Influence of Solar Activity Cycles on Earth's Climate

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Technical Note

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Summary

There are three solar-related phenomena that may influence the terrestrial environment. First, we have the solar electromagnetic radiation, where clear effects are found on stratospheric ozone generation and subsequent temperature and dynamical impacts. The second phenomenon is the continuous flow of charged coronal protons and electrons known as the solar wind. Its interaction with our magnetosphere creates magnetic disturbances as well as variations of atmospheric circulation patterns. The third solar-related phenomenon is the solar wind modulation of galactic cosmic rays, with evidence of an inversely correlation to atmospheric cloud cover. After presenting these phenomena, we describe different methods to analyze solar influences and how to establish adherent significance measures.

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1 Introduction

Already in ancient Greece, around 400 B.C., Meton observed sunspots (*Hoyt and Schatten*, 1997). After twenty years of solar studies he came to the conclusion that high solar activity, i.e. high number of sunspots, is associated with wet weather in Greece. Today the observations of Meton could have been associated with the changes of the North Atlantic Oscillation (NAO) (*Hurrell et al.*, 2003).

In 1976 *Eddy* (1976) estimated how the solar activity had varied during 5000 years using ^{14}C measurements of tree rings (see Figure 1). He showed that the Sun has gone through periods of very high solar activity and other periods of very low solar activity. It is interesting to notice that high solar activity coincided with warm periods on Earth and low solar activity with cold periods.

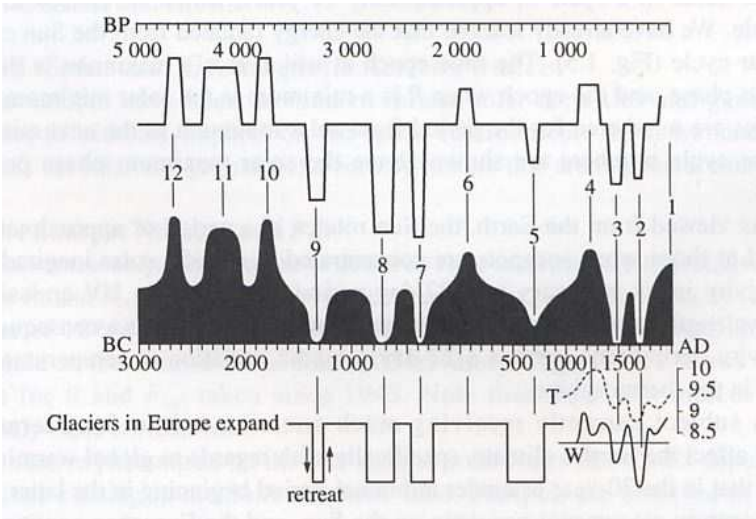

Figure 1: Shown is the relation between the derived solar activity from ^{14}C measurements during 5000 years. Periods 2 and 3 correspond to the cold periods during the Maunder and Spörer minima. Period 4 corresponds to the warm Middle Age. Period 12 marks the prosperity of the Sumerian civilization, 11 the maximum building of the pyramids in Egypt, 10 the Stonehenge era, and 6 the height of the Roman Empire.

Today, however we realize how extremely complicated, non-linear, and dynamic the climate system is. That the climate depends on non-linear interactions between many components such as that between the atmosphere and oceans, between the atmosphere and land, between the atmosphere and ice, between the atmosphere and biosphere, etc. These interactions are governed by physical, chemical, and biological processes. These processes are also influenced by external factors. One such factor is the solar activity. To understand how severe the influence of human activity is on the climate we first need to understand the natural variations. A summary of reports of solar influences on Earth is presented in Table 1. A compilation of all references presented in this report is stored at the Swedish Institute of Space Physics.

YEAR	REFERENCE	SOLAR-CLIMATE RELATION
400 B.C.	Meton (*Hoyt and Schatten*, 1997)	High SA give increased P in Greece
1651	Riccoli (*Hoyt and Schatten*, 1997)	High R give increased T on Earth
1801	*Herschel* (1801)	Sunspots influence price of wheat
1875	*Blanford* (1875a,b)	Increase in insolation => increase evaporation => clouds and P
1878	*Chambers* (1878)	SLP low during sunspot maxima
1878	*Broun* (1878)	R anti-correlated with SLP over S. Asia
1879	*Hill* (1879)	T variations in India greatest near R_{min}
1879	*Archibald* (1879a,b)	SLP in St. Petersburg correlated with R
1890	*Brückner* (1890)	30-year variations in T, SLP and P 34.8±0.7 year periodicity from Sun
1896	*MacDowall* (1896)	T extremes frequent around R_{max}
1901	*Lockyer and Lockyer* (1901)	Variations in SCL
1902	*Richter* (1902)	T in Europe compares with R, northern lights, and declination of geomag. field
1903	*Nordmann* (1903)	11-years T-cycle in tropics anti-correlated with R
1906	*Schuster* (1906)	Sunspot cycle of 33.375, 13.57, 11.125, 8.38, 5.625, 4.81, 3.78, and 2.69 years
1908	*Abbot and Fowle* (1908)	T-variations probably directly related to variations in insolations
1908	*Bigelow* (1908)	11-year cycle in the geomagnetic field, T, humidity, and SLP over Europe
1913	*Abbot and Fowle* (1913)	Volcanic eruptions block out light
1974	*Wilcox et al.* (1974)	Influence of solar magnetic field on tropospheric circulation
1977	*Kelly* (1977)	SA influence on SLP
1987	*Reid* (1987)	SA influence on SST
1988	*Labitzke and van Loon* (1988)	SA, QBO and stratospheric T
1989	*Tinsley et al.* (1989)	SCL affect cyclogenesis
1991	*Friis-Christensen and Lassen* (1991)	SCL related to land surface T
1995	*Lean et al.* (1995)	Reconstruction of solar irrad. from 1610
1996	*Haigh* (1996)	Correlation between UV radiation and tropospheric jets
1997	*Svensmark and Friis-Christensen* (1997)	Cosmic rays flux and global cloud cover
1999	*Thejll and Lassen* (2000)	Variations in SCL and climate
2001	*Neff et al.* (2001)	P in Oman correlated with SA
2002	*Boberg and Lundstedt* (2002)	Solar wind and the NAO
2003	*Gleisner and Thejll* (2003)	Solar variability and the troposphere

Table 1: A summary of some found evidence of a solar influence on Earth. T=Temperature, R=sunspot number, SA=solar activity, SLP=sea level pressure, SCL=sunspot cycle length, SST=sea surface temperature, QBO=quasi-biennial oscillation, UV=ultra violet, NAO=North Atlantic Oscillation.

2 Solar influences

Solar magnetic fields are the main cause for solar activity. The magnetic field is produced in a layer between the convective zone and the radiation zone in the solar interior. When the field reaches a certain threshold, it begins to rise towards the surface. When the field emerges through the surface it causes solar surface phenomena like sunspots, plages, and faculae. As the magnetic field continues to evolve out in the solar atmosphere, energy is built up in field structures due to convective motions and irregularities. This stored energy can be released in the form of solar flares or coronal mass ejections. Furthermore, the global magnetic field opens up and becomes the interplanetary magnetic field, an important part of the solar wind structure.

There are three categories of solar parameters that can influence the Earth's climate. First we have the electromagnetic radiation of the Sun. This category includes both the total solar irradiance (TSI) or spectral components such as the ultra-violet (UV) radiation. The second category deals with a possible direct solar wind influence, whereas the third category is focused on influences from galactic cosmic rays, modulated by the solar wind.

2.1 Solar electromagnetic radiation

At the solar surface the solar magnetic field creates a variation of the total electromagnetic radiation: Sunspots decrease the irradiance but faculae and chromospheric network increase the irradiance (Figure 2). Large flux tubes are dark and thin flux tubes are bright. The colossal sunspots of October 2003, e.g., caused a reduction of the total irradiance of 0.34%.

Stratospheric temperatures are strongly correlated with the 11-year sunspot cycle (*Labitzke*, 1987; *Labitzke and Matthes*, 2003). Both the TSI and solar UV radiation follow the variation of the solar activity. Changes in the TSI are too small to explain this temperature response, but the solar UV variation has a larger amplitude ($\sim$ 5%, see *Lean et al.* (1997)). *Hood et al.* (1993) showed how the solar UV affect the radiative heating and dynamics of the stratosphere through photochemical ozone generation. Later, model studies confirmed a solar UV impact on ozone budget, temperature, and dynamics in the stratosphere (*Balachandran and Rind*, 1995; *Haigh*, 1999). Furthermore, the amount of ozone varies with the solar rotation period of 27 days (*Williams et al.*, 2001).

As mentioned earlier, during the Maunder Minimum the solar activity was extremely low. We would therefore expect that also the UV radiation was low. *Shindell et al.* (2001) has shown how this low UV affected the ozone and how this caused a low NAO and herewith a lower temperature. Climate models by *Shindell et al.* (2001) gave locally a temperature reduction of up to 1.5 °C. Globally, however the temperature only decreased 0.2-0.3 °C.

2.2 Solar wind plasma and the interplanetary magnetic field

The solar wind plasma and magnetic field interact with the Earth's magnetosphere leading to a number of different phenomena in the magnetosphere, ionosphere, atmosphere, and on the ground.

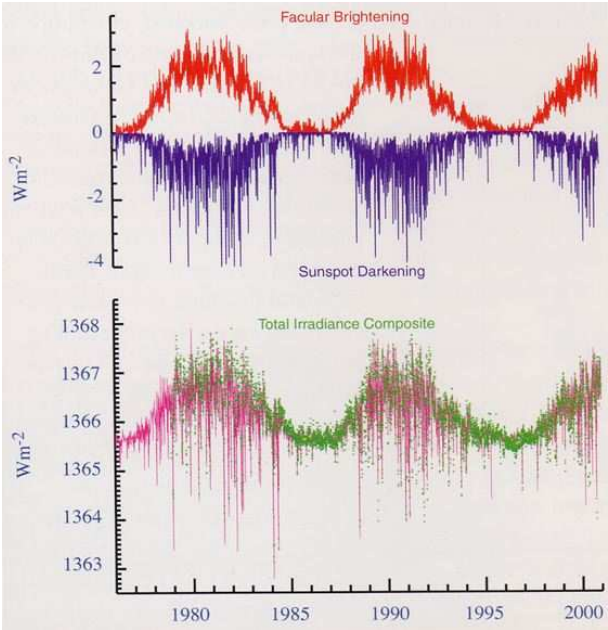

Figure 2: TSI variation with the solar cycle is shown. The contribution from the bright faculae and networks dominate the contribution from sunspots. That explains why the TSI is higher during solar maximum. Courtesy of J. Lean, NRL, USA.

The energy is transfered from the solar wind mainly via magnetic reconnection on the dayside magnetopause, but also through viscous interaction (*Baumjohann*, 1986). In-situ satellite measurements and ground based radar, ionosonde, and magnetic field measurements are utilized to derive physical parameters or indices (*Mayaud*, 1980).

In the outer magnetosphere, at geostationary orbit ($6.6R_{\mathrm{E}}$), the energetic electrons (MeV) are strongly modulated by the solar wind (*Blake et al.*, 1997). Coronal mass ejections (CMEs) are often associated with shocks in the solar wind with simultaneous increase in density and velocity together with a turning magnetic field. CMEs cause flux drop-outs of energetic electrons at geostationary orbit (*Onsager et al.*, 2002). In contrast, coronal holes lead to high speed solar wind streams that occurs regularly in phase with the solar rotation over periods of several months and leads to recurring geomagnetic activity. The high speed streams are also associated with increased flux levels of the MeV electrons at geostationary orbit (*Baker et al.*, 1997). Several empirical models exist that predicts the flux variation using solar wind data (*Wintoft and Lundstedt*, 2000; *Li et al.*, 2001) or geomagnetic data (*O'Brien and McPherron*, 2003).

Through the acceleration of charged particles from the geomagnetic tail during storms the ring current flowing in the equatorial plane is enhanced. The *Dst* index was especially derived to study the ring current based on horizontal geomagnetic variations measured from stations equidistantly distributed around the magnetic equator (*Sugiura*, 1964; *Mayaud*, 1980). Several different functions have been suggested that relates the solar wind parameters to *Dst*. In an early model by *Burton et al.* (1975) the magnetopause current seen in *Dst* is first removed by introducing a pressure correction term that involves the solar wind particle density and velocity. Then the main phase of the *Dst* variation may be modelled by a non-linear function of the dawn-dusk solar wind electric

field $E_y = -VB_z$. Finally, the *Dst* recovery phase, when the ring current decays, is modelled by an exponential decay term with a constant decay rate. Later, other combinations of different powers of the solar wind parameters have been used and also time varying decay terms. However, with the introduction of neural networks (*Lundstedt*, 1991), and subsequent improvements, e.g. (*Lundstedt et al.*, 2002), it has been shown that neural networks generally perform better which means that they are capable of finding more general coupling functions.

An overall measure of geomagnetic activity caused by a solar wind interaction with our magnetosphere is described by the *Kp* index (*Mayaud*, 1980). The *Kp* index is obtained as the mean value of the disturbance levels in the two horizontal field components over a three-hour time period at 13 sub-auroral stations (48° to 63° geomagnetic latitude). Because of the time resolution and the geographic positions of the observatories, the different storm phases during solar maximum (*Gosling et al.*, 1991) and during the declining phase of the solar cycle (*Tsurutani et al.*, 1995) are not resolved in detail. However, *Kp* is often used in solar-terrestrial studies and empirical models have been developed that predicts *Kp* from the solar wind (*Boberg et al.*, 2000).

The ionosphere is a highly conducting region extending from about 100 km altitude to 1000 km. The F-layer shows a strong diurnal, season, and solar cycle variation, as well as a strong variation with geomagnetic activity. The ionospheric F-region storm may be divided into positive and negative storms (*Prölss*, 1993). Negative ionospheric storms typically develop after the onset of a geomagnetic storm during the preceding night. A possible explanation of this effect is that the ionosonde station moves with the rotation of the Earth under the ionospheric disturbance zone. As the auroral zone starts its expansion during the night, the ionosonde moves out of the disturbance zone into the daytime side while the magnetospheric storm is developing. Then, during the following night, the ionosonde reaches the disturbance zone, and the ionospheric negative storm starts. As the disturbed ionosphere is also convected into the daytime, the negative storm persists for the whole day. On the other hand, positive ionospheric storms are mainly observed in the daytime and are seen to follow the magnetospheric storm a couple of hours later. The hypothesis is that a travelling atmospheric disturbance (TAD) is generated by the magnetospheric storm, which travels from high latitudes towards the equator. The positive ionospheric storm should thus be predictable a couple of hours in advance, while the negative storm should be predictable up to a day in advance. This was explored by *Wintoft and Cander* (2000) using the *AE* index as input.

Measurements of the local geomagnetic field are the basis for the geomagnetic indices. The idea with an index is to extract some physical process from the geomagnetic data and simultaneously simplify a complex picture. However, indices have their limitations (*Baumjohann*, 1986) and this is especially the case when coupling models become more refined. Models have been developed that directly couples solar wind variations with local magnetic field variations (*Gleisner and Lundstedt*, 2001; *Weigel et al.*, 2003) at high time resolution (minutes). Another interesting parameter is the geoelectric field that is related to $\mathrm{d}B/\mathrm{d}t$. Empirical models have also been developed that couples the solar wind to the variation ΔB of the local geomagnetic field (*Weigel et al.*, 2002; *Wintoft*, 2004).

It has been known for a long time that even the structures of the solar wind, such as the fast solar wind and sector boundaries, can influence the weather and climate through the so-called atmospheric electric field between the Earth and the ionosphere (*Lundstedt*, 1984). *Boberg and Lundstedt* (2002, 2003) also showed that the solar wind can influence the atmospheric conditions

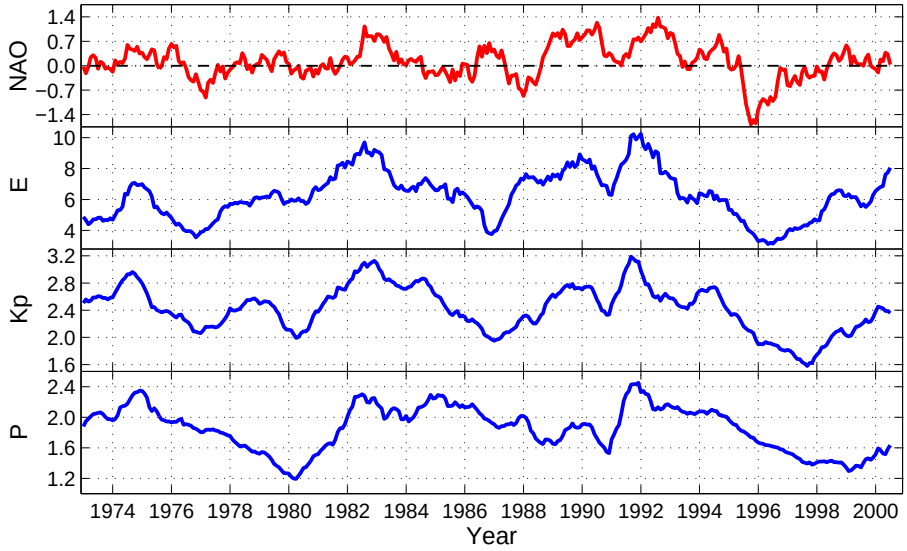

Figure 3: The NAO index is shown versus the solar wind electric field $E = B_s V$ in units 10^{-4} Vm^{-1}, geomagnetic activity represented by the Kp index and the solar wind pressure $P = nV^2$ in units 10^6 m^{-1}s^{-2}.

given by the NAO. A strong correlation between the solar wind electric field and the NAO was found (Figure 3).

The relation found by *Boberg and Lundstedt* (2002, 2003) is strongest during the winter months, as expected, and with a one month delay. This delay could be explained through what *Baldwin and Dunkerton* (2001) found, namely that strong variations in the stratospheric circulation can propagate down to the troposphere within 15-50 days. Model studies indicate that the influence of geomagnetic activity on the stratosphere is comparable to that of solar UV radiation (*Arnold and Robinson*, 2001). *Bucha and Bucha, Jr.* (1998) observed enhanced tropospheric flows in connection to strong geomagnetic activity. They suggested a mechanism where winds are generated in the thermospheric polar cap followed by a downward motion through the stratosphere and troposphere.

2.3 Cosmic rays of high energetic particles

Svensmark and Friis-Christensen (1997) showed that the variation of galactic cosmic rays, which is inversely related to solar activity, can have influences on climate through a variation of Earth's cover of clouds (Figure 4) (*Marsh and Svensmark*, 2000b). *Svensmark and Friis-Christensen* (1997) suggest that at times of high solar activity, with reduced cosmic rays entering Earth's atmosphere, less clouds are formed at low altitudes hereby increasing the temperature. At low solar activity the opposite is true, with a decrease in temperature. The influx of cosmic rays are modulated by the strength of the solar coronal and interplanetary magnetic fields. This magnetic field has been found to have increased over the latest 150 years (*Stamper et al.*, 1999; *Solanki et al.*, 2000).

Marsh and Svensmark (2000a,b) suggested that the relationship between cosmic rays and cloud

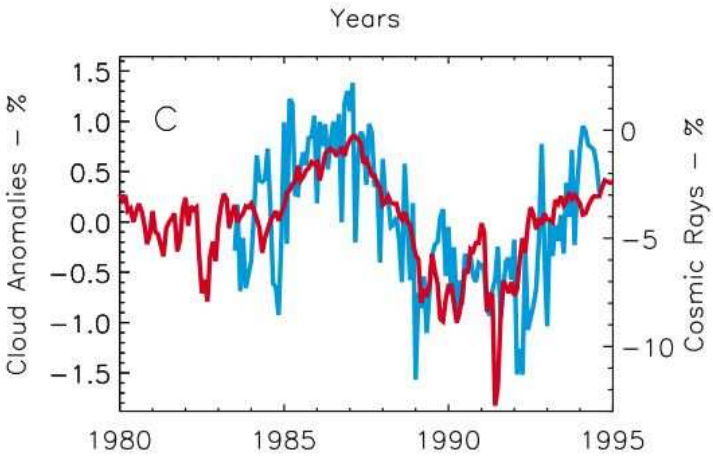

Figure 4: The solar activity is inverse related to the cosmic ray flux. The variation of the cosmic ray flux (red) and Earth's cover of low clouds (>680hPa) (blue) is shown. Courtesy of H. Svensmark.

amount was consistent with a mechanism involving ionization and aerosol nucleation. This mechanism could influence the activation of cloud droplets in the lower atmosphere and thereby influence cloud radiative properties (*Pallé Bagó and Butler*, 2000; *Yu*, 2002). Cosmic rays are the main source of ionization in our atmosphere (*Bazilevskaya*, 2000). But their total energy is low compared to the solar radiative energy, and some form of amplification mechanism is required to make cosmic rays influence our climate.

3 Methods of Analysis

To rule out incidential co-variations between causally unrelated time series as a cause of the apparent Sun-climate relations, correlation results must be interpreted on the background of stringently derived significance levels. Especially the overestimation of the number of degrees of freedom often leads to erroneous conclusions. One way to determine significance of results is to use Monte-Carlo simulations of the statistical procedures on surrogate data (*Theiler and Prichard*, 1996) and subsequently inspect the distribution of the correlations in the surrogate data. The surrogate data are generated by scrambling the harmonic phases of a series ensuring that the Monte-Carlo procedure can perform the Null-hypothesis test on data series that are physically unrelated to the target series but which have the necessary similarity in statistical terms. Using this method, one gets a percentage of trials that achieved a similar or lower correlation enabling estimates of how likely the result is to be a non-random occurrence.

However, there is an arbitrary choice of the significant level when performing a null-hypothesis testing, whether it concerns a found correlation or it concerns the choice between different models. Based on information theory *Akaike* (1974) suggested "an information criteria" (AIC) as a way of selecting the best model from a set of models and without having to compute any significant levels. Using AIC the optimal model is the model that minimizes the errors but also taking into account the number of free parameters. *Russel and Ginskey* (1995) applied a variant of AIC to model the diurnal variation of the horizontal geomagnetic field component, and *Higuchi and Ohtani* (2000) have used AIC to identify large-scale field-aligned currents and to determine geomagnetic Pi2 onset time (*Higuchi et al.*, 2002). For an overview of AIC and use of information theory in model selection see e.g. *Burnham and Anderson* (2002).

3.1 Exploration

3.1.1 Fourier analysis

Fourier analysis is a mathematical analysis that attempts to find cycles within a time series of data after detrending the data. The Fourier transform decomposes a waveform or function into sinusoids of different frequencies which sum to the original waveform. It identifies or distinguishes the different frequency sinusoids and their respective amplitudes (*Brigham*, 1988). The Fourier transform of $f(x)$ is defined as

$$F(s) = \int_{-\infty}^{\infty} f(x) \mathrm{e}^{-i2\pi xs} \mathrm{d}x. \tag{1}$$

Since the Fourier transform $F(s)$ is a frequency domain representation of a function $f(x)$, the s characterizes the frequency of the decomposed sinusoids and is equal to the number of cycles per unit of x (*Bracewell*, 1965).

3.1.2 Wavelet methods

Today the use of wavelet techniques has become a common method of analysing solar-terrestrial data. Good introductions to the use of wavelet transforms are given by *Torrence and Compo* (1998) and *Kumar and Foufoula-Georgiou* (1997). Wavelet analysis is a powerful tool; both in finding the dominant mode of variation and also to study how it varies with time, by decomposing a non-linear time series into time-frequency space. The wavelet transform of a function y(t) is given by

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

where a is the scale dilation, i.e. the compressing and stretching of the wavelet g, b is the translation parameter, i.e. the shifting of g, and g^* the complex conjugate of g. The commonly used Morlet wavelet is defined as a complex sine wave, localized with a Gaussian and given by

$$g(t) = exp(i\omega_0 t - \frac{t^2}{2}), \tag{3}$$

where ω_0 is a phase constant. To analyze a discrete signal $y(t_i)$ we need to sample the continuous wavelet transform on a grid in the time-scale plane (b, a). By setting $a = j$ and $b = k$, the wavelet coefficients $w_{j,k}$ are

$$w_{j,k} = j^{-1/2} \int_{-\infty}^{+\infty} y(t) g^*(\frac{t-k}{j}) dt. \tag{4}$$

When the wavelet coefficient magnitudes (WCM) are plotted for the scale and the elapsed time, a so-called scalogram is produced. Many times series observed in physics consist of a deterministic part with a superimposed stochastic component. *Wernik* (1997) introduced a method to study that, based on non-linear filtering of the wavelet coefficients. The deterministic strong part is obtained by setting all wavelet coefficients less than a certain threshold equal to zero. The inverse wavelet transform is then used to calculate the corresponding time series. The stochastic weak part is obtained by setting all wavelet coefficients greater than that threshold level equal to zero. The inverse wavelet transform is then used to calculate the corresponding time series. New wavelet spectra are finally calculated for each partial time series.

Ampligrams and time-scale spectra (*Liszka*, 2003) can be looked upon as a generalization of the above technique, a kind of bandpass filtering in the WCM domain analogues to Fourier analysis in frequency domain. They can be used to separate independent components of the signal, assuming that the different components are characterized by different wavelet coefficient magnitudes (spectral densities).

3.2 Description

Principal component analysis (PCA) can be used to reduce the dimension of a multidimensional data set (*Jolliffe*, 2002). Assume that $\mathbf{x} = (x_1, \ldots, x_p)^T$ is a p-dimensional random variable observed n times and collected into the $p \times n$ matrix $\mathbf{X}$. With PCA the matrix $\mathbf{X}$ is transformed into the $p \times n$ matrix $\mathbf{A}$ according to

$$\mathbf{A} = \mathbf{EX} \tag{5}$$

where $\mathbf{E}$ is a $p \times p$ matrix containing the eigenvectors found from $\mathbf{X}$. The rows in $\mathbf{A}$ are orthogonal and thus the covariance matrix of $\mathbf{A}$ contains zeros except on the main diagonal. Further, the rows in $\mathbf{A}$ are sorted so that the explained variance increases with increasing row index. To reduce the dimension the last q rows of $\mathbf{E}$ are chosen leading to the $q \times p$ matrix $\mathbf{E}_1$. The reduced $q \times n$ matrix is obtained from

$$\mathbf{A}_1 = \mathbf{E}_1 \mathbf{X}. \tag{6}$$

The shape of the eigenvectors may also give clues to interesting features in the data. Applications of PCA in climate research can be found in *Preisendorfer* (1988). A related method is the independent component analysis (ICA) (*Hyvärinen et al.*, 2001) that has been applied to separate signals in global temperature series (*Fodor and Kamath*, 2003).

Self-organised maps (SOM) (*Kohonen*, 1995) belong to the class of unsupervised neural networks. Unsupervised means that the training algorithm does not make use of any output data, instead it learns from the statistics in the input data. A common use of SOM is to transform a multi-dimensional input space to, usually, a one- or two-dimensional map. The transform is topology preserving which means that nearby points in the input space are mapped to nearby positions on the map. This is especially useful if one suspects that the points in the multi-dimensional input space are confined to a curve or a surface. The SOM has been applied to solar wind data to classify geoeffective events (*Wintoft and Lundstedt*, 1998).

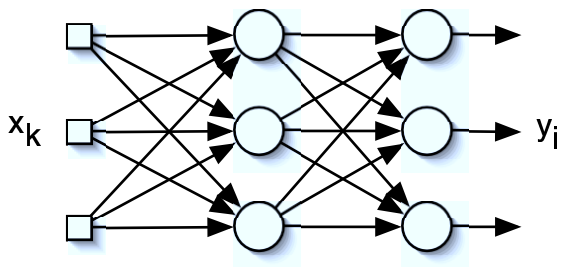

Figure 5: The figure shows a diagram of a feed-forward neural network with one hidden layer.

Artificial neural networks (ANN) consist of a broad range of models that are capable of finding patterns, or mappings, from the data using a learning algorithm. For an overview see e.g. *Haykin* (1998). The most widely used ANN is the feed-forward neural network (FFNN). A diagram form of a FFN with one hidden layer is shown in Figure 5. The function implementing the FFNN can be written as

$$y_i = f\left(\sum_j v_{ij} g\left(\sum_k w_{jk} x_k + b_j\right) + a_i\right) \tag{7}$$

where x_k is input k and y_i output i. The functions $f(\xi)$ and $g(\xi)$ are known as the transfer functions and the choice of these depends on the problem to be solved. For a mapping from a continuous input to a continuous output the choice is often a linear function $f(\xi) = \xi$ at the output layer and a sigmoid-type function $g(\xi) = \tanh \xi$ at the hidden layer. The one-hidden-layer FFNN is capable to approximate any continuous valued function (*Cybenko*, 1989) given that the number of hidden neurons is large enough. The free parameters, i.e. the weights v, w and biases a, b, are found using a learning algorithm that iteratively adapts the weights and biases so as to minimise the errors between the FFNN output and the observed output. To model dynamic systems some kind of

memory must be added. This can be accomplished by introducing time delayed inputs (*Lundstedt and Wintoft*, 1994) or by using feed-back connections (*Lundstedt et al.*, 2002).

4 Conclusion

Solar activity comes in many different shapes. They are all believed to be driven by energy release from the solar magnetic field. Many proposed relationships between solar activity and weather/climate can be found in the literature (see Table 1). The controversy of these relationships originates in the lack of an accepted physical mechanism linking solar variability to climate changes. The part of solar activity that can have a direct influence on Earth's environment can be divided into three categories: a) electromagnetic radiation; b) solar wind and interplanetary magnetic field; and c) solar wind modulated galactic cosmic ray infall. A literary survey on these three categories have been carried out from a solar activity point-of-view. The result of this survey will be used later on in this project.

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