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Changing response of the North Atlantic/European winter climate to the 11 year solar cycle

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Abstract

Recent studies have presented conflicting results regarding the 11 year solar cycle (SC) influences on winter climate over the North Atlantic/European region. Analyses of only the most recent decades suggest a synchronized North Atlantic Oscillation (NAO)-like response pattern to the SC. Analyses of long-term climate data sets dating back to the late 19th century, however, suggest a mean sea level pressure (mslp) response that lags the SC by 2–4 years in the southern node of the NAO (i.e. Azores region). To understand the conflicting nature and cause of these time dependencies in the SC surface response, the present study employs a lead/lag multi-linear regression technique with a sliding window of 44 years over the period 1751–2016. Results confirm previous analyses, in which the average response for the whole time period features a statistically significant 2–4 year lagged mslp response centered over the Azores region. Overall, the lagged nature of Azores mslp response is generally consistent in time. Stronger and statistically significant SC signals tend to appear in the periods when the SC forcing amplitudes are relatively larger. Individual month analysis indicates the consistent lagged response in December–January–February average arises primarily from early winter months (i.e. December and January), which has been associated with ocean feedback processes that involve reinforcement by anomalies from the previous winter. Additional analysis suggests that the synchronous NAO-like response in recent decades arises primarily from late winter (February), possibly reflecting a result of strong internal noise.

1. Introduction

Solar forcing is potentially an important source of decadal climate variability over the North Atlantic/European region (Gray *et al* 2010, Lockwood *et al* 2010, Sirocko *et al* 2012). Solar influences over this region are believed to be mediated by circulation anomalies that project onto the North Atlantic Oscillation (NAO; Hurrell *et al* 2003), one of the most prominent modes of atmospheric internal variability. The solar impact on the NAO-like circulation anomalies is believed to primarily originate from the stratosphere as a result of the variability of solar ultraviolet irradiance (Haigh 1994), with possible contributions from the presence of solar wind driven high energy particles (Andersson *et al* 2014, Seppälä and Clilverd 2014). These anomalies drive temperature and circulation anomalies in the upper stratosphere (Frame and Gray 2010) that can be transferred downward to the surface through wave-mean flow interactions (Kodera and Kuroda 2002, Lu *et al* 2017a), ultimately projecting onto the NAO-like pattern (Kodera and Kuroda 2005, Matthes *et al* 2006, Ineson *et al* 2011). Quasi-decadal variability is also probably intrinsic to the ocean-atmosphere system (Czaja and Marshall 2001, Czaja and Frankignoul 2002). However, there is also the possibility that the internally generated quasi-decadal variability can be synchronized by external forcing such as volcanic or solar forcing (e.g. Ottera *et al* 2010, Thiéblemont *et al* 2015).

The surface climate response to the 11 year solar cycle (SC) appears to depend on the time period selected for analysis. Through analyzing long-term mean sea level pressure (mslp) and sea surface temperatures (SSTs) since late 19th century, Gray *et al* (2013) identified a significant positive mslp response to the SC over the Azores (i.e. in the region of the southern node of the NAO) with a lag of 2–4 years. This result was supported by a follow-on study (Gray *et al* 2016) that analyzed a much longer data period extending back to 1660. The origin of the observed lags has been attributed to the extended memory of ocean heat content anomalies (Scaife *et al* 2013, Andrews *et al* 2015, Kodera *et al* 2016), or the solar wind/geomagnetic activity that peaks several years following the SC maximum (S_{max}) (Maliniemi *et al* 2014). However, the lag depends on the month(s) included in the analysis. For example, Brugnara *et al* 2013 analyzed JFM (January–February–March) data for the period 1750–2002 and found a zero-lag response, in contrast to the 2–4 year lag found by Gray *et al* 2013 who examined DJF (December–January–February). Gray *et al* 2016 resolved this apparent disagreement by showing that the zero-lag response in JFM was due to the choice of the later winter months (especially February–March) which appear to be dominated by the atmospheric (stratospheric) SC forcing which is synchronized with the SC, rather than the early winter months (December–January) when a lagged ocean feedback is dominant.

Nevertheless, Woollings *et al* 2010 and Chen *et al* 2015 found a positive NAO-like response pattern that coincides with the S_{max} for the most recent period from ∼1958, even though they analyzed the December–January–February (DJF) months and thus included the early winter months in their analysis. The discrepancy can be partly attributed to the difference in the solar index employed, because these two studies used magnetic open solar flux to characterize solar activity, which has a slightly different temporal evolution to the more commonly used F10.7 cm solar radio flux or sunspot number indices. Nevertheless, the very recent studies of Kodera *et al* (2016) and Lu *et al* (2017a) employed the F10.7 cm index and consistently find a significant positive NAO-like circulation pattern synchronized with the SC when the period since 1979 is examined, despite using different analysis methods.

This discrepancy raises an important scientific question as to whether there is a coherent SC signal or whether the signal is an analysis artifact. To date this question has received little attention and is not well understood, which makes it difficult to include the solar variability into the practices of weather and climate prediction. Therefore, understanding the nature and cause of time variations in the SC signals is of great importance. In an attempt to examine such variations, we perform a lead/lag multiple linear regression (L-MLR) analysis with a sliding window of 44 years over the period 1751–2016. Our results confirm the ∼3 year lagged mslp response over the Azores region found by Gray *et al* (2013, 2016). The previously identified synchronized (lag zero) SC-NAO relationship since the 1970s is found to be isolated in the historical record, suggesting that it may be a result of the confounding noise. The study is organized as follows. Section 2 describes the data and methods employed. Section 3 identifies the time variations of the SC signals and explores the possible causes. Section 4 summarizes and discusses the results.

2. Data and methods

2.1. Data

In this study, the Hadley Centre Sea Level Pressure (HadSLP2) dataset for the period 1851–2004, and HadSLP2r for the period 2005–2012 are employed (Allan and Ansell 2006), these two data sets can be found at www.metoffice.gov.uk/hadobs/. The NCEP/NCAR reanalysis is also used to extend the mslp data to 2016. Monthly sunspot numbers (SSN) are used to quantify the 11 year solar cycle (http://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/SUNSPOT/). The NAO index (NAOI) is defined as the mslp difference between Gibraltar and Iceland (Jones *et al* 1997). Our analysis focuses primarily on Northern Hemisphere winter, defined as the average of December, January and February (DJF).

The DJF mean stratospheric aerosol optical depth (AOD) averaged over the Northern Hemisphere is employed to represent volcanic influences (Sato *et al* 1993). We use the DJF mean SST over the region 5°N–5°S and 180–90°W to represent El Niño and Southern Oscillation (ENSO), which is derived from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) data set (Rayner *et al* 2003). For the analysis extending back to 1751 the reconstructed NAO (Luterbacher *et al* 1999), Niño 3.4 (Wilson *et al* 2010), and stratospheric AOD (Crowley and Unterman 2013) indices are used to fill the gap between 1751 and the HadSLP2/HadISST period. A reconstructed monthly averaged gridded mslp data (Luterbacher *et al* 2002) confined to the region (30°W–40°E; 30°N–70°N) is also used. This data set covers the period 1659–1999 (http://www.ncdc.noaa.gov/paleo/paleo.html). To ensure homogeneity, these data sets were adjusted to have the same mean and standard deviation values with the observations for the overlap period. The anthropogenic index for this extended analysis is represented by a linear trend, because the anthropogenic radiative forcing data is not available before 1850.

2.2. The lead/lag multiple linear regression method

The multiple linear regression (MLR) method is frequently used to separate the influences of the SC from other sources of variability and has been widely applied to various climate data sets (Lean and Rind 2008, Frame and Gray 2010, Roy and Haigh 2010, Brugnara *et al* 2013). Following Gray *et al* (2013), a lead/lag multiple linear regression (L-MLR) method is used here to isolate the SC influences at different lead and lag times. We obtain the response of a climate variable over location x (a vector) in year t at l years leading/lagging the SC using the following equation:

$$T(x,t)=C_{\mathrm{SSN}}(x)\cdot \mathrm{SSN}(t-l)+C_{\mathrm{VOLC}}(x)\cdot \mathrm{VOLC} +C_{\mathrm{ENSO}}(x)\cdot \mathrm{ENSO}(t) +C_{\mathrm{TREND}}(x)\cdot \mathrm{TREND}(t)+\varepsilon(x,t) \quad (1)$$

The four indices employed in the L-MLR equation (1) are: (1) SSN: the DJF mean SSN at l year lag (note that time-variations greater than 15 years were subtracted from the SSN time series by applying a low-pass filter technique, to ensure that we only extract the quasi-11 year SC signal); (2) VOLC: the DJF mean stratospheric AOD averaged over the Northern Hemisphere to represent volcanic influences; (3) ENSO: the DJF mean SST over the region 5° N–5° S and 180–90° W to represent ENSO; and (4) TREND: a linear trend term.

To deal with autocorrelation in the residual term ε a pre-whitening procedure is employed in the MLR analysis (details are described in the appendix of Chen *et al* 2015). The procedure is repeated three times until most grids satisfy the Durbin–Watson test to ensure the residuals are whitened (Durbin and Watson 1971). After this, a1000-trial bootstrap re-sampling test is employed to measure the statistical significance level of the regression coefficients. In each trial, all the indices employed in the L-MLR equations were resampled (with replacement) to estimate the uncertainty in the solar signal. The climate responses to the SC are denoted by the regression coefficients of SSN, scaled to represent the atmospheric differences between S_{max} and solar minimum (S_{min}) years for the selected time intervals.

In order to examine the temporal evolution of the SC signal, a 44 year sliding L-MLR analysis with different leads/lags between 0–5 years is performed for the extended period 1751–2016. A sliding window length of 44 years contains roughly four sunspot cycles. This length of the sliding window was selected to be a compromise between being sufficiently long to maximize the chance of achieving statistical significance while being short enough to resolve time-periods with different SC responses. Assigning the regression coefficients to the center of the time window (centered on the 23rd year) yields the time varying solar signals for the time period 1773–1995.

When the separate Azores/Icelandic regions are examined, these are based on (latitudinally-weighted) area-averages in a rectangular box bounded by 30°W–15°W and 30°N–40°N for the Azores and bounded by30°W–15°E and 60°N–70°N for Iceland. Results were insensitive to the precise definition of these boundaries.

3. Results

3.1. Time average solar signals over the North Atlantic/European region

Firstly, we examine the 11 year SC signals in mslp at 0–5 year lags for 1851–2016 (left panel of figure 1). This time-period is selected so that the results can be compared with those of Gray *et al* (2013). At 0–1 year lags, the signals are generally weak and insignificant over the entire region. A statistically significant ($p < 0.05$) positive signal emerges subsequently around the Azores at 2–4 year lags, with a negative but statistically insignificant signal around the Iceland at the same time. This result confirms the 2–4 year lagged response first reported by Gray *et al* (2013), although the estimated lag between SSN and the Azores mslp anomaly is slightly shorter than theirs, primarily because Gray *et al* (2013) used the annual mean SSN to quantify the 11 year SC, while the present study employs the DJF-averaged SSN instead. Although the mslp response pattern bears some resemblance to the positive (negative) phase of the NAO 2–4 years following S_{max} (S_{min}), there are also notable differences. In particular the pattern is weighted more towards the Azores region. The maximum amplitude of DJF mslp response over the Azores is ~3 hPa, while the standard deviation (STD) of the DJF mslp around the Azores is 2–3 hPa, therefore the SC effects contribute a substantial fraction of year-to-year variations for this region. There is a maximum negative mslp anomaly of less than 2 hPa in the northern part of the NAO (i.e. Iceland), only equivalent to ~0.5 STDs of the wintertime Iceland mslp variability, which is not sufficiently strong to be distinguished from the background variability.

Notably, when the data sets of the recent decades were employed, numerous previous studies had suggested a significant NAO response synchronized with the SC (i.e. zero-lag), including significant negative Iceland mslp anomalies (e.g. Woollings *et al* 2010, Ineson *et al* 2011, Chen *et al* 2015, Kodera *et al* 2016 and Lu *et al* 2017a). This synchronized response since ~1970s is also confirmed by examining the spatial pattern of the DJF regression analysis over the recent period

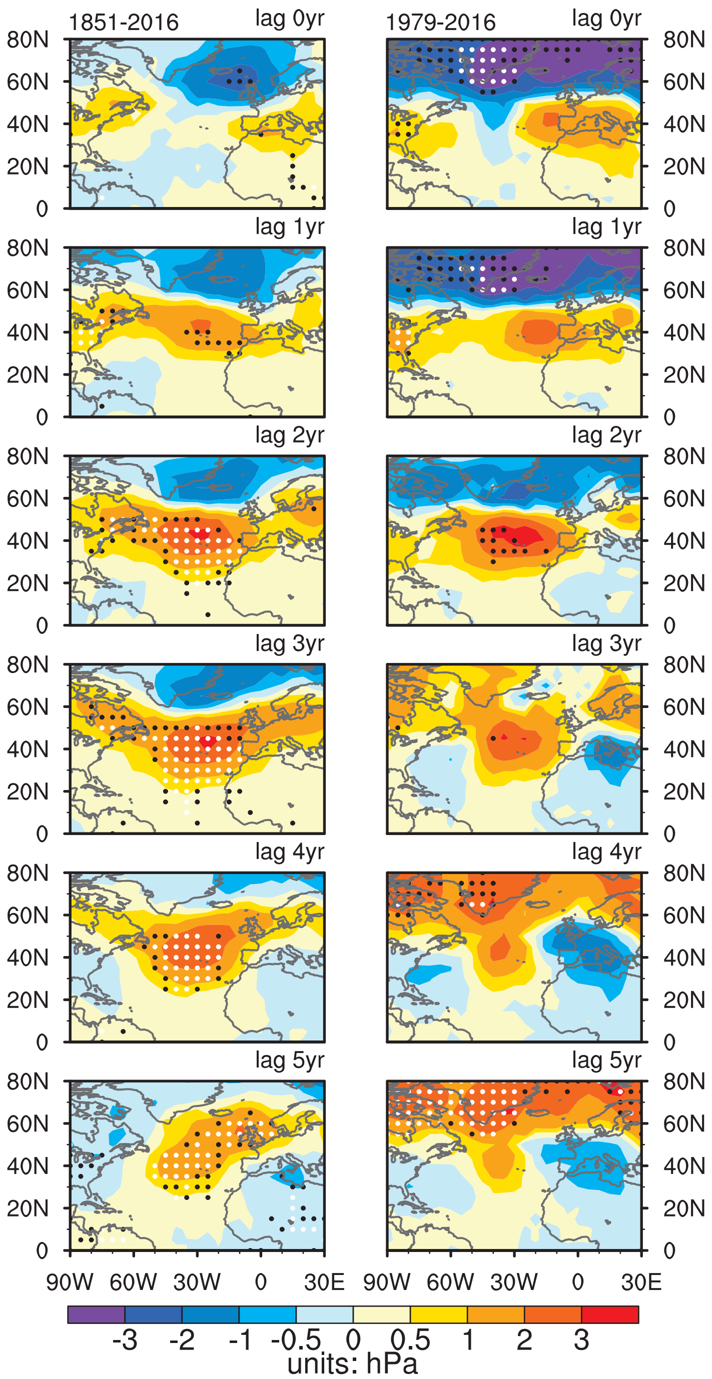

Figure 1. The estimated SC signals in the DJF mslp at 0–5 year lags using the L-MLR in equation (1) for the period 1851–2016 (left panel) and 1979–2016 (right panel). Solid black (white) dots denote regions where the regression coefficients are statistically significant at the 10% (5%) level (i.e. $p < 0.1$ ($p < 0.05$)) after pre-whitening and a 1000-trial bootstrap resampling test.

1979–2016 shown in figure 1 (right panel), the period has been chosen to match as closely as possible the periods examined by earlier studies (e.g. Kodera *et al* 2016 and Lu *et al* 2017a). It is clear that the estimated SC signals over the recent period are quite different from those over the period 1851–2016, suggesting a changing nature of the SC signals. Therefore, it is necessary to further explore the nature and causes of time variations in the SC signals, including the possible reasons for the significant synchronized response since ~1970s.

3.2. Time variations of the solar signal

Figure 2(*a*) shows the DJF-averaged SC response from a series of 44 year sliding window regression analyses of the NAOI over the period 1751–2016 in which the solar index is employed at different lead/lag times between 0–5 years. The year (x-axis) is labeled according to the central year of the 44 year window and the y-axis shows the lead/lag time employed. The shading shows the amplitude of the SC response from each of the individual regression analyses and solid black (white) dots denote that the regression coefficients are

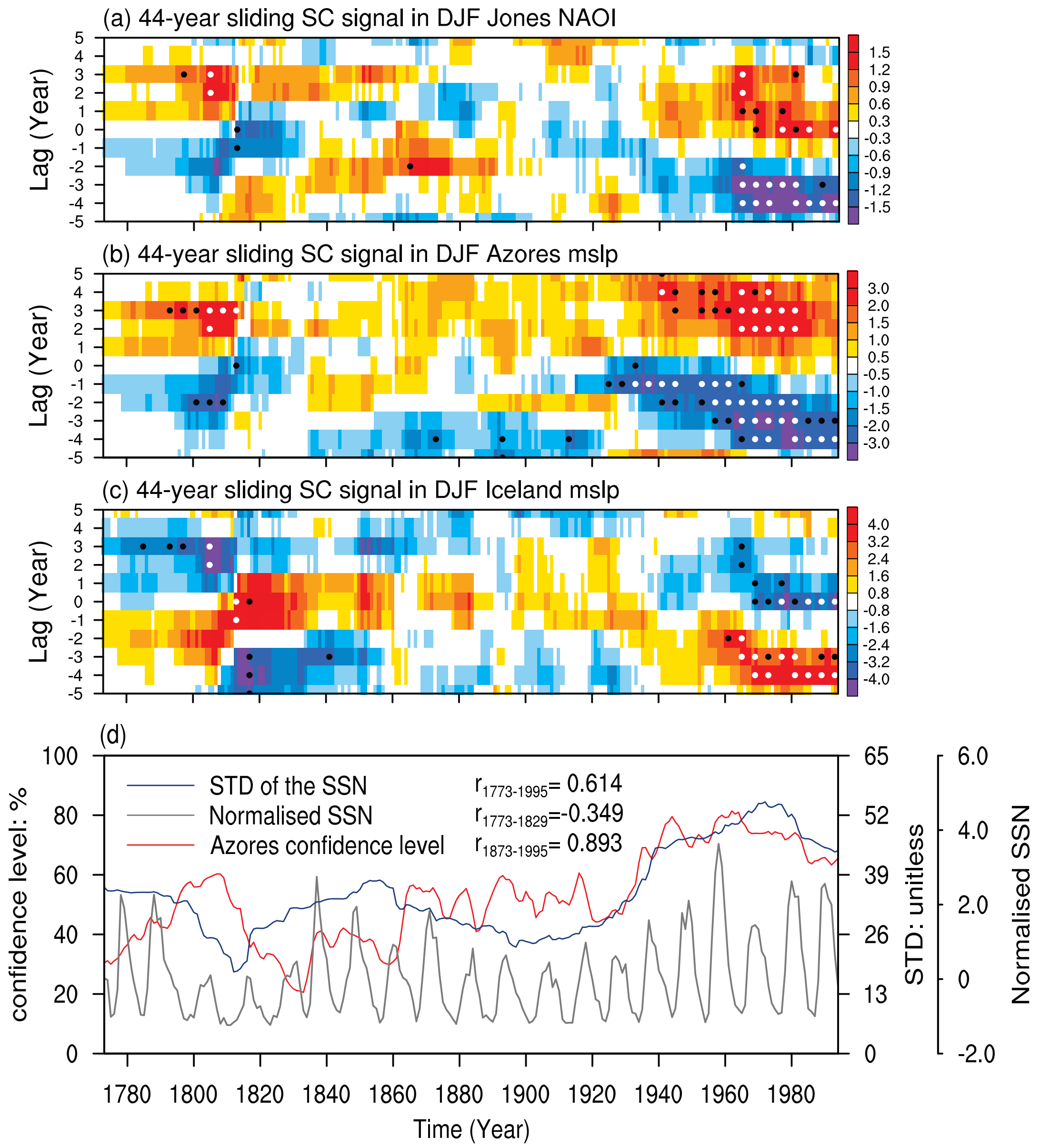

Figure 2. The temporal variations in the estimated SC signals for the period 1751–2016. (*2a*) shows the estimated SC signals in the DJF NAOI (unitless) at −5 to +5 year lags with a sliding window of 44 years using the L-MLR in equation (1). The *x*-axis, year, is labeled according to the central year of the 44 year window. Solid black (white) dots denote that the regression coefficients are statistically significant ($p < 0.1$ ($p < 0.05$)) after pre-whitening and a 1000-trial bootstrap resampling test. (*2b*) is the same as figure 2(*a*), but for SC signals in the DJF Azores mslp (unit: hPa). (*2c*) is the same as (*2b*), but for SC signals in the DJF Iceland mslp (unit: hPa). (*2d*) shows 44 year sliding standard deviation of SSN (blue line) against 44 year sliding all-lags-averaged confidence level of the SC signal in Azores mslp based on the L-MLR analysis (red line), as well as the standardized DJF SSN (grey, unitless). All-lags-averaged confidence level denotes averaged confidence level from lag −5 year to lag +5 years at a given time interval.

statistically significant at the $p < 0.1$ ($p < 0.05$) level after pre-whitening and a 1000-trial bootstrap resampling test. Although there are coherent periods showing a positive anomaly at ~3 year lag e.g. 1780–1860 and 1930–1980, overall the signal shows very little statistical significance and is sporadic in nature so that an MLR analysis performed using the whole period (not shown) shows no statistically significant response in the NAOI, which is consistent with Gray *et al* 2013.

Notably, as figure 1 demonstrates, the dominant DJF SC response is found over the Azores region, so we examine the two components of the NAO separately; figure 2(*b*) shows the corresponding 44 year sliding window regression analysis over the Azores region. The lagged nature of the Azores mslp SC response is evident for most of the time intervals during 1751–2016 with positive (negative) responses predominantly evident at several years lagging (leading) the SC, although statistical significance is only achieved over limited time intervals because of the relatively short time window employed. This lagged nature of the response is insensitive to the choice of the sliding window length, as tests obtain nearly identical results with sliding window lengths of 33, 37 and 41 years (see figure S1 available at stacks.iop.org/ERL/13/034007/mmedia).

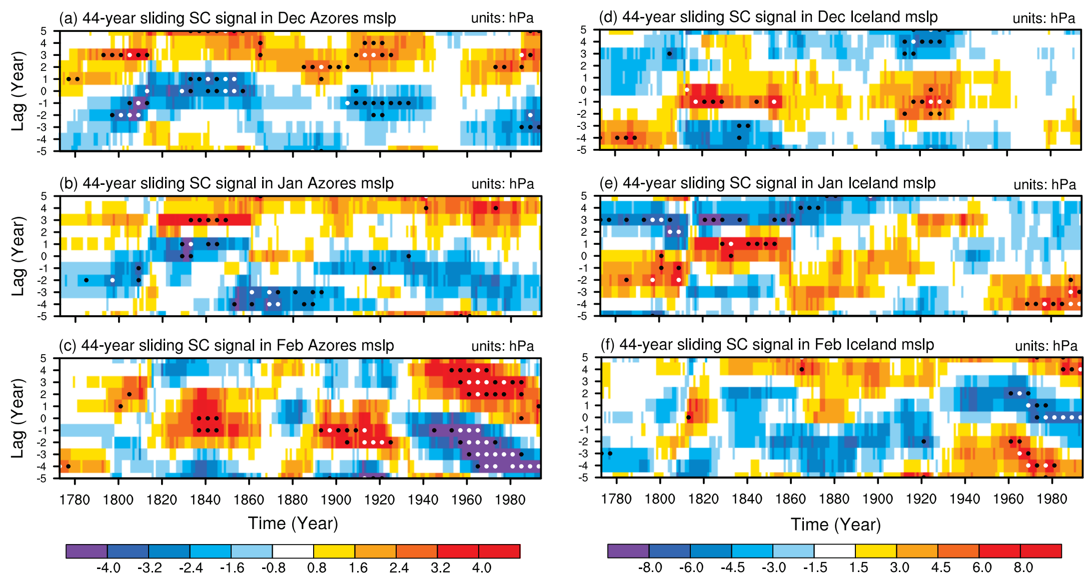

Figure 3. (*a–c*) is the same as figure 2(*b*), but showing 44 year sliding SC signals in the Azores mslp for individual winter months, i.e. December (*a*), January (*b*) and February (*c*). (*d–f*) is the same as figure (*a–c*), but for SC signals in the Iceland mslp (unit: hPa).

Although the lagged nature of the Azores mslp response is relatively consistent throughout the historical record, its robustness and statistical significance exhibit substantial long-term variations. The stronger and significant Azores mslp responses ($p < 0.1$ at 2–4 years lag and 2–4 years lead) are mainly detected before ~1810 and after ~1930, while weak responses can be found during 1860–1930. An intriguing hint is that there seems to be a connection between the strength of solar variability and significance of the Azores responses, as the period when the Azores response is most significant is also the period when solar variability is strongest (in the mid-20th Century). To demonstrate this further, figure 2(*d*) shows the 44 year sliding average of SSN standard deviation and also the corresponding time-series of the statistical confidence of the Azores mslp response (averaged over all lags i.e. from lag −5 year to lag +5 year). A higher value of the averaged confidence level shows that the SC signal can be distinguished more clearly from the background noise and/or other external forcing during that time period. The correlation between the two time series is 0.614 ($p = 0.02$) for the whole time period (1773–1995), and it is even higher for the period 1873–1995 ($r = 0.893$, $p < 0.01$). However, in earlier times the weaker periods of solar variability do not correspond to the weakest responses, and the correlation is even opposite in sign and less significant for the period 1773–1829 ($r = -0.349, p > 0.1$), possibly because the earlier reconstructed data before 1850 is of poorer quality. (The p values of these above correlations are obtained by a 10000-trialbootstrap resampling test, in each trial the sequence of all the years using for analysis are resampled before performing the time-sliding L-MLR analysis and the corresponding correlation analysis). A possible explanation is that the larger amplitude of solar forcing is favorable for the SC responses to be distinguished from the confounding noise. On the other hand, the variation in significance may also result from reinforcement/cancellation between early and late winter responses, as will be discussed later in this section.

The corresponding DJF regression analysis over the Icelandic region (figure 2(*c*)) shows an opposite structure to the Azores response at some time periods and at some lags. For example, the negative (positive) response at 3 year lags (2 year leads) in the period 1780–1810 corresponds well with the Azores signals, but with opposite sign. There is a similar correspondence in the period 1860–1930, with a particularly weak SC response over Iceland as well as the Azores. But overall the Icelandic response is sporadic in time and shows differences in the timing when compared with the Azores during certain periods, e.g. the positive SC signals maximize at 2–4 year lag (2–4 year lead) over the Azores in the period from ~1970, while the negative SC signals over Iceland maximize at zero-lag. This mismatch in the lag of the response after ~1970 will be examined in more detail later.

In summary, figure 2 suggests that a DJF-averaged SC response is present over both the Azores and Iceland during certain periods but with differences in timing that mean their combination into a single NAOI obscures the true nature of SC signal. The same is true of averaging over all winter months, since taking a DJF-average can result in the partial cancellation of SC signals in the individual months. Gray *et al* (2016) showed that the ~2–4 year lagged response was primarily seen in the early winter months (December and January) while the February response was more clearly seen at lag-zero i.e. synchronized with the SC.

Figure 3(*a–c*) show the 44 year sliding window regression analysis of the Azores SC signal from each

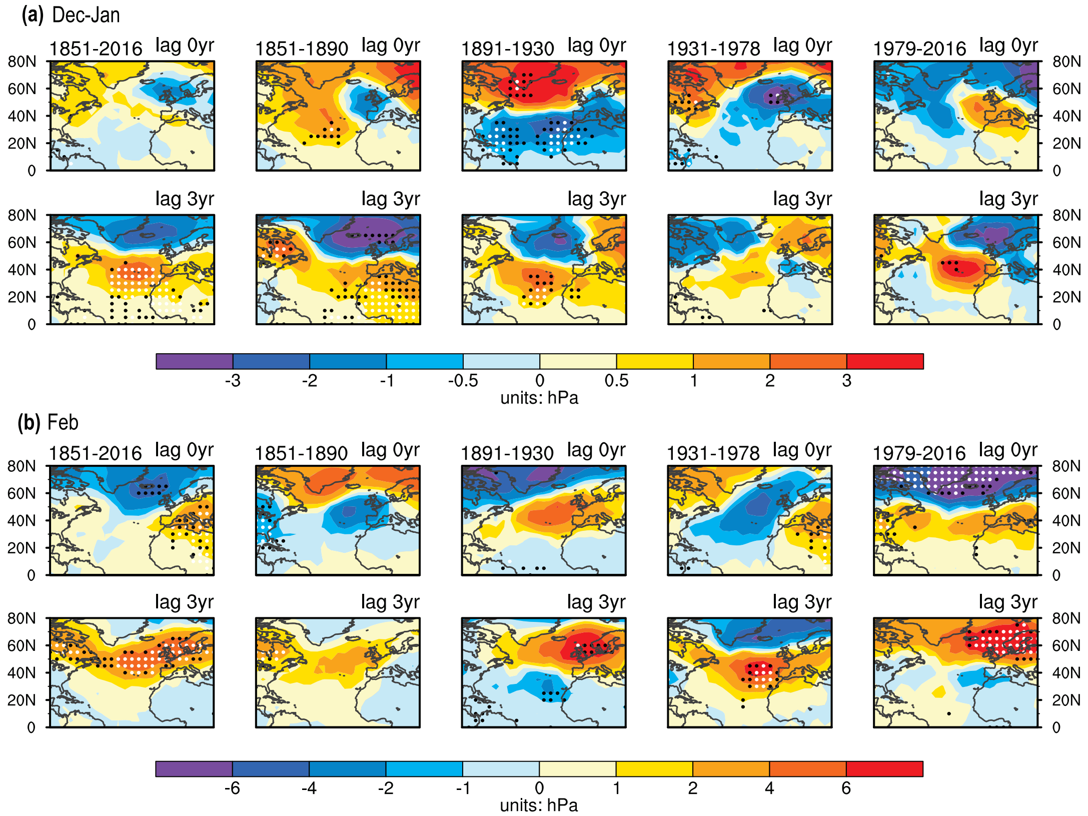

Figure 4. The estimated SC signals in the early winter (December–January, (*a*)) and late winter (February, (*b*)) mslp at 0- and 3-year-lag using the L-MLR in equation (1) for the period 1851–2016 and four subperiods (i.e. 1851–1890, 1891–1930, 1931–1978 and 1979–2016). Solid black (white) dots denote regions where the regression coefficients are statistically significant at the 10% (5%) level (i.e. $p < 0.1$ ($p < 0.05$)) after pre-whitening and a 1000 trial bootstrap resampling test.

individual winter month. The December and January responses are similar and both consistently show lagged signals, with mainly positive anomalies at 2–5 year lag throughout the entire period. The statistical significance of the December response is generally greater than in January. In some periods (e.g. ~1800–1860, ~1900–1930) the maximum (positive) response is seen at relatively large lags so that there are significant negative anomalies at zero-lag. In February, on the other hand, the signal is rather variable, sometimes with a maximum (positive) response at zero lag (around 1840, 1890–1930, 1980-present) and sometimes with a 2–4 year lag, mainly in the intervening periods. In some periods (e.g. 1820–1860, 1890–1930) this results in patterns of anomalies in February at lag zero that are opposite to those in December/January and hence there is substantial cancellation in the DJF-mean, whilst in other periods (e.g. 1930–1960) the responses in all three months are of the same sign and reinforce each other. This underlines the importance of analyzing the response in terms of early winter/late winter months.

In figure 3(*d–f*) the corresponding 44 year sliding window regression is shown for the Icelandic region. As already noted, there is very little statistical significance because of the larger intrinsic variability, and overall the responses show less consistency than those of the Azores. Nevertheless, the pattern of response is similar to the Azores in most time periods, but with mainly negative lagged anomalies (and positive zero-lag anomalies) in December and January. February is again more variable, with some similarities to the Azores structure (but of opposite sign).

The above analysis of each individual winter month suggests a lagged response in early winter (December–January) which is relatively stable, as well as a variable response in late winter (February). In addition to the sliding window analysis, these findings can be further confirmed by time-averaged responses in separate periods. In figure 4 the epoch 1851–2016 (when HadSLP2 is available) is divided into four subperiods, i.e. 1851–1890, 1891–1930, 1931–1978 and 1979–2016, among them 1891–1930 and 1979-present have an evident synchronized behavior in late winter, while1851–1890 and 1931–1978 are periods that do not.

During early winter (see figure 4(*a*)), the zero-lag response for 1851–2016 is rather weak, with inconsistent response patterns in each subperiods. At 3 year lag, the response pattern is NAO-like with more statistical significance over the Azores region, very similar to the DJF mean response in figure 1. This is consistent with the analysis of Gray *et al* 2016 that suggested the lagged response signal in DJF comes primarily from early winter months, associated with ocean feedbacks that involve reinforcement by anomalies from the previous winter. Note this pattern is present not only in the whole period but also in three out of the four subperiods (except for 1931–1978), confirming the stable nature of the early winter responses shown in figure 3, although there is more statistical significance in 1851–1890 and 1891–1930 than in 1979-present.

The late winter (see figure 4(*b*)) response at zero-lag for 1851–2016 exhibits a NAO-like pattern, with statistical significance detected at Iceland and the southern Europe. According to G2016 this pattern reflects an immediate top-down solar forcing from the stratosphere. But the response pattern is very inconsistent among subperiods, possibly due to more dynamical variability resulting from the effect of sudden stratospheric warmings (SSWs) during late winter. In addition, a significant Azores response at 3 years lag is also found in late winter of 1851–2016, primarily arising from a strong and significant lagged response during 1930–1980. Again, this response is inconsistent among sub periods. This might suggest that a lagged solar influence associated with reemergent ocean signals is also present in late winter, but that the high dynamical noise masks the response to a degree. Another possibility is that the February response is influenced by both the direct stratospheric forcing and indirect ocean feedbacks, so the presence or absence of a lag in the mslp response in February may depend on which effect is more dominant.

3.3. The synchronized solar signal in recent decades

There is a significant NAO-like response pattern synchronized with the SC (i.e. zero-lag) during 1979–2016, including significant negative Iceland mslp anomalies (see right panel of figure 1). But the sliding window analysis in figure 2 shows this significant synchronized DJF response is isolated in the historical record, i.e. it never appears in any other time intervals before 1970s. This leaves two possibilities that the recent synchronized relationship is a result of changes in physical mechanisms or just a result of chance fluctuation.

The early/late winter analysis in figure 4 shows that, the significant synchronized Iceland/NAO response in the DJF average during 1979–2016 arises primarily from late winter (i.e. February). The response amplitude during February exceeds −6 hPa around the Iceland region (figure 4(*b*)), with a large area of statistical significance, while the amplitude of the early winter (figure 4(*a*)) response is much weaker by contrast. It increases the chance that the derived synchronized signal is caused by aliasing with internal noise. In addition, the 3 year lagged response over the Azores region is still presentin early winter during 1979–2016 (figure 4(*a*)), suggesting the previously proposed ocean feedback mechanism also operates in this period, although the 3 year lagged response becomes less evident in the DJF average due to a cancellation between early and late winter.

4. Summary and discussion

Previous observational studies show conflicting results regarding the SC influences on North Atlantic/European winter climate. Through analyzing long-term mslp and SST data sets, Gray *et al* (2013) identified a significant positive DJF mslp response to the SC mainly over the Azores region 2–4 years following S_{max}. On the other hand, studies that analyzed only the recent decades showed a clearly positive DJF NAO response that was synchronized with S_{max} (i.e. zero-lag) and included a significant negative mslp anomaly over the Icelandic region in addition to the Azores (e.g. Woollings *et al* 2010, Chen *et al* 2015, Kodera *et al* 2016). After considering the potential impacts from the selection of season window (e.g. DJF/JFM) and choice of solar index, this discrepancy still exists, suggesting that the SC signals may have shifted with time.

To understand the nature and cause of time variations in the SC signals, an MLR analysis has been performed with a sliding window of 44 years over the extended period 1751–2016. While there is no overall statistically significant response in the DJF NAO at any lag, we confirm a statistically significant mslp SC response at ∼2–4 year lag over the Azores which is consistent over most of the time intervals during 1751–2016, i.e. positive (negative) responses tend to appear at several years lagging (leading) the S_{max} periods (figure 2). This lagged response was found to come mainly from the early winter (December/January) months (figure 3), confirming the results of Gray *et al* (2016). We additionally identified a correlation between the SC signals and the SC amplitude: robust and significant lagged SC signals over the Azores tend to appear in the periods when the SC amplitudes are relatively larger (figure 2), especially in the period since ∼1870 when the observational data are more reliable.

These general results from the extended period 1751–2016 contrast with those of Maliniemi *et al* (2014) who analyzed the wintertime surface temperature and NAO anomalies during 13 sunspot cycles (1869–2009) by defining four composites according to the different SC phases: minimum, ascending, maximum and declining phase. They found a statistically significant NAO response, which was not found in this study, and this was evident in all but one solar cycle (see their figure 6) while we find a relatively more robust response during certain time periods. These discrepancies can possibly be explained by the different analysis techniques: regression analysis is able to take account of other influencing factors such as volcanic eruptions, ENSO etc which a composite analysis cannot; on the other hand by splitting into four composites the ascending/descending SC phases (which may not be symmetric) can be examined separately, which is not possible in the regression analysis.

An examination of the recent period since the 1970s was also performed in order to understand the NAO-like response synchronized with SC found in other studies. Figure 2 indicates this significant synchronized DJF response is isolated in the historical record, i.e. it never appears in any other time intervals before 1970s. Early/late winter analysis suggests that the synchronous SC-NAO relationship in DJF since the 1970s arises primarily from late winter (i.e. February). Therefore it increases the chance that the observed synchronized SC-NAO relationship is just a result of confounding noise, since dynamical internal noise is typically very strong during February.

The changing nature in some aspects of the observed SC signals, e.g. the NAO response, has raised skepticism about whether there is a coherent signal or whether the signal is an analysis artifact (Van Oldenborgh *et al* 2013). The results of the present study have important implications on this issue. We found the lagged nature of mslp response over the Azores region generally consistent in time, particularly in early winter, which puts the previously identified connection between SC and North Atlantic surface climate on a sounder basis.

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