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Solar association with winter synoptic situations in the north Atlantic - European sector

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Abstract. A series of daily atmospheric flow over the British Isles (the Lamb weather types, LWT) is used to detect possible relationship in winters of the 20th century with the *aa* index, a proxy of solar activity, and the quasi-biennial oscillation of stratospheric winds (QBO). Our aim is to address different methodological flawns impairing the conclusions of previous studies. We find statistically significant changes in the occurrence of LWT when grouped according to synoptic situations defined by their succession. Combined high *aa* index and westerly QBO conditions are found to favour the group of LWT which corresponds to more northern location of storm tracks in the north Atlantic. Easterly QBO conditions are found to favour the group of LWT which corresponds to more southern location of storm tracks, or to a blocked circulation over Europe. This latter group of LWT is also favoured in the month following sudden stratospheric warmings of the polar vortex, and this is consistent with a contribution of the polar vortex to these solar and QBO associations with LWT. For a large part these results compare well with previous studies; they are slightly more statistically significant and are not impaired by the methodological problem of time resolution. However, our results are not consistent throughout the 20th century, and it is not possible to decipher whether this is due to shortcomings of the data or to a non-stationary relationship due to the marked secular trend in the solar activity.

1 Introduction

Since the discovery of the 11-yr solar cycle by Schwabe in the 19th century, numerous studies did claim detecting this cycle in various series, including in local weather. In most cases the purported correlations did not pass a thorough statistical analysis (e.g., Pittock, 1978, 1983; Flueck and Brown, 1993; Laut, 2003; van Oldenborgh et al., 2013). Much later, satellite measurements did show that the associated fluctuations in solar energy (irradiance) are indeed very small: without amplification, these fluctuations imply surface temperature variations of less than 0.1 K, hardly detectable within its variability. Various amplification mechanisms have been proposed. Some of them, named ‘top-down' mechanisms, suppose that solar modifications of the middle atmosphere could propagate down to the troposphere and the surface (Kodera and Kuroda, 2002). The UV flux and energetic particles precipitation, both modulated by the sun, do affect the mesosphere and stratosphere, with changes in the stratospheric winds and the northern polar winter vortex. In support of such hypothesis,

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correlations between the solar cycle and northern polar or mid-latitude tropospheric fields seem to improve when accounting for the quasi-biennial oscillation of the tropical zonal stratospheric winds (QBO) (e.g., Labitzke and van Loon, 1988; van Loon and Labitzke, 1988; Baldwin and Dunkerton, 2001), although such improvement is still questioned (e.g., Gray et al., 2013). Also, a downward propagation of a solar signal from the stratosphere to the troposphere has been reported (e.g., Baldwin and Dunkerton, 2001; Matthes et al., 2010). Hence, a consistent picture of 'sun-weather' or 'sun-climate' relationships has emerged over the recent decades.

Yet these relationships still rely on weak statistics (e.g., van Oldenborgh et al., 2013), and may not be stationary in time (e.g., Chiodo et al., 2019). In fact, the statistical significance of most reported correlations is weak. Salby and Shea (1991) detailed two statistical weaknesses, which have been seldom addressed: (a) the possibility of low frequency aliasing by high frequencies, and (b) the low level of significance due to the shortness of the records.

(a) The problem of aliasing arises when the sampling frequency of time series is not high enough to describe the variability of its fluctuations. To infer correlations with the solar cycle, most studies use winter or annual averages of climatic data, hence with a sampling frequency of one per year. This sampling frequency aliases part of the power spectrum of these data, exactly the part with frequency at and above 0.5 per year (the Nyquist-Shannon frequency), i.e. the part with period at and below two years. In fact, most of the stratospheric and polar vortex variability is related to sudden stratospheric warming (SSW) and thus to QBO, with a large part of their power spectrum at a period at and above two years. Hence, using a sampling frequency of one per year removes a large part of the variance of the climatic data and transfers it to lower frequencies, closer to the 11-yr period of the solar cycle. Salby and Shea (1991) showed that this transfer of variance increases the correlation of climatic series with the 11-yr solar cycle. An even stronger aliasing is made when separating ('stratifying') climatic data according to the phase (westward or eastward) of the QBO: by doing so, the sampling frequency of climatic data is halved to about 0.5 per year, with a corresponding Nyquist-Shannon frequency of 0.25 per year (i.e., a period of 4 years). Salby and Shea (1991) showed how this stratification completely removes the QBO variance and transfers it to lower frequencies, thereby increasing the decadal variability and the correlation with the 11-yr solar cycles.

(b) Salby and Shea (1991) also pointed the weakness of correlations based on short records, typically covering 3 to 4 solar cycles. Climatic records usually do have some autocorrelation, which lowers the number of degrees of freedom and thus the significance of the correlation with the solar cycles. This problem was already underlined in earlier studies (e.g., Labitzke and van Loon, 1988; Barnston and Livezey, 1989). In a 'best test' experiment using a climatic model forced by 10 identical solar cycles, Shindell et al. (2020) could hardly detect any significant tropospheric impacts out of the unforced variability, which suggests that the length of records may be limiting the detection of very small signals. Another limitation of using short periods of time is the possible non-stationarity of the solar-climate relationship. Some studies showed that the strong correlation found over recent decades is not found over earlier periods, typically over the first decades of the 20th century: this suggests that either the correlation is found by chance or that the solar-climate relationship is not stationary (Thejll et al., 2003; van Loon and Meehl, 2014; Chiodo et al., 2019).

If Salby and Shea (1991) showed how these technical problems weaken the significance of correlations claimed by most studies, they also underlined that this weakness does not rule out the existence of sun-climate relationships. Hence, it is surprising that even recent studies did not address these technical problems, using annual or seasonal average of climatic parameters, and/or short periods of time containing few solar cycles, typically 5 (ERA reanalysis) to 7 (NCEP reanalysis) (e.g., Roy, 2018).

In this study we compare solar and QBO records to synoptic activity in the North Atlantic – European sector using a series of weather types. Although the synoptic activity in this region is well known for its complex origin (e.g., Woollings, 2010), there exists a marked decadal variability which may be sensitive to the 11-yr solar cycle. We try to address the technical problems detailed above which impair this kind of correlation, by using data at the daily frequency, and using records of about one century long with almost ten solar cycles. More specifically, we address three questions:

(A) Can we find statistically significant correlations between solar cycles and synoptic activity in this sector?

(B) How different are such correlations if using a synoptic record totally independent of reanalysis simulations?

(C) How stationary over time is this sun-weather relationship?

Our aim is not to thoroughly examine all aspects of the sun-weather relationship in our series, but to answer to these questions with more confidence than in previous studies.

In the second section we describe the synoptic records, solar and QBO indices used for this study, underlining their differences with other similar series used in previous studies. In the third section we test the sensitivity of synoptic activity to the solar cycles and QBO. In the fourth section we discuss these results with respect to previous studies.

2 Data and methods

2.1 The Lamb weather type series: a historical series of synoptic observations

The questions of how much climate is variable, typically on inter-annual to decadal timescales, and why it is so much variable, have a long history. Hubert Lamb served as forecaster for the British meteorological office and was later professor at the University of East Anglia in UK. He brought an important contribution to the field of climate variability, by building up an observational record of the synoptic activity over the British Isles (so called Lamb weather type series, Lamb 1972), and by exploring possible forcings of this variability (devising the famous dust veil index to account for volcanic eruptions, Lamb 1970).

The Lamb weather type catalogue (LWT catalogue) consists of almost 50,000 days of circulation conditions prevailing over the British Isles, starting in 1861 and ending in 1997. These conditions were manually classified by inspecting synoptic charts over decades of work. The synoptic situation is described either by the prevailing wind flow direction (with its geographic direction: N, NE, E, etc.), or by an anticyclonic(A)/cyclonic (C) center over the British Isles, or a mix of both for some days. These 26 situations were simplified in further studies to the 'main' seven Lamb types, which are A, C, and the directions of flow N, E, S, W, and NW. (Note that a similar classification was done for Eastern Europe by Hess and Brezowsky 1977.) Hubert Lamb was much aware of possible biases in this classification, especially related to the varying quantity and quality of the available charts, and to the subjectivity of the analysis. To estimate and somehow limit these

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biases, he replicated and compared analysis for some periods, and analysed non adjacent periods to prevent introducing long term trends over the whole series (Lamb, 1992).

Later in the 1980s, algorithms were developed to automate the classification of synoptic situations from meteorological analysis (Lejenäs and Økland, 1983). A first advantage of such automatic analysis is a fantastic gain of time. A further advantage is the explicit definition of the synoptic situations, which makes these analysis both objective and replicable. Jones et al. (1993) adapted such an algorithm to the British Isles region to automatically infer the corresponding LWT (see Jones et al., 2014 for an update of this series). (Note that Jones et al. used two different reanalysis systems to produce their LWT series: 20CR up to 1947, and NCEP from 1948 onwards.) In the following we refer to the original LWT series as the ‘subjective’ series and to the Jones et al. reconstructed series as the ‘objective’ series.

Various approaches have been used to analyse the synoptic activity and classify it into situations, leading to different expressions (‘weather types’, ‘weather regimes’, ‘circulation types’, etc.). For the northern Atlantic – European sector these various approaches have been described and compared by the COST-733 project (Philipp et al., 2014). Each approach or definition for weather type has advantages and drawbacks. The LWT definition is based on a spatially limited area, the British Isles (rather than the whole North Atlantic basin, for instance). However, the flow direction over this area is very sensitive to the location of cyclones in the north Atlantic: by using LWT it is possible to constrain the trajectory of cyclones along their track from the main cyclogenesis region (along the Eastern American coast) to Europe (fig. 5 of Dacre and Gray 2009). If this track has a northward trajectory, a high pressure system extends towards the British Isles. If this track has a more zonal trajectory, this high pressure system shifts southward, leading the way to a temporary westerly flow, or a southerly flow followed by cyclonic conditions. Hence, using LWT allows us to reconstruct not only the synoptic situation but also its development over time. To illustrate what can be inferred from LWT in terms of synoptic situation, Figure 1 shows the average sea level pressure (SLP) field associated with each LWT. The synoptic situations are quite distinct, and representative of typical synoptic situations. To illustrate how these situations can be related over time, Figure 2 shows the average SLP of a frequent 5-day sequence of LWT, AAAWA (Anticyclonic regime interrupted by a westerly day): a crest of high pressure extends over the British Isles, and cyclones are circulating north of it, passing south of Greenland to Scandinavia. On day four, the cyclone is located just north of the British Isles, as signed by a westerly flow. Hence, the simple approach of defining LWT with the prevailing flow direction makes LWT particularly adapted to reconstruct the trajectory of (extra-tropical) cyclones in the north Atlantic. By contrast, statistical approaches for defining circulation types, like principal component analysis and clustering, produce contrasted modes of circulation, which are more adapted to study their meteorological impacts rather than the circulation itself (e.g., Beck and Philipp, 2010).

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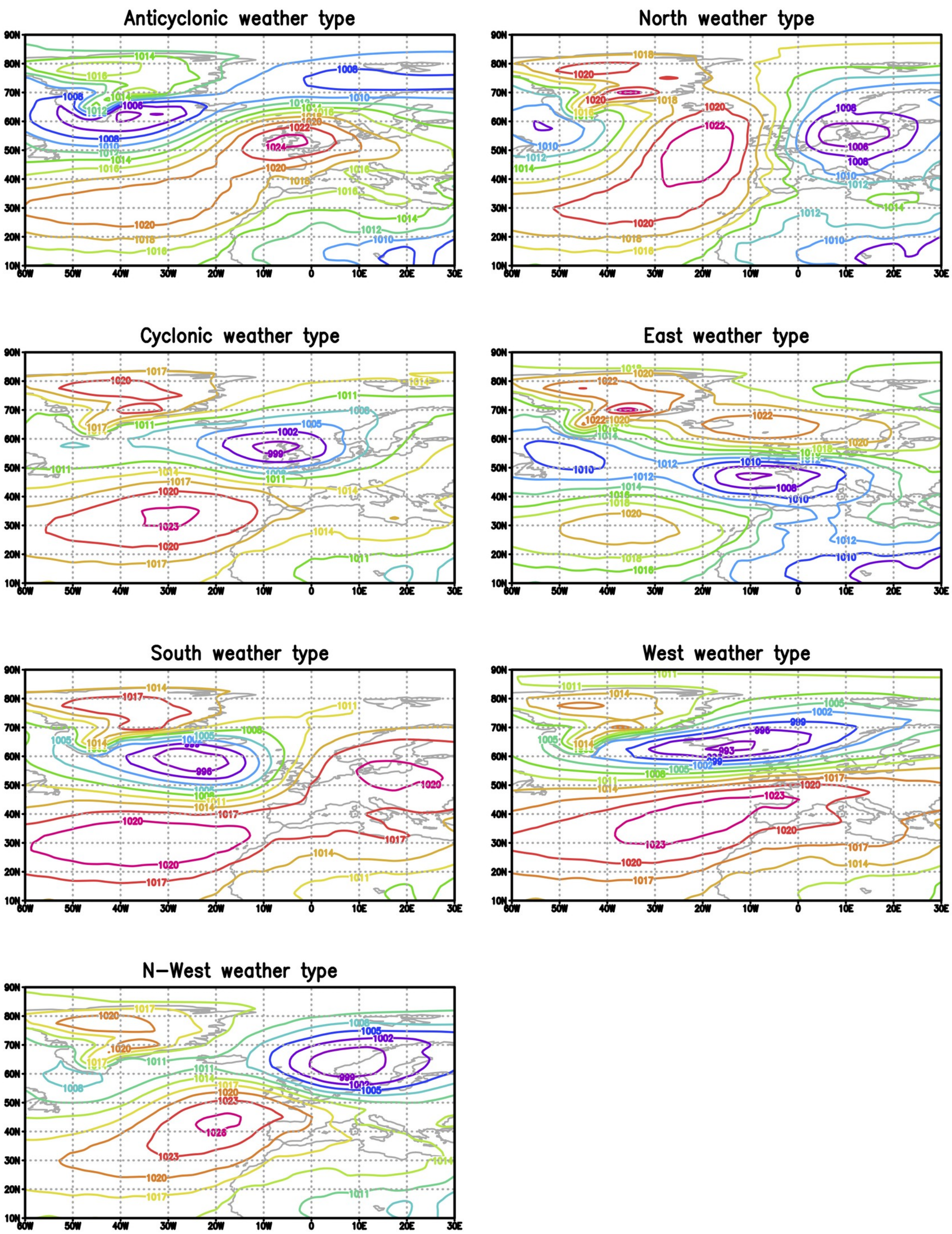

Figure 1. Average sea level pressure (SLP) for each daily WT over the period 1948-2014 (NCEP reanalysis)

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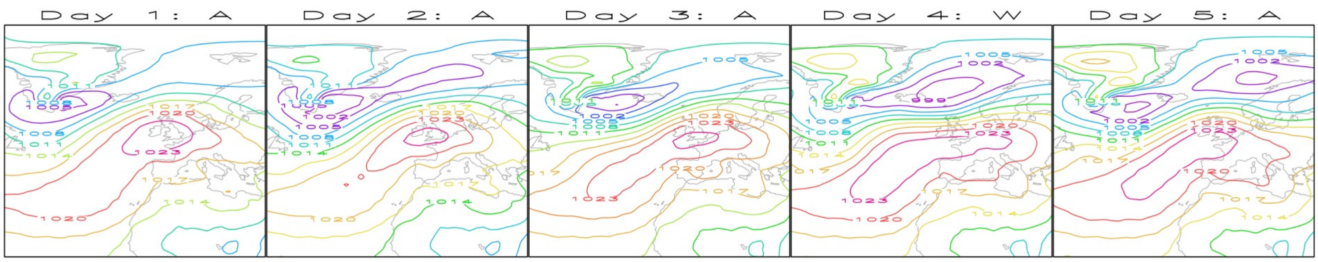

Figure 2. Average SLP field associated to each day of the 5-day sequence AAAWA over the DJFM winters of the 1948-2014 period (NCEP reanalysis)

In addition to the variety of approaches used to classify circulation patterns, all studies have used reanalysis outputs (typically sea level pressure or 500 hPa geopotential height). Reanalysis data are produced by assimilating observations with a meteorological model; hence they are always close to, but slightly different than the real atmospheric state. Their capacity to realistically reproduce solar-weather relationship is also limited by the fact that the classically used reanalysis do not account for solar cycle forcing (Fujiwara et al., 2017), so that a solar-weather relationship could only arise from assimilating meteorological conditions (NCEP was not forced by solar cycles whereas 20CRv2 and ERA5 were so). This limitation for detecting solar-weather relationship was already pointed out by Baldwin and Dunkerton (1989) who acknowledged that the difference between analysis series was as strong as the inter-annual variability of fields. In the North Atlantic - European sector, Hanson et al. (2004) compared the occurrence and trajectory of cyclones analysed from different reanalysis series and found large differences. More specifically, Stryhal and Huth (2017) compared series of circulation types obtained from different reanalysis and found substantial differences at the daily time scale (up to 22 % of days with different circulation types). Since the historical 'subjective' LWT series is an entirely manual classification, it is independent of reanalysis series and describes the actual synoptic conditions. Hence, it offers a rare opportunity to address solar-weather relationship at the daily time scale based only on observations rather than on reanalysis.

To compare to the solar activity, we focus on occurrence of LWT, as well as on succession of LWT over five days ('sequence'), as representing the development of synoptic situations in the Euro-Atlantic domain. The duration of five days was adopted as a trade off between diversity and statistics of sequences. Shorter sequences are less diverse and thus more often represented within a given period: larger numbers help improve the statistics; however shorter sequences do not constrain so well a synoptic development. On the contrary, longer sequences are more diverse: a higher diversity better describes synoptic activity, but is more complicated to interpret, and is associated with lower occurrence and thus weaker statistics. We use both the subjective and objective series of LWT, simplified to the seven main Lamb types, as detailed by Delaygue et al. (2019). The simplification scheme favours the anticyclonic and cyclonic types (A & C), and slightly increases the number of undefined days (at most 10 %). We focus on the extended winter season (Dec.-Jan.-Feb.-March, DJFM) because solar-weather correlations are higher for this period, which is interpreted as a stronger coupling through planetary wave activity.

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2.2 Indices of solar activity and of the QBO

As an index of solar activity, we use the *aa* geomagnetic index, which is sensitive to fluctuations in the terrestrial magnetosphere forced by the solar (open) magnetic field (Mayaud, 1972). A monthly mean of this index is available from 1868.

Previous studies of sun-weather relationship have mostly used sunspot number (total or group number, SSN; e.g. Huth *et al.*, 2006; Schwander *et al.*, 2017; Roy, 2018) or the radio flux at 10.7 cm (F10.7) (e.g., Huth, Cahynov and Kysely, 2010). There is some confusion on which solar variability is considered, and which climatic mechanisms could be associated with. Studies have considered that both SSN and F10.7 indices are adequate to represent irradiance variability ranging from a decade (the 11-yr solar cycle) to centuries (e.g., Roy and Haigh, 2011; Roy *et al.*, 2016; Maliniemi, Asikainen and Mursula, 2018; Maliniemi *et al.*, 2019). However, it is well documented that SSN and F10.7 indices fail to adequately represent centennial variability. These indices are related to total and UV irradiance because both are controlled by the (closed) magnetic dynamics affecting the photosphere, expressed by sunspots. However, at annual and longer time scales, the irradiance variability is controlled by faculae and network dynamics on the photosphere, not by sunspots, so that SSN and irradiance changes have only very indirect relationship (e.g., Wang et al., 2005). Especially, the marked decline in the solar activity over the last decades has provided clear evidence of the SSN limitation to quantify total and spectral irradiance variability: direct measurements by satellites have shown a return to low values of irradiance during the two recent minima (2008 and 2018) whereas F10.7 and SSN minima are bounded to the same values as before (Fröhlich, 2009; Lockwood, 2010; and see discussion in Woollings et al., 2010). In order to simulate multi-decadal changes in the solar irradiance, simple models use either the varying length of solar cycles (Lockwood and Stamper, 1999) or the average SSN (or F10.7) over a full solar cycle (Wang et al., 2005), but not their annual or seasonal averages. On the other hand, the *aa* index is sensitive to impacts of the open (or coronal) solar magnetic flux on the terrestrial magnetosphere, which controls energetic particle precipitation. It contains marked variability over the 11-yr and centennial timescales.

The studies cited above aimed at uncovering climatic impacts of solar variability, but also discussed their physical mechanisms, typically stratospheric variability through UV absorption or NOx production, vs. GCR flux or electric circuit affecting cloud condensation nuclei rate (Roy *et al.*, 2016). For both objectives, it is important to clarify that different solar indices used to stratify or to regress climatic data describe different components of solar variability and address different climatic mechanisms.

Specifically, since SSN and F10.7 indices are mostly periodic (~11-yr) and with the same minimum values, using these indices to stratify climatic data leads to a purely decadal sampling. On the contrary the *aa* index has varying minima and leads to a very different sampling of years. Figure 3 illustrates this sampling difference with a stratification based on terciles (i.e., high/low solar activity represented by the upper/lower tercile of an index). (Note that this stratification in terciles is a good compromise by providing enough data for robust statistics.) In the bottom part of the graph, the dots represent years of the upper or lower tercile of each index. Using SSN (grey dots), about all 11-yr cycles are represented in both terciles over the whole period. Using instead the *aa* index (black dots), 11-yr cycles are only present in the lower tercile at the beginning

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of the 20th century and of the 21st century, and in the upper tercile in the second part of the century. Hence, using SSN (or F10.7) to regress climatic data limits the inference of climatic impacts to the 11-yr solar cycle, because this variability dominates the index amplitude. In addition, this forcing is antisymmetric since SSN minima are all close to or at zero, whereas maxima bear some centennial variability. Note that some studies tried to numerically introduced some centennial trend in the SSN series: for instance Maliniemi et al. (2018) subtracted the long term trend to the SSN series. Since minima are almost constant, this detrending artificially transfers part of this long term trend from the maxima to the minima, making the SSN series more symmetric.

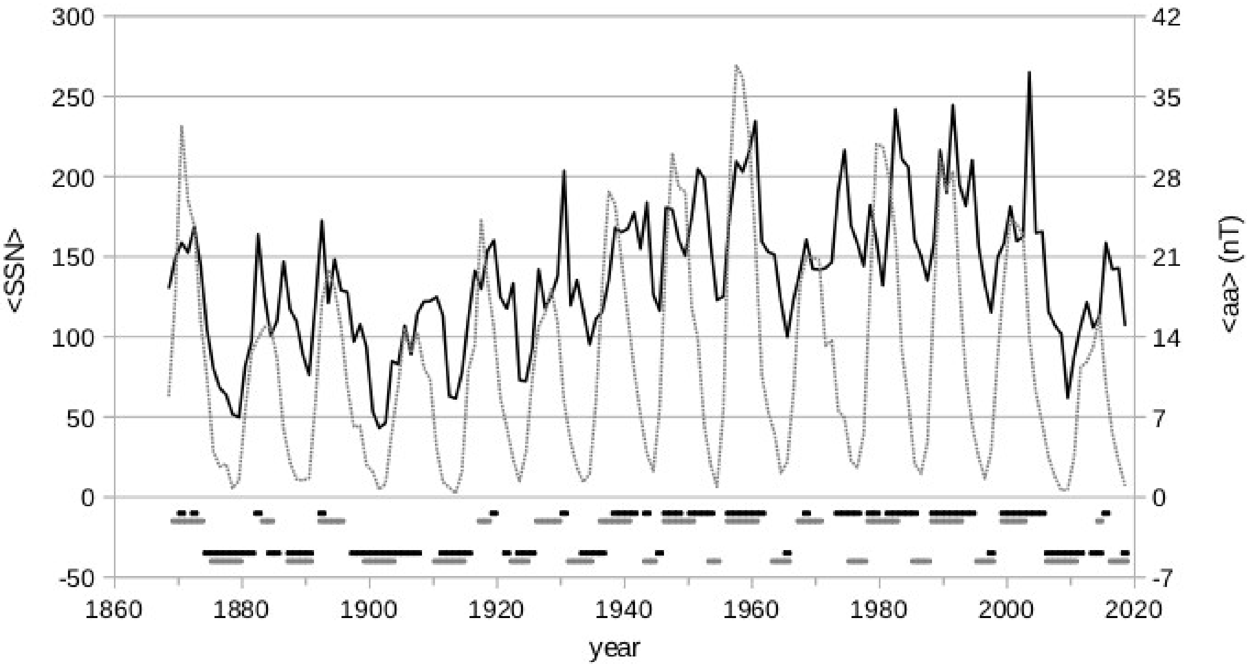

Figure 3. Time series of annual averages of SSN (International sunspot number, SILSO, in grey) and magnetic aa indices (Mayaud 1972, in black), over 1868-2018. The bottom part shows the years stratified by either indices (same color coding as curves) in their upper or lower tercile (missing years belong to the middle tercile).

In our study we use the *aa* index to stratify the LWT series in terciles, as used by Woollings *et al. (*2010). The *aa* index is not exactly in phase with SSN (and with the solar irradiance), with maxima in the descending phase of SSN (Fig. 3). The *aa* index has a marked trend along the 20th and 21st centuries typical of reconstructed irradiance (e.g., Krivova et al., 2007). Hence, by using this *aa* index we address possible impacts of its long term trend rather than of the typical 11-yr cycle (Fig. 3). The climatic mechanisms addressed with this index could be related to energetic particle precipitation.

We account for the QBO to test whether it modulates the impact of the solar activity on LWT. For this, we further stratify the LWT series by the QBO phase (westerly or easterly winds). As explained in the Introduction, stratifying our series with a quasi-biennial period has no aliasing effect because we use daily series of LWT. We use the QBO reconstruction of

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Brönnimann et al. (2007) which starts in 1908. This reconstruction consistently used the ERA40 reanalysis since 1957. Before this date, discrete measurements and proxies of wind directions were used by Brönnimann et al. to constrain the oscillation phase at different levels. The reliability of this QBO reconstruction drops before 1957, which may impair inferring the sensitivity of LWT to QBO. Using this QBO series limits the period of study to 1908-1996 with the 'subjective' LWT series (with eight solar cycles) or 1908-2014 with the 'objective' LWT series (with almost ten solar cycles). Since the QBO propagates vertically, its phase has to be defined at some level. We have tested different pressure levels and the most consistent results have been found with a QBO phase defined by the wind direction at the 30 hPa level, a pressure level classically used in previous studies. This phase definition is used in the following.

To stratify the daily LWT, both *aa* index and QBO phase were interpolated to the daily resolution. The tropical wind speed and direction could only be reconstructed with a monthly resolution since 1908. However, the *aa* index is available with a 3 h resolution, so that we could also test how much its time resolution impacts its relationship with LWT occurrence. We found that the associated changes in LWT occurrence become more systematic and larger when increasing the smoothing of the *aa* index. The associated largest changes in LWT have been found using a decadal smoothing of the *aa* index (averaged over 61 months with a Gaussian filter with a width of 10 months). Although synoptic activity has a typical time scale of few days, LWT changes can only be associated with long term changes in the *aa* index. This result is consistent with previous studies showing that solar activity at periods shorter than the 11-yr one cannot be detected in climatic observations, because they are smoothed out by the climatic system which acts as a low pass filter.

To sum it up, combining solar activity stratification and QBO stratification of LWT series provides us with six periods of time to compare: with high (upper tercile) *aa* index, with low (lower tercile) aa index, or with intermediate (medium tercile) *aa* index, and independently with eastward tropical wind direction (positive QBO) or with westward wind direction (negative QBO).

3 Results

3.1 Changes in occurrence of LWT associated with the *aa* index and the QBO

A preliminary work was to explore the sensitivity of each LWT to solar and QBO conditions by comparing their occurrence over the different periods. However, these differences are small, and/or not systematic or symmetric between the different solar and QBO conditions, so that discussing their relationship with each of the seven LWTs proved difficult. Hence, LWT were gathered into two groups based on their sensitivity: A & W & NW, in one group, and C & N & E & S, in the other. These two groups approximately contain the same number of days. W & NW directions correspond to zonal (eastward) circulation and N & E & S directions to anti-zonal (westward) circulation. However their association with A & C is not obvious, and in Section 3.2 we try to clarify this association by looking to sequences of days. This association of LWTs into two groups helps analyse LWT changes and interpret them in a synoptic way. In the following, we focus on the mean proportion of each LWT group in the winter days, and how these proportions vary under specific QBO and solar conditions.

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The relationship between LWT proportions and QBO/solar conditions is quantified by the difference in LWT proportions between two periods. The significance of this difference is quantified by its ratio to its uncertainty, the typical 't-parameter' (used for the so-called t-test). Since this uncertainty has to quantify the heterogeneity of LWTs within each period, we use the classical standard error on the mean. This error may be calculated with a reduced number of days to account for the dependency of LWT over time; however the average life time of LWT is lower than two days so that such a correction was not considered. To check this uncertainty, a Bootstrap technique was used by resampling days in each period (see below), with the advantage of making the days independent. This technique shows that the standard deviations calculated on resampled days are very close to the errors on the mean on the full period, which confirms our choice of uncertainty. These statistics are tabulated in Tables 1 to 3. In addition to these statistics, the significance of LWT proportion differences is illustrated with histograms of the proportions calculated by resampling the series with a Bootstrap technique. Each pool of days with specific QBO/solar conditions is resampled (with replacement) to produce a new series of days of the same size. This resampling is repeated 2000 times to produce 2000 estimates of LWT proportions. (Note that the average and standard deviation of these 2000 proportions are very close to the actual average and standard error on the mean given in Tables 1-3.)

3.1.1 Changes over the longest period 1908-2014

We first show results for the whole period 1908-2014, which covers almost ten solar cycles. Figure 4 shows the histograms of the 2000 LWT proportions, representing different periods and conditions. The black histograms represent the distribution of LWT proportions over the whole winter period. The A, W & NW LWT collectively represent 54 % of these days, the C, N, E & S LWT 45 % (the remaining 1 % of these days correspond to undefined days). The histograms in blue, red, and magenta represent, respectively, the distribution of LWT proportions over the winter days with a specific (westerly or easterly) QBO phase, a specific (higher or lower tercile) *aa* index, and the combined QBO & solar conditions. The proportions of LWT are hardly different under both QBO phases. They are, however, very different under both solar conditions, as well as under the combined QBO & solar conditions. For instance, over the days with the *aa* index in its higher tercile ('high solar'), the A, W & NW LWT are more abundant by almost 6 %. As expected, the other LWT (C, N, E & S) are less abundant, by 7 %. The t-parameter, used to discuss the significance of these changes, amounts to about 4 with specific solar conditions, and almost 5 by combining westerly QBO to high solar solar conditions. Discussing the significance of these differences requires the distribution of the averaged proportions, which is not precisely known. We discuss this significance in two different ways. First, the Bootstrap technique is used since it is actually well designed to infer the empirical distribution of tails. We resampled one million times the days over different conditions to create an empirical distribution of LWT proportions. For instance with high solar conditions, we find only 8 values in one million of A, W & NW LWT proportions lower than their averaged proportions over all winter days. This represents a risk of 8.10^{-6} for falsely considering the difference of 5.8 % as real. The second way is to assume that LWT proportions have a Gaussian distribution, given the large number of days. The risk of falsely considering the difference of 5.8 % as significant is then the probability left above the t-parameter value of 4.3, hence about 9.10^{-6}. These risk levels are thus found very close with both approaches. For the combined high solar and westerly QBO conditions, the change in the A, W & NW LWT proportion of 9.7% has a t-parameter of 4.77: a Bootstrap

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resampling gives 1-2 values in one million lower than the proportion of all winter days, and the Gaussian distribution gives a left probability slightly less than 10^{-6}. Again the risk levels are very close. More generally, with the Gaussian distribution, t-parameter values of 3, 4, and 5 correspond to residual probabilities of about 10^{-3}, 3.10^{-5}, and 3.10^{-7}, respectively. These low levels of risk suggest that LWT changes with t-parameter above 3 can be considered as significant.

Combining specific QBO & solar conditions does not systematically lead to a stronger change in LWT occurrence, what could be expected if QBO conditions were to amplify the solar impact. Changes are in fact much stronger by combining westerly QBO to the 'high solar' conditions than changes associated to each separate condition (magenta distribution on Fig. 4a). Combining easterly QBO to the 'low solar' conditions leads to changes that are intermediate between those over each separate condition (magenta distribution on Fig. 4b).

Table 1. Proportions of LWT groups over different sets of winter days of the LWT 'objective' series, over the period 1908-2014. Days are stratified by conditions given in the first column. The relative difference to the full period is also given, as well as the t-parameter (bolded if higher than 3). The t-parameter is the ratio between the absolute proportion difference to the largest error on the mean (i.e., the one calculated over the shortest period). (Note that values are rounded for readability.)

Proportions of LWT groups over 1908-2014					
conditions / LWT group	days #	A + W + NW		C + N + E + S	
		proportion and relative difference	t-parameter	proportion or relative difference	t-parameter
reference: all winter days	12973	0.54		0.45	
westerly QBO	6076	0.54 (+0.3 %)	0.3	0.45 (-0.5 %)	0.3
high solar*	4493	**0.57 (+5.8 %)**	**4.3**	**0.42 (-7.1 %)**	**4.3**
west. QBO & high solar*	1985	**0.59 (+9.7 %)**	**4.8**	**0.40 (-11.8 %)**	**4.9**
easterly QBO	6897	0.54 (-0.3 %)	0.3	0.45 (+0.4 %)	0.3
low solar*	4125	**0.51 (-5.6 %)**	**3.9**	**0.48 (+6.8 %)**	**4.0**
east. QBO & low solar*	2225	0.53 (-3.0 %)	1.6	0.47 (+3.9 %)	1.7

* 'high/low solar' = days with smoothed *aa* index in its higher/lower tercile

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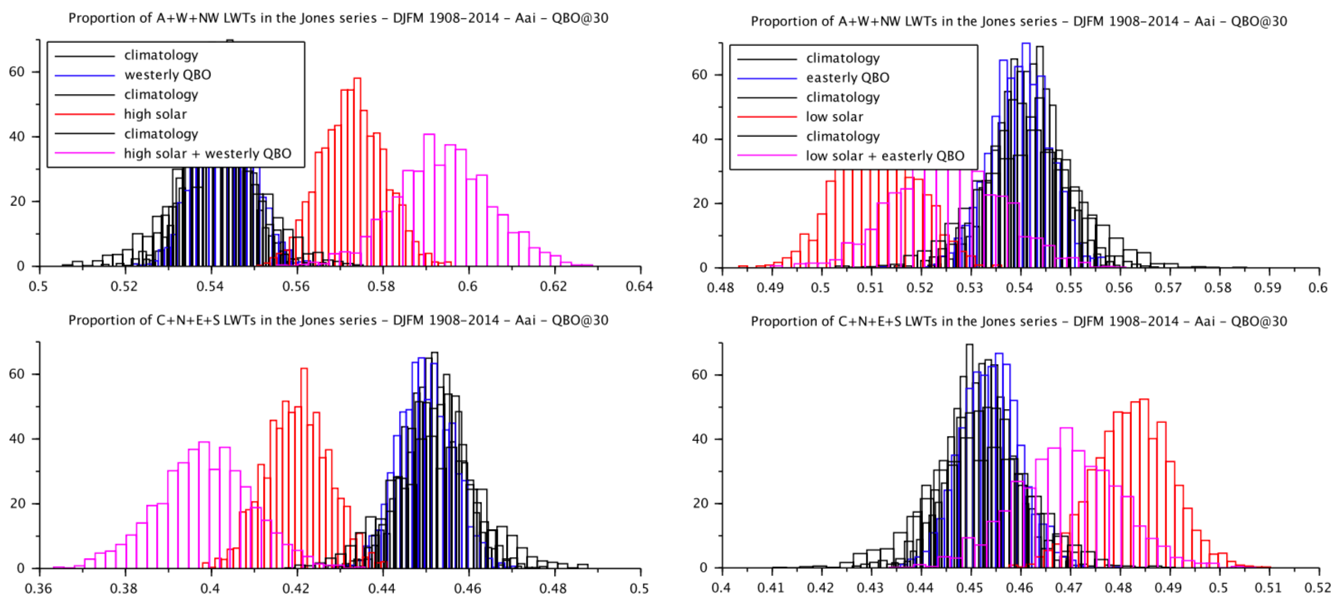

Figures 4a-d. Distribution of LWT proportions in the 2000 resamplings of specific periods over 1908-2014. Top panels (a-b) show proportions of days with A, W, or NW LWT, bottom panels (c-d) days with C, N, E, or S LWT. Left panels (a-c) compare these proportions over all winter days (black) and over winter days with westerly QBO (blue), smoothed *aa* index in the higher tercile (red), and combined conditions (magenta). Right panels (b-d) compare the LWT proportions over all winter days (black) and over winter days with easterly QBO (blue), smoothed *aa* index in the lower tercile (red), and combined conditions (magenta). Means and standard deviation of the distributions are very close to those given in Table 1.

These changes in LWT proportions found over the longest period 1908-2014 call for two comments. First, these changes are small, but some are highly significant. To put this significance level into context, we compare it with the ones reported by Anstey & Shepherd (2014) in their review of the Arctic vortex sensitivity to the QBO and solar cycle. The largest difference in the vortex strength, found between WQBO/SCmin and EQBO/SCmin conditions (their Fig. 5c), has a risk level of 1 % (or two times 0.5 % since two-sided), and the next largest difference has a risk level of 12 %. In addition to being highly significant, the differences in LWT occurrence do not suffer from the statistical biases described by Salby and Shea (1991) (see discussion above). Secondly, our results suggest that the QBO phase alone has no (significant) impact on LWT occurrence, although its association with the solar activity (*aa* index) seems to amplify its impact (Fig. 4a for W-QBO and high solar conditions). Such amplification is in line with the original work of Labitzke and colleagues on the Arctic vortex. However this does not appear to hold for the E-QBO and low solar association (Fig. 4b). In order to explore this inconsistency, changes in LWT occurrence are explored over two separate periods, with the aim of testing reliability of the results shown above.

3.1.2 Changes over sub-periods: stationarity and data reliability

The results described above suggests that LWT occurrences are only sensitive to the QBO phase when associated to the *aa* index, and not for all phases. Although reasons for this inconsistency may be physical, we test here two simple explanations: that the time series of QBO phase is biased (typically before enough data can constrain it, see Section 2.2) and affect the LWT sensitivity, or that the sensitivity is correct but not stationary over time. For this test, changes in LWT proportions are calculated over two sub-periods, 1908-1957 and 1958-2014, which have contrasted solar activity, lower in the first part of the 20th century and higher during the second part (Fig. 3). Over the latter period, the time series of QBO phase is much more reliable (see discussion in Section 2.2). The sub-periods have not exactly the same duration: about 43 % of winter days in the former, 57 % in the latter. The choice of 1958 comes from the availability of reanalysis data to constrain the QBO and stratospheric sudden warming (SSW) events (discussed later).

Figure 5 shows the proportions of the A, W & NW LWT over both sub-periods, under different winter conditions; the corresponding statistics are given in Table 2. (Only this LWT group is shown since proportions for the other group are almost symmetric.) The upper panels compare with Fig. 4a (with westerly QBO and/or high *aa* index), the lower panels with Fig.4b (with easterly QBO and/or low *aa* index). During days with high *aa* index (upper panels), these LWT were in higher proportion, and the relative increase is about the same over both sub-periods (+3.4 % and +4.2 %). (Note that the relative increase over the whole period, by +5.8%, is not the average of these figures because the LWT proportions are different between the two sub-periods.) During days with low *aa* index (lower panels of Fig. 5), these LWT were in lower proportion only over 1908-1957 (by -6.8 %). We note some concomitance: these LWT are more sensitive to high *aa* index over 1958-2014, a period with mostly high *aa* index, and more sensitive to low *aa* index over 1908-1957, a period with mostly low *aa* index (Fig. 3). The possibility that this concomitance could arise from a sampling bias, is not obvious: in each sub-period, the absolute numbers of days with opposite solar phase are still quite high: 1311 and 1502 days over each sub-period. Lastly, the quasi-absence of sensitivity of these LWTs to low solar conditions over the most recent period (Fig. 4d) is surprising. The calculations were redone over slightly different sub-periods of equal duration, 1908-1961 and 1961-2014. The sensitivity of LWT are similar, with one interesting exception: A, W, and NW LWT are slightly less abundant over days with low *aa* index over both sub-periods, a sensitivity more consistent with the other results.

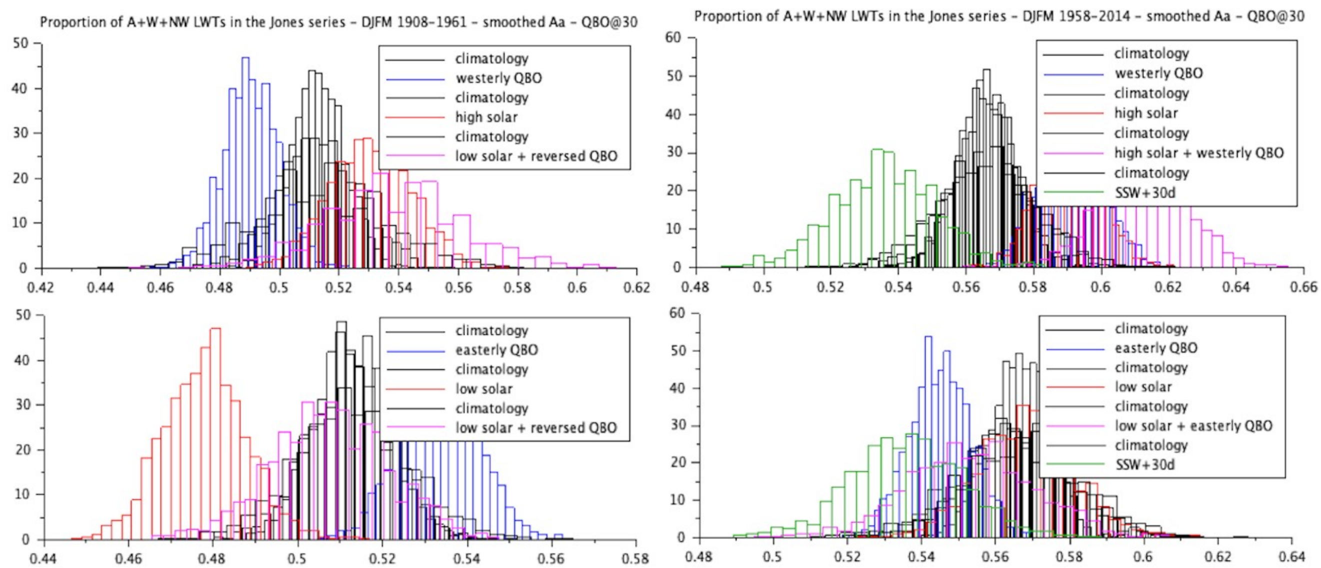

Figure 5. *Idem* Fig. 4 but for the sub-periods 1908-1957 (left) and 1958-2014 (right). Only proportions of the LWT group A, W & NW are shown (those for the other LWT group are mostly symmetric). Upper panels: westerly QBO and high solar conditions (compare with Fig. 4a). Lower panels: easterly QBO and low solar conditions (compare with Fig. 4b).

Table 2. Same as Table 1 except over periods 1908-1957 and 1958-2014 (only for the A, W & NW LWT group). 'Days #' is the number of winter days with the specific conditions specified in the first column. For clarity only the relative differences are given.

Changes in the A, W & NW LWT occurrence over different periods						
conditions / period	1908-1957			1958-2014		
	days #	relative difference	t-parameter	days #	relative difference	t-parameter
reference: all winter days	6063			6911		
westerly QBO	2881	-4.5%	2.5	3195	+4.3%	2.8
high solar*	1310	+3.4%	1.3	3183	+4.2%	2.8
west. QBO & high solar*	483	+4.9%	1.1	1502	**+8.0%**	**3.6**
easterly QBO	3182	+4.0%	2.3	3716	-3.7%	2.6
low solar*	2624	**-6.8%**	**3.6**	1502	0.4%	0.2
east. QBO & low solar*	1379	-1.0%	0.4	847	-2.2%	0.7

* 'high/low solar' = days with smoothed *aa* index in its higher/lower tercile

The sensitivity of these LWT to the QBO phase is less clear than for the solar phase, since it is reversed over both sub-periods: there are more A, W & NW LWT during days with W-QBO than with E-QBO over the 1958-2014 period, but less over 1908-57. This explains why LWT are found not sensitive to the QBO phase over the full period 1908-2014 (Fig. 4).

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However, these changes and the associated t-parameters are weak. Contrary to the solar phase, a sampling bias of the QBO phase is not expected since the proportions of both phases (westerly and easterly) are not different between the two sub-periods. However, contrary to the solar phase, the QBO phase is not well constrained before the use of reanalysis data (i.e., before 1957), because the signal recorded in surface pressure is very weak (Brönnimann et al., 2007). Hence, we cannot rule out the possibility that the reversed sensitivity of LWT over the period 1908-57 is due to a shift in the reconstructed QBO phase. (A hint of a possible problem in this QBO reconstruction before 1957 is the almost constant phase length, whereas it is much more variable after this year.) If we focus on the latter sub-period, 1958-2014, A, W & NW LWT are found more abundant during the W-QBO and less during the E-QBO (by 4.3 % and -3.7 %, respectively, with t-parameters of 2.8 and 2.6). These LWT are even more abundant during winter days combining a W-QBO and high *aa* index (+8.0 %), and also less abundant during winter days combining an E-QBO and low *aa* index (-2.2 %, although weakly significant).

Drawing conclusions on the sensitivity of LWT separately analysed over two sub-periods is thus not obvious. An optimistic view is that the sensitivity of these LWT to the *aa* index (solar phase) has consistently the same sign, but its value is variable. Also, it is not necessary to associate the QBO phase to the *aa* index to detect a significant solar association with LWT, in agreement with several works (e.g., Camp & Tung 2007). However, the LWT sensitivity to the QBO phase is not consistent, with reversed signs over the sub-periods: this explains why this sensitivity is almost absent over the full period 1908-2014. There is no obvious explanation for this inconsistency, and we cannot rule out a problem with the QBO series used to stratify the days. A conservative approach would be to give more credit to the analysis of QBO impact on the most recent period since 1957, which benefits from reliable data. Over the period 1958-2014, A, W & NW LWT are about equally sensitive to the west and east QBO phases (in opposed directions), and combining the west phase to high *aa* index gives the strongest impact found on these LWT (8 %).

A last question raised by previous studies is how much using reanalysis data influences the detection of a sun-weather relationship. For this, we recalculate changes in LWT occurrence with the 'subjective' original LWT series, which is totally independent of reanalysis data. The covered period is somehow shorter, 1908-1996. It is split into two equal sub-periods, 1908-1952 and 1952-1996, to test how the quality of data could influence the LWT sensitivity (but note that sampling size is very low with some conditions). In addition to the QBO series, more reliable after 1957, the original LWT series benefited from more synoptic charts and high altitude observations after World War II. This LWT series also contains more undefined days (about 10 %) than the 'objective' series used above. Table 3 lists the statistics of the A, W & NW LWT proportions under different conditions, and compares with Table 2. Changes over the most recent period (1952-1996) are quite consistent with the ones calculated with the objective LWT series (over 1958-2014). Changes associated with high solar conditions appear even stronger. Over the first sub-period (1908-1952) though, changes are not consistent, neither with the ones over the most recent period nor with the ones calculated with the objective LWT series.

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Table 3. Same as Table 2 but with the 'subjective' original LWT series, over the sub-periods 1908-1952 and 1952-1996 (only for the A, W & NW LWT group).

Changes in the A, W & NW LWT occurrence over different periods						
conditions / period	1908-1952			1952-1996		
	days #	relative difference	t-parameter	days #	relative difference	t-parameter
reference: all winter days	5426			5366		
westerly QBO	2529	-3.6%	2.0	2552	+4.0%	2.1
high solar*	959	-6.5%	2.3	2709	**+6.9%**	**3.8**
west. QBO & high solar*	249	-9.3%	1.6	1360	**+10.1%**	**3.9**
easterly QBO	2897	+3.1%	1.9	2814	-3.6%	2.0
low solar*	3073	-0.3%	0.2	594	-2.7%	0.7
east. QBO & low solar*	1572	+3.7%	1.7	273	-3.9%	0.7

* 'high/low solar' = days with smoothed *aa* index in its higher/lower tercile

This exploration of changes in LWT occurrence associated to QBO and/or solar phase shows that some consistent signals emerge, but few are robust and statistically significant, i.e. most are not reproducible over different periods or by using slightly different data sets, and thus cannot be attributed to any forcing. The most robust and significant changes are found over the most recent decades, in response to both QBO and/or solar phases. Contrary to the conclusions of Labitzke and colleagues (mostly drawn for the Arctic vortex), a robust signal associated to the *aa* index (solar phases) is detected without the association with a QBO phase.

We now try to interpret these changes in LWT occurrence, looking to sequences of LWT as representing synoptics.

3.2 Changes in synoptics: LWT sequences

As discussed in Section 2.1, the Lamb weather types are defined by the regional flow of air, determined by the large-scale synoptic situation. By construction, LWT cannot be influenced individually by different solar or QBO conditions, but only their occurrence and succession representing synoptic situations. These synoptic situations are driven by lows crossing the northern Atlantic basin. As a trade-off we consider sequences of LWT over five days (Section 2.1).

A first approach for exploring these LWT successions was to extract all 5-day sequences from the series. These sequences are used to explore the association of LWT found in Section 3.1 (i.e., A, W & NW vs. C, N, E & S), and also to which synoptic situations correspond these sequences. Over all DJFM winter days of the period 1908-2014, there are 12542 5-d sequences and 3280 different ones. This latter figure is only 1/5 of the possible 16807 combinations of the 7 LWT (i.e. 7^5), which shows that LWT are not randomly associated. These sequences are dominated by the AAAAA sequence (about 8%) and by the CCCCC sequence (about 3 %), the next one is much less frequent (< 1 %) and the following as well. The most

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frequent ten sequences represent about 15 % of all sequences, so that the remaining 85 % is spread over thousands of different sequences, which leaves very small numbers. However, within this diversity of LWT combinations, some LWT are found more often associated: outside of the dominating AAAAA and CCCCC sequences, 25 % of the sequences contain either a combination of only A, W and NW LWT, or a combination of only C, N, E and S LWT. This shows how strongly these specific LWT are linked together in the synoptic situations, and why they are found more sensitive to QBO or solar forcing (Sect. 3.1).

These associations of LWT give way to typical synoptic situations, which were explored by calculating their average SLP from the NCEP reanalysis, as detailed in Section 2.1. (Note that the average SLP associated to one LWT, shown on Fig. 1, is slightly different from the average SLP associated to this LWT *within* some specific 5-d sequence, shown on Fig. 2.) As illustrated by Figure 2, the combinations of A, W and NW LWT correspond to situations of high pressure over or close to the British Isles and a low located south Greenland. This low happened to migrate north-eastward towards the Svalbard, very north in the Atlantic basin. Figure 6 illustrates two other typical situations related to the other group of LWT (C, N, E and S). The first, ASCCCC, shows the eastward migration of a low towards the British Isles, replacing a high pressure system. The other, CCCCN, shows a high pressure ridge extending from the Azores northward, perturbing the westerly flow circulation with a situation close to an Omega blocking. A comparison of the occurrence of the most frequent sequences under westerly QBO and high solar conditions shows that the sequences with the A, W and NW LWT are more frequent (by up to ~10 %), and conversely that the sequences with the C, N, E and S LWT are less frequent (Tables 1&2). Hence these conditions seem to promote synoptic situations with a north-eastward migration of lows, located high north in the Atlantic basin, whereas easterly QBO & low solar conditions promoted eastward migration of lows at lower latitudes, or even blocked situations.

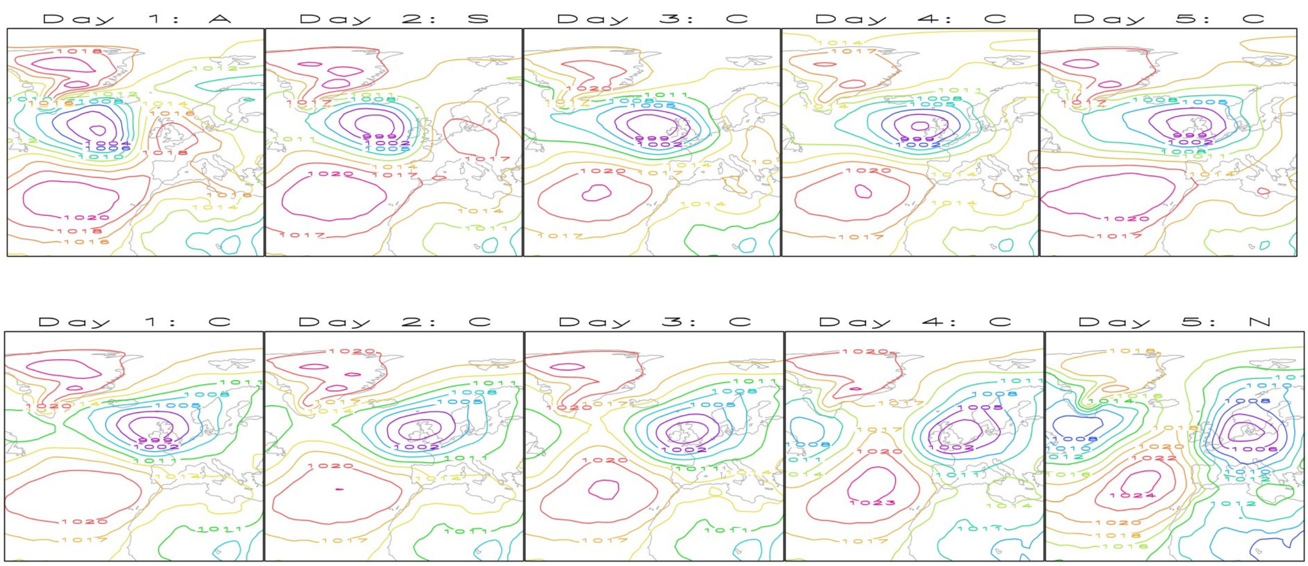

Figure 6. Average SLP fields associated to each day of two 5-day sequences, ASCCC (top) and CCCCN (bottom), over the DJFM winters of the 1948-2014 period (NCEP reanalysis)

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However, comparing the frequencies of sequences proved a difficult task, for two reasons. First, there are more than 3000 different sequences, each in very small number, so that their statistics is weak. Secondly, interpreting individual sequences in terms of synoptic conditions is not easy, and not feasible for 3000 different ones. A possibility would be to group sequences which frequently occur in a row: for instance AWAAA, AAWAA, AAAWA are obviously parts of a longer sequence corresponding to the travelling of a low in the northern part of the Atlantic. But such association between sequences is difficult to conduct systematically.

Another approach for exploring these LWT successions was followed, by considering the transitions between daily LWT. Because synoptic situations are organized and not random, the daily occurrence of any LWT strongly depends on the LWT occurring the day before (that is, this occurrence is not equal to its average one). For instance, among days with a westerly flow (W, Fig. 1), 38 % are followed by the same LWT, 22 % by an anticyclonic A situation (when the high has migrated northward), and 21 % by a day with a cyclonic C situation (when the low has migrated southward), but almost never by an easterly or northerly day. (Note that transitions may look synoptically abrupt, like C to A: this comes from simplifying the original 26 LWT into only 7. Considering 26 LWT would make transitions smoother but more difficult to analyse.) These frequencies of transitions are given in Table 4, which readily shows how much some transitions are preferred in LWT sequences. We looked to changes in these frequencies under different QBO and solar conditions, over the period 1958-2014 (which provides the most consistent changes in LWT occurrence). After extensive comparison, few transitions were considered both important and significant in explaining changes in LWT frequencies discussed above (Table 2). These transitions are given in Table 5. The changes are limited to few percents, but they are consistently stronger under high solar & westerly QBO conditions.

Table 4. Frequencies of LWT transition for winters in the objective series during the period 1958-2014 (in %), discounting undefined LWT. (For instance, 19 % of winter days with the NW LWT were followed by the W LWT.)

day N / day N+1	NW	W	S	E	N	C	A
NW	13.0	10.4	1.8	0.0	10.5	6.2	3.0
W	19.4	38.1	16.7	0.0	4.8	12.0	14.0
S	5.4	8.3	30.9	5.0	3.6	9.4	12.2
E	1.0	0.1	4.4	43.4	2.4	3.5	2.2
N	9.1	0.5	0.1	6.1	19.4	6.0	1.9
C	21.8	21.1	32.7	12.5	13.7	49.6	4.6
A	29.8	21.5	12.5	31.9	45.6	12.4	61.7
sum	*99.5*	*99.9*	*99.2*	*98.9*	*100.0*	*99.1*	*99.6*

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Table 5. Changes in the frequencies of some LWT transitions (Table 4) under different conditions, in the objective LWT series over the period 1958-2014. (Changes with a t-parameter higher than 3 are in bold.)

	all winter days (6910d)	westerly QBO (3194 d)		high solar* (3182 d)		west. QBO & high solar* (1501 d)	
LWT transition	frequency	diff.	t-param.	diff.	t-param.	diff.	t-param.
C to C	50%	-2.8%	1.6	-1.1%	0.5	-3.1%	0.8
S to C	33%	-0.1%	0.1	-2.8%	0.9	-7.2%	2.0
W to A	22%	0.4%	0.2	3.2%	1.2	**10.6%**	**3.0**
W to C	21%	0.5%	0.3	-4.4%	1.9	-5.3%	1.9
S to A	13%	0.3%	0.2	4.7%	2.0	5.9%	1.3

* 'high solar' = days with smoothed aa index in its higher tercile

To discuss the significance of these changes, which are small, we use again a bootstrap approach to estimate the standard error on the mean. For this we use a bootstrap technique based on blocks of days, described in the Appendix A. As for changes in LWT occurrence, we calculate the *t*-parameter as the ratio of frequency difference to the standard error on the mean. These statistics are given in Table 5.

Contrary to the changes in LWT occurrence, the *t*-parameter is small, at best 2 to 3, because changes are small. However, as for the LWT occurrence, the combination of westerly QBO and high solar conditions is associated with much stronger changes than each condition alone. These conditions were found to promote A, W and NW LWT (Table 2), and these transition changes help explain how. Westerly QBO is associated with small changes but a shortening of the Cyclonic persistence. High solar conditions are associated with more frequent S to A transitions and less frequent W to C transitions. The combination of westerly QBO and high solar conditions is associated with more frequent W and S to A transitions and less frequent W and S to C transitions. The changes shown in Table 5 have promoted the A, W & NW LWT at the expense of the C, N, E & S LWT, by affecting the transitions either within one group of LWT or between both groups. These changes favoured the northward shift of a combined high & low pressure system, as opposed to the westward progression of a low over the British Isles (Fig. 2 & 6).

4 Discussion

A statistical approach has been followed to explore the associations between solar activity, QBO phase, and LWT occurrence, and their significance. If different QBO and solar conditions have been explored, we mostly focus on the specific conditions associated with the largest and most consistent changes in LWT, low *aa* index and the combination of W-QBO & high *aa* conditions. Few changes in LWT occurrence, however, appear statistically significant. An alternative definition for the QBO phase was tested (at 50 hPa instead of 30), and SSN series was tested as an index of solar activity. Using these indices lead to both weaker and much less significant changes in LWT occurrence, and changes less consistent across time.

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Considering (5-d) sequences of LWT allows us to link the daily LWT with synoptic situations. Hence changes in LWT occurrence can be interpreted as changes in the progression of lows across the Atlantic basin (i.e., of storm tracks): during periods with westerly QBO and high *aa* index, this progression is more frequent and more poleward, with less frequent southward position of lows and less situation of blockings characterised by meridional circulation (N, E & S LWT). A low *aa* index is consistently found associated with these latter LWT and more southward or blocked synoptic situations. Hence, these changes in synoptic situations are found more complex than the simple 'zonal' vs. 'meridional' approach of atmospheric flows, and better match an interpretation in terms of modes of variability or weather regimes. Especially, the positive NAO phase can be readily related to the north-eastward progression of lows across the Atlantic, which corresponds to sequences including mostly A, W and NW LWT (fig. 1&6; W LWT is actually very close to the NAO pattern). On the contrary, the Eurasian mode is a meridional mode corresponding to sequences with C, N, E & S LWT (Fig. 6; N LWT is actually very close to the EU2 pattern).

This approach linking LWT occurrence with the position of storm tracks allows us to compare our results with previous studies. Especially, Huth et al. (2009) tested the sensitivity of the northern hemisphere winter modes of variability (by analysing the large scale pressure variance over the period 1953-2003) to the QBO phase (defined at 45 hPa) and the 11-yr solar variability (with the F10.7 index). They found the strongest sensitivity during winters which combined W-QBO and high solar conditions, with a more zonal and more northward circulation. These changes were associated with the NAO and East Atlantic (EA) modes, which centers of action were both stronger and displaced northward. Conversely, the E-QBO winters have a more meridional circulation associated with the Eurasian (type 2) mode and weaker NAO and EA zonal modes shifted southward. Our results are quite consistent with these ones in terms of changes in the location and strength of storm tracks.

Brugnara et al. (2013) tested the sensitivity to SSN of several climatic series over long periods, as well as outputs of the long 20CR reanalysis. They did not find a relationship between NAO and SSN. However, they found a consistently stronger meridional gradient of pressure in the northern Atlantic basin and a more zonal circulation over Western Europe associated with higher SSN. Schwander et al. (2017) used a series of flow types similar to the LWT but defined over Central Europe, and over a much longer period (1763 to 2009). Flow types in both classifications can be related from their associated mean SLP field (compare our Fig. 1 and their Fig. 3). They found a more zonal circulation, and less blockings, during periods of high SSN. Interestingly, they looked to three different periods, and found that changes were mostly significant over 1763-1886 (the oldest one) and much less over 1958-2009 (the most recent one), with even some reversed changes. These studies did only consider solar activity (with SSN) and not QBO to stratify the data, and they found that relationships varied over the long periods they considered (which may point to non stationary relationship and may also arise from the varying quality of the data). The limited results we have shown seem to be consistent with these previous ones in terms of meteorological changes under contrasted solar activity, with the merit to being slightly more statistically significant.

Even if a consistent picture of a solar impact on meteorological conditions in the northern Atlantic has somehow emerged, it is clear that each individual study has provided contrasted results, not stationary over long periods of time, and with very weak statistics. On the other hand, many studies did propose that solar activity and QBO could have

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meteorological impacts through the modulation of the strength of the winter polar vortex. Since this modulation is primarily related to sudden stratospheric warming events (SSW), we have tested the association between these events and LWT occurrence: if the associations found above with solar and QBO variabilities are real impacts, and not just statistical artifacts, they should hold with SSW. We use the SSW catalogue of Butler et al. (2017), with 36 events over the period 1958 to 2015. Synoptics changes related to SSW have been reported to last between ten days up to two months, hence the 30 days following the SSW were sampled to calculate the changes in LWT occurrence over these (36×30) specific days. The limited number of SSW does not bear so much statistical limitation in terms of counterfactual days to compare with. Firstly, by far these SSW events did happen in January or February (23 over 36), and only 10 % of the sampled days were in April (i.e., outside our DJFM winters). Secondly, over the period 1958 to 2014, these sampled days did not significantly occur during any preferred solar and QBO phases since the ratio of their high-to-low solar or E-to-W QBO occurrence is close to these ratio over all winter days. We found that during these days following a SSW, LWT were different than over winters on average, with more C, N, E & S LWT (+7.2 %, t-parameter of 2.1) and thus less A, N & NW LWT. These changes are limited and the associated statistics is weak, but they are consistent with changes in atmospheric circulation and weather regimes (a southward shift of storm tracks and more often blocked situations) detected after SSW by previous studies (e.g., Baldwin and Dunkerton, 2001; Kidston et al., 2015; Domeisen et al., 2020).

5 Conclusions

Most studies of sun-weather relationship did claim significant association and conclude to solar impacts (with additional modulation by the QBO). However methodological weaknesses have hindered the credibility of sun-weather studies. Our work is very limited in scope but to re-evaluate this problem of detection. A first problem is the aliasing of decadal timescale by a too short sampling frequency of the data. Our daily data allow us to avoid this problem. A second and third problems are related to the shortness of the series, which limits both the statistical significance of tests and the possibility to test the stationarity of sun-weather relationship. We use a century long series, and find significant differences in the occurrence of LWT stratified by solar and QBO phases. However, looking separately to the first and second part of the 20th century shows contrasted results. Whether these contrasted results are due to biased data in the first period, or to the non stationarity of sun-weather relationship is not clear. For instance if only a high solar activity is able to synchronize the decadal variability in the north Atlantic - European area (Thiéblemont et al., 2015), the solar activity may have been too low in the first part of the 20th century to have a detectable climatic imprint.

Studies on sun-weather relationship did not clarify enough which part of the solar variability they accounted for; and it is probable that the variety of results found in previous studies at least partly arises from using different indices of solar activity. Most studies have used SSN or F10.7: these indices contain the 11-yr solar variability but little of its secular variability. It is not obvious that the atmospheric circulation did response to a purely decadal forcing in the northern Atlantic region (e.g., van Loon and Meehl, 2014), and some studies have actually tried to include some secular solar variability, possibly to improve correlations. We have used here the aa index which much better describes the secular variability than the

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other indices, and less the 11-yr cycles. In terms of mechanisms, the *aa* index is sensitive to the magnetosphere variability and thus describes energetic particle precipitation in the middle atmosphere and polar vortex.

We find significant changes in LWT mostly under combined high *aa* index and W-QBO conditions, and under E-QBO conditions. Although we analyse daily LWT occurrence, their (5-day) sequence characterises storm track location and activity in the northern Atlantic basin. The combined high *aa* index and W-QBO conditions are found to favour a group of LWT which corresponds to more northern location of storm tracks. E-QBO conditions are found to favour a group of LWT which corresponds to more southern location of storm tracks, or to a blocked circulation over Europe. This latter group of LWT is also found more frequently following an SSW, which is some hint of a link with the polar vortex variability. These results compare well to seasonal analyses of previous studies. The merit of our study is small but to show that sun-weather relationship can be detected even when properly addressing the methodological weaknesses which have undermined previous studies. This relationship was found stronger using the *aa* index than with SSN, and this may point to different mechanisms implied in the relationship.

Appendix A: Block bootstrapping of daily LWT

A standard bootstrapping of the daily LWT does not provide their transition frequencies: this is because randomly selecting days makes them independent, so that transition frequencies converge to the mean frequency of each LWT. (Mathematically, the probability of some LWT X occurring after the LWT Y, P(X/Y), is equal to P(X) if X and Y are independent). Hence a standard bootstrap technique cannot account neither for the persistence of LWT nor for their dependence, which both exist over few days. The typical lifetime of LWT is about two days, so that the transition frequency between the same type of LWT is high (Table 4). To account for this synoptic persistence, we use a bootstrap technique based on blocks of days (e.g., Wilks, 1997). Briefly, blocks of n days are randomly chosen within the daily series of LWT and rearranged in order to reconstitute a series of the same size. The problem is to set the block length n. In our case this setting is readily determined because the exact transition frequencies are known (calculated over each full period). Hence, we adjust n so as to minimize the RMSE between the exact frequencies and the ones given by the bootstrap block technique. For the whole winter period a broad minimum for RMSE is found around $n = 100$ d. This bootstrap technique based on blocks provides us with an estimate of the uncertainty on the mean transition values, uncertainty that we calculate as the standard deviation over 2000 block samples. As for changes in LWT occurrence, we calculate the t-parameter as the ratio of frequency difference to the standard deviation on this frequency. These statistics are given in Table 5. (Note that we did not account for the few artificial transitions created by re-arranging blocks of days.)

Data availability. The LWT series are available from the Climatic Research Unit of the University of East Anglia (https://crudata.uea.ac.uk/cru/data/lwt/). The *aa* index is provided by Service international des indices géomagnétiques (http://isgi.unistra.fr).

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