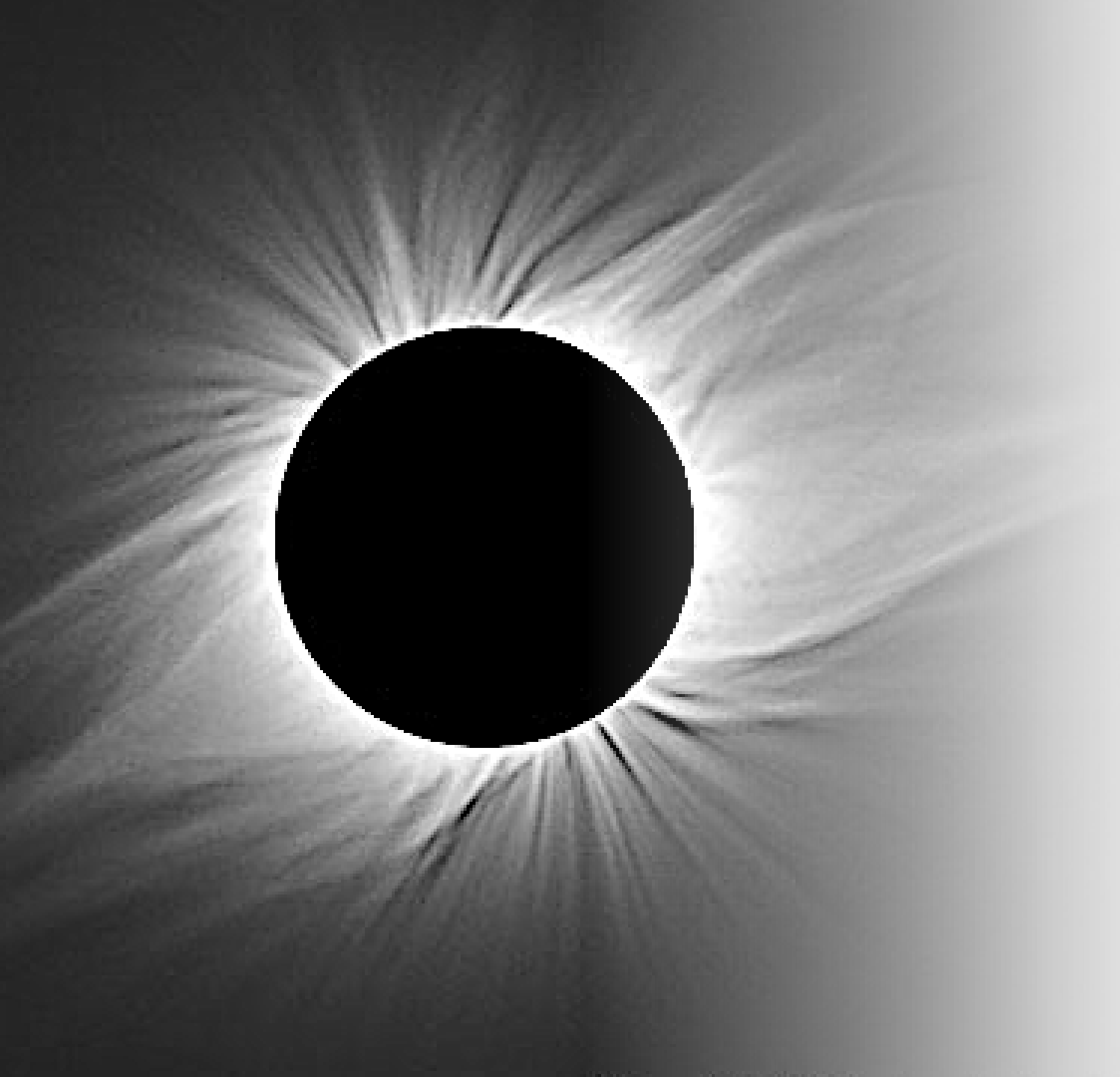


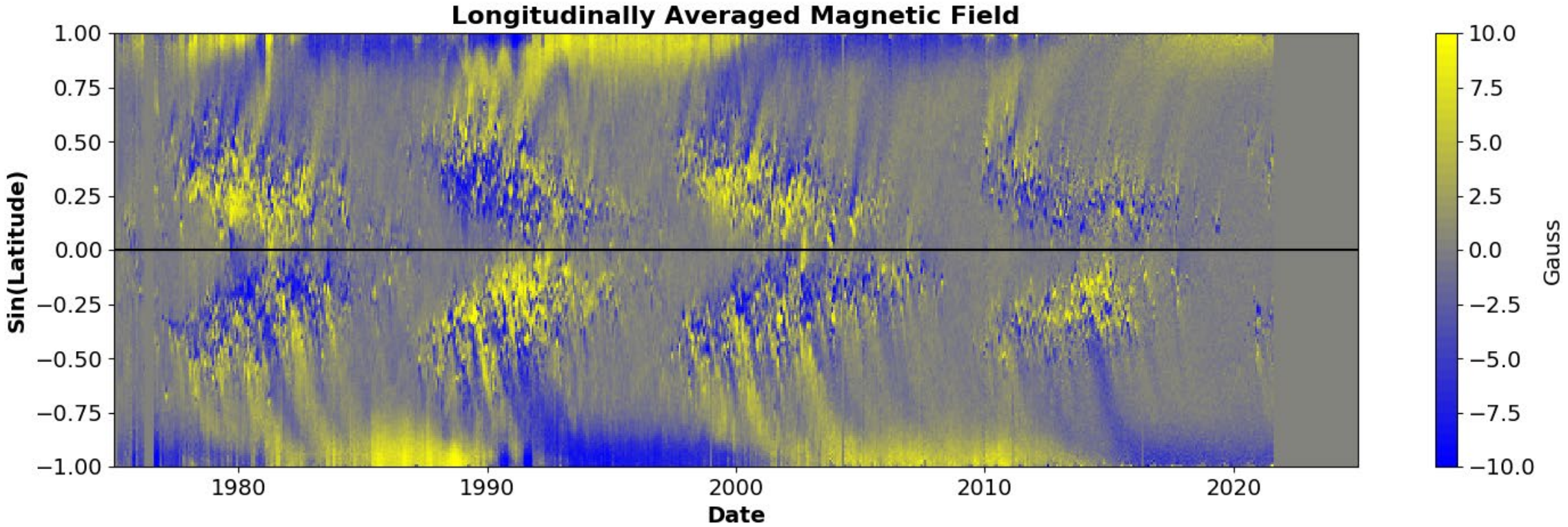
The Sun and Heliosphere at Solar Cycle Minima Past and Present

David H. Hathaway

Stanford University

A Short History of the Sun's Photospheric Magnetic Field

We've had "daily" measurements of the Sun's Earthside magnetic field since the mid-1970s. (There were a few occasional observations dating back to Horace and Harold Babcock's in the 1950's.) This short history tells us much about the Sun and the heliosphere, but longer records – of sunspots, geomagnetic activity, and radio isotopes in tree rings and ice cores can help to fill in further details.

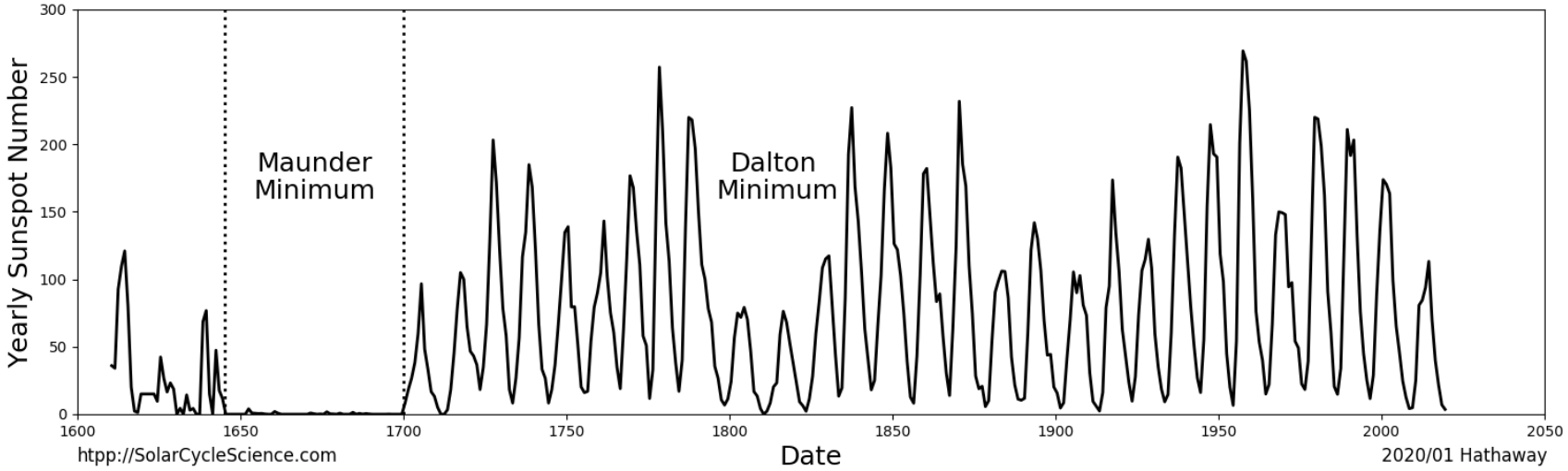


Mission Statement: My own interest is to better understand the solar dynamo. Conditions at cycle minima reveal a key dynamo characteristic – field conditions at minima are predictors of the size of the following cycle.

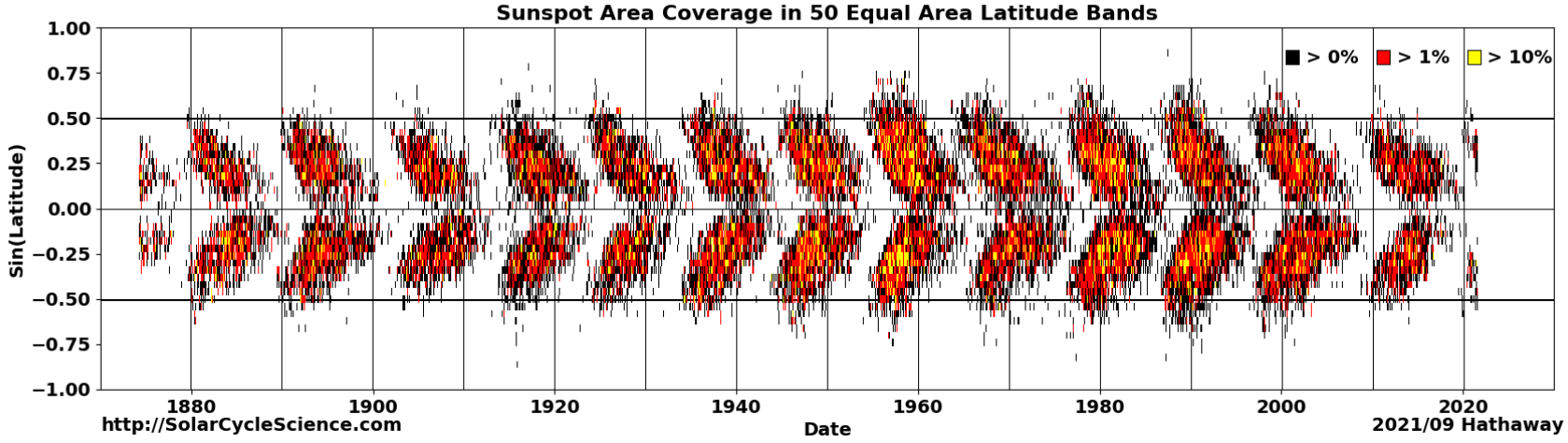
Outline

- **Characterize minima using the sunspot record**
  - **Cycles overlap to varying degrees at minima**
  - **Relationships between cycle minima and following maxima**
- **Geomagnetic Activity at minima vis-à-vis the following cycle maxima**
- **Polar fields at minima vis-à-vis the following cycle maxima**

The sunspot record



The 400-year record of sunspot numbers provides a direct measure of solar activity levels revealing the 11-year cycle and the100-year Gleissberg Cycle modulation of cycle maxima and minima.



The 150-year record of sunspot group areas and positions reveals the equatorward drift of the active latitudes and the overlap of the cycles at minima.

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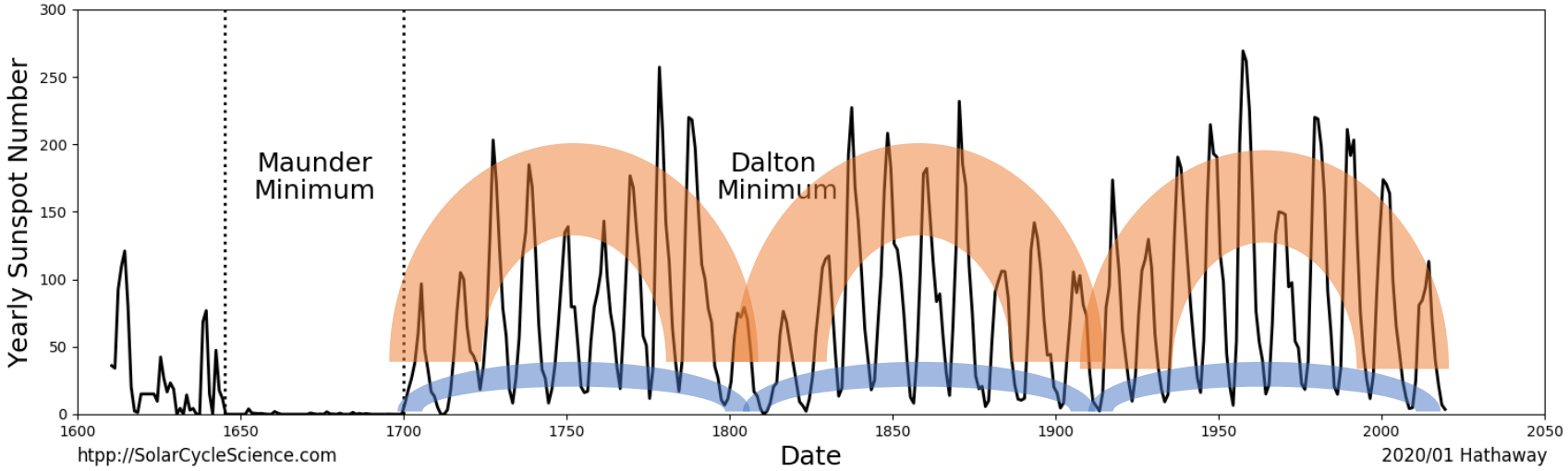

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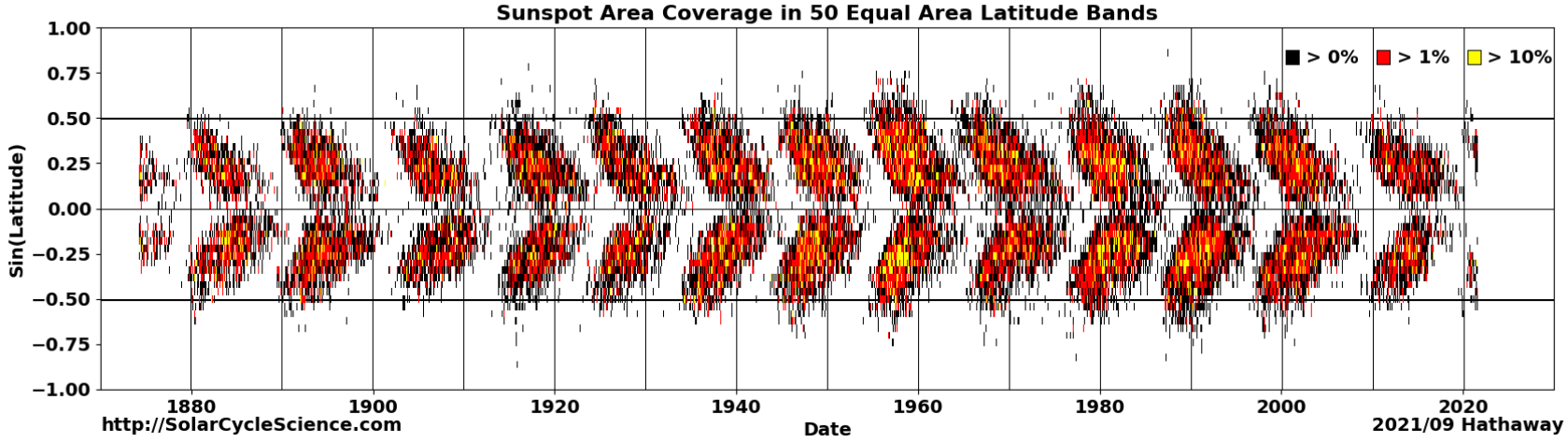

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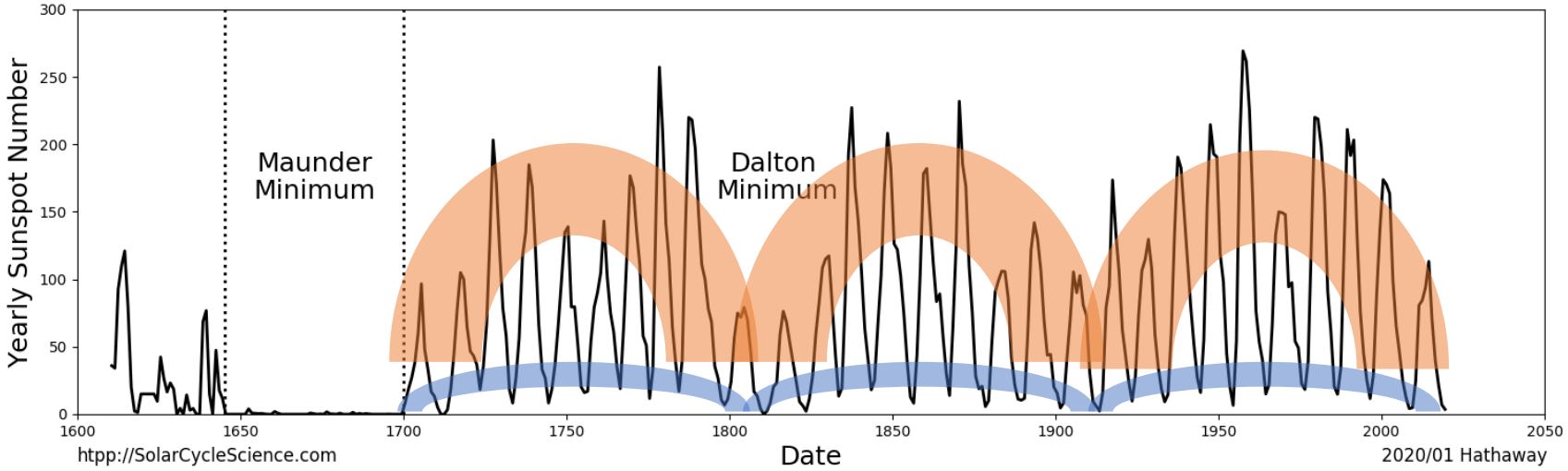

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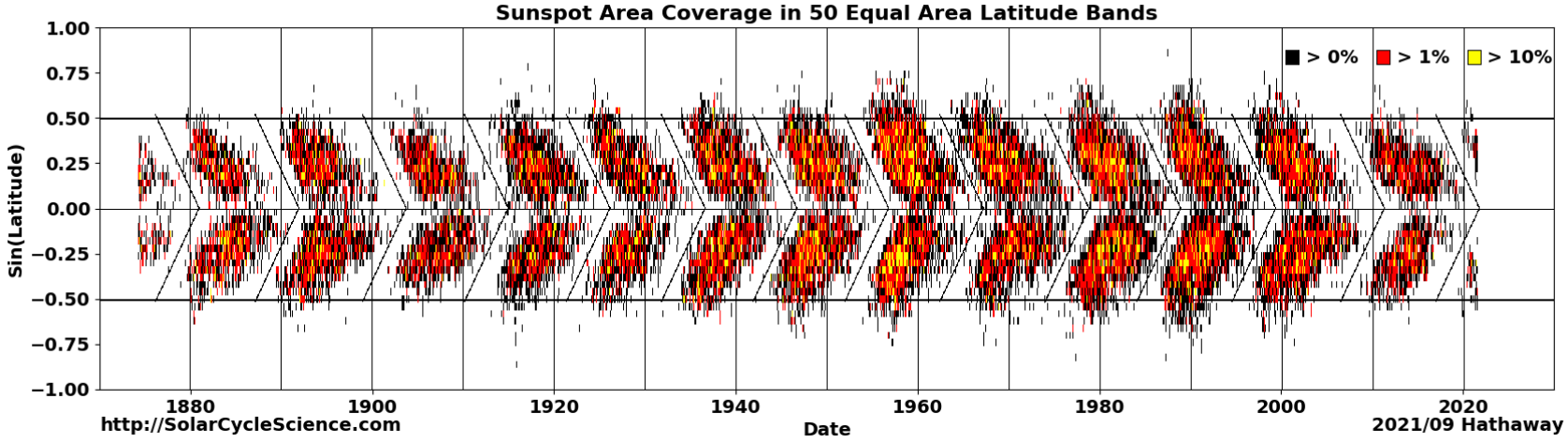

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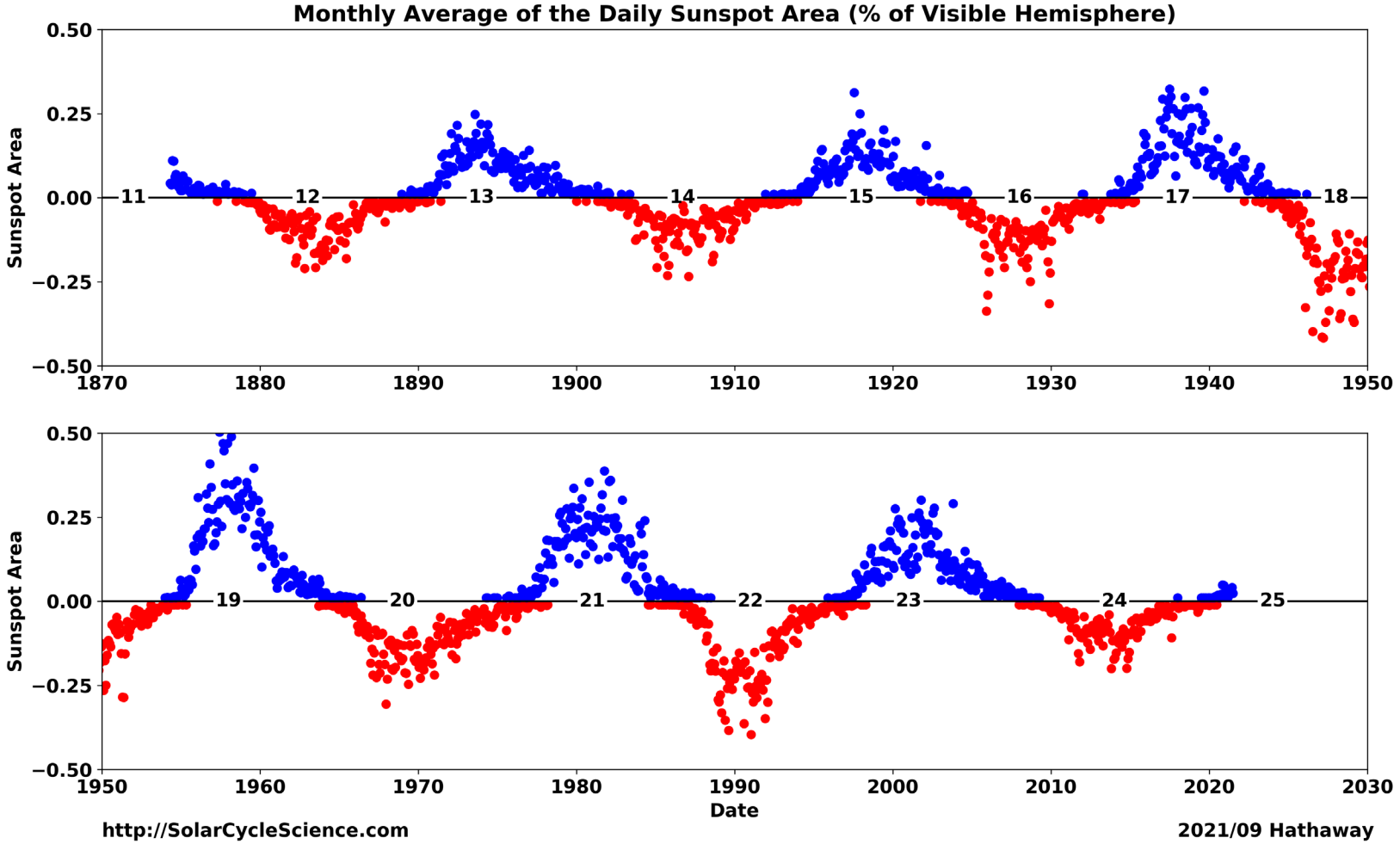
Overlaps at minima



Cycle overlaps can be investigated using latitude information to place sunspot groups in the appropriate sunspot cycles.

Typically, big cycles are preceded by a high minimum with considerable overlap - but exceptions occur.

Big Cycle 19 was preceded by a low minimum with little overlap.

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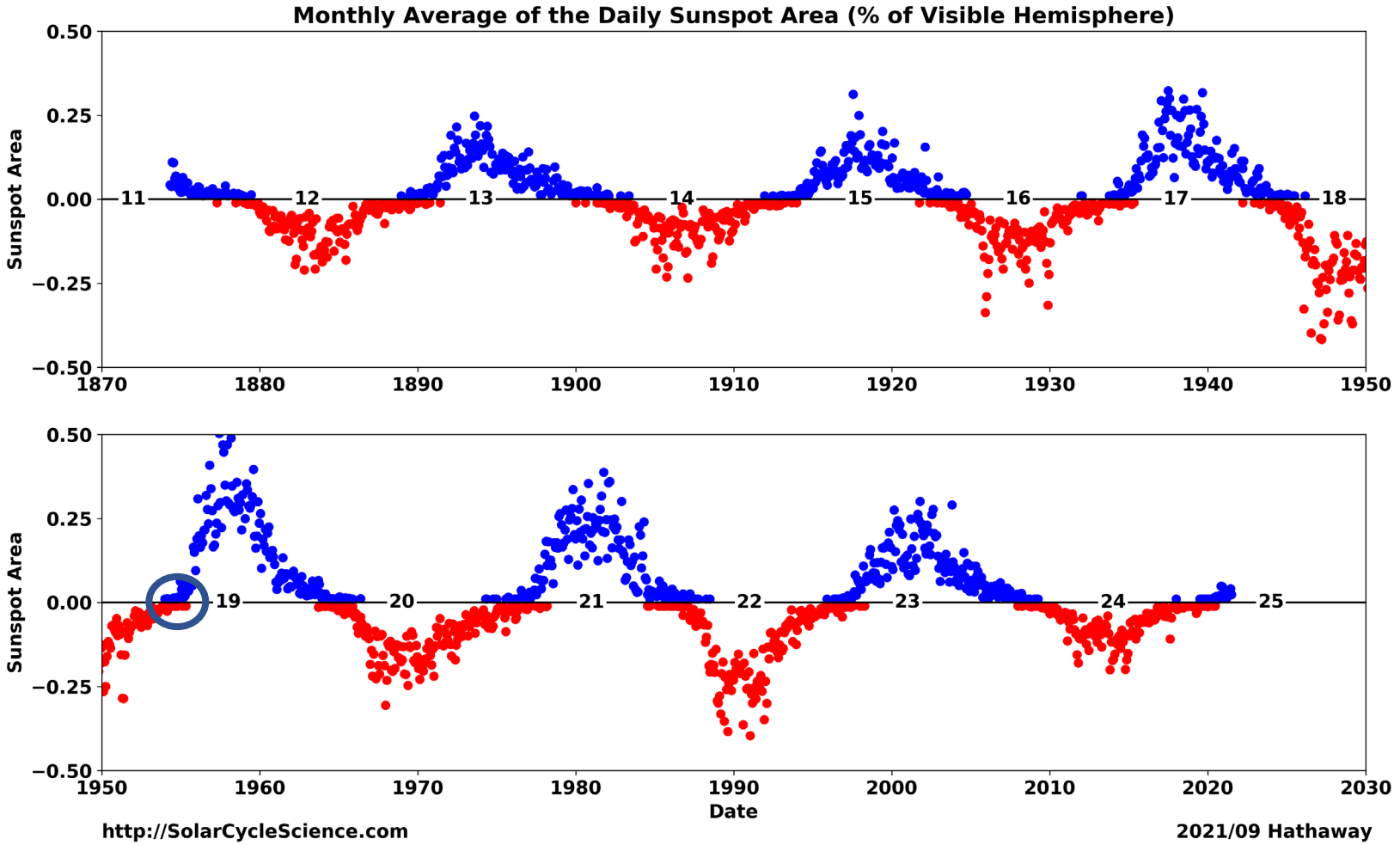

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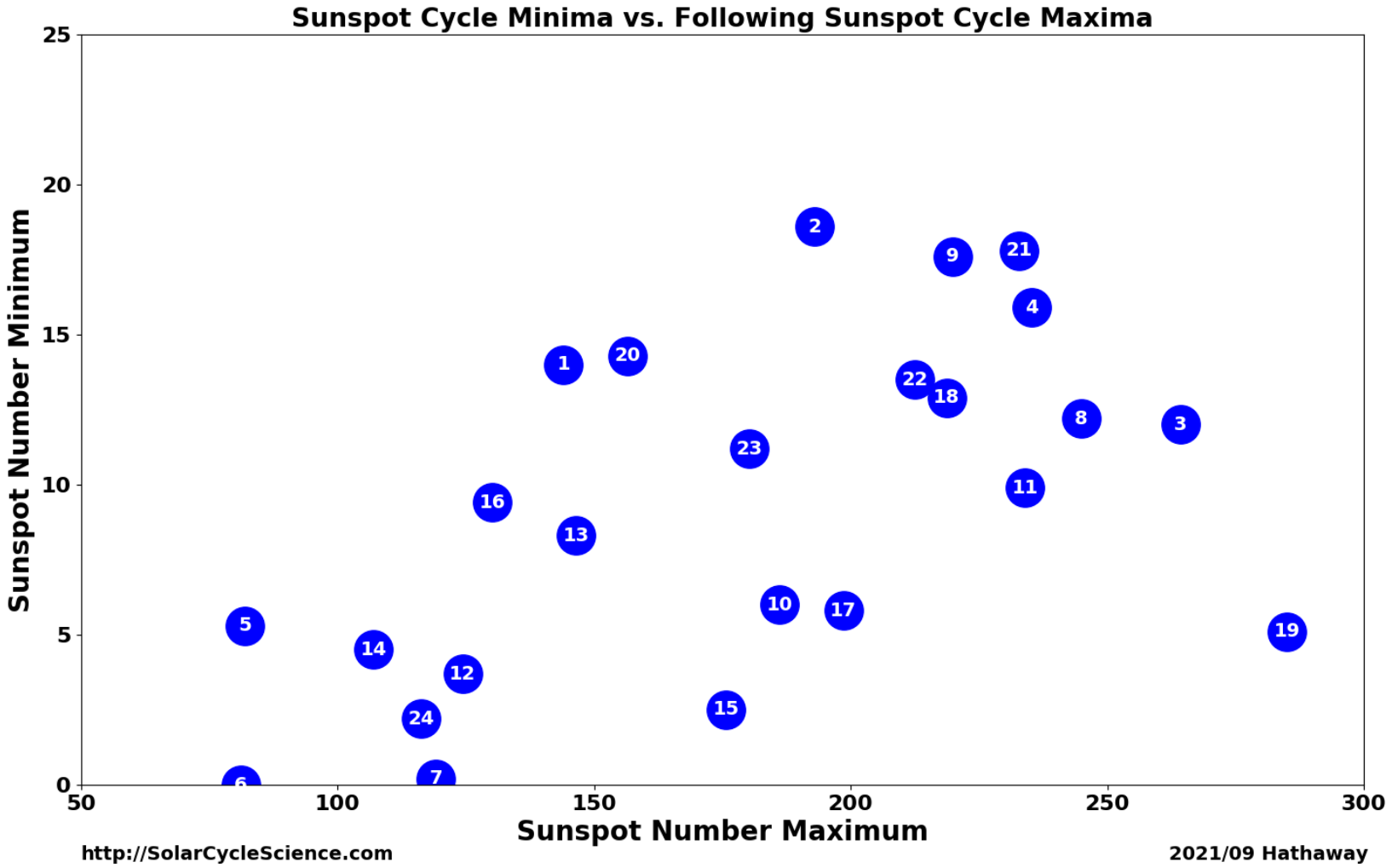
Sunspot Minima vs. Following Maxima



Here, smoothed sunspot number minima are plotted as functions of the following smoothed sunspot number maxima. This shows the tendency for small cycles to be preceded by low minima and large cycles to be preceded by high minima – but with considerable scatter and Cycle 19 as an outlier.

(Note: the smoothed sunspot number minimum for Cycle 24/25 was 1.8.)

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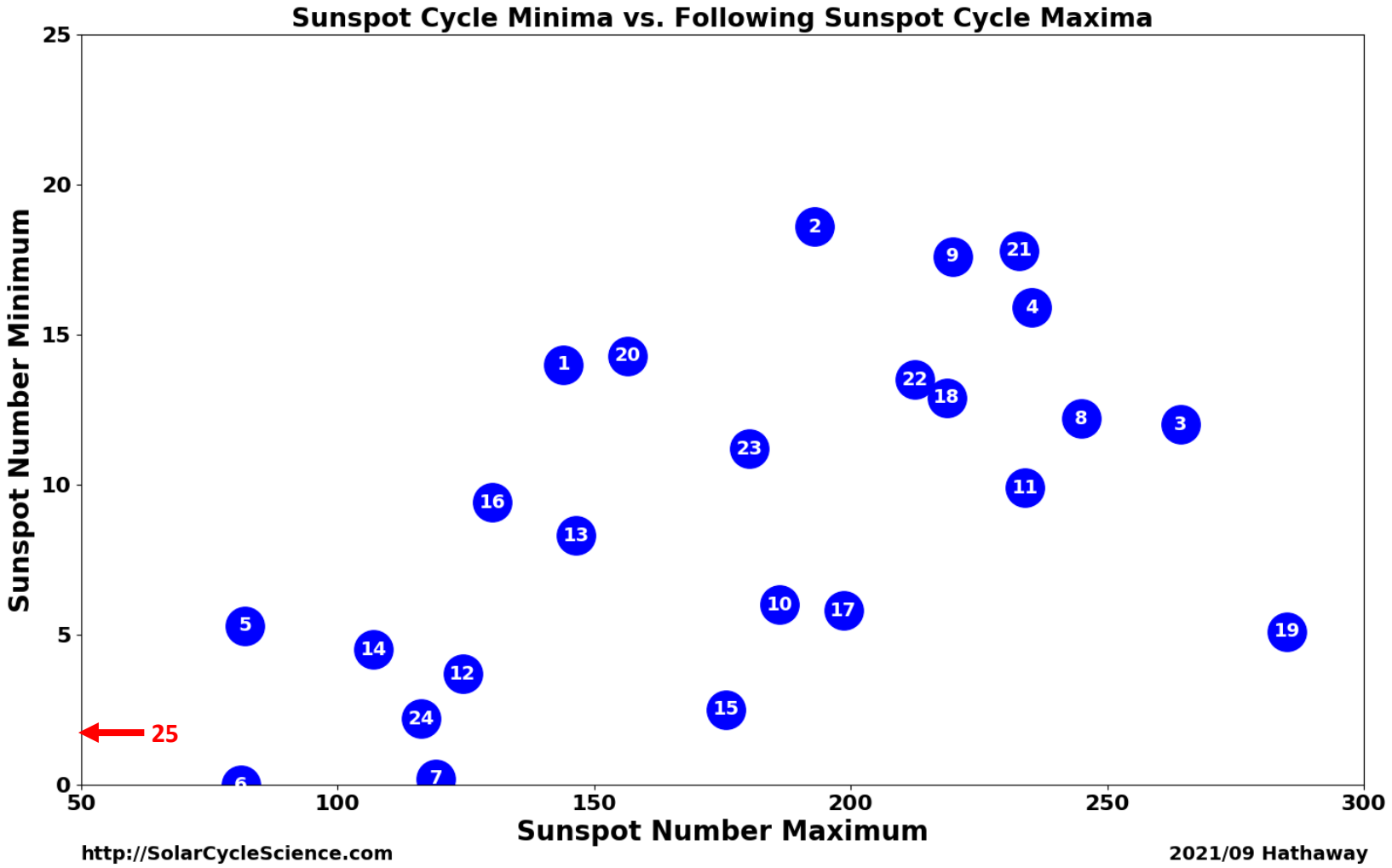

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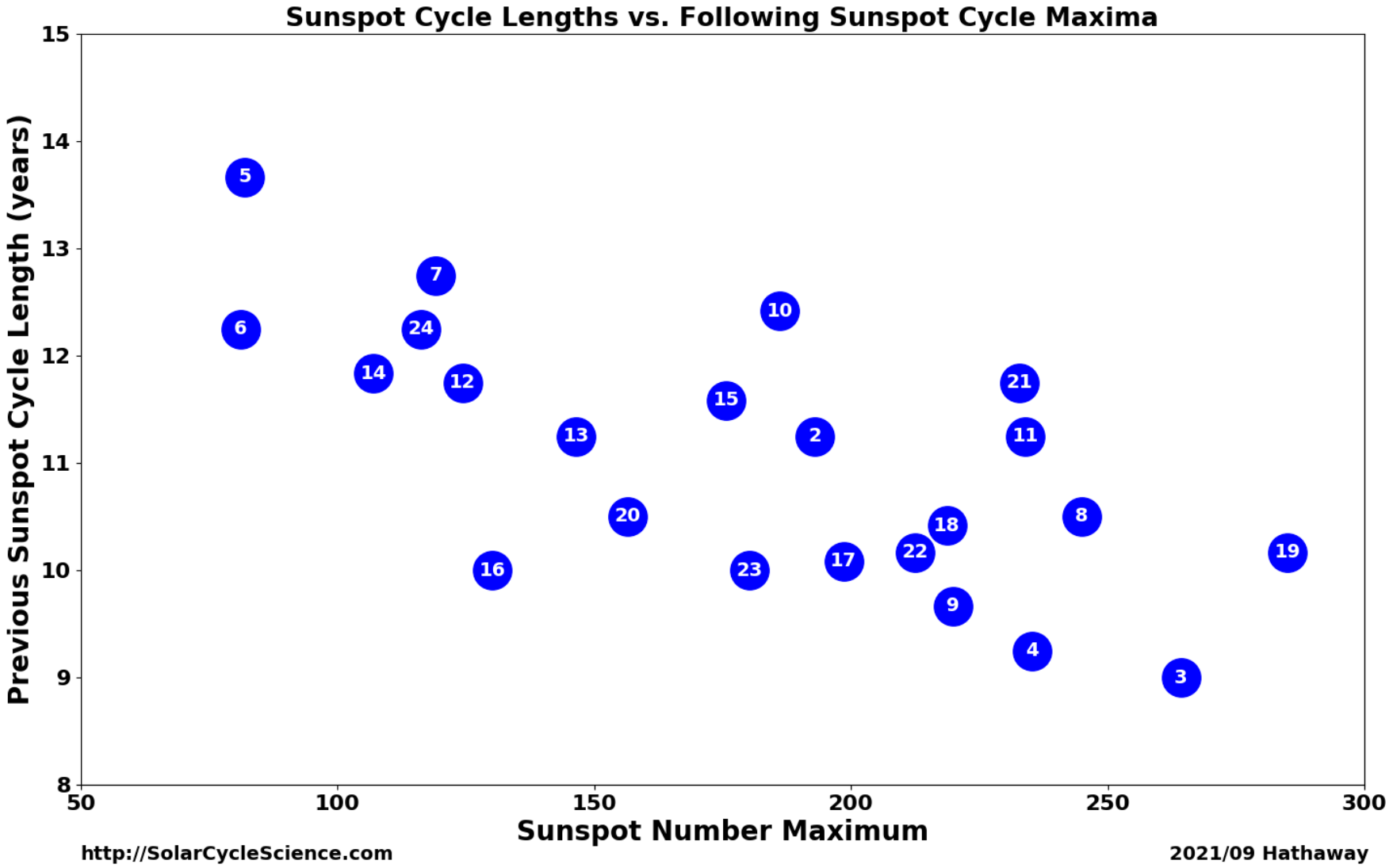
Cycle Length vs. Following Maxima



Plotting cycle lengths (elapsed time from one minimum to the next) as functions of the following smoothed sunspot number maxima shows the tendency for small cycles to be preceded by long cycles and large cycles to be preceded by short cycles – but, again, with considerable scatter.

(Note: the length of Cycle 24 was 11.0 years.)

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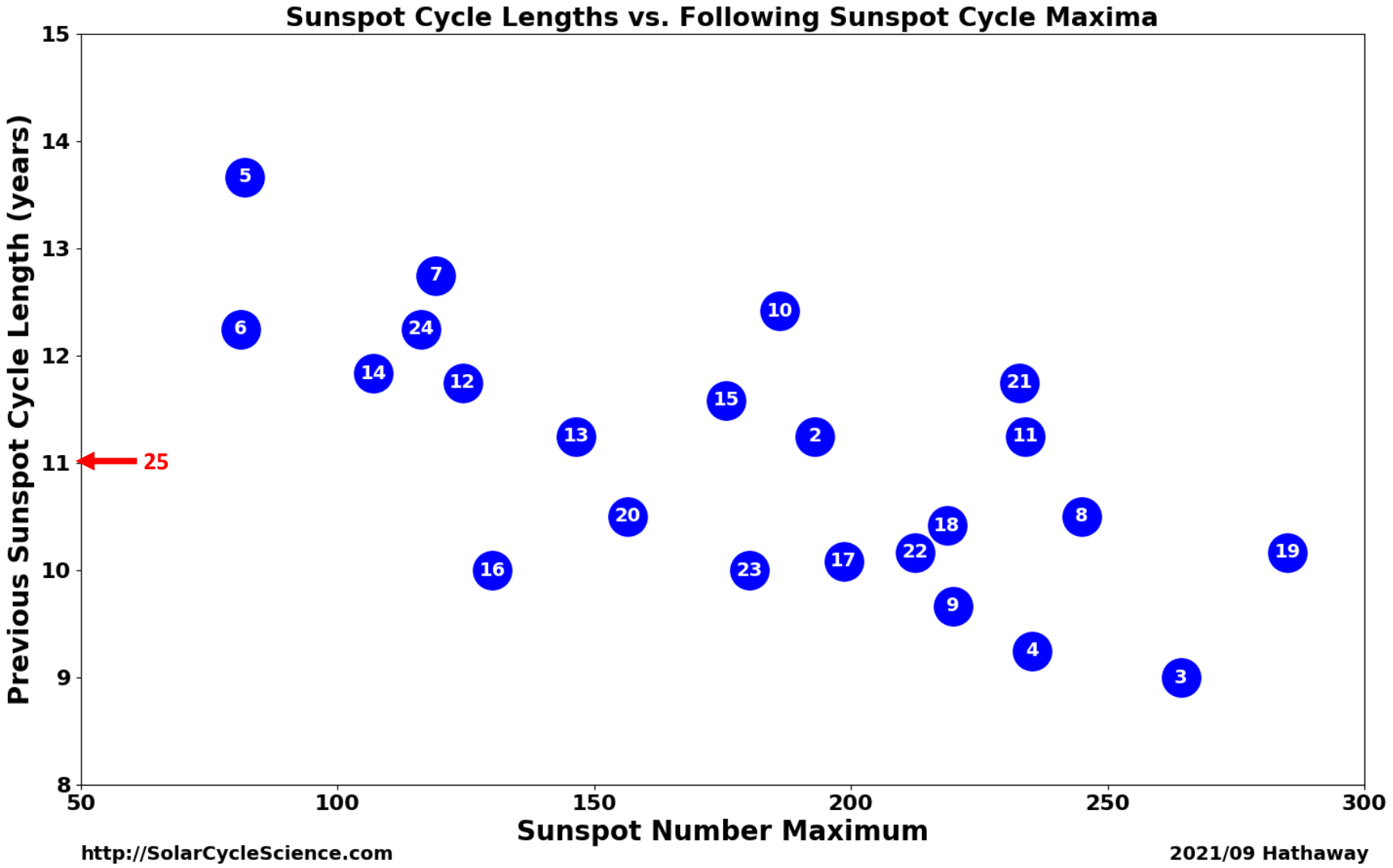

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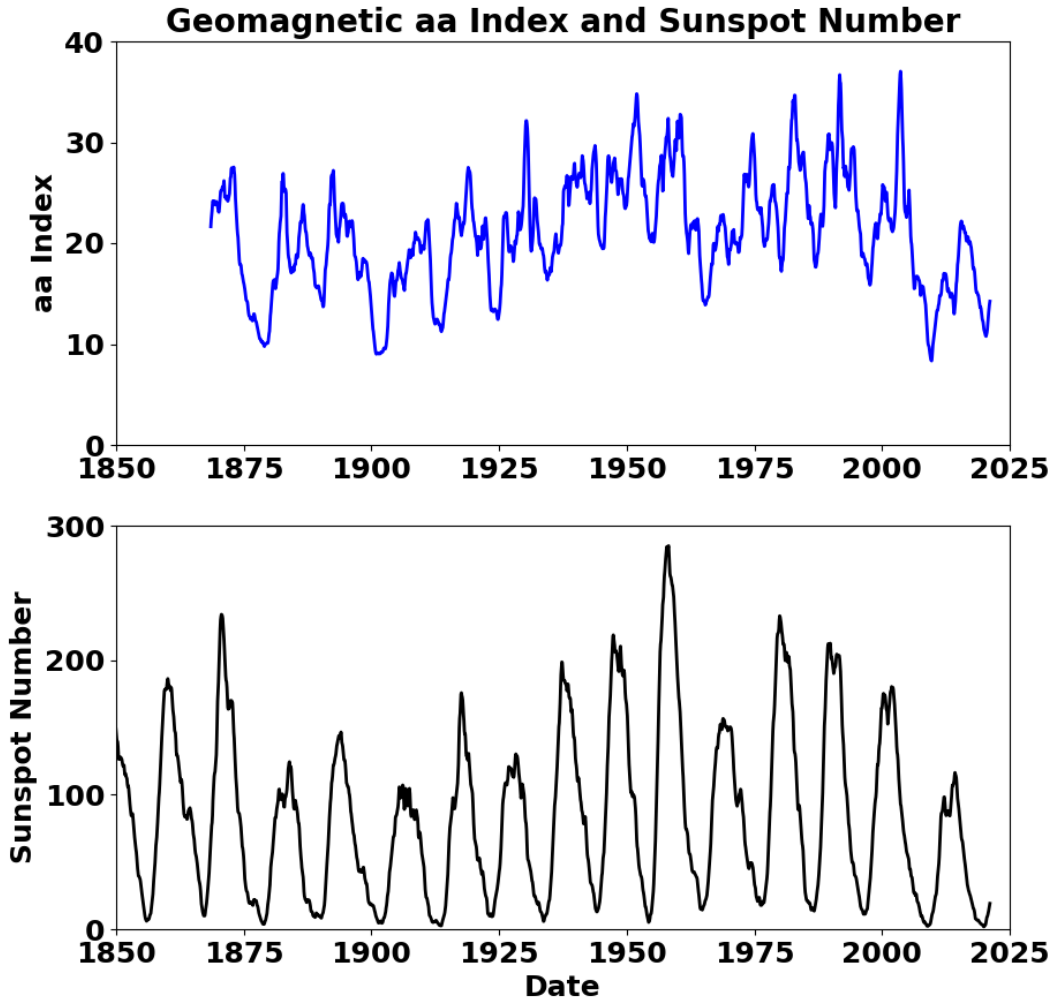
The Takeaway from Sunspot Numbers

- **Large cycles tend to start early and leave behind high minima – largely as a result of cycle overlap**

Geomagnetic Activity Record



Geomagnetic observatories have obtained data on local geomagnetic field variations since the early 1800's. A "global" network of two antipodal stations – one in England and one in Australia - has operated since 1868 and provides data every 3 hours on variations in the Earths magnetic field in the form of the "*aa* Index." These variations are known to be related to solar wind disturbances which are, in turn, related to solar activity and to recurrent high speed solar wind streams.

Ohl (1966) noted that minima in the *aa* index occur at about the time of sunspot cycle minima and are predictors of the amplitude of the following cycle.

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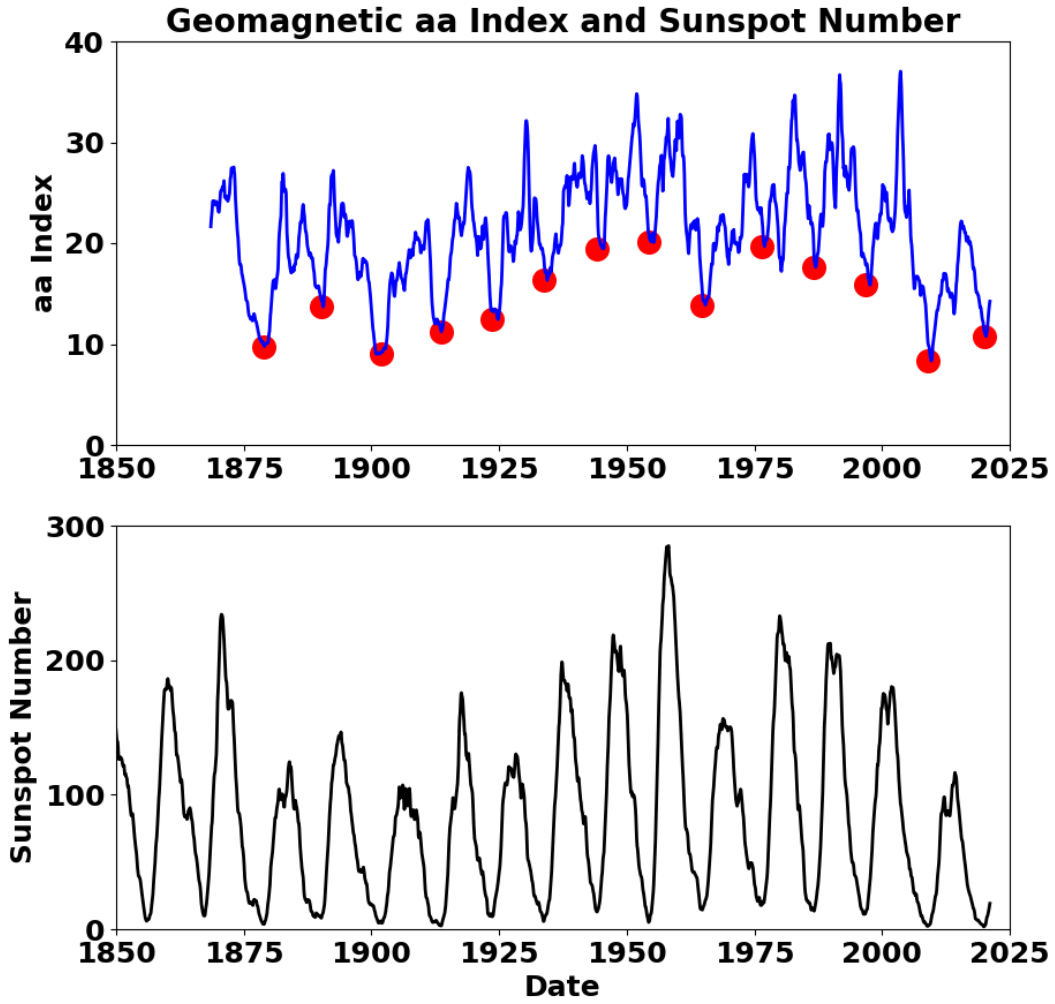

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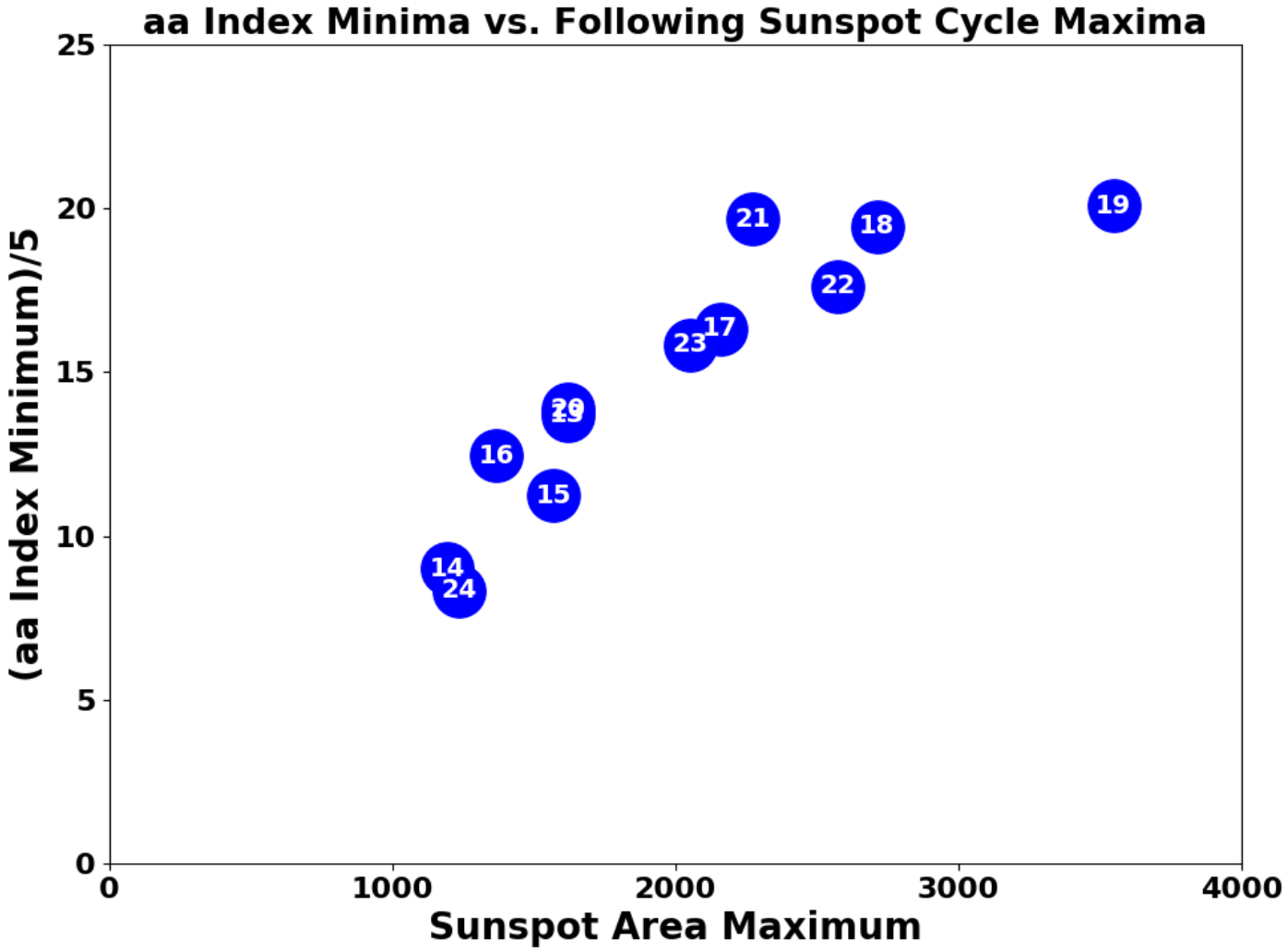
Geomagnetic Activity at Minima vs. Following Maxima



Plotting these minima in the *aa* index as functions of the maximum in sunspot area of the following cycle indicates a nearly linear relationship – with data from 13 cycle minima.

Cycle 19 appears to be an outlier with a lower than expected minimum in the *aa* index.

(Note that the *aa* index minimum at Cycle 24/25 minimum was 10.8.)

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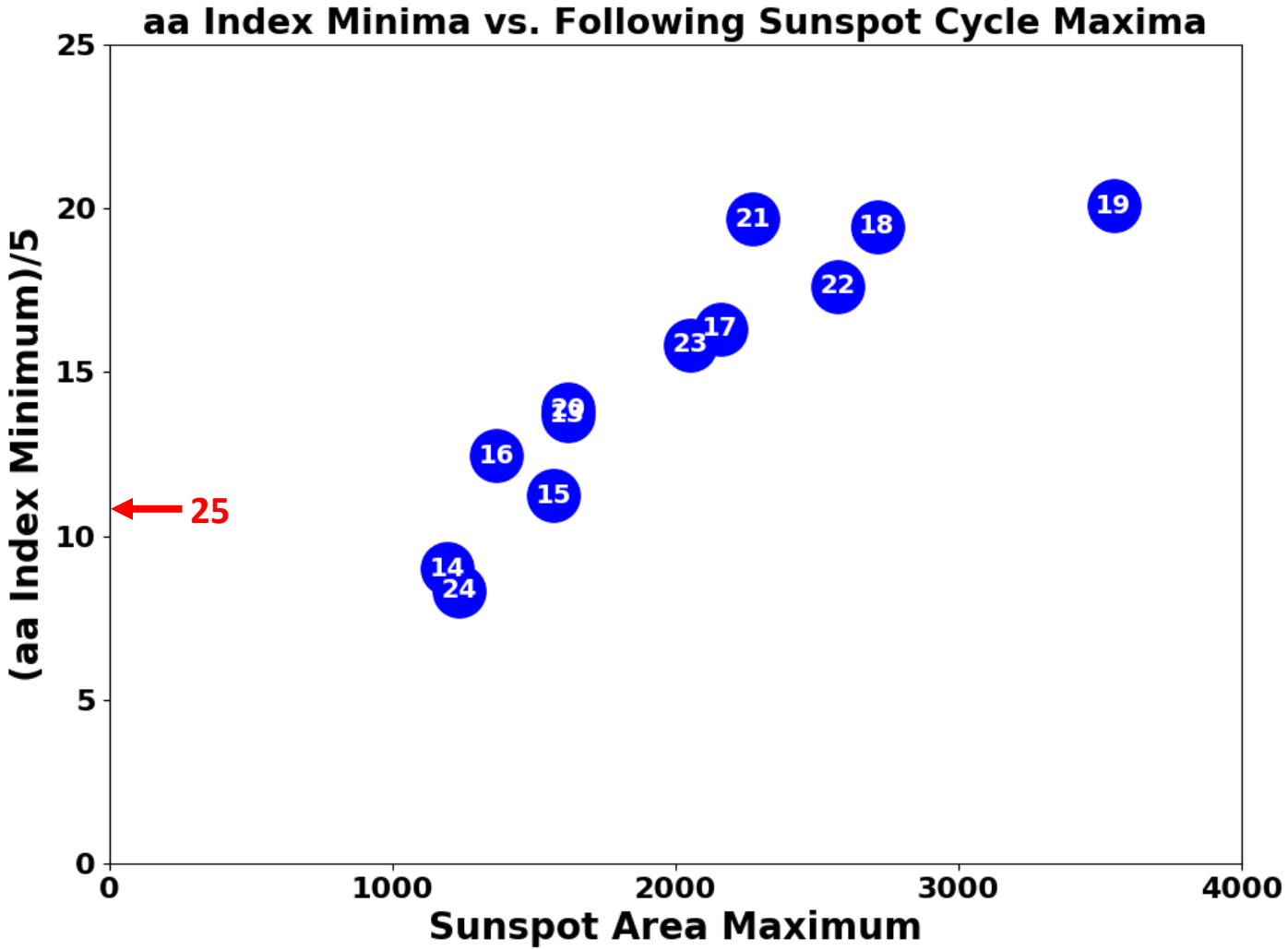

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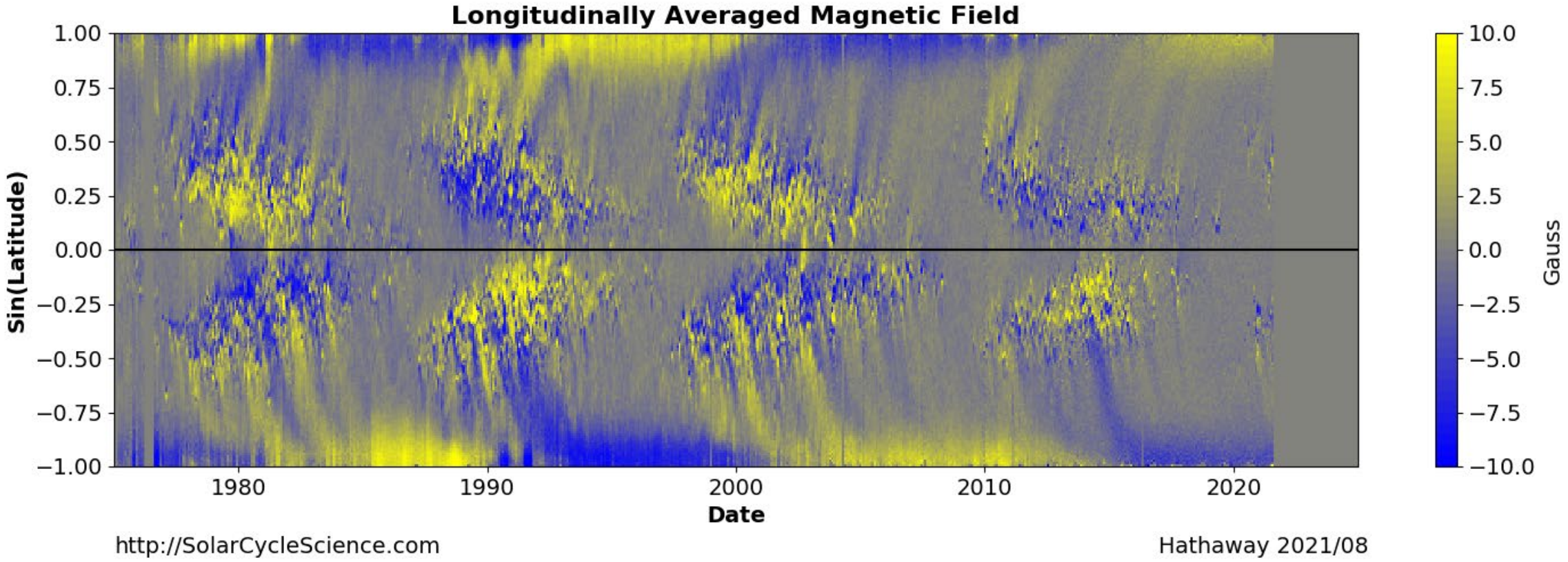
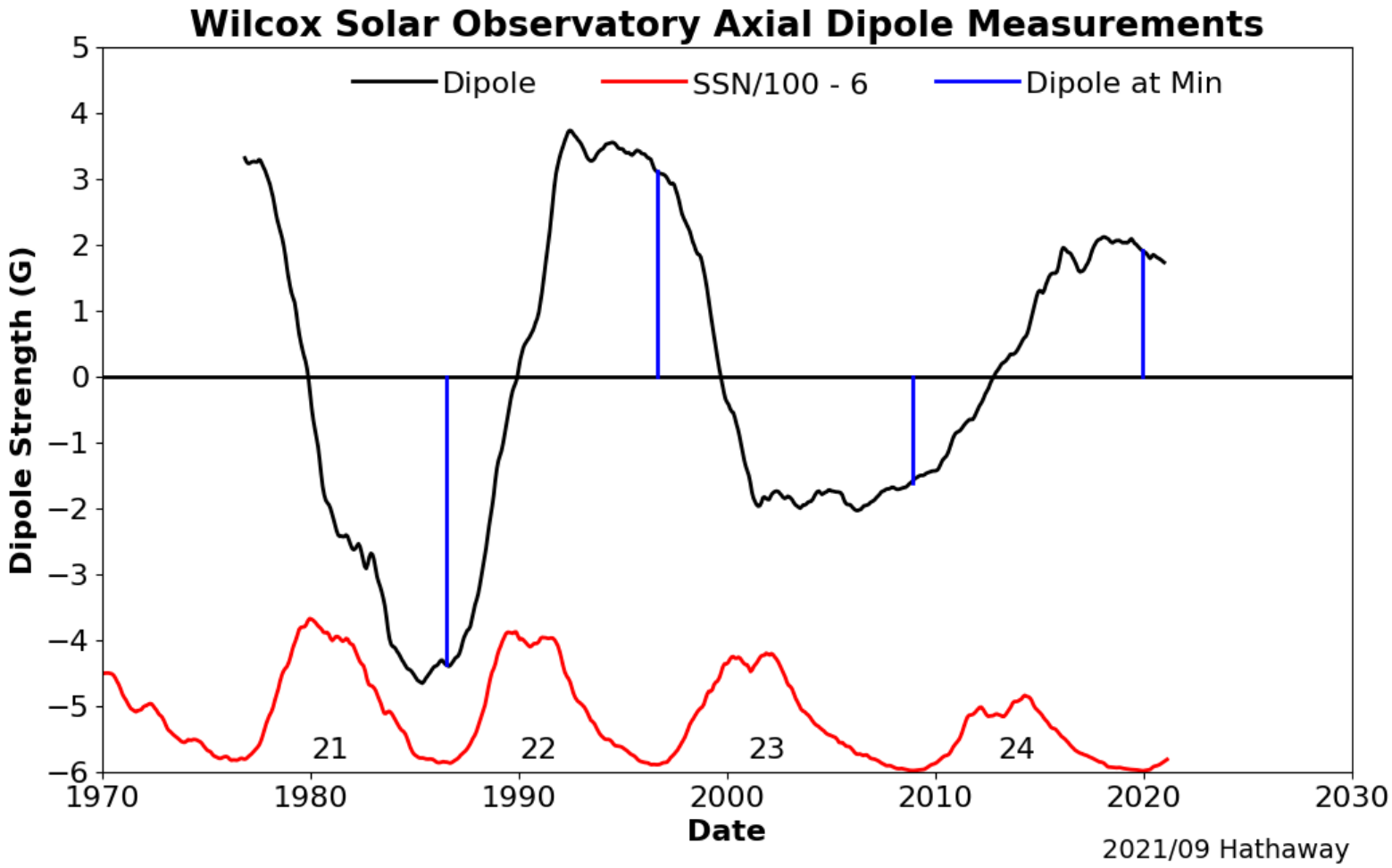
Photospheric Field Measurements

Measurements averaged over individual Carrington rotations from the Kitt Peak National Observatory 512 channel magnetograph, the National Solar Observatory SOLIS instrument, the SOHO/MDI instrument, and the SDO/HMI instrument are averaged over longitude to produce this record of the Sun's magnetic field.



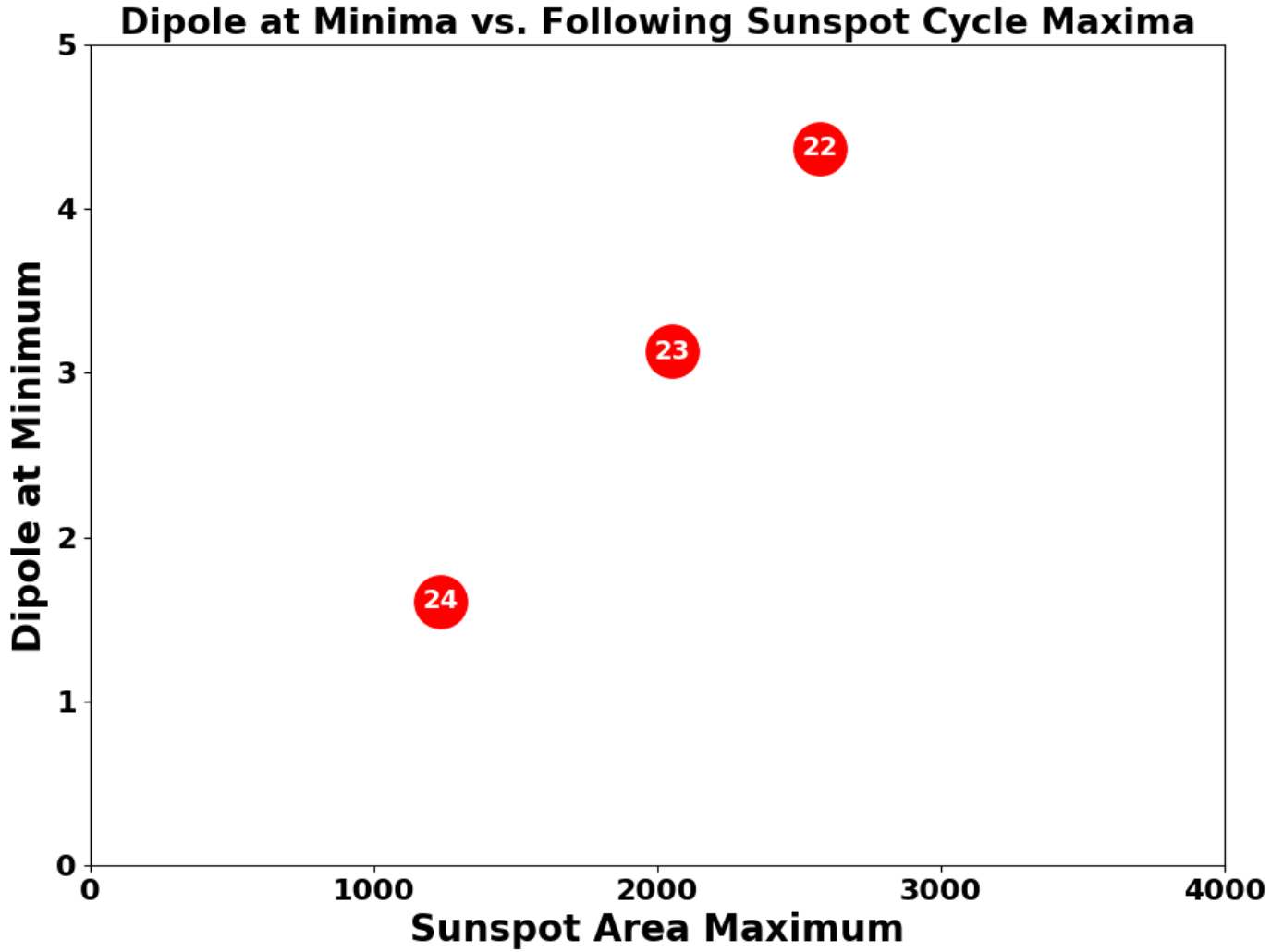
Axial Dipole Strength at Minima



Measurements from Stanford University's Wilcox Solar Observatory have less spatial resolution but come from a single well calibrated and characterized instrument.

This plot shows the axial dipole at the photosphere with the vertical blue lines showing the strength of the axial dipole at the last four minima.

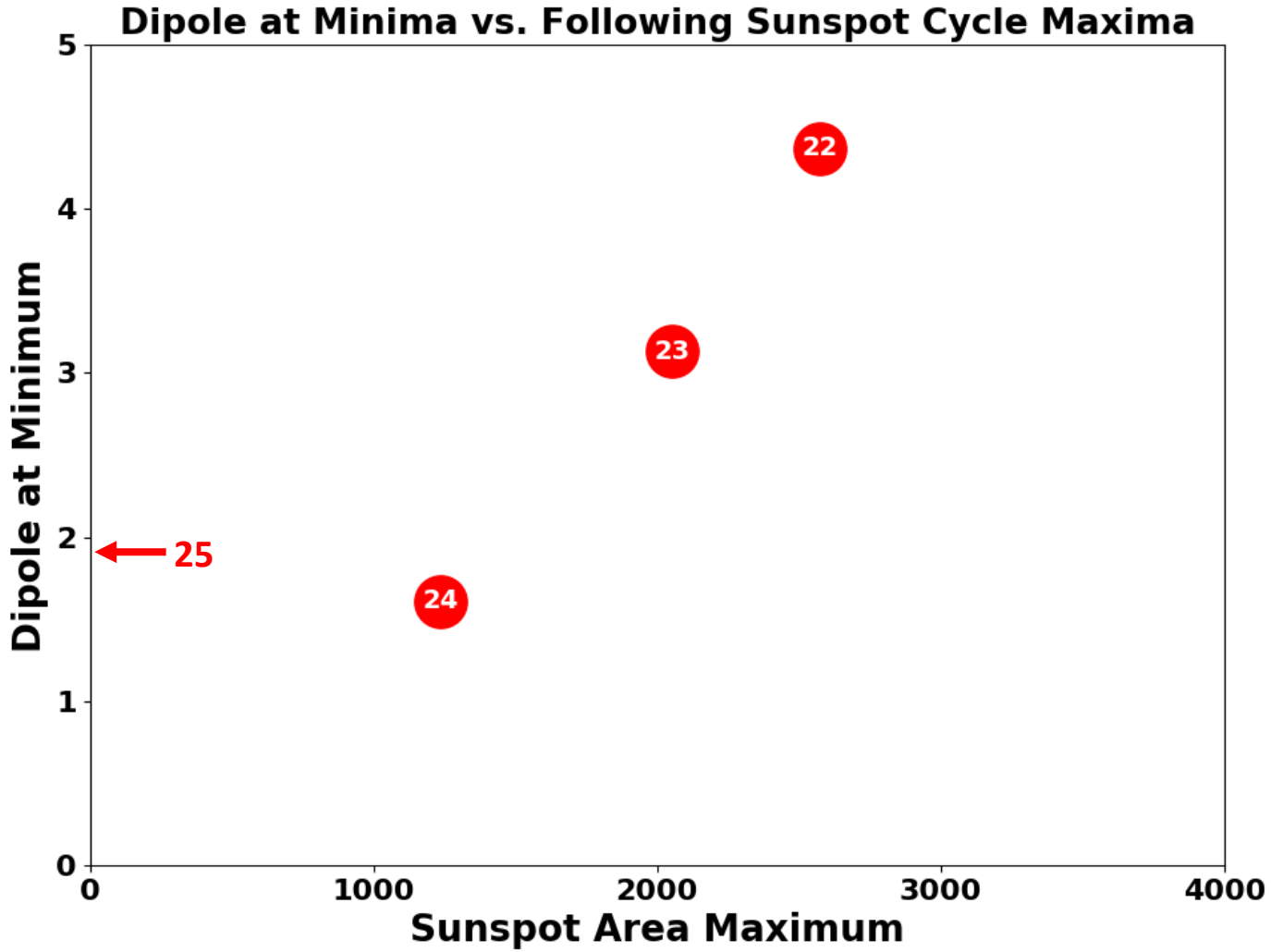
Axial Dipole at Minima vs. Following Maxima



Plotting the axial dipole strength at minima as functions of the maximum daily sunspot area for the following cycle indicates (albeit with only three points) a nearly linear relationship between the axial dipole strength at minimum and the size of the following maximum.

(Note that the axial field strength at Cycle 24/25 minimum was 1.91.)

Axial Dipole at Minima vs. Following Maxima



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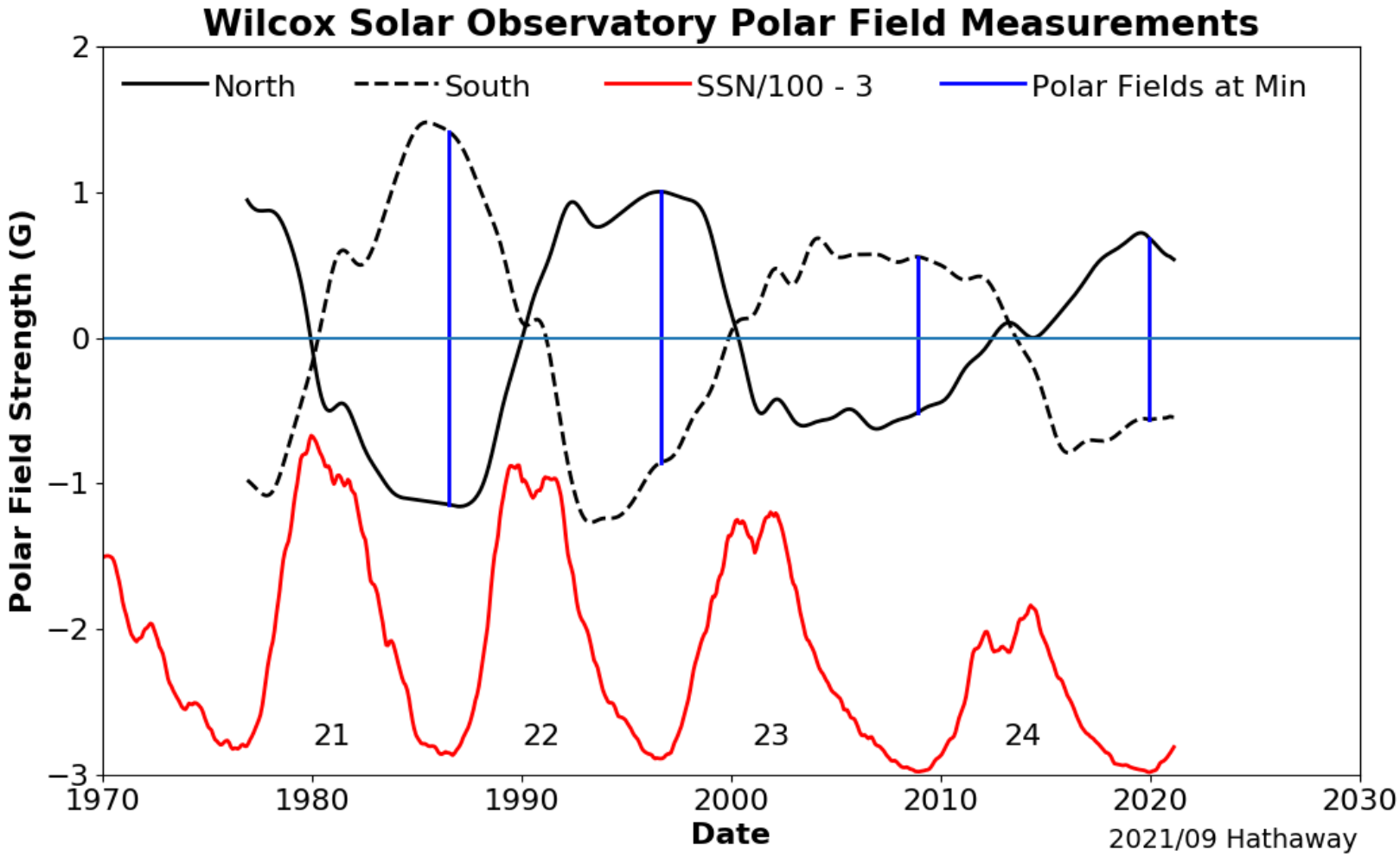
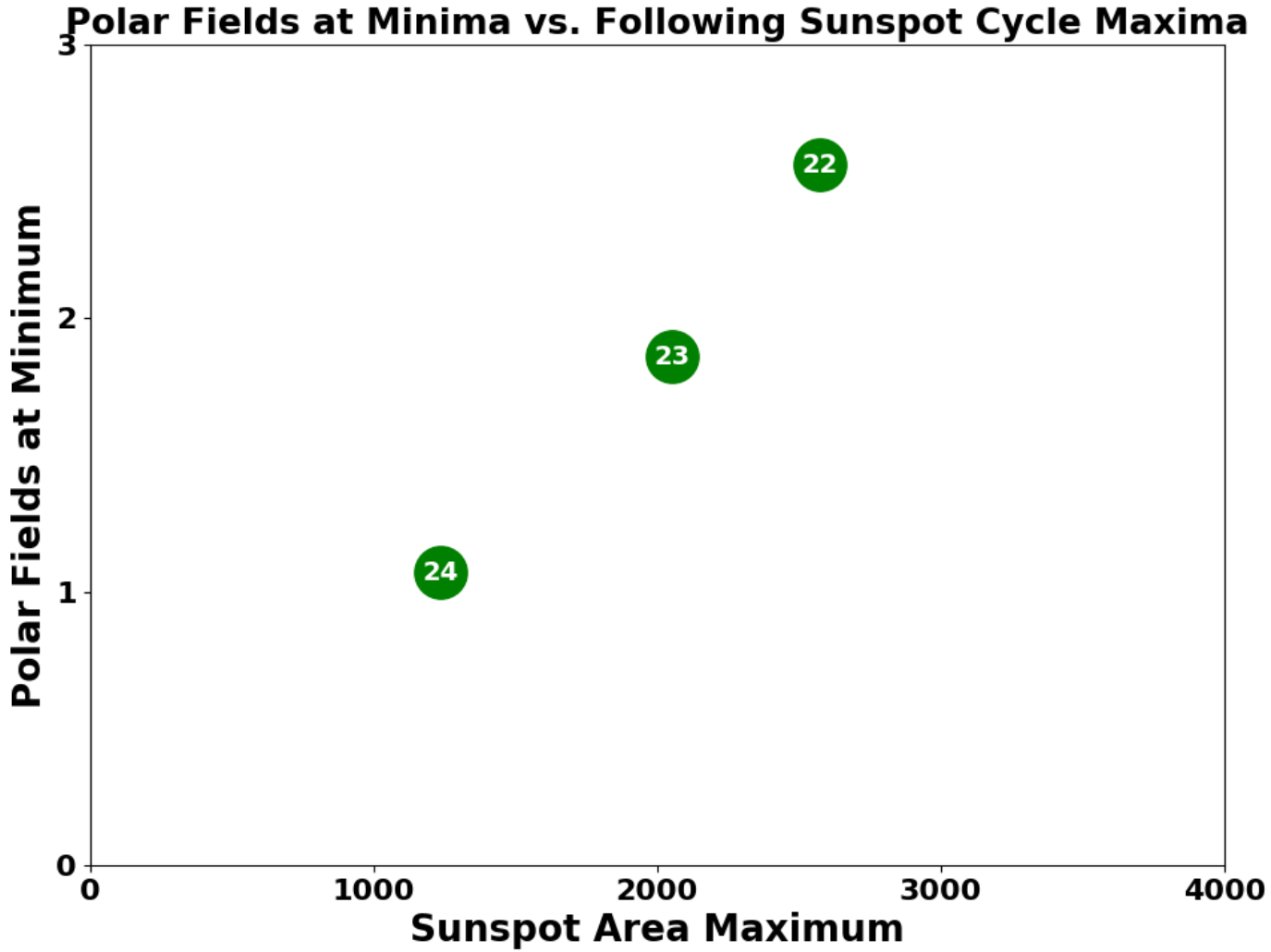
Polar Fields at Minima



The Wilcox Solar Observatory measures the polar fields above 55° in its northernmost and southernmost pixel. These measurements are shown by the black lines here – solid for the north and dashed for the south.

The vertical blue lines show the polar fields at minima.

Polar Fields at Minima vs. Following Maxima



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(Note that the polar field strength at Cycle 24/25 minimum was 1.25.)

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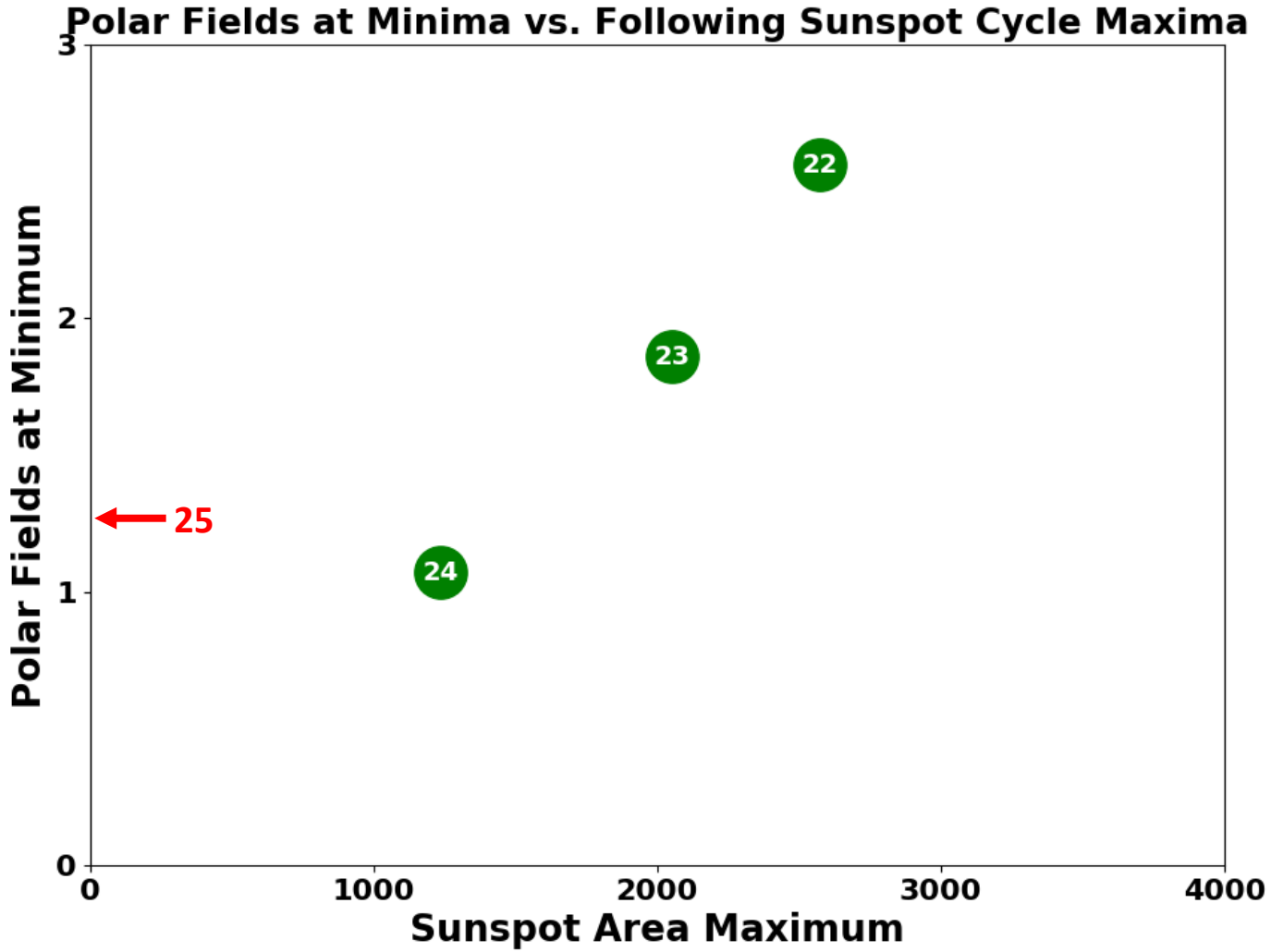

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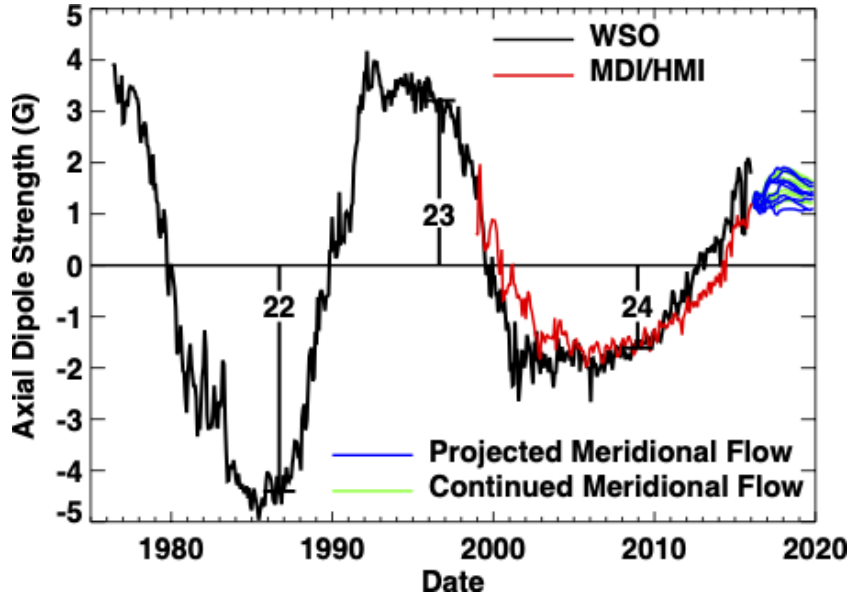
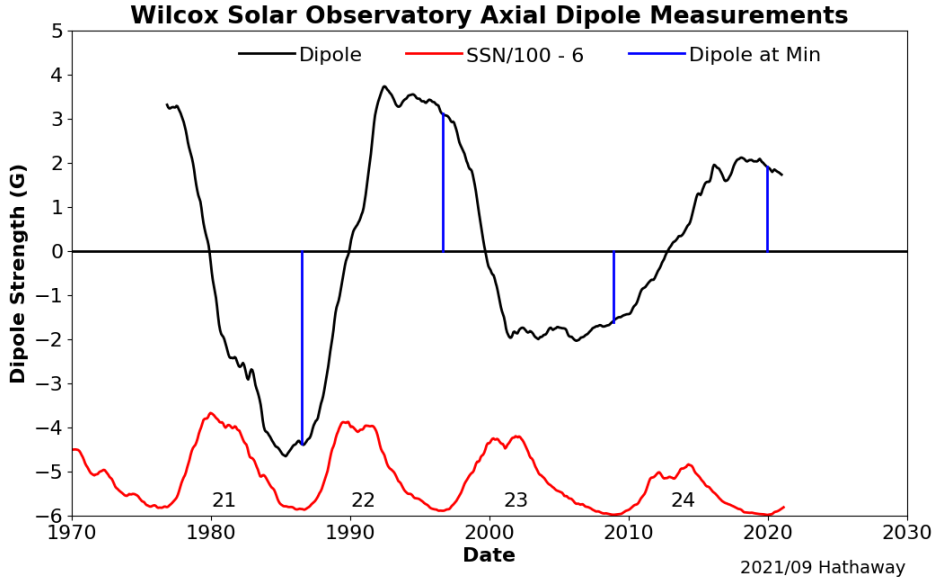
(Note that the polar field strength at Cycle 24/25 minimum was 1.25.)

Predicting Polar Fields at Minimum before Minimum

In Hathaway & Upton (2016) we used our Advective Flux Transport code, with flows well constrained by observations, to simulate the evolution of the Sun's polar magnetic fields from early 2016 to the end of 2019. We added new active regions using those from the same phases of Cycle 14 in 32 realizations with differing active region tilts, convection patterns, and meridional flow profiles.

We predicted that the polar fields would be similar to those at Cycle 23/24 minimum and that Cycle 25 would be similar to Cycle 24.





Conclusions

- Small cycles tend to start late and leave behind a long cycle and a low minimum sunspot number
- Geomagnetic activity minima at sunspot cycle minima are accurate predictors of the strength of the following cycle
  - These geomagnetic minima seem to be proxies for the polar fields/axial dipole – can this connection be shown via modeling of recent, well observed minima?
- Polar fields and the axial dipole at cycle minima appear to be accurate predictors of the strength of the following cycle (based on only three cycles but supported by dynamo theory)
- Cycle 25 will be another small cycle like Cycle 24

The Babcock Dynamo – still good after all these years