Long-Term Variability of Summer Temperature in the Southern Part of South America—Is There a Connection with Changes in Solar Activity?

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Abstract: Reconstruction of the summer (December–February) temperature of the southern part of the South American continent was studied in the time interval 900–1995. Significant temporal variations with periods of ca 520 years, ca 220 years, and 90–150 years have been found. Since bicentennial and century-type climatic oscillations can be a manifestation of the respective solar cycles of Suess and Gleissberg, the correlation between the corresponding climatic and solar periodicities was investigated. Data on the concentration of cosmogenic beryllium in the ice of the South Pole, solar modulation potential, and total solar irradiance, reconstructed using cosmogenic isotopes, were used as indicators of activity of the Sun. It turned out that there was no correlation between bicentennial and century-long variations in solar activity and temperature in the southern part of the South American continent. On the other hand, a fairly significant (c.l. 0.92–0.94) correlation between the multi-centennial (periods of 393–548 years) temperature variations and solar proxies was found. Based on these results, it is difficult to draw an unambiguous conclusion about the solar forcing on the climate of South America. It is more important that the results obtained confirm the existence of natural variations in the Earth’s climate with periods close to solar cycles but independent of changes in solar activity. The presence of such periodicities can seriously complicate the identification of the solar influence on the climate, which should be taken into account in further solar-climatic studies.

Keywords: dendroclimatology; climate; solar activity

1. Introduction

For a long time, researchers have been looking for the possible influence of solar activity on Earth’s climate [1–3]. Study in this area has advanced considerably in recent decades, and a significant amount of evidence has been collected to show that solar activity influences climate both directly via the total solar irradiance [4] and indirectly via corpuscular cosmic radiation, mainly galactic and solar cosmic rays [5,6]. Nevertheless, the detailed physical mechanism that explains the relationship between solar activity, space weather, and climate is still uncertain [7]. Most of the evidence for solar-climate relationships comes from the Northern hemisphere (this part of the globe is better covered by climate data), while the evidence from the Southern hemisphere is not so abundant (see [8]). Moreover, there is evidence of the existence of several inherent variations in the Earth’s climatic system with periods close to those of solar cycles [9]. These periodicities can distort the solar influence on the climate and make it difficult to identify real solar-climatic relationships. Recent progress in the development of regional proxies makes it possible to study long-term and large-scale climate variability in the Southern hemisphere as well. Neucom et al. [10] reconstructed austral summer (winter) surface air temperature fields back to AD 900 in Southern South America (SSA). Neucom et al. [10] used 22 annually resolved proxies covering a wide area of SSA (20°–55° S, 30°–80° W), SSA is the most perspective part of the continent for the search for solar influence since it is situated at the highest latitudes—a
zone where geomagnetic rigidity cutoff is lower and the penetration of cosmic ray particles, which may potentially affect the Earth’s climate, into the atmosphere is facilitated. This work is devoted to the search for a possible solar-climatic relationship in the high-latitude part of South America by means of the reconstruction [10] and solar activity proxies and using Fourier and wavelet analysis.

2. Materials and Methods

The data on the total solar irradiance (TSI), solar modulation potential Φ, and beryllium concentration in Antarctic ice used in the work are shown in Figure 1 and described in Table 1.

![Figure 1](image.png)

**Figure 1.** (A)—summer temperature in SSA [10]; (B)—concentration of \(^{10}\)Be in Central Antarctica relative to the 843-1876 AD average [12]; (C)—solar modulation parameter [12]; (D)—total solar irradiance [11].

**Table 1.** Solar and temperature reconstructions.

| Reference             | Type of Proxy Data                  | Reconstructed Value       | Period   |
|-----------------------|-------------------------------------|---------------------------|----------|
| Neucom et al. [10]    | Multiproxy                          | Austral summer temperature | AD 900–1995 |
| Bard et al. [11]      | \(^{14}\)C, \(^{10}\)Be from South Pole | TSI                       | AD 843–1961 |
| Delaygue and Bard [12]| \(^{10}\)Be from South Pole and Dome Fuji (77°19′ S, 39°42′ E) | Φ                         | AD 695–1982 |
| Delaygue and Bard [12]| \(^{10}\)Be from South Pole and Dome Fuji (77°19′ S, 39°42′ E) | \(^{10}\)Be             | AD 695–1982 |
In the present work, I used reconstructions of the total solar irradiance and solar modulation parameter $\Phi$ obtained from Antarctic cosmogenic records because the studied area in SSA lies close to the high latitude Antarctic region. The high latitude part of the globe is a zone where geomagnetic rigidity cutoff is lower and the penetration of cosmic ray particles, which may potentially affect the Earth’s climate, into the atmosphere is facilitated. Obviously, the same cosmic ray fluxes produce a beryllium record in Antarctic ice, and therefore, if the solar-climatic relationship, mediated by cosmic rays, really exists, it should be more clearly identified by solar proxies from Antarctica. A study on the concentration of cosmogenic isotopes in natural archives is the basic tool for the reconstruction of solar activity prior to the instrumental epoch (before the beginning of the 18th century). Cosmogenic radiocarbon $^{14}\text{C}$ and radioberyllium $^{10}\text{Be}$ originate in the Earth’s atmosphere due to the effect of energetic galactic cosmic rays, which are effectively modulated by solar activity. These isotopes have long been known as reliable indicators of variations in solar activity at periods longer than about 80–100 years [13–15]. Reconstruction of various solar activity parameters is carried out by means of the data on cosmogenic isotopes and using various model assumptions of terrestrial processes that affect the concentration of these radionuclides in natural archives (geomagnetic field variations, distribution within the Earth’s system). In the present work, I used both two reconstructions and a raw $^{10}\text{Be}$ record in order to examine whether the model assumptions can influence the result. The study was performed by means of both the Fourier and wavelet approaches. I used: (a) Fourier spectra, normalized by variance, (b) local and global wavelet spectra obtained by means of the complex basis of Morlet [16], and (c) wavelet filtration performed by means of the real MHAT basis [16].

3. Results

Visual inspection of Figure 1 shows that the decrease in temperature in SSA by 0.6–0.8 $^\circ\text{C}$ during the 15th–16th centuries (apparent manifestation of a Little Ice Age) coincides with the minimum of total solar irradiance (the Spoerer minimum of solar activity). This may mean a positive relationship between long-term changes in temperature and solar activity. A study of long-term empirical and model-estimated patterns of solar irradiance forcing performed by Waple et al. [17] showed that in SSA, the surface temperature actually responded positively to changes of TSI in the long (multidecadal/century) time scale. Spectral properties of the reconstruction [10] were studied by means of wavelet and Fourier analysis. The second-order polynomial trend was preliminarily subtracted. Results of the analysis are shown in Figure 2B–D.

Both Fourier and wavelet analysis showed that there were significant time variations in the SSA temperature record with periods of about ca 530 years, about 250 years, and 90–140 years. These variations have already been found in the climate of various regions of the globe. Century-scale climate variability is worldwide but more pronounced in the Northern hemisphere [18–20]. The quasi-200-year climate variations manifested themselves in climate-related processes throughout both the Northern and Southern hemispheres (see Raspopov et al. [21] and references therein). The ca 550-year variation has so far only been found in the Northern hemisphere [22,23]. All three periodicities can be attributed to the influence of the solar cycles. The presence of the century-long cycle of Gleissberg and the bi-centennial cycle of Suess (de Vries) in solar activity have been established quite reliably (see [24]). Ca 500-year solar variation was reported by Lihua et al. [25]. Ogurtsov et al. [26,27] found evidence for the influence of the cycle of Gleissberg on temperature in Northern Fennoscandia. Raspopov et al. [21] found evidence for climatic (both temperature and precipitation) variations associated with the ca 200-year de Vries cycle in Central Asia. Xu et al. [23] reported a possible link between ca 500-year variations in solar activity in East Asia. That is why it is reasonable to investigate a possible relationship between the revealed temperature variations in SSA and changes in solar activity. Cross-wavelet spectra were calculated to examine the possible relation between summer temperature in SSA and solar activity. The two of them are shown in Figure 3.
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Cross-wavelet spectra show common features in the wavelet power of the temperature and solar time series, such as the peaks at 137, 216, and 520 years. Thus, cross-wavelet analysis also testifies in favor of the possible influence of solar activity on the climate of SSA. For further examination of a possible relationship between the solar-type temperature variations in SSA and activity of the Sun, correlation coefficients were calculated between time series wavelet filtered in the multi-centennial (393–548 years), Suess (186–282 years), and century-long (58–157 years) scale bands. It was found (see Figure 4) that SSA temperature shows some correlation with the solar activity proxies in multi-centennial scale band: $R_l(\text{SSA}, \text{TSI}) = 0.92 \ (p = 0.945)$, $R_l(\text{SSA}, \Phi) = 0.89 \ (p = 0.924)$. Confidence levels $p$ were estimated using a statistical experiment (see [26]). No correlation was found between bicentennial and century-long variations in temperature and solar activity. The obtained results are illustrated in Figure 4.
Figure 3. (A)—Local cross-wavelet power spectrum of temperature in SSA [10] and Φ [12]; (B)—local cross-wavelet power spectrum of temperature in SSA [10] and TSI [11]; (C)—global cross-wavelet spectra of temperature in SSA and Φ (thin gray line) and TSI (thick black line). The spectra are normalized to 0.95 confidence level calculated for red noises with the corresponding AR(1) coefficient.

Although the synchronism of multi-centennial oscillations in solar activity and climate looks convincing, it is premature to draw conclusions based on just two cycles.
Wright et al. [28] show that changes in solar irradiance could markedly affect the Southern Annular Mode—the leading pattern of atmospheric variability in the extratropical Southern Hemisphere, which strongly affect atmospheric circulation and, as a result, temperature, and precipitation across the Southern hemisphere, including SSA. On the other hand, analysis of only two multi-centennial cycles is not enough for a reliable conclusion, and thus further study using longer proxy series are required. More importantly, the detected bicentennial and century-type variations in SSA temperature do not correlate with the

Figure 4. SSA temperature [10] and solar modulation parameter $^{10}$Be in Antarctic ice [12] wavelet filtered in: (A)——SSA temperature [10] and solar modulation parameter [12] wavelet filtered in century-long (58.1–156.7 years) scale band, (B)——SSA temperature [10] and $\Phi$ [12] wavelet filtered in bi-centennial (186.1–282.4 years) scale band, (C)——SSA temperature [10] and $\Phi$ [12] wavelet filtered in multi-centennial (282.1–427.6 years). (D)——SSA temperature [10] and TSI [11] filtered in multi-centennial (393.4–548.7 years). Second-order polynomial trends were removed from all series. Thin lines show temperature, thick lines show solar proxies.

4. Discussion and Conclusions

The analysis performed showed a possible relationship between long-term (ca 530 year) variations in solar activity and temperature in SSA. The multi-centennial variations in total solar irradiance and temperature in Southern South America have been developing synchronously throughout the entire millennium. Figure 4D shows that the peak-to-peak amplitude of ca 530-year variation in TSI and temperature in SSA is 0.5–0.6 W × m$^{-2}$ (forcing of ca 0.1 W × m$^{-2}$) and about 0.08 °C, respectively. The temperature sensitivity in SSA to long-term changes in solar irradiance is about 0.5 °C × W$^{-1}$ × m$^2$ (see Figure 7 of [17]); thus, variation in solar forcing of 0.1 W × m$^{-2}$ can produce a corresponding variation of 0.05 °C in temperature. This means that the direct impact of the solar irradiance changes can explain a significant part of the multi-centennial variation in the temperature in SSA. Variability of the TSI can also influence the climate of SSA indirectly. Model experiments by Wright et al. [28] show that changes in solar irradiance could markedly affect the Southern Annular Mode—the leading pattern of atmospheric variability in the extratropical Southern hemisphere—which strongly affect atmospheric circulation and, as a result, temperature, and precipitation across the Southern hemisphere, including SSA. On the other hand, analysis of only two multi-centennial cycles is not enough for a reliable conclusion, and thus further study using longer proxy series are required. More importantly, the detected bicentennial and century-type variations in SSA temperature do not correlate with the
corresponding solar cycles. This provides new evidence in favor of the existence of natural variations in the Earth’s climate with periods close to the periods of solar cycles but not related to changes in solar activity, which is consistent with the results of [9]. The presence of such periodicities can seriously complicate the identification of solar-climatic relationships and serve as one of the reasons why long-term studies of the relationship between the Earth’s climate and solar activity have not yet yielded unconditionally reliable results. Therefore, this issue requires further study using new long temperature proxies from different parts of the world.

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