Manifestation of the 11-year solar cycle in the North Atlantic climate

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Abstract. Analysis of fluctuations in the climate of the North Atlantic associated with the 11-year solar cycle is done using empirical data of the sea level pressure (SLP) and sea surface temperature (SST) for 1870-2012 and data of the North Atlantic Oscillation (NAO) index and Central England temperature. Emphasis is placed on the regions of the Icelandic and Azores atmospheric centers of action (CA). Methods of multiple linear regression and cross-wavelet analysis are used. The analysis reveals decadal oscillations of the SLP lagging by ~3 years relative to the sunspot number, in the area of the Azores CA in the winter and autumn seasons. SLP variations that are approximately in phase with the solar cycle are noted in autumn in the Icelandic CA. Solar-related SLP variations in the Icelandic CA in winter occur approximately in anti-phase with the variations in the Azores CA, at smaller lag behind the solar cycle. SLP variations associated with the solar cycle are comparable in amplitude to variations due to the El Nino–Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO). SST variations associated with the solar cycle are also revealed. They are several times weaker than variations due to the AMO, but of the same order of magnitude as variations due to the ENSO. The relation of the NAO index to the solar cycle is alternating and experiences modulation with a period of about 50 years.

1. Introduction

Influence of the 11-year solar cycle on the Earth’s climate is a subject of many studies [1]. One important large-scale pattern of the atmospheric circulation affecting the climate on the vast territory from the east American coast to Siberia is the North Atlantic Oscillation (NAO) [2]. Solar influence on the NAO was studied in a number of papers; see [3] for the recent review. Significance of a solar signal in the NAO is still disputed. According to [3], the relation of the NAO index to the solar cycle changes sign periodically, which can mask the relationship on a large time interval.

Numerical climate modeling showed the possibility of the lagged response of the North Atlantic climate to the solar cycle including response of sea surface temperature, with a lag of several years [4–6]. Lagged solar signals were revealed in the sea level pressure and sea surface temperature in the Azores region in winter [7–9] and in the NAO index in winter and summer [3].

Here we present analysis of relation of climate parameters in the North Atlantic to the 11-year solar cycle using data of long term observations.
2. Observational data
The following monthly mean data are used in the work.
1. Sea level pressure (SLP) data for 1850–2012 from the UK Hadley Centre Sea Level Pressure (HadSLP2) data set (https://www.metoffice.gov.uk/hadobs/hadslp2/). These are an update of data presented in [10].
2. Sea surface temperature (SST) for 1870–2018 from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) data set (https://www.metoffice.gov.uk/hadobs/hadisst/) [11].
3. NAO index for 1823–2018 from the Climatic Research Unit, University of East Anglia (https://crudata.uea.ac.uk/cru/data/nao/). These are an update of data reported in [12].
4. Near-surface air temperature in Central England since the middle of XVII century from the Met Office Hadley Centre (https://www.metoffice.gov.uk/hadobs/hadcet/data/download.html).
5. Sunspot number from the World Data Center SILSO, Royal Observatory of Belgium, Brussels (http://www.sidc.be/silso/datafiles).
6. Stratospheric aerosol optical depth from the NASA Goddard Institute for Space Studies (https://data.giss.nasa.gov/modelforce/stratera/). (Used as a predictor in the regression model).

The SLP and SST data are gridded data. For the use in this paper, these data were averaged over areas of the strongest lagged responses of SLP and SST reported in [7]. The coordinates of the areas are 50°W–20°W, 25°N–45°N and 30°W–5°W, 55°N–70°N; they correspond to regions of the Azores and Icelandic centers of action (CA) of the atmosphere, respectively.

In the multiple regression model (see the next section), Nino3.4 and Atlantic Multidecadal Oscillation (AMO) indices are used. We calculated the Nino3.4 index by averaging SST over region with coordinates 170°E–120°W, 5°S–5°N as suggested by the NOAA Climate prediction Center (https://www.cpc.ncep.noaa.gov/data/indices/). This index serves an oceanic proxy of the El Nino–Southern Oscillation (ENSO). The proxy of the AMO was calculated as area-averaged SLP over the North Atlantic within 0° and 70°N (see https://www.esrl.noaa.gov/psd/data/timeseries/AMO/) which was subsequently smoothed by the Kaiser-Bessel filter [13] with cutoff frequency 0.1 year⁻¹, to emphasize multidecadal variations.

Since the SLP and SST data sets are not the same in length we only show results for 1870–2012.

3. Methods of analysis
We use for the analysis the multiple linear regression and cross-wavelet methods. Our cross-wavelet method has specific features described in detail in [3, 14]. Here we use two characteristics of cross-wavelet analysis: local coherency and local correlation. The local coherency characterizes the highest correlation of wavelet transforms of two signals at period P within the time interval of length P. The highest correlation and an appropriate time shift (lag) between the two transforms are determined under shifting one transform relative another. Note that the local coherence can be positive or negative. The local correlation at prescribed lag is the correlation coefficient between the wavelet transforms at period P, one of which lags behind another by the lag value.

The multiple linear regression model is used to identify signals associated with the 11-year solar cycle and other predictors and estimate magnitudes of these signals. To solve the system of the regression equations the method suggested in [15–16] is used, which allows taking into account autocorrelation of data on long time scales.

The regression model includes the following predictors: the free member, the linear term, two sunspot number series, two Nino 3-4 indices, the AMO index, and monthly mean aerosol optical depth. The latter is used to represent effects of major volcanic eruptions.

Two solar proxies are used to represent the lagged solar cycle effect. One proxy is the sunspot time series as it is. The other one is the forward shifted in time sunspot number series such that its correlation with the original series is zero. Therefore the two proxies are orthogonal to each other. Since the 11-year solar cycle dominates in variability of solar activity we can approximately consider they as orthogonal harmonic functions of the same period, like sine and cosine. The response to the shifted sunspot number lags after the actual solar cycle by quarter period. Therefore calculating
together responses to the original and shifted sunspot numbers we can derive the sum magnitude and phase (lag) of the solar cycle effect. The shift at which the two sunspot number series are orthogonal to each other within the period of the analysis 1870–2012 is equal to 34 months, which, multiplied by 4, corresponds well to the solar cycle period.

Similarly, the two Nino3.4 indices, one actual and another shifted forward to be orthogonal to the former, are used to represent the lagged effect related to the ENSO. The shift at which the two Nino3.4 series are orthogonal to each other is equal to 14 months. Multiplication by 4 gives 4.7 years, the value that is within the ENSO period band [18]. However unlike the solar activity, the ENSO (and the Nino3.4 index) has not a clear periodicity with dominant amplitude. Therefore the lag of the response to Nino3.4 cannot be determined analogously to the lag of the response to the solar cycle.

All regression coefficients in the regression model are expanded into Fourier pairs corresponding to the annual and sub-annual harmonics to account for seasonal dependence of the effects. The number of pairs is equal to 2 for all the coefficients except the coefficients at the sunspot number terms for which four Fourier pairs are used, to account for the solar cycle effect in more detail.

Two sets of multiple regression calculations were performed. In one set, the regression model included the full aforementioned list of predictors. These calculations are intended to estimate the AMO effects. Remind that the AMO index is obtained by smoothing. However smoothing diminishes number of independent values, and in this sense the AMO index differs from other predictors which consist of unsmoothed monthly values. For this reason, the regression model in the other set of calculations did not include the AMO index. Nevertheless, since the solution method allows accounting for autocorrelation on very large time scale, the influence of the AMO is taken into account indirectly in these calculations (see for example [19]). These calculations are intended to estimate effects of other predictors. We note that these estimates are very close to estimates of the appropriate effects obtained in calculations by the regression model including all the predictors.

4. Results

Multiple regression analysis was applied to the SLP, SST, and NAO index data of the same length, i.e. for 1870–2012. Cross-wavelet analysis was applied to the NAO index and Central England temperature (CET) data of the full length.

4.1. Multiple regression analysis

At first we present estimates of the AMO effects on the SLP and SST. These estimates are convenient to use as reference effects to be compared to solar effects, because the AMO is an inherent feature of the ocean variability.

Figure 1 shows estimates of the amplitudes of the AMO effects on SST and SLP in the Icelandic and Azores CA as function of season. The amplitudes are normalized by the AMO standard deviation. The leftmost values in the plots are annual estimates. The AMO effect on SST is seasonally dependent (Fig. 1a). The amplitudes are within 0.15–0.4°C. The SST changes in the Icelandic CA due to the AMO are generally larger than the changes in the Azores CA. Maximum effects fall on autumn; herewith the maximum occurs earlier in the Icelandic CA.

The amplitude of the SLP changes associated with the AMO is of about 1 hPa and less (Fig. 1b). The maximum effect is manifested in late winter–early spring in the Icelandic CA. The AMO-related changes in the Icelandic CA in summer are opposite to the AMO. Change in sign of the effect in the Icelandic CA results in that the effect for the entire year is not manifested. The SLP changes in the Azores CA associated with the AMO are small and generally opposite to the AMO.

Effects of the solar cycle on SST and SLP in the two regions and on the NAO index are demonstrated by Figures 2 and 3. Black solid curves and dots show magnitudes of (lagged) responses to the solar cycle, while gray dashed curves and dots correspond to lags. Lag values are only shown for statistically significant responses. Note that magnitude units are the SST, SLP, and NAO index changes from the phase of solar minimum to the phase of solar maximum. They are obtained by multiplying the appropriate regression coefficients by the mean max-minimum peak difference of the
Figure 1. Annual (dots in the left parts of the plots), monthly (curves and dots in the middles of the plots) and seasonal (curves and dots in the right parts of the plots) estimates of the AMO effect on (a) sea surface temperature and (b) sea level pressure in the Icelandic (blue) and Azores (red) centers of action. Vertical bars are the 95% confidence intervals. Red and blue curves are slightly shifted relative to each other for better distinguishing of the confidence intervals.

Figure 2. Magnitude (black) and lag (red) of the solar cycle effect on sea surface temperature in the (a) Icelandic and (b) Azores centers of action. Vertical bars are the 95% confidence intervals. Lag is only shown for statistically significant solar effect. Horizontal axes are explained in the capture to Fig.1.

Sunspot number in the appropriate data interval. A negative magnitude value denotes that, at the respective lag, response to the solar cycle is in anti-phase with it.

The SST changes in the Icelandic CA associated with the solar cycle are of about 0.1°C and less (Fig. 2a). The maximum effect is observed in late spring–early summer at lags 2–3 years and in autumn at lags 1–2 years. The annual estimate of the SST response to the solar cycle is statistically
As in Fig. 2 but for the SLP in the (a) Icelandic and (b) Azores centers of action and (c) for the NAO index.

Figure 3. As in Fig. 2 but for the SLP in the (a) Icelandic and (b) Azores centers of action and (c) for the NAO index.

insignificant. The SST changes in the Azores CA related to the solar cycle are generally less than in the Icelandic CA (Fig. 2b). The maximum positive effect is observed in late autumn and winter (approaching 0.1°C in December) at lags close to 4 years. The strongest negative (antiphase) effect at 2-year lag falls on summer. The annual SST response to the solar cycle in the Azores CA is small but statistically significant. The lag of the response is of about 4 years. Therefore, the SST responses for the entire year in the two regions follow the solar cycle with lags, and the lag is larger in the Azores CA.

Comparison of Fig. 2 to Fig. 1 shows that the SST changes in the regions of the two CA associated with the 11-year solar cycle are several times less than the changes associated with the AMO.

The SLP changes associated with the solar cycle are within 2 hPa in the Icelandic CA and 1 hPa in the Azores CA (Fig. 3). Statistically significant effect in the Icelandic CA manifests itself in autumn through early spring (Fig. 3a). There is a large increase in the lag of the SLP response from November to March accompanied by change of the sign of the response magnitude. Statistically significant effect in the Azores CA is manifested in winter to early spring (Fig. 3b). Like in the Icelandic region there is an increase in the lag of the SLP response in the Azores region during winter and early spring, but at generally larger lag values.

Comparing Figs 3a and 3b we note that the solar effects on SLP in the two regions in winter and for the entire year are opposite in sign (compare respective annual and seasonal estimates of the magnitudes). In winter, the SLP in the Icelandic CA changes approximately in anti-phase with the solar cycle, at average lag close to 1 year, while the SLP in the Azores CA follow the solar cycle at average lag of about 3 years. A 3-year lag is also characteristic of the entire-year response in the Azores CA. The entire-year response in the Icelandic CA is in anti-phase with the solar cycle.

Roughly opposite solar-related variations of the SLP in the two regions for winter and the entire year can, in principle, result in a solar signal in the NAO index. Indeed Fig. 3c shows that for the same time interval, 1870-2012, there are appropriate effects in the NAO index, at an edge of statistical significance. On the monthly basis, Fig. 3c indicates solar effect in August, October, and December at
Comparing the solar effects in the SLP to the effects due to the AMO we deduce that the solar effect on the SLP is comparable to the AMO effect.

The Nino3.4 effects on SST in the Icelandic and Azores CA are shown in Fig. 4. In-phase, not-lagged, responses to Nino3.4 are shown in black while the lagged orthogonal responses are shown in gray. The latter are determined by the regression coefficients corresponding to the shifted Nino3.4 series. The amplitude of the Nino3.4 effect is generally less than 0.1°C. Since both the components of the SST response related to Nino3.4 are usually non-zero simultaneously, the total response lags after the Nino3.4 index. We can determine the lag in some simplest cases. For example the not-lagged autumn and winter responses in the Icelandic CA (Fig. 4a) and the not-lagged winter response in the Azores CA (Fig. 4b) are close to zero while the appropriate orthogonal responses are not zero and negative. Therefore the SST response to Nini3.4 in these cases lags behind it by about 1 year and 2 months and the appropriate changes in SST are opposite to changes in the lagged Nino3.4 index.

The effect of Nino3.4 on the SLP is shown in Fig. 5. Its amplitude is of about 1 hPa and less. The maximum in the Icelandic CA manifests itself in March and September and is approximately in phase with Nino3.4 (Fig. 5a). In the Azores CA, the lagged orthogonal response is, as a rule, relatively small and, therefore, the SLP changes due to Nino3.4 are roughly in anti-phase to the changes in the Nino3.4 index for the most part of year (Fig. 5b). Comparison of Figs 5a and 5b shows that the Nino3.4-related changes in the SLP in the two regions are approximately opposite to each other during the late winter–early spring and late summer–early autumn periods.

Comparison of the solar effects and the Nino3.4 effects on the SLP shows that they are of the same order of magnitude.

4.2. Cross-wavelet analysis

Figure 6a shows the local coherency between the NAO index and the sunspot number as function of time and period of variations. The temporal structure of the coherency at the period of the solar cycle is alternating. The relation of the NAO index to the solar cycle undergoes quasi-periodic modulation
with period of about 50 years. The modulation is emphasized by Fig. 6b presenting the local correlation between the NAO index and the sunspot number at 7-year lag of the NAO index behind the sunspot number. Note that the alternating character of the relationship between the NAO index and the solar cycle leads to a decrease in correlation between them within the whole or sufficiently long time period.

Our analysis in [3] shows that there is a positive correlation on the decadal scale between the NAO and sunspot number, as presented in Fig. 6a. The coherency between the NAO index and the sunspot number is shown in Fig. 6a, with the coherency being highest at a period of about 50 years. The modulation is further illustrated by Fig. 6b, showing the local correlation between the NAO index and the sunspot number at a 7-year lag. Note that the alternating character of the relationship between the NAO index and the solar cycle leads to a decrease in correlation between them within the whole or sufficiently long time period.

Figure 5. As in Fig. 4 but for the sea level pressure in the (a) Icelandic and (b) Azores centers of action and (c) for the NAO index.

Figure 6. (a) Local coherency between the NAO index and the sunspot number; (b) local correlation of the NAO index with the sunspot number at the 7-year lag; (c) local coherency between Central England temperature and the sunspot number. Arrows at bottom correspond to maxima of solar impact on climate; see [3].
index and CET modulated by the AMO. Using this fact we can extend analysis of the solar impact backward in time for more than hundred years. Figure 6c presents the local coherency between CET and the sunspot number. It shows that the quasi-periodic structure at the solar cycle period manifests itself in the solar–CET relationship as well.

5. Short discussion of the results
The results obtained for the Azores region confirm earlier results of [7–8] concerning the lagged solar effect on SST and SLP in winter. We obtained the ~4-year lag for the winter SST response and ~3-year lag for the SLP response to the solar cycle in this region, which are close to the lags reported in [7–8]. In addition, we obtained estimates of solar effects on SST and SLP in the region of the Icelandic CA. Moreover, we extended the analysis to a full year and obtained estimates of solar signal for different seasons.

An important and interesting question is the reason of the 50-year modulation of the solar–NAO index and solar–CET relationships. The AMO is not the reason since its mean period differs significantly from 50 years and there is no correspondence between the AMO phases and any features of distributions in Fig. 6. Trying to find another candidate for the modulation, we depict at bottom of Fig. 6 the arrows that correspond to presumable maxima of solar impact on climate; see [3] for detail. For better visualization, their positions are marked by vertical dashed lines through the whole plots. These maxima, except the first one (after 1730), correspond well to certain features in Fig. 6. The probability of that these coincidences are random is very small (see [3]). We can therefore suppose that the 50-year modulation of the solar–NAO relationship is due to multidecadal variations of solar impact on climate.

Comparing Figs 3a and 3c we note that the seasonal course of the magnitude of the solar signal in the NAO index is similar to the inverse seasonal course of the solar effect on SST in the Icelandic region. It is likely, therefore, that the solar influence on the NAO and, as a consequence, via it on the climate on the more vast territory is determined primarily by susceptibility to the solar cycle effect in the Icelandic region.

Comparing Figs 4a and 4b we see some regularity in manifestation of the Nino3.4 signal in SST in the Azores and Icelandic regions. This signal includes two orthogonal components. One is a more or less constant component, especially in the Azores region. Another is a seasonally oscillating component, and its seasonal variation in the Icelandic region lags by about a month relative to the seasonal variation in the Azores region. We note that the oscillating component is responsible for the direct Nino3.4 effect on SST in the Azores region and for the lagged effect in the Icelandic region, while the not-oscillating component is responsible for the lagged Nino3.4 effect on SST in the Azores region and for the direct effect in the Icelandic region. Remembering that the time shift between the two Nino3.4 proxies is equal to 14 months, we conclude that the Nino3.4 signal in SST is transferred in direction from the Azores region to the Icelandic region, and this process takes 14–15 months.

6. Conclusions
Main conclusions from the reported results are as follows.

Decadal variations of the SLP and SST in the neighborhoods of the Icelandic and Azores CA in certain seasons are related to the 11-year solar cycle.

The relation manifests itself with a delay relative to the solar cycle.

The solar-related changes in SST are of the same order as the ENSO-related changes but several times less than the changes due to the AMO.

The solar-related changes in the SLP are of the same order as the changes associated with the ENSO and AMO.

The solar-NAO index relationship is alternating and experiences modulation with a period of about 50 years.
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