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Solar signals in instrumental historical series of meteorological parameters

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Abstract. One of the main objectives of climatologists is to understand to what extent climate variations observed during the last century are due to anthropic influence and what role the natural fluctuation of the climate system plays. The Sun is the source of energy that warms us, therefore that is where to look for the main causes (direct or indirect) of the natural variations in terrestrial climate. Several studies have been made into trying to understand how the variation in energy radiated from the Sun influences climate. In particular, in the literature there are many studies aimed at identifying the periodicity of different solar cycle activities in meteorological data series. The main problem is the difficulty in finding long homogeneous instrumental series. This study shows the results obtained and the hypotheses advanced by analysing a database of secular instrumental series, reconstructed by us, concerning a large area of Europe surrounding the Alps.

Key words. Sun-climate relationships – climatic changes – solar activity

1. Introduction

The land surface absorbs the radiation it receives from the Sun. (in particular short waves - ultraviolet - that can cross the atmosphere very easily, whose energy, due to atmospheric and oceanic circulations, is distributed and then re-emitted towards space in the form of longer wave radiation (infrared). On a general global scale the energy received from solar radiation is more or less balanced by that radiated towards the outside of the Earth. Anything that changes the rate of absorption or re-emission, or somehow changes the process of redistribution of energy in the atmosphere between the atmosphere and the ocean, can influence terrestrial climate. The causes that provoke effects on terrestrial climate can be divided into two categories: natural and anthropic. Among *natural causes* there are: variations in the Sun's radiation (that will be examined in detail later); the interaction between the different components of the climate system (as, for example, atmosphere and ocean, which leads to phenomena such as el Nio); volcanic eruptions, that disgorge great amounts of dust into the atmosphere, and alter its transparency to the Sun's rays; and continental drift. By "anthropic causes" we mean all those effects that are somehow connected to mankind's action

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for example: the introduction of greenhouse and aerosol gases into the atmosphere (that alter processes of absorption and re-emission of radiation); and exploitation of the land (a cause of changes in the albedo). All these climatic changes can have a negative or a positive effect on the radiation balance:

- an increase in the concentration of greenhouse gases causes a reduction in the Earth's efficiency at radiating towards space, which leads to positive radiation forcing that tends to heat the low layers of the atmosphere;
- tropospheric aerosols of anthropogenic origin (coming from the combustion of fossils and organic materials) can reflect or absorb solar radiation depending on their characteristics. Furthermore, they can alter the amount of cloud cover, as well as the reflectiveness off the clouds themselves.

The climate's response to the variation in this radiation forcing may occur on different time scales, just think about the great thermal capacity of the oceans and the dynamics of the polar caps. Climatic changes caused by mankind's influence are hidden in a background of natural changes that occur on a wide range of time and space scales, caused by external forcing (such as changes in radiation) or simply the result of complex interactions between the various components of the climate system. One of the main aims of climatologists, besides identifying climate changes in progress, is to understand the anthropic influence on such changes, and to do that it is necessary to quantify the contribution of single forcing factors, including solar changes. There are different opinions about the latter aspect especially among those who study models for the forecast of future scenarios: some maintain that the changes in the Sun's activity have little effect on climate changes and that considering them in the models would only further complicate an already complex area of research and add more uncertainty to the results. Anyway, results obtained by comparing instrumental data of global temperature of the last 150 years with simulated values show that the greatest contribution to warming is anthropic. However, the uncertainty about the results must be underlined: by comparing the forecasts for the next 100 years obtained by different models a wide range of possible scenarios can be observed. On the other hand one mainstream of thought is that the variation in radiation is surely a relevant forcing factor of terrestrial climate. This hypothesis is supported by experimental data.

2. Variations in solar radiation and terrestrial climate

Solar radiation on our planet may vary fundamentally for two reasons: one is astrophysical, related to the changes in solar activity due several phenomena (sunspots, Sun wind, flares, getti di massa coronale, etc.) that have a temporal cyclic nature, and one is astronomical, due to small changes in the relative position between the Sun and the Earth. Let us examine the latter aspect.

2.1. Milankovitch's theory

If we consider the history of our planet, marked by a succession of glacial and post glacial eras, we can understand how the changes in solar radiation have had a fundamental role; in this case it is not changes intrinsic to solar activity that have caused these climatic upsets, but small changes that the Earth's orbit and its axis of rotation and revolution undergo over time and they change its position in relation to the Sun.

The mutual gravitational attraction of the Earth and other planets causes changes in the eccentricity of the orbit: it ranges from a maximum of 0.0655 to a minimum of 0.0018 in 100,000 years (being currently equal to 0.017). The inclination of the Earth's axis with regards to the ecliptic is not constant: it varies between a maximum of 24° 20' and a minimum of 21° 55' within a period of about 41,000 years.

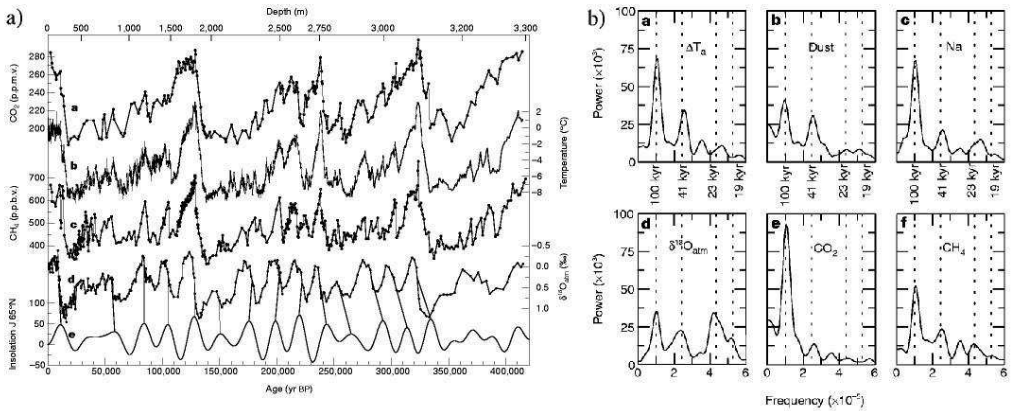

Fig. 1. a) Vostok's temporal series; b) Spectral properties of Vostok's temporal series (from Petit et al. (1999))

The Earth's axis, currently inclined at 23° 27' in relation to the orbital plane, describes a cone, with its tip in the centre of the Earth, in a period of about 26,000 years and in the opposite direction to that of the planet's rotation (Luni-Solare precession). The changes in the inclination of the Earth's axis implies an identical change in the line of the equinoxes: it will move in a clockwise direction as the Luni-Solare precession and with the same period (50" of arc per year). To complicate things another millenary motion contributes: that of the major axis of the Earth's orbit (line of apsides), which is in the same direction as that of the line of the equinoxes, thus reducing the period. In conclusion there is a precession of the equinoxes with a periodicity around 19,000 years and 23,000 years.

In the 1930's Milankovitch presented the results of a theoretical study on climatic changes based on the possible combinations of millenary motions. When all motions have the effect of diminishing summer solar radiation there is a glacial phase, in the opposite case there is a retreat of the glaciers.

The recent completion of Antarctic glacial sampling at the Russian station of Vostok enabled the reconstruction of climatic changes up to 420,000 years into the past (Petit et al. 1999). From a spectral analysis of the historical series, rather marked temporal oscillations emerged around the periods of 100,000 years, 41,000 years and between 19,000 and 23,000 years that seem to confirm Milankovitch's theory (figura 1). Another very interesting aspect is the trend of carbon dioxide concentration: as can be well seen, the concentration of atmospheric CO_2 has not always been constant, but has varied over time, parallel to temperature, certainly not caused by mankind (figura 1).

2.2. *Solar activity and terrestrial climate*

It should be noted, first of all, that there are few scientists who research this subject, and for most of those who do the Sun-climate relationship is only a minor topic of their study. That explains why little progress has been made. In fact, from 1850 to 1992 the number of publications on the subject is about 1,900, which corresponds to 0.25% of scientific publications in a year. However, there has been increased interest in the last 10 years: at the beginning of the 1990's studies by Friis-Christensen and Lassen (Friis-Christensen and Lassen 1991) have given new impetus to this area of research, leading to new important results. There is, however, a lot to do in order to understand the phenomenon.

Direct measures of solar radiation on the Earth's atmosphere are only available for recent decades, that is since the first satellites were launched to measure it. To study the effects of solar variations on the climate, in particular for the past, when anthropic influence on climatic changes was irrelevant, its activity should be studied by indirect measures (proxy data). The index mostly used as proxy data for solar activity is the number of sunspots (Wolf Sunspot Number of Zurich). Other markers that are often used are the geomagnetic indexes "aa", whose series begin in the second half of the 1800's, and authors available from far earlier times. With regards to the climate, the marker most widely used to study the variations over time is undoubtedly temperature. Also in this case direct measures can be used, i.e. instrumental series, or proxy data. The advantage of direct measures is to provide more precise information of the variable studied, the greatest disadvantage is the scarce temporal cover: obviously instrumental series of meteorological parameters begin from when instruments became available to measure them. Proxy data allow us to go back much further in time, but uncertainty is greater and it increases the further back we go. Proxy data are useful to study changes over a very long time scale with a wide range (this range must be greater than the uncertainty of the proxy data ??), but they cannot provide any significant information about short-term changes within a narrow range; for this instrumental series are indispensable.

2.2.1. From the XVII century to the present

Since the first sunspots were observed, we have tried to understand whether they have any influence on the terrestrial climate. The first study dates back to 1645 when Antonii Mariae de Rheita of Antwerp observed that when the number of sunspots increased, the climate was stormier and colder. Riccioli in 1651 and Kircher in 1671 arrived at similar conclusions.

n 1729 J. B. Weidenburg of Helmstadt associated cold and stormy weather to an increased number of sunspots. Herschel in 1809 and Flaugergues and Gruithuisen in 1823 did the same. After years of observation they concluded that the climate was hot when there were no sunspots and cold when there were several. 1870 is a particularly important date: C. Piazzi Smyth submitted an article to the Royal Society with a title that claimed, based on solar radiation measurement of the period 1837-1869, the existence of an 11-year cycle in temperature, and that this must be induced by the Sun. This article was published only several months after it was submitted. In the meantime, in 1871, E. J. Stone submitted another study that arrived at the same conclusion, and an argument broke out between the two authors as to who was the first to discover this phenomenon. The same periodicity in temperature was observed by Wladimir Koppen in 1873. He added that the clearest signal was a negative correlation between temperature and sunspots from 1815 to 1854, whereas, from 1777 to 1790 the correlation was positive. In 1914 Wladimir Koppen updated his study with a century of data and arrived at the same conclusion. Therefore, since the early 1900's all studies have reached the same conclusion, i.e. that temperature is inversely correlated to the number of sunspots. In the decades that followed there were many contrasting results and a lot of confusion that led to a loss of the argument's credibility. The main problem was the inversion of the sign of correlation between the two variables.

This fact has notable implications on the scientific results of the era. In fact, without taking this fact into consideration, a simple spectral analysis gives different results according to the time interval considered, and thus different researchers obtain contradictory results. Today there are more sophisticated techniques of spectral analysis (wavelet and cyclographs) that show the appearance and disappearance of a given periodicity. Robert G. Currie started a systematic re-examination of temperature in the 1970's, which continued until the 1990's, by using new spectral analysis techniques (MESA). In 1974 he published an analysis of 226 stations distributed over the planet and found a signal around a periodicity of 10.6 years in many of them. In the same time interval the periodicity found in the sunspots was 10.7 years.

Until now, as far as periodicity is concerned, we have only considered the variations in 11 years of solar and climate activity, but the Sun presents variations even on longer time scales that seem to be parallel to some climatic variation. In 1853 Wolf had already observed a cycle of 83 years in the sunspots. However, this discovery had been forgotten for a long time until the early decades of the 1900's. In this period in particular W. Gleisberg noticed an 80-90 year periodicity and published so many articles about it that since then this variation became known as the *Gleisberg cycle*. In the series of sunspots (from 1700 to the present) only three Gleisberg cycles can be observed and they are too few to conclude anything. Recent techniques have enabled the use of the abundance of some cosmogenic isotopes (^{10}Be and ^{14}C) to reconstruct solar activity on much longer scales. Let us examine an example of reconstruction obtained by ^{14}C (Eddy 1976; Eddy and Boornazian 1979). The curve of ^{14}C (figure 2) follows the envelope of sunspots quite faithfully including the Dalton Minimum and the Maunder Minimum. Going back in time the Spoerer Minimum can be observed (around 1500) and the Medieval Optimum (the Viking colonisation goes back to this period; the name Greenland gives an idea about the environment at this time, very different from the present perennial glacial extensions).

Before Eddy's study, the period relevant to the Mounder minimum was not considered in the analysis because it was thought to be due to measurement errors.

Based on all the correspondence found among an abundance of ^{14}C and historic climatic information, Eddy concluded that the sunspot envelope was a good indicator of radiation. From that moment on it was preferred to sunspots as the best proxy data of solar activity. In 1991 Reid (Reid 1991) noticed a fair agreement between the sunspot envelope and the surface temperature of the oceans (SST). However, this study was criticised because SST measurements are sporadic and mainly based on observations by ships. Besides, measurement techniques have changed over time, making the construction of an autoconsistente series difficult. Friis-Christensen and Lassen (Friis-Christensen and Lassen 1991) used the sunspot envelope (number of sunspots per cycle) as proxy data of solar activity and compared it with the mean Northern Hemisphere temperature, from 1850 to the present, to observe some inconsistencies: generally the sunspot envelope signal seems to be late with regards to the temperature, and that is contrary to what we would expect for any influence of solar activity on terrestrial climate. Having confirmed that, the authors looked for a new solar index to better describe temperature trend in the Northern Hemisphere. They chose the length of the solar cycle, and what they found was an excellent match between the two series, even though this can only be a qualitative judgement, given the low number of data.

3. A new 240-year temperature database: study of the solar signal

In the scope a European project (AlpClim) more than 100 temperature series were collected (some of them beginning in 1760) according to alpine region (from 43 to 49 degrees of latitude and from 3 to 19 degrees of longitude). This series was rigorously homogenised (the details of the work are in Böhm et al. (2001)). The result was a mean series of alpine temperature over 240 years with a good signal/noise ratio due to the high number of stations.

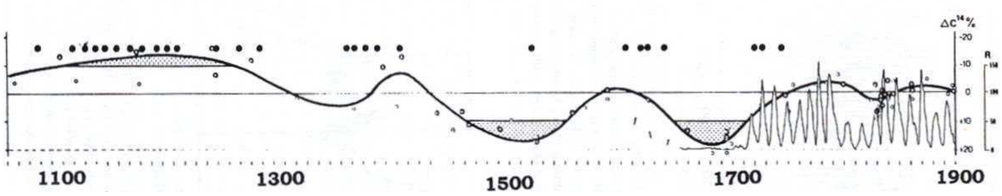

Fig. 2. Values measured of ^{14}C (thick curve) and number of sunspots (thin curve) (from Eddy (1976); Eddy and Boornazian (1979))

We used this series (Mean Alpine Temperature, MAT) to study the Sun-climate relationship by extending the analysis into the past, until 1760.

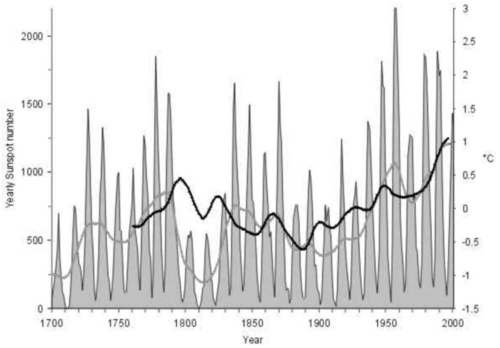

Fig. 3. Series of alpine temperature (black curve) and sunspots (shaded areas)

Figure 3 shows the annual anomalies of MAT and the sunspot series (Rz) filtered with a passa-basso Gaussian filter with a 22-year window. The long-term behaviour of Rz matches the temperature especially for the 1860-1998 period, whereas for the first part of the series the relationship is not as clear. However, some relationships can be noted, for example a minimum in temperature at the Dalton minimum around 1810. It should be remembered that the quality of the series of sunspots is debatable before 1818 (McKinon 1987). Besides, they are not representative of the solar activity in its entirety. The analyses performed by Friis-Christensen and Lassen (Friis-Christensen and Lassen 1991) were repeated with this new database (figure 4). By using the mean sunspot number inside every cycle and the length of the Schwabe cycle as a proxy for solar activity, there is a marked reduction in the correlation with the temperature in the period before 1850.

3.1. Spectral analysis

We studied the periodicities in the MAT by spectral analysis. Figure 5a shows only a peak around 7.8 years, which is a typical periodicity of the North Atlantic Oscillation (figure5b), whose spectrum also shows a peak indicating a solar-type periodicity (11 years). Considering the two periods, 1760-1890 and 1890-1998, separately, an increase in the significance of the 7.8-year peak is noticed in the second part of the series, as well as the appearance of solar periodicities (11 and 22 years), which were not present in the spectrum concerning the first part of the series. To understand better the behaviour of the periodicities observed throughout the length of the series, we carried out a more powerful spectral analysis by using cyclographs (Galli 1988). With this type of analysis it can be studied whether or not a periodicity persists throughout the length of a series with the same phase, and if not, when it is stronger or weaker. Figures 6a and b show the behaviour of the Schwabe and Hale periodicities throughout the 260 years of the MAT: in both cases there is a phase inversion in the second half of the 1800's, with a significance greater than 95% in the second

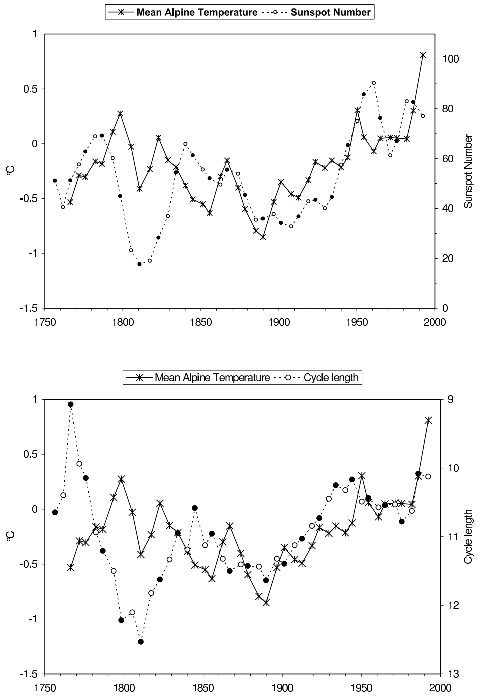

Fig. 4. Anomalies of MAT (scale on the left) and trend of the mean value of number of sunspots inside every cycle (top graph) and the length of the solar cycles (bottom graph). The full circles represent the minimum to minimum cycles; the empty circles represent the maximum to maximum cycles.

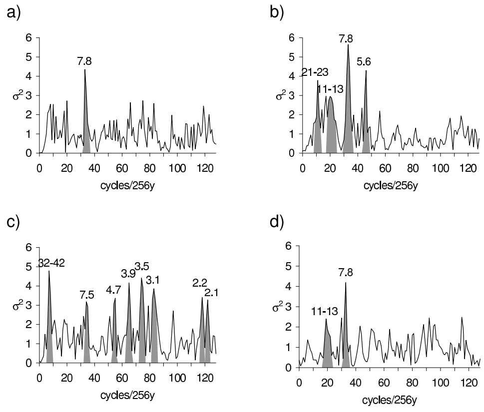

Fig. 5. Spectral analysis of alpine temperature a) for the 1760-1998 period, b) for the 1890-1998 period, c) for the 1760-1890 period and d) of the NAO for the 1890-1998 period

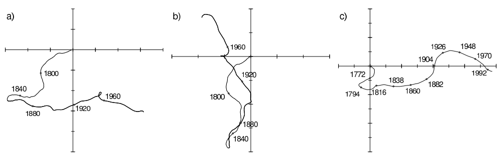

Fig. 6. Cyclographs of the Schwabe (a) and (b) Hale periodicities for alpine temperature and 11-year periodicity for sunspots (c)

part of the series. If we observe the cyclograph of the 11-year periodicity, calculated for the series of sunspots, we can see that before 1850 said periodicity was less than 11 years, whereas after that date, it was greater (since the curvature was towards the left and towards the right respectively before and after 1850). Based on these elements and the results obtained by Tobias and Weiss (2000) the following hypothesis can be made: terrestrial climate has a high internal variability supporting oscillations with many frequencies; the direct effect of the variations on the Sun's radiation in driving climatic changes is thought to be rather small and amplification mechanisms are needed to favour the role of solar variability; resonances may play a key role in the dynamics of the climate system: when a frequency typical of solar forcing is near a frequency of the climate system, then there is a great increase in the Sun's role.

4. Recent results: cosmic rays as the missing link in the Sun-climate relationship

It is known that our atmosphere is continuously bombarded by a flow of particles (mainly protons) coming from outside our solar system (cosmic rays) that is more or less intense depending on solar activity. Cosmic rays, entering the atmosphere, lose energy when they hit and ionise air molecules (they are one of the main sources of ions present in the atmosphere around which the humid air condenses and leads to the formation of clouds). Marsh and Svensmark (2000), studying global cloud cover from satellite data for the last 20 years, observed a good correlation between the mean amount of cloud cover at low altitude (below the level of 680 hPa) and the flow of cosmic rays. They suggest that this might be the missing link explaining the connection between solar and climate activity; in fact, an increase in mean cloud cover at low altitude causes a decrease in temperature on the ground and vice versa.

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