Received: 16 March 2019 | Revised: 8 August 2019 | Accepted: 21 August 2019 | Published on: 19 November 2019

DOI: 10.1002/qj.3657

Quarterly Journal of the Royal Meteorological Society RMetS

RESEARCH ARTICLE

Assessing North Atlantic winter climate response to geomagnetic activity and solar irradiance variability

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Funding information
Academy of Finland, ReSoLVE Centre of Excellence (project no. 307411). V.M. was also paid in part by the Norwegian Research Council under contract 223252/F50.

Abstract

Recent studies suggest a response in the North Atlantic winter circulation which lags by a couple of years with respect to sunspot maximum. This has been explained by two different top-down mechanisms: a solar wind driven particle effect in the polar atmosphere during the declining phase of the solar cycle, and the re-emergence and amplification of heat anomalies in the Atlantic Ocean produced by enhanced solar ultraviolet (UV). Here we study how December to February climate is affected by two solar-related drivers: geomagnetic activity (proxy of particle precipitation) and sunspot activity (proxy of solar UV) during 1948–2017. We use reanalysis data of sea-level pressure (SLP) and zonal wind (U) to show that both geomagnetic activity and sunspot activity independently and simultaneously produce atmospheric circulation responses in the North Atlantic whose evolutions clearly differ from each other. Geomagnetic activity produces a strengthening of the polar vortex and a negative poleward SLP gradient between mid- and high latitudes, resembling a positive NAO-type circulation pattern during December to February. Solar UV produces a positive U anomaly in the low-latitude stratosphere during December, which moves poleward and downward during the winter resulting in a negative poleward SLP gradient between mid- and high latitudes during February. We find the lagged sunspot activity responses in SLP to form zonal pressure patterns (wave-train structure) resembling the Eurasian pattern. Geomagnetic activity responses remain essentially the same when we introduce the lag with respect to sunspot activity supporting its independency as a driving mechanism. Our results suggest that solar wind related particle precipitation and (lagged) solar UV mechanism provide independent, significant circulation signals in the North Atlantic winter.

KEYWORDS

geomagnetic activity, lagged response, North Atlantic, solar–climate interaction, space weather, sunspot activity

1 | INTRODUCTION

Solar activity is known to affect the Northern Hemisphere winter climate (Gray *et al.*, 2010). In particular, geomagnetic activity and solar irradiance variability can have observable surface temperature and sea-level pressure (SLP) responses in the North Atlantic region (Kodera, 2002; Seppälä *et al.*, 2009; Ineson *et al.*, 2011; Maliniemi *et al.*, 2013). Two top-down mechanisms have been proposed to explain how a Sun-related activity can affect the upper atmosphere and reach the surface in the North Atlantic sector during winter. One is related to solar ultraviolet (UV) irradiance (e.g. Kodera and Kuroda, 2002) and the other to solar wind driven particle precipitation (e.g. Baumgaertner *et al.*, 2011). Both of these mechanisms intensify the stratospheric and tropospheric zonal winds by affecting the amount of ozone and radiative heating in the mesosphere and the stratosphere (Seppälä *et al.*, 2014).

Increased solar UV radiation during solar maximum enhances ozone production and UV absorption in the low-latitudinal stratosphere (Haigh, 2007), which leads to enhanced low-latitudinal heating and an increased meridional temperature gradient (Frame and Gray, 2010). The zonal circulation in the winter at mid/high latitudes is intensified due to the thermal wind balance (Holton, 2004). This zonal wind anomaly moves poleward and downward as winter progresses (Ineson *et al.*, 2011), leading to a positive North Atlantic Oscillation (NAO) pattern in late winter (Baldwin and Dunkerton, 2001; Kidston *et al.*, 2015). These stratospheric perturbations due to increased solar UV also lead to expansion of the Hadley cell and the poleward shift of the Ferrell cell (Haigh *et al.*, 2005).

Particles precipitating into the upper polar atmosphere during polar night produce reactive nitrogen (NO_x) (Sinnhuber *et al.*, 2012) and hydrogen oxides (HO_x) (Andersson *et al.*, 2014). These are able to destroy ozone in catalytic reactions in the mesosphere and in the upper stratosphere (Fytterer *et al.*, 2015; Arsenovic *et al.*, 2016; Andersson *et al.*, 2018). HO_x is short-lived and can influence ozone only in the mesosphere (Andersson *et al.*, 2014). However, NO_x has a prolonged lifetime in the polar night and can descend down to stratospheric altitudes with the prevailing winter circulation (Funke *et al.*, 2014). This is called the indirect effect of particle precipitation (Randall *et al.*, 2007). Ozone depletion at high latitudes can lead to thermal changes in the mesosphere/stratosphere, which can have a dynamical effect by accelerating the polar vortex (Baumgaertner *et al.*, 2011; Rozanov *et al.*, 2012; Seppälä *et al.*, 2013) and leading to a positive NAO (Maliniemi *et al.*, 2014).

Recent studies of long-term surface climate in winter have shown that the positive NAO response related to sunspot activity (SA) is obtained in late winter (February) (Gray *et al.*, 2016), whereas in early winter (December) a positive SLP anomaly over the Azores is observed 2–4 years after the sunspot maximum (Gray *et al.*, 2013; 2016). Solar wind driven particles/geomagnetic activity (GA) has a strong positive relation with NAO without any lag (Maliniemi *et al.*, 2016). GA maximizes a few years after sunspot maximum due to the occurrence of high-speed solar wind streams from coronal holes (Ruzmaikin and Feynman, 2001; Mursula *et al.*, 2015).

Solar UV irradiance and total solar irradiance (TSI) correlate well with sunspots at interannual and decadal time-scales (Lockwood and Fröhlich, 2007). Therefore the direct driving of NAO by solar UV cannot explain the observed early winter lag with respect to the sunspot cycle. In order to account for this lag, an additional mechanism related to the solar UV influence has been proposed. This includes the Atlantic Ocean acting as a heat store, producing a lagged SLP response over the Azores by strengthening the original ocean signal over several years with continuous solar UV forcing (Scaife *et al.*, 2013; Andrews *et al.*, 2015). The sea-surface temperature (SST) anomaly in the North Atlantic Ocean can survive from one winter to the next below the shallower ocean mixed layer in summer, and re-emerge from there during the following autumn/early winter (Timlin *et al.*, 2002; Deser *et al.*, 2003; Taws *et al.*, 2011).

Many studies have proposed that the North Atlantic SST anomalies can predict the state of the NAO (see e.g. Smith *et al.*, 2016, and references therein). In addition to the NAO, which is the main circulation pattern in the winter North Atlantic region, another low-frequency circulation pattern called the Eurasian pattern (EU) influences the North Atlantic/Eurasian region (Barnston and Livezey, 1987; Liu *et al.*, 2014). It consists of a quasi-zonal pressure tripole between the region around the Azores and in north Siberia representing the waviness of the polar front. In a recent study by Liu *et al.* (2014) it has been shown to be forced primarily from the ocean.

In this article we study the response of winter atmospheric circulation to geomagnetic activity (proxy for particle precipitation) and (lagged) sunspot activity (proxy for solar UV irradiance) during 1948–2017. We use the multiple linear regression method including also El Niño/Southern Oscillation (ENSO) and volcanic activity as additional explanatory factors. The article is organized as follows: in section 2 we describe the data and methods. In section 3 we show the results of SLP and zonal wind (U) variability related to GA and SA and in section 4 with lagged SA. Concluding remarks are given in section 5.

2 | DATASETS AND STATISTICAL METHODS

We use the monthly atmospheric NCEP/NCAR reanalysis of SLP and U (Kalnay *et al.*, 1996) provided by the National Oceanic and Atmospheric Administration (NOAA). National

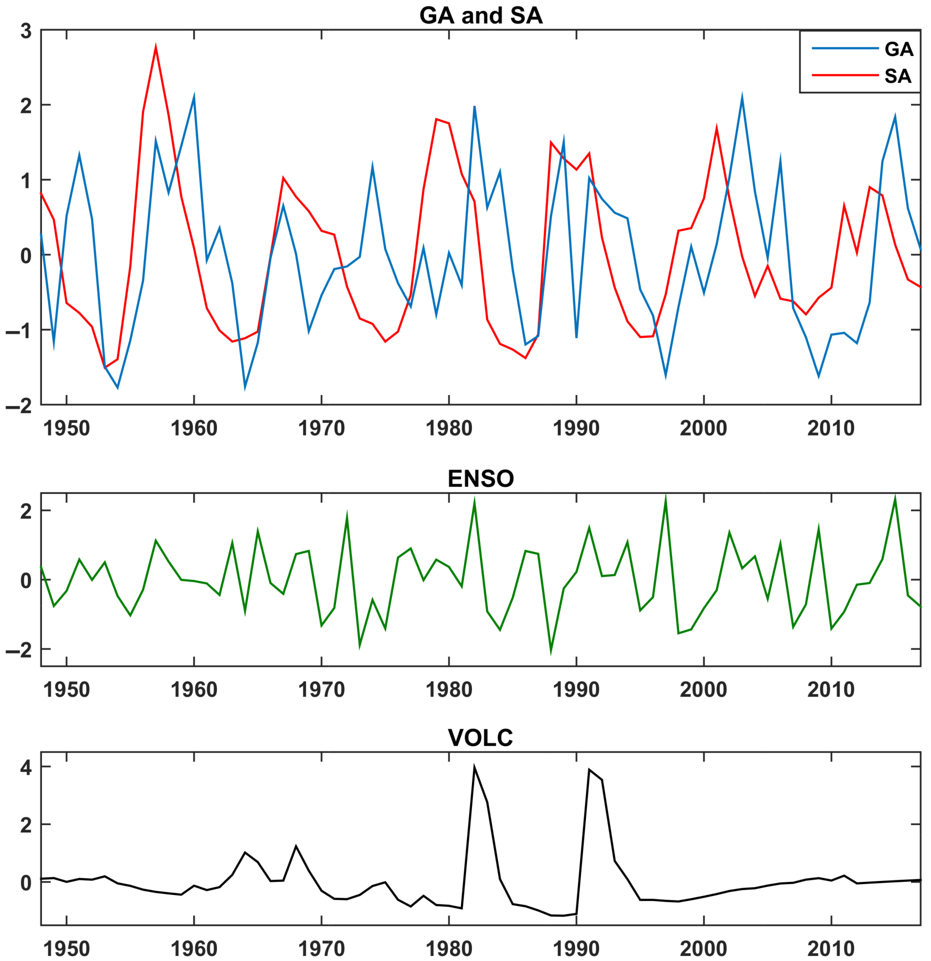

FIGURE 1 Time series of December (top) geomagnetic activity and sunspot activity, (middle) ENSO and (bottom) volcanic activity during 1948–2017. In each time series the 31-year smoothly varying trend is removed and the data are standardized

Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) data are gridded in latitude–longitude bins (2.5° ×2.5°) with 17 pressure levels from 10 to 1,000 hPa in U. Sunspot numbers provided by Solar Influences Data Analysis Center are used as a proxy for solar UV irradiance, and monthly averaged geomagnetic activity (aa index) provided by the International Service of Geomagnetic Indices is used as a proxy for solar wind/energetic particle related activity. For ENSO, the monthly Niño3.4 sea-surface temperature of NOAA is used, and the stratospheric optical depth (Sato *et al.*, 1993) averaged over the Northern Hemisphere represents volcanic activity. The volcanic activity index is extended from the end of 2012 to the end of 2017 with zero values. Direct links to the data sources are available in the Acknowledgements. The December time series of all explaining variables can be seen in Figure 1.

We use multiple linear regression (MLR) with four explaining variables: GA, SA, ENSO and volcanic activity (December values). In each SLP bin we calculate the MLR separately for the three winter months (December to February) over the time period of 1948–2017 in the Atlantic/Eurasia (0°N–90°N and 90°W–90°E). For U we calculate latitude–pressure (0–90°N and 10–1,000 hPa) plots in the Atlantic/Eurasia stratosphere/troposphere for winds averaged over 90°W–90°E in 1948–2017. We also studied lagged SA responses so that December values of preceding winters are used together with other explaining variables without a yearly lag.

The long-term trend is removed from all variables before MLR. This is done by subtracting a smoothly varying 31-year average generated by the LOWESS method (LOcally WEighted Scatterplot Smoothing: Cleveland and Devlin, 1988) from the average values. After this, the results depict mainly the interannual variability (thus removing e.g. the effect of anthropogenic climate change, the oceanic multidecadal variability and the centennial changes of GA and SA). After this trend removal, explaining variables are standardized before the regression. The results related to regression analysis are presented as the response in SLP (in hPa) and U (in m/s) to one standard deviation increase of the explaining variables.

Regressions are calculated using the Cochrane–Orcutt method (Cochrane and Orcutt, 1949). In this method the residual term is modelled as an autoregressive AR(1) process

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instead of white noise as in regular regression. This is an iterative process, where the residual term is converged to have only an uncorrelated white noise term. After this procedure the significance of regression parameters can be calculated using Student's *t*-test (this would not be correct with the autocorrelative residual term). A detailed description of the regression model and its benefits can be obtained in our recent articles (Maliniemi *et al.*, 2018; Salminen *et al.*, 2019).

Geomagnetic activity and sunspot activity are both produced by the magnetic activity of the Sun, but have only a partly similar cyclic behaviour (Ruzmaikin and Feynman, 2001). Their mutual correlation is still notable, e.g. about 0.27 (P-value < .05) for detrended December averages of 1948–2017 (Figure 1). Thus one might argue that multicollinearity is a problem in the regressions. To study this we calculate the Variance Inflation Factor (VIF), which is a commonly used diagnostic for multicollinearity (Allison, 1999). VIF is calculated for each explaining variable from an MLR with the other explaining variables, yielding the total R^2. VIF is simply $1/(1 - R^2)$. Usually VIFs larger than 2–2.5 are considered to have a multicollinearity issue (Allison, 1999). In our case VIF for December values is 1.16 for GA, 1.09 for SA, 1.07 for ENSO and 1.10 for volcanic activity. In the case of 2-year lagged SA, VIF is 1.39 for GA, 1.44 for SA, 1.07 for ENSO and 1.14 for volcanic activity. All these are well below 2 and thus we can assume that the multicollinearity is not a major issue.

3 | GEOMAGNETIC AND SUNSPOT ACTIVITY RESPONSES IN SLP AND U

Figure 2 shows the regression coefficients of GA and SA to SLP in separate winter months (December–February) in 1948–2017. The other explaining variables (ENSO and volcanic activity) are also important but have been discussed in earlier studies (e.g. Roy and Haigh, 2011; Gray *et al.*, 2013; Maliniemi *et al.*, 2018) and are not our primary interest here. Moreover, for these variables we found results to be very similar to earlier studies (not shown). GA produces a pressure dipole consisting of a negative anomaly at high latitudes and a positive anomaly at midlatitudes, which shifts slightly during the different winter months. A negative signal occurs around Scandinavia and the Norwegian Sea in January, and in the Barents Sea in December and February. A positive signal is located around the Azores and the west Mediterranean during January, and in the east Mediterranean during December

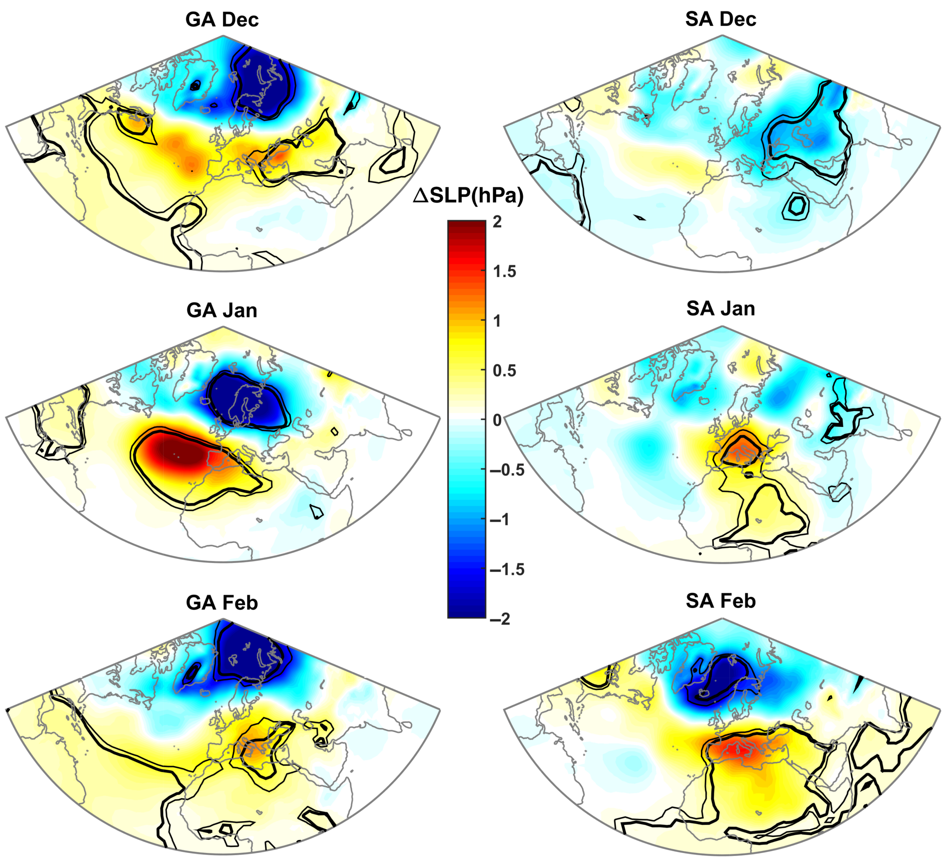

FIGURE 2 Regression coefficients of GA (left) and SA (right) to SLP in North Atlantic and Europe (0°N–90°N, 90°W–90°E) during winter months 1948–2017. Maps for same month are from the same regression analysis (also including ENSO and volcanic activity as explaining variables, not shown). Maps show the variation in SLP (hPa) related to one standard deviation increase in GA or SA. Thick (thin) black lines mark the p-value of .05 (.10)

and February. The pattern of January best resembles the NAO pattern.

The SLP response to SA (Figure 2) is very similar to that found earlier (Gray *et al.*, 2016). There is a negative pressure anomaly in east Europe in December. The signal in January is mainly a positive anomaly in the Mediterranean and North Africa. During February a significant negative signal over Iceland and a positive signal in the Mediterranean/North Africa emerges. This late winter (February) SA response has been shown earlier to be related to the solar UV top-down mechanism (Ineson *et al.*, 2011).

Figure 3 shows the regression coefficients of GA and SA to U during the three winter months in 1948–2017. The GA signal in U is mainly seen as enhanced westerlies around 60–70°N during all winter months, which corresponds to a strengthened stratospheric polar vortex (Kidston *et al.*, 2015). This westerly wind enhancement extends from the surface to the mid-stratosphere (10 hPa) and is significant from the surface to the lower stratosphere in December and January, and from the surface to the mid-stratosphere (10 hPa) in February. In January, westerlies are weakened around 30°N and at the pole which is consistent with the SLP patterns in Figure 2. This U anomaly supports the view that the surface signal produced by GA develops in the stratosphere and progresses to the troposphere (Baumgaertner *et al.*, 2011; Kidston *et al.*, 2015). These signals are consistent with earlier studies (Seppälä *et al.*, 2013; Maliniemi *et al.*, 2018) showing that the anomalous westerly wind related to GA lasts through the whole winter.

The SA signal in U shows a westerly anomaly developing in the mid-stratospheric subtropical region around 30°N in December, which moves poleward and downward reaching the troposphere at around 50–60°N in February. A similar development was found earlier, e.g. by Ineson *et al.* (2011) in both observations and modelling, and is consistent with the top-down forcing by solar UV (Kodera and Kuroda, 2002). The movement of U anomalies poleward and downward may result from wave–mean flow interaction, where planetary waves diverge in the wind shear region (Matthes *et al.*, 2006). In addition, a significant westerly jet develops in the equatorial upper troposphere that peaks in February. This agrees with results by Haigh *et al.* (2005) showing an expansion of the meridional Hadley cell in response to increased solar UV activity. The U signal in February at 50–60°N is consistent with the SLP signal in Figure 2 showing a significant surface response.

Results in Figures 2 and 3 show clearly that the responses in the atmosphere related to GA and SA evolve differently.

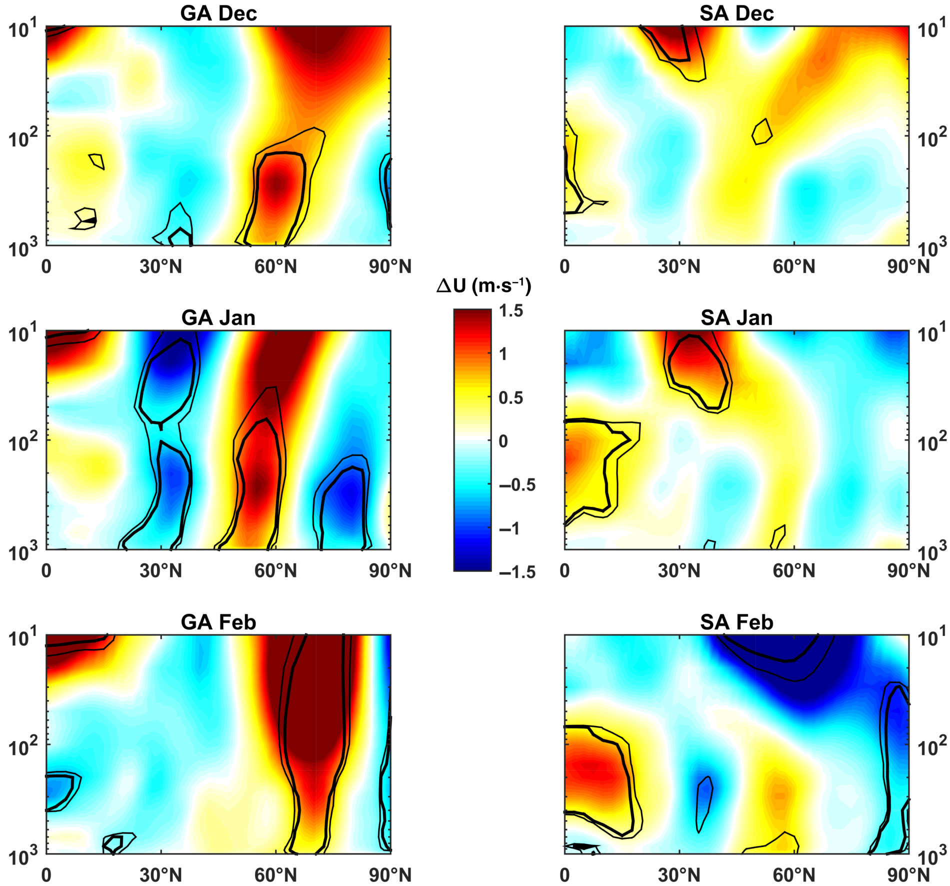

FIGURE 3 Same as in Figure 2 but to ΔU (m·s^{-1}) in latitude–height (height expressed as pressure in hPa) plot from longitudinal region 90°W–90°E during 1948–2017

Responses to GA can be seen in all months as strengthening of the polar vortex, which leads to significant surface anomalies through the stratosphere–troposphere interaction. However, responses to SA evolve over winter starting in December from the subtropical stratosphere and reaching the surface in February.

4 | LAGGED SUNSPOT ACTIVITY RESPONSE IN SLP AND U

Figure 4 shows the regression coefficients of lagged SA to SLP in December, January and February of 1948–2017. Figure 4 also shows the regression coefficients of GA to SLP without a lag. In each regression of Figure 4, GA, ENSO (not shown) and volcanic activity (not shown) are taken without a lag while SA is taken with increasing precedence (1-year: 1947–2016, 2-year: 1946–2015). Results indicate that the GA response hardly changes when we increase the lag of SA (results for GA in Figures 2 and 4 are very similar). This indicates that both of these solar-related forcing parameters produce individual effects on the atmospheric circulation and are not mixed in the regression.

Lagged SA signals in Figure 4 show clearly that the response of the SLP to SA changes with increasing lag. Negative SLP anomaly in December moves from east Europe (Figure 2) for lag 0 to south/west Europe for lag 1. In December for lag 2, significant positive anomalies develop in the Azores and in northwest Russia. In January for lag 1 a significant negative anomaly develops south of Greenland and for lag 2 this negative anomaly extends further east, while a positive anomaly develops in the Norwegian Sea. In February with lags 1 and 2 the negative anomaly in Iceland and the

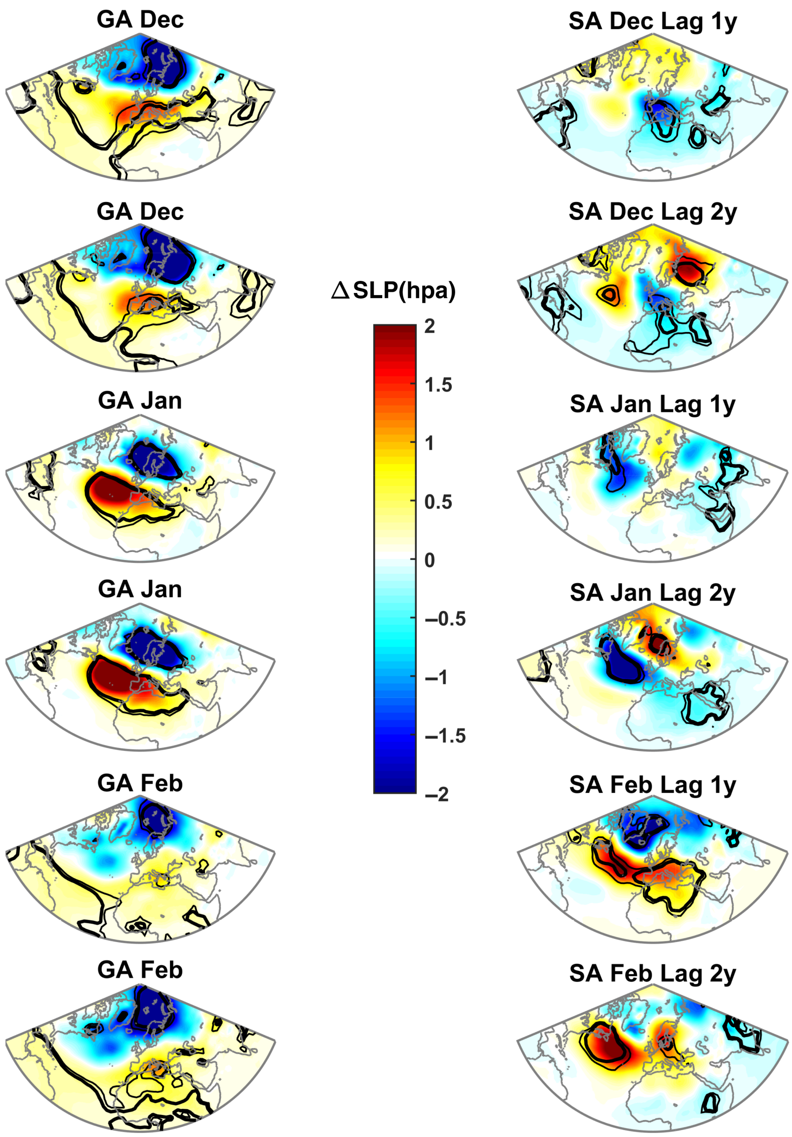

FIGURE 4 Regression coefficients of (left) GA and (right) lagged SA, to SLP in December, January and February. Adjacent maps are from the same regression analysis where GA, ENSO (not shown) and volcanic activity (not shown) are taken without a lag and SA is taken with a lag (1-year and 2-year). Thick (thin) black lines mark the p-value of .05 (.10)

Norwegian Sea weakens from lag 0 (Figure 2). At the same time the positive anomaly moves from the Mediterranean to the Azores and towards Canada in lag 2. These results agree for the most part with Gray *et al.* (2016) (see their Fig. 5), although they do not show Russia in their analysis.

Figure 5 shows a similar lag analysis for U. One can see that the GA responses hardly change from Figure 3 when we introduce the lagged SA. This again supports the individual effects of these different solar-related forcings. Lagged SA signals in U in December (Figure 5) show a positive anomaly in the equatorial upper troposphere developing with increasing lag (Haigh *et al.*, 2005). One can also see that the westerly wind anomaly of the mid-stratospheric subtropical region in December lasts until lag 1 but is no longer significant in lag 2. This might be an indication that the top-down solar UV forcing lasts on an average only 1 year after sunspot maximum. This is also partly supported by the autocorrelation of SA (0.72 for lag 1 and 0.27 for lag 2).

Lagged January SA signals in U show an emerging westerly anomaly around 40°N and a negative anomaly north of 60°N, especially for lag 2. Lagged February SA signals in U show that the response obtained with lag 0 (Figure 3) remains similar but fades with increasing lag. Note also that the westerly wind anomaly in the equatorial upper/mid-troposphere that increases with a lag in December by contrast fades away with a lag in January and February.

Results in Figure 4 show that the lagged SA responses to SLP are significant in all winter months with lags 1 and 2, but change considerably from lag 0 (Figure 2). The pattern forming in December with increasing lag resembles the so-called Eurasian pattern (EU), with high-pressure centres in the Atlantic and northwest Russia and a low-pressure centre in the North Sea/west Europe (wave train-like structure) (Barnston and Livezey, 1987). However, the pattern in January with lag 2 is shifted westwards compared to December with lag 2. The positive anomaly is in Scandinavia/Norwegian Sea

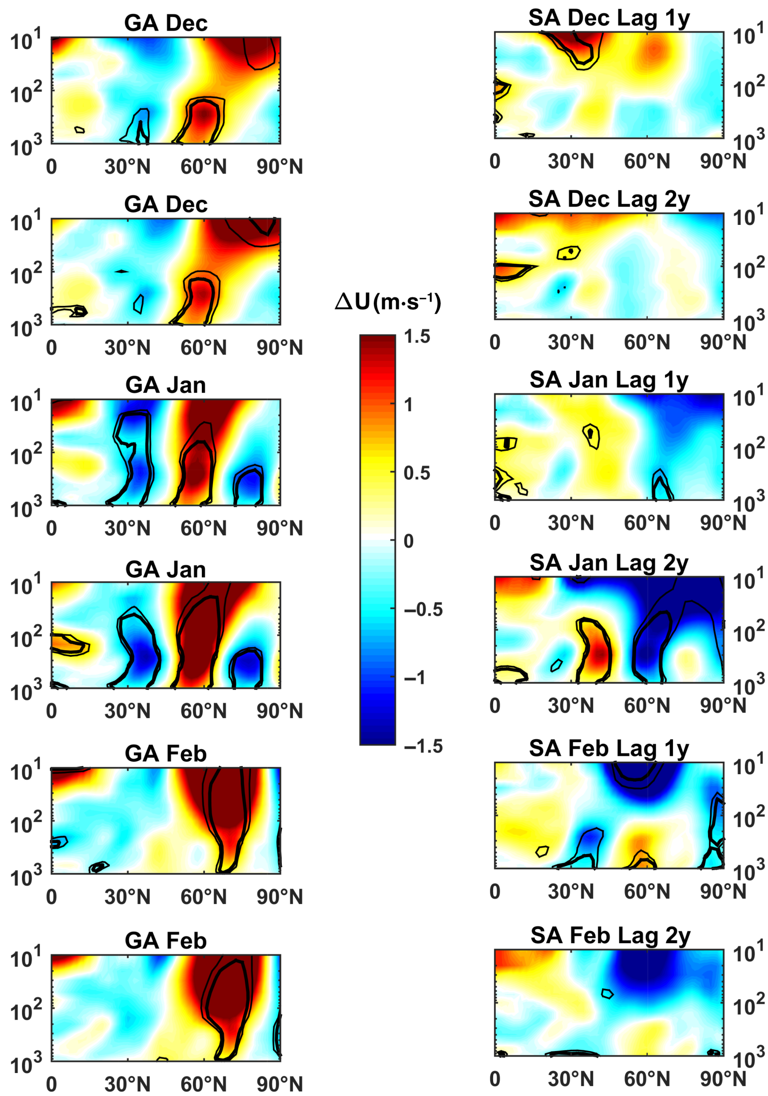

FIGURE 5 Same as in Figure 4 but to ΔU (m·s^{-1}) in latitude–height (height expressed as pressure in hPa) plot from longitudinal region 90°W–90°E during 1948–2017

and negative anomalies are located between Newfoundland and the British Isles and in north Russia. Yet, this pattern shares a similar wave-train structure to that in December, albeit with somewhat opposite anomalies. In February with lag 2 the pattern is also somewhat zonally structured with positive anomalies between Newfoundland and the Azores and in the Baltic Sea, and (weak) negative anomalies in Iceland and north Russia. Consequently, these patterns represent the waviness of the polar front in the North Atlantic/Eurasian sector (Liu *et al.*, 2014). Brugnara *et al.* (2013) have also earlier indicated a positive relation between sunspot activity and the EU pattern in the long-term datasets. Liu *et al.* (2014) have shown that the EU pattern is likely driven by anomalous SST over the North Atlantic, in agreement with a circulation model study by Gambo *et al.* (1987). These patterns are not visible in Figure 5 because calculating zonal means averages out the opposite signals in the same latitudinal band.

Ma *et al.* (2018) have shown that the lagged response to sunspot activity in the Azores is sometimes significant even with lags 3 and 4 years when a very long time period since the mid-eighteenth century is considered. We also tested if adding longer lags to SA (3 and 4 years) would show up significant responses in our considered time period (not shown). We did not obtain considerable changes compared to the 2-year lag case. Rather, for a 3-year lag the overall pattern started to fade and the response for a 4-year lag started to resemble the opposite signal to the lag 0 case, corresponding to the sunspot minimum. At the same time the GA response was closely similar, independent of the SA lag. This is also in accordance with Ma *et al.* (2018) who show that after the 1940s the lagged response in the Azores is mainly observed in lag 2 years. However, with the current study we cannot rule out the possibility that in earlier times longer lags have also been important. Related to this, the surface response to GA also includes long-term variability (Maliniemi *et al.*, 2016), becoming increasingly more significant in the latter part of the twentieth century. Due to the lack of reliable observational and reanalysis data above the surface before the 1940s, causes are difficult to determine using methods obtained here. Thus, it would be highly relevant to study these phenomena also with sophisticated chemistry–climate models over very long time intervals.

5 | CONCLUSIONS

In this article we have studied the response of the winter (December to February) atmospheric circulation in the North Atlantic/Eurasian sector to two different solar-related forcings, geomagnetic activity which is a proxy for energetic particle precipitation, and sunspot activity which is a proxy for solar UV irradiance. We showed that the previously found responses of the atmosphere to geomagnetic activity and to (lagged) sunspot activity are observed simultaneously and independently. The GA signal was seen as a negative SLP anomaly around Scandinavia and as a positive anomaly around the Azores and south Europe, and as a positive U anomaly in midlatitudes in the stratosphere and the troposphere. This pattern indicates an accelerated polar vortex (Kidston *et al.*, 2015). The pattern was seen throughout the winter, shifting slightly poleward in February. These responses to GA hardly changed when we introduced the lagged SA response. This underlines the independence of these two solar-related drivers.

A positive NAO-type pattern was obtained in February related to SA in both SLP and U. A positive U anomaly emerges in the subtropical mid-stratosphere in December and progresses poleward and downward (via wave–mean flow interaction), reaching the troposphere in February. These results are in agreement with earlier studies of GA and SA effects on winter surface climate (Ineson *et al.*, 2011; Gray *et al.*, 2016; Maliniemi *et al.*, 2016) and support the two different top-down mechanisms related to particle precipitation and solar UV.

When we studied the lagged SA response, SLP anomalies with opposite pressure centres roughly in the same latitudinal band emerged in all months for lag 2, resembling the waviness of the polar front. The lagged SA signal in SLP around the Azores in early winter has previously been suggested to occur by the re-emergence and amplification of SST anomalies driven by top-down solar UV forcing in the years following sunspot maximum (Andrews *et al.*, 2015). In addition, the EU pattern has been shown to be primarily driven by anomalous North Atlantic SST (Liu *et al.*, 2014). We showed here that the lagged SA signal in December resembles the EU pattern and shifts westward and rearranges somewhat in January and February.

The results obtained here verify that both particle precipitation and solar UV variability affect the winter climate in the North Atlantic. This is even true in the case of lagged solar UV response. Our results suggest that these two forcing parameters drive independent and simultaneous but notably different winter circulation patterns. This is important to acknowledge also when applying solar-related forcings to climate projections (Matthes *et al.*, 2017).

ACKNOWLEDGEMENTS

We acknowledge the financial support by the Academy of Finland to the ReSoLVE Centre of Excellence (project no. 307411). V.M. was also paid in part by the Norwegian Research Council under contract 223252/F50. We thank all data providers: NOAA physical science division for NCEP/NCAR reanalysis data (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.derived.html) and for Niño3.4 (http://www.esrl.noaa.gov/psd/data/correlation/nina34.data), NASA for stratospheric aerosol optical depth

data (http://data.giss.nasa.gov/modelforce/strataer), the International Service of Geomagnetic Indices (http://isgi.unistra.fr/) for aa index, and Solar Influences Data Analysis Center (http://sidc.oma.be/sunspot-data) for sunspot data. All data used in this study are available free of charge.

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How to cite this article: Maliniemi V, Asikainen T, Salminen A, Mursula K. Assessing North Atlantic winter climate response to geomagnetic activity and solar irradiance variability. *Q J R Meteorol Soc*. 2019;145:3780–3789. https://doi.org/10.1002/qj.3657