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Scaling of photospheric magnetic field observations

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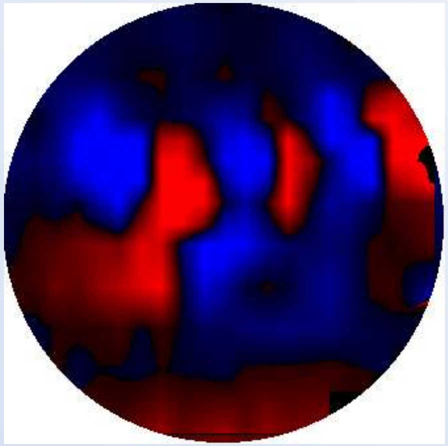
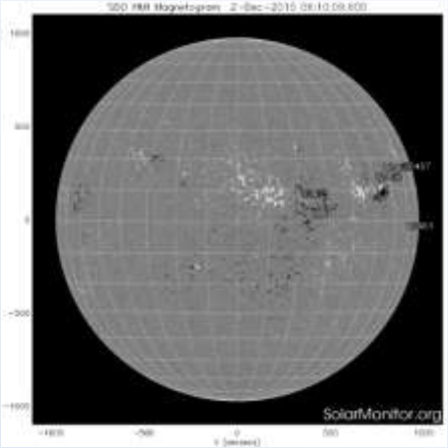
Solar observations

- First observations of the large-scale photospheric magnetic fields were carried out in Mount Wilson in mid 1950s.
- Since these early days, observations have been done in various places using different instrumentation and data processing techniques.
- The most continuous and homogenous data series is measured in Wilcox Solar Observatory since 1976. Other instruments with higher spatial resolution do not cover several solar cycles without significant updates.

Babcock, July 1953


WSO, 29.11.2015



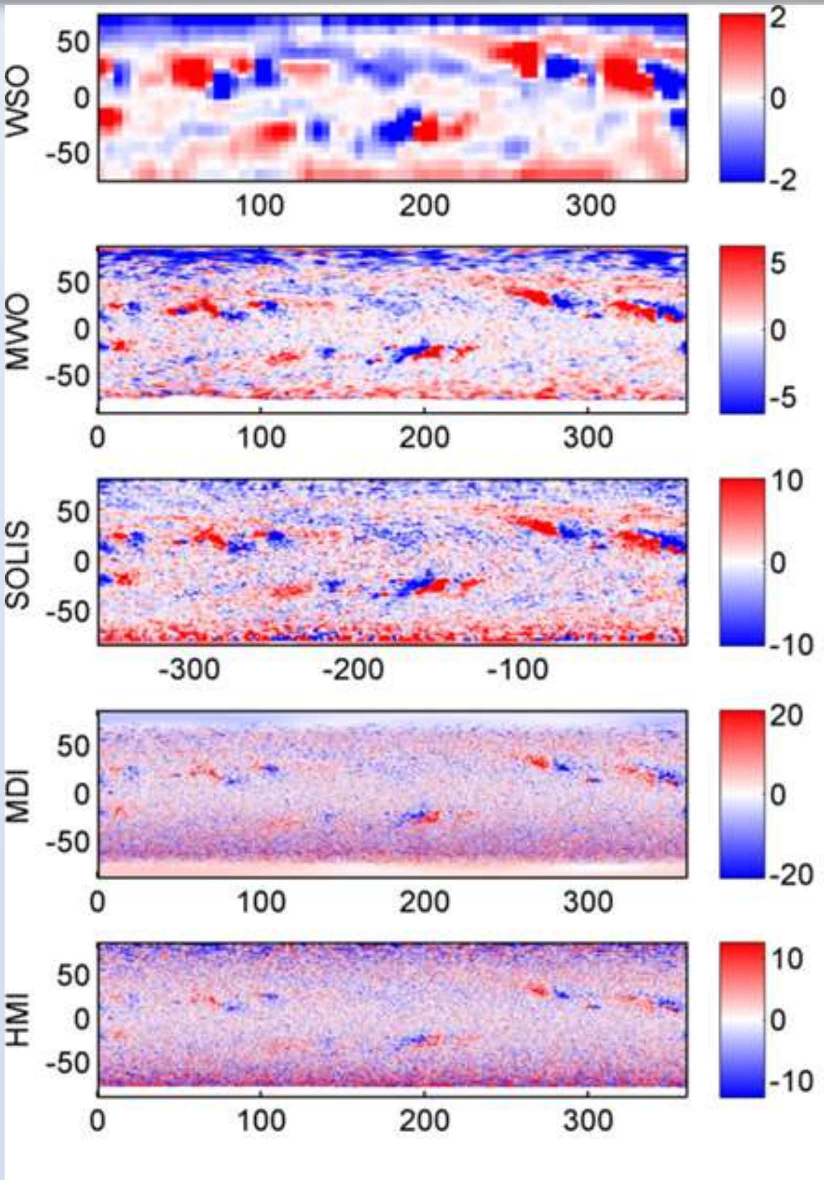
HMI, 2.12.2015

Data

- Radial or line-of-sight (WSO and MWO) component of the photospheric magnetic field
- Rotational (synoptic) maps in longitude – sine(latitude) or longitude – latitude (MWO) grid

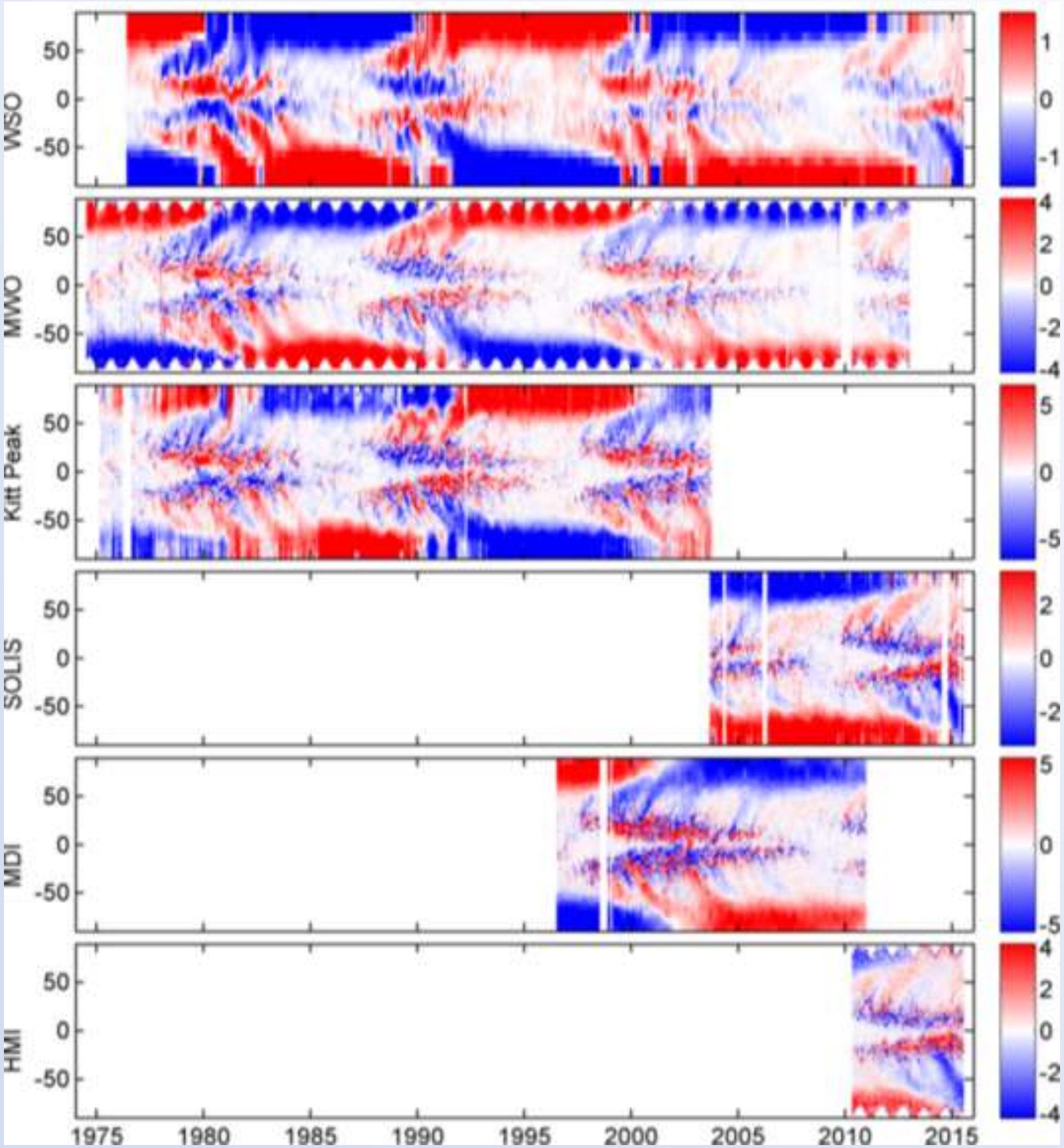
Data	Spectral line	Carrington rotations	Time	Resolution
WSO	Fe 525nm	1641-	1976.3 -	72*30
MWO	Fe 525nm	1617 - 2131	1974.5 – 2013	971*512
Kitt Peak SPMG	Fe 868.8nm	1863 - 2006	1992.8 – 2003.7	360*180
SOLIS	Fe 630.15nm	2007-	2006.4 -	360*180
SOHO/MDI	Ni 676.8nm	1909 - 2104	1996.4 – 2011.1	3600*1080
SDO/HMI	Ni 617.3nm	2096-	2010.4 -	3600*1440

Synoptic maps



- Colormap saturates at ±5*median of absolute value
- All data sets show a fairly similar large scale structure, but have different absolute levels and different small scale features.
- Spatial resolution varies significantly and causes deviations.
- Major differences in polar fields, mainly due to different resolutions and also to different filling methods.

Magnetic butterfly diagrams



- Longitudinal averages show similar large scale structures and solar cycle evolution in all six data sets.
- Higher resolution data show more complicated structures, especially in active regions.
- Even polar fields appear slightly differently in high resolution data.
- Differences between polar fields are largest during polarity reversals. Low resolution instruments indicate earlier reversal.

Challenges with polar fields

Polar fields are highly important for coronal structure, solar wind and heliospheric magnetic field, as well dynamo modeling, but they are poorly visible and hard to observe.

Data	Polar field
WSO	Low resolution data; highest pixel at 75.2°; no (need for) filling
Kitt Peak and Solis	Polar fields are filled in synoptic maps
MWO	Synoptic map includes the visible area of solar disk up to ±74.2° - ±85.8°, but highest pixels are often erroneous; no filling made.
MDI	Polar fields are filled
HMI	Synoptic map includes the visible area of solar disk, up to ±76.3° - ±87.9°; some errors at high latitudes; no filling made.

Methods

- Assume a potential magnetic field, i.e., no currents between the boundaries.
- Leads to Laplace equation which has a solution in terms of the harmonic expansion of the observed magnetic field.
- Inner boundary condition: observed magnetic field is radial.
- Outer boundary condition: coronal source surface magnetic field is radial.
- This leads to radial functions C(r,n) and D(r,n)

- This method is called the PFSS model

$$B_r(r,\theta,\phi) = \sum_{n=1}^{\infty}\sum_{m=0}^{n} P_n^m(\cos\theta)(g_n^m \cos m\phi + h_n^m \sin m\phi)C(r,n)$$

$$B_\theta(r,\theta,\phi) = -\sum_{n=1}^{\infty}\sum_{m=0}^{n} \frac{\partial P_n^m}{\partial\theta}(\cos\theta)(g_n^m \cos m\phi + h_n^m \sin m\phi)D(r,n)$$

$$B_\phi(r,\theta,\phi) = \sum_{n=1}^{\infty}\sum_{m=0}^{n} P_n^m(\sin\theta)(g_n^m \cos m\phi - h_n^m \cos m\phi)D(r,n)$$

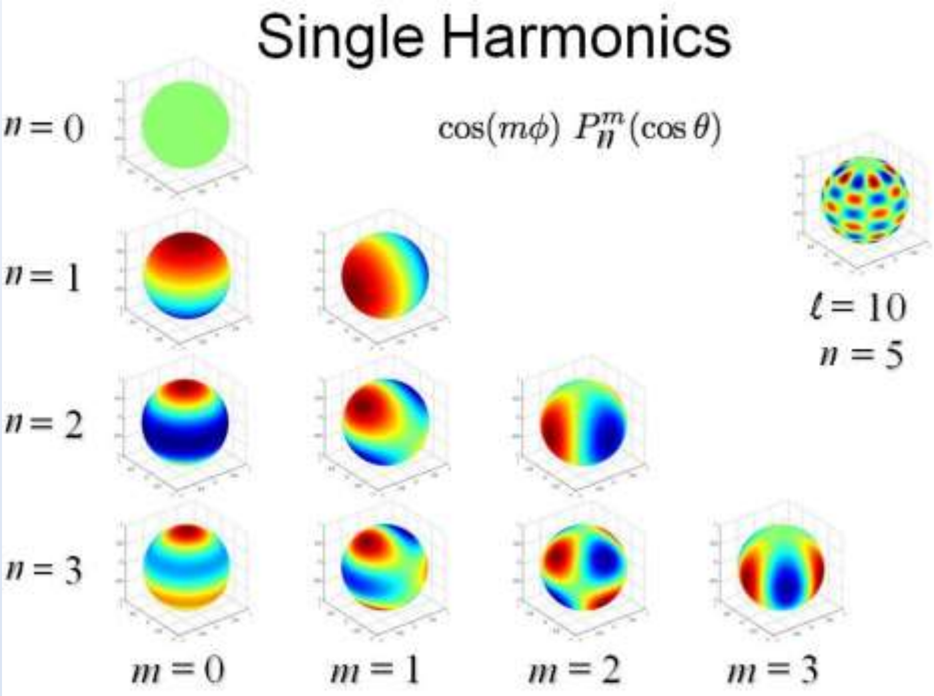
Methods

- Harmonic coefficients are solved as follows:

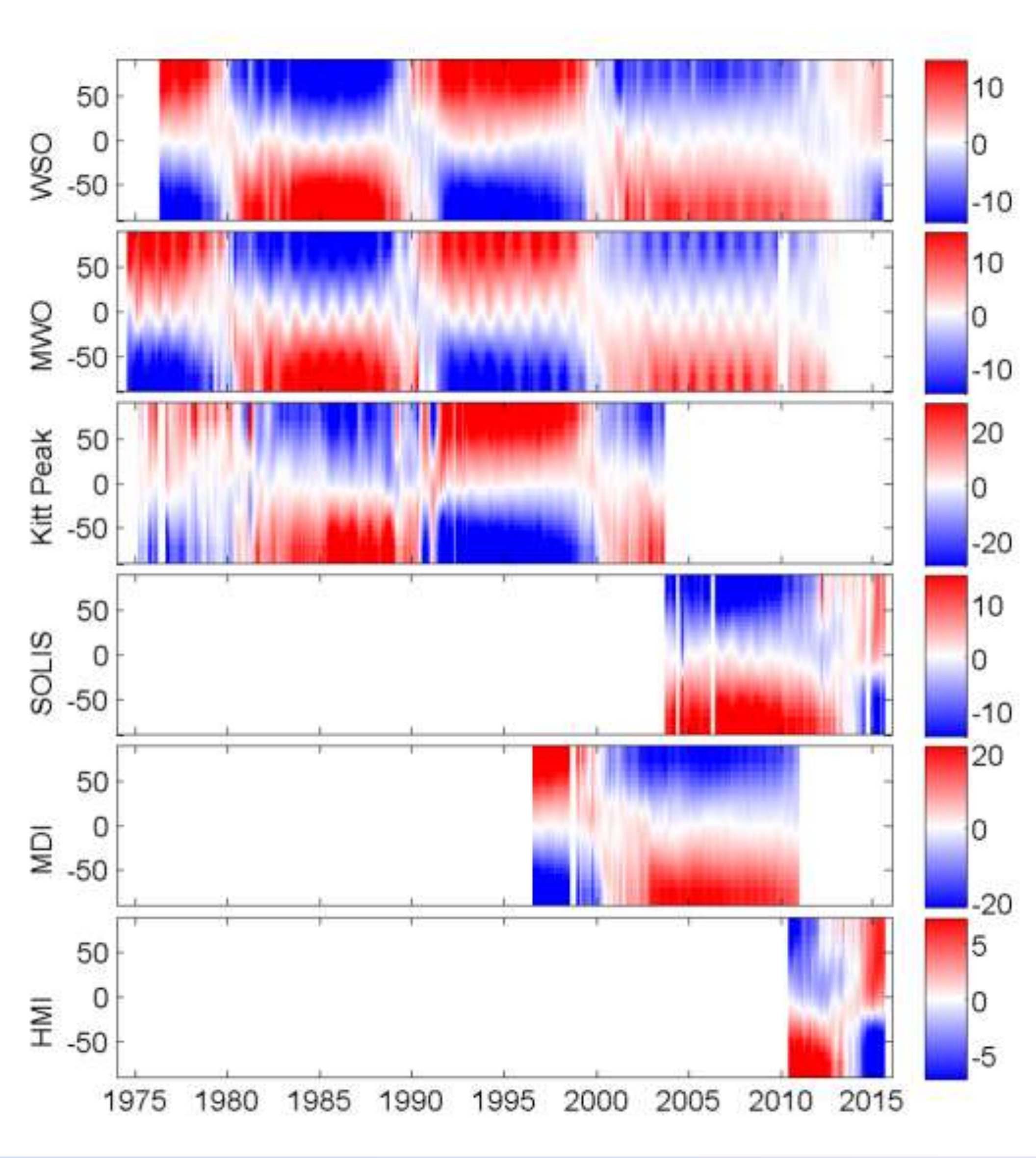
$$\begin{Bmatrix} g_n^m \\ h_n^m \end{Bmatrix} = \frac{2n+1}{X \cdot Y} \sum_{i=1}^{X} \sum_{j=1}^{Y} \frac{B_{j,i}^{phot}}{\sin\theta_i} P_n^m(\cos\theta_i) \begin{Bmatrix} \cos(m\phi_j) \\ \sin(m\phi_j) \end{Bmatrix}$$

- Resolution in observations defines the highest possible (physically meaningful) n in the harmonic expansion.

- WSO aperture size is 3 arcmin, which corresponds to n_{max} = 16 in longitude, but only n_{max} = 2 for high latitude fields.

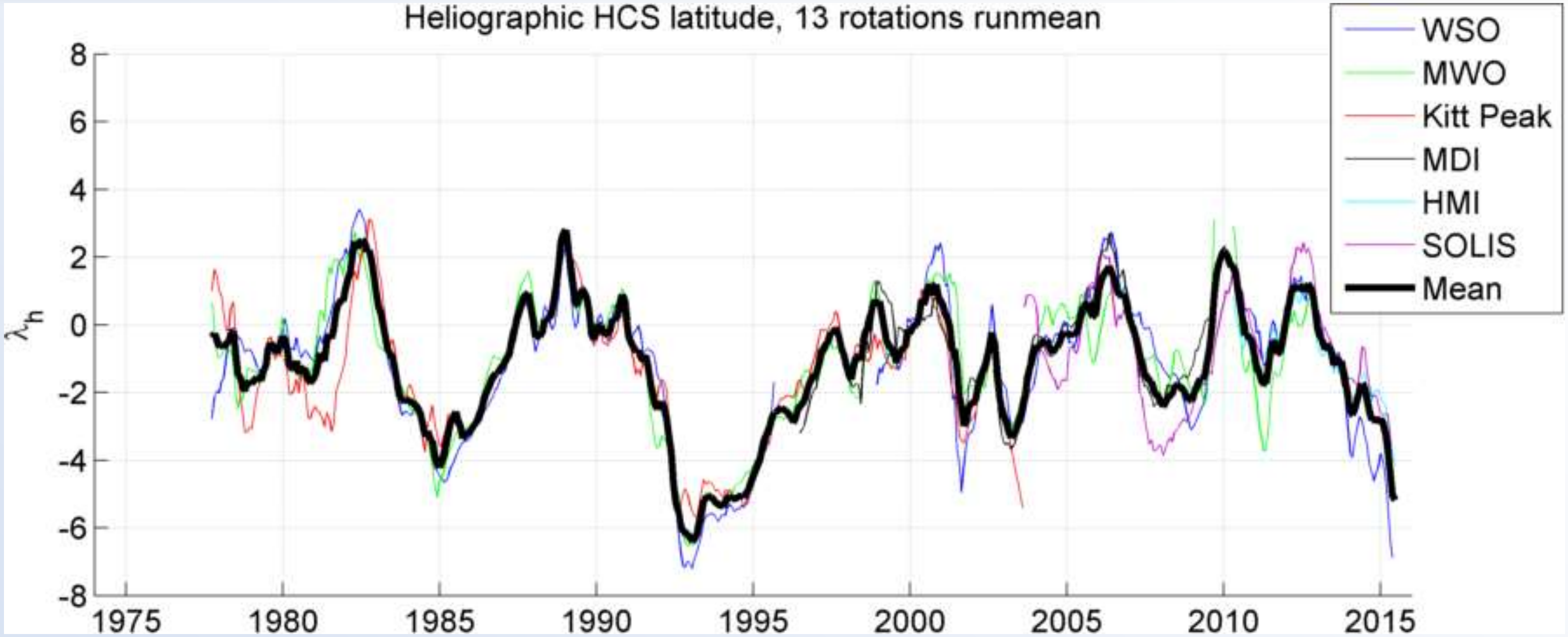


Coronal magnetic field



- We calculate the coronal magnetic field using PFSS model and photospheric observations of the six data sets.
- Longitudinal averages show
  - Solar cycle evolution
  - Hemispheric asymmetries
  - Vantage point (b_0) effect
  - Some obvious errors
  - Scaling between data sets is different than in photospheric magnetic field

Hemispheric asymmetries

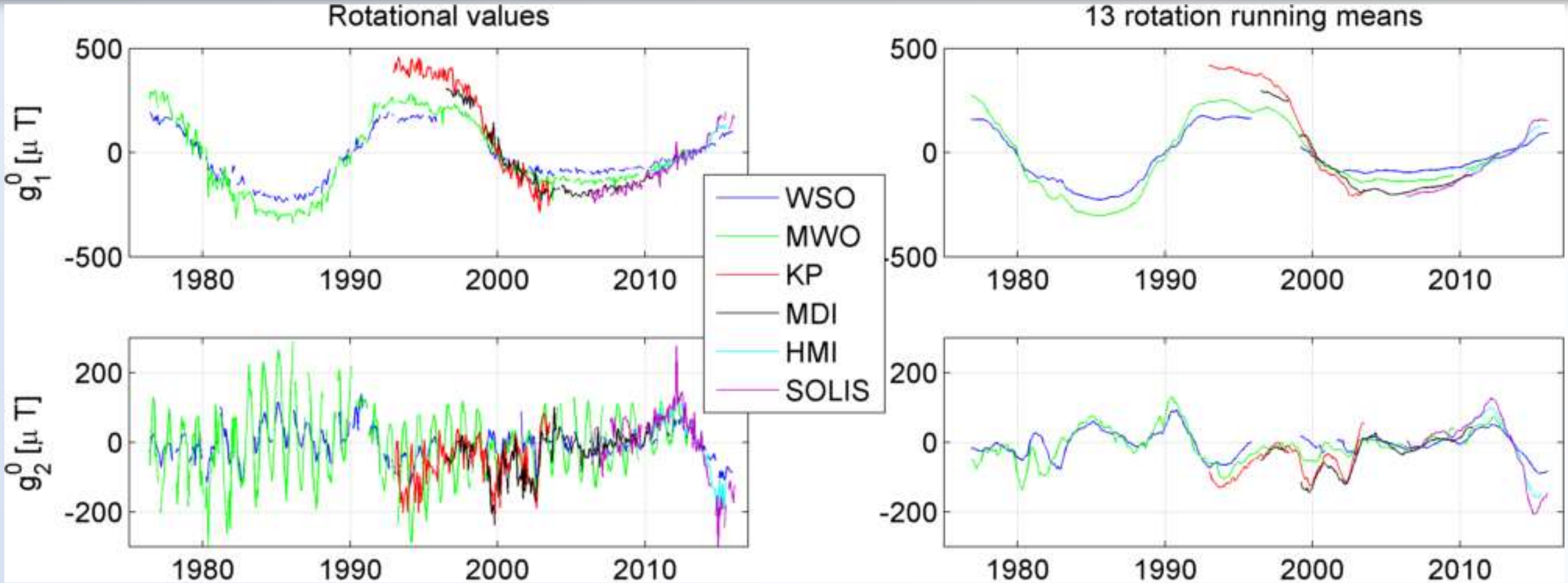


- The average heliographic latitude of the heliospheric current sheet in the solar corona.
- Derived using PFSS model and six different data sets, with obviously erroneous data being removed.
- Very systematic agreement between the six different data sets.
- Overall, significant southward dominance.

Scaling

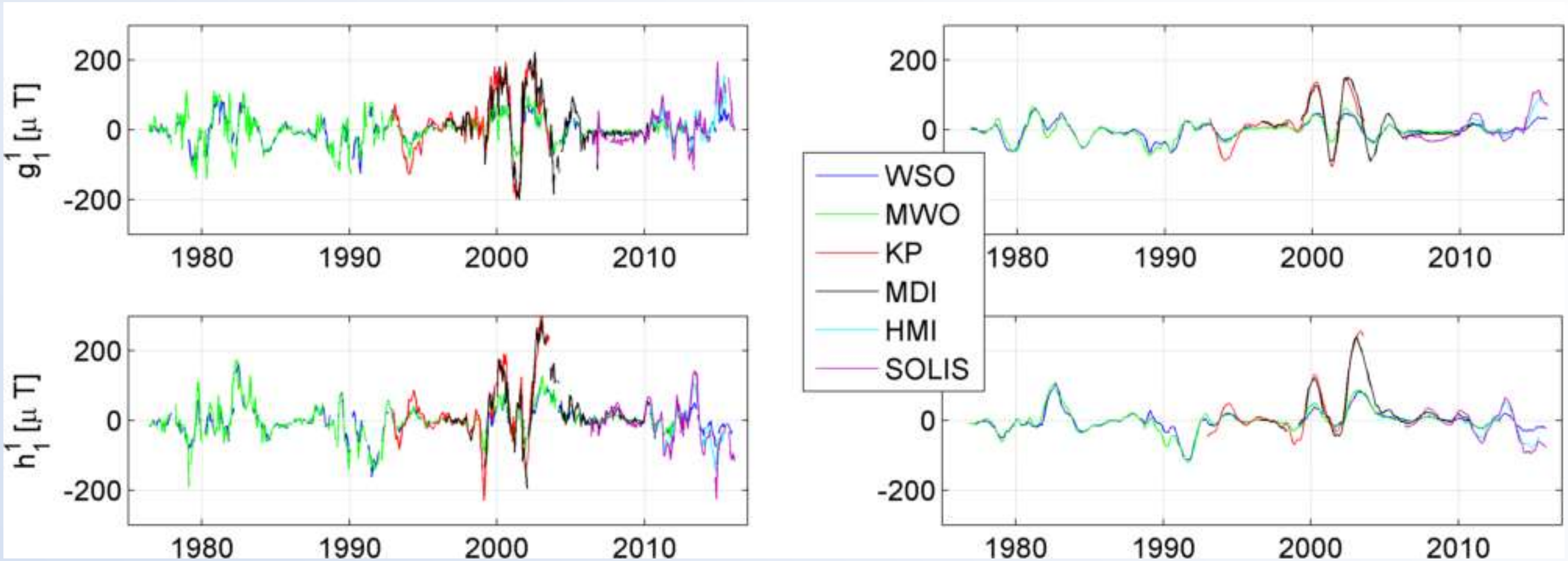
- Several reasons why different data sets show different overall field strength
  - Magnetograph saturation, spatial resolution, spectral line, method of solving magnetic field from observations, etc.
- Several methods to correct saturation
  - Single coefficient (Svalgaard, 1978)
  - Latitude dependent correction (Ulrich 1992, Wang 1992)
- Scaling between data sets exists (is needed), even though "the ground truth" is not known (Riley et al, 2013).
- The effect of scaling is linear in PFSS model, but non-linear in MHD models

Harmonic coefficients



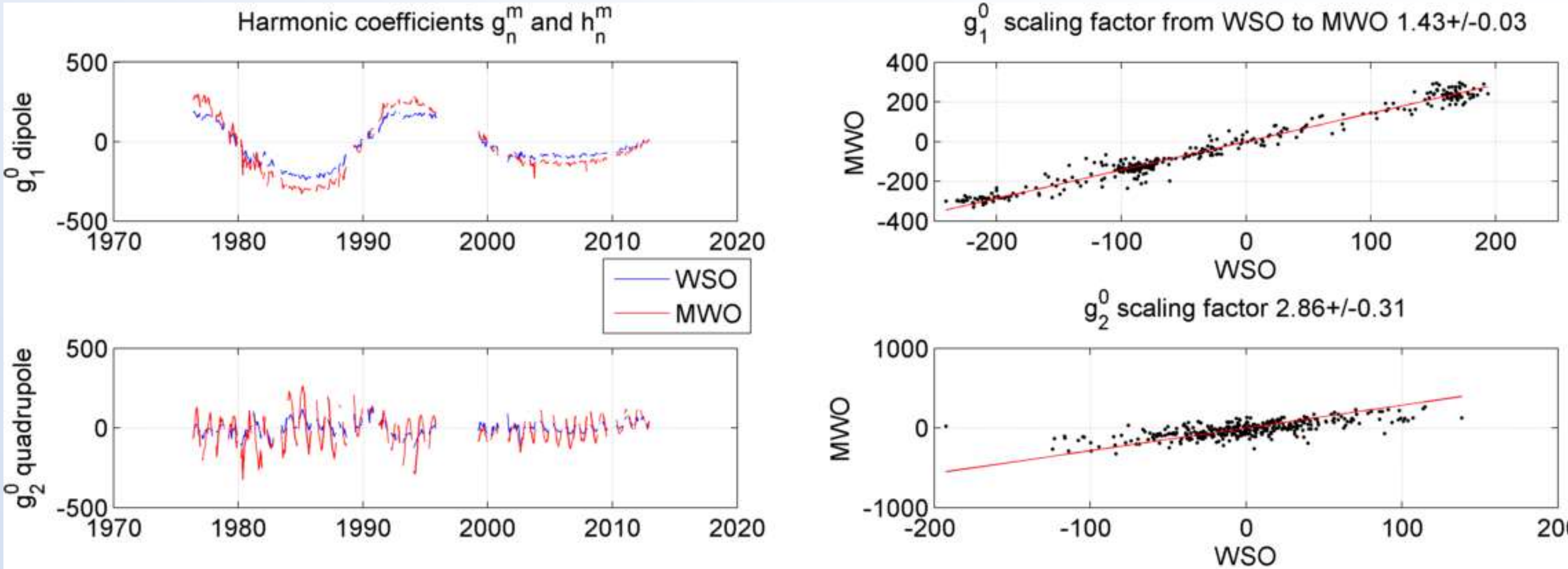
- Axial dipole shows similar solar cycle variations in all six data sets, but the magnitude is consistently different.
- Axial quadrupole has a very strong annual oscillations (due to b_0 –effect), especially in MWO data.
- The 13 rotation running mean removes annual effects and results are much more coherent.

Harmonic coefficients



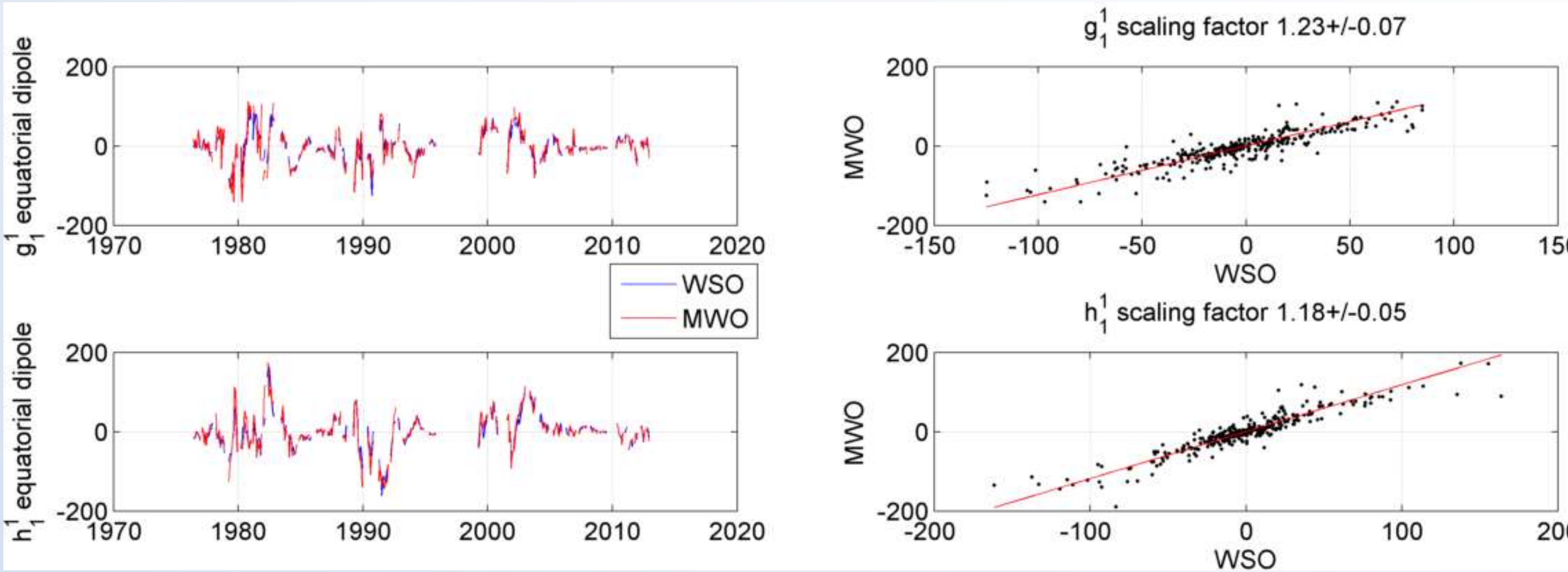
- Equatorial dipoles show very similar behaviour in all data sets.
- WSO and MWO indicate roughly same magnitude, other data (with different spectral line and higher spatial resolution) yield significantly larger values.

Scaling between data sets



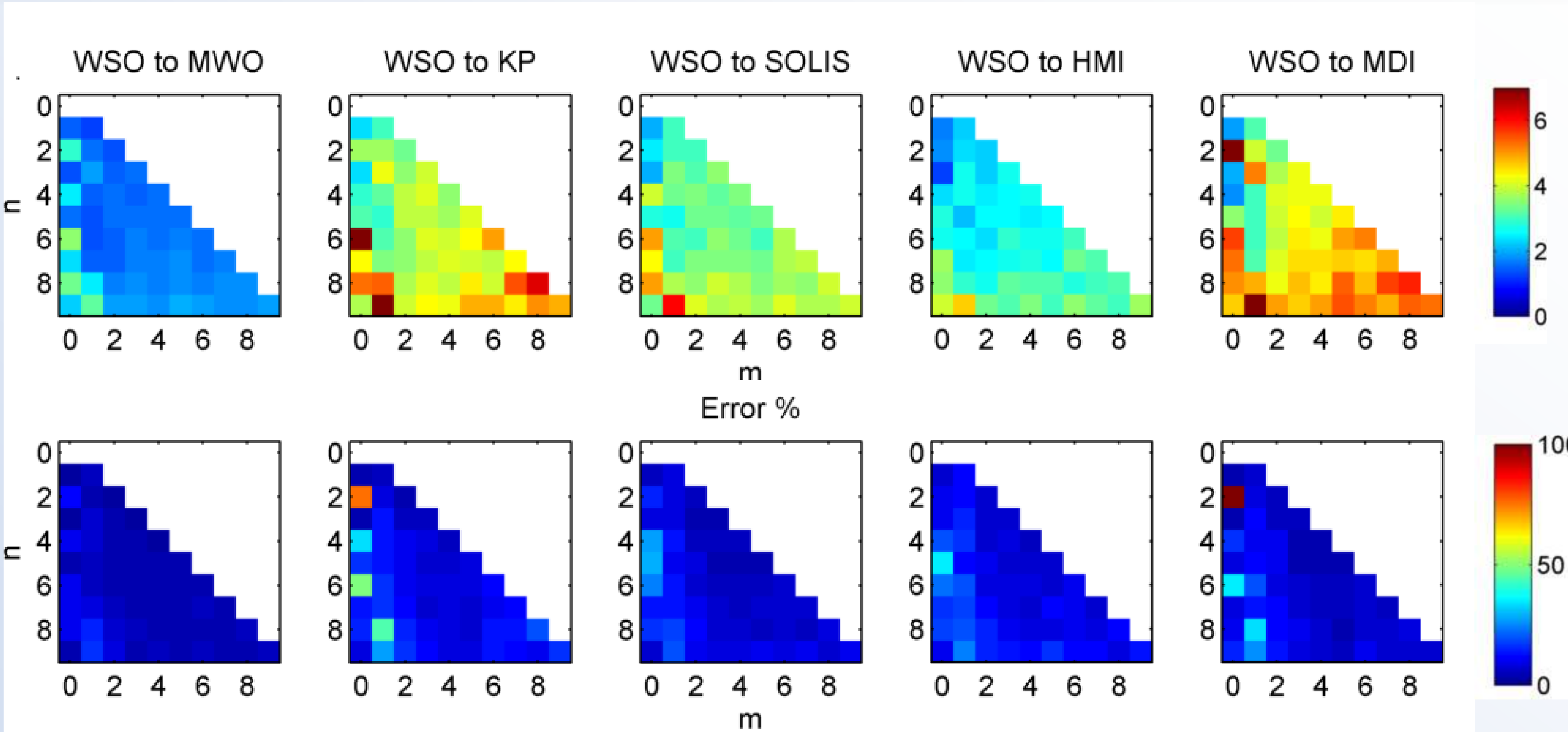
- Rotational values of axial dipole and quadrupole, using only synoptic maps without data gaps.
- Scatter plots and linear regression line indicate very stable scaling for dipole term.
- Error bars are much larger for quadrupole term, this relates to the multiple issues in polar field observations and data processing.

Scaling between data sets



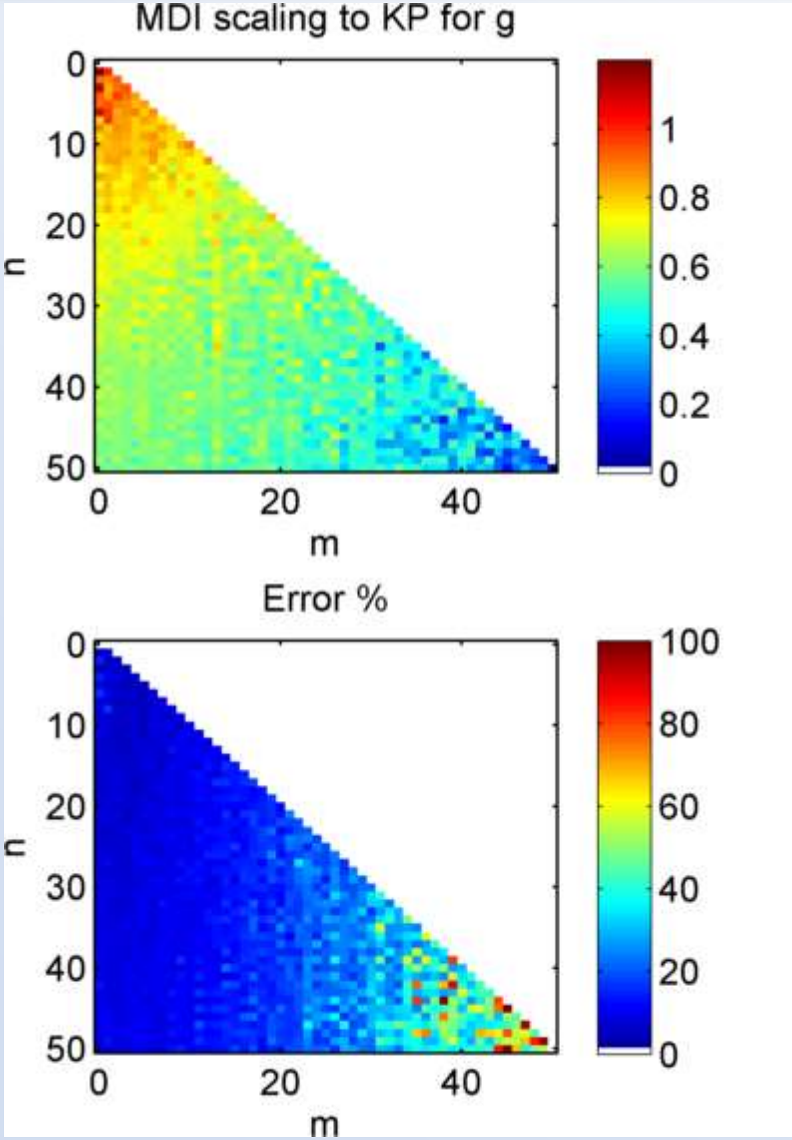
- Equatorial dipoles g_1^1 and h_1^1 scale very well and error bars are small.
- This indicates that active region observations in MWO and WSO agree very well

Scaling coefficients for g to WSO



- Coefficients with m =0 scale differently from others, which is due to the differences in polar field observations.
- Scaling factors for dipole term, which is the most essential for coronal field, is less than 3 for all data sets.

Limitations in g and h scaling



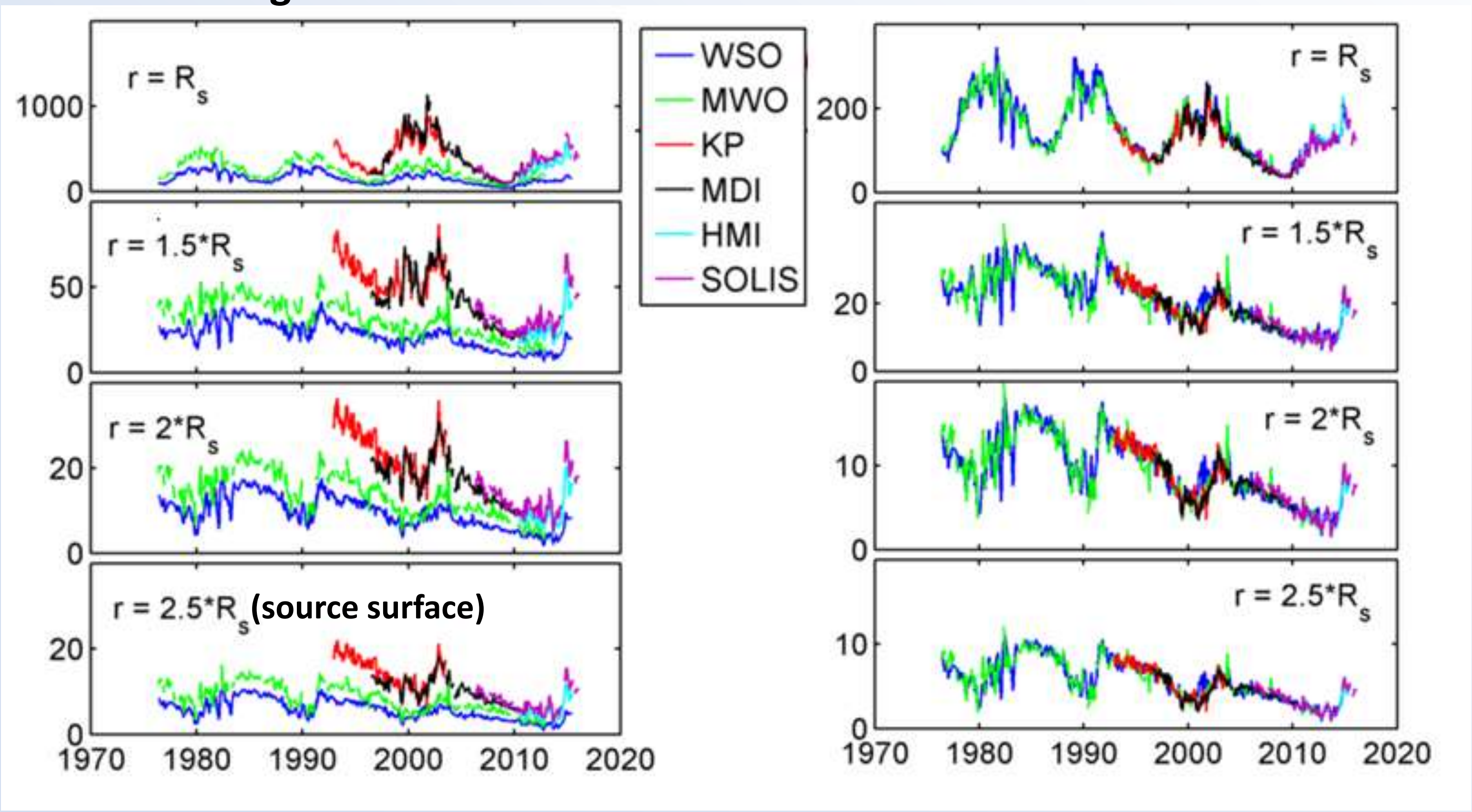
Thanks to Iiro Virtanen

- High resolution observations allow to use larger n_{max}
- MDI to Kitt Peak scaling using data from CR 1916 – 2006 indicates that scaling factors are functions of m and n, but relative error seems to increase with m.
- Increasing error bars corresponds to a large scale structure size, beyond m = 30 MDI and KP synoptic maps do not depict similar structures.

Example:
Unsigned magnetic flux density |Br|

- Magnetic field between photosphere and corona derived using PFSS-model (n_{max}=9), first with original synoptic maps and then with scaled maps.
- Unsigned magnetic flux density |Br| at four different altitudes.

Original data **Scaled data**



Conclusions

- Six magnetograph data sets depict similar large scale structures, but scaling is in general different.
- Multipole expansion offers a good method to scale observations using scaling between harmonic coefficients.
- Scaling is relevant up to certain limit (m = 30?) which corresponds to a scale where different synoptic maps still depict similar structures.
- Scaling factors based on histogram techniques should not be used for scaling before applying harmonic expansion, because that leads to largely overestimated coronal magnetic flux densities.

Virtanen I.I., and K. Mursula, Photospheric and coronal magnetic fields in six magnetographs, Consistent evolution of the hemispheric asymmetry, A&A in press, 2016.

Virtanen I.I., and K. Mursula, Photospheric and coronal magnetic fields in six magnetographs, Scaling of photospheric magnetic field observations, in preparation 2016.