There is also a tension between the urgency of deploying CCS and the time needed for engaging in a subtle process of social learning. In practice, this tension may be moot, because the rollout of CCS has been far slower than expected. Nevertheless, project developers and other advocates seized by the urgency of deployment and value for money may continue to under-invest in social learning, which could represent a significant opportunity lost. Markusson and colleagues[2] show that the ways in which projects are designed, structured and organized have strong implications for the learning that occurs within and around them — which might in turn bring significant rewards in terms of knowledge diffusion and societal and political support. The question is whether policymakers and project developers are willing to invest more than rhetoric in a wider definition of learning. ❒

*David Reiner is at Judge Business School, University of Cambridge, Cambridge CB2 1AG, UK.*
*e-mail: dmr40@cam.ac.uk*

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SOLAR PHYSICS

# Shining a light on solar impacts

Comparing changes in temperature and solar radiation on centennial timescales can help to constrain the Sun's impact on climate. New findings regarding the minimum activity level of the Sun reveal that comparisons made so far may have been too simplistic.

Mike Lockwood

Light and heat from the Sun power Earth's climate system, so it is often thought that changes in solar output must be responsible for large changes in climate. This thinking neglects a key fact about the Sun; it is very large. The huge thermal capacity of the outer part of the Sun means that there are only very small changes in the temperature of — and hence in the amount of radiation emitted by — the solar surface on millennial and shorter timescales. Almost all the changes that do occur on these timescales are caused by changes in magnetic fields in or near the surface. Observations from space show that the amount of radiation emitted by the Sun has varied by only about 0.1% over recent decadal-scale solar cycles[1]. Now two groups — Schrijver *et al.*[2], writing in *Geophysical Research Letters*, and Shapiro *et al.*[3], writing in *Astronomy and Astrophysics* — have produced strikingly different estimates of the changes that occur on centennial timescales.

The amount of solar radiation that reaches unit area at the average distance of the Earth from the Sun is known as the total solar irradiance (TSI). This quantity is thought to have been unusually low during the so-called Maunder minimum in the second half of the seventeenth century, when the Sun was almost devoid of sunspots. Temperatures were also unusually low during this period, at least in parts of the Northern Hemisphere, so it is often called the Little Ice Age. Evaluating the solar contribution to the warming since the Little Ice Age as well as the change in average TSI between the Maunder minimum and recent decades provides a unique opportunity to constrain the effect that centennial-scale changes in solar activity have on climate[4].

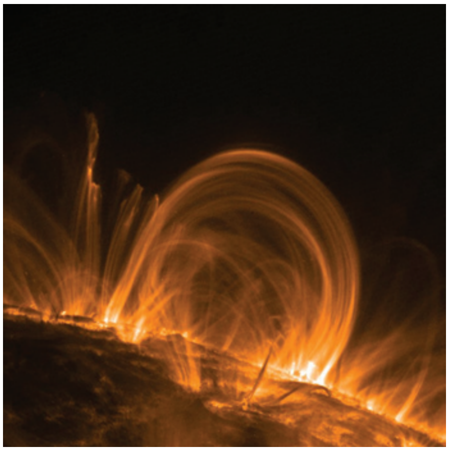

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**Figure 1 |** Loops in the Sun's magnetic field. The loops are visible because hot, dense, electrified gas known as plasma flows along them. Large-scale bundles of magnetic field (such as those shown) affect the amount of radiation emitted by the Sun where they thread the solar surface in 'active' regions. But debate remains about the variability of much smaller-scale surface fields that could affect emissions from the 'quiet' Sun between active regions. Schrijver *et al.*[2] and Shapiro *et al.*[3] suggest that errors in the quantification of the activity of the quiet Sun could mean that estimates of solar irradiance during the Maunder minimum are inaccurate — but they call for corrections in opposite directions. Image taken by the Transition Region and Coronal Explorer (TRACE) satellite.

Initially, our best estimates of this centennial-scale change in TSI were large[5]. These early estimates were based on surveys of the amount of radiation emitted by 'Sun-like' stars, but the results of subsequent, larger surveys did not confirm the key result, nor support its application to our Sun. More recent estimates have been derived by first quantifying the relationships between sunspot number, the solar magnetic flux and TSI over recent decades, then using these relationships to reconstruct TSI during the Maunder minimum. The reconstructions are based on records of sunspot number (derived from direct observations) and of the magnetic flux at the top of the solar atmosphere (derived from historic geomagnetic data or from cosmogenic isotopes in ice cores).

These studies (for example, ref. 6) indicate that the change in TSI since the Maunder minimum is comparable to the amplitude of recent solar cycles — approximately 0.1%. To put this number in context, a 0.1% change in TSI equates to a change in radiative forcing of the Earth's climate of 0.24 W $m^{-2}$ (ref. 7), which is small compared with the total forcing estimated to have been caused by increasing greenhouse-gas concentrations over the past century of about 2.5 W $m^{-2}$ (ref. 4). Schrijver and co-workers[2] argue that even 0.24 W $m^{-2}$ may be an overestimate for the long-term change in TSI, whereas Shapiro and colleagues[3] suggest that a value of near 1 W $m^{-2}$ is more likely. Where these two papers differ is in their treatment of the 'quiet' Sun: the sections of the solar surface without large-scale magnetic fields that occur between 'active' regions (where the radiated energy is known to be influenced by the magnetic field[1,6]) (Fig. 1).

Schrijver and colleagues[2] looked at the implications of the most recent minimum of the solar cycle, which took place in 2009. This minimum is unprecedented in the age of modern instruments[7], with a prolonged spell of sunspot-free days, and is in some respects similar to conditions during the Maunder minimum. They studied emissions from quiet-Sun regions and found no detectable difference in activity between the recent low solar minimum and previous minima, leading them to conclude that the activity level they observed represents a minimum or 'baseline' that also occurred during the Maunder minimum. This, in turn, suggests that the Maunder minimum TSI was closer to present-day levels than previously thought.

This conclusion is not shared by Shapiro and collegues[3]. They point out that very high-resolution observations show a great deal of small-scale magnetic structure on the surface of the Sun, which is not resolved in the images studied by Schrijver and colleagues[2]. Hence, even in the apparently quietest areas there is still a mosaic of regions with different magnetic field strengths[8]. They argue that if this fine-structure magnetic field dissipates, the activity of the 'quiet' parts of the Sun will decrease too. In the absence of any long-term data of sufficient resolution to detect these changes in the quiet Sun, Shapiro *et al.* assume their effect on TSI varies with the 22-year running average of solar activity, as reflected in cosmogenic isotope data from ice cores, which suggests that TSI was considerably lower during the Maunder minimum. This assumption cannot yet be tested, and their procedure may well over-estimate the decrease in TSI during the Maunder minimum, but the possibility of a decay in the quiet-Sun field means that Schrijver and colleagues may well have underestimated it.

To this confused picture, recent research adds yet another substantial complication: it seems that TSI may not even be the best parameter with which to quantify solar influences on climate. This is because recent satellite measurements indicate that the amount of ultraviolet radiation emitted by the Sun (which is responsible for the vast majority of the variability in TSI) is much more variable than previously thought, and that variations in the amount of visible and infrared radiation are actually in anti-phase with TSI[9]. These findings suggest that ultraviolet emissions were considerably lower than previously thought during the Maunder minimum, but that visible and infrared emissions were larger. The validity of these data has been questioned, but they are supported by changes in stratospheric ozone concentration[9], and should not be dismissed out of hand. Ultraviolet radiation influences Earth's stratosphere, which in turn affects the lowermost portion of the atmosphere[3], and may thus have unexpected 'top down' effects on climate[10].

Neither of the papers discussed here[2,3] gives a strong reason, as yet, to radically alter our current estimates of the change in TSI between the Maunder minimum and recent decades. However, they do point to the uncertainties that are still inherent in reconstructions of TSI over past centuries, and we should be prepared to have to revise the reconstructions — yet again — in the future.

Revising the estimates of the change in TSI one way or the other makes little difference to our understanding of the solar contribution to the rise in global temperatures over the past century, which is thought to be on the order of 10% or less[11]. This is because many studies calculate the solar contribution to recent climate change using robust statistical methods that depend on the 'shape' of changes in solar radiation over time, but not their amplitude. Nevertheless, the work of Schrijver and co-workers[2] and Shapiro and colleagues[3] is important for understanding the energy balance of the Earth and how it changes, and the two studies will doubtless spark further debates. Solar activity is presently declining[12], potentially returning the Sun towards Maunder minimum conditions[7], and the rate at which this transition occurs may ultimately determine how quickly these debates are resolved. ❐

*Mike Lockwood is at the Department of Meteorology, University of Reading, Earley Gate, PO Box 243, Reading RG6 6BB, UK and at RAL Space, Rutherford Appleton Laboratory, Harwell Campus, Chilton, Didcot, Oxfordshire OX11 0QX, UK.*
*e-mail: m.lockwood@reading.ac.uk*

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MITIGATION

# A sweetener for biofuels

The climate impact of biofuels is usually considered in terms of their net effect on greenhouse-gas emissions. The expansion of sugar cane into pastureland for biofuel production is now shown to also exert a direct local cooling effect.

Richard A. Betts

Greenhouse-gas emissions are not the only way in which humans can alter climate. Changes in the characteristics of the Earth's surface can also play a role, by affecting the fraction of the Sun's radiation that is absorbed by the planet, as well as the flows of energy and moisture into the atmosphere from the surface. Although emissions and uptake of carbon dioxide by forestry and agriculture are considered within policy discussions aimed at avoiding dangerous climate change, the changes in land-surface characteristics that accompany them are usually overlooked. Writing in *Nature Climate Change*, Loarie and colleagues[1] consider the case of sugar cane grown for use as biofuel in Brazil, and find that