# Neural Network Prediction of Solar Cycle 25

## Abstract

The ability to predict the future behavior of solar activity has become of extreme importance due to its effect on the near-Earth environment. Predictions of both the amplitude and timing of the next solar cycle will assist in estimating the various consequences of Space Weather. Several prediction techniques have been applied and have achieved varying degrees of success in the domain of solar activity prediction. These techniques include, for example, neural networks and geomagnetic
precursor methods. In this, various neural network based models are developed and the model considered to be optimum was used to estimate the shape and timing of solar cycle 24. Given the recent success of the geomagnetic precursor methods, geomagnetic activity as measured by the aa index is considered among the main inputs to the neural network model. The neural network model developed is also provided with the time input parameters defining the year and the month of a particular solar cycle, in order to characterise the temporal behaviour of sunspot number as observed during the last 12 solar cycles. The structure of input-output patterns to the neural network is constructed in such a way that the network learns the relationship between the aa index values of a particular cycle, and the sunspot number values of the following cycle. This prediction model estimated an average solar cycle 24, with the maximum occurring around July 2012 [± 11 months], with a smoothed monthly maximum sunspot number of 125 ± 18.

The next step to this is to compare various models developed already for solar cycle 24 and predict the next solar cycle, i.e. solar cycle 25 predicted to start in early 2020. Moreover, incorporating inputs like solar flux and magnetic activity at solar equator and poles from a dynamo model could lead to better results and would be the next thing in line.

## Theoretical Background

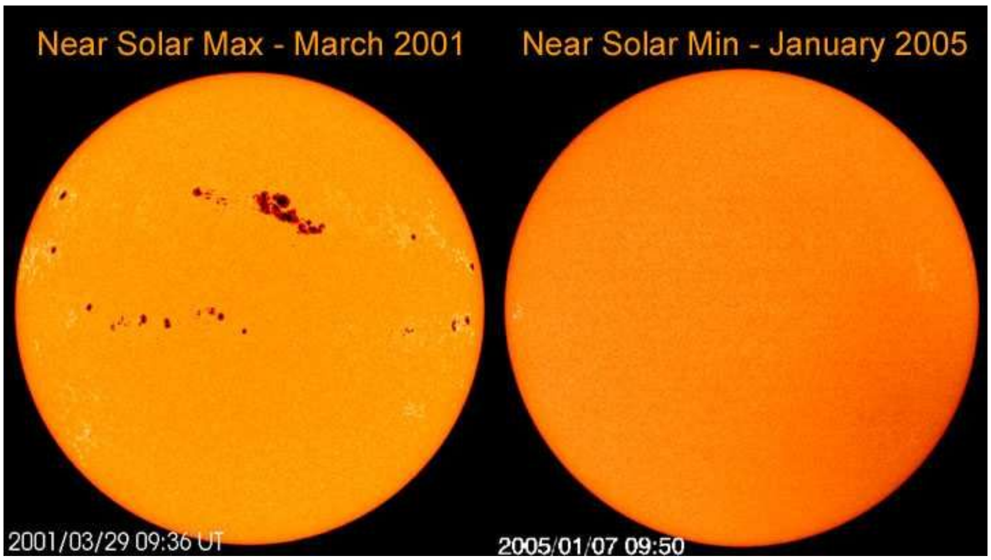
### Sunspots and the solar activity cycle

Sunspots are dark spots observed on the solar surface. First European observations were made by Galileo in 1610 soon after the invention of the telescope. A measure of the sunspots which show an 11-year cyclic variation represents a common indicator of solar activity. This cyclic variation of sunspots, known as the Solar Cycle (SC), was first discovered by Samuel Heinrich Schwabe in 1843 through extended observations of sunspots. The Sunspot Number (SSN) was introduced by a Swiss astronomer Rudolf Wolf in 1848, who reconstructed back to 1700 the evident presence of the 11-year cycle in the number of sunspots.

The relative sunspot number (R), is generally called the International Sunspot Number and is defined according to Conway by the equation:

$R = k(10g + f)$

where f is the number of individual spots, g is the number of groups, and k is a standardisation factor depending on observational conditions. The number of spots varies with an 11-year period on average. From one cycle to another, variations in SSN amplitude are also observed.




The above figure is an Illustration of solar maximum and minimum periods. Very few or the absence of sunspots on the solar disc are observed near solar minimum. A large number of sunspots correspond to the period of high solar activity. [Images courtesy of SOHO; retrieved from: www.windows.ucar.edu/sun/solar variation]

The modern understanding of sunspots is that the sunspot cycle is closely related to the magnetic structure of the Sun. In 1908, the American astronomer G. E. Hale suggested a 22 year solar magnetic cycle where the sun's dipolar magnetic field reverses every 11 years. Therefore, for modelling purposes, at least 22 year's worth of data is required.

## Space Weather

Solar activity is the dynamic energy source behind all solar phenomena driving Space Weather (SW). During an active solar period, violent eruptions occur more often on the Sun. Solar flares and vast explosions known as Coronal Mass Ejections (CMEs) shoot energetic and highly charged particles towards Earth. The ensuing ionospheric and geomagnetic disturbances greatly affect power grids, critical military and airline communications, satellites, Global Positioning System (GPS) signals and may even threaten astronauts with harmful radiation. The same storms illuminate night skies with brilliant sheets of red and green known as aurorae or northern and southern lights (http://www.noaa.gov; http://www.sec.noaa.gov). All these phenomena are most frequent near the maximum of each 11-year cycle of solar activity.

The Maunder minimum (1645-1715) refers to a period when very few sunspots were observed. During this period, the Earth's climate was cooler than normal.This period mimics the solar cycle climate change connections and is the subject of many studies. As indicated by Sello (2001), the particles and electromagnetic radiation flowing from solar activity outbursts are important for long term climate variations.

## Sunspot equilibria

The Sun's magnetic field is due to the movement of its plasma. As the solar plasma moves, any magnetic field line is pulled along with it: the magnetic field lines are frozen into the solar material. The Sun's magnetic field can therefore exert a force on the solar plasma and create structures such as sunspots. The out- ward pressure of the strong magnetism from the Sun's interior do not expand nor disperse because the internal gas holds the magnetic fields together, concentrating and holding them within sunspots.

The interaction of plasma and the magnetic field can be modelled using the principles of magnetohydrodynamics (MHD), as summarized from Kivelson and Russell (1995):

MHD approximations provide us with two main reduced MHD equations, one for the plasma velocity u, and another for the magnetic field B. The induction equation:

$$\partial B/\partial t \;=\; \nabla \times (u \times B) \times \nabla^{2} B$$

where, $\eta = \frac{1}{\mu\sigma}$ is the magnetic diffusivity. In the above equation, the ratio of the first term to the second term on the right is the magnetic Reynolds number: $R_m = \frac{uL}{\eta} = \mu_0 \sigma u L$ which is enormous for solar phenomena (10 6 − 10 12 ) and L is a characteristic scale length for changes of the field and flow. Thus, the magnetic field is frozen into the plasma.

The second reduced MHD equation is the momentum equation:

$$\rho \frac{du}{dt} = -\nabla p + j \times B + \rho g$$

where j is the current density; p is the plasma pressure; ρ the plasma density and g is a constant representing the effect of gravity.

On the right hand side of the above equation, the first two terms represent the effects of the thermal pressure and the magnetic pressure and curvature. The magnetic force can be decomposed by writing:

$$j \times B = -\nabla\left(\frac{B^2}{2\mu_0}\right) + \left(\frac{B \cdot \nabla}{\mu_0}\right)$$

in which the first term on the right represents the effect of a magnetic pressure force acting from regions of high to low magnetic pressure [$p_B = B^2/2\mu_0$]. The ratio of the plasma pressure to the magnetic pressure is conventionally represented by the symbol β where:

$$\beta = \frac{p}{p_B}$$

In solar active regions, the magnetic forces are more dominant than the thermal pressure force. Equilibria of sunspots can be described by the force balance:

$$j \times B - \nabla p + \rho g = 0$$

Along the magnetic field, there is no contribution from the magnetic force and there exists a hydrostatic equilibrium between pressure gradients and gravity. In places like active regions, the magnetic field dominates, and the above equation reduces to:

$$j \times B = 0$$

and the fields are said to be force free.

As explained again in Kivelson and Russell (1995), a magnetic-flux tube below the surface tends to rise by the process of magnetic buoyancy. Lateral total pressure (plasma and magnetic) balance between the flux tube and its surrounding field-free region ($p_0$) implies that:

$$p + \frac{B^2}{2\mu} = p_0$$

and so: $p < p_0$. For smaller temperature differences, we can write $\rho < \rho_0$ .Hence, the flux tube is less dense than its surroundings and experiences an upward buoyant force. When the tube rises and breaks through the solar surface, it creates a pair of sunspots of opposite polarity as often observed.

The figure shows magnetic ropes breaking through the solar photosphere to form sunspots, appearing in pairs of opposite polarity. This illustration which compares a bipolar sunspot with a polar U-shaped polar magnet was done by Randy Russell using an image from NASA's TRACE satellite.[Image retrieved from: http://www.windows.ucar.edu/]

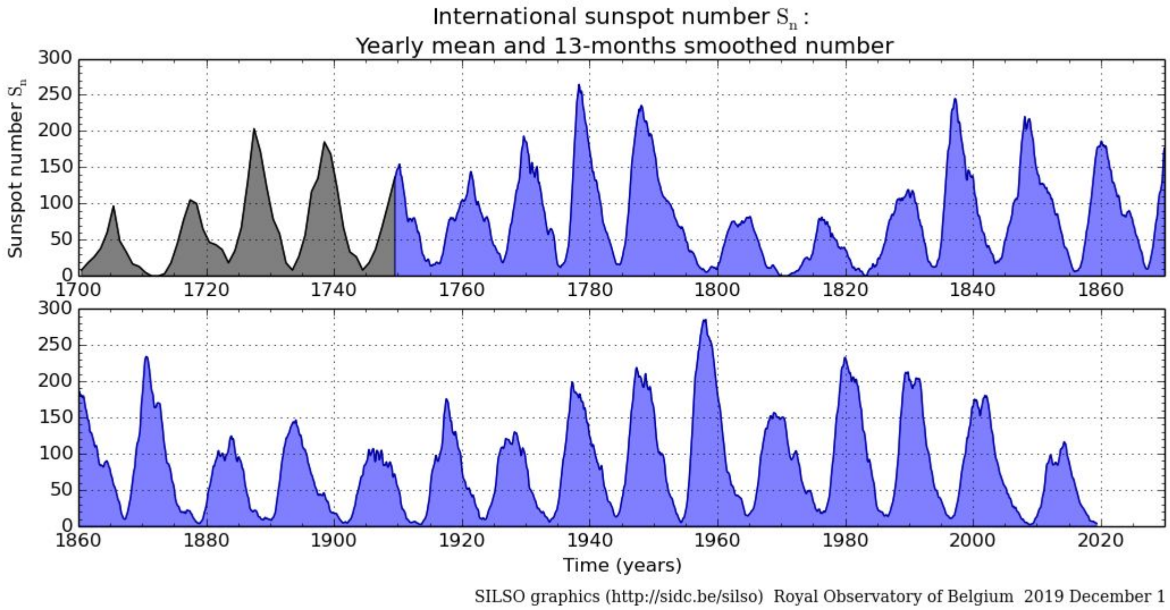
# The data: input - output parameters

One of the fundamental requirements for predicting using NNs is the determination of suitable input-output parameters for the learning process.

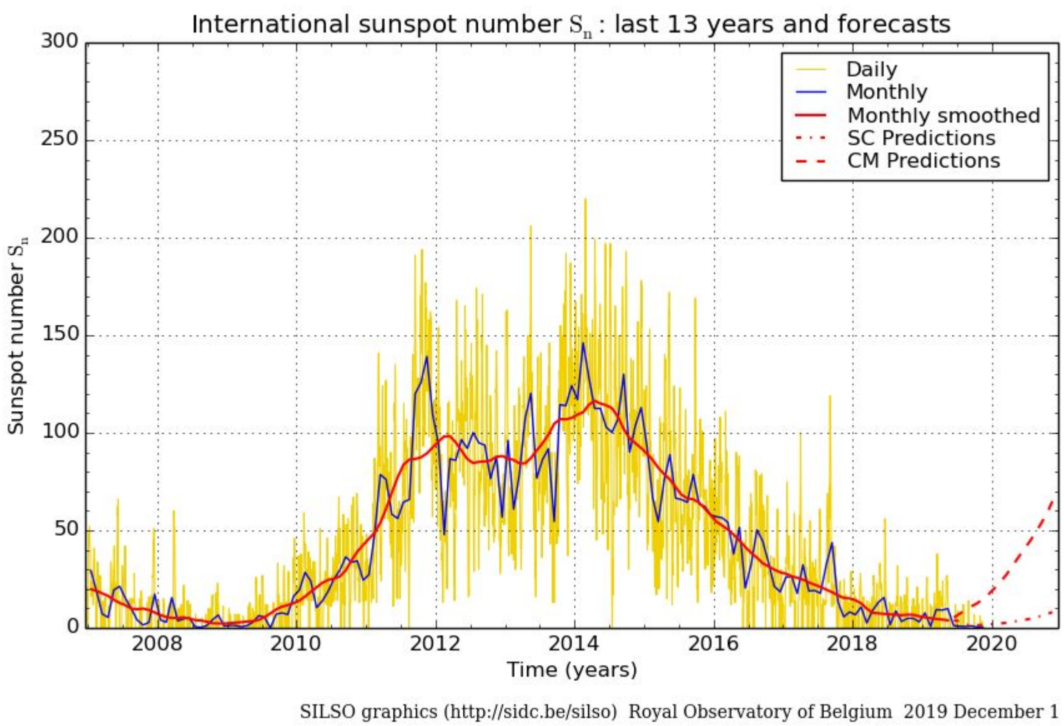
## International Sunspot Number

The relative sunspot number R introduced by R. Wolf in 1848 is the common measure of solar activity. Also known as Wolf's number or the International Sunspot Number (SSN), it is a standard daily index constructed from many measurements and the daily values are averaged monthly to remove the variations associated with the Sun's 27-day synodic rotation period.

Generally the index follows an 11-year cycle, but as can be seen from the figures below, the raw data exhibits complex variability in amplitude, shape and duration from cycle to cycle. These high fluctuations in sunspot numbers are mostly observed near solar maximum. It is this extreme variability which makes the SSN, one of the most difficult time series to predict.




The above is a plot of the average monthly SSN against time. An 11-year cyclic period is clearly seen, but the shape and amplitude of the SCs change from one cycle to another.




The above plot shows complex fluctuations in daily sunspot number during solar maximum.

The smoothed monthly SSN is commonly used to characterise the solar cycle maximum. Both the SIDC and NGDC provide smoothed monthly SSN data. This smoothing is done in order to minimise the short-term complex variations (even on a monthly scale) observed in the raw data. The often used smoothing function is the 13-month running mean defined by Conway (1998) as:

$$R_i^{smooth} = \frac{1}{13} \sum_{j=-6}^{6} R_{i-j}$$

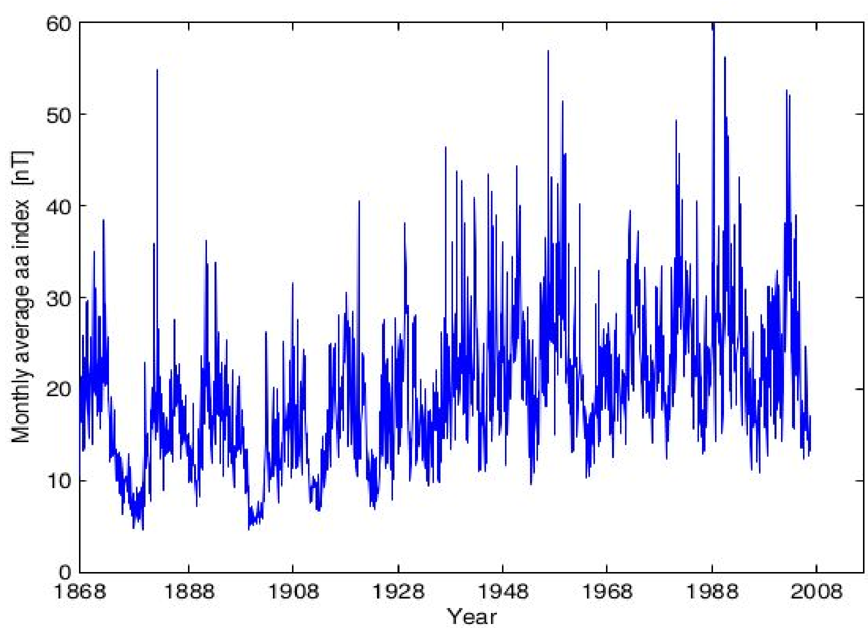
where i is the actual month to be smoothed, and j is the number of monthly average SSNs over which R i is calculated before and after the month of interest.

## Geomagnetic aa index

The geomagnetic aa index measures the global geomagnetic activity and provides one of the longest data sets which can be used in the analysis of solar terrestrial phenomena.

The aa index is a three-hourly global geomagnetic activity index determined from the K-indices scaled at two antipodal sub-auroral observatories, currently Hartland in UK, and Canberra in Australia. The three-hourly aa index is the mean of the northern and southern values, weighted to account for small differences in the latitudes of the two stations. In units of nT (nanoteslas), daily values of the aa index are computed from an average of 8 three-hourly values. The index strongly correlates with the Ap index which is derived using data from more extensive observatory networks.

The advantage of using aa indices for research purposes is the fact that the time series spans back to 1868, further than any other planetary index. The aa data appear (in units of nT) in the Solar Geophysical Data (SGD) reports of NOAA.




The above figure shows variation of aa index over various solar cycles.

## The time input parameters

The SSN temporal behavior is characterized by the parameters such as cycle minimum date, cycle maximum date, cycle maximum amplitude, cycle rise time to maximum as well as cycle fall time to minimum.

Assuming an approximate 11-year cycle, and considering the daily and monthly sunspot number data bases, time inputs characterising the year of a particular cycle (year index), the month number and day number in a particular year of the cycle, were defined. In order to accommodate the known periodicities and avoid discontinuities in the numerical values used to represent these time inputs, the cyclic components of month number, day number and year index were defined according to the work by Williscroft and Poole (1996) and McKinnell and Friedrich (2007), as follows:

$$YIS = \sin(\frac{2\pi \times YI}{11}) \qquad YIC = \cos(\frac{2\pi \times YI}{11})$$

$$MNS = \sin(\frac{2\pi \times MN}{12}) \qquad MNC = \cos(\frac{2\pi \times MN}{12})$$

where,

- YIS: the sine component of year index
- YIC: the cosine component of year index
- MNS: the sine component of month number
- MNC: the cosine component of month number

Hence, in addition to the geomagnetic aa index and SSN, the above defined parameters were considered as time inputs for the developed NN model.