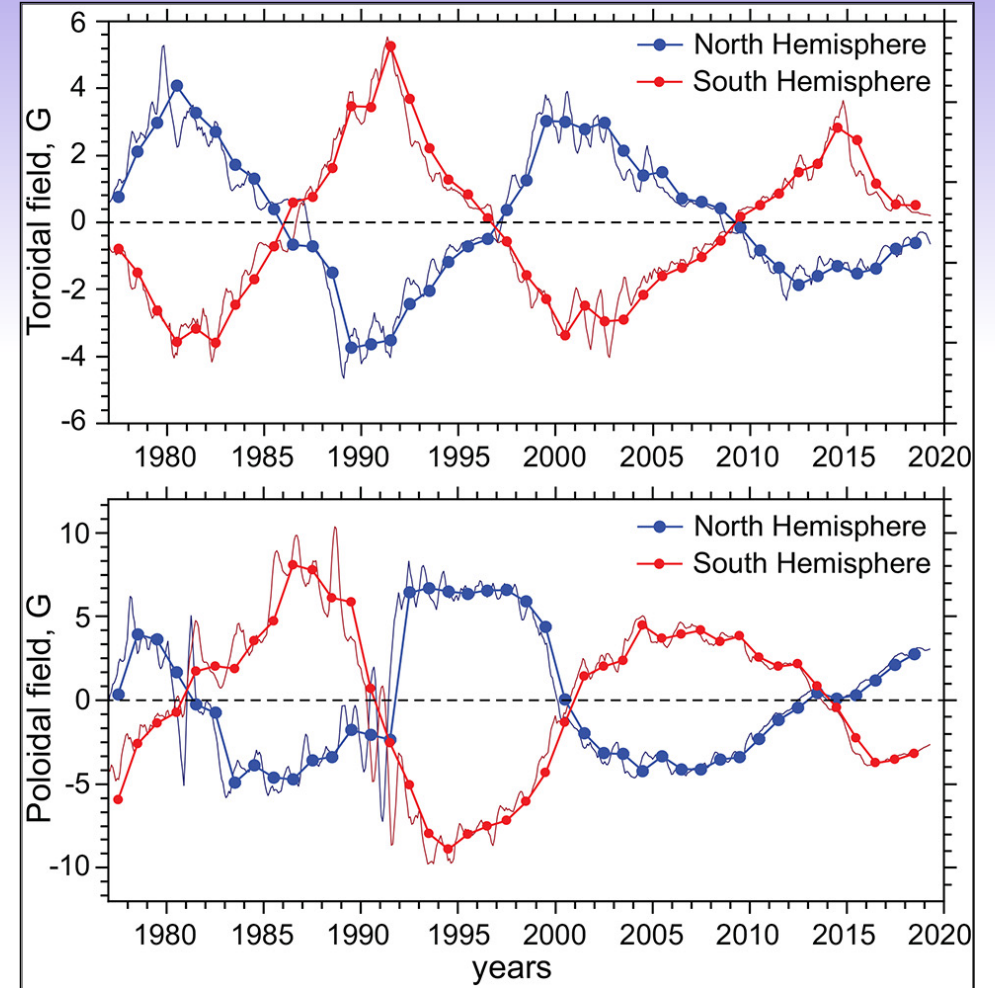
- 1) the signs of the last available observation (for toroidal field) and the corresponding model solution should be the same;
- 2) the exact model solution for the prediction phase must be consistent with the model solution for the reconstruction phase (no solution flattening, jumps, or 'bumps', but the solution may shift according to the new initial condition);
- 3) the corrected solution (first-guess estimate) at the initial moment of time during the prediction phase should not be greater than the best-estimate variations of the toroidal field;
- 4) the phase discrepancy between the exact model solution and observations should not be greater than 2 years.

Solar activity forecast using synoptic magnetograms

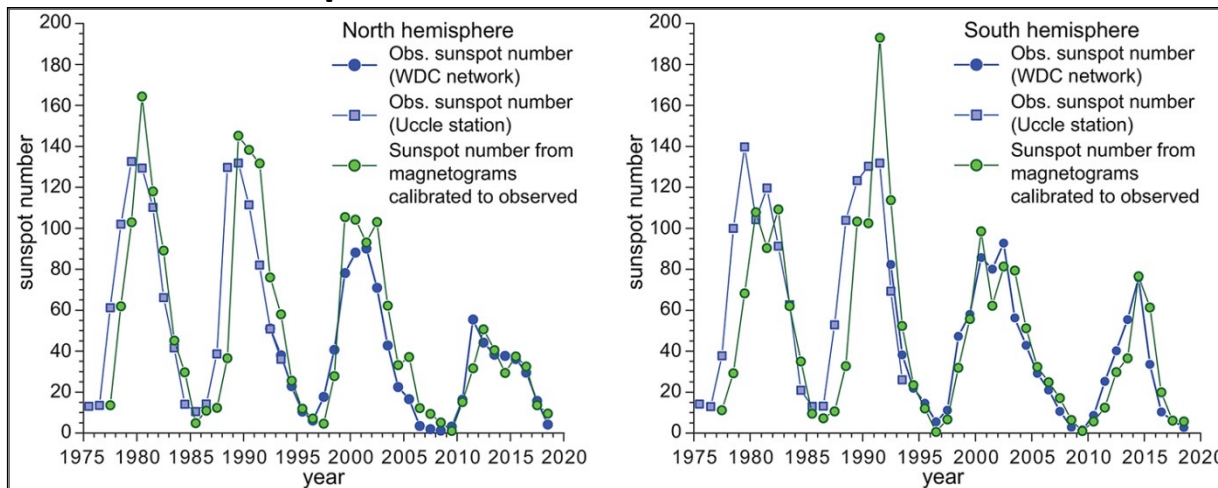
Synoptic magnetograms: KPO, SOLIS, SoHO/MDI, SDO/HMI



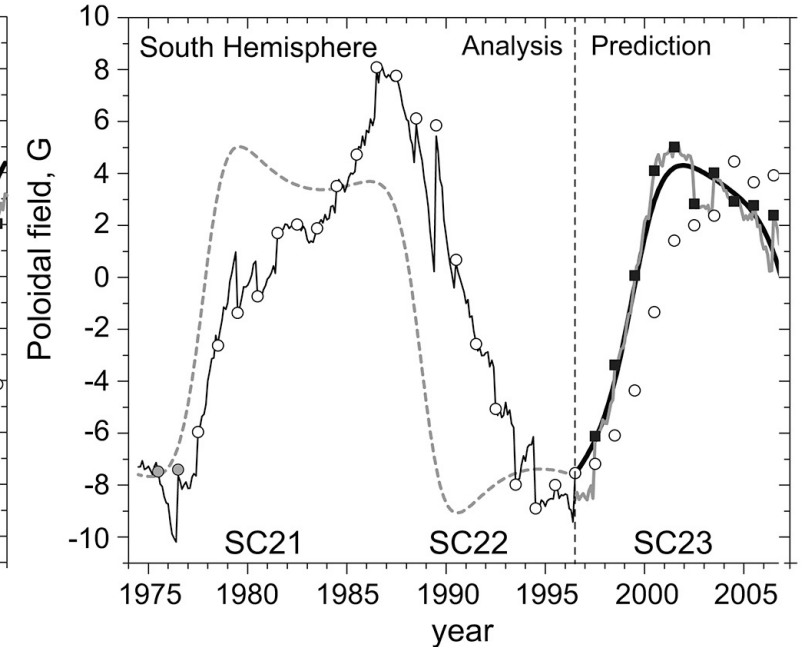
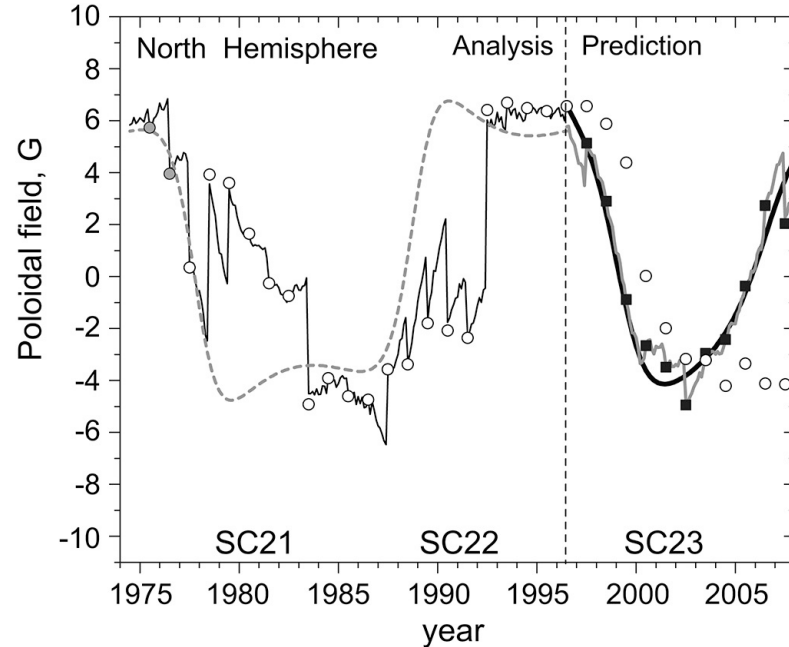
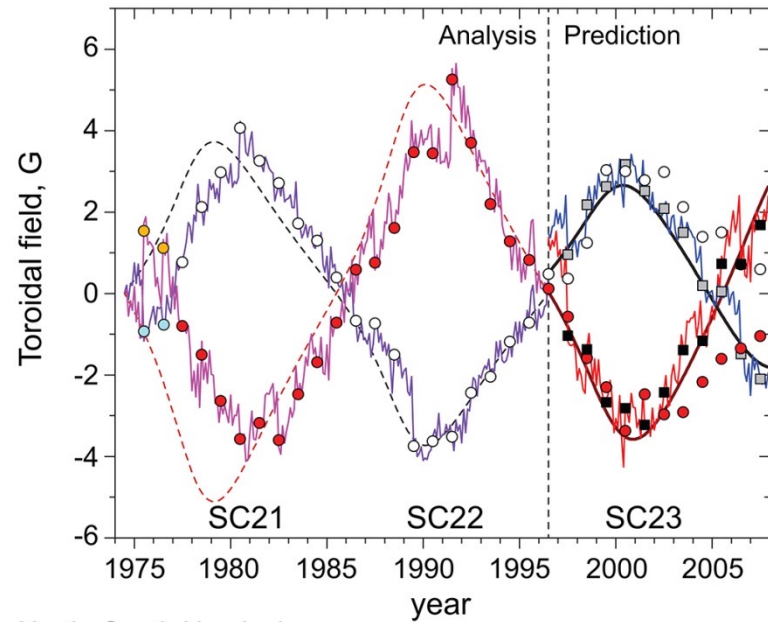
Toroidal and poloidal magnetic field components



Sunspot number: observed vs. estimated



Magnetic field 'test' forecast for Solar Cycle 23



North South Hemispheres

----- Initial model solution

----- Corrected model solution

○ Observations

— Initial prediction of the field

— Prediction of the field with included uncertainties

■ Estimated annual observations of the field

● Synthetic observations of the toroidal field

----- Initial model solution

----- Corrected model solution

— Initial prediction

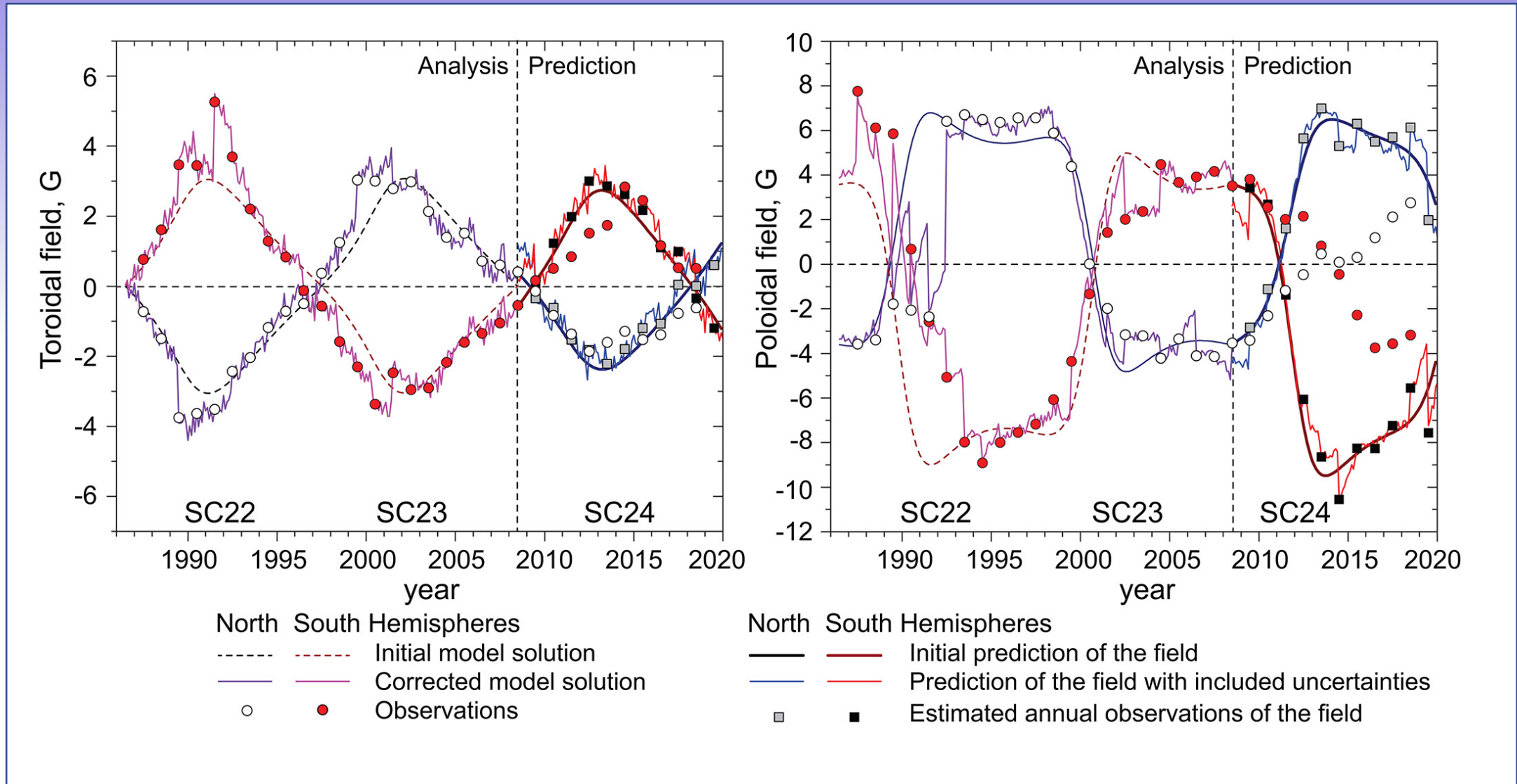
— Prediction with uncertainties

○ Observations

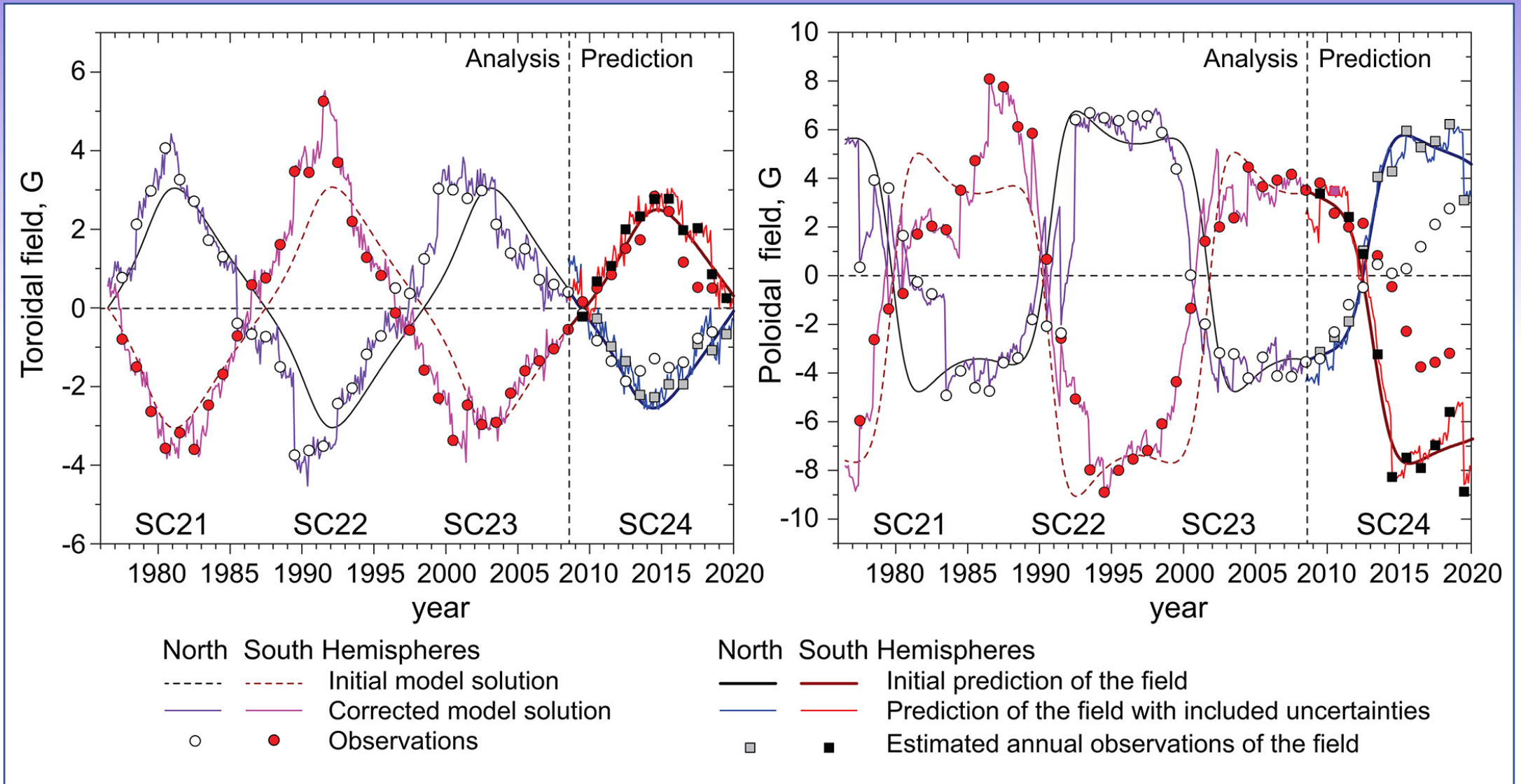
■ Estimated annual observations

● Synthetic observations

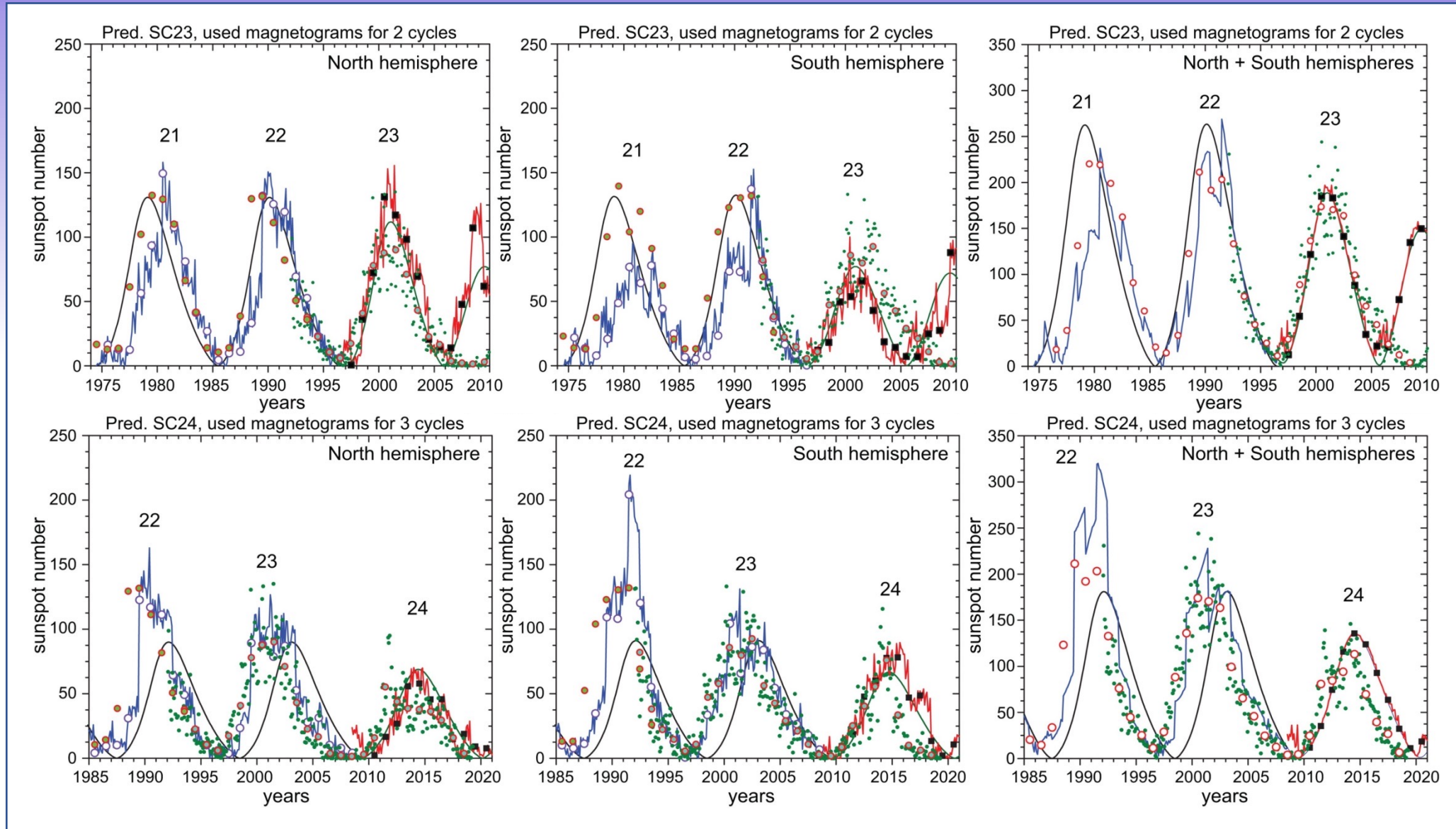
Magnetic field 'test' forecast for Solar Cycle 24



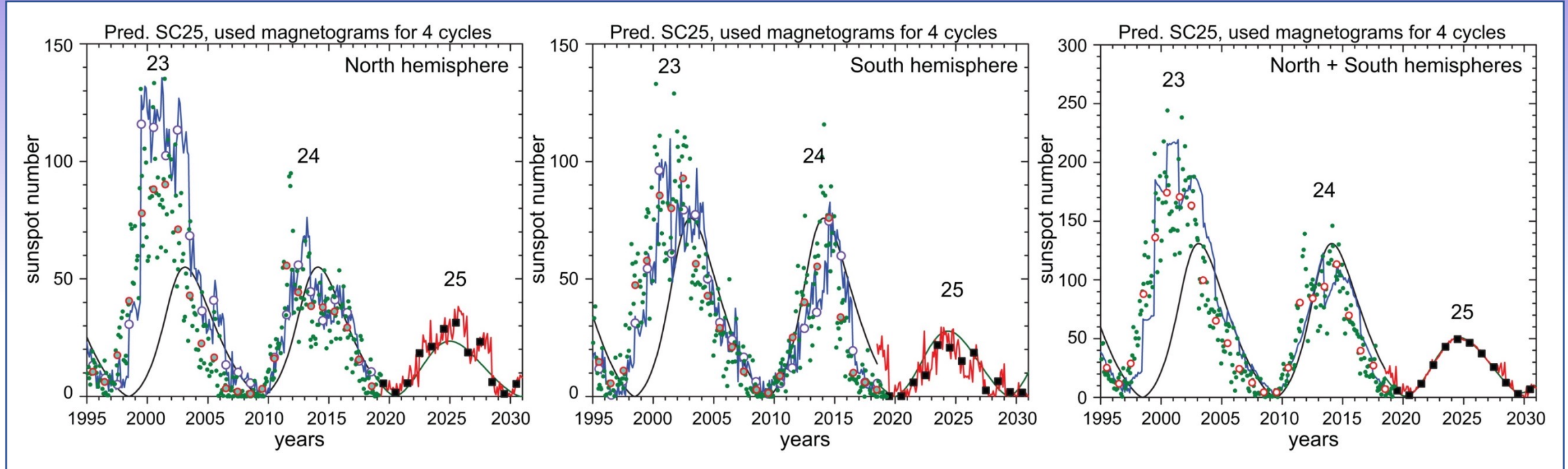
Magnetic field 'test' forecast for Solar Cycle 24



'Test' sunspot number predictions of Solar Cycles 23 and 24



Prediction for Solar Cycle 25



Solar Cycle 25 will be weaker than the current cycle and will start after an extended solar minimum during 2019 - 2021. The maximum of activity will occur in 2024 - 2025 with a sunspot number maximum of about 50 ± 15 with an error estimate of $\sim 30\%$.

SC25 will start in the Southern hemisphere in 2020 and reach maximum in 2024 with a sunspot number of $\sim 28 (\pm 10\%)$. Solar activity in the Northern hemisphere will be delayed for about 1 year (with error of ± 0.5 year) and reach maximum in 2025 with a sunspot number of $\sim 23 \pm 5 (\pm 21\%)$.

Conclusions

- Recent studies based on sunspot number data series show the possibility of obtaining a reasonable solar-cycle prediction by assimilating the data from only the two previous solar cycles.
- We combined all available synoptic observations from the National Solar Observatory and the SOHO and SDO space mission archives. We found that two cycles of synoptic magnetograms can provide a reasonable forecast of solar activity for the following solar cycle.
- Taking into account poloidal field observations can noticeably improve the forecast, particularly when the data from three preceding cycles are assimilated in the model.
- Forecasts hemispheric toroidal field variations are in good agreement with observations, at least up to the following solar maximum, and often make a reasonable prediction for the whole activity cycle. Forecasts poloidal fields are in good agreement with observations for up to two years in the case of assimilation of data from two preceding activity cycles, and for about three years if data from three cycles is assimilated.
- According to the presented analysis, the next Solar Cycle (25) will start after an extended solar minimum during 2019 – 2021 and is expected to be weaker than the current cycle. The maximum of activity will occur in 2024 - 2025 with a sunspot number at a maximum of about 50 with an error estimate of $\sim 30\%$. SC25 will start in the southern hemisphere in 2020 and reach maximum in 2024 with a sunspot number of ~ 28 (with error of $\sim 10\%$). Solar activity in the northern hemisphere will be delayed for about 1 year (with an error of ~ 0.5 year) and reach maximum in 2025 with a sunspot number of ~ 23 (with an error of $\sim 21\%$).