Comparison of radionuclide-based solar reconstructions and sunspot observations the last 2000 years

Christopher Artursson

Dissertations in Geology at Lund University,
Bachelor's thesis, no 390
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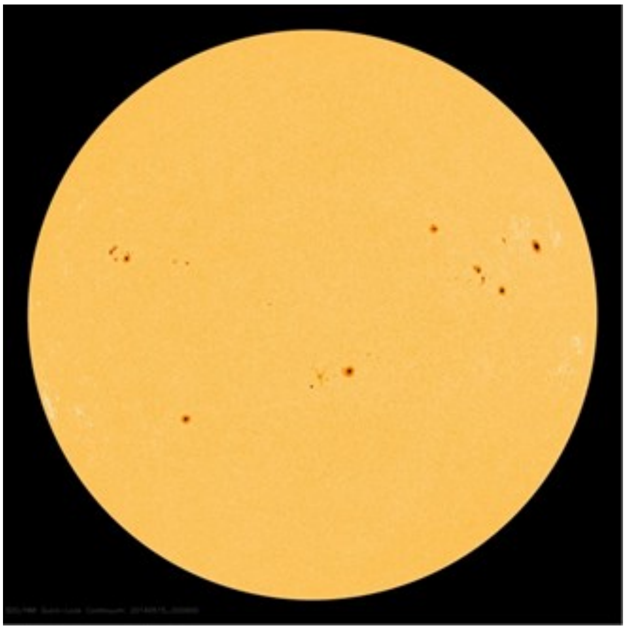

Department of Geology
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Contents

Cover Picture: Sunspots on the surface of the sun (spaceweather.com).

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Abstract: The sun is an important reason to why there is life on earth. To be able to predict future solar activity it is important to uncover past solar activity and its cyclicity. This thesis investigates the solar activity throughout the past 2000-years to the beginning of 21th century. Diagrams which contain relevant data from radionuclide and sunspot records have been constructed to get a better overview of solar activity variations during the investigated period. They show a trend of increasing span in solar maxima and minima from year 0 to present.

Correlation analysis between radionuclide records and naked sunspot number (sunspot archives) resulted in bad correlation. This in contrast to the results when radionuclide records were correlated to GSN (Group sunspot numbers) data based on telescope observations, which resulted in a better correlation. The conclusion is the naked eye sunspot record is very difficult to use as a primary source for estimating past solar activity, apart from a few periods with a high amount of observations.

Keywords: solar reconstruction, radionuclide, sunspot, correlation, analysis

Supervisor: Raimund Muscheler

Subject: Quaternary geology

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En jämförelse mellan radionuklid-baserade solrekonstruktioner och solfläck observationer de senaste 2000 åren

CHRISTOPHER ARTURSSON

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Sammanfattning: Solen är en stor orsak till varför det finns liv på jorden. För att försöka förutsäga framtidens solaktivitet så är det viktigt att ta reda på den förgångna solaktiviteten och dess cyklicitet. Den här uppsatsen undersöker solaktiviteten de senaste 2000-åren från Kristi födelse till i början av 2000-talet. Diagram som innehåller relevant data ifrån radionuklider och solfläckar har konstruerats för att få en bättre vy över den undersökta perioden. De visar på en trend med ökande kontrast i solens aktivitet med högre minima och maxima från år 0 fram tills idag.

När radionukliderna blev korrelerade mot solfläckar baserat på de historiska arkiven gav det en dålig korrelation. Resultatet var det motsatta när radionuklider blev korrelerade mot GSN ("Group sunspot number"), som är baserat på teleskopobservationer. Slutsatsen är att arkivet med nakna solfläckar är svårt att använda som primär källa för att ta reda på den gångna solaktiviteten, förutom några få perioder med en större andel av observationer.

Nyckelord: sol rekonstruktion, radionuklid, solfläck, korrelation, analys

Handledare: Raimund Muscheler

Ämnesinriktning: Kvartär geologi

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1 Introduction

This thesis is a literature review based on long sunspot observational records complemented with a comparison to radionuclide-based solar activity reconstruction. The aim is to investigate the quality of such sunspot records with analytical methods such as correlation analysis, i.e. to compare sunspot and radionuclide data to investigate how well these correlate within the last 2000 years. Sunspots can be viewed in *Fig 1*. The sunspot data consists of historical records going as far back as to the Chinese Shang Dynasty (1500-1050 B.C) (Vaquero & Vázquez 2009). These records are based on naked-eye observations of the sun and records differ in detail and may be influenced by human errors. One of the more recent recollections has been made by Wittmann & Xu (1987). They have sampled the available documents from historical records covering the time period from 165 BC to 1684 AD, making data more accessible for scientists to interpret. Another researcher Yau (1988) claims that most of the earlier collection, including the one from Wittmann & Xu (1987), suffers from "omissions, dating errors or the inclusion of apparently spurious data". Therefore he has made his own recollection he consider more trustworthy. More about these data can be found in the section reviewing the available sunspot records. The Introduction of telescopic devices during the 17th century paved the way for more careful observational and analyzing methods. Two of the most commonly used methods to estimate the sunspot number are called the Group sunspot number (GSN) and the International sunspot number (ISN). These are reviewed in the section of analyzing methods of sunspots.

Two of the most commonly used radionuclides in this context are ^{14}C (carbon-14) and ^{10}Be (beryllium-10). Briefly the origin of these isotopes derive from a reaction between high energy particles from solar eruptions or galactic cosmic rays (GCR) and earths atmosphere. The latter meaning high-energy particles most likely from supernova explosions in our galaxy. (Muscheler 2013; Reedy & Arnold 1972; Sjolte, 2014, pers. Comm., 2th June). They are indirectly reflecting variations in solar activity via the solar magnetic field shielding of galactic cosmic rays. Using these Isotopes is today our most reliable source for determining solar variations far back into the past (Muscheler et al. 2007).

2 Methods

The used methods in this thesis involve primarily literature studies and analyzing of different sunspot and radionuclide records. These involve comparison and correlation analysis.

2.1 The correlation coefficient

Correlation analysis is an important method to get an overview of how much in common different records

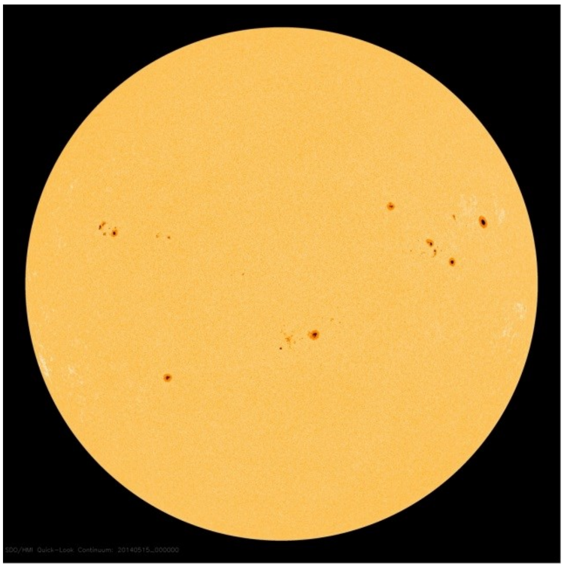


Fig 1. Sunspots observed on the sun 15/05/2014 (spaceweather.com).

exhibit. The most important variables which affect the coefficient are the time variations and the periodicity. Pearson correlation coefficient is defined as below:

$$\rho_{X,Y} = \frac{\text{cov}(X,Y)}{\sigma_X \sigma_Y} = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2} \times \sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

X and *Y* represents two data series. Cov stands for covariance which corresponds to the numerator. The numerator describe the mean of the *X* respectively the *Y* series subtracted with each individual data value. The sigma represents standard deviation and the amount of variation or dispersion from the mean value. The *n* represent the amount of data compared.

The correlation coefficient can fluctuate between 1 and -1. Correlation number 1 means perfect correlation and -1 perfect anti-correlation. In subsequent analysis (*Fig 2*, *3*, *4*) the x-axis represents time and the y-

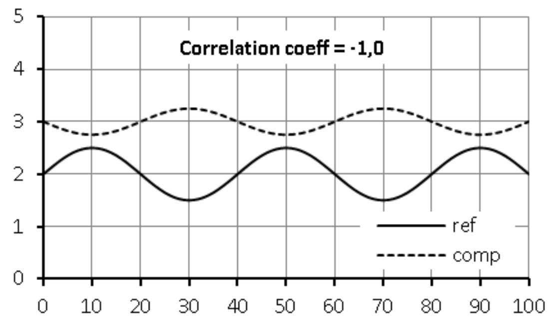


Fig 2. Time chart showing anti-correlation between 2 curves.

axis represents sunspot number or radionuclide values. In general when data sets are compared one wants specific values to estimate the level of agreement. For instance in the ^{10}Be and ^{14}C section when you have high solar activity and high geomagnetic field intensity you also get a decrease in radionuclide production (*Fig*

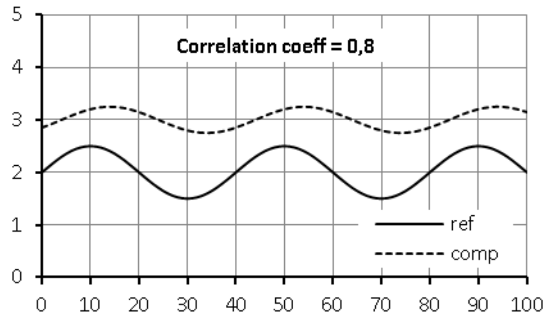


Fig *3* Time chart showing a slightly displaced curve from perfect correlation.

8). This means one can expect an anti-correlation between sunspot and radionuclide data. The opposite applies if data between sunspots or radionuclides are compared to one another and the correlation coefficient is expected to approach 1 (*Fig 3*). If the correlation coefficient approaches 0 then no correlation exist (*Fig 4*) (Taylor 1990).

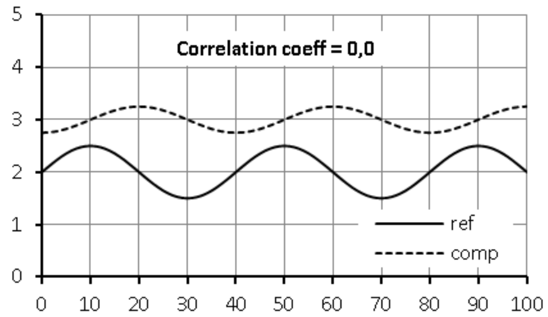


Fig 4 Time chart showing 2 curves with no correlation.

Records with missing values at certain years have been neglected. This can otherwise lead to misleading correlation information. The same applies to records of which have several measurements within a year if compared to a record which just have one. The correlation number is separated into categories which explain how good the correlation is. The categories are as following (Hagell 2010):

Poor correlation (0,0-0,3)
Fair correlation (0,3-0,5)
Moderately strong correlation (0,6-0,8)
Very strong (0,8-1,0)

3 Background

3.1 The solar cyclicity

The sun follows a periodic cycle of activity which has a strong relation to sunspots. A period of high amount of sunspots usually equals a maximum in sunspot cyclicity amplitude. The cause of solar cyclicity is not fully understood. One theory is that the cyclicity has a connection to "generations of strong toroidal (doughnut shaped) magnetic fields in the sun by combined effects of convection and differential rotation on the sun"(Javaraiah et al. 2012). In the year 1844 Henrik Schwabe was the first year to notice a distinct cyclicity of sunspot occurrence. Since then more discoveries have led to theories and suggestions of additional sunspot cycles. There are 4 cycles which are often referred to: the 11, the 22 years cyclicity, the 88 years cycle (Wolf-Gleissberg cyclicity) and the 207 years DeVries cycle. The 22 years cyclicity set itself apart from the other three by being connected to polarity changes in the magnetic field but it is expressed by the visible 11 year sunspot cycle (Mursula et al. 2001; Hathaway 2010; Braun et al. 2005)

3.2 The naked eye sunspot

The naked eye sunspot archives are from three parts of the world: Europe, the Arabian domains and eastern Asia (mostly China and Korea) the latter of which 95% of the records comes from (Stephenson 1990). The first notation used as a sunspot recollection is dated from 165 BC from eastern Asia (Wittmann & Xu 1987). It is known that observations of the sun were made already between 1500-1050 BC (Vaquero & Vázquez 2009). According to Vaquero & Vázquez (2009) questions arise when trying to translate these into usable data. One is the observational methods, which can affect the accuracy of the sunspot observation. The frequencies of observations i.e. a high amount of observations within a limited time period increase the likelihood of a more trustworthy record. The capacity of which records are able to reflect past solar activity, the quality for each individual observer tends to vary quite a lot where some observations are more detailed than others.

Three observations of importance can be made when going through the Oriental records of naked eye sunspot observation (*Fig 5*).

There are only sporadic reports of sunspot observations
The reports are relatively frequent in China and Korea during the 12th to 13th century
There is a peak in the sunspot observational records around 1370 A.D

The gaps in the naked eye sunspot data can be explained in various ways through climatic/historic and sociological factors. To be able to observe the sunspots it is necessary to have a filter for the eye to be able to see individual spots on the sun. According to Usoskin & Kovaltsov (2004) meteorological phenomena such as clouds, dust storms and gases from volcanic eruptions could provide such a filter. Furthermore the amount of clouds and dust storms are affected by seasonal changes. In the Middle East dust storms usually occur in late winter and spring thus increasing the probability of sunspots being seen during this season of the year. Similar conditions are present in the orient when annual dust storms from the Takla makan, Ordos and Gobi desert dim the sky above China and Korea

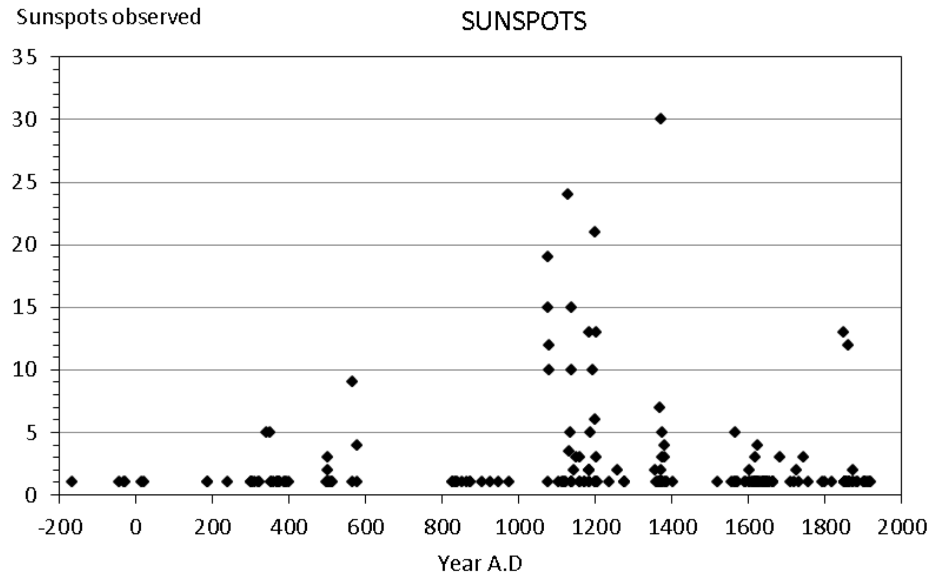


Fig 5. Sunspot observed in the orient between 200 BC and 2000 A.D. Each point represents one individual source reference (Wittmann & Xu 1987).

(Yau 1988).There is some evidence that the ancient Chinese used ink poured into water which became blackened. The inked water reduced the sunlight and could then be used to observe the sun (Wang & Siscoe 1980). The records are also depending on the predominant traditions at the time. At some periods during the oriental history emperors in the Far East had different priorities in terms of observation of the sun. It is noted by Stephenson (1990) that within a period of 1800 years there were extensive records done by only 6 out of 150 emperors. These represent over half of the data covered within the timeframe (Vaquero & Vázquez 2009). In addition to spontaneous and sparse observational records, geopolitical conflicts have led to sacking of cities that led to the disappearance of important documents. One of these sackings occurred in the Táng Dynasty capital Changon about 755 AD. Compared to the sunspot number at the corresponding time period there is a distinct poor uniformity between 600 and 800 AD (see *Fig 5*) (Yau 1988).

3.3 The international sunspot number

With the introduction of telescopic devices during the 17th century a more accurate observation of sunspots was possible. This was the foundation of a more scientific approach for sunspot observations. There are two major analyzing methods when extracting information from sunspot observations. The international sunspot number (*Fig 6*) (also in literature called the Wolf sunspot number and the Zürich sunspot number) and the group sunspot number (*Fig 7*). The international number is named after Johann Rudolf Wolf who was a famous Swiss astronomer and mathematician. He collected much of the available data at the time concerning sunspots and used them to calculate the cyclicity of the quantity of sunspots present on the sun's surface. He defined as following:

$$R_z = K(10g + N)$$

R_z = International sunspot number

g = number of sunspot groups

N = Individual sunspots

K = correction factor for each observer

The Wolf sunspot number is defined as "ten times the number of sunspots groups plus the number of individual sunspots multiplied by a correction factor (K) for each observer (Hoyt et al. 1994)
This is because each observer has its own scale when it comes to determining sunspots. In other words the purpose of the number is to rescale the raw sunspot number in this case to the one of Rudolf Wolf (SIDC 2008). Wolf used so called primary observers. These observers were considered to be more reliable in terms of regular sunspot observations during a longer period of time. The primary observers that are used today when calculating the sunspot number are mentioned in Hoyt& Schatten (1998). It is considered among scientists that the data which covers from 1848 to present is reliable. The data from 1818 to 1847 is considered good. The data from 1749 to 1817 is questionable. Earlier data is considered to have poor quality (Hoyt et al. 1994). In addition to the primary observers in periods where there is a lack of data these are filled in with a secondary and perhaps even a tertiary observer. The factor K in the ISN formula accounts for possible biases between observers. K is determined through ration-

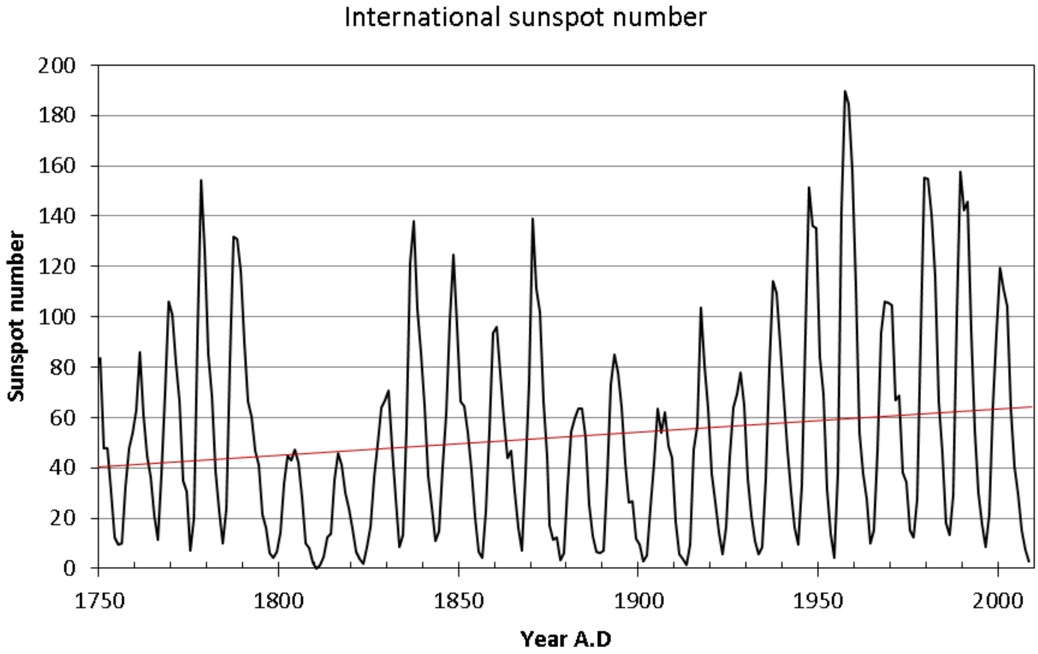


Fig 6. International sunspot number from 1750-2010. The red line represents the overall up going trend of the sunspot number. Diagram is based on data from SIDC.

ing the primary observer to wolf standard and rationing the secondary and tertiary observers to the primary observers. Even with filled gaps of secondary and tertiary observers there were still gaps in the data that needed to be treated in some way. Wolf solved this through adding magnetic needle observations into the calculations. This method is based on measuring the geomagnetic activity and works as following. When the sun is active the compass needle fluctuates more. This is due to the solar wind carrying a magnetic field that interacts with the geomagnetic field. When there is less solar activity these fluctuations decrease. During Wolf's era these measurements were primarily done between 1760 and 1860 in European cities (Hoyt & Schatten 1998). However according to Hoyt & Schatten (1998) his method has some considerable flaws when determining the long-term sunspot activity. Wolf missed a lot of data that was either inaccessible to him or he was not aware of. Today we have data from 330 observers with 147462 observations, this in contrast to Wolf who only had 213 observers with 81525 observations. This is an increase of approximately 80% in data. Secondly there are thoughts about the way International sunspot is calculated. When a sunspot occurs on the surface of the sun it is not always easy for an observer to tell if it is one or several sunspot you see in one tight area. *Fig 1* shows how difficult it can be for an observer to interpret the sunspots.

3.4 The group sunspot number

The definition of GSN is similar to the ISN with the difference that focus lies on the number of grouped sunspots and does not recount the tiniest spots. This makes the result more internally consistent especially because the records are mostly of the amount of sunspot groups on the surface of the sun and not of each individual sunspot. This makes perhaps GSN technique easier when analyzing solar activity. The GSN number is defined as follows (Hoyt & Schatten 1998).

$$R_G = \frac{12{,}08}{N} \sum K_i' \times G_i$$

R_G= The group sunspot coefficient

G_i = Number of sunspots recorded by i:th observer

K_i = Correction factor

N = the number of observers used to form the daily value

12,08 = Normalization number to make the mean number as close to the International sunspot number as possible.

The number 12,08 depends slightly on how many observers there are and of how many observations have been done to the specific sunspot. As more data is added to the data base the normalization number can change which Hoyt & Schatten (1998) validates after having added another 100 000 observations since their earlier work the number increased for 11.93 to present 12.08 (Hoyt et al. 1994). The Royal Greenwich Observatory (RGO) is the primary observer in the case of

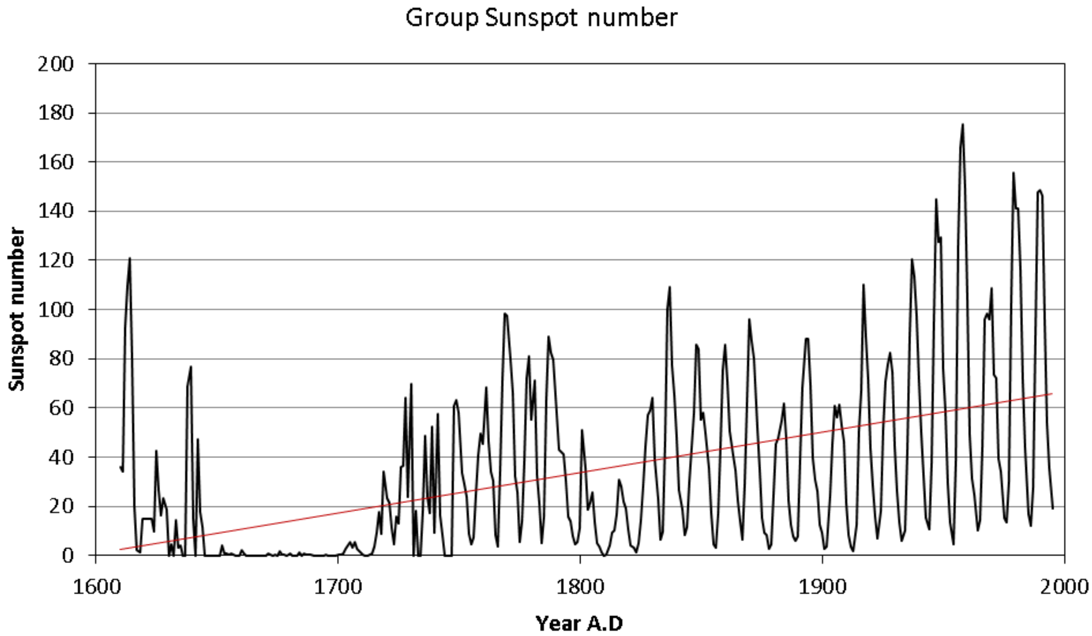


Fig 7. Group Sunspot number from 1610-1995. The red line represents the overall up going trend of the sunspot number. Diagram is based on data from SIDC monthly sunspot number modified by Raimund Muscheler to give an annual average of the sunspots.

GSN. They have regularly been observing between year 1874 and 1976 using the GSN formula and the record is considered to be the most reliable observations during the time period. Hoyt & Schatten (1998) conclude there are three systematical errors disturbing the accuracy of the group sunspot numbers.

- Missing observations
- Insecurities of K values
- Errors from random daily values
- Drifts from K values

In addition to these uncertainties it is worth mentioning as indicated earlier that group sunspot number is based primarily on the RGO observations which makes it more difficult if the purpose is to trace sunspot activity further back in time since secondary observers can lower the accuracy of the data. Hoyt& Schatten (1998) concludes a high quality observer is one that has many observations and comparisons with the primary observer (RGO).

A comparison between the International sunspot number and the group sunspot number have been made by Hathaway et al. (2002). He concluded the GSN is better to decide long term behavior of solar activity but ISN is better to track recent sunspot changes. Since ISN keeps track of also individual sunspots.

3.5 The radionuclides ^{14}C, ^{10}Be

Tracing solar activity can be done by observing the amount of sunspots and solar phenomena such as solar magnetic flux (McCracken et al. 2004).
However, to trace solar activity further back in time several radionuclides can be used. Two of the most commonly used radionuclides are ^{14}C and ^{10}Be, both created through nuclear reactions in the earth's atmosphere. To get an overview of the production process an explanation of the accumulation process will be provided.

These isotopes have their origin in high energy particles from solar eruptions or GCR. The latter are products of supernova explosions in our galaxy (Muscheler 2013; Reedy & Arnold 1972; Sjolte, 2014, pers. Comm., 2th June). The galactic cosmic ray particles consist of 87% protons, 12% helium and 1 % of heavier nuclei (Simpson 1983). The cosmic rays are partly deflected by the earth magnetic shield. This is true apart from the magnetic poles where the magnetic shield is weaker in contrast to earth's equator. In periods when solar activity is higher than usual these particles are more strongly shielded by the solar magnetic shield. The relationship between the geomagnetic field intensity and the solar modulation function can be observed in *Fig 8*. A strong geomagnetic field intensity and solar modulation function equals a decreased radionuclide productivity and the opposite for increased productivity (Muscheler 2013).

The GCR's that make it into the atmosphere result in a cascade of reactions, some of these result in the production of ^{10}Be and ^{14}C. ^{10}Be is produced through spallation reaction (fragmentation of a nuclei caused by an impact or stress) when high energy particles hit oxygen and nitrogen in the atmosphere. The ^{14}C however is produced through secondary reaction associated with the nitrogen when slower thermal neutrons are the cause of the ^{14}C production (Lal 1967; Lal 1998).

3.6 Assembling of ^{14}C, ^{10}Be data

The collection of radionuclides is done to several materials. The most common ways of extracting ^{14}C data may be the usage of tree rings (dendrochronology). The records have then been extended with the utilization of varved sediments, speleotherms, corals, plant macrofossils and foraminifera (Reimer et al. 2013). ^{14}C isotopes are found in the biosphere, hydrosphere and lithosphere where the oceans are considered to be a big part of the ^{14}C is concentrated (Castagnoli & Lal 1980). These combined data from all the available ^{14}C sources have been calibrated into a statistical analysis called the International calibration series, which is updated periodically when more data become accessible. The latest updated version (Intcal13) is shown in *Fig 9 (a)*.

In total the ^{14}C data spans thousands of years outside the investigated 2000-years interval. In the investigated time period ^{14}C data based on tree rings is the dominant method of extracting data and is supported by ^{14}C marine data (Reimer et al. 2013). Using lake sediments to extract data for ^{14}C and ^{10}Be is a relatively new aspect of radionuclide dating (Ramsey et al. 2012). The data which derives from this source can suffer from spurious results from several sources. Factors which can affect the obtained data could be the release of old carbon from catchment, variable sedimentation characteristics, lake productivity, hydrology, geochemistry, biology, nutrient transport and soil properties. Change in any of these properties usually depends on the local anthropogenic activity, the landscape evolution or/and climate variability (Berggren et al. 2013).

Compared to ^{14}C the ^{10}Be data is almost only collected from ice cores. It is transported with the help of aerosols and there after deposited mostly through rain or/and snowfall. This is defined as “wet” deposition in contrast to “dry” deposition, which is the accumulation due to gravitational settlement. These aerosols have a mean atmospheric residence time between 1 - 2 years (Raisbeck et al. 1981; Beer et al. 1990). Dust-borne ^{10}Be particles can cause spikes in the data series which is not equal to the past production of that period. The particles attracts additional ^{10}Be within the ice (Muscheler 2013). To complicate things even further the ^{10}Be data is influenced by fluctuating amount of aerosols in the atmosphere which is necessary for the transportation for the radionuclide. This amount differs in time periods and the deposition also varies between locations. These factors are important keeping in mind when evaluating the location of an ice core sample (Baumgartner et al. 1997). Fluctuations and disturbance in precipitation rate, atmospheric mixing and scavenging efficiency are usually called “climate noise”. The best way to reduce these imperfections is to correlate several ice cores from different locations. This method makes it possible to exclude deviating values from each core and to make an as trustworthy record as possible (Beer et al. 1990). Measurement

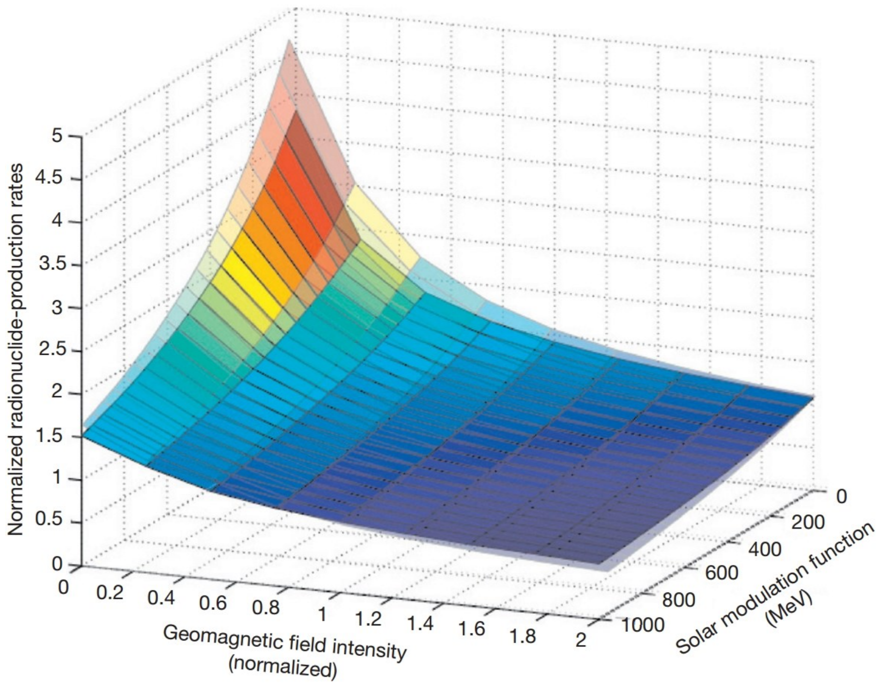


Fig 8. Radionuclide production of ^{14}C and ^{10}Be depending on the solar modulation and the geomagnetic field intensity. ^{14}C is presented as the transparent 3D curve while ^{10}Be is solid (Muscheler 2013).

uncertainties are in the range of 4-10% due to the deposition process. In conclusion it is possible to say that the difficulties to interpret data is due to 3 reasons (Muscheler 2013).

Climate weather influences on ^{10}Be transport and deposition.
Measurement quality issues.
Dating uncertainties.

4 Results

4.1 The solar activity records

To reconstruct past solar activity, a diagram with compiled information of past variations in ^{10}Be, ^{14}C and sunspot observations has been created (*Fig 9*). The data have been picked to fill the desired time period. The used records are as following:

- Naked eye sunspot from the orient (shown in *Fig 5* and in *Fig 9*) (Wittmann & Xu 1987).
- The group sunspot number (shown in *Fig 7* and *Fig 9* (*c*)) (from the SIDC archive).
- The international sunspot number (shown in *Fig 9* (*c*)) (From the SIDC archive).
- ^{10}Be flux of GRIP ice core (Greenland Ice core Project) (Vonmoos et al. 2006).
- ^{10}Be flux of NGRIP ice core (North Greenland Ice Core Project) (Berggren et al. 2009).
- ^{14}C production based on Intcal13 (Muscheler et al. 2007).

At first glance the records shares one common pattern, the distinct change in ^{14}C and ^{10}Be and in sunspot numbers close to present. This is true, apart from the historical sunspot observation. It can be due to different reasons. For instance as mentioned in the section 3.2 there are physical limitations for what is necessary for observing a sunspot, among others dust storm or clouds. There is no evidence the weather pattern have influenced this in anyway as for the 1950's. Another idea would be that ISN and GSN are more sensitive to change because of more accurate observation through telescopic devices. It is more likely ISN/GSN have gradually replaced naked eye sunspots observations.

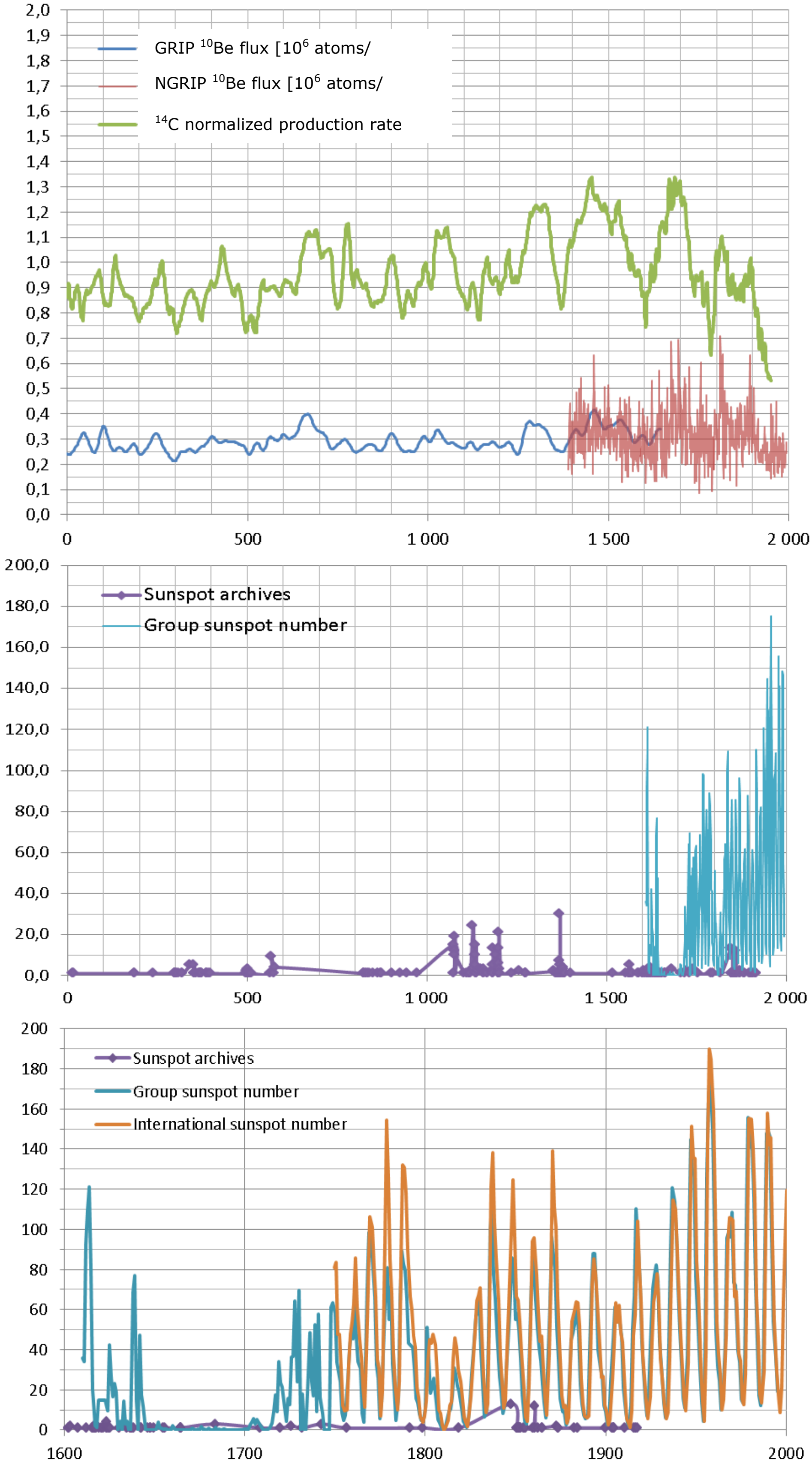
The overall trend of increasing amount of sunspots (GSN and ISN numbers) and a decreasing amount of radionuclide production indicates higher solar activity not seen in at least 2000 years. One question we may ask ourselves: is it possible to see a trend of increasing solar activity cyclicity to present? There is no obvious answer to the question other than what we can interpret based on the data we have. On a short timescale as 2000 years it's difficult to observe a trend. What we can see though is an increasing contrast of higher and lower solar activity going to present. If this trend is to continue: what if we have reached the solar maxima and are heading into a solar minimum? A more detailed understanding of the solar physics is needed to answer this question.

4.2 Investigation of correlation between sunspot and radionuclide records

Several comparisons between records have been done to see how well they correlate to one another. Primarily these comparisons have been focused on comparing radionuclide and different sunspot observational records. In order to get a basic understanding of the difference in correlation between radionuclides sources we firstly started to investigate the correlation between the longest records of ^{10}Be (GRIP ice core) and ^{14}C (Intcal13). The number received were 0,75 which is a moderately strong correlation (see section 2.1). This means the probability of the records respond to the same changes in solar activity is better. GRIP and NGRIP ice core exhibit a correlation coefficient of 0, 22. By using a statistical technique called "moving average" we can see if a better correlation could be reached when focusing on the longer-term changes. By averaging 5 values to one during a 5 year interval, values which were too deviant from the other could be dampened. With the help of this technique the correlation coefficient increases to 0,43. This value is much better but one has to keep in mind that less independent data points often result in a better correlation coefficient since more values also increase the amount of spurious data. This increase in correlation coefficient indicates that both records more closely show the common solar induced production signal. The remaining differences can be due to the ice cores being from different places which have been affected differently by deposition processes.

The correlation between historical sunspot from Wittmann & Xu (1987) and the ^{14}C Intcal13 series gave us the correlation number of -0,01 and 0,01. There are two values because the historical archives are based on frequency of sunspots and therefore several sources the same year could have been observing the same sunspot. The first number (-0,0) the highest number of sunspot observations were included in the analysis, which basically means if 2 observers have recorded 1 observation and a third observer has recorded 2 observations the same year then the latter has been prioritized. With the positive correlation coefficient the quantity of observations has instead been prioritized. The correlation number is too close to 0 to contain any useable data (see section 2.1).

Moving into the 16th and the 19th century the International sunspot number and the group sunspot number becomes accessible as a replacement to the historical sunspot observations. If these are correlated to one another the number of 0,96 is received. This is a very strong correlation. Maybe it's not surprising since they are mostly using the same records within the period they are overlapping. If the GSN is compared to the NGRIP ice core ^{10}Be data the correlation coefficient is -0,33 and if ^{14}C and GSN are correlated to each other a value of -0,6 is presented. Both values are negative which is expected since the GSN is compared to radio-



(*a*)

(*b*)

(*c*)

Fig 9. Diagrams showing radionuclide and sunspot intervals. X-axis shows time in A.D and Y-axis sunspot number or radionuclide values.

nuclide data and should be anti-correlated.

5. Discussion

The solar activity has changed substantially during the last 2000 years with the biggest change occurring during the last 600 years. The correlation analysis was done with series judged by the author to be the most important for an inter comparisons. The thesis tried to make good use of the historical sunspot notations by comparing observations to other related records, such as ^{14}C and ^{10}Be.

The amount of sunspots observation was not only related to increase/decrease in solar activity but also to the interest and possibility recording solar activity. This basically means a period of time which is characterized by a high amount of observation does not necessarily mean that the period was characterized by a higher solar activity but it might only reflect the interest in such observations. This statement is supported if the naked eye sunspot archives is compared to the ones of ^{10}Be and ^{14}C where for instance 800-900 A.D describes a limited solar activity (*Fig 9* (*a*, *b*)). If compared to 1000-1200 A.D the frequency of observation is much higher but the solar activity reflected by the radionuclides proves it was approximately the same. The naked eye sunspot record is irregular to changes in solar activity apart from 2 periods (1077-1204) and (1356-1382) where observations seem to correspond to changes in radionuclide production. The strong correlation coefficient between the ^{10}Be GRIP ice core and the Intcal ^{14}C data proves that they indeed reflect the same trend in solar activity. Comparing the ^{10}Be data from the GRIP and NGRIP ice cores the low correlation is surprising. Comparing two ^{10}Be records one would expect a high correlation between them. One possible explanation are local variations of precipitation or topography which possibly can change the ^{10}Be flux. It could also be due to the NGRIP and GRIP data have different resolution when sampled, which means the records could vary in frequency. To really compare these ice cores the records NGRIP should be resampled and try to match the same resolution as the GRIP record (Muscheler, 2014, pers. Comm., 2th June).

Compared to the naked eye sunspot number the ISN and GSN is recorded more or less frequently which makes it much more usable when determining solar activity. Studying the time interval in which GSN and naked-eye observations are overlapping (1600-1900 A.D) we conclude that the historical sunspot number is not a reliable record of solar activity variations.

5. Conclusion

The radionuclide records remain the most trustworthy records for sun activity during the last 2000-years. The naked eye sunspot archives have a limited use until the ISN and GSN are introduced as methods tracing past solar activity. The correlation analysis reflects a trend where the correlation between naked eye sunspot archives and other records show poor values and provides no substance for further investigation. When the sunspot archives are replaced by the GSN and ISN when moving into the 17th century the correlation show up more promising results.

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7.1 Sunspot Data

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