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How unusual is today's solar activity?

Arising from: S. K. Solanki, I. G. Usoskin, B. Kromer, M. Schüssler & J. Beer *Nature* 431, 1084–1087 (2004)

To put global warming into context requires knowledge about past changes in solar activity and the role of the Sun in climate change. Solanki *et al.*¹ propose that solar activity during recent decades was exceptionally high compared with that over the preceding 8,000 years. However, our extended analysis of the radiocarbon record reveals several periods during past centuries in which the strength of the magnetic field in the solar wind was similar to, or even higher than, that of today.

Solanki *et al.* combine radiocarbon (¹⁴C) data, visually observed sunspot numbers and models to extend the historical sunspot record over the Holocene. They exclude the most recent 100 years of the ¹⁴C record, which are influenced by ¹⁴C-depleted fossil-fuel emissions and atomic-bomb tests conducted since AD 1950. We extend the analysis of the radiocarbon record to AD 1950, which allows us to link the ¹⁴C-based solar reconstruction to instrumental measurements of solar magnetic modulation that cover the past 68 years^{2,3}.

The Sun influences the production rate of ¹⁴C in the Earth's atmosphere by modulating the galactic cosmic-ray flux through its magnetic field. Increased magnetic field in the solar wind causes a stronger deflection of galactic cosmic rays and lower radionuclide production rates in the atmosphere and vice versa. However, the atmospheric ¹⁴C concentration also depends nonlinearly on the geomagnetic field intensity and the global carbon cycle. These factors and their uncertainties need to be carefully included in the reconstruction of solar activity.

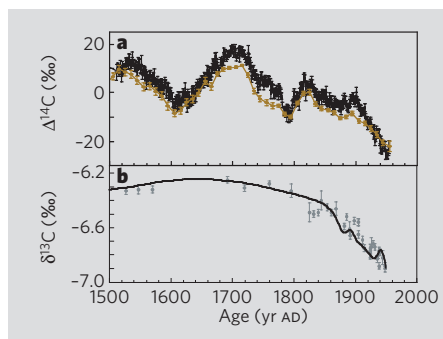


Figure 1 | Measured atmospheric ¹⁴CO₂, ¹²CO₂ and ¹³CO₂:¹²CO₂ ratios and model results for $\delta^{13}\text{C}$ from AD 1500 to 1950. $\Delta^{14}\text{C}$ and $\delta^{13}\text{C}$ denote the per mil deviations from a standard. **a**, Tropospheric radiocarbon from tree-ring measurements from the Northern Hemisphere⁴ (black) and Southern Hemisphere⁵ (brown). Error bars show one standard deviation. **b**, The Law Dome (Antarctica) $\delta^{13}\text{C}$ record¹⁴ (dots) compared with the output of the Bern model (black line). Error bars show one standard deviation.

We reconstructed ¹⁴C production rates from radiocarbon records^{4,5} (Fig. 1a) using two box-diffusion type carbon-cycle models, the box-diffusion⁶ and the Bern model⁷, and a three-dimensional ocean model coupled to a four-box land biosphere. The ¹⁴C production record was transformed^{8,9} into a record of the solar modulation parameter that describes the solar influence on galactic cosmic-ray deflection by normalizing it to neutron-monitor and ionization-chamber data covering the recent decades². Alternatively, balloon-borne estimates of galactic cosmic-ray deflection³ were used instead of the ionization-chamber data. Like Solanki *et al.*¹, we assumed that natural variations in the carbon cycle were small during the past millennium, which is consistent with ice-core CO₂ and ¹³CO₂ data and models¹⁰. We considered uncertainties in ¹⁴C data, fossil CO₂ emissions, the geomagnetic field and model parameters. Results are similar across the range of models and simulations. Calculations using the Northern⁴ or Southern⁵ Hemisphere ¹⁴C record, or both, reveal that differences between the ¹⁴C records do not affect our main conclusions.

It is standard practice to model the observed dilution of the atmospheric isotope ratios caused by the addition of isotopically depleted carbon from fossil and land-use sources. Emissions from fossil sources are prescribed, emissions from land-use sources are inferred from the atmospheric carbon budget, and the two-way exchange fluxes between reservoirs are simulated. The dilution of ¹⁴C is governed by the same processes that affect ¹³C. The good agreement between modelled ¹³C and ice-core data (Fig. 1b) supports the reconstructed rate of ¹⁴C production.

The comparison between the physical quantities, the ¹⁴C-production rate and the solar-modulation parameter, and the visually based sunspot record reveals similarities and striking differences (Fig. 2). The 11-year solar cycle is distinct in all records. On the other hand, solar magnetic modulation was higher or comparable to today during the late eighteenth (and twelfth) century and around AD 1600, whereas sunspot numbers were highest over the recent decades. Sunspot numbers fell to zero during the Maunder Minimum (AD 1650–1700), whereas ¹⁴C production and solar modulation continued to vary. The balloon-borne measurements³ imply lower values for the solar modulation parameter than the ionization-chamber data². Those data seem preferable because they agree better with the solar-modulation changes inferred by Solanki *et al.*¹ than do the balloon-borne measurements³. If

we include the Northern and Southern Hemisphere ¹⁴C records (three-dimensional model) and normalize the data to the balloon-borne record, we obtain very similar levels of solar modulation (black curve in Fig. 2b).

In any case, and irrespective of the data set applied, the recent solar activity is not exceptionally high (Fig. 2). The ¹⁴C results are broadly consistent with earlier reconstructions based on ¹⁰Be data from the South Pole, which show that production rates around AD 1780 and in the twelfth century were comparable to those observed today¹¹. We conclude that

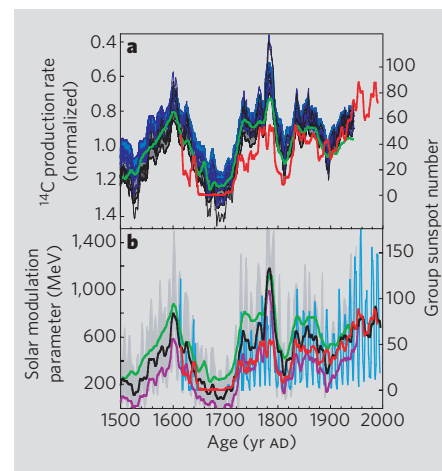


Figure 2 | Radiocarbon production rate and solar modulation parameter compared with the group sunspot number. **a**, ¹⁴C-production rates (blue) were calculated from the Northern Hemisphere ¹⁴C record with two carbon-cycle models^{6,7}; fossil-fuel emissions ($\pm 10\%$) and air-sea CO₂ exchange rate ($\pm 30\%$) were varied systematically in sensitivity calculations (various lines). The shadowed area shows the 1σ errors resulting from 100 Monte Carlo simulations. We included Northern Hemisphere⁴ and Southern Hemisphere⁵ ¹⁴C data in a three-dimensional ocean model calculation (green line). The black curves show the ¹⁴C-production rate corrected for the geomagnetic field intensity^{8,9}. The red curve shows the group sunspot number¹⁵. All records are normalized and show 11-yr averages. **b**, The solar modulation parameter was calculated¹⁸ from the ¹⁴C-production rates and from ionization-chamber and neutron-monitor data². The grey band shows results from annual ¹⁴C data, including the error range based on the Monte Carlo calculations and uncertainties in the geomagnetic data⁹. The black line shows 11-yr averages (best estimate). Unfiltered (blue) and 11-yr-averaged (red) sunspot numbers¹⁵ are shown for comparison. The green line shows the three-dimensional model results. The purple line depicts results using an alternative neutron-monitor record³ that indicates a stronger trend from 1937 to 1950 than the ionization-chamber data².

the link between the visually based sunspot numbers and solar-modulation parameter is neither straightforward nor yet understood, and also that solar modulation must have reached or exceeded today's magnitudes three times during the past millennium.

Uncertainties in low-frequency changes increase when reconstructions are extended from the past few centuries to the past millennia. The low-frequency Holocene ^{14}C variations can largely be explained by changes in the geomagnetic field as they lie within the errors of the archaeomagnetic data set used for correction¹². Some palaeomagnetic records¹³ indicate higher geomagnetic intensities around 7000 BC, which indicate that solar activity could have been lower during this period than is suggested by Solanki *et al.*¹.

What do our results mean for climate change? It is speculative to translate solar magnetic modulation quantitatively into irradiance because we do not have a clear mechanistic understanding or evidence from data. Still, records of solar magnetic modulation

proxies are often used as direct indicators of solar irradiance in climate and carbon-cycle model calculations (see ref. 10, for example). The reconstruction by Solanki *et al.* implies generally less solar forcing during the past millennium than in the second part of the twentieth century, whereas our reconstruction indicates that solar activity around AD 1150 and 1600 and in the late eighteenth century was probably comparable to the recent satellite-based observations. In any case, as noted by Solanki *et al.*, solar activity reconstructions tell us that only a minor fraction of the recent global warming can be explained by the variable Sun.

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CLIMATE

Solanki *et al.* reply

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Muscheler *et al.*¹ claim that the solar activity affecting cosmic rays was much higher in the past than we deduced² from ^{14}C measurements. However, this claim is based on a problematic normalization and is in conflict with independent results, such as the ^{44}Ti activity in meteorites and the ^{10}Be concentration in ice cores.

Our results² are based on ^{14}C -production rates, Q , before AD 1900, which largely avoids the uncertainties arising from the extensive fossil-fuel-burning signal³ commonly called the Suess effect; however, Muscheler *et al.*¹ determine the relative ^{14}C -production rate (normalized to a mean value of unity) up to AD 1950. Their values were then scaled by a constant factor, determined such that the inferred cosmic-ray modulation strength, Φ , matches the values determined from ionization-chamber data measured after AD 1937. Uncertainties in the correction for the Suess effect thus directly translate into errors in Φ . Muscheler *et al.* assert that the dilution of ^{13}C is governed by the same processes that affect ^{14}C , but this is an oversimplification. Although both isotopes are affected by fossil-fuel emissions, ^{13}C is, in addition, influenced by land-use changes. Further model parameters are thus available for adjustment when reproducing ^{13}C , so that this isotope cannot be used as an independent check on the ^{14}C reconstructions.

The calibration procedure for Φ seems

problematic because ionization chambers have uncontrollable drifts⁴. Moreover, the combined data record⁵ of the Cheltenham ionization chamber (AD 1937–53) and neutron monitors (since AD 1953), on which Muscheler *et al.* base their analysis, represents not the real cosmic-ray intensity but rather its detrended and normalized variation⁶. Direct balloon-borne measurements show that the cosmic-ray intensity before AD 1950 had a strong declining trend. As a result of scaling the ^{14}C -production rate on the basis of these inappropriate data, Muscheler *et al.* infer too low an average value of Q and, accordingly, too high a value of Φ . Because of the nonlinearity of the relationship between both quantities, this leads to particularly significant effects for small values of Q and results in a strong amplification of the associated large Φ values. The use of a more appropriate data set⁴ leads Muscheler *et al.* to results that are largely consistent with our reconstruction, except for a short period around AD 1780 (purple curve in their Fig. 2b). However, they instead use their problematic original scaling ('best estimate', black curve).

By contrast, our model² consistently reproduces the values of Φ determined from modern cosmic-ray measurements without any scaling or parameter adjustment. Comparing the values of Φ determined from the ^{14}C -production rate before AD 1900 and the values computed from the group sunspot number up to the

present⁷, we find that both curves match each other before AD 1900 (see supplementary information in Solanki *et al.*²) and, at the same time, that the latter Φ agrees very well with the values derived from neutron-monitor and balloon data⁸, in contrast to the claim by Muscheler *et al.*¹.

Furthermore, their large values of Φ contradict the integrated cosmic-ray flux measured by the abundance of ^{44}Ti (half-life of about 60 years) in meteorites^{9,10} that have fallen since AD 1766. The ^{44}Ti activity in meteorites is completely independent of transport effects and redistribution in the Earth's atmosphere, so it provides direct measurements of past cosmic-ray flux. The 'best estimate' of Muscheler *et al.* yields a ^{44}Ti activity that is systematically too low, whereas our reconstruction fits the measurements well.

The abnormally high modulation parameter around AD 1780 obtained by Muscheler *et al.* is also not reflected in results obtained for ^{10}Be . South Pole data¹¹ from around AD 1780 show about 55% of the Maunder minimum level, whereas the value of $\Phi = 1,200$ MeV proposed by Muscheler *et al.*¹ would imply a much stronger reduction, to about 30% (ref. 12). Similarly, ^{10}Be data from Greenland do not show a prominent dip at around AD 1780. Neither do other proxies (such as sunspots¹³, aurorae¹⁴ and polar nitrates¹⁵) indicate particularly strong solar activity around AD 1780.

We conclude that by basing their normalization procedure on inappropriate data, Muscheler *et al.* have heavily overestimated the solar modulation parameter before AD 1950, which was further exaggerated by the nonlinear relation between Q and Φ .

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