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ICTP-COST-USNSWP-CAWSES-INAF-INFN
International Advanced School
on
Space Weather
2-19 May 2006

Solar Activity: Exploration with Wavelets

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The Sun: Space Weather Applications

2) Solar activity: Exploration with wavelets

ICTP-COST-CAWSES-INAF-INFN, Trieste, 2006

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Swedish Institute of Space Physics,
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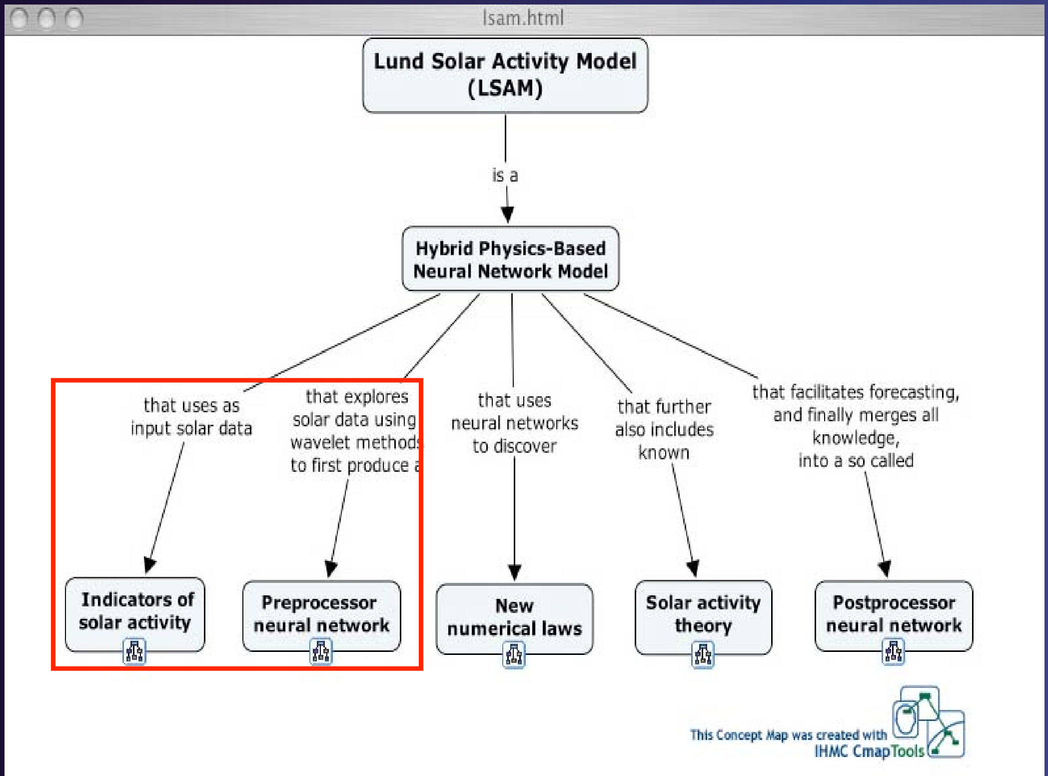
Outline of my second talk

- Lund Solar Activity Model
- Wavelet methods (scalograms, ampligrams, MRA, wavelet power and wavelet coherence)
- Methods applied on solar activity indicators
- Transients, cycles, trends discussed

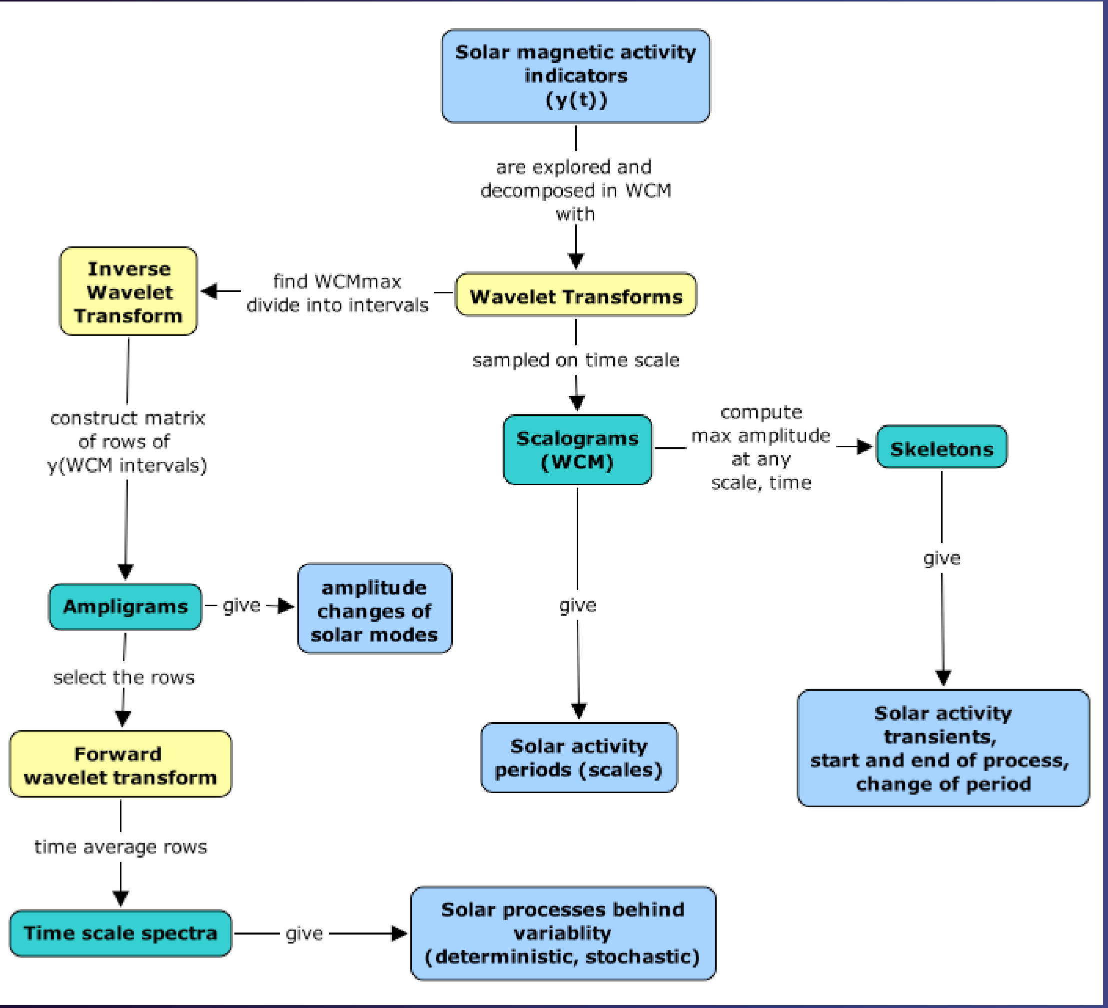
Lund Solar Activity Model (LSAM)

The goal of our research program is to create a new indicator (model/LSAM) of solar magnetic activity so we can better predict space weather, space climate and effects. Wavelet methods are used to extract information about solar magnetic activity (e.g. trends, transients, about Bp, Bt, AR), which then will be used as input to our neural network prediction model.



(Lundstedt, H., Adv in Space Res., 37, 2006)

Wavelet Methods



Wavelet transform, Morlet wavelet, and Wavelet Coefficient (WCM = Wavelet Coefficient Magnitude)

$$w(a,b) = a^{-1/2}\int_{-\infty}^{+\infty} y(t)g^*\left(\frac{t-b}{a}\right)dt$$

$$g(t) = \exp(i\omega_0 t - \frac{t^2}{2})$$

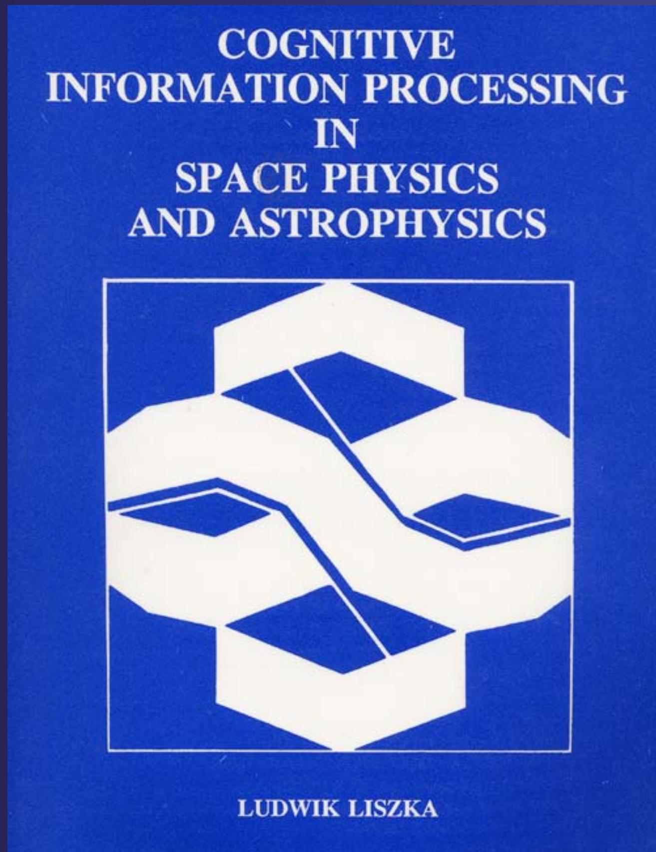
$$w_{j,k} = j^{-1/2}\int_{-\infty}^{+\infty} y(t)g^*\left(\frac{t-k}{j}\right)dt$$

Lundstedt, H., Liszka, L. and R. Lundin,:Solar activity explored with new wavelet methods, Annales Geophysicae, 23, 1505-1511, 2005

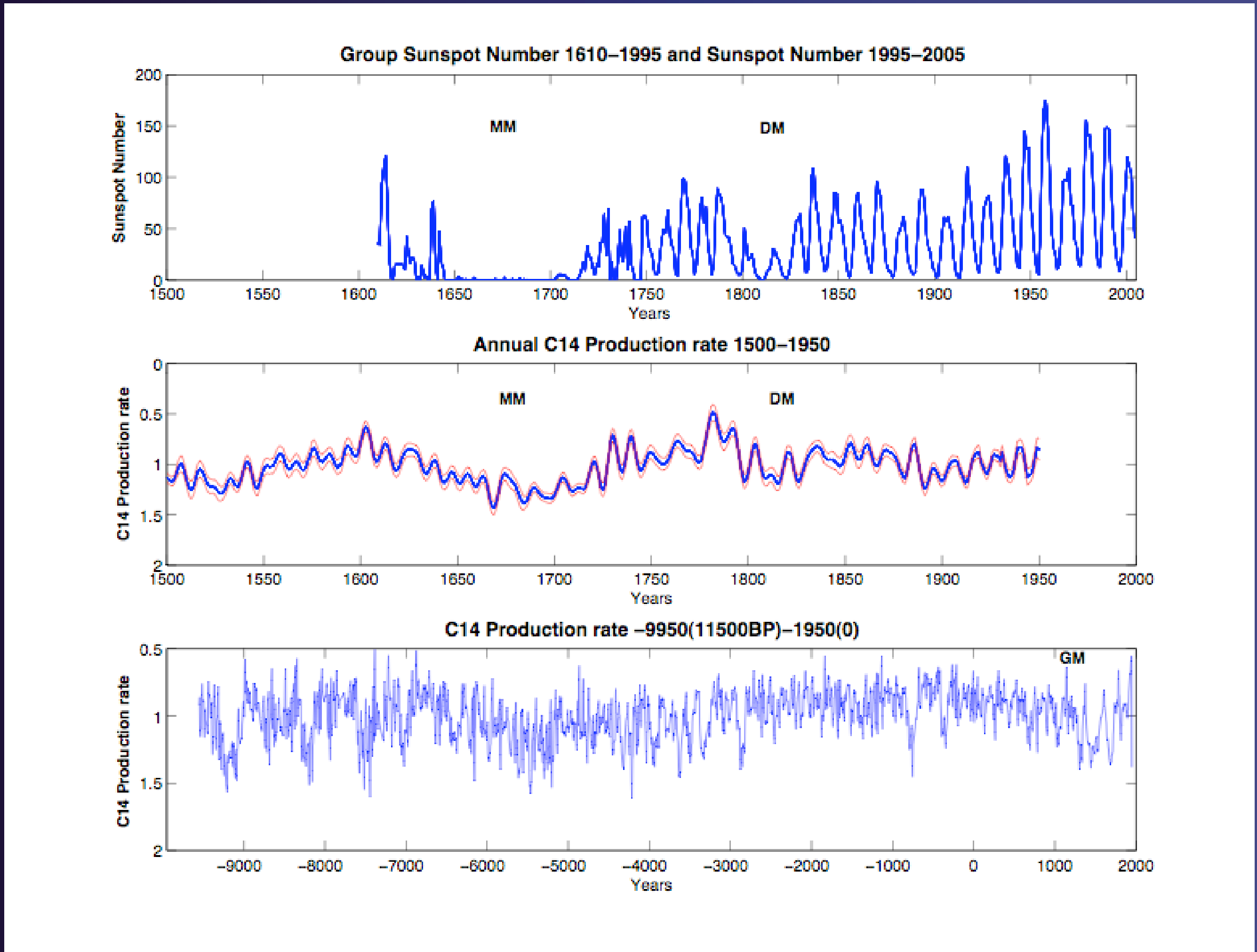
Wavelet Methods
(Liszka and Wernik)

Download software

www.irf.se (Umeå,Lund)

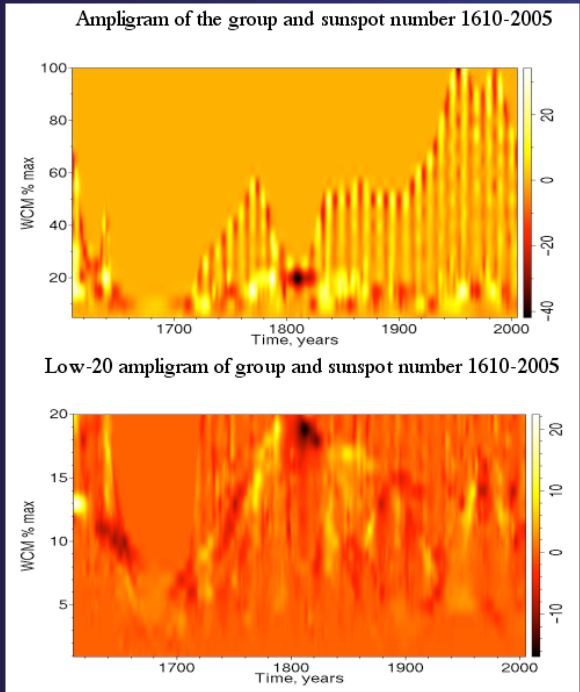


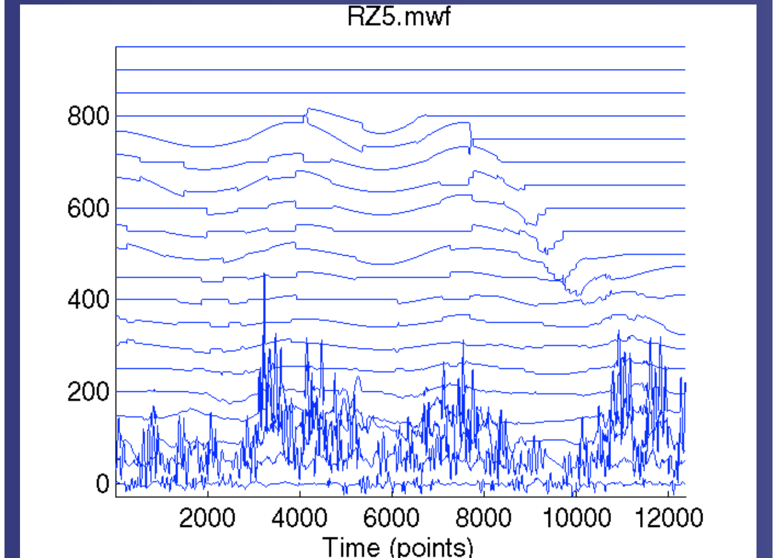
Indicators: Rg/Rz
C14 production rate



Trends in Sun's 4.6 billion years activity based on studies of, 400 years observations of sunspot number (toroidal field) and 11500 years of C14 production rate (poloidal field) values.

Sunspots



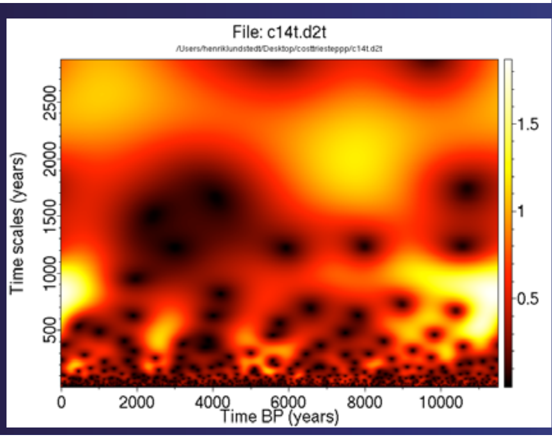


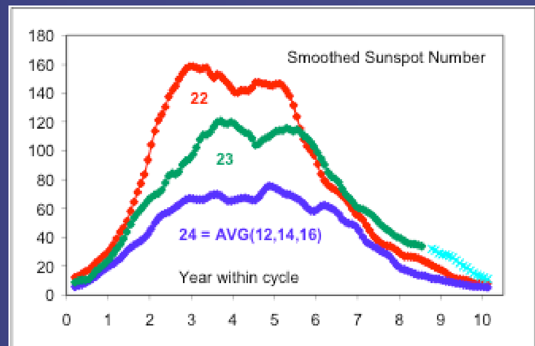
Solar activity seems to be characterized by oscillations of different scales that arise and die, no ever lasting cycles.

C14 production rate

2300-2500 y-->

900-1100 y-->
400-500 y-->
190-210 y-->



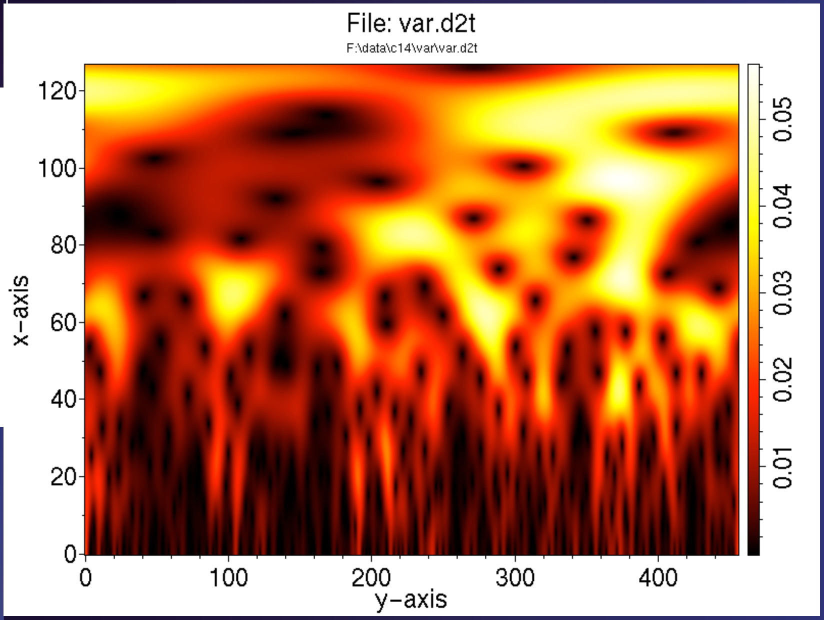


Svalgaard. et al., 2005, Predict a weak Cycle 24.

Scalogram of VAR(C14 production rate) Maunder minima, year 2100 activity

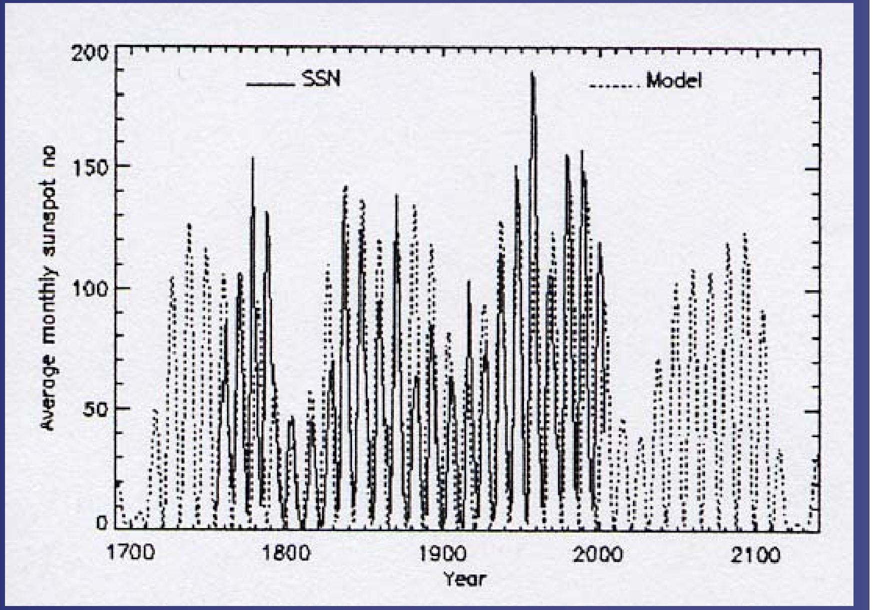
Time Scale

450 y



Time elapsed (25x years)

Lundstedt et al., 2005



Clilverd, et al., Astron & Geophys. 44, 2003

Scalograms and Skeletons of an Ampligram of Rg

Multiresolution analysis

Multiresolution analysis (MRA): the idea is to separate the information to be analyzed into a "principal" (low pass) and a "residul" (high pass) part. The process of decomposition can then be applied again to both parts.

Engineers' filter approach

$$s = A_J + \sum_{j \le J} D_j$$

$$A_{J-1} = A_J + D_J$$

$$D_j(t) = \sum_{k \in Z} C(j,k)\Psi_{j,k}(t)$$

$$C(a,b) = \int s(t)\frac{1}{\sqrt{a}}\Psi\left(\frac{t-b}{a}\right)dt$$

$$a = 2^j, b = k2^j, (j,k) \in Z^2$$

(s = signal, A = approximation, D = detail, a = scale, b = time shift, j = level)

Mathematicians' wavelet matrix approach

$$f(x) = \sum_{k=-\infty}^{\infty} c_k\varphi_k(x) + \sum_{s=1}^{m-1}\sum_{j=0}^{\infty}\sum_{k=-\infty}^{\infty} d_{jk}^s\psi_{jk}^s(x),$$

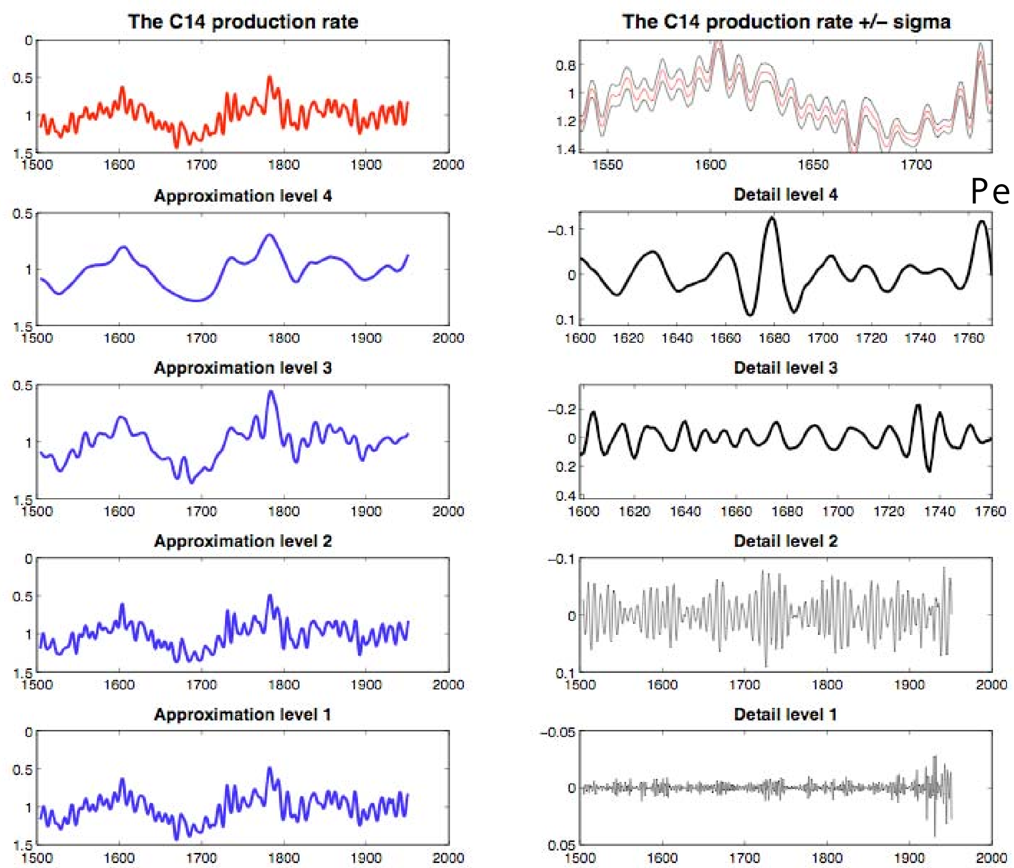
$$c_k = \int_{-\infty}^{\infty} f(x)\varphi_k(x)dx$$

$$d_{jk}^s = \int_{-\infty}^{\infty} f(x)\psi_{jk}^s(x)dx$$

$$f'(x) = \sum f_k\varphi'(x) + \sum f_{jk}\psi'_{jk}(x)$$

Wavelets are to functions what the positional notation is to numbers. Solving differential equations may then be carried out by differentiating the function represented by the wavelet series.

C14 production rate shows variation of the poloidal field (PF). During Maunder minimum the toroidal field (TF) didn't exceed a certain threshold and therefore no sunspots



P-Period

22y

11y

5.5y

2.5y

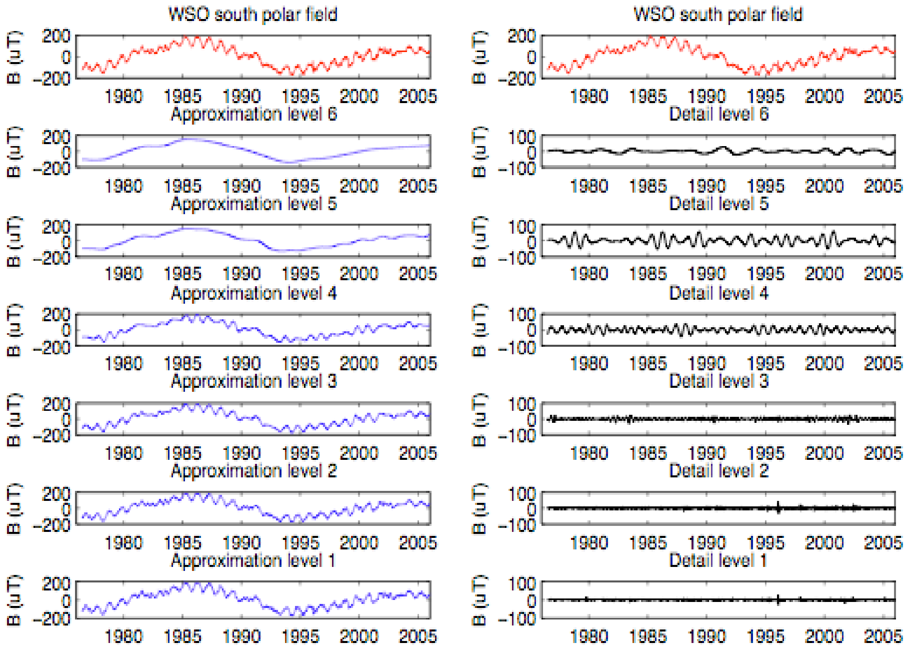
C14 shows the variation of the poloidal field. (Be10, Beer et al., 1998)

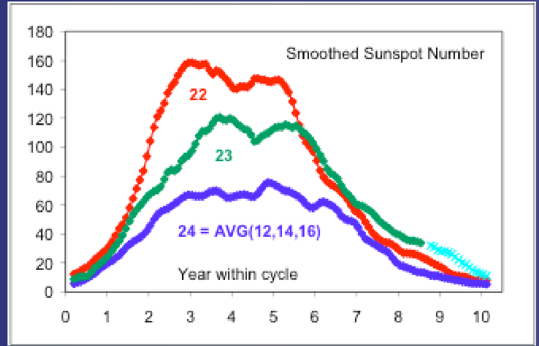
We also see high solar activity about 1600 and in the end of 1700, not seen in Rg.

Lundstedt, H. Liszka, L., Lundin, R. and R. Muscheler, Long-term solar activity explored with wavelet methods, Annales Geophysicae 24,1-9 2006

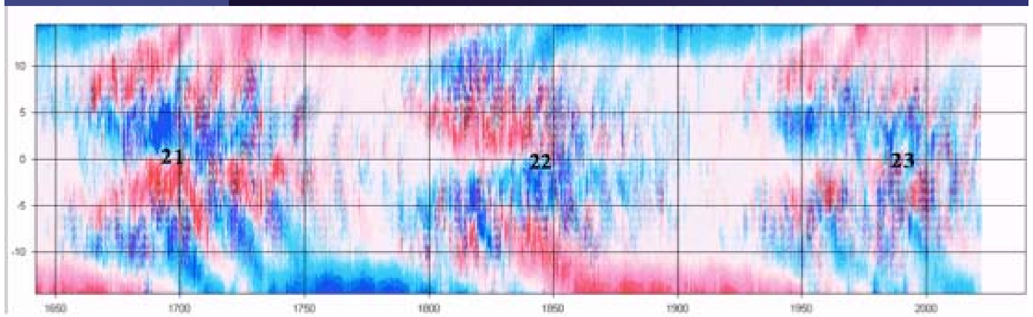
MRA of WSO polar magnetic field

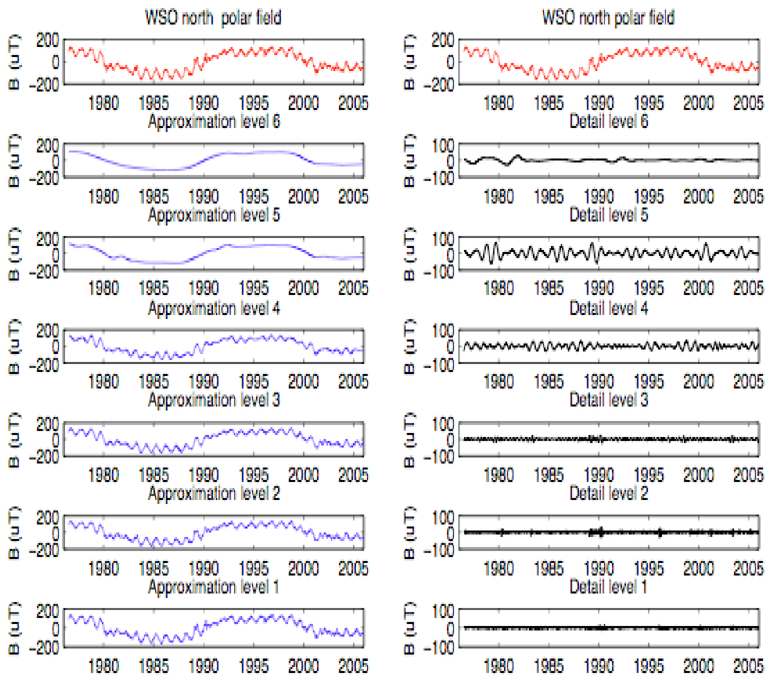
Precursor of next "cycle 24 maximum"





Svalgaard. et al., predict a weak Cycle 24.

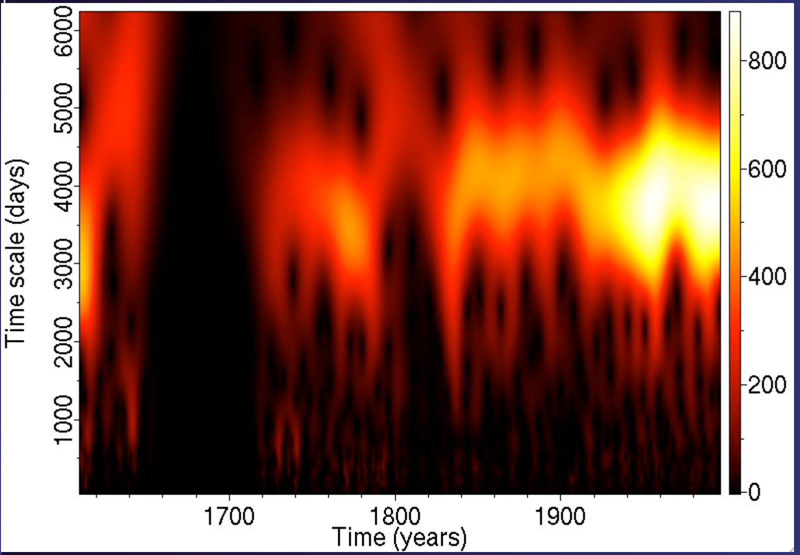


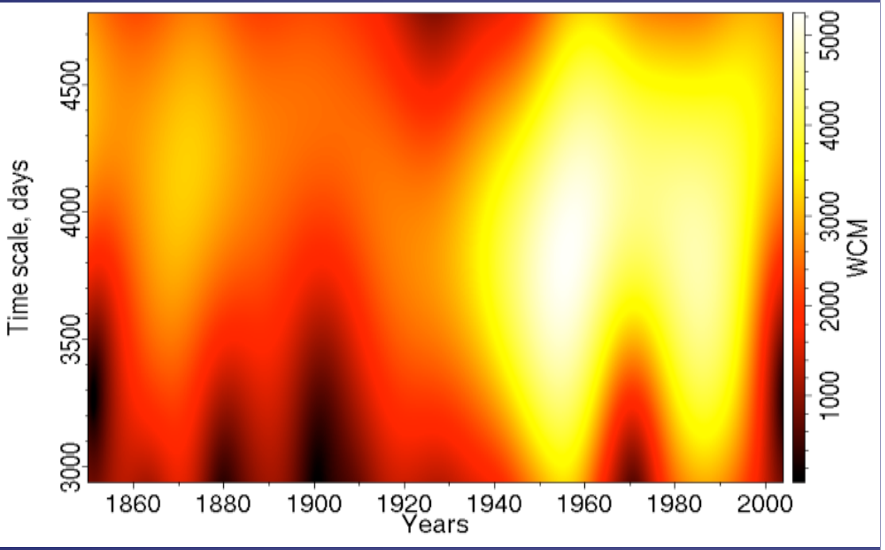


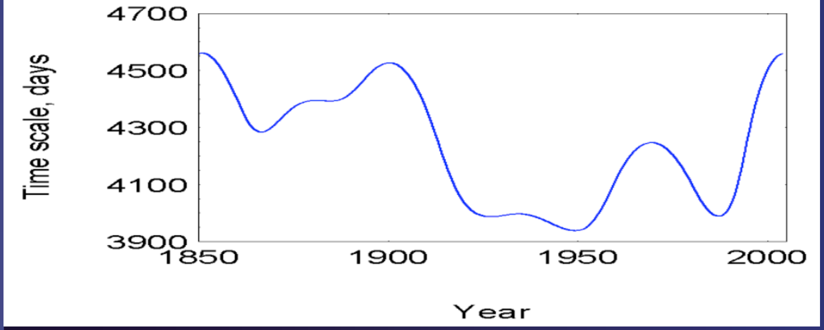
Solar cycle length (time scales) Vs. solar activity (WCMmax)

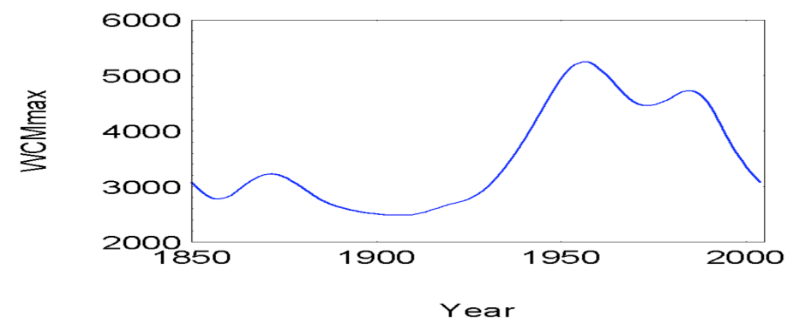
$$R_G = \frac{12.08}{N} \sum k_i G_i$$

$$R_z = k(10g+f)$$



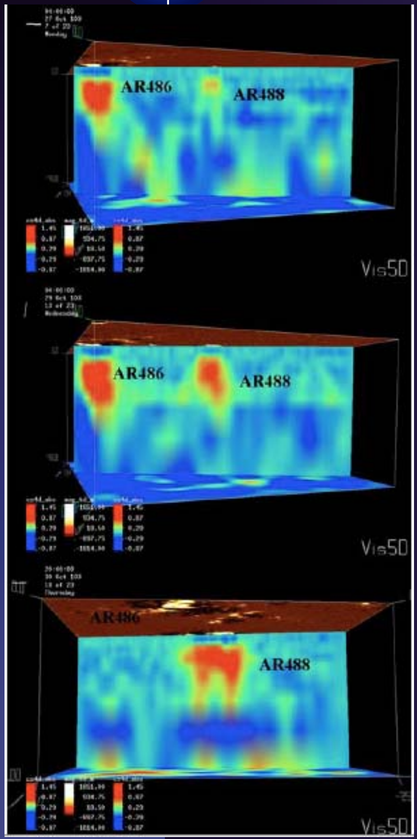




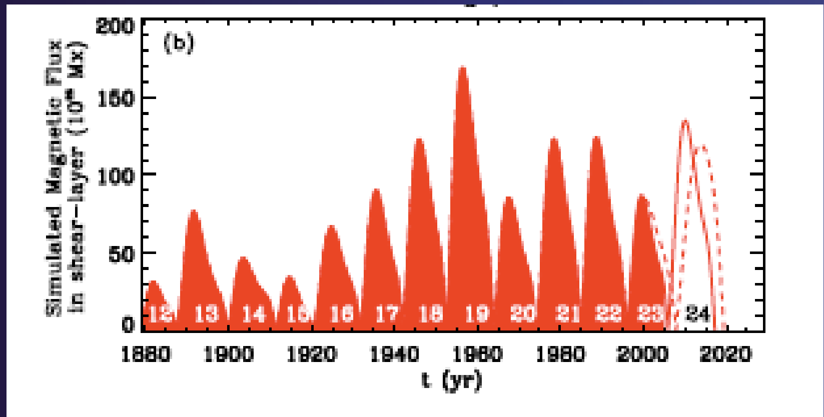


(Lundstedt et al., Annal. Geophys., 2004)

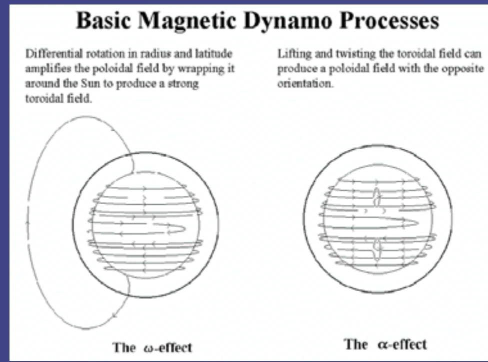
Different view on next "cycle 24"

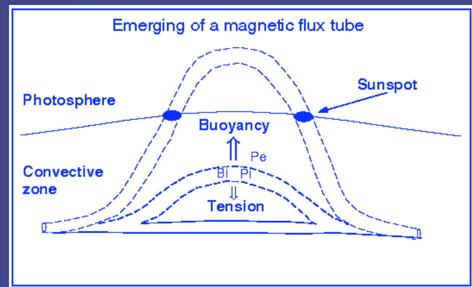


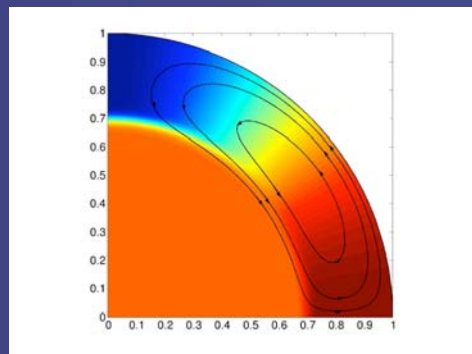
Kosovichev, A.G, IAU Symp., 223, 2004



Dikpati, Toma, Gilman, GRL, 33, 2006
State of the art α ω transport dynamo





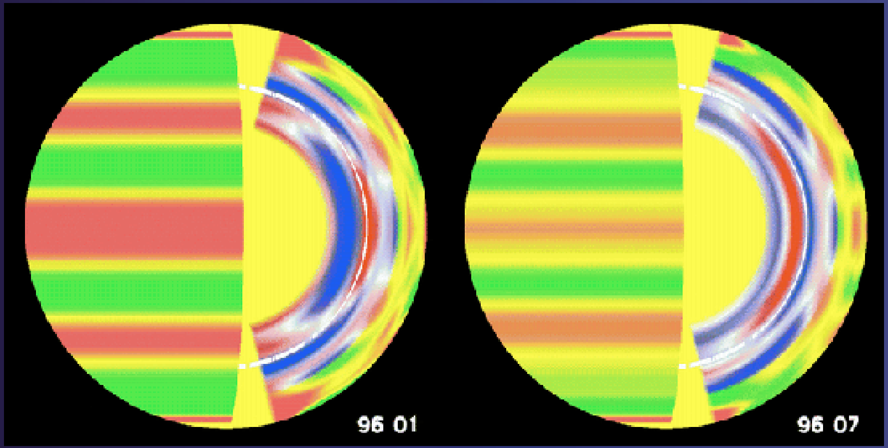


Predictions of cycle 24
NASA plans to arrange a prediction panel meeting on cycle 24

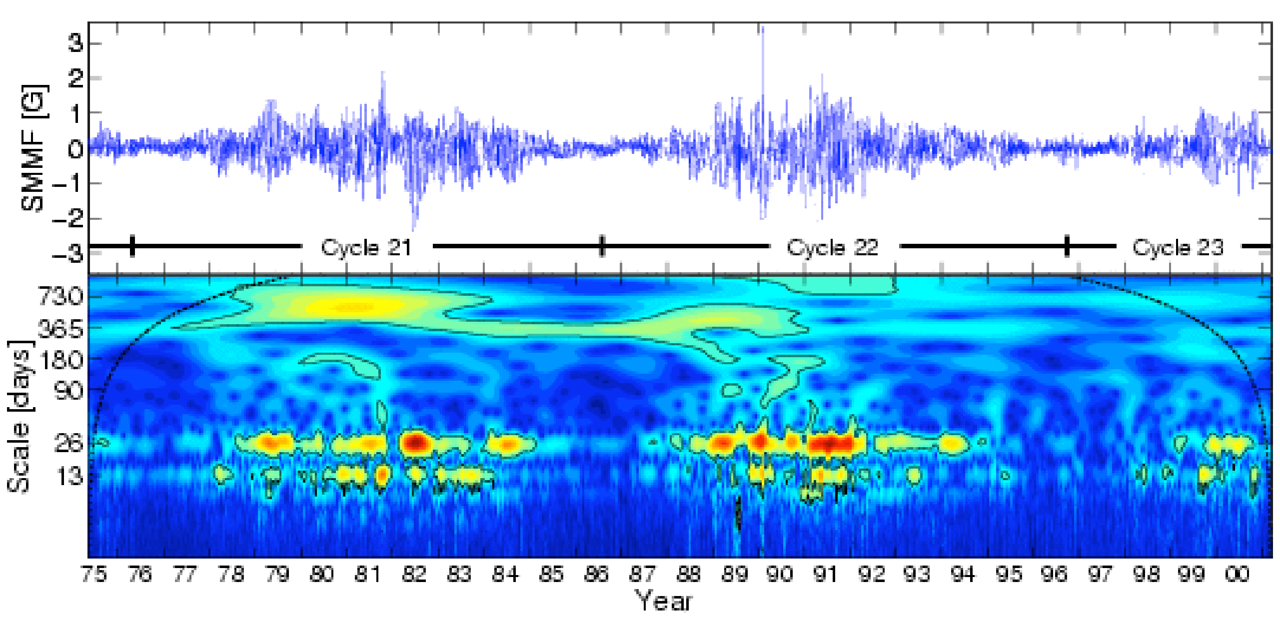
Predictions of cycle 24

- D. Hathaway (**strong cycle**), based on the assumption that a fast meridional circulation speed during cycle 22 would lead to a strong solar cycle 24.
- G. Ali et al., (Rz = 145 (2011-2012)),based on spectral analysis and neurofuzzy modeling.
- K. H. Schatten (Rz = 100±30), based on the view that the Sun's polar field serves as a predictor of solar activity on the basis of dynamo physics.
- J-L. Wang et al,, (Rz = 83.2-119.4), based on statistical characteristics of solar cycles.
- Kane, R. P. (Rz= 105), based on statistical regression analysis of the sunspot number and geomagnetic activity.
- S. Duhau (Rz= 87.5±23.5), based on a non-linear coupling function between sunspot maxima and aa minima modulations found as a result of a wavelet analysis.
- L. Svalgaard et al., (Rz = 75±10), based on the solar polar magnetic field strength at sunspot minima.
- Badalyan et al., (Rz not exceeding 50), based on statistical characteristics of solar cycles.
- G. Maris, et al., (low), based on observing the flare energy release during the descendant phase of cycle 23 (empirical method).
- M. Clilverd et al., (**weak cycle**), based on the variation of the atmospheric cosmogenic radiocarbon.

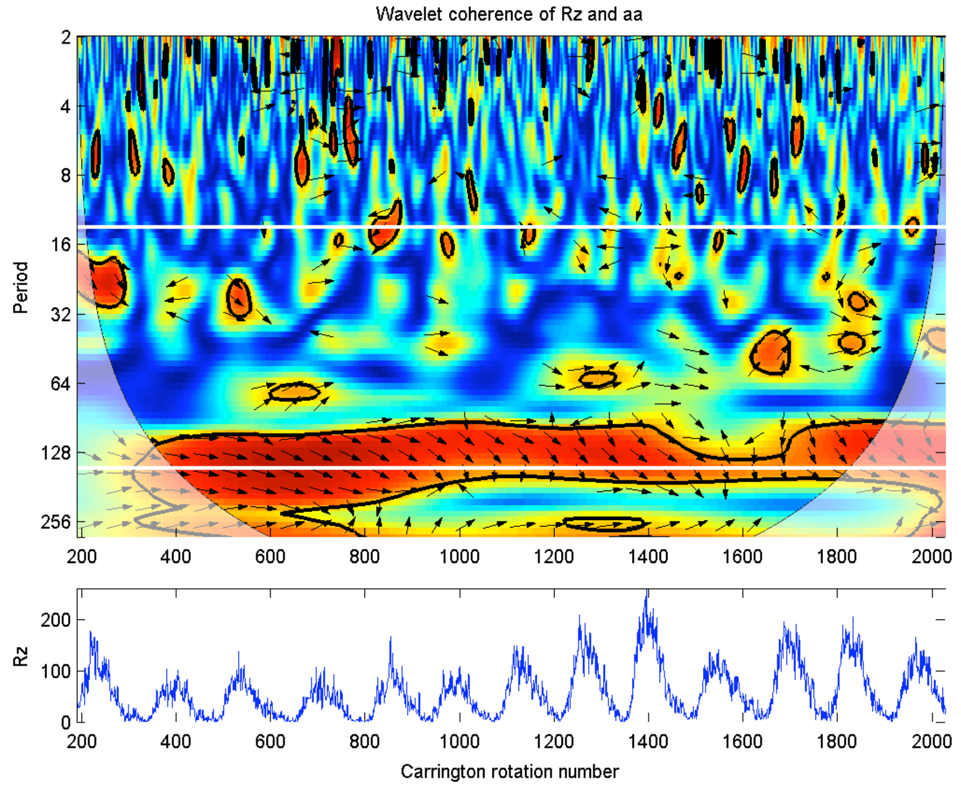
Wavelet power spectra
WSO meanfield



MDI shows how the dynamo changes (1.3y)



Wavelet coherence
Rz/aa



The wavelet approach allows us to study time-varying co-variation at different scales between two signals using wavelet coherence (*Grinsted et al.*, 2004). The wavelet coherence is defined as

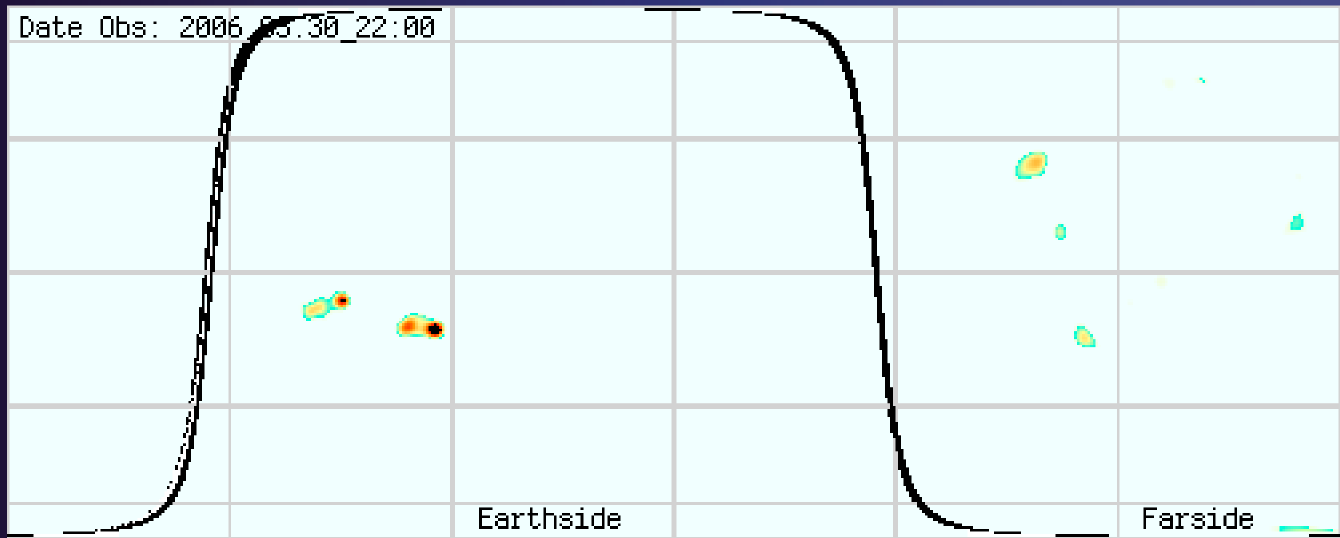
$$R_n^2(s) = \frac{|S(s^{-1}W_n^{XY}(s))|^2}{S(s^{-1}|W_n^X(s)|^2)S(s^{-1}|W_n^Y(s)|^2)} \quad (5)$$

where s is the scale, n the sample index of time series X and Y, S is a smoothing operator, W_n^X and W_n^Y are the wavelet coefficients for the two time series, respectively. The cross wavelet transform is defined as

$$W^{XY} = W^X W^{Y*} \quad (6)$$

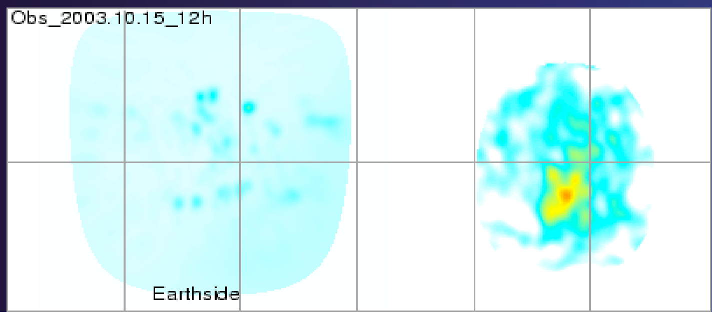
where $*$ denotes the complex conjugate.

Magnetic maps of the WHOLE Sun
SOHO/MDI/Stanford/P. Scherrer

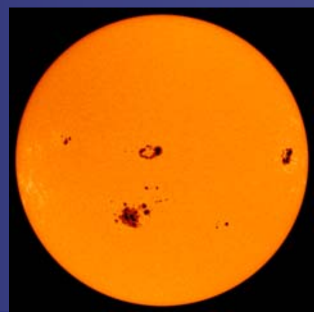


Farside images computed from MDI sound travel time analysis.
Earth-side images are magnetic flux observed by SOHO-MDI.
These files are updated daily!!

14-15 Oct, 2003



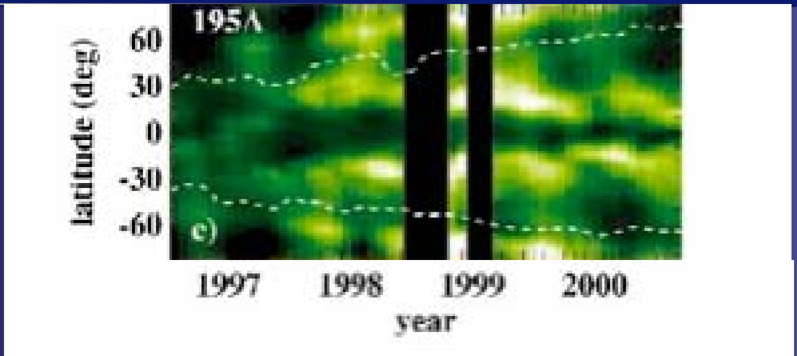
30 Oct, 2003



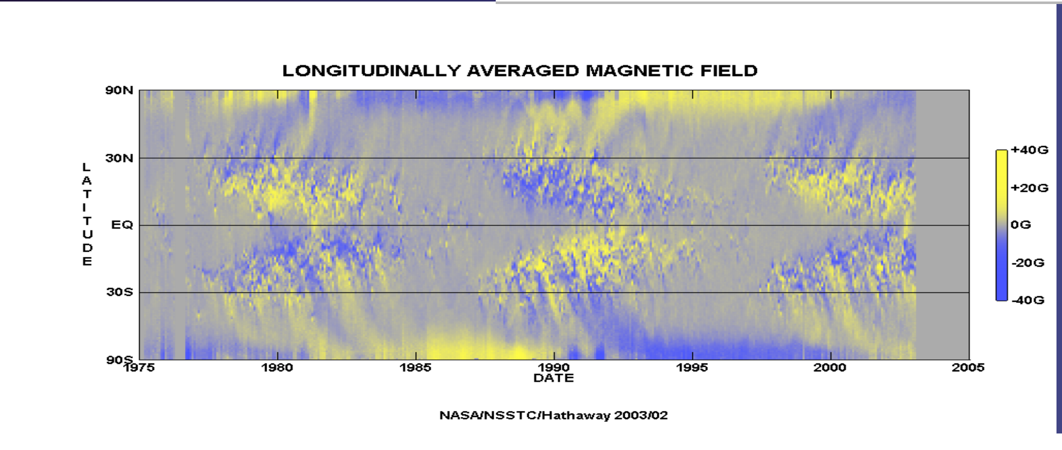
CR averaged synoptic maps give the long-term variation of the whole Sun's state (3D)

The Corona

(Courtesy: Benevolenskaya, E. et al., ApJ, 2001)

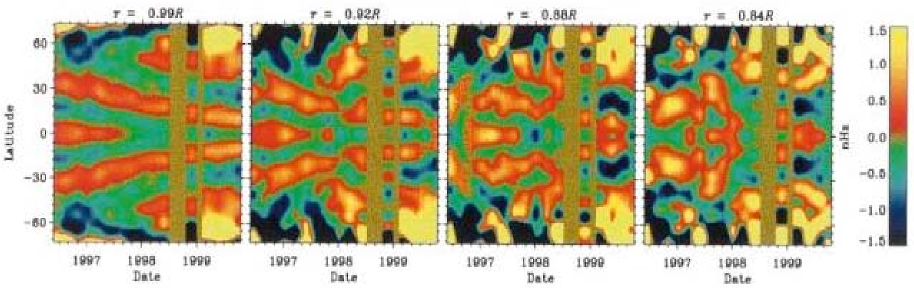


Solar surface

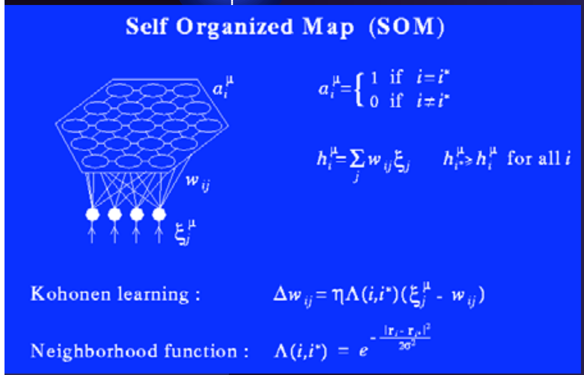


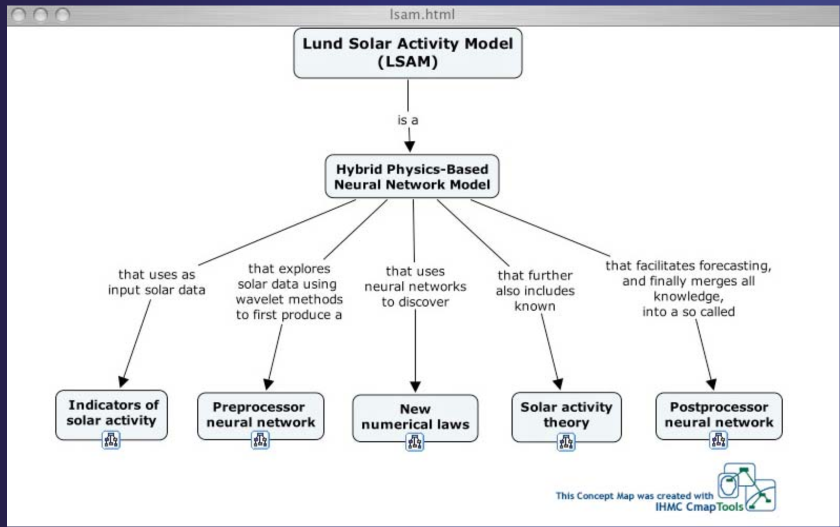
Subsurface

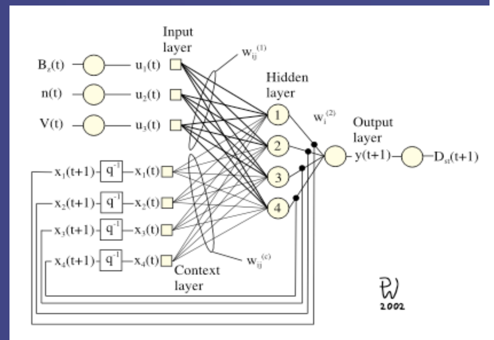
(Courtesy: Howe et al., 2000 and GONG)

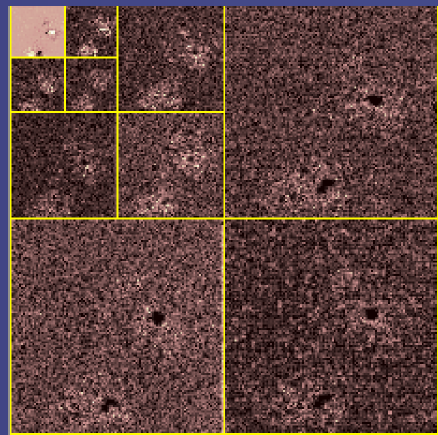


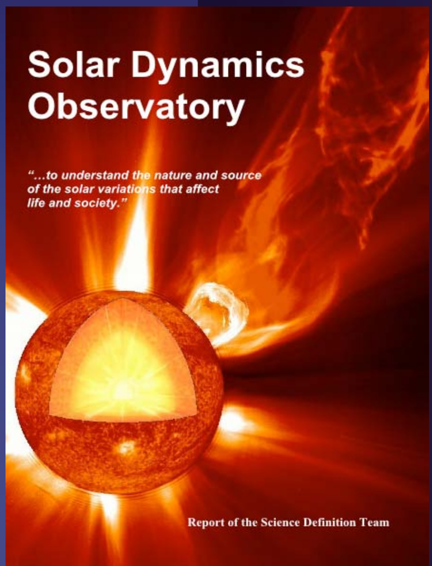
The final goal: to put this new picture into a hybrid physics-based neural network prediction model





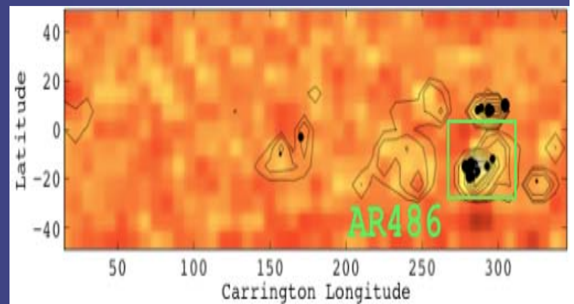






• Neural network based real-time forecasts are allready running at our RWC of ISES of many space weather effects. We are now presenting the wavelet outputs to neural networks.

• However, we also need real-time synoptic maps of activity below, on and in corona and that will not be available until SDO (NASA, launch 2008)



Solar Activity: Exploration, Understanding and Prediction Workshop in Lund September 19-21, 2005 (www.lund.irf.se/workshop/)

Participants not on photo: Krister Bengtson (E.ON,Sweden), Axel Brandenburg (Nordita,Denmark), Alexi Glover (ESA/ESTEC), Alain Hilgers (ESA/ESTEC), Christian Jacobsson (E.ON,Sweden), Nina von Krusenstierna (Aerotech, Sweden), Rickard Lundin (IRF-Umeå), Nigel Marsh (DNSC,Denmark), Gunilla Sundberg (E.ON,Sweden), Henrik Svensmark (DNSC,Denmark) and Bo Thidé (IRF-Uppsala).

THE END

of

Second Talk