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 correction[12]. Some palaeomagnetic records[13] 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 deduced[2] 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 results[2] are based on ^{14}C-production rates, Q, before AD 1900, which largely avoids the uncertainties arising from the extensive fossil-fuel-burning signal[3] 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 drifts[4]. Moreover, the combined data record[5] 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 variation[6]. 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 set[4] 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 model[2] 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 present[7], 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 data[8], 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 data[11] 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 sunspots[13], aurorae[14] and polar nitrates[15]) 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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