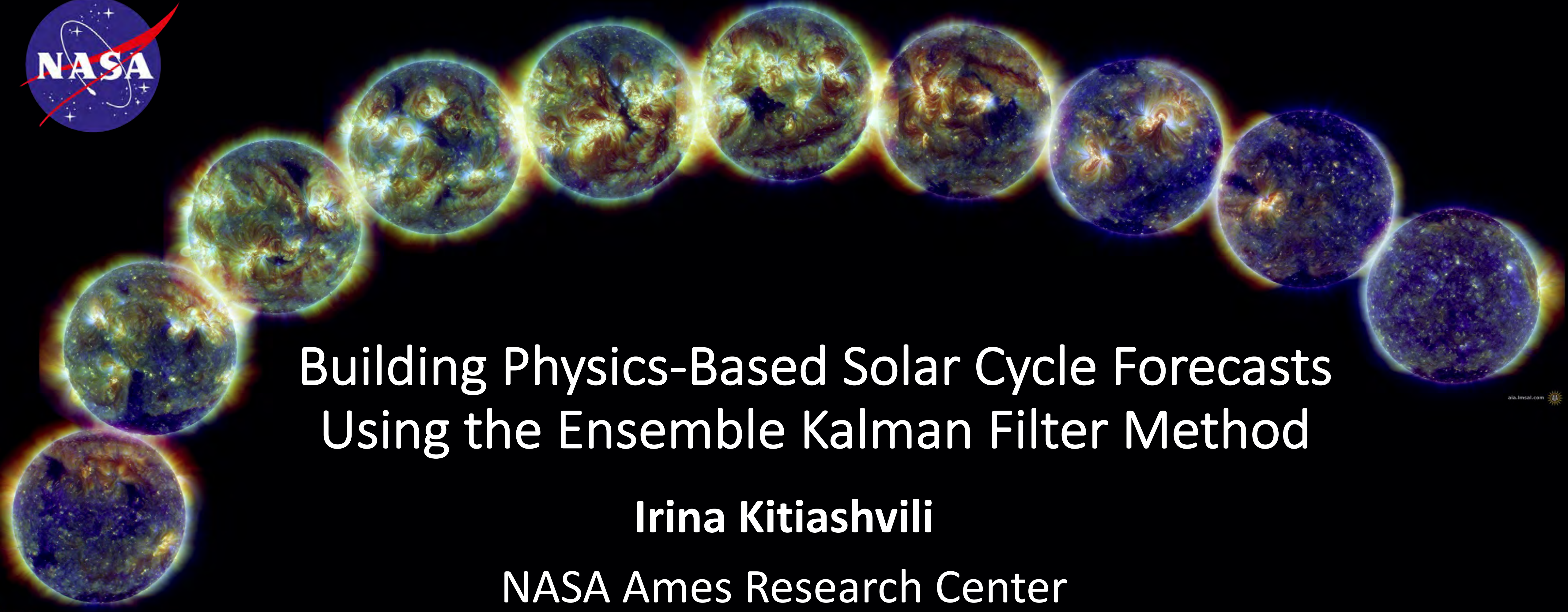


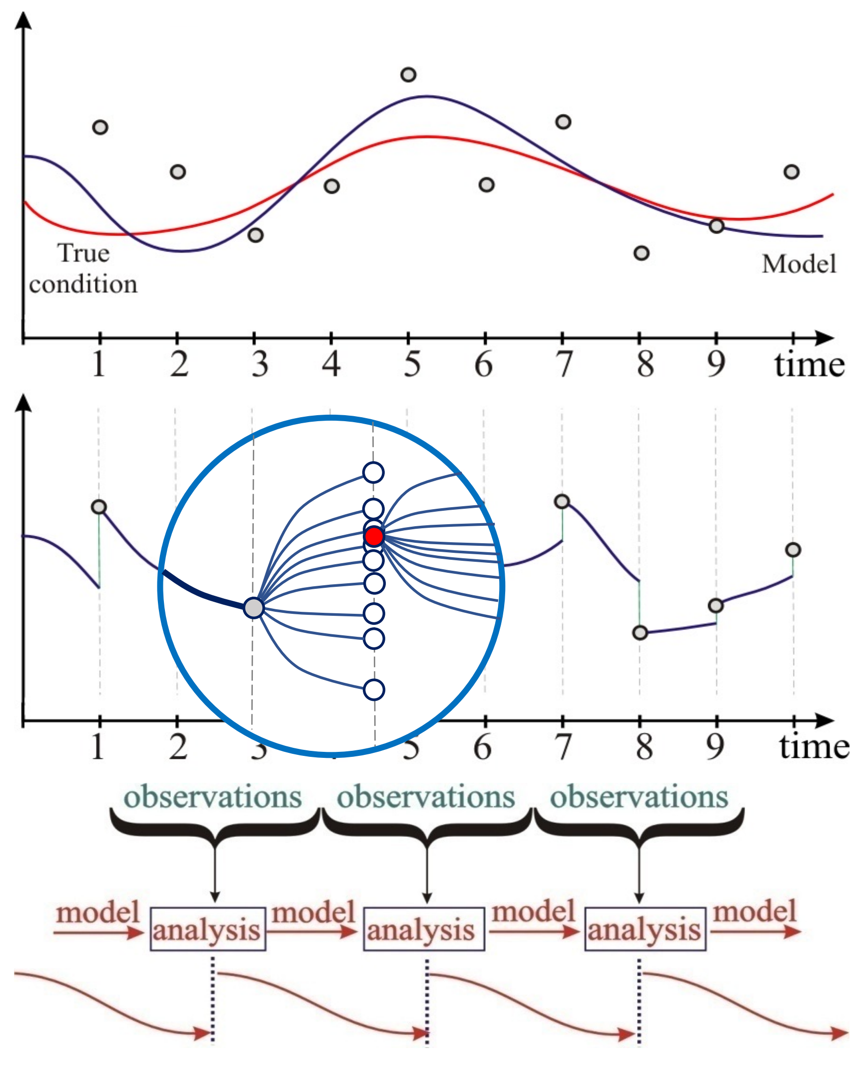
Building Physics-Based Solar Cycle Forecasts Using the Ensemble Kalman Filter Method

Irina Kitiashvili

NASA Ames Research Center

The research is funded by the NSF SHINE program AGS-1622341

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.

$$d_j = M\psi^t + \varepsilon_j$$ observations

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

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

$$\psi_j^a = \psi_j^f + K\left(d_j - M\psi_j^f\right)$$ Best estimate of a state

$$K = \left(C_{\psi\psi}^{\ e}\right)^f M^T \left(M\left(C_{\psi\psi}^{\ e}\right)^f M^T + C_{\varepsilon\varepsilon}^{\ e}\right)^{-1}$$ 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-Kleeorin-Ruzmaikin (PKR) Dynamo Model

$$\frac{\partial A}{\partial t} = \alpha B + \eta \nabla^2 A$$

$$\frac{\partial B}{\partial t} = G \frac{\partial A}{\partial z} + \eta \nabla^2 B$$

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.

+

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

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

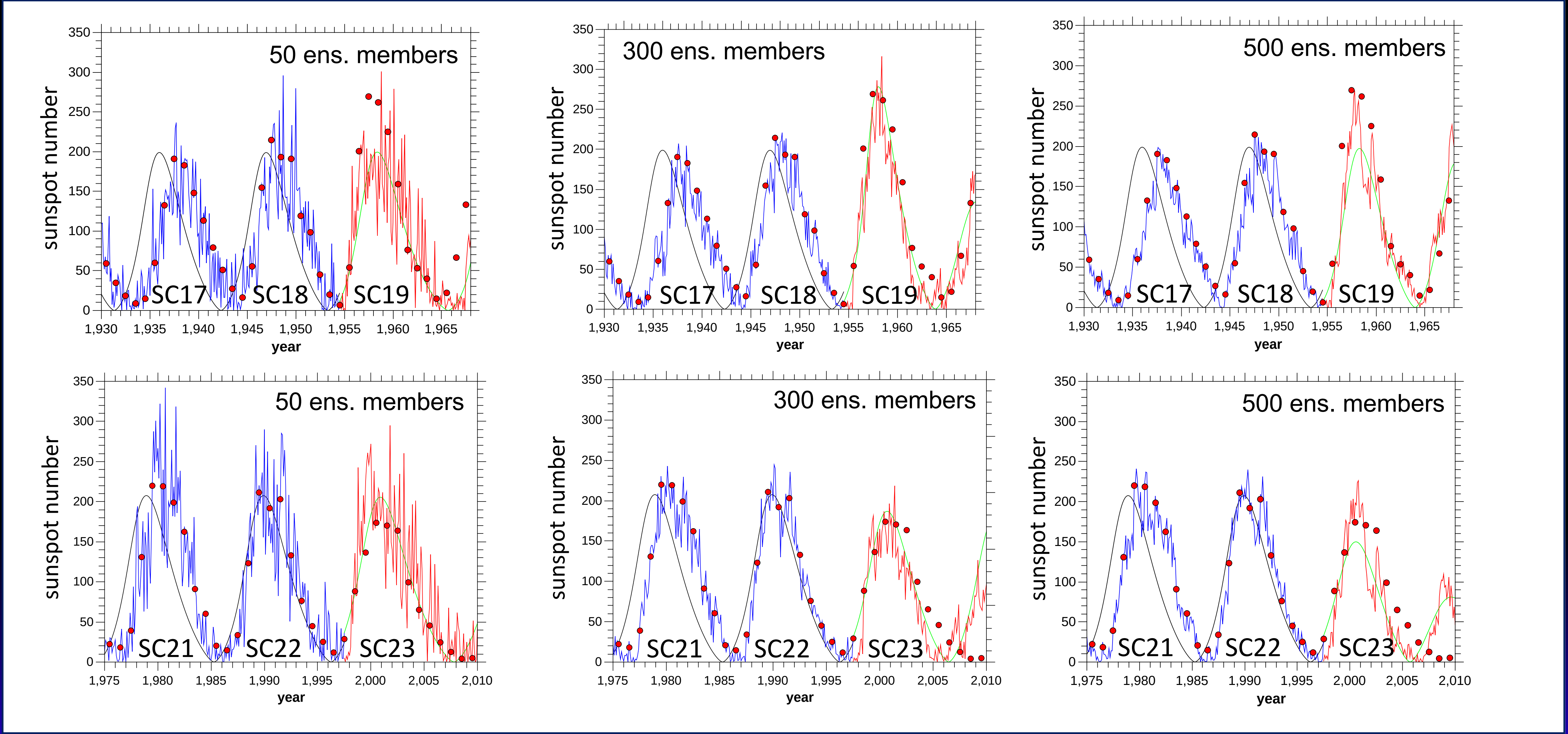
$$\alpha = \alpha_k + \alpha_m$$

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

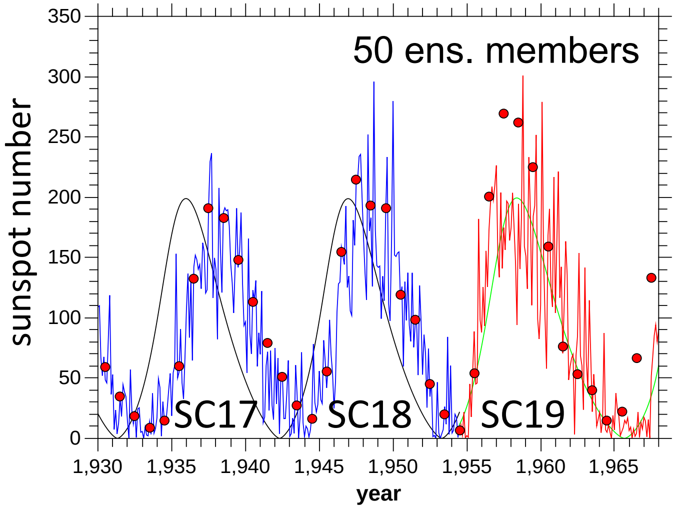
$$\alpha_m = (\tau/12\pi\rho)\langle \mathbf{h}(\nabla\times\mathbf{h})\rangle$$

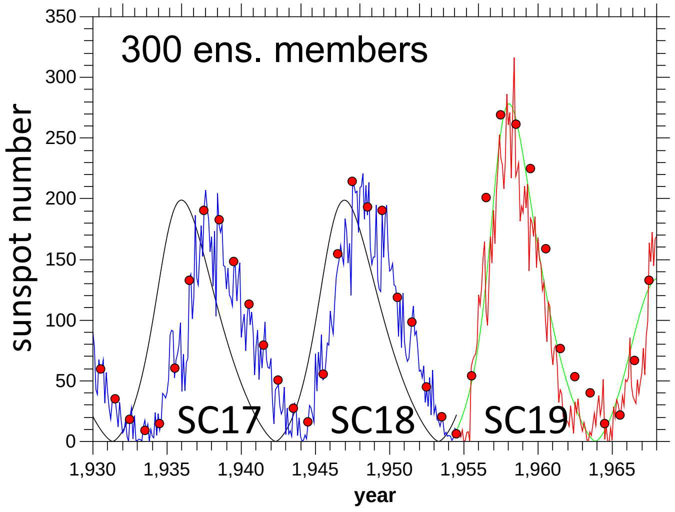
G is the large-scale radial shear; u is turbulent velocity; h is turbulent magnetic field; α_k and α_m are the kinetic and magnetic helicities; $\mu \approx 0.1$; ρ is the density; η is sum of the turbulent and molecular magnetic diffusivities;

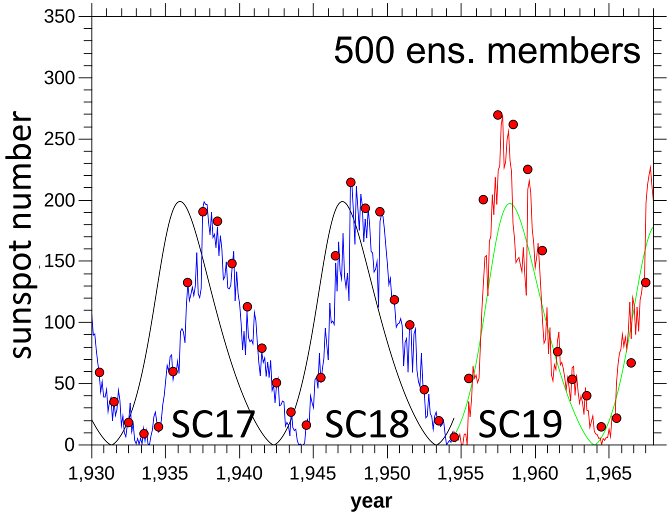
Effect of the Ensemble Kalman Filter Parameters on Predictive Capabilities of Solar Cycles

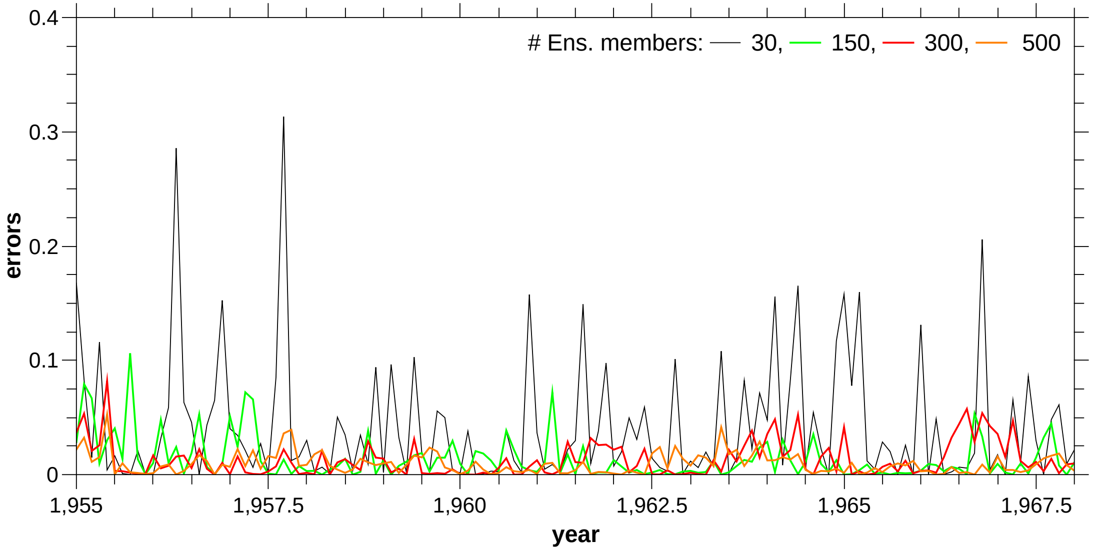


Effect of the Ensemble Kalman Filter Parameters on Predictive Capabilities of Solar Cycles



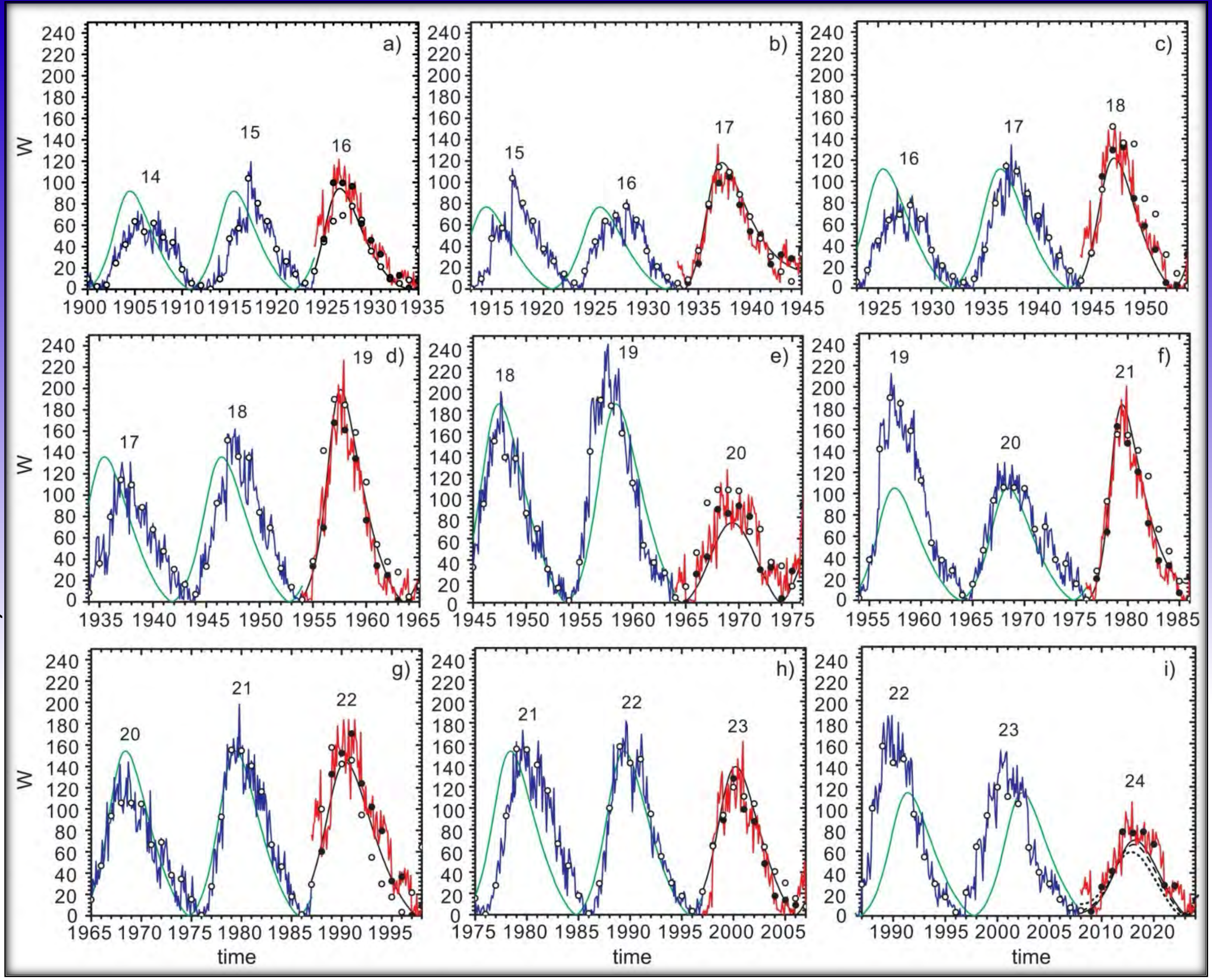




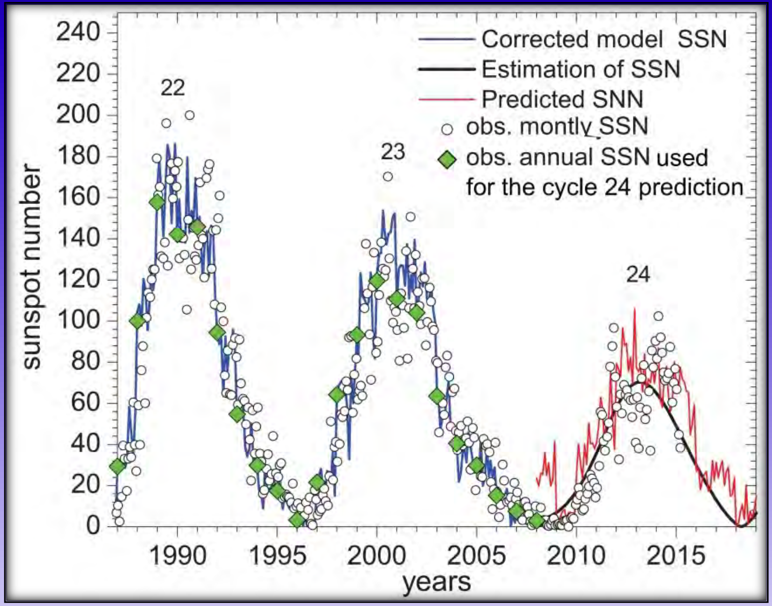


For synthetic observations during prediction of Solar Cycle 19

Forecast of solar activity with long sunspot number time-series

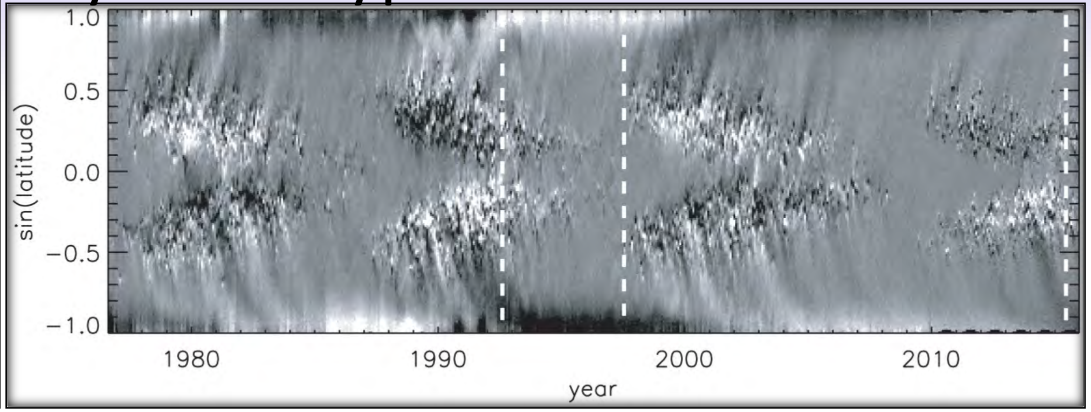


Kitiashvili & Kosovichev, 2008

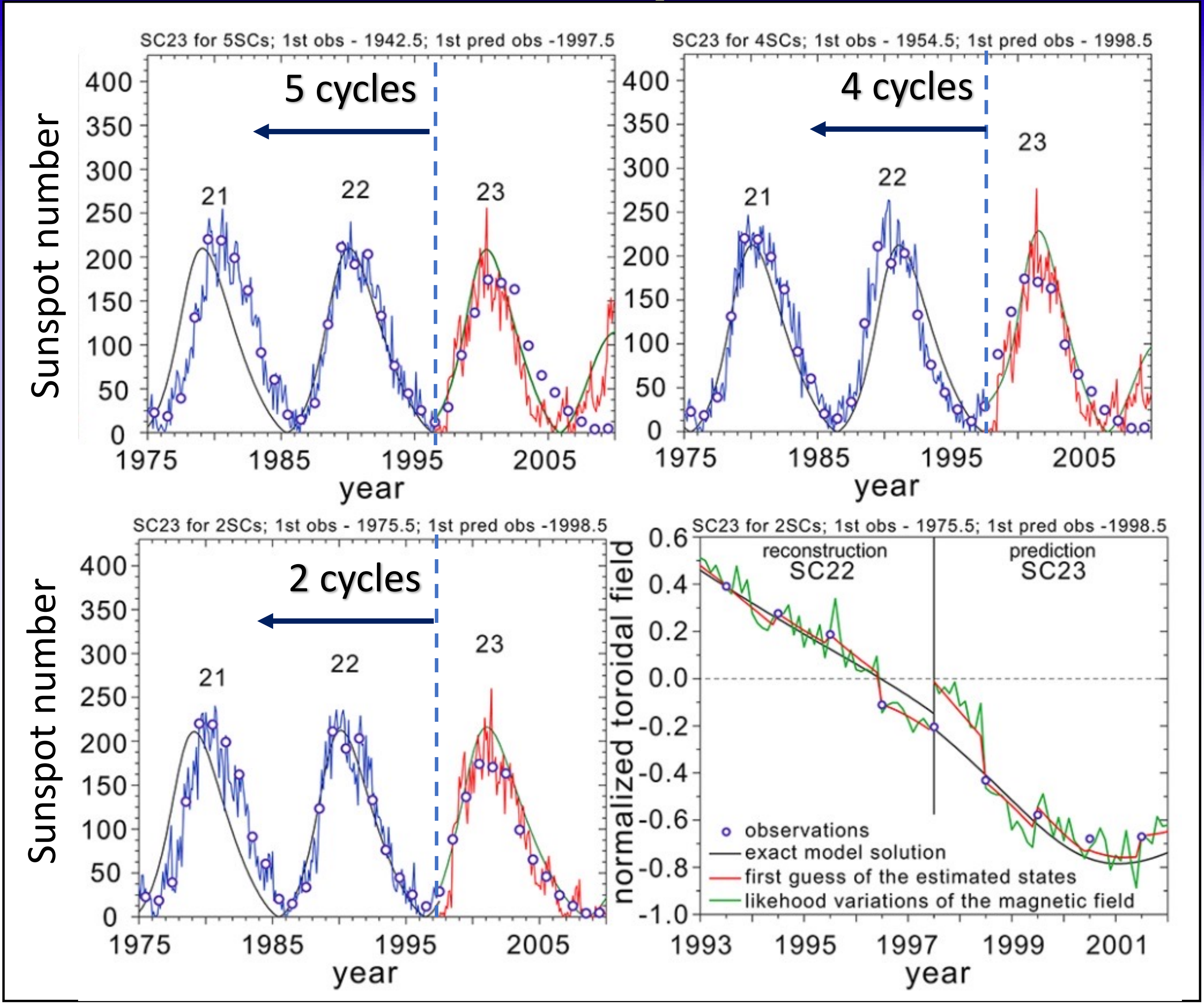


Kitiashvili, 2016

Early solar activity prediction



Forecast of solar activity with short sunspot number time-series



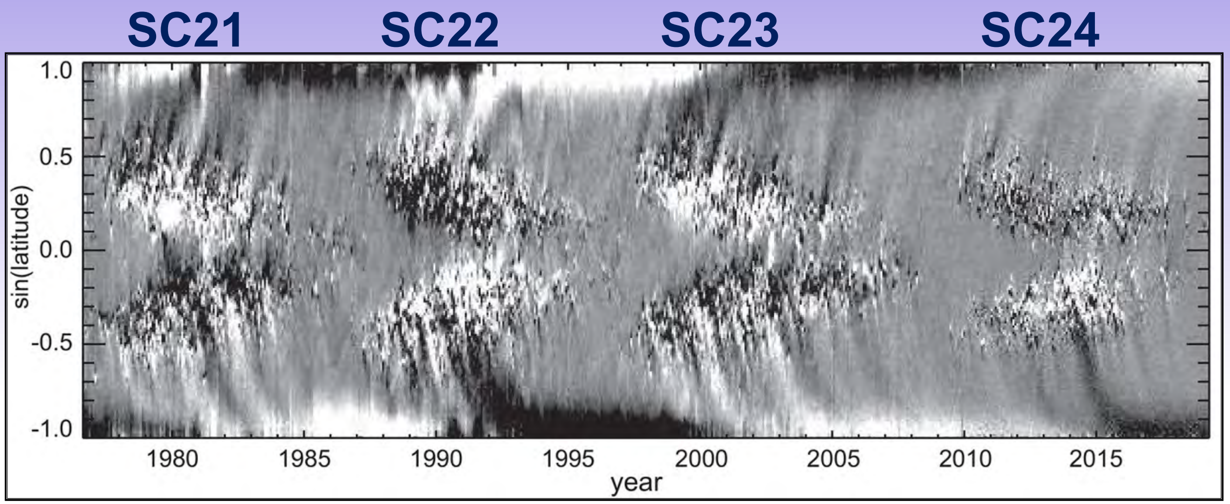
Kitiashvili, 2020

Criteria to identify an accurate model prediction:

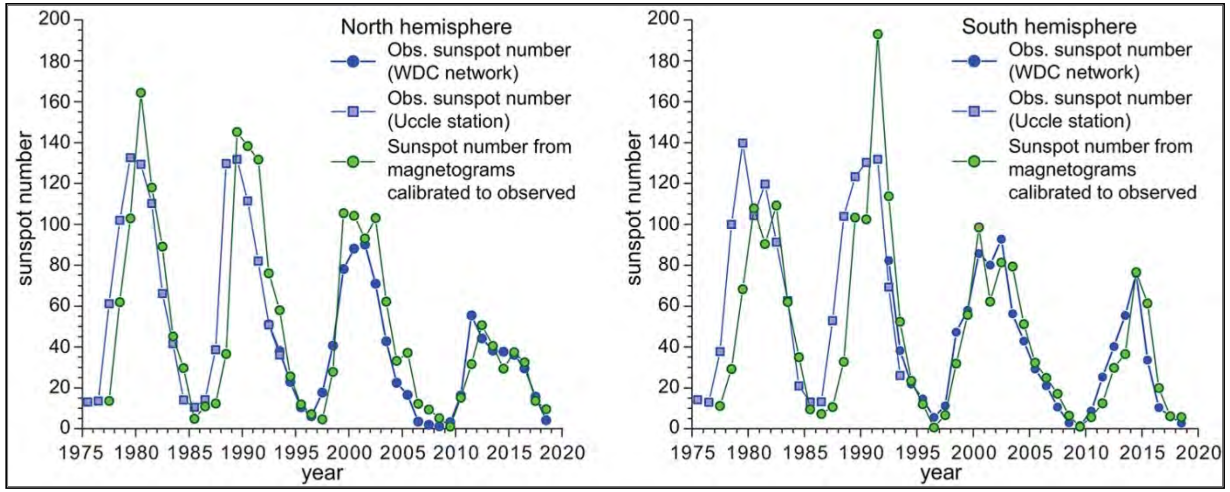
1) **the signs of the last available observation (for toroidal field) and the corresponding model solution should be the same;**
2) **the exact model solution for the prediction phase must be consistent with the model solution for the reconstruction phase (no solution flattening, jumps, or 'bumps', but 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

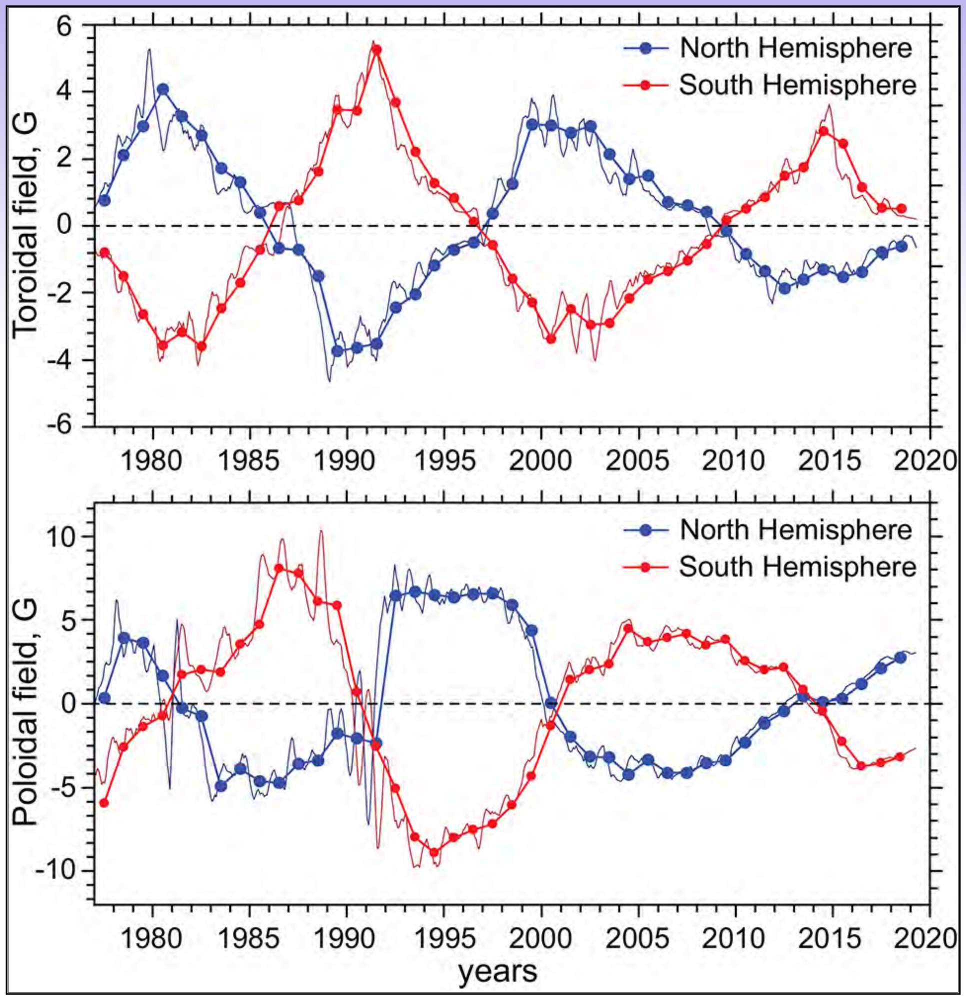
Synoptic magnetograms: KPO, SOLIS, SoHO/MDI, SDO/HMI



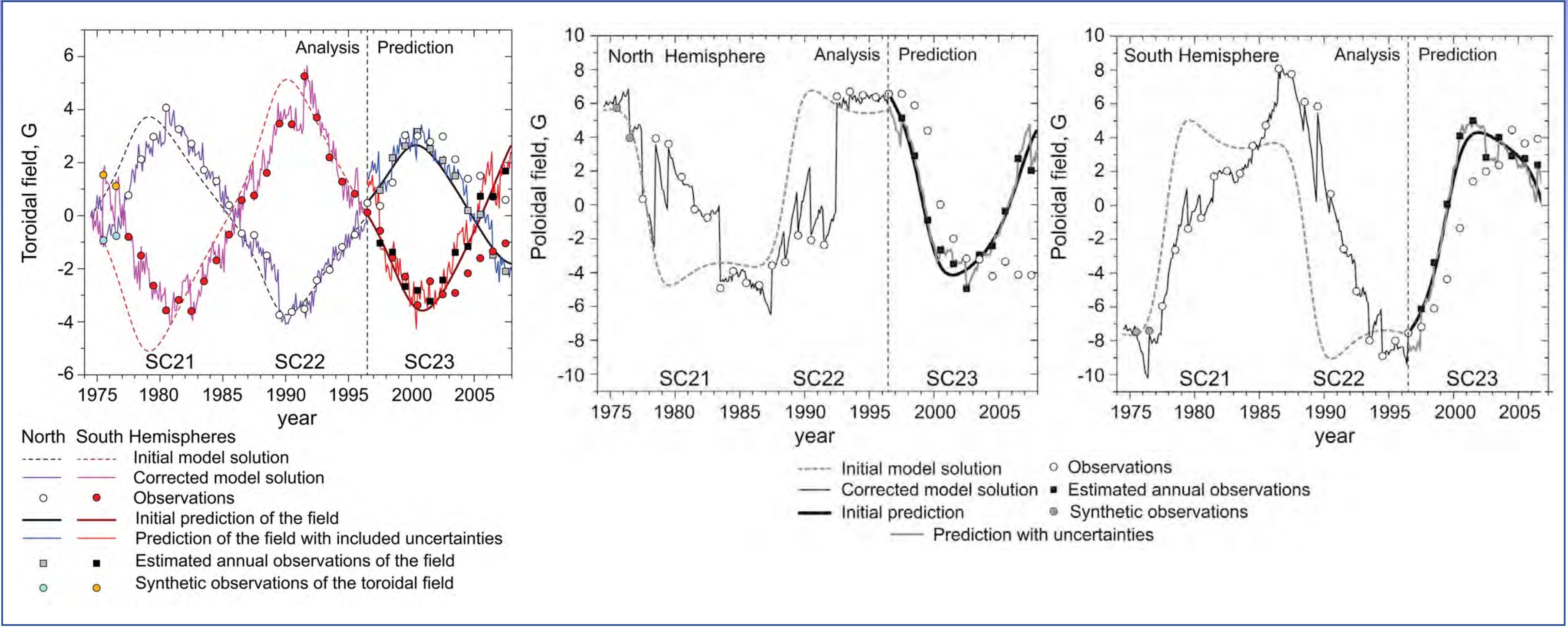
Sunspot number: observed vs. estimated



Toroidal and poloidal magnetic field components

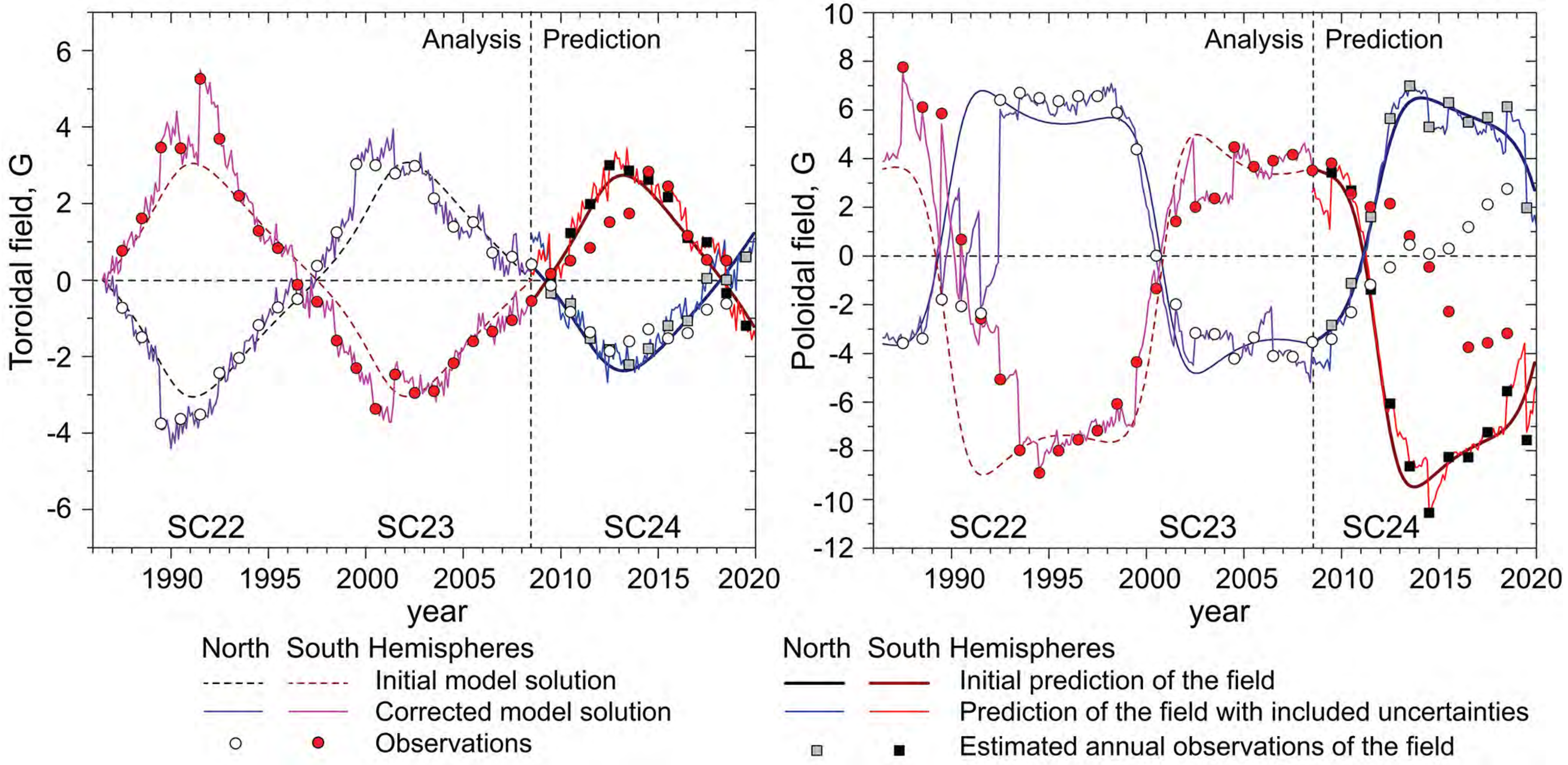


Magnetic field ‘test’ forecast for Solar Cycle 23



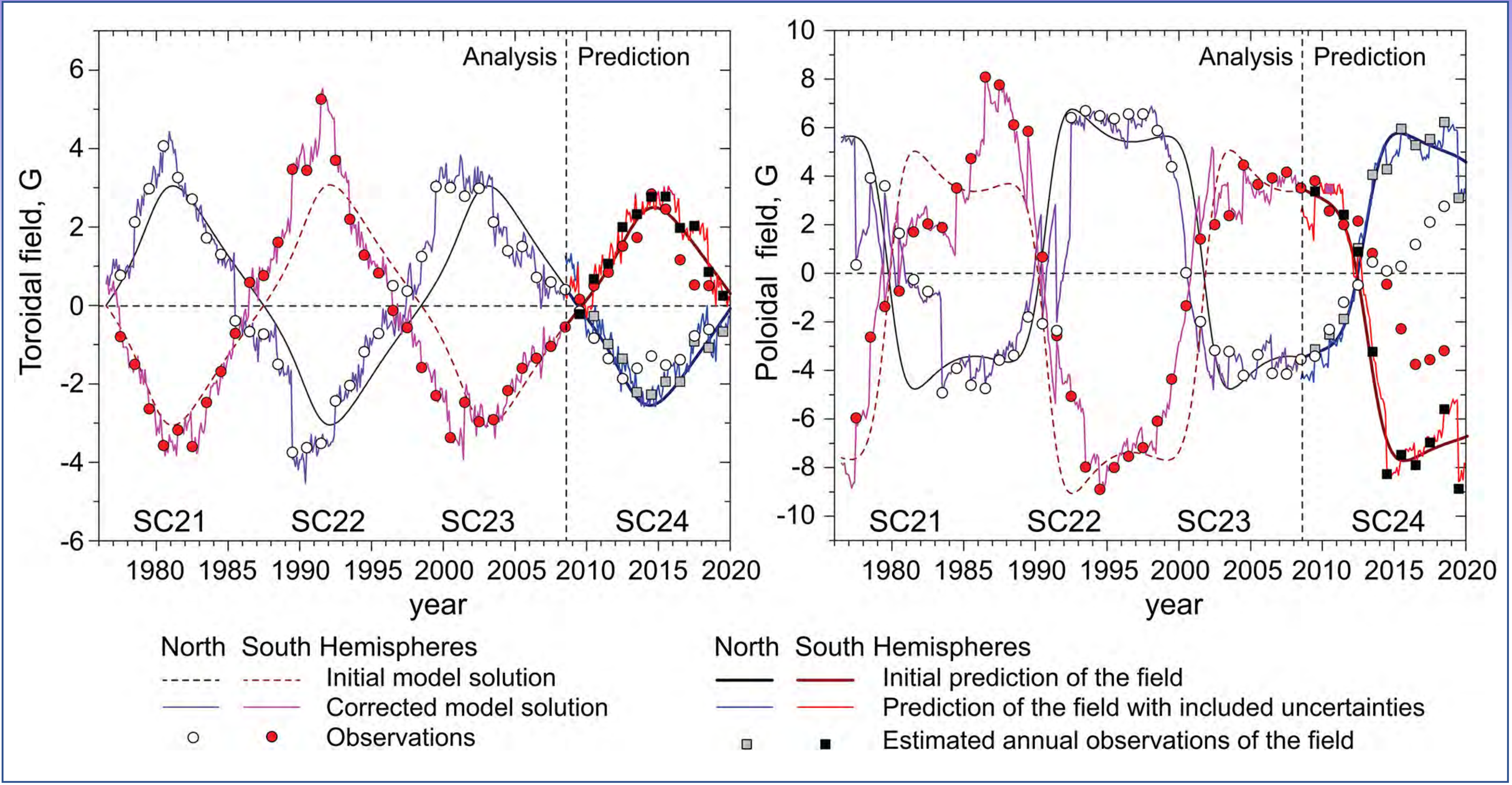
Kitiashvili, 2020

Magnetic field 'test' forecast for Solar Cycle 24



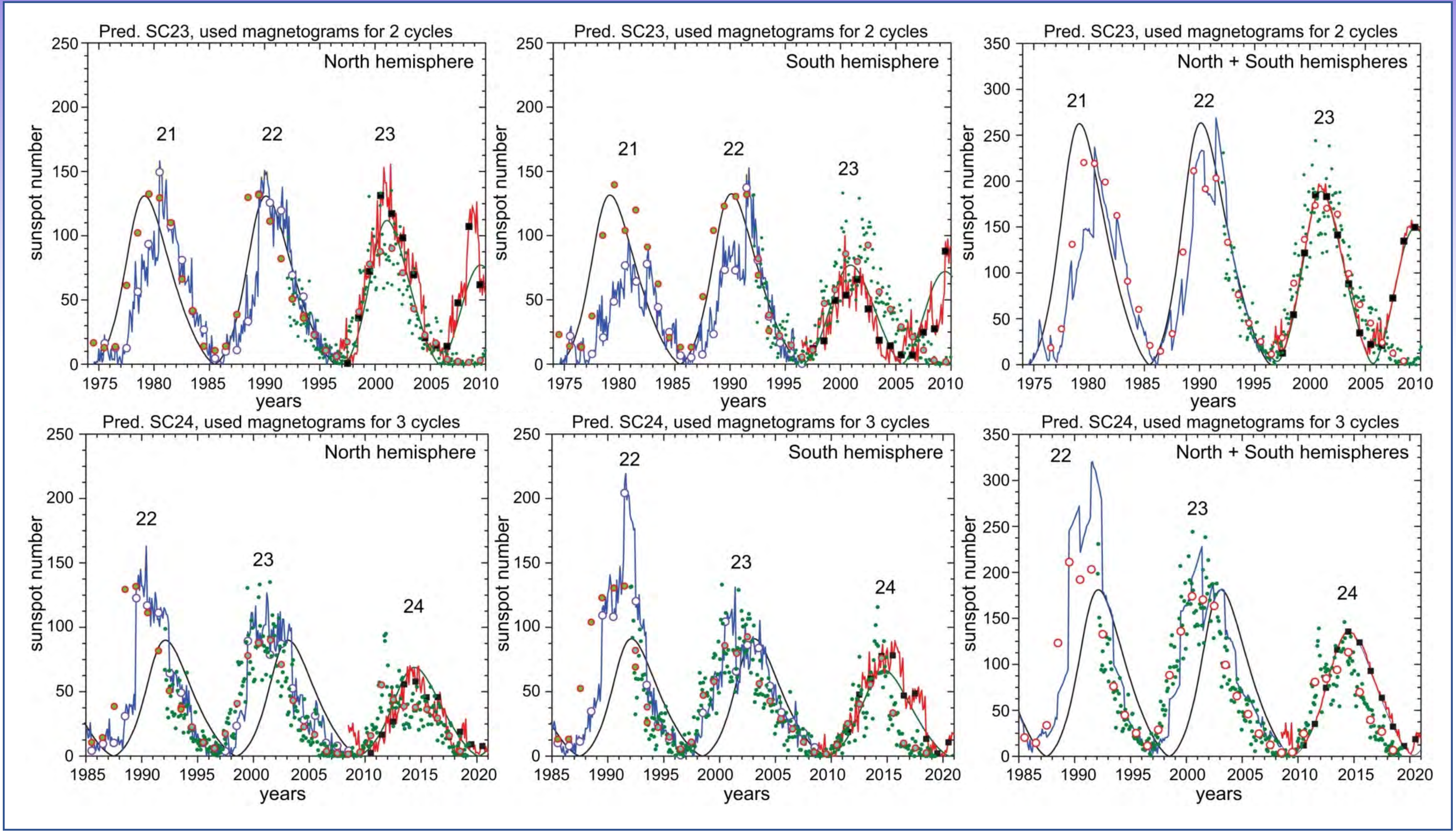
Kitiashvili, 2020

Magnetic field ‘test’ forecast for Solar Cycle 24



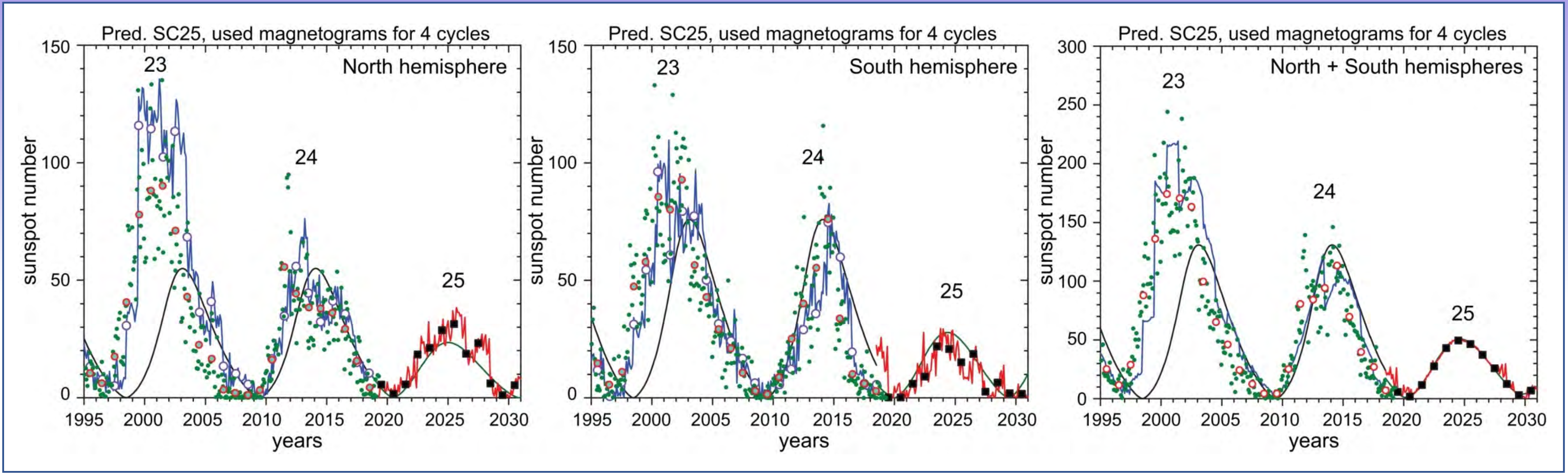
Kitiashvili, 2020

‘Test’ sunspot number predictions of Solar Cycles 23 and 24



Kitiashvili, 2020

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 $\pm$ 15 with an error estimate of ~30%.

SC25 will start in the Southern hemisphere in 2020 and reach maximum in 2024 with a sunspot number of ~28 ($\pm$ 10%). Solar activity in the Northern hemisphere will be delayed for about 1 year (with error of $\pm$ 0.5 year) and reach maximum in 2025 with a sunspot number of ~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.
- Forecast 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. Forecast 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 ~30%. SC25 will start in the southern hemisphere in 2020 and reach maximum in 2024 with a sunspot number of ~28 (with error of ~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 ~21 %).