Advances in model-based predictions of decadal and "seasonal" solar activity

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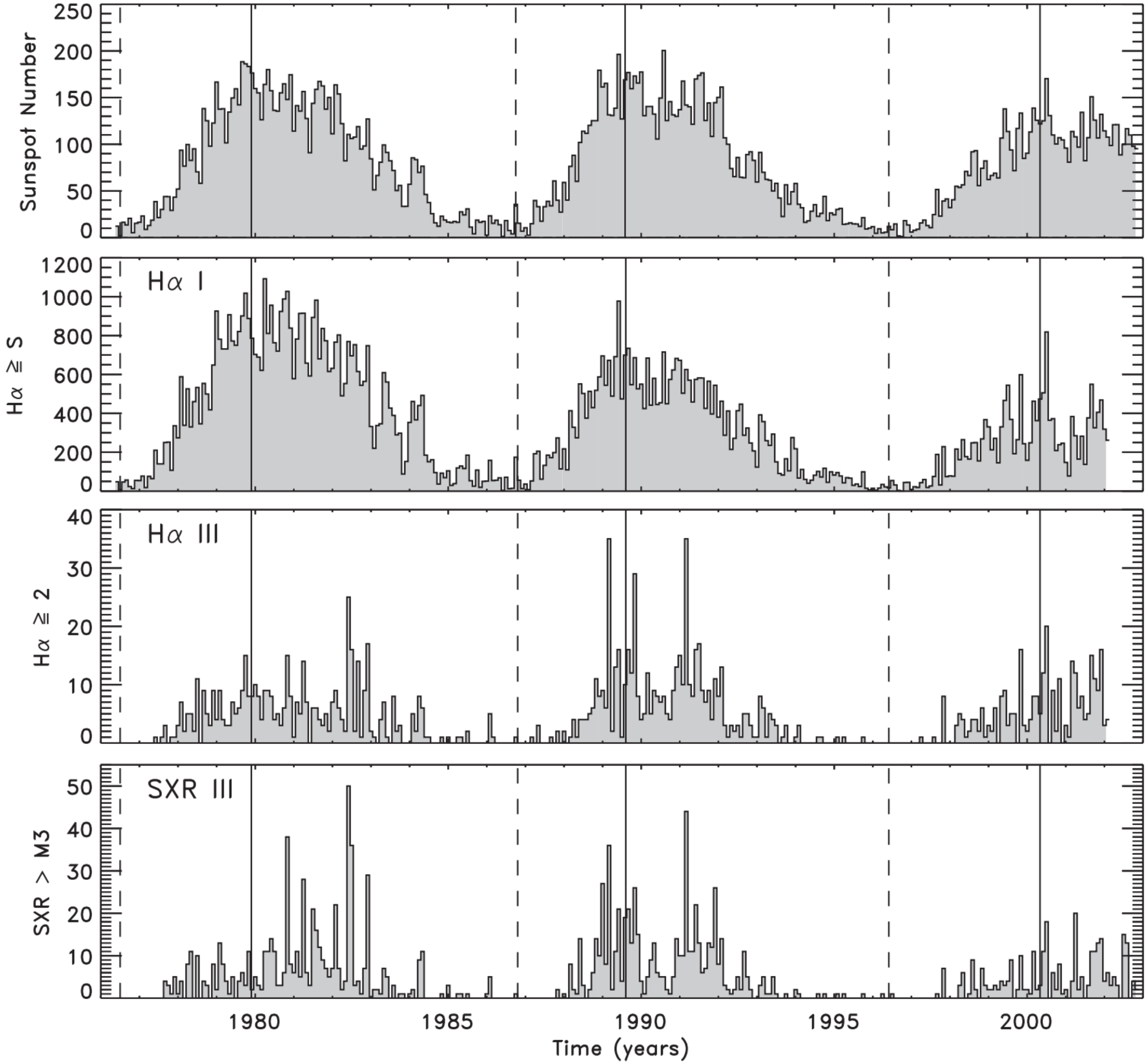
July 10, 2019

NSF

This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the National Science Foundation under Cooperative Agreement No. 1852977.

Statistical properties of sunspots and flares



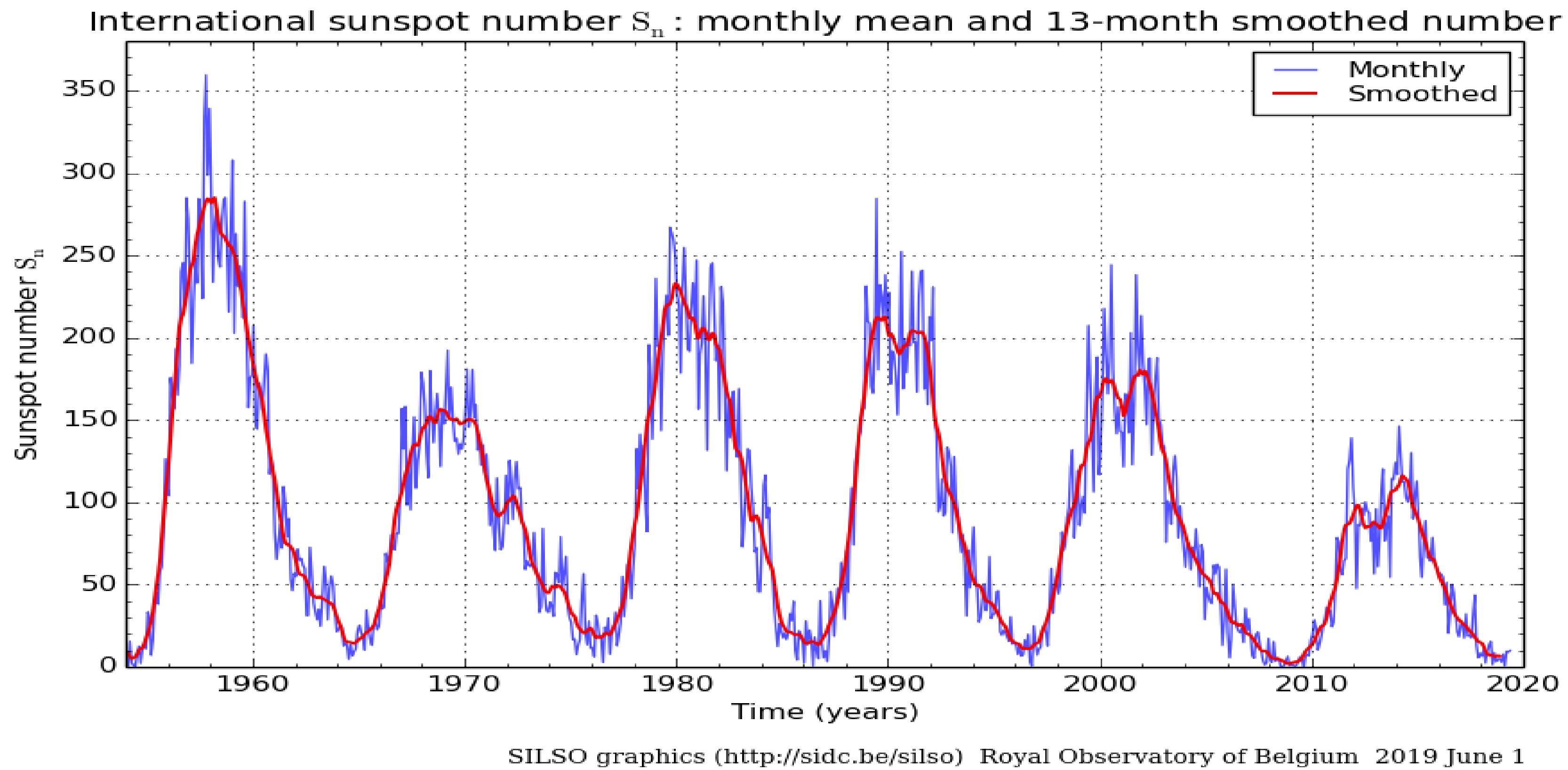
M. Temmer, SoHO 23, ASP Conf. Ser., 428, 2010

Occurrence of solar flares and hence the associated space weather events is strongly correlated with solar activity.

Majority of the energetic solar flares occurs during the peak and early declining phase of a solar cycle

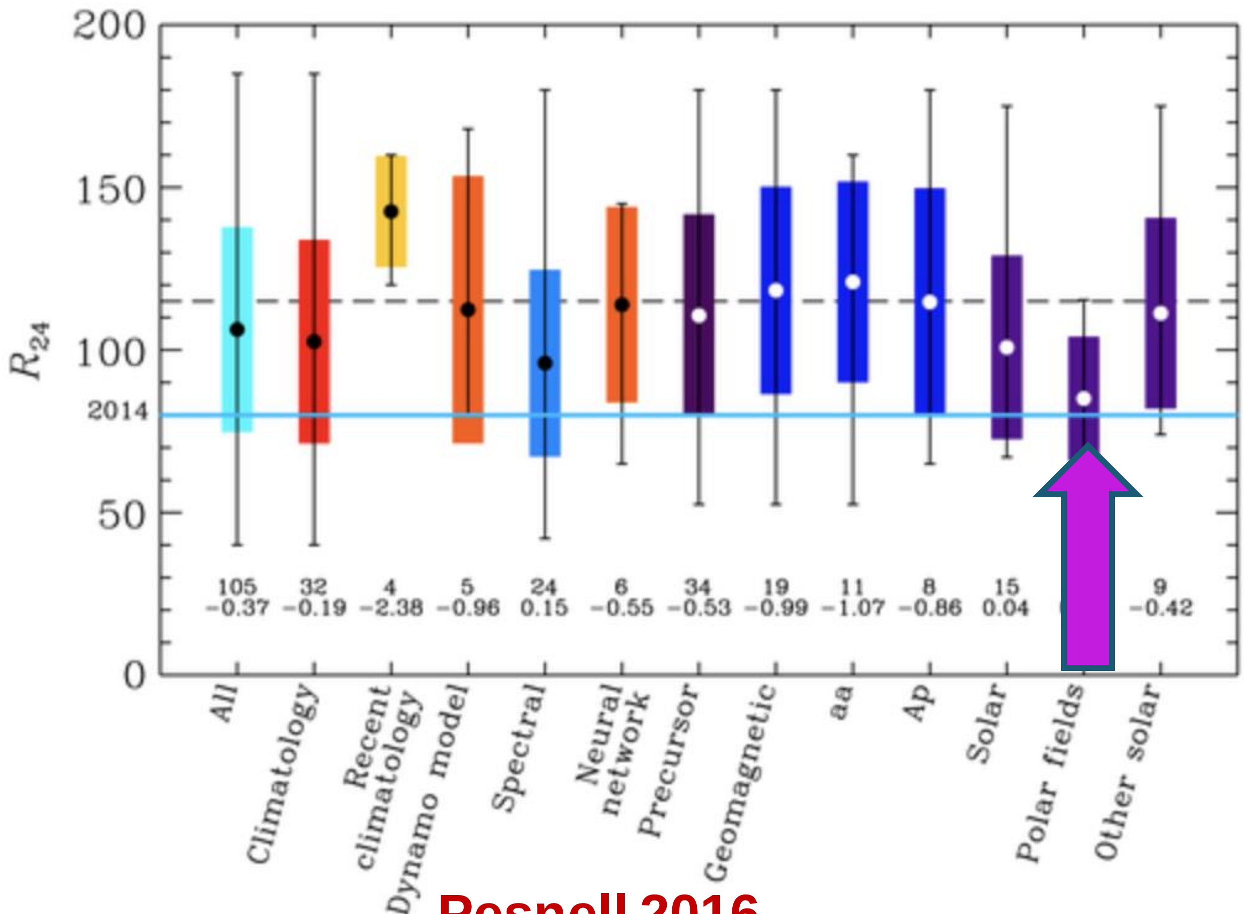
Accurate prediction of the amplitude and timing of a cycle peak is very important

Revisiting solar cycle 24 prediction



- **Solar cycle 24 is ending, and cycle 25 is on the verge of onset**
- **Cycle 24 has been the weakest cycle in 100 years**
- **Cycle 24 has the largest difference in timing between N and S peaks**

Various prediction methods



Pesnell 2016

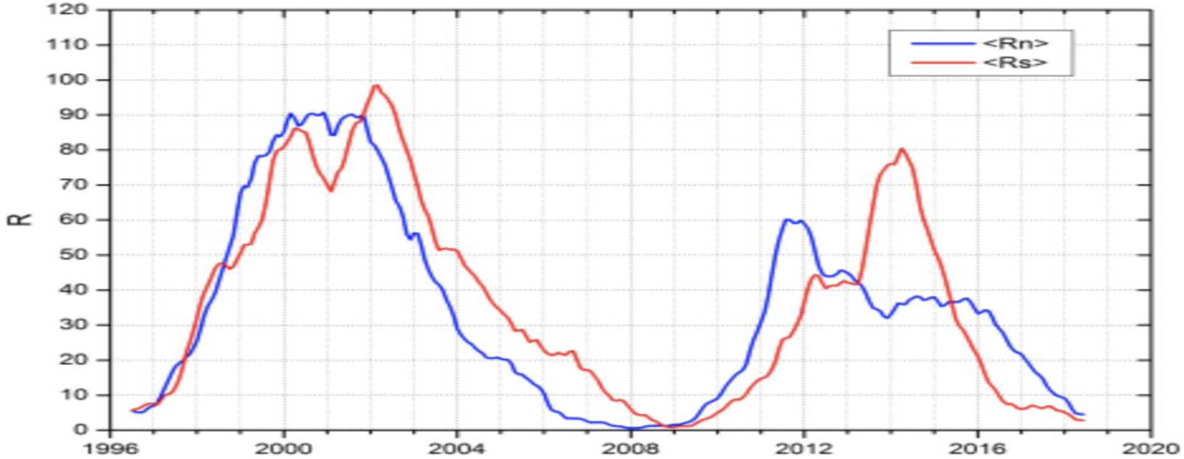
The only prediction method that is close to the observed peak of cycle 24 is a polar field precursor method.

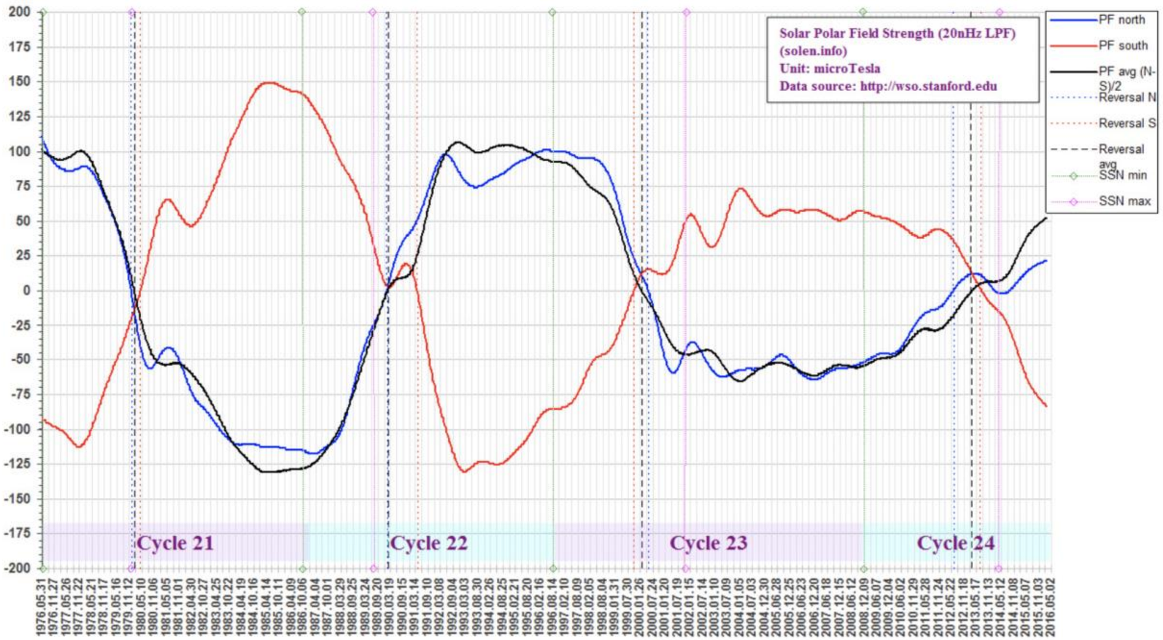
All other methods predicted a higher-than-observed cycle 24 peak.

Why?

Polar field precursor method works for total cycle (N+S); perhaps it is not so good predictor for the cycle-peaks in North and South hemispheres separately

Large phase-shift for hemispheric peaks





- North and South polar fields were similar during the minimum at the end of cycle 23, but the cycle 24 in the south was about 25% stronger than the north

- Notice an almost 3-year difference in the timing of the North and South hemispheres’ peaks, with the North peaking first

Issues concerning North/South differences

- Observations indicate that the solar cycles in the North and South hemispheres are weakly decoupled, for example, solar minima in North and South occur within one year of each other, while the maxima can be as much as 3 years apart
- Hale's polarity law is followed for almost all active regions, but there are exceptions (such as some "rogue" spots at the end of cycle 23)
- Almost all dynamo models operate in two hemispheres separately, only weakly coupling N&S hemispheres
- Since the two hemispheres are observed to be nearly in synch at minimum, it is not surprising that the polar fields at that time are similar in amplitude.
- Logically from this observation the precursor methods would predict similar next cycle peak amplitude and timing, but that was not the case for cycle 24.
- To make further progress, hemispheric predictions are needed separately

Dynamo-based prediction schemes for cycle 24

- Dynamo model-based prediction-scheme was developed for solar cycle 24

- *Dikpati et al. (2006)* issued three predictions for cycle 24:
  a) delayed onset -- validated
  b) 30-50% stronger than cycle 23 – predicted too high compared to observed
  c) south stronger than north -- validated

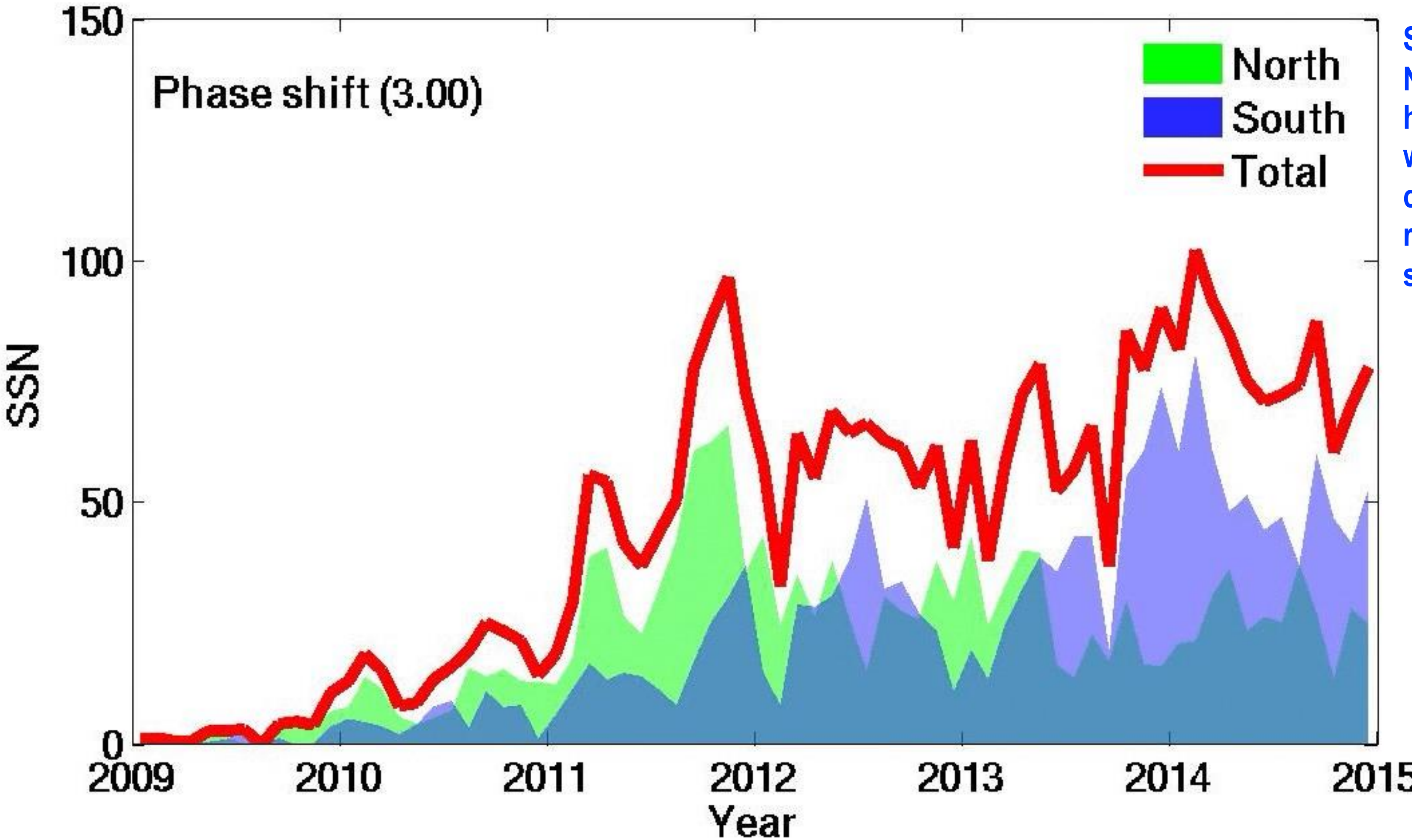
- *Choudhuri et al. (2007)* issued peak prediction for cycle 24:
  a) 35% weaker than cycle 23 – close, but low compared to observed

- *Kitiashvili & Kosovichev (2009)* issued peak prediction for cycle 24:
  a) 30% weaker than cycle 23 – validated

The first two models are Babcock-Leighton dynamos; the third one is a nonlinear alpha-omega "box" model

Why hasn't cycle 24 been strong as predicted by Dikpati et al. (2006)?

1. Phase shift between North and South cycles was not considered in dynamo simulation

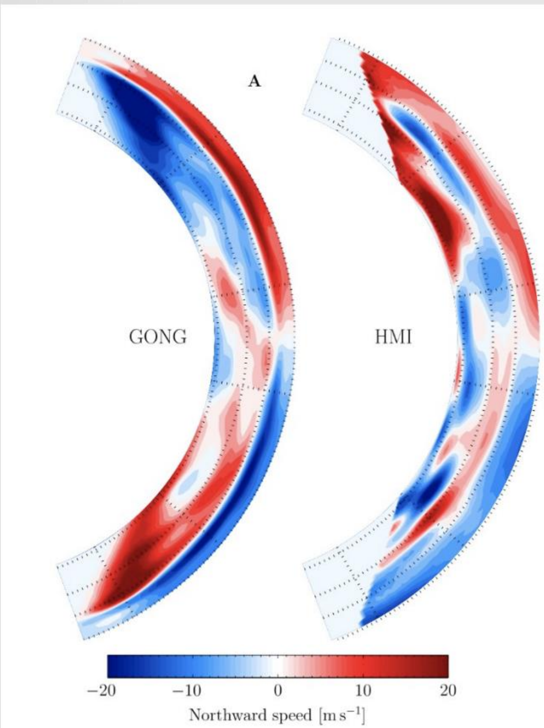


Synchronized North and South hemispheres would have made cycle 24 relatively stronger

Why hasn't cycle 24 been strong as predicted by Dikpati et al. (2006) (contd.)

2. Meridional circulation is not always a steady, single-celled flow, as assumed in the prediction models

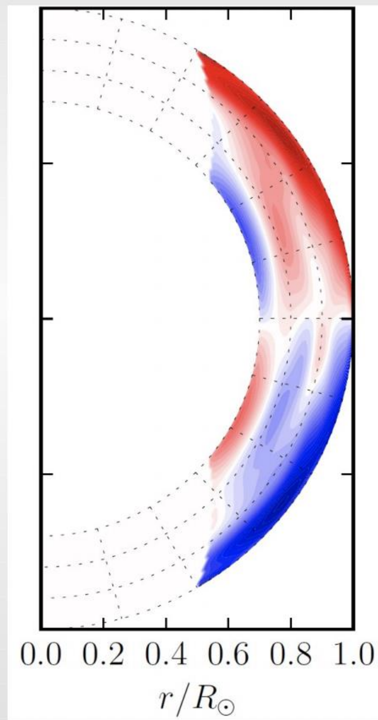
GONG 2004-2012 HMI 2010-2012



Zhao et al. (2013)

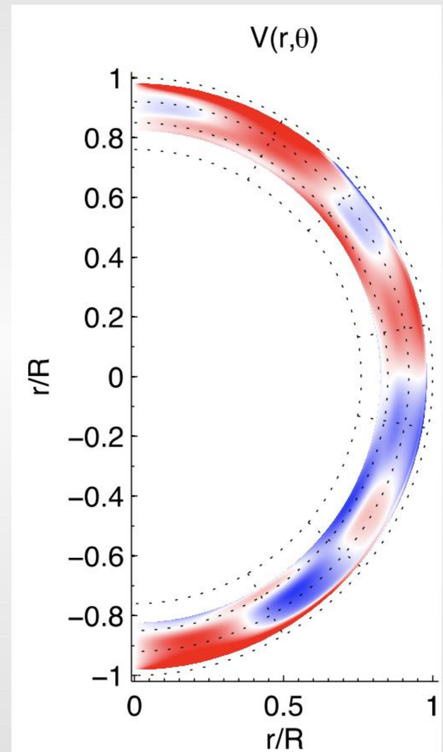
Jackiewicz et al. (2015)

HMI 2010-2012

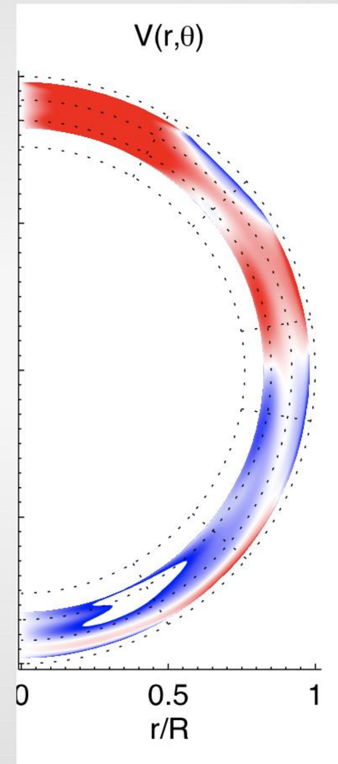


Rajaguru & Antia (2015)

MDI 2004-2010



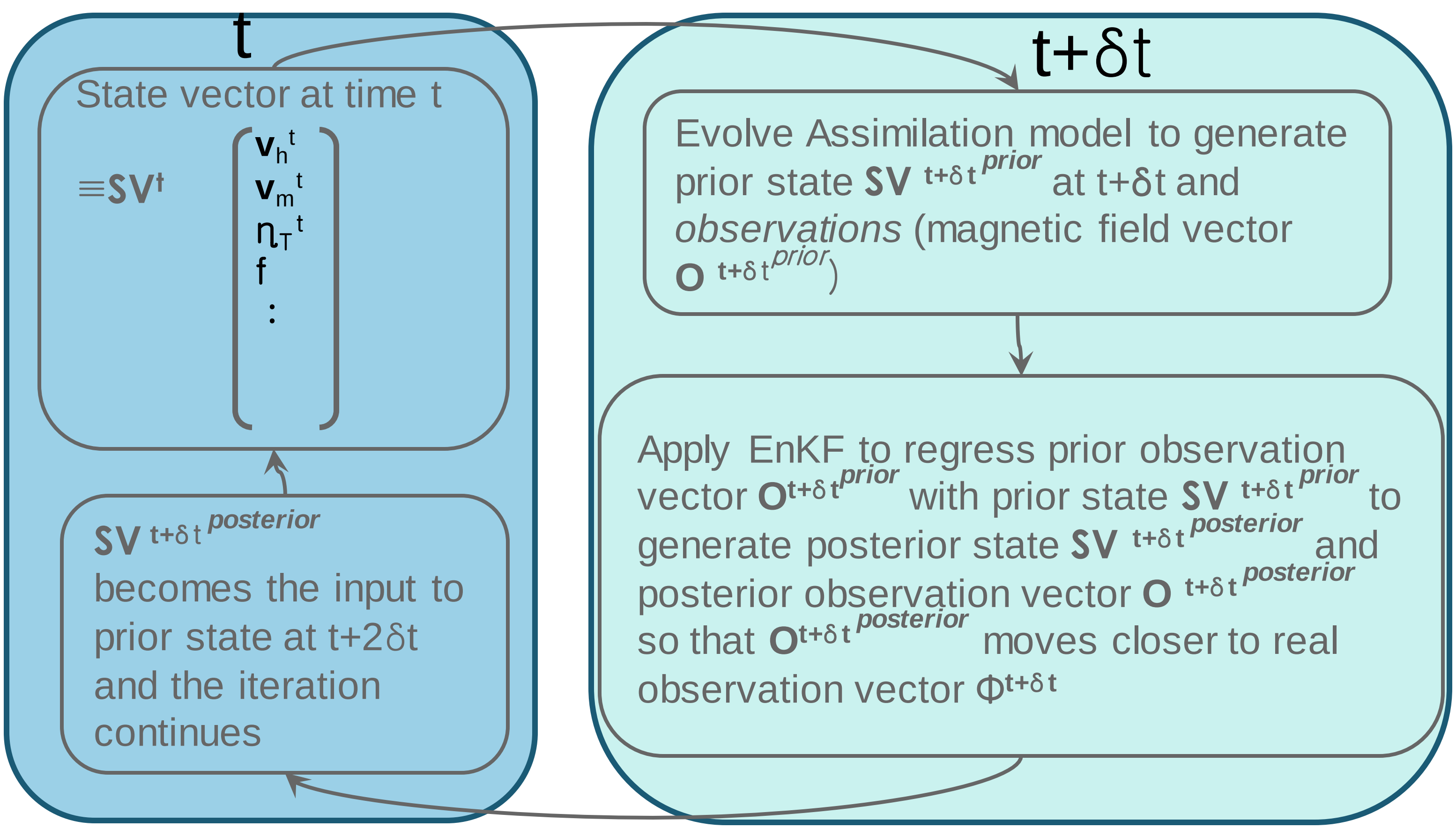
HMI 2010-2014



(Schad et al. 2013)

Why hasn't cycle 24 been strong as predicted by Dikpati et al. (2006) (contd.)

3. **Data assimilation was under-utilized;** only data-nudging was used to drive the model. Full-scope data assimilation methods allow for continuously updating the model with data and hence correcting the initial conditions and model-outputs



Dikpati, Anderson & Mitra, 2014, 2016a, 2016b

Data Assimilation and Ensemble Forecast of Cycle 25 by Labonville et al. 2019

- A peak of monthly-smoothed ssn between 75 and 118
- 6 months' delay in onset of North cycle
- South 20% stronger than North

Why two BL-dynamo-based prediction schemes (Dikpati et al. 2006) and Choudhuri et al. 2007) for cycle 24 produced such different predictions?

Often said that the difference comes from the two dynamo models operating in two different diffusivity regimes, with Choudhuri et al. 2007 model having the higher diffusivity.

If that were so, Choudhuri et al. 2007 would get much too short solar cycle period (~3 years)

In fact, Choudhuri et al. 2007 model also operated in low-diffusivity regime, because it used two different diffusivities: high one for poloidal fields, and low one for toroidal fields.

Since toroidal fields dominate the dynamics, the model is really operating in the low diffusivity mode, and that's why dynamo cycle-period comes out to be ~11 year.

Why two BL-dynamo-based prediction schemes (Dikpati et al. 2006) and Choudhuri et al. 2007) for cycle 24 produced such different predictions (contd.)

The real reason for the difference in cycle 24 strength prediction is the treatment of Babcock-Leighton surface poloidal source:

Dikpati et al derived the BL poloidal source in the form of equatorward-migrating Gaussian calibrated using observed surface magnetic flux from the decay of active regions

Choudhuri et al. injected the observed polar fields during cycle minimum.

In effect, Choudhuri et al. model becomes a form of polar field precursor model for solar cycle prediction. As has been pointed out in the literature no dynamo model is needed for this method.

In any case, even if polar fields from previous minimum is a valid predictor of overall next cycle's amplitude, do we understand the physical connection between polar fields and next sunspot cycle's amplitude?

Role of polar fields in sunspot cycle's prediction

Issues with polar fields:

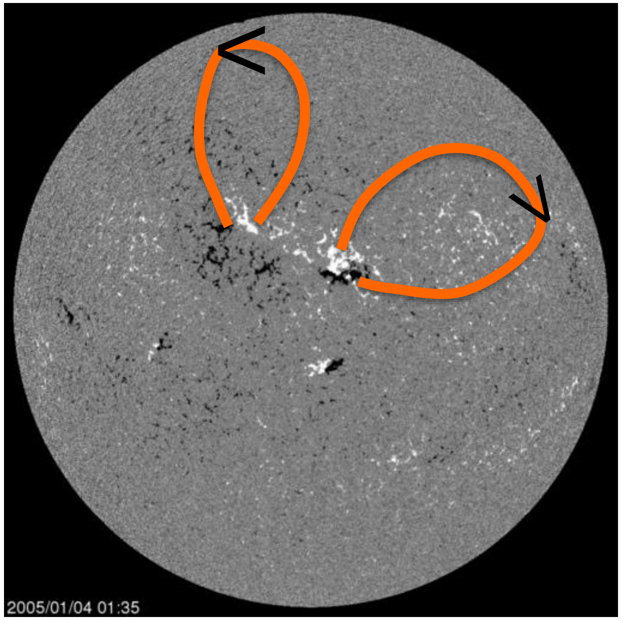
foreshortening effects in old magnetogram data

latitudes where they sink below

how much flux is recycled for forming the seed of the next cycle

role of "rogue" active regions: if big, they can significantly change both the BL source and the polar fields

Likely very difficult to predict



2005 January

Can Machine Learning / Information Theoretic Technology help estimate the properties of connection between polar fields and sunspots?

Wing et al. 2018 have demonstrated that :

- information from polar fields to sunspot number peaks at lag time of 30-40 months, after which remains at a
- persistent but low level for 400 months, indicating some multicycle memory
- Both mc and flux emergence (proxy by the sunspot number) transfer information to the polar field
- Gives some consistency with surface transport models and BL flux-transport dynamo models
- Transfer of information from mc to ssn peaks at approximately one sunspot cycle

These results show promise for exploring the physical connection between polar fields and next cycle' sunspots

How are we doing about onset-timing prediction?

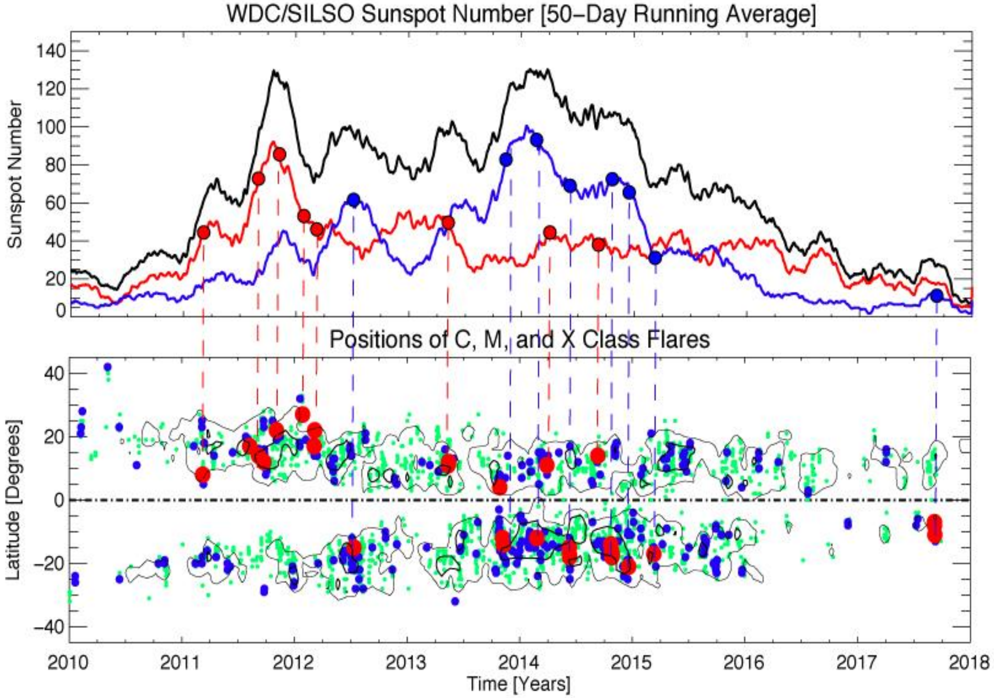
We are really making a lot of progress !

We physically understand several plausible mechanisms for the onset of a cycle – all give consistent answer

- ✓ Late onset of cycle 24 was explained by longer path of the Sun's conveyor belt and consequently a slow-down in the equatorward return flow (*Dikpati 2004*; *Dikpati et al. 2010, GRL*)
- ✓ Slow-down in meridional circulation during the declining phase of cycle23 produced delayed onset of cycle 24 (*Nandy et al. 2011, Nature*)
- ✓ Onset of a new sunspot cycle occurs within a few weeks after the cessation of the old cycle at the equator (*Saba et al. 2005, ApJ; McIntosh et al. 2019, Sol. Phys., Dikpati et al. 2019, Nature)*

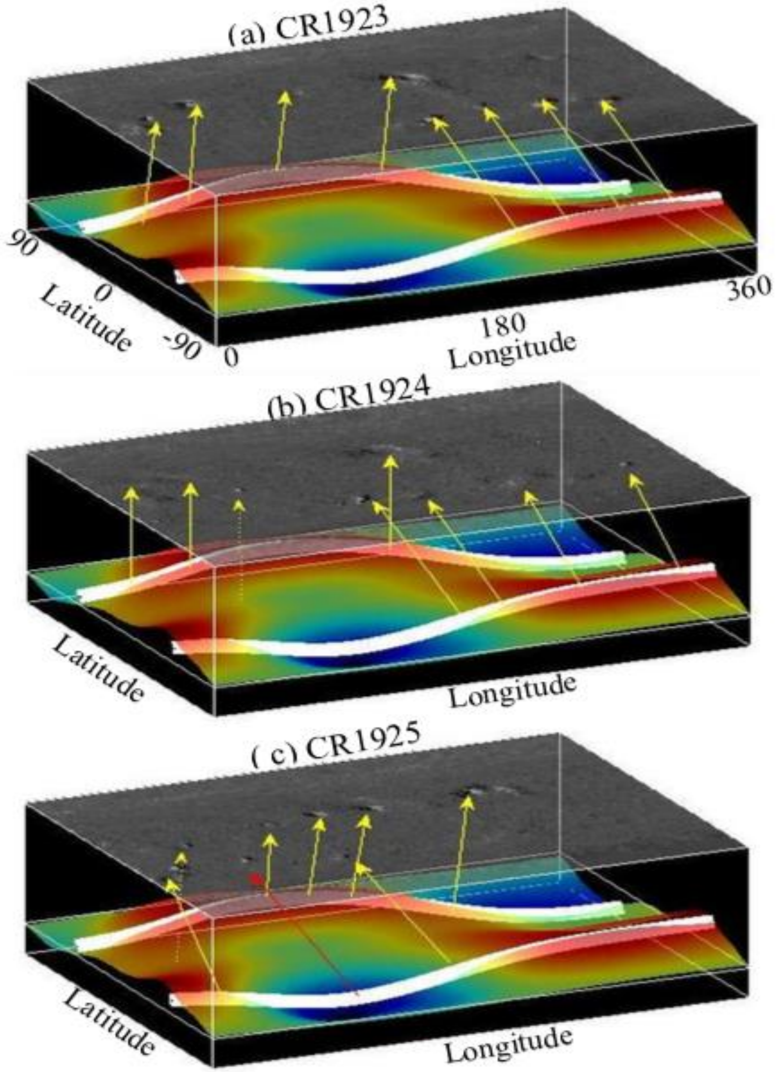
Further scope of improvement

- Accurately predicting the strength of an upcoming solar cycle during the end of the previous cycle requires following the phase-by-phase progression
- A solar cycle does not progress as a nice, smooth sinusoid, instead progresses in the form of a bursty phase of activity followed by a relatively quiet phase
- This short-term "seasonal" variability has amplitude similar to decadal solar cycle variability
- Major energetic events (flares and CMEs) that cause hazardous space weather occur during the bursty solar season



- Note that a Carrington type event occurred even in this "weakest in 100-years" cycle 24, but it occurred in a bursty phase (July 2012)
- Therefore, it is very important to predict not only the timing, but also the location and strength of activity bursts, as the solar cycle progresses

Simulating latitude and longitude locations of activity bursts

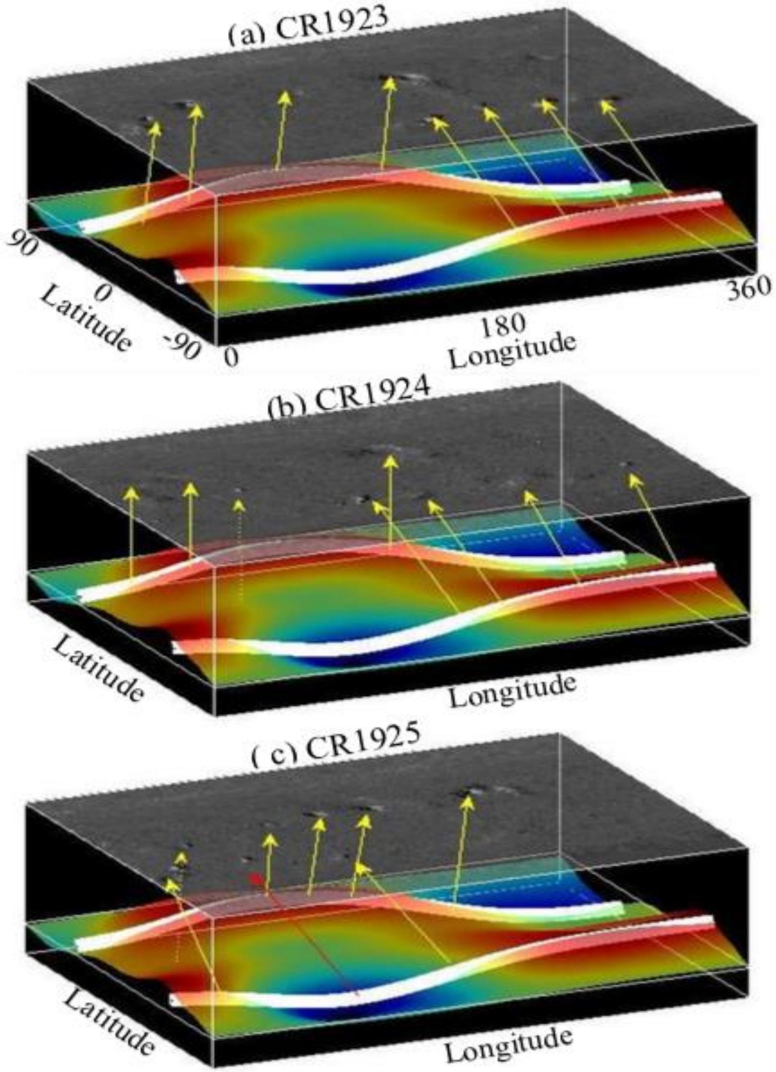


- Simulating longitude-averaged solar cycle features is not enough; we must physically understand the latitude as well as longitude locations of activity bursts, and should be able to simulate and predict them.

- Then only we can further refine the physics behind the emergence of sunspots – why they occur where and when they occur, and hence the solar cycle prediction scheme

3 frames represent a sequence of 3 Carrington rotations (CR1923, 1924, 1925) for both surface magnetograms (semi-transparent grey-shaded maps on top of each frame) together with positions of the tachocline MHD-SWT model bulges (red-orange color maps) and depressions (blue-green color maps), as well as banded toroidal magnetic fields (thick white tubes).

Simulating latitude and longitude locations of activity bursts



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Conclusions

- There are many promising improvements that can be made in longitude-independent dynamo-based forecast models for the solar cycle
- Models for simulating and forecasting longitude-dependent sources of activity are just beginning and also show great promise
- Accurately predicting N/S asymmetries in activity amplitude and phase will be particularly important
- Applying modern data assimilation techniques has promise for greatly improving outcomes of model-based simulations and predictions
- Beyond the traditional dynamo and surface-transport models, treated as initial value problems, information theoretic methods applied to both long-term observations and to model-outputs can help determine important physical links that remain to be included in models