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The minimal solar activity in 2008–2009 and its implications for long-term climate modeling

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[1] Variations in the total solar irradiance (TSI) associated with solar activity have been argued to influence the Earth's climate system, in particular when solar activity deviates from the average for a substantial period. One such example is the 17th Century Maunder Minimum during which sunspot numbers were extremely low, as Earth experienced the Little Ice Age. Estimation of the TSI during that period has relied on extrapolations of correlations with sunspot numbers or even more indirectly with modulations of galactic cosmic rays. We argue that there is a minimum state of solar magnetic activity associated with a population of relatively small magnetic bipoles which persists even when sunspots are absent, and that consequently estimates of TSI for the Little Ice Age that are based on scalings with sunspot numbers are generally too low. The minimal solar activity, which measurements show to be frequently observable between active-region decay products regardless of the phase of the sunspot cycle, was approached globally after an unusually long lull in sunspot activity in 2008–2009. Therefore, the best estimate of magnetic activity, and presumably TSI, for the least-active Maunder Minimum phases appears to be provided by direct measurement in 2008–2009. The implied marginally significant decrease in TSI during the least active phases of the Maunder Minimum by 140 to 360 ppm relative to 1996 suggests that drivers other than TSI dominate Earth's long-term climate change. **Citation:** Schrijver, C. J., W. C. Livingston, T. N. Woods, and R. A. Mewaldt (2011), The minimal solar activity in 2008–2009 and its implications for long-term climate modeling, *Geophys. Res. Lett.*, *38*, L06701, doi:10.1029/2011GL046658.

1. Introduction

[2] The simultaneous occurrence of the Little Ice Age and the Maunder Minimum remains pivotal in establishing the dependence of Earth's climate on solar influences [*Lean*, 2010]. This dependence is frequently attributed to a secular change in TSI. Estimation of the TSI during that period has relied on estimates of total and open unsigned magnetic fluxes based on extrapolations of simple ad-hoc dependences approximated from correlations with sunspot numbers [*Hoyt and Schatten*, 1993; *Tapping et al.*, 2007; *Vieira and Solanki*, 2010] - the only direct centuries-long record on solar activity - or even more indirectly via modulations of galactic cosmic rays reflected in radioactive-nuclide concentrations in polar ice [*Fröhlich*, 2009; *Steinhilber et al.*, 2009].

[3] The recent extended sunspot minimum during 2008 and 2009 showed the Sun in an unusually inactive state. In the yearly-averaged sunspot number, SSN (see Figure 1 for data from 1818 onward for which daily sunspot numbers are available), only five of 28 cycles since 1700 had a minimum lower than in early 2009, most recently in 1913. From mid-2008 until 2009/09, the fraction of spot-free days fluctuated around 82%, unprecedented in the age of modern instrumentation.

[4] In 2008 and 2009, very few, and only relatively small, sunspot-carrying active regions were observed. In contrast, thousands of small magnetic bipolar regions (the "ephemeral regions" with unsigned fluxes from ~ 10^{18} Mx to a few times 10^{19} Mx) emerged every day [*Hagenaar et al.*, 2003], and many more even smaller flux bundles [*Harvey et al.*, 2007].

[5] This unusually inactive state can be used to test proposed relationships between sunspot number, the solar magnetic field, and TSI, because it allows the solar photosphere to approach its globally quiescent state. This forms a baseline activity level that is independent of the global sunspot cycle. We argue here that this state has not been observed before for the global Sun during the instrumental period of the past century, although - as we argue below - it is regularly observed locally in the quiet-Sun network.

[6] When no active regions emerge, the continual emergence of the ephemeral regions and their subsequent dispersal is the only source of flux to maintain the "quiet-Sun network". Quiet-Sun network comprises a salt-and-pepper pattern of small concentrations of magnetic flux in which frequent flux cancellations are statistically balanced by the emergence of new ephemeral regions.

[7] In contrast to the active-region population which shows a very pronounced cyclic modulation, the ephemeral-region emergence frequency appears very nearly, if not truly, constant [*Hagenaar et al.*, 2003, 2008]. In very quiet Sun, i.e., in regions well away from the dispersing flux of decaying active regions, the emergence frequency of ephemeral regions varies by at most 10% over a five-year period from cycle maximum to near minimum [*Hagenaar et al.*, 2008], while yearly-averaged sunspot numbers changed by close to a factor of 40.

2. The Quietest-Sun Magnetic Network

[8] The brightness of the solar chromosphere (a relatively warm, magnetically-dominated atmospheric domain that extends up to some 4000 km above the surface) increases with the magnetic flux density threading the surface beneath it [*Schrijver et al.*, 1989], and thus provides a proxy of solar magnetic activity. The chromospheric brightness observed in one of the dominant spectral lines (the K line of singly-ionized

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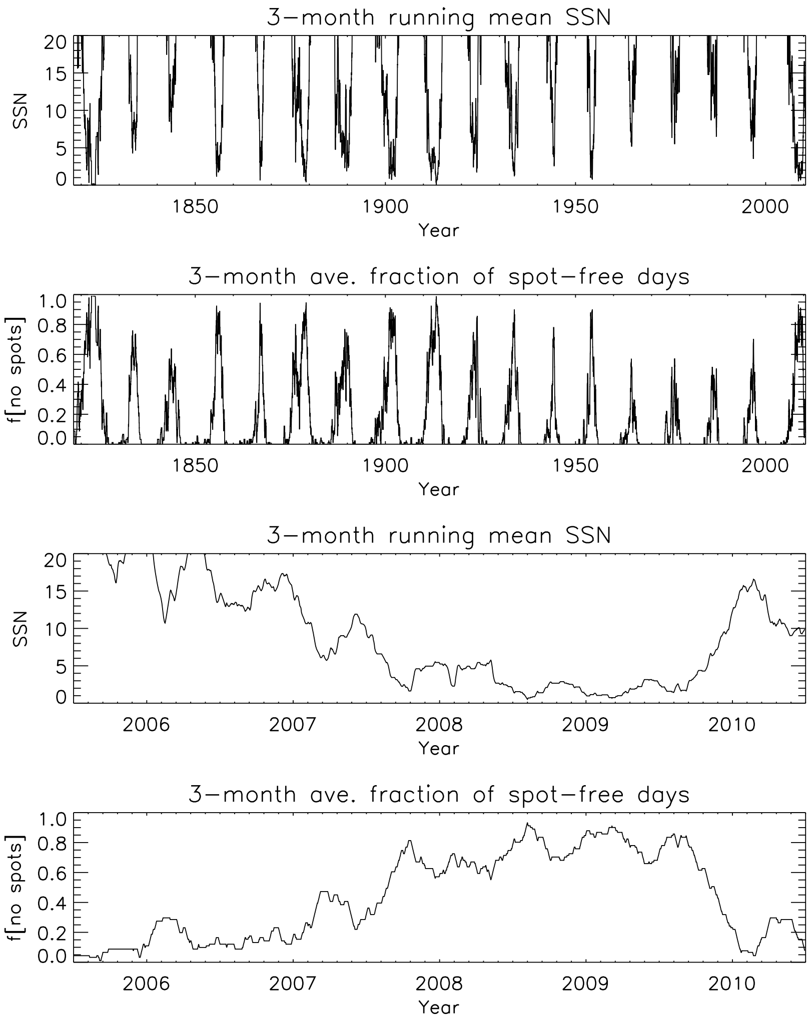

Figure 1. (top) Three-month running means of the yearly sunspot number, SSN (showing only the lowest values, starting in 1818 from which time onward daily sunspot numbers are available), and below it the corresponding fraction of spot-free days. (bottom) As above, for the declining phase of the solar cycle and the extended minimum in 2008 and 2009. Sunspot data from the Solar Influences Data Center (http://sidc.oma.be).

calcium; upper histogram and pluses in Figure 2) thus tracks the sunspot cycle, including the very low level of global activity in 2008 and 2009. The Ca II K signal for the quietest regions observed near the center of the solar disk (lower histogram and diamonds in Figure 2) shows an upward scatter because on some days there simply is no truly quiet network amid the decay products of active regions, but the sample of observations shows more frequently a characteristic low value that exhibits no significant trend over a 37-y period [*Livingston et al.*, 2007], neither on the time scale of the sunspot cycle nor on a multi-decadal time scale (a linear fit to the data - shown in Figure 2 - yields a change relative to the average value of $-(0.3 \pm 1.0) \times 10^{-4}$ yr^{-1}, which is statistically insignificant). It appears that ephemeral regions in the quietest regions on the solar surface are generated by a process unmodulated by the global dynamo.

[9] What happens on the larger scales when active regions cease to emerge? A marked paucity in emerging active regions for well over a year causes the solar surface to be largely wiped clean of active-region decay products, with only patches of weak flux imbalance surviving underneath coronal holes (see Animation S1 of the auxiliary material).[1] This is a consequence of the advection of the surface magnetic field in plasma flows on a range of scales.

[10] On the smallest scales, the random walk caused by the (super-)granular convection is characterized by an effective diffusion coefficient of $D = 250$–400 km/s^2 [*Wang et al.*, 1989; *Schrijver and DeRosa*, 2003]. The time scale on which a bipolar active region decays by such a random-walk mixing is of order 0.7 y for a relatively small region with a polarity separation of 30 Mm (as observed in 2008 and 2009), after which only 10% of the original flux survives, by then widely dispersed into a weakly enhanced ephemeral-region network.

[11] On larger scales, the slow poleward meridional wind aids in the formation of the polar caps and their coronal holes [*Wang et al.*, 2005, 2002; *Schrijver and Liu*, 2008]. The time scale for the meridional flow to transport flux from the activity belt to high latitudes is of order $\hat{t} = R_\odot/v_0 \sim 2$y

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL046658.

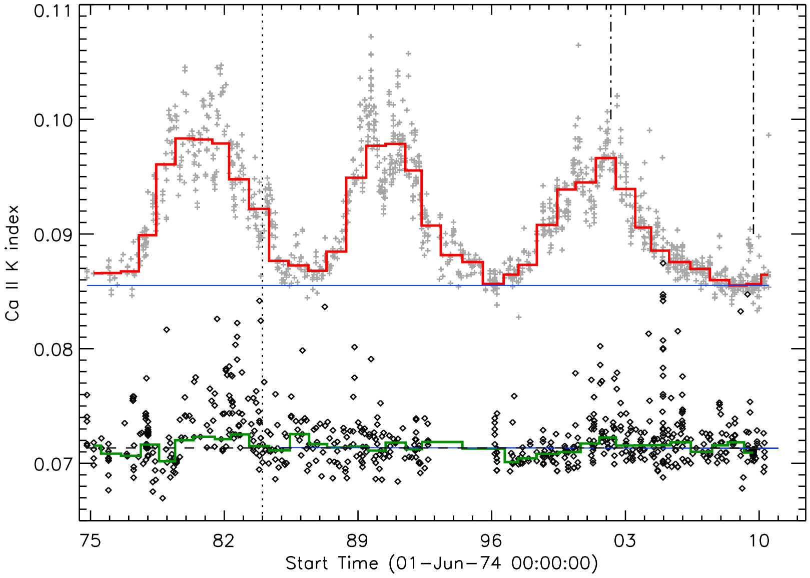

Figure 2. Solar chromospheric activity as measured in singly-ionized calcium (Ca II K) since 1974 [*Livingston et al.*, 2007]. Pluses show the full-disk signal relative to a nearby wavelength interval originating at the solar surface; the (red) histogram shows the median values for 12-month intervals and the horizontal line indicates that median level for the first half of 2009. Diamonds show the disk-center signal prior to 1984 (the dotted vertical line), after which the quietest patch near to disk center was observed. The (green) histogram shows the median values for 12-month intervals excluding points over 0.074 that are characteristic of enhanced rather than quiet network (a linear fit to the disk-center values from 1984 onward is shown by the blue line). The full-disk and disk-center signals are offset because of differential center-to-limb variations in the line center and line wing signals.

for a characteristic meridional flow of $v_0 \approx 10$ m/s (for solar radius $R_\odot$).

[12] Thus after a long absence of active regions, we are left almost exclusively with the rapidly recycled network fed by the persistent population of ephemeral regions, underneath a largely structureless corona between the polar caps. Coronagraphic image sequences reveal that the high-corona and inner-heliosphere in this period do still show some activity, but mostly of a different kind than typical CMEs, and then only infrequently (see auxiliary material).

[13] The GOES solar-coronal X-ray signal in the deepest phase of the most recent cycle minimum remained mostly below its minimally detectable level, with only very faint upward excursions, reaching the A1 level of minimal flaring only once between mid-February and late-March of 2009.

[14] This leads us to the hypothesis that the Sun was as quiet as it can be by 2009, with the remnants of past active regions very nearly wiped out but for the relatively weak polar caps mostly at latitudes above ~ 70°. This is also consistent with the clearly lower absolute global magnetic flux in Figure 3 and a global Ca II K signal in Figure 2 that was markedly lower in 2009 than in 1986 and marginally lower than in 1997.

[15] We note that, despite the relatively strong sunspot cycle preceding it, the polar-cap field was only about half its usual cycle-minimum strength in 2008–2009 [*Schrijver and Liu*, 2008] and the interplanetary magnetic field also reached record lows [*Mewaldt et al.*, 2010]. This has been attributed to effects of three-dimensional flux transport [*Schrijver et al.*, 2002; *Schüssler and Baumann*, 2007], large-scale surface advection [*Wang et al.*, 2005; *Hathaway and Rightmire*, 2010], and active-region tilt-angle changes [*Cameron et al.*, 2010], or perhaps some combination that is yet to be established. This lack of understanding related to the flux-transport modeling is associated with large uncertainties in estimates of the Sun's open (or heliospheric) magnetic flux over the centuries that make it very difficult to assess the precision of TSI estimates for the past centuries that rely on such indirect metrics of solar activity.

3. From the Present-Day Sun to the Maunder Minimum

[16] Empirical relationships between sunspot number, the solar magnetic field, and the TSI are based on various observational intervals within the range from 1965 to a few years ago, i.e., over periods during which the yearly-averaged sunspot number was always at least twice that of the 2008–2009 period (Figure 1), with the fraction of spot-free days over any 3-month period less than 50% for all but a very few, short-lived, exceptional intervals, compared to an average value of ~ 82% in 2008–2009.

[17] Using linear approximations (in varying mixes of instantaneous and hysteresis-allowing relationships) for the trends linking sunspot number to the resulting global surface magnetic flux and its associated TSI may work reasonably well within the range of historical conditions over which the relationships were fitted to available observations. In unusual conditions, however, such relationships are put to a critical test, as exemplified in Figure 3. After 1996, the red diamonds in Figure 3 show the total unsigned surface flux as estimated from observations made by SOHO's MDI. The models by *Tapping et al.* [2007] and *Vieira and Solanki* [2010], which

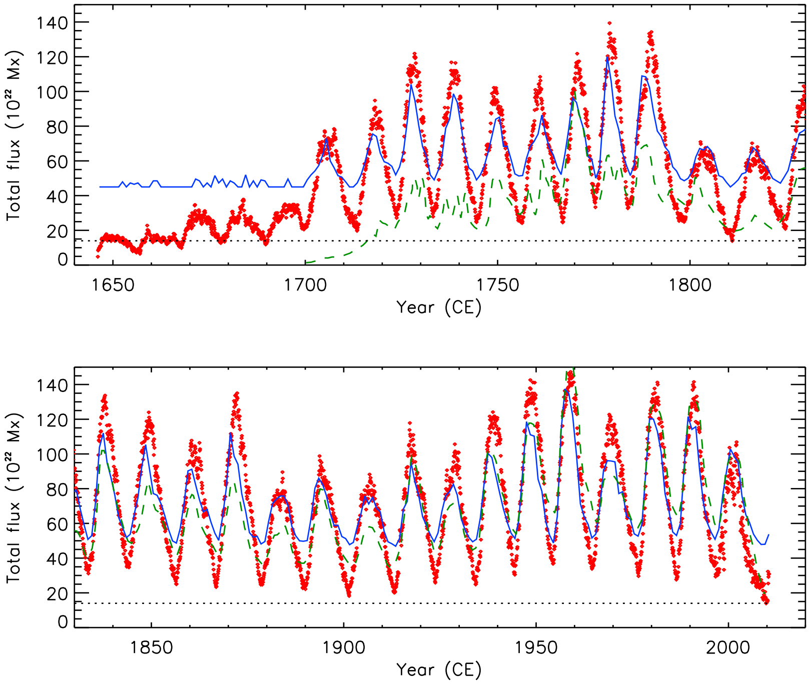

Figure 3. Total absolute magnetic fluxes on the Sun for three models: solid/blue: flux estimate [*Tapping et al.*, 2007] based on a partitioning between 'strong field' and 'weak field' components, scaled from sunspot numbers using their equations (1) and (4); dashed/green: a multi-component flux model [*Vieira and Solanki*, 2010] with time-dependent couplings, multiplied by 1.25 (going back to 1700); diamonds/red: flux-dispersal model based on the yearly-average sunspot number [*Schrijver et al.*, 2002], with points from July 1996 onward based on assimilated magnetic maps [*Schrijver and DeRosa*, 2003] based on SOHO's MDI [*Scherrer et al.*, 1995] sampled once per 25-d period. The multipliers are chosen to bring the fluxes around 2000–2003 to a common scale. The horizontal dotted line shows the flux level characteristic of August-September 2009.

follow the recent observed flux level only relatively poorly, differ markedly throughout the period of overlap since 1700 CE. The models by *Vieira and Solanki* [2010] and a similar model by *Krivova et al.* [2010] (not shown) have 8 and 9 free parameters, respectively, which are determined by fits to various observational constraints. These fits would have the ephemeral-region emergence rate scale with the strength of the sunspot cycle (albeit more extended in time), which is inconsistent with our results discussed in Section 2. A third model [*Schrijveret al.*, 2002] to estimate the unsigned surface magnetic flux going back to the middle of the 17th Century (red diamonds in Figure 3 prior to 1996) is based on a surface flux-transport model that uses the sunspot number records to determine flux emergence with 2-dimensional surface dispersal based on observed properties of the solar field. This model has no free parameters, assuming only that the frequency of active-region emergence changes over time in direct proportion to the yearly-averaged sunspot number. That model used a weak cycle variation for ephemeral regions, effectively lowering their emergence rate by a factor of about 2 during the first three sunspot minima in the Maunder minimum relative to the most recent three prior to 2008–2009; this scaling results in an unsigned flux estimate during these early cycle minima slightly lower than the minimum level in 2009 indicated by the dotted horizontal line.

[18] When extrapolated over hundreds of years, these flux estimates diverge markedly. Consequently, relationships with derived quantities, such as TSI, also diverge and thus exhibit substantial biases and uncertainties for climate modeling and for the attribution of the Sun's variability as the cause of the Little Ice Age. We suggest that rather than using such model-dependent extrapolations to estimate the TSI, the uniquely quiet solar conditions in the first part of March of 2009 may be taken to be characteristic of the deepest phases of the Maunder minimum.

[19] The TSI appears to be mostly, if not entirely, set by the counteracting effects of dark pores and sunspots and the bright small concentrations of magnetic field (the faculae) on an otherwise constant background [*Lean and Woods*, 2010]. In view of the above, the observational records suggests that the network faculae associated with the ephemeral regions were the same in early 2009 as at any very quiet time in the past, and that this is consequently true also for the TSI during the Maunder Minimum.

[20] The faculae within the flux-imbalanced polar caps do not alter this conclusion. The polar caps in early 2009 have an obvious imbalance between the two magnetic polarities, which causes them to be the source regions of most of the heliospheric field, and to be the foundation of substantial coronal holes. From the TSI perspective, however, it is not the net but the total flux density (or facular number density) that is important. For the period 2009/02/28 to 2009/03/24, the assimilation model based on SoHO's MDI magnetograms [*Schrijver and DeRosa*, 2003] shows an average absolute flux density of 3.21 Mx/cm^2 with a standard deviation in the daily averages of 0.06 Mx/cm^2 in the zones poleward of 70°; in comparison, the same quantity for the

front of the disk within 60° of disk center has a value of 3.4 ± 0.5 Mx/cm^2 (after a correction for Gaussian instrumental noise of about 15 Mx/cm^2 in the original magnetograms [*Hagenaar et al.*, 2008], which are averaged over 5 measurements and rebinned to 4 × 4 original pixels prior to assimilation, resulting in a net noise level of 1.7 Mx/cm^2). These values do not differ significantly, i.e., the polar-cap faculae are statistically undifferentiable from the lower-latitude near-limb faculae.

4. Conclusions

[21] After an unusually long lull in sunspot activity in 2008–2009, the Sun's magnetic activity everywhere except in the polar caps decreased to a level that, within the uncertainties, is identical to that found in the quietest areas between decayed active regions, sustained by small magnetic bipoles called ephemeral regions. This level was observed not to vary significantly over the past 37 years. Consequently, this minimal level of activity appears to be independent of the waxing and waning of active-region fields and their decay products that thread the solar convective envelope in significantly differing amounts throughout the sunspot cycles. Whereas we have to allow for the possibility that this minimal state of activity is influenced by a long-term magnetic memory of the Sun [e.g., *Charbonneau et al.*, 2004], the observations show that any such hysteresis has a time scale that must be substantially longer than the 37-year observational record, consistent with our hypothesis that this minimal level of activity is likely essentially that which the Sun exhibited during the Maunder Minimum.

[22] Therefore, we argue that the best estimate of the magnetic flux threading the solar surface during the deepest Maunder Minimum phases appears to be provided by direct measurement in 2008–2009. If surface magnetic variability is the principal driver of TSI changes, then that same period yields a direct estimate of the TSI in that era, yielding values 140 to 360 ppm lower than in 1996 [*Fröhlich*, 2009; *Gray et al.*, 2010]. Earlier studies estimate the TSI for the Maunder Minimum to be 400–1100 ppm lower than in 1996 [*Tapping et al.*, 2007; *Steinhilber et al.*, 2009; *Wang et al.*, 2005; *Krivova et al.*, 2007].

[23] We note that even though the heliospheric field reached low levels unprecedented during the space age, the polar caps persisted as sources of the heliospheric field and, correspondingly, as polar coronal holes. In early 2009, a few perturbations occur every day (see Animation S1); these are mostly relatively gradual reconfigurations of the helmet streamer structures, with very few events that are reminiscent of cycle-maximum CMEs. Yet, this ongoing activity and the persistent large-scale dipolar field may not be characteristic of the least-active Maunder Minimum phases.

[24] If the 2008–2009 solar magnetic activity is indeed similar to the Maunder Minimum level as we argue here, then it would appear that drivers other than TSI dominate Earth's long-term climate change. This implies that new studies are warranted concerning the Sun-climate relationship, including the construction of the solar spectral irradiance that incorporates the persistence of the ephemeral-region population, the diagnostic value of the geomagnetic indices, the differences between heliospheric and surface magnetic fields, the derivation of Earth's temperature record during the Maunder Minimum, the feedback processes that may amplify the climate response to solar forcing, and the effects of volcanos [*Crowley*, 2000] and other climate drivers internal to the Earth system during and after the Maunder Minimum.

[25] **Acknowledgments.** The Editor thanks two anonymous reviewers.

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