Enhanced signature of solar variability in Eurasian winter climate

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[1] We demonstrate that open solar flux (F_s, derivable from geomagnetic data) exhibits stronger correlations with atmospheric circulation variations than conventionally-used measures of solar activity. The circulation anomalies are particularly enhanced over the North Atlantic/Eurasian sector, where there are large changes in the occurrence of blocking and the winter mean surface temperature differs by several degrees between high- and low-solar terciles. The relationship is stronger and simpler for F_s, being more linear between high- and low-solar winters. While the circulation anomalies strongly resemble the North Atlantic Oscillation they also extend deeper into Eurasia, especially in high-solar conditions. This distinct signature may be useful for the detection and attribution of observed changes and also the identification of dynamical mechanisms.
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1. Introduction

[2] In the recent winter of 2009/10, much of Europe and Asia endured unusually low temperatures, with winter mean values several degrees below the long-term climatology in many locations. This was part of a hemispheric anomaly pattern associated with atmospheric circulation anomalies projecting strongly onto the negative phase of the North Atlantic Oscillation/Northern Annular Mode (NAO/NAM; see NAO time series in Figure 1). This dominant pattern of atmospheric variability is known to respond sensitively to a variety of different forcings, one of which is solar variability. Many different studies are in agreement that there is a weak, but significant, influence of solar variability on atmospheric circulation [e.g., *Haigh*, 2003; *Labitzke*, 2005; *Lean and Rind*, 2008; *Frame and Gray*, 2010; *Gray et al.*, 2010].

[3] Here we use the open solar flux (F_s) to quantify solar activity. Like more commonly-used measures (such as sunspot number, R, and the $F10.7$ solar radio flux index), F_s is larger at the maximum of the solar cycle and peak values vary in a similar manner to the peaks in R. However, unlike R and $F10.7$, F_s also varies from one solar minimum to the next and recent work suggests this may also be true, to a lesser extent, of the UV solar irradiance which influences the stratosphere [e.g., *Lockwood et al.*, 2010b]. F_s can be measured from interplanetary satellites and from geomagnetic activity data [*Lockwood et al.*, 2009]. In this paper we use the geomagnetic activity measure as this is a homogeneous observational dataset over the ERA-40 interval. F_s can also be modelled using a continuity equation: R is used to quantifty the source term (the rate at which magnetic flux emerges through the solar atmosphere) and the loss rate computed using two empirical linear loss terms. This model explains why F_s has some similarities to R and $F10.7$ but also some significant differences. Using this model to extend the F_s record back in time, *Lockwood et al.* [2010a] demonstrated a clear statistical connection between F_s and observed central England temperatures since 1700 (as regional anomalies from the hemispheric mean). While no attribution statement is possible, the recent cold winter is clearly consistent with this connection. Other factors, such as El Niño may also have had an influence.

[4] The aim of the present paper is to extend the analysis of *Lockwood et al.* [2010a] by examining the statistical relationship between F_s and observed atmospheric circulation patterns over the last 50 years, and contrasting this with the corresponding $F10.7$ relationship. Several previous studies have suggested a complicated picture, with only a weak time mean atmospheric circulation change in response to solar variability but changes in the nature of preferred flow patterns and weather regimes [*Kodera*, 2003; *Huth et al.*, 2008; *Barriopedro et al.*, 2008]. However, the circulation anomalies may appear stronger when geomagnetic indices are used [e.g., *Bochníček and Hejda*, 2005]. As will be shown, F_s does indeed suggest a simpler and stronger solar influence on atmospheric circulation, which is particularly enhanced in the Atlantic/Eurasian sector.

2. Data

[5] We use atmospheric circulation data from the ERA-40 reanalysis [*Uppala et al.*, 2005]. We focus on the December–February (DJF) season, with 44 complete winters from 1957/58 to 2000/01. Additional blocking data for years since 2001 is provided by the ERA-Interim reanalysis. In addition to general circulation diagnostics we examine statistics of atmospheric blocking, as described by the blocking index of *Woollings et al.* [2008]. This is a two-dimensional index which identifies blocking as a reversal of the meridional gradient of potential temperature on the dynamical tropopause. We use the blocking episodes: events which are selected to be persistent and quasi-stationary by requiring that they remain within 10° of longitude of a given location for at least 5 days. We also make use of the time series of the NAO as defined by the NOAA Climate Prediction Center using rotated principal component analysis (obtained from www.cpc.noaa.gov).

[6] To characterise solar variability we use both the 10.7 cm radio flux [see *Dudok de Wit et al.*, 2009] and the open solar flux of *Lockwood et al.* [2010a]. Winter time series of the solar indices are calculated by linear interpolation from the annual values. Recent variations of both

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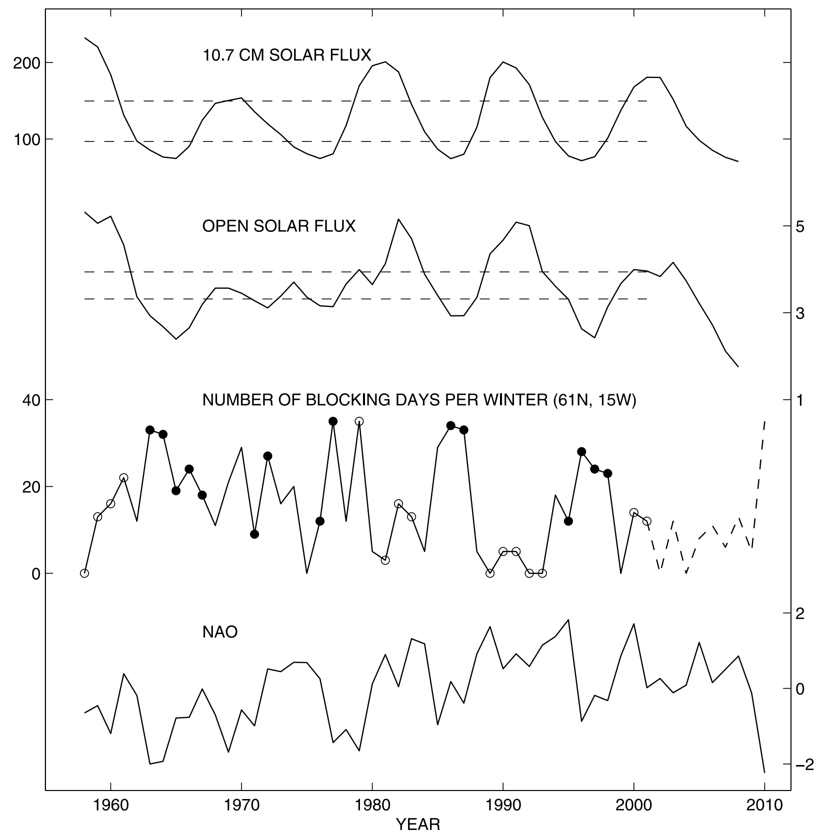

Figure 1. Time series of winter $F10.7$ and F_s, with horizontal dashed lines showing the terciles over the ERA-40 period. Also shown is the DJF NAO index from CPC and a simple count of the number of blocking days per winter at the location marked in Figure 4. Winters in the high-solar tercile according to the F_s are marked with open circles and those in the low-solar tercile with filled circles. The dashed line shows the extension of the series to winter 2009/10 using ERA-Interim.

indices are shown in Figure 1. Compared to $F10.7$ the F_s is less regular and exhibits greater long-term drift in the extrema of the 11-year cycle. Over the ERA-40 period there is no detectable linear trend in either time series.

3. Composite Analysis

[7] Following *Barriopedro et al.* [2008] we segregate the data according to the terciles of the solar indices. The terciles as calculated over the ERA-40 period are shown as dashed lines in Figure 1. Winters with solar values above the upper tercile are named high-solar winters, and those below the lower tercile low-solar winters. Figure 2 shows the 500 hPa geopotential height field (Z500) in high- and low-solar winters as anomalies from the ERA-40 climatology. Using $F10.7$ the circulation anomalies are weak with little significance, and generally non-linear between high- and low-solar winters, as seen in the previous studies cited above. However, using F_s there are several regions of anomalies which are significant and, to some extent, linear between high- and low-solar winters. There is an interesting combined annular/wavenumber three pattern in the Southern Hemisphere, but the strongest anomalies consist of NAO-like meridional dipoles in the North Atlantic. While largely linear, there are important asymmetries between these, in particular in the downstream extension of the anomaly pattern into Eurasia during high-solar winters.

[8] These Atlantic/Eurasian circulation anomalies are of large enough amplitude to have a detectable influence on surface climate. Figure 3a shows the difference of the mean sea level pressure (MSLP) and near surface air temperature between low- and high-solar winters using F_s. For comparison the pattern associated with the NAO is shown in Figure 3b. This pattern was obtained by regressing the fields onto the time series of the NAO, and has been scaled so that the MSLP maximum over Iceland is of the same magnitude as in Figure 3a. This scaling factor is -1.05, so that the anomalies in the difference map are of roughly the same magnitude as one standard deviation of the winter NAO, i.e., of considerable size. Similarly the linear regression map of the MSLP onto the F_s has an Icelandic anomaly equivalent to 0.42 standard deviations of the winter NAO (not shown).

[9] While the anomaly pattern is very similar to that associated with the NAO, there are some differences. In particular the pattern is shifted and extended eastward compared to that of the NAO. Both MSLP and temperature anomalies are weaker over the West Atlantic/North America and stronger over Eurasia when compared to the NAO anomalies. Note that detrending the MSLP and temperature fields has a negligible effect on the resulting patterns. Also the NAM pattern is virtually identical to the NAO over the region shown, so that the difference in pattern cannot be accounted for by NAO/NAM differences. To test whether the two MSLP patterns in Figures 3a and 3b are significantly

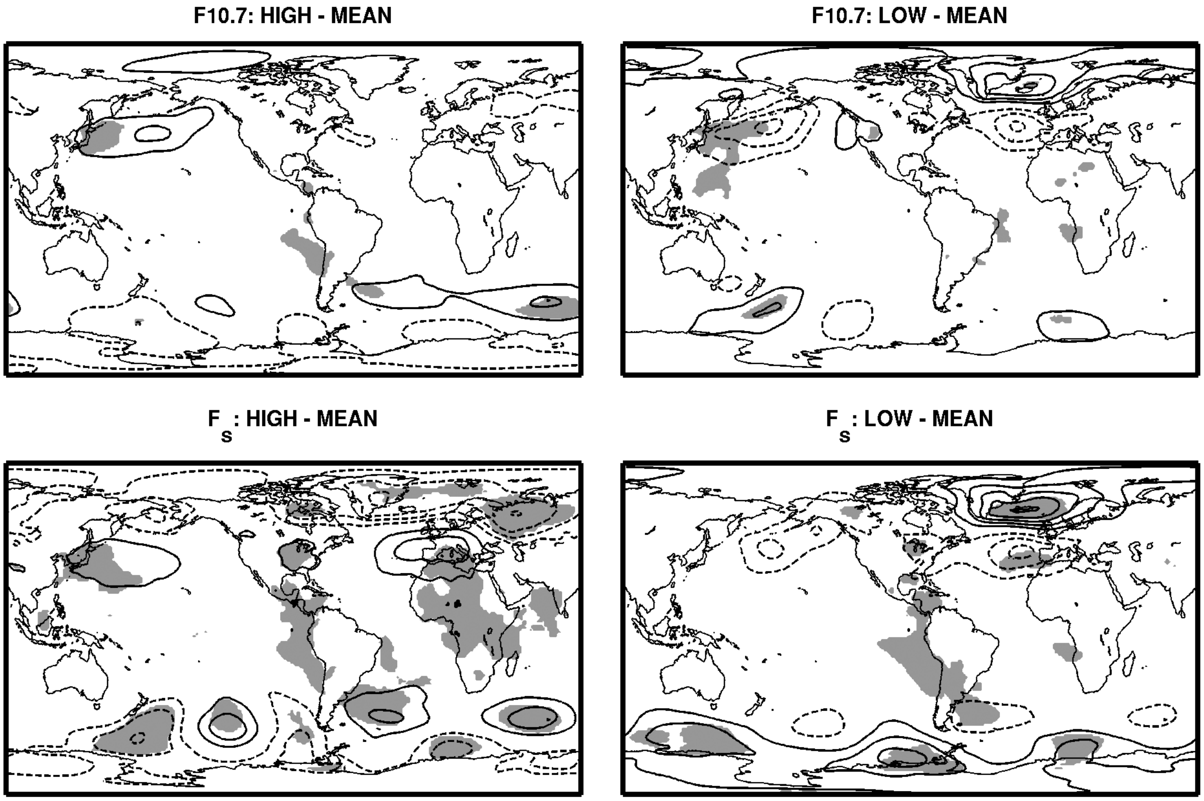

Figure 2. Composites of Z500 for the high- and low-solar winters (DJF) according to both the *F*10.7 and F_s solar indices. The maps are shown as anomalies from the ERA-40 climatology, contoured every 5 m, with negative contours dashed and the zero contour omitted. Shading indicates significance at the 95% level, using a two-sided Monte Carlo test with 1000 trials.

different a bootstrap test has been employed, resampling the sets of winters in order to estimate the sampling uncertainty. This suggests that the two patterns are significantly different at the 93% level (Figure 3c).

[10] Several of the coldest periods in Europe during the 2009/10 winter were associated with blocking events, in which the mild prevailing westerlies were replaced with cold northerly and easterly winds. *Barriopedro et al.* [2008] recently presented evidence that solar variability modulates various aspects of blocking behaviour, so we compare in Figure 4 the anomalous occurrence of blocking in the high- and low-solar terciles, as defined by both *F*10.7 and F_s. Using *F*10.7 the results are very similar to those of *Barriopedro et al.* [2008], showing an increase in blocking across the Atlantic basin during low-solar winters but a more spatially dependent pattern in high-solar winters. The signature in the Pacific is more linear, also in agreement with *Barriopedro et al.* [2008]. However, as with the height anomalies, the total area of statistical significance is relatively small. In contrast, using F_s gives a strong, significant pattern in the East Atlantic/European sector with anomalies that are more linear between high- and low-solar winters. The relation with Pacific blocking is also linear but has lower significance, and is associated with only weak flow anomalies (Figure 2).

[11] The blocking frequency anomalies in Figure 4 are sizeable, with low-solar winters experiencing of the order of 10 more days of blocking per winter than high-solar years, against a long-term mean of around 15 days per winter (see climatology shown by *Woollings et al.* [2008, Figure 2]). An example time series of blocking occurrence at one particular location in the East Atlantic, where the relation is strongest, is also shown in Figure 1. (Time series for neighbouring locations show very similar behaviour.) Agreement between variations in blocking occurrence and F_s variations is clear. Almost all of the winters with very high blocking occurrence were low-solar winters, and conversely most of those with very infrequent blocking were high-solar winters. In Figure 1 we also show the extension of the blocking time series to include the 2009/10 winter using ERA-Interim (dashed line). The prevalence of blocking in this winter is clearly consistent with the long-term relation identified in the earlier data.

4. Discussion

[12] We have shown that using the open solar flux, derived from geomagnetic activity, as a measure of solar activity gives stronger correlations with atmospheric circulation than obtained with the conventionally-used solar activity indices. The relation is also simpler, being largely (but not completely) linear between high- and low-solar winters. While anomalous circulation is seen around the globe in response to solar variability it is particularly enhanced over the North Atlantic and Eurasia, where the difference in surface temperature between high- and low-solar winters is of the order of a few degrees and the circulation anomalies are of the same order as the standard deviation of the NAO.

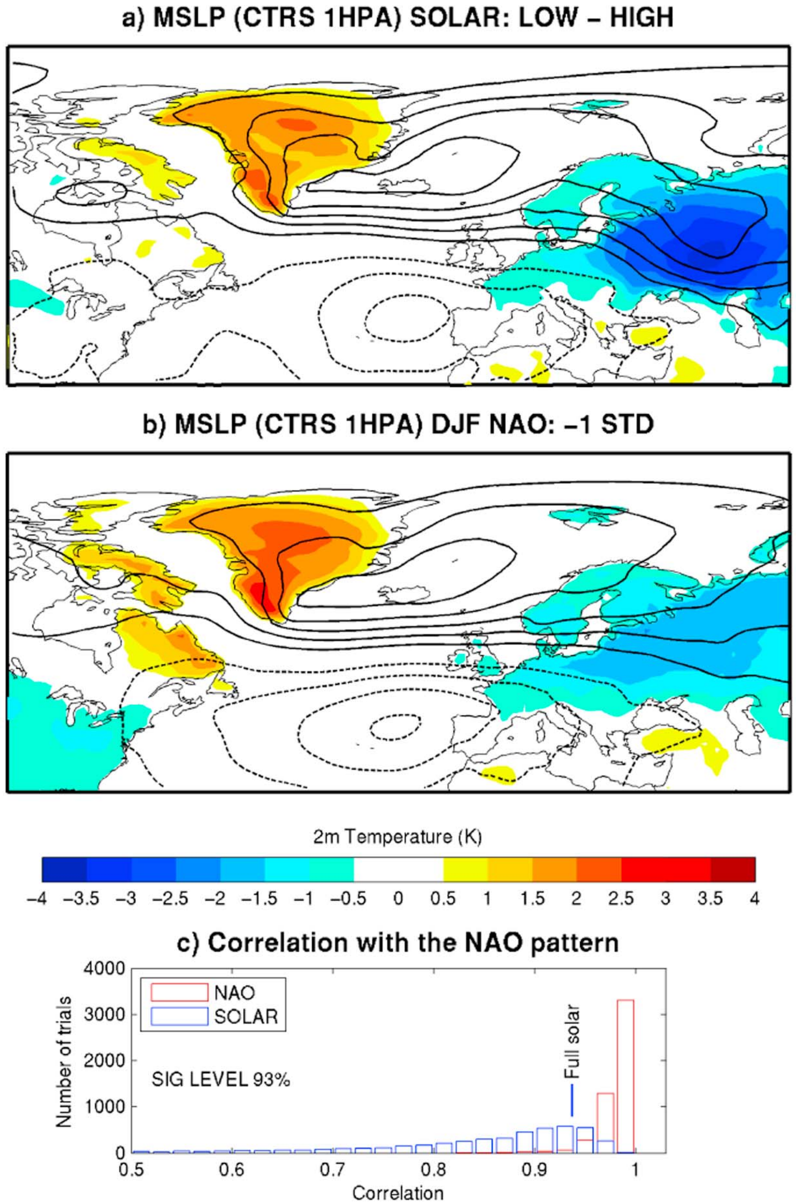

Figure 3. (a) Composite difference map of winter-mean MSLP and 2 m temperature between low- and high-solar winters defined using F_s. (b) Scaled anomalies associated with the NAO for comparison. (c) Results of a 5000-trial bootstrap resampling test on the difference between the patterns in Figures 3a and 3b, using the pattern correlation with the full NAO pattern as a test statistic. In each trial the 15 high- and 15 low-solar years were resampled (with replacement) to estimate the uncertainty in the solar signal. Similarly, in each trial the 44 winter means were resampled and the leading EOF was calculated over the region shown to estimate the uncertainty in the NAO pattern. The significance was calculated as the area of the intersection of the distributions divided by the area of their union.

This is perhaps not too surprising given the unique configuration of the North Atlantic jet stream which makes it particularly susceptible to forcing. This strong regional response may shed some light onto the apparent solar signal in Atlantic/European paleoclimate records [e.g., *Bond et al.*, 2001; *Hormes et al.*, 2006]. These findings suggest that solar variability could provide a valuable source of skill for seasonal-decadal climate prediction. The atmospheric circulation response to solar forcing also provides a valuable test case with which to evaluate the skill of climate models in simulating the response to changes in external forcing.

[13] One proposed mechanism for solar variability to influence the lower stratosphere is via a modulation of the vertical propagation of planetary waves into the stratosphere in wintertime [*Kodera and Kuroda*, 2002; *Gray et al.*, 2004]. These influence the variability of the stratosphere and hence the troposphere via the NAO/NAM. This is the so-called 'polar route' of stratospheric influence [see, e.g., *Gray et al.*, 2010]. The circulation response to solar forcing shown here certainly includes a strong Atlantic jet stream response which is very well described by the NAO. However, it also appears to have a signature which is distinct from the NAO.

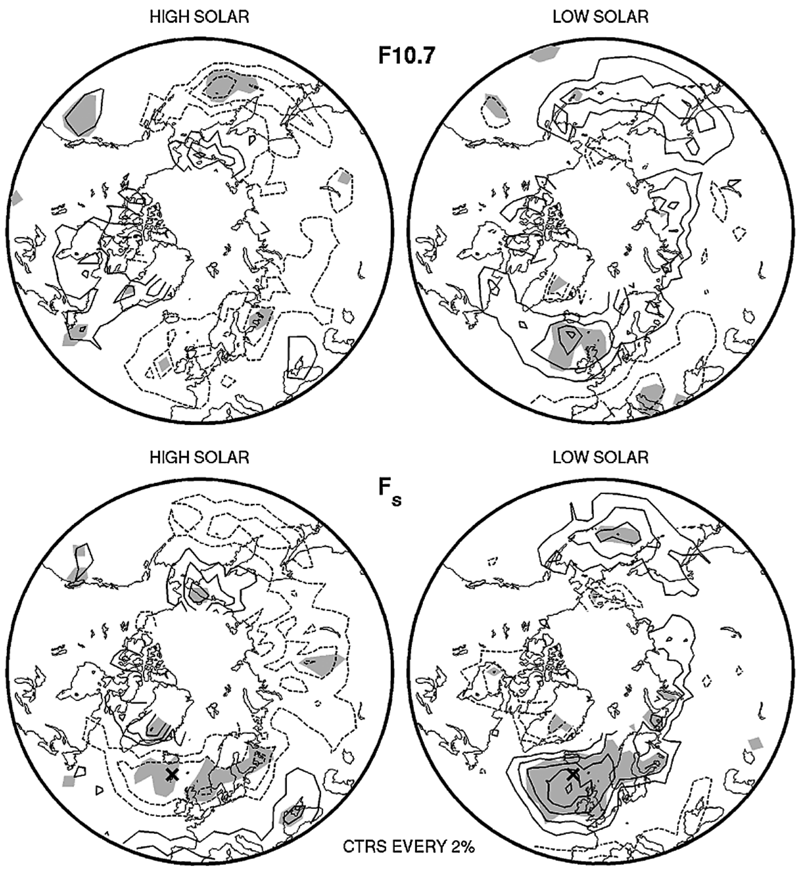

Figure 4. Composite anomalies of blocking episode frequency in high- and low-solar winters using both $F10.7$ and F_s. Contours are drawn every 2%, with negative contours dashed and the zero contour omitted. The grey shaded areas show where the anomalies are significant at the 95% level, using a two-sided Monte Carlo test with 1000 trials in which 15 winters are chosen at random, to give an estimate of the anomalies which could occur through sampling. The location of the example time series in Figure 1 is marked with 'x'.

The circulation pattern is weighted more towards the eastern part of the North Atlantic and features a pronounced extension into Eurasia. Similarly, the changes in blocking are limited to the East Atlantic and extend into Scandinavia, while variations in blocking associated with the NAO are centred in the West Atlantic [*Woollings et al.*, 2008]. This distinct signature may be useful for the detection and attribution of observed changes in circulation. It also acts to focus attention on certain dynamical mechanisms, for example on the LC1-type anticyclonic Rossby wave-breaking which is more common towards the downstream end of the storm track [e.g., *Martius et al.*, 2007]. The signature in blocking is markedly different from that which *Woollings et al.* [2010] found to lag variations in the stratospheric polar vortex. This suggests that the direct influence of changes in tropical lower stratospheric temperatures on the refraction of storm track eddies could be important, as demonstrated by *Simpson et al.* [2009], especially since F_s also shows stronger links with these lower stratospheric temperatures [*Lockwood et al.*, 2010b].

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