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The influence of solar activity on action centres of atmospheric circulation in North Atlantic

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Abstract. We analyse the response of sea level pressure and mid-tropospheric (500 hPa) geopotential heights to variations in solar activity. We concentrate on the Northern Hemisphere and North Atlantic in the period 1948–2012. Composite and correlation analyses point to a strengthening of the North Atlantic Oscillation and weakening (i.e. becoming more zonal) of the Pacific/North American pattern. The locations of points with lowest and highest sea level pressure in the North Atlantic change their positions between low and high solar activity.

Keywords. Meteorology and atmospheric dynamics (Climatology)

1 Introduction

There is a lot of interest in establishing the influence of solar activity upon atmospheric circulation as accurately as possible, since this contributes to quantifying effects of solar variability on terrestrial climate. This also offers the possibility of increased accuracy for decadal predictions (Smith et al., 2013). The horizontal pattern of sea level pressure (SLP) field is the main driver of the atmospheric circulation. Strong correlations between wintertime temperature and pressure disturbances in Europe, on the one hand, and solar activity, on the other hand, are observed at long-term timescale (decennial–centennial) (LeMouel et al., 2009; Woollings et al., 2010). Variations in phase with solar cycles were observed in North Atlantic SLP (Kelly, 1977). The early work of Rumney (1968) suggested that the strongest solar signal over the North Atlantic is associated with regions where the polar fronts are mainly located. These are in principal regions of high cyclonic activity (Gleisner and Thejll, 2003). Correlations between various solar proxies and sea level pressure in the Arctic region of Canada and Greenland (Mansurov et al., 1974; Page, 1989) and a clear relation between solar activity and the position and intensity of Aleutian Low and Californian High (Christoforou and Hameed, 1997) were found using the mean composite difference method. Recent studies show that there is an apparent clear response to the solar cycle in the lower stratospheric geopotential structure (Labitzke and van Loon, 1995, 1988; van Loon and Labitzke, 1993; Bochníček et al., 2012).

Several studies indicate that atmospheric circulation in the northern mid-latitudes, and in particular in the Euro-Atlantic sector, becomes more zonal during high solar activity (Bochníček and Hejda, 2002; Huth et al., 2006, 2008; Barripedro et al., 2008). This may be related to a strengthening of the North Atlantic Oscillation (NAO), which is an atmospheric oscillation ("seesaw") between the Icelandic low and Azores high with a direct impact on the atmospheric circulation in the Northern Hemisphere and on climate conditions in most of Europe (Hurrell et al., 2001). A correlation between sunspot numbers and the NAO index was identified on long timescales (Boberg and Lundstedt, 2002), with high solar activity related to positive NAO phase. Other studies found a negative correlation between the same parameters, however (Kirov and Georgieva, 2002). Studies on Maunder Minimum have indicated a direct relationship between the low solar activity during this period and the negative NAO phase (Wanner et al., 2008; Slonosky et al., 2001; Luterbacher et al., 2001; Xoplaki et al., 2001; Shindell et al., 2001; Langematz et al., 2005). A reduction in SLP at 20–40° N in the Pacific sector during high solar years was mentioned by van Loon and Meehl (2008) in a study applying the composite mean difference method. These results were confirmed by Roy and Haigh (2010) by means of multiple linear regression applied to time series of 155 years. They found a region of positive anomaly of about 5 hPa in the North Pacific corresponding to a weakening of the Aleutian low during high solar years. Generally, an expansion of the zonal mean Hadley cell and a poleward shift of the Ferrel cell was observed during solar maxima (Brönniman et al., 2006; Haigh, 2003, 1996; Larkin et al., 2000; Matthes et al., 2006).

Due to a weak signal of solar activity in SLP, some authors have tried in the last period to apply a multiple linear regression technique to estimate the SLP response to solar forcing during northern winter as a function of phase lag. Recent studies of Gray et al. (2013) and Hood et al. (2013) investigated the SLP response to solar signal as a function of phase lag during northern winter, using a long data set (more than 130 years). Hood et al. (2013) found that the NAO index progress from a mainly negative phase prior to solar maximum to a mainly positive phase at and following solar maximum while Gray et al. (2013) found that the NAO index is significantly positively enhanced several years after solar maximum.

2 Data and methodology

We use monthly averages of SLP and 500 hPa geopotential height (GPH) from the NCEP/NCAR reanalysis (Kalnay et al., 1996), for a 65-year period 1948–2012, which constitutes 6 full solar cycles, for a region between 20° N and the North Pole. SLP data are available on a grid with the zonal and meridional step of 5°. Similar to the majority of other studies, the cold season (October to March) and winter (December to February) are only analysed here. NCEP/NCAR data were selected because of the possibility of using both SLP and 500 hPa GPH data in our attempt to search for a relation throughout the lower and middle troposphere between the atmospheric circulation and solar activity, and also because they are regularly updated, and so available until recently.

Data were divided into low and high solar activity months according to the solar activity level, using the sunspot number as a proxy. Solar activity is considered to be high (low) if the associated sunspot number is in the upper (lower) third of the entire data set, similarly to Barriopedro et al. (2008). Differences of the composite GPH and SLP between the high and low solar activity were then calculated. The statistical significance of the differences between high and low solar months was tested using the Student test for the difference of means. Direct and 1-month lagged Pearson correlations between solar activity and SLP (GPH) were calculated. This method is used for simplicity and in the future we plan to use a multiple regression method which is attested in recent works (Gray et al., 2013) as a method that can yield information about other possible sources of pressure variations, such as El Niño–Southern Oscillation. On the other hand, the composite approach that we use can be considered more robust and general than linear regression because the latter assumes a linearity of the atmospheric response, which may not be realistic.

The positions of the major centres of action of atmospheric circulation were localized as the lowest (highest) value of SLP in the Euro-Atlantic domain, extending between 20 and 90° N and 70° W and 30° E. Separate frequency maps, showing where these centres are located, were created for high and low solar months. The lowest SLP in the domain can be identified with the Icelandic low, while the highest SLP coincides either with the Azores high or with the high-pressure centre over Greenland. Differences in the latitudinal and longitudinal distribution of both pressure formations between high and low solar activity were assessed using the two-sample Kolmogorov–Smirnov test. In brief, the two-sample KS-test determines whether two data sets were drawn from the same distribution or generating process and its main statistic (D) looks for the largest difference between the empirical cumulative distribution functions of the two samples (Wilks, 2006).

3 Results and discussions

3.1 Composite and correlation analysis

Figure 1 shows the mean difference between high and low solar activity for 500 hPa GPH (in metres, left) and for SLP (in hPa, right) in winter. Regions where the difference is statistically significant are shown with black or white lines. The differences between high and low solar activity reach for 500 hPa GPH as much as 50 m (when the whole cold season is considered; not shown) and 30 m during winter. The SLP variation reaches ± 3 hPa during winter.

The relation of tropospheric circulation to variations in solar activity is strongest in the North Atlantic. The statistical significance of differences is mostly rather marginal, only small regions exhibiting significant differences. An increase in GPH and SLP during high solar conditions can be seen over the Iberian Peninsula and western Mediterranean; similar effects were obtained on a longer period by Brugnara et al. (2013) and Gray et al. (2013). On the other hand, decreases of GPH and SLP concentrate in the vicinity of Iceland and over the North Sea. This can be interpreted as a strengthening of both permanent pressure formations, and possibly also their slight shift eastwards. Taken together, this implies a strengthening of the NAO and an intensification of the westerly flow from the North Atlantic into Europe. This also supports Woollings et al. (2010) and van Oldenborgh et al. (2013) who found the same pattern of relation-

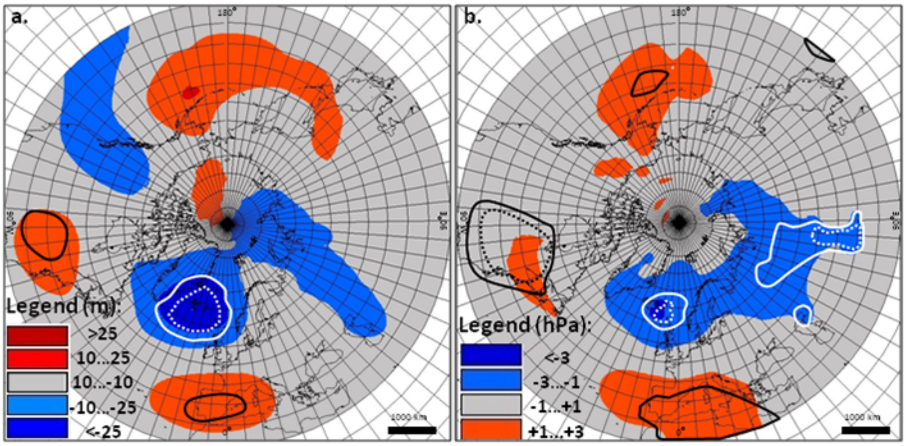

Figure 1. Mean difference between months with high and low solar activity for the 500 hPa GPH (in metres) (left) and SLP (in hPa) (right), for winter. Regions with statistical significance of differences are delimited by continuous (10 % significance level) and dotted (5 % level) lines, indicating positive (black) and negative (white) correlation.

ship between solar activity and 500 hPa GPH for a longer period in the North Atlantic–European sector and is in a very good agreement with e.g. Bochníček and Hejda (2002), Huth et al. (2006, 2008) and Barriopedro et al. (2008) who report an intensification of westerlies or NAO under high solar conditions, using different analysis tools. On the other hand, our results disagree with Kirov and Georgieva (2002), who however analysed autumn, and an older study by Girs and Kondratovich (1978) cited by Kirov and Georgieva (2002); both of these studies found a shallower Icelandic low and weaker Azores High to be related to high solar activity. However, this contradiction might be only apparent, since the correlation between solar activity and NAO is not constant on various timescales depending on the secular phase of solar cycle (Georgieva et al., 2012), the level of geomagnetic activity (Li et al., 2011), and possibly also the phase of the quasi-biennial oscillation (van Loon and Labitzke, 1988; Huth et al., 2009).

In the North Pacific/North American sector, the solar signal is more significant in the SLP field. The association of the Aleutian low with solar activity is opposite to the Icelandic low: its intensity tends to decrease (i.e. its GPH and SLP tend to increase) with increasing solar activity. This is in line with several previous studies (Christoforou and Hameed, 1997; van Loon and Meehl, 2008; Roy and Haigh, 2010; Gray et al., 2013; Hood et al., 2013; Scaife et al., 2013); however, we note that the amplitude and significance of the difference between high and low solar activity is smaller than in some of these studies. The disagreement in the amplitudes is probably due to the fact that the period of our analysis is much shorter (65 against at least 130 years). A similar response, i.e. higher GPH and SLP in high solar activity, occurs over the eastern US, while the opposite, although insignificant and only in GPH, is observed over the western shore of North America where high solar activity is accompanied with lower GPH values. The spatial pattern of the differences is reminiscent of the mid-latitude part of the Pacific/North American (PNA) teleconnection pattern, the four centres of which are located over Hawaii, the Aleutian Islands, western US/Canada, and southeastern US; for more details on the PNA pattern and its relevance for the North American climate, see e.g. Leathers et al. (1991). The response of the PNA pattern to solar activity can be interpreted as its weakening, i.e. shift to lower values, accompanied with a more zonal flow over North America, in solar maxima. Changes in the position of the action centres of the PNA pattern, although not in its amplitude, in response to solar activity were reported by Huth et al. (2006). Atmospheric circulation, and more so SLP, seems to be sensitive to solar effects also in Central Asia.

The composite analysis is accompanied by directly calculating Pearson correlations between solar activity and 500 hPa GPH (Fig. 2a). The areas of significance are of similar size and strength as for the composites in Fig. 1a. The similarity between the patterns of significant differences and significant correlations suggests that the response to variations in solar activity are mostly linear because Pearson correlations are a measure of the linearity of association while the composite analysis reflects a monotonicity of the association rather than its linearity. Since the response of tropospheric circulation to solar activity is unlikely to be immediate, we calculated also 1 month lagged Pearson correlations between GPH and solar activity (Fig. 2b). They show only marginal differences relative to simultaneous correlations, which confirms the appropriateness of analysing circulation data with zero lag relative to solar activity.

3.2 Solar activity versus SLP centres

A small but significant shift in the position of the grid point with lowest SLP in the Euro–Atlantic sector, which approximately represents the position of the Icelandic low, is ob-

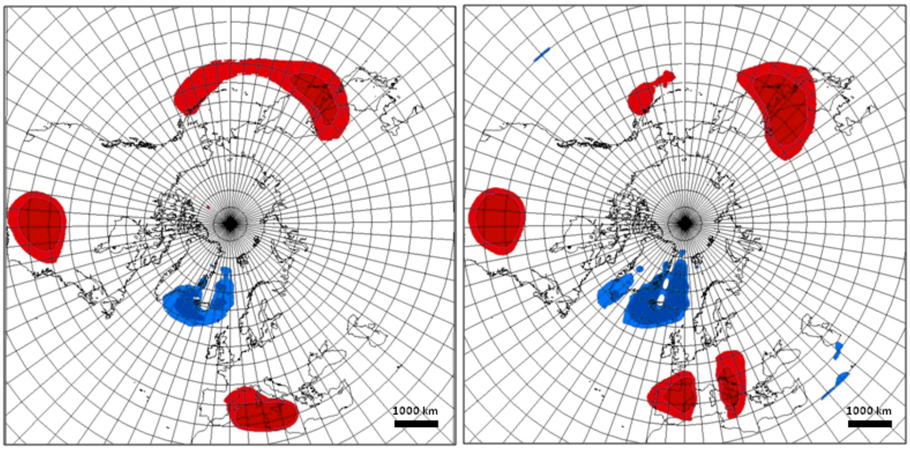

Figure 2. Pearson correlation between solar activity and 500 hPa GPH: direct (left) and 1 month lagged (right). White means no significant correlation, light red (blue) stands for significant positive (negative) correlations at 10 %; dark red (blue) shows regions of positive (negative) correlation (5 % significance).

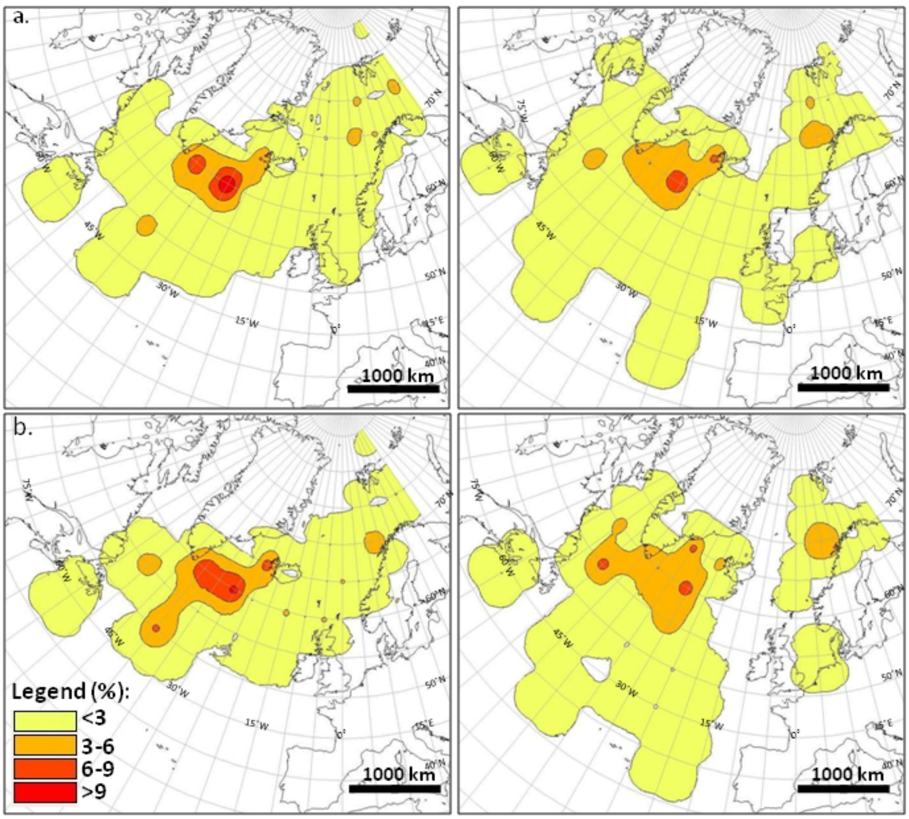

Figure 3. (a) Upper panel: relative frequency (%) of the lowest mean SLP occurring during high (left) and low (right) solar months for the cold season (October–March). **(b)** Lower panel: relative frequency (%) of the lowest mean SLP occurring during high (left) and low (right) solar months for winter (December–February).

served when the solar activity varies from high to low. Figure 3 shows the frequency of occurrence of the lowest SLP value. During high solar activity the position of the cyclone is more geographically confined and its most frequent position is south of Greenland, in the area bounded by 25–55° W and 55–65° N. There is also a second preferred location of the lowest SLP near and north of the Norwegian coast, between 5 and 15° E, which may correspond to the eastward shift of the

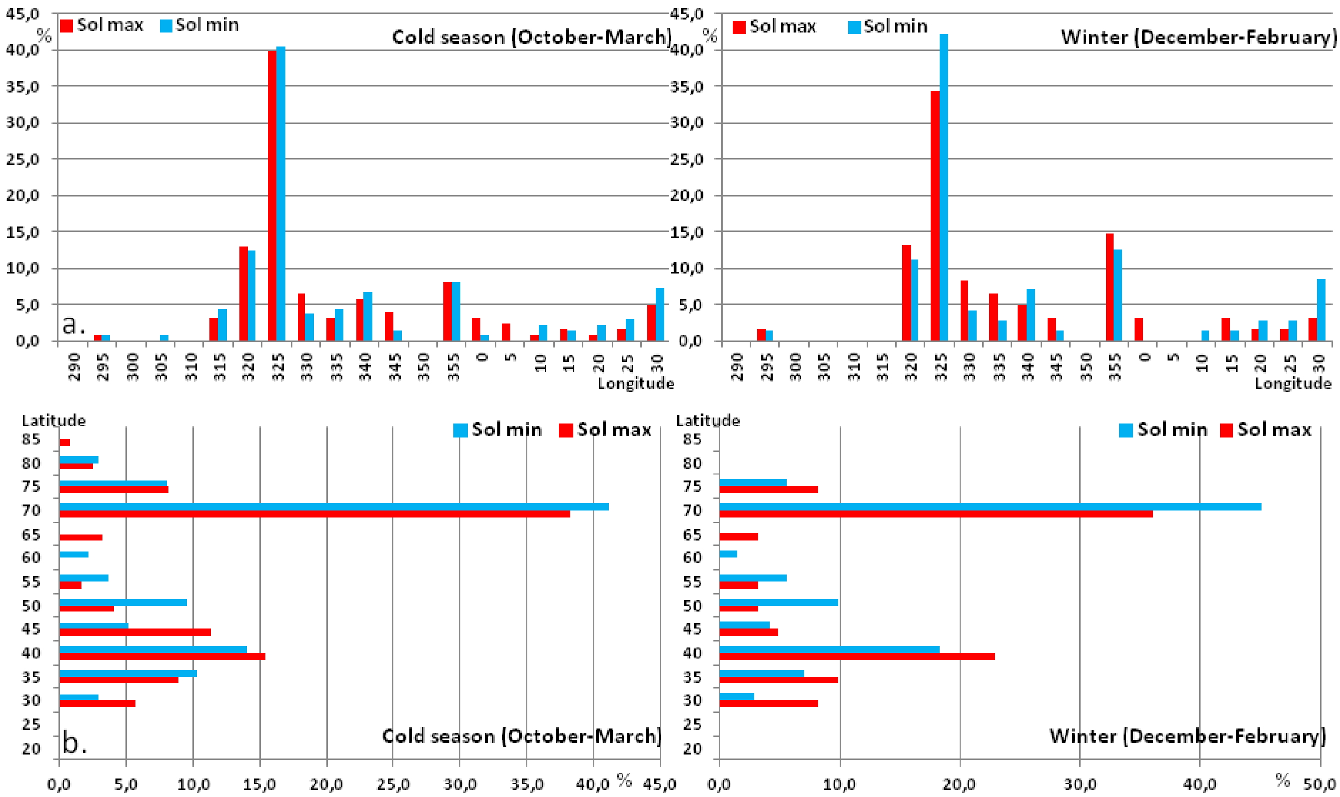

Figure 4. (a) Longitudinal relative frequency of the minimum SLP occurrence during cold season (left) and winter (right) for different solar activity conditions. **(b)** Latitudinal relative frequency of the minimum SLP occurrence during cold season (left) and winter (right) for different solar activity conditions.

NAO pattern during its positive phase presented by Peterson et al. (2003). One should note that the former region (around 40° W and 60° N) is also known as the main domain of Icelandic cyclogenesis (Schneidereit et al., 2006) at the polar front; thus suggesting a possible connection between solar activity and cyclogenesis, mentioned e.g. by Veretenenko et al. (2006). The overall shape of the area where Icelandic cyclones occur, mainly its spatial consistency over the North Sea in high solar activity, points to the fact that during high solar conditions, the northeasterly track of cyclones over this area is more favoured, supporting results of Huth et al. (2006) and Barriopedro et al. (2008) who observed a tendency toward a stronger zonal circulation.

A comparison of the latitudinal and longitudinal positions of the lowest and highest SLP between the high and low solar activity is provided in Figs. 4 and 5, respectively. First we examine the Icelandic low (Fig. 4). Its longitudinal distribution is clearly bimodal, with maxima around 30 to 40° W and 10° E. In high solar activity, the western maximum is more geographically confined; in particular the frequencies west of 45° W are much lower than in low solar activity. The other feature of interest is higher frequencies between the two longitudinal maxima, i.e. between 0 and 20° W in high solar activity. This again points to a more zonal-like circulation in high solar activity. The differences are stronger for winter than for the entire cold season, suggesting that the solar effects are indeed most pronounced in the winter months in the North Atlantic–European region.

Figure 5 shows the variation of the maximum SLP location in the Euro–Atlantic region with solar activity. The location of the SLP maximum appears to be less dependent on solar activity compared to the SLP minimum. Two action centres manifest as the positions of the highest SLP: the Azores anticyclone and the high over Greenland. They can be easily distinguished by their latitude: while the former is located mostly between 30 and 50° N, the latter occurs mainly between 70 and 80° N. Both act as the SLP maximum with approximately the same share of 50 %. Worth mentioning is the tendency of the Azores anticyclone to be located more southward in solar maxima and of the Greenland high to be more southward in solar minima; both effects are more pronounced in winter than in the longer cold season. A more northward position of the maximum SLP in low solar activity reflects a stronger and/or more frequent Greenland high, which is in line with the finding by Barriopedro et al. (2008) that blocking situations over the North Atlantic are more frequent and last longer in low solar activity. On the other hand, the Azores high plays a stronger role in high solar activity,

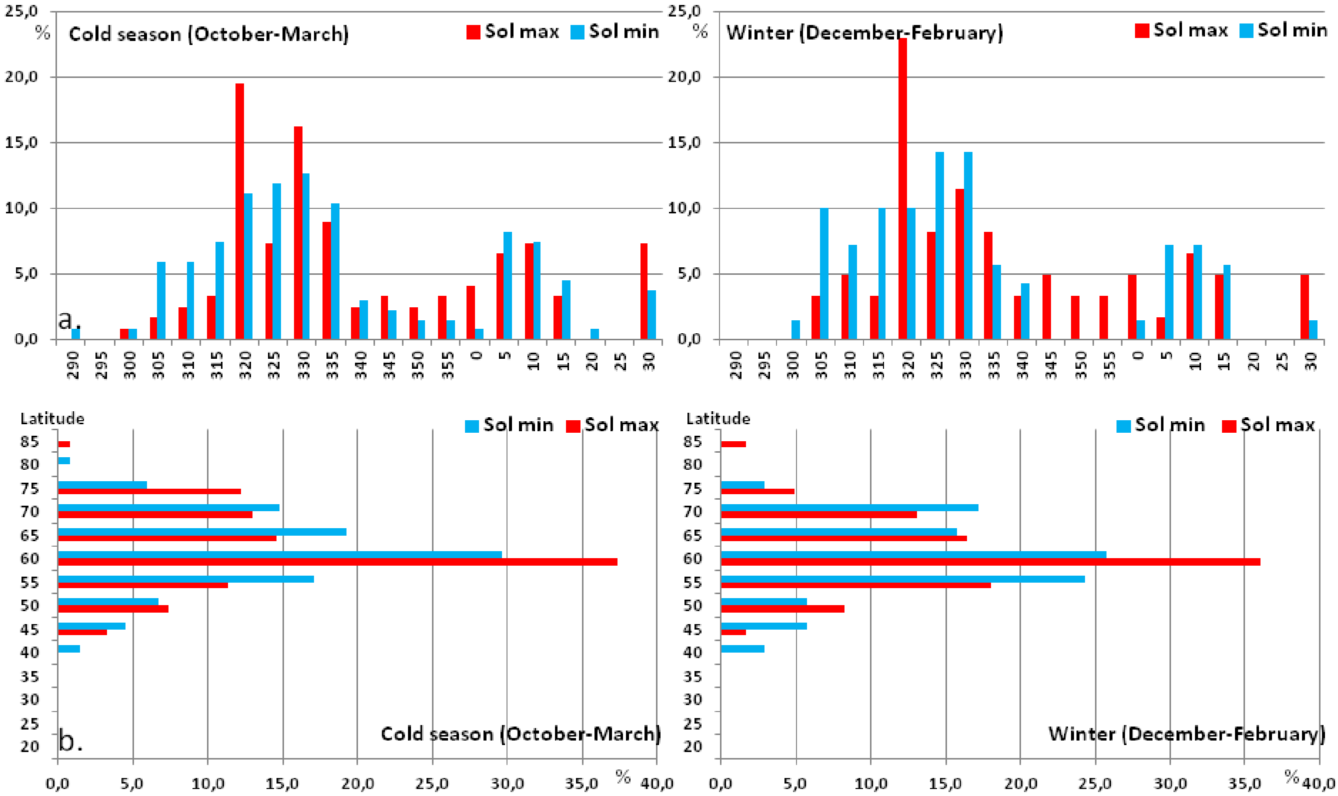

Figure 5. (a) Longitudinal relative frequency of maximum mean SLP during cold season (left) and winter (right). **(b)** Latitudinal relative frequency of maximum SLP during cold season (left) and winter (right).

reflecting, among others, its considerably larger geographical extent (Kodera, 2003; Huth et al., 2006).

Figures 6 and 7 synthesize information from Figs. 4 and 5 using boxplots. They demonstrate a slight shift of the Icelandic low towards north and west in high solar activity and a southward shift of the high SLP centre. We may look at the longitudinal and latitudinal distributions of the positions of the lowest and highest SLP as statistical distributions. The two-sample Kolmogorov–Smirnov test comparing the high and low solar months suggests that the null hypothesis that both the high and low solar data were drawn from the same distribution cannot be rejected in any of the four cases (highest and lowest pressure; latitudinal and longitudinal distribution).

4 Conclusions

The composite and correlation analyses suggest that the response of lower tropospheric circulation, represented by SLP and 500 hPa GPH here, to solar activity is strongest in the North Atlantic where both the Icelandic low and Azores high are strengthened, and so is the NAO. The signal related to solar activity is somewhat weaker in the Pacific and North American domain where a tendency towards a negative phase of the PNA pattern in high solar activity is observed.

Solar maximum conditions favour a higher occurrence of the minimum of SLP around the main region of Icelandic development of low-pressure systems, along the northeasterly track of the cyclones. During solar minimum conditions, the spatial distribution of the minimum SLP is more diffuse, extending to subtropical latitudes on a wider area. The occurrence of lows close to the Norwegian coast seems to be favoured also by low solar activity. Differences of ± 50 m (cold season) and ± 30 m (winter) were observed for 500 hPa, while a high to low solar difference of ± 3 hPa sea level pressure could lead to a significant strengthening of the westerly flow in mid-latitudes.

Generally the direct connection between solar activity and the location of pressure centres of action in the North Atlantic is rather small, but this could be a signal which can propagate in the lower troposphere by other positive feedback mechanisms. Maximum solar months are related to a stronger pressure gradient between the Azores high and the Icelandic low, i.e. to positive NAO phases. The lowest and highest pressure in the North Atlantic shift their position, as can be seen from the histograms of their longitude and latitude, but these shifts do not reach statistical significance.

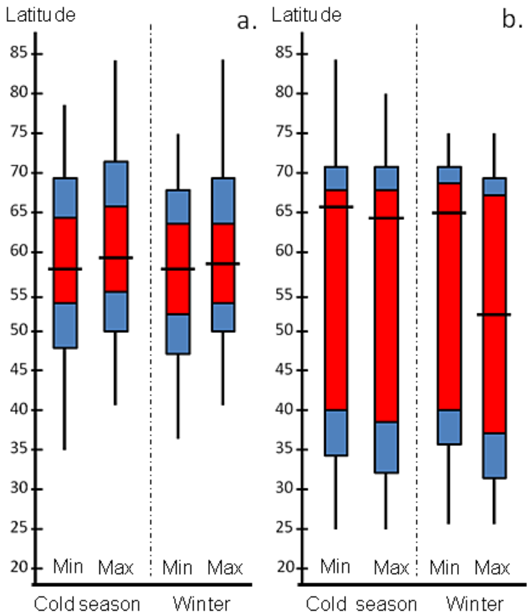

Figure 6. Cumulative latitudinal position frequency of minimum SLP **(a)** and maximum SLP **(b)** for different solar activity conditions (horizontal line, mean position; red box – frequency between first and third quartile; blue box – frequency between first and last decile; whiskers – appearance).

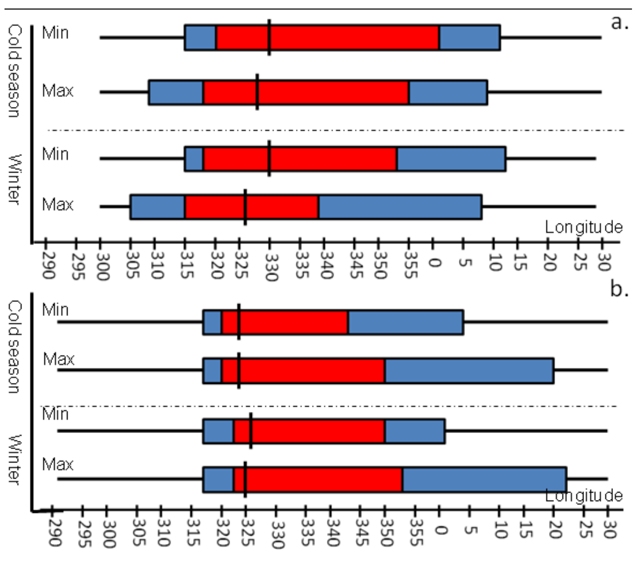

Figure 7. Cumulative longitudinal position frequency of the minimum SLP **(a)** and maximum SLP **(b)** for different solar activity conditions (horizontal line, mean position; red box – frequency between first and third quartile; blue box – frequency between first and last decile; whiskers – appearance).

The solar effect on atmospheric circulation in the North Atlantic can be described as a tripole mechanism. During solar maximum conditions the differences between the Icelandic Low and Azores High increase, while the Greenland High decreases. Solar minimum conditions reinforce the high pressure above Greenland together with a weakening of the other two North Atlantic pressure centres.

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