Author's response

Review 1

The manuscript presents a detailed investigation of 11-yr solar cycle influence on weather types. Thetopicisofinterestforthepaleoclimateandsolar-terrestrialcommunities, although a detailed knowledge of the weather types and their variability may be too farfetched for most of the CP readers. Some description of weather type characteristics is needed. Besides a new, unique reconstruction of weather types, the authors analyze a set of 4 simulations with a climate model forced by Total Solar Irradiance, only. This is a somewhat a strange model configuration and weakens the merit of the simulations for detecting mechanisms, as the "top-down", which believed to be the key mechanism influencing the weather types (see Introduction) is neglected. Most parts of the manuscript are well written and reading is straightforward and easy, except the discussion part where it is difficult to pair results of this study to the text. There are some points other that need further clarification and improvement before publication of the paper.

We thank the reviewer for the constructive comments. We agree on most comments and included the suggestions in the revised manuscript. The description of the model in our first manuscript was too vague and was improved in the new version since the model is forced by SSI. We decided to leave out the low frequency solar variability of the model since it is not in the scope of the papers and only brings confusion. We focus only on the 11-year solar cycle from 1958 to 1999 to compare with reanalysis data. The model includes bottom-up and top-down mechanisms.

Methodology

Weather types are analyzed by the means of composites. The 11-yr solar cycle is sliced in three groups/day of low, moderate and high activity. Are these groups of near equal size? I am concerned about the role of internal variability in the composites and how affects results. How confident are the authors that compositing results in true solar signals? Splitting the record to 50 yr chunks offers too little to this regard because it provides little evidence of consistency over time. This is recognized by the authors: "P8 L13 Although it can be difficult ...". I would suggest to split to two sub-periods at best. For the same reason, Figure 7 can be supplied as a supplementary.

The groups are not exactly of equal sizes since more volcanic eruptions occurred under low solar activity. We added a table with the size of the groups. The confidence is quite high since the signal in some types in significant over 250 years, and also because it is consistent with previous studies. The signal found in the occurrence of weather types is consistent with the within-type differences. The significance was added on the within-type composites difference plots.

We kept the 1958-2009 sub-periods as a comparison with Huth et al. (2008). We reduced the number of sub-periods to have only two (1763-1886 and 1887-2009).

Significance in solar minimum

I always consider the solar minimum as the least perturbed state of climate not necessarily the reverse of the solar maximum. It is puzzling to me that the most noticeable changes in WSW and W types are detected in solar minimum, when the forcing is weakest. Could the authors elaborate on the reasons/mechanisms that can explain strongest signals in solar minimum and not maximum?

We cannot provide any reasons why the signal could be stronger under low solar activity compared to high activity. We think that it comes from the fact that the long-term mean is also perturbed. If the low activity phase is not perturbed (one third of the months), then two thirds are perturbed (moderate and high). The long-term mean is therefore also perturbed and the differences under low solar activity seem larger. We could take the low solar activity phase as a (unperturbed) reference and then we would observe a strong increase in the occurrence of W and WSW types under moderate and high solar activity.

Model simulations

Perhaps I am missing something here, but my understanding is that the SOCOL simulations are forced only by TSI and in particular by the strong Sapiro et al. TSI reconstruction. There is nothing wrong by choosing a strong TSI reduction to facilitate the signal-to-noise detection. My objection here is on the specification of TSI and not SSI variability. Is there any particular reason to assume that solar signals in weather types are attributed to the "bottom-up" mechanisms? Most of the discussion in introduction emphasizes the importance of "top-down" mechanisms in transferring signals on the surface, a mechanism which apparently is missing in model runs without SSI forcing. In such a case, the low resemblance between reanalysis and modelled signals is not surprising to my understanding. Moreover, some similarities discussed in P.10 L30 is a matter of coincidence to me. So, it is difficult to understand the overall point of Section 3.4 given that the SOCOL runs are missing key mechanisms. The weakness of the simulations should be discussed in the text.

We realize that the model description in the Manuscript is lacking some information. The model was not forced by SSI and can include top-down and bottom-up mechanisms. We have rewritten the description of the model (Section 2.6). We now only focus on the 11-year cycle and have removed the part on the low frequency of the solar variability.

Mean difference (Section 3.1)

Do results of figure 5 compare with Fig1 of Ineson et al., 2011? Difficult to say for SLP. For temperature, I see some similarities but some differences as well. I could also consider presenting lagged anomalies (see my following comment).

The SLP and temperatures differences in Figure 5 (now Figure 4) are similar to Figure 1 of Ineson et al. (2011) with some variations in the location of the maximum differences. Differences are similar over Europe but quite different over the North

Atlantic and Greenland. For example the positive SLP difference over Scandinavia in Figure 5 (now Figure 4) does not extend as far east (over Greenland) as in Ineson et al. (2011)

Weather type classification (Section 2.2)

This section assumes a reader familiar with the different weather types and their within type differences. I am afraid this won't be the case for most of the CP readers. For example, what does the "well discriminated types (P4 L 31)" mean? Or, "days with probability higher than 75%". I think a concise description of the main characteristics of the weather types is needed.

Since the submission of the first manuscript the paper describing the weather types and reconstruction method has been published online (Schwander et al., 2017). We do not want to describe all the method again in this paper but tried to improve a little the description of the weather types to make it more understandable. The probability refers to the method of reconstruction, it's just an indication on the quality of the reconstruction since there is no comparison possible with another weather types time series over such a long period. The reader should look at Schwander et al. (2017) for more information.

Lagged responses

The authors in P12 3rd paragraph, briefly discuss the lagged response of westerly types and try to compare with Gray et al. and Thieblemont et al., results. Same in P8 last paragraph. Inferring time lags is very interesting subject and I would recommend a proper presentation, dedicating, perhaps, even a new Section. This could be a valuable contribution to the number of recent papers discussing time lags as they can highlight the importance of atmosphere-ocean coupling.

Since the strongest signal in weather types occurrences is found without any lag we decided not to focus on lags. However, we added a new figure with lags (Figure 6) and extended slightly the discussion.

Some additional considerations,

P1. L27: stratospheric ozone + "and heating".

We have made the correction.

P2. L10: "phase lag is expected": Perhaps this is not true by the sole action of "topdown" mechanisms. An atmosphere-ocean coupling is required for lags longer than one year at least.

We agree, we have mentioned that it is only a short lag in this case.

P2 L20: found a response

Thank you, we have corrected this.

P3. L3: do you mean Gray et al., 2010?

Yes

P3 L4: This is hardly true. Gray et al, show surface signals.

We have reformulated the sentence.

P3. I think the second paragraph should also be extended by discussing results of more recent model intercomparison such as CCMVal or SolarMIP. See (Austin et al., 2008; Hood et al., 2015; Misios et al., 2015; Mitchell et al., 2015) and references therein.

Thank you for the suggestion, the discussion have been completed with some more references.

P3 L25: “It allows us ... weather statistics”. Is this true? What is the main difference to Huth et al., 2008b?

The difference to Huth et al. (2008b) is that we have almost 250 years of daily weather types (~50 years for Huth). We have modified the sentence to mention that we have a longer time series of data.

P4 L4: Description here is rather confusing. You should clarify that you analyze a merged dataset and not ERA-40 and ERA-int separately. Please elaborate how stitching was performed.

We have made the description of ERA-40 and ERA-Interim clearer.

P4 L17: Is it one of the revised products of sunspot numbers?

Yes, we have added this information.

P4 L29: “from 1958 to 1998”. Why not till 2009?

Because some of the instrumental data used for the reconstruction stop in 1998. The reference was taken over a period where all data were available (see Schwander et al., 2017).

P6 L25: CO2, CH4, N2O (subscripts)

We have added the subscripts.

P7 L6: A quantitative difference of the forcing, long term and 11-yr cycle, should be given here.

We have rewritten the section on the model simulations, and we now only focus on the 11-year cycle.

P7 L10: ...66th thresholds of sunspot numbers?

Yes, we have completed the sentence.

P7 L11: Still not clear how percentiles are calculated. Have you subtracted the 11-yr solar cycle before?

When we speak about the 11-yr solar cycle we always speak about the monthly sunspot number on which the percentiles where computed. The was used also for the Shapiro reconstruction and is visible in the reconstruction although it is sometime masked by the low frequency variability. We have decided to focus only on the period 1958-1999 in the model simulations as a comparison with the reanalysis data. The low frequency variability of the solar variability during the period 1958-1999 is stable and we can focus only on the 11-yr solar cycle.

P11-13: It is very difficult to follow the discussion of the results. Please point to the associated figures.

We have rewritten some parts of the discussion and pointed to the corresponding figures.

P13, L11: "only partially". This is a wishful thinking!

We have removed this, it is true that we do not see the same signal in model simulations.

Figure 5: Difficult to separate SLP from geopotential signals. Please consider splitting this panel in two.

We did not split the figures but we have adapted it to make it more understable.

Austin, J. et al., 2008. Coupled chemistry climate model simulations of the solar cycle in ozone and temperature. J Geophys Res-Atmos, 113(D11): D11306. Hood, L. et al., 2015. Solar Signals in CMIP-5 Simulations: The Ozone Response. Q. J. Roy. Meteorol. Soc., 141: 2670–2689. Misios, S. et al., 2015. Solar Signals in CMIP5 Simulations: Effects of Atmospherre Ocean Coupling. Q. J. Roy. Meteorol. Soc. Mitchell, D.M. et al., 2015. Solar Signals in CMIP-5 Simulations: The Stratospheric Pathway. Q. J. Roy. Meteorol. Soc., 141: 2390-2403.

References

Muthers, S., Anet, J. G., Stenke, A., Raible, C. C., Rozanov, E., Brönnimann, S., Peter, T., Arfeuille, F. X., Shapiro, A. I., Beer, J., Steinhilber, F., Brugnara, Y. and Schmutz, W.: The coupled atmosphere-chemistry-ocean model SOCOL-MPIOM, 5 Geosci. Model Dev., 7(5), 2157–2179, doi:10.5194/gmd-7-2157-2014, 2014

Schwander, M., Brönnimann, S., Delaygue. G., Rohrer. M., Auchmann, R., Brugnara, Y. Reconstruction of Central European daily weather types back to 1763. International Journal of Climatology. doi: 10.1002/joc.4974. 2017.

Weusthoff, T.: Weather Type Classification at MeteoSwiss - Introduction of new automatic classification schemes, Arbeitsberichte der MeteoSchweiz, (235), 46, 2011.

Review 2

Review of the paper "Influence of solar variability on the occurrence of Central European weather types from 1763 to 2009" by Mikhaël Schwander et al., MS No.: cp2017-8

General comments

The paper uses a novel weather type classification that was constructed by the authors in a previous recent study, in order to identify and assess the potentially important regional aspects of solar variability effects on the weather types in central Europe for the period from 1763 to 2009. The present paper expands the use of the weather type classification and contains new material.

However, the paper needs major improvements before it is considered for publication.

The authors try to assess and compare the shorter term (11years) solar variability effect to the long-term (secular and super secular) changes, occurring at periods of 90-years or more. This attempt is not very successful, as it is not clear throughout the paper where they discuss which time scale. All sections of the paper, mainly the introduction, the data sections and the discussion on the model study, and, of course the conclusions, should be rewritten so that the paper's message is conveyed clearly to the reader. Suggestions on major issues are given below.

We thank the reviewer for the constructive comments. We have rewritten and improved most parts of the paper to make it more understable. We agree that some important information was missing to have a good understanding of the methods. The model simulations description has been rewritten since it does include SSI. We have decided to focus only on the 11-year solar cycle to be more consistent and leave out the low frequency solar variability since it does not add any relevant conclusions to the paper. We have rewritten or corrected most part of the paper.

Specific Comments

The introduction section is rather poor on bibliography, and could be enriched more;. e.g.on page 3, line 5 they refer to Gray et al., 2005, an older paper compared to Gray et al., 2010. Moreover, they should at least mention the work of Meehl et al., 2009, or van Loon and Meehl, Seppala et al., 2009, Rozanov et al., 2012, Scaife et al., 2013, and at least refer to the work by e.g. Mitchell et al., 2015, Misios et al., 2016 on the solar signal in the CMIP5 simulations. (A relatively recent review on the mechanisms and effects is given also by Seppälä et al, 2014).

We agree that some important references were missing. We have completed the introduction with some more recent papers-

The data section is incomplete. In the very first paragraph they mention that they used ERA-40 and ERA-Interim. My impression is that these two reanalysis data sets have been used as one. However, it is not clear if this is the case and, if yes, if there has been any check done on the homogeneity of the data, or if the possible discrepancies have been identified and corrected.

We agree that some description of the data was missing. ERA-40 (from January 1958 to August 2002) and ERA-Interim (from September 2002 to March 2009) have been used together. The reason why ERA-40 was used until August 2002 and ERA-Interim from September 2002 is because the reference classification used to produce CAP7 (Schwander et al., 2017) was originally computed with ERA-40 (1958-2002) and ERA-Interim (2002-2009). For more information on the reference classification (CAP9) please see Weusthoff (2011). We tried to stay consistent with CAP7 (and therefore with CAP9) and use these two reanalysis dataset over the same two periods. The data were remapped to 1° x 1° in order to be combined together. We have not found any discrepancies.

Section 2.1 should be clearly written, and the indices they used for the 11-year and longer term variability presented in a very clear way. For example, there is no call to Figure 3 in this section. They refer to Figure 4 but with no explanation as to what it contains, and the reader is left puzzled, since the Shapiro reconstruction is shown there without it being mentioned in the text. Moreover, I could not understand why they mention in the text that the fact that the sunspot cycle does not become negative is a limitation (this is also mentioned again later in the paper).

We agree on the comment; this section has been improved and the corresponding figures are now mentioned and better presented.

Section 2.3

It is not clear what are the time scales they discuss. Do they refer to the 11-year of the secular cycles? This should be very clearly mentioned here as well. The mechanism they refer to is the top-down mechanism, in which the stratospheric response and the signal transfer from there to the troposphere is the main pathway. This leads us to

We focus only on the 11-year solar cycle.

Section 2.6, where they describe the model simulations. Again in line 21 they refer to low and high solar activity, with no clear indication as to what they mean. Moreover, and for the model simulations: Was TSI the only forcing? Or did they use also the appropriate SSI forcing? Was the model run in its full version with the interactive ozone response in the stratosphere? How is it achieved if one uses TSI variations only? Was the solar effect on ozone included in any way? If SSI variability with the solar cycle and the stratospheric response is not included, then one can have only the bottom up mechanism, and the comparison to e.g. Ineson et al. is not straight forward. In addition, what is the meaning of "It has the advantage to be a predominant forcing in the model.."? It is also not clear how the 11-year solar cycle is handled here. The Shapiro index and its use to define "large solar activity", "moderate amplitude" should be more clearly written.

We have realized that the description of the model simulations in the manuscript was not clear enough. SSI is included in the model. We have rewritten the paragraph presenting the model simulations.

"It has the advantage to be a predominant forcing in the model.." means that since the Shapiro reconstruction has a higher amplitude (~6 w/m^2) than any other reconstruction, it consists of a strong forcing in the model. The upper boundary of the uncertainty of the Shapiro reconstruction was used as moderate amplitude (~3 w/m^2) in the model. Also the Shapiro reconstruction includes the 11-yr solar cycle (based on the sunspot number) although it is often masked by the low frequency amplitude.

The analysis of the low frequency solar activity in the model did not bring any relevant conclusions to the papers. So we have decided to focus only on the period 1958-1999 in the model simulations as a comparison with the reanalysis data. Also the low frequency variability of the solar variability during the period 1958-1999 is stable and we can focus only on the 11-yr solar cycle.

Page7 line9-10, on the volcanic activity and the years that were removed. Why do you state there to "note that many of the important eruptions occur during a solar minimum". Is there any possible connection? How does the removal affect your statistics if it was mainly done for solar minimum years? And more importantly, what type of solar minimum? Sunspot, or secular?

We are not aware about any connection between volcanic eruptions and the solar cycle. The fact that more volcanic eruptions occurred under low solar activity phases has mostly an impact on the size of (number of months) of the low solar activity class. We have added a table with the size of each group (table 2).

Page 7, lines 15 -18. How exactly was the anthropogenic forcing removed? What were the predictors? Was there only one predictor? Which one?

The predictor consists in the radiative forcing applied in the model calculated from major greenhouse gases (CO2, CH4, N2O and CFCs). They were taken from the PMIP3 database (Etheridge et al., 1996, 1998; Ferretti et al., 2005; MacFarling-Meure et al., 2006).

Section 3.3 Significance in the differences should be given. The same holds for every place where differences are discussed.

We have added significance on the differences plots. Also we have corrected it in Figure 5 (now Figure 4) since we have found a small error in the significance plotted.

4 Discussion Page 11, lines 18-19. It is accepted that the 11-year cycle effects project onto tropospheric circulation patterns like the Arctic Oscillation (AO) and the North Atlantic Oscillation (NAO) rather than are directly correlated to NAO or AO

We have reformulated the sentence to make it clear that we are not speaking about a direct correlation.

5. Conclusions page 14, lines 4-6. The present simulation and the forcings used (if indeed SSI variability and ozone related variability have not been used) do not allow the investigation of the top-down mechanism, which is in the heart of the weather type response..

SSI and the related ozone variability are included in the model.

References

Etheridge, D., Steele, L., Langenfelds, R., Francey, R., Barnola, J., and Morgan, V.: Natural and anthropogenic changes in atmospheric CO2 over the last 1000 years from air in Antarctic ice and firn, J. Geophys. Res., 101, 4115–4128, doi:10.1029/95JD03410, 1996.

Etheridge, D. M., Steele, L. P., Francey, R. J., and Langenfelds, R. L.: Atmospheric methane between 1000 A.D. and present: Evidence of anthropogenic emissions and climatic variability, J. Geophys. Res., 103, 15979–15993, doi:10.1029/98JD00923, 1998.

Ferretti, D. F., Miller, J. B., White, J. W. C., Etheridge, D. M., Lassey, K. R., Lowe, D. C., Meure, C. M. M. F., Dreier, M. F., Trudinger, C. M., Van Ommen, T. D., and Langenfelds, R. L.: Unexpected changes to the global methane budget over the past 2000 years, Science, 309, 1714–1717, doi:10.1126/science.1115193, 2005.

MacFarling-Meure, C., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R., Van Ommen, T., Smith, A., and Elkins, J.: Law Dome CO2, CH4 and N2O ice core records extended to 2000 years BP, Geophys. Res. Lett., 33, L14810, doi:10.1029/2006GL026152, 2006.

Schwander, M., Brönnimann, S., Delaygue. G., Rohrer. M., Auchmann, R., Brugnara, Y. Reconstruction of Central European daily weather types back to 1763. International Journal of Climatology. doi: 10.1002/joc.4974. 2017.

Weusthoff, T.: Weather Type Classification at MeteoSwiss - Introduction of new automatic classification schemes, Arbeitsberichte der MeteoSchweiz, (235), 46, 2011.

List of relevant changes made in the manuscript

The main correction oi the revised manuscript concerns the model simulations. We have realized that the description of the model (Section 2.6) was not clear so we have rewritten it to make it more understandable. In addition, we have reduced the part focusing on the model. The analysis of the low frequency of the solar activity does not add any relevant information to the paper since we focus on the 11-year solar cycle. We therefore only use the model with the 11-year cycle for the period 1958-1999 to compare with the reanalysis.

In the introduction, we have added some reference as suggested by both reviewers.

We have improved the description of the data and methods since some information was missing on the ERA-40 and ERA-Interim and on the model. We added some sentences to make the weather types description clearer.

The number of sub-periods for the histograms (Fig. 5) was reduced and we have added a figure focuses on the lags (Fig. 6) as suggested by one of the reviewers.

Significance have been added on difference plots (Fig. 4, 7 and 8).

A table was added with the size of each group (number of months) for the different periods analyzed (Table 2.).

The discussion was adapted and made clearer.

Most of the figures were computed again since there was a small error in the data (some volcanic years have not been removed). However, it has no impact on the discussion and conclusions of the paper.

Since we have decided not to focus on the low frequency, we have remove Fig. 4, 11 and 12 (from the first manuscript).

Influence of solar variability on the occurrence of Central European weather types from 1763 to 2009

Mikhaël Schwander[1,2], Marco Rohrer[1,2], Stefan Brönnimann[1,2], Abdul Malik[1,2]

[1]Institute of Geography, University of Bern, Bern, 3012, Switzerland
[2]Oeschger Centre for Climate Change Research, University of Bern, Bern, 3012, Switzerland

Correspondence to: Mikhaël Schwander (mikhael.schwander@giub.unibe.ch)

Abstract. The impact of solar variability on weather and climate in Central Europe is still not well understood. In this paper we use a new time series of daily weather types to analyse the influence of the 11-year solar cycle on the tropospheric weather of Central Europe. We employ a novel, daily weather type classification over the period 1763-2009 and investigate the occurrence frequency of weather types under low, moderate and high solar activity level. Results show a tendency towards fewer days with westerly and west south-westerly flow over Central Europe under low solar activity. In parallel, the occurrence of northerly and easterly types increases. ~~Changes are consistent across different sub-periods.~~ For the 1958-2009 period, a more detailed view can be gained from reanalysis data. Mean sea level pressure composites under low solar activity also show a reduced zonal flow, with an increase of the mean blocking frequency between Iceland and Scandinavia. Weather types and reanalysis data show that the 11-year solar cycle influences the late winter atmospheric circulation over Central Europe with colder (warmer) conditions under low (high) solar activity. Model simulations used for a comparison do not reproduce the imprint of the 11-year solar cycle found in the reanalyses data.

1. Introduction

The effects of solar activity changes on weather and climate in Europe are still not well understood. Although there is both empirical and model evidence of an imprint of the 11-yr sunspot cycle in the stratosphere, climate effects at the Earth's surface are less clear, nor are the mechanisms understood. Considering the rather small changes in the incoming energy over an 11-yr sunspot cycle of ca. 0.1% (and perhaps also over longer periods), many of the suggested mechanisms are indirect and involve changes in atmospheric circulation (Gray et al. 2010; Seppälä et al. 2014, for a review). Therefore, analysing changes in atmospheric circulation with regard to the 11-yr sunspot cycle ~~(and perhaps longer-term changes)~~ might help to better attribute climatic changes to solar forcing. In this paper we analyse the imprint in atmospheric circulation.

Solar activity can have effects on the atmospheric circulation through three different mechanisms. These effects may arise from direct changes in total solar irradiance (TSI), from changes in stratospheric ozone and heating induced by changes in solar UV, or from changes in stratospheric ozone induced by energetic particles, whose flux is modulated by solar activity. The ~1 Wm^{-2} variation in TSI over an 11-yr sunspot cycle corresponds to a change in the radiation forcing of about ~0.17 Wm^{-2} (Haigh 2003; Gray et al., 2010). This change in radiation forcing is estimated to cause a change in Earth's surface temperature of approximately 0.07 K and - with a lagged response - to changes in sea-surface temperatures (SSTs) (Gray et al., 2010; Stevens and North, 1996; White et al., 1997). Circulation effects (bottom-up mechanism) may arise from unequal heating or ocean feedbacks that might involve the North Atlantic (Thiéblemont et al., 2015). The increased UV radiation during sunspot maxima leads directly to an ozone increase and associated heating in the upper stratosphere (~40 km) (e.g., Matthes et al., 2004; Sitnov, 2009) and to changes in tropospheric circulation via downward propagation from the stratosphere (top-down mechanism). The suspected effects project strongly onto the North Atlantic European sector (Baldwin et al. 2001). The energetic particle flux (proton and electron), which is peaking in the declining phase of the sunspot cycle, leads to the production of NO_x in the mesosphere and stratosphere, which can destroy ozone in the stratosphere (Andersson et al., 2014; Päivärinta et al., 2013; Solomon et al., 1982). Through downward propagation, the troposphere can be affected, but a short phase lag is expected. Rozanov et al. (2012) showed that precipitating energetic particles can influence the chemical composition of the atmosphere as well as its dynamic down to the troposphere. The mechanisms might lead to different temporal (i.e., lagged or not) or spatial circulation changes, hence it is important to well characterise the circulation response of the 11-year solar cycle.

For all of the mechanisms, the response is expected to be pronounced over the North Atlantic European sector. In fact, many observation-based studies have found effects of the 11-year sunspot cycle in European weather and climate (e.g., Barriopedro et al., 2008; Brugnara et al., 2013; Huth et al., 2007; Ineson et al., 2011; Lockwood et al., 2010; Van Loon and Meehl, 2014). The impact of solar activity on variability modes such as the Atlantic Oscillation (AO) or the North Atlantic oscillation (NAO) is often investigated. The AO - which is correlated with the NAO - was shown to be influenced in his intensity and variability by the 11-year solar cycle (Huth et al., 2007). The NAO was found to be linked to the 11-year cycle with a positive (negative) pattern being associated to high (low) solar activity (e.g., Gimeno et al., 2003; Ineson et al., 2011; Lockwood, 2012; Sfîca et al., 2015; Woollings et al., 2010). Ineson et al. (2011) found a response~~d~~ to low solar activity in models which is similar to the negative NAO pattern. A similar pattern under low solar activity was found by Woollings et al. (2010). Brugnara et al. (2013) did not find a significant correlation between the solar activity and the NAO, although they found a reduced westerly flow over the North Atlantic under low solar activity. (Van Loon and Meehl, 2014) found that the NAO is enhanced when in phase with solar maxima, as when it is out of phase the NAO is negative. Thiéblemont et al. (2015) found that the solar activity influence project onto the NAO with the strongest signal visible ~~the NAO/solar activity coupling to be the strongest~~ with a 3-year lag. A similar lag was also found in Gray et al. (2013). Scaife et al. (2013) proposed a mechanism to explain this lag through the direct response to solar UV irradiance change and the effect of the Atlantic SST on the NAO. The ~~correlation~~ link between solar activity and the NAO is not supported by all studies. van Oldenborgh et al. (2013) found no statistically significant linear relation between the sunspot number and the NAO.

The North Atlantic circulation shows a response to the 11-year cycle, which leads to changes in the European weather that could only be visible on short time-scales. Atmospheric circulation over Europe is strongly correlated to the NAO and hence solar activity is thought to have an influence on weather conditions in Europe in winter. Studies show a preference of cold winters in Europe to be associated with minima in the 11-year solar cycle (e.g., Lockwood et al., 2010; Sirocko et al., 2012). Changes in the atmospheric circulation over the North Atlantic linked to solar activity might have an impact on European weather on short time-scale. For example Barriopedro et al. (2008) analysed the duration in days of blockings linked to solar activity. They found that North Atlantic blocking persistence increases under low solar activity and they are positioned more to the east.

Model simulations have also been used to investigate the solar activity impact on climate (see Gray et al., 2010 for a review)~~(see Gray et al., 2005 for a review)~~. Uncertainties are however still large concerning the response in the troposphere. Models can reproduce the main influence of the solar activity on the troposphere but some of them have difficulties to reproduce details. For instance, Gray et al. (2013) found a lag in the solar response over Europe and the North Atlantic in observation data which was not confirmed by model simulations. Gray et al. (2013) also concluded that there is no consensus between climate models on the influence of the 11-year solar cycle and the linked mechanisms. Matthes et al. (2003) compared the response of several global circulation models to the 11-year solar signal over Europe and the North Atlantic. One of their conclusions was that the late winter dynamical response in the model is not comparable to observations. More recently the solar signal was analysed in CMIP-5 simulations (Hood et al., 2015; Misios et al., 2016; Mitchell et al., 2015). For instance Mitchell et al. (2015) found a lag in the North Atlantic surface response to the 11-year solar cycle in the models but weaker than in the observations. Not all models reproduce a similar response to the 11-year solar cycle in the stratosphere compared to observations, but some of them do reproduce an increase of the polar night jet under high solar activity (Misios et al., 2016).

Others studies looked at the impact of solar activity on climate at longer time-scales. Martin-Puertas et al. (2012) used lake sediments to analyse variations in wind strength and the ^{10}Be accumulation rate for solar activity from 3300 to 2000 years before present. They found windy conditions in Western Europe during late winter under a long period of low solar activity. Moffa-Sánchez et al. (2014) used foraminifer shells to reconstruct the sea surface temperature and salinity of the North Atlantic over the past millennium. They found a correlation between centennial-scale variations in hydrography and total solar irradiance. On a shorter time-scale, Sirocko et al. (2012) analysed the occurrence of cold winters in Europe back to 1780 using documentary data. Sirocko et al. (2012) found cold winters in Europe to be often linked to the low activity phase of the 11-year solar cycle. The time resolution of these studies covering a long period is coarse (centennial-scale) or in the case of Sirocko et al. (2012) the method shows some weaknesses as explained in van Oldenborgh et al. (2013).

In this study, we analyse the influence of the 11-year solar cycle on Central European weather types. The aim is to identify how the variations in the mean atmospheric circulation over Europe can be explained by changes in the occurrence of weather types. For this we apply a similar approach as Huth et al. (2008b) by looking at the occurrence of weather types over Central Europe. There is a large panel of weather type classifications (WTCs) available for Europe based on various methods and covering different periods (Huth et al., 2008a; Philipp et al., 2010, 2014). Here we use a unique data set of daily weather types covering the period 1763-2009 (Schwander et al., 2017) ~~(Schwander et al., accepted)~~. It allows us for the first time to investigate the impact of the 11-year solar cycle on European climate with an analysis of weather statistics over almost 250 years. This analysis is performed by looking at changes in weather type occurrence as well as within-type changes. We complete this analysis by comparing changes in reanalyses data with model simulations.

This paper is structured as follow. The data and the methods used to analyse the solar activity influence on weather types, reanalysis data and model simulations are explained in Section 2. The results are presented in Section 3 and discussed in Section 4. We conclude this work in Section 5.

2. Data and Methods

For our analysis of the impact of 11-year solar cycle, we first computed the mean differences between low and high solar activity for the sea level pressure (slp), 500 hPa geopotential height (z500), 850 hPa temperature (t850) and blocking frequency for the period 1958-2009 for January to March (JFM). For this, we used the ERA-40 (from January 1958 to March 2002, Uppala et al., 2005) and ERA-Interim (from January 2003 to March 2009, Dee et al., 2011) reanalyses data set (same method as in Section 2.5) and the monthly sunspot number as a measure of solar activity (Section 2.1). A two-tailed Student’s t test was used to determine the 95~~9~~% probabilities that the low and high solar activity composites are from two different populations. Then we extended the analysis by using weather types (Section 2.2) with focus and the occurrence changes (Section 2.3) and within-type differences (Section 2.4). The method for the blocking frequency used in the differences composites is described in Section 2.5. Finally, the mean differences computed from reanalyses were compared with model simulations (Section 2.6).

2.1 Solar activity

The monthly sunspot number is used as a measure of the 11-year solar cycle (Fig. 1). It is the longest record of solar variability available; daily sunspots data are available starting from 1818 but monthly or yearly data go back to 1700. Sunspots correspond to zones of strong magnetic field; therefore, many visible sunspots are synonym of an active sun as the quiet sun is free of any spot. The sunspots time series captures well the 11-year solar cycle and can therefore be used as a proxy for quantifying solar activity. ~~However, one limitation is that the sunspot number cannot be negative. The sun’s activity might still vary even if no sunspots are visible; all sunspots minimum are not necessarily of the same TSI level (see Fig. 4).~~ The sunspots data were retrieved from the Sunspot Index and Long-term Solar Observations (SILSO) and World Data Center for the production, preservation and dissemination of the international Sunspot Number website from the Royal Observatory of Belgium. We use the revised data series available since the 1st of July 2015. ~~Additionally to the Sunspot Number, we also used a TSI reconstruction from Shapiro et al. (2011). This reconstruction was used as forcing in the four model simulations used in this study (see Section 2.6).~~

2.2 Weather type classification

Weather types are used to determine if the circulation differences observed in reanalyses are only due to changes in the mean circulation or if they result from a change in the occurrences of weather patterns. Weather types are a summary of recurrent dynamical patterns over a specification region, in our case Central Europe and the Alpine Region. For this, we use the CAP7 (cluster analysis of principal components) WTC (Schwander et al., 2017)~~(Schwander et al., accepted)~~. CAP7 is a daily time series of weather types representing the mean atmospheric circulation in the Alpine Region and Central Europe over the period 1763-2009. This classification is a reconstruction of the CAP9 classification used by the Federal Office of Meteorology and Climatology MeteoSwiss (Weusthoff, 2011). CAP9 starts in 1957 and is updated to the present. The weather types were computed with the ERA-40 and ERA-Interim reanalyses dataset. For CAP7, CAP9 was used as referenced from 1958 to 1998 and was reconstructed back to 1763 using early instrumental data from European weather stations. The classification was reduced to 7 types (hence CAP7) by combining similar, not well discriminated types. Although CAP9 was originally computed for the Alpine Region and contains a limited number of patterns, it – as well as CAP7 – captures the main circulation patterns over Europe and the North Atlantic. The 7 types with their names and abbreviations are presented in Table 1. The weather types can be used to analyse changes in the frequency of occurrences (between-type changes, Section 2.3) from 1763 to 2009 and to investigate changes in their composite (within-type changes, Section 2.4) with reanalysis data from 1958 to 2009. The mean frequency of occurrence of each type for ~~January to March~~ ~~(~~JFM~~)~~ over the period 1763 to 2009 is shown in Fig. 2~~1~~. The z500 and slp composites for 1958-2009 computed with ERA-40 (1958-2002)~~/~~ and ERA-Interim (2003-2009) for JFM are shown in Fig. 3~~2~~. The classification contains three continental types (NE, E and N), two westerly types (WSW and W), one cyclonic type (WC), and one anticyclonic type (HP). CAP7 is the only objective times series of daily weather types which covers almost 250 years in Europe. It also covers a longer period than any existing reanalysis (from which weather types can also be computed). For more information on the method of reconstruction, see Schwander et al. (2017)~~Schwander et al. (accepted)~~. The daily weather types CAP7 are completed with a probability value of each day being correctly classified (relative to the reference classification). Since CAP7 is a reconstruction and cannot be compared to any other WTC back to 1763, this probability value provides an indication on the reliability of the classification for each day. This allows us later to omit days with a probability lower than a certain threshold (e.g. 75%).

2.3 Weather type occurrences

The following method is similar to the procedure applied in Huth et al. (2008b) but the CAP7 dataset used here covers a longer period of time. A comparison with Huth et al. (2008b) can however be done over the second part of the 20th century. To capture the influence of the sun on weather patterns, changes in the frequency of occurrence of the CAP7 weather types relative to variations in solar activity are analysed. It was shown that the strongest influence of solar activity on the low troposphere is visible during the late winter months because of the delayed propagation of the signal from the stratosphere to the troposphere (Ineson et al., 2011). Thus, the weather type analysis as well as reanalyses and model simulations analyses are performed on months of JFM. The sunspot number data was first divided in three categories, low, moderate and high solar activity using the 33rd and 66th percentile as thresholds (see Fig. 1). This method assumes that all solar minima reach a similar low intensity as the number of sunspot cannot go below zero. The daily weather types were then classified to the corresponding solar activity level. For each weather type we computed the ratios of the frequency for each solar activity level (low, moderate, high) relative to the long-term mean. Results are calculated for the period January 1763 to March 2009 as well as for ~~five~~ three sub-periods: 1763-1886, 1887-2009, and 1958-2009 (period of reanalysis data) for a comparison with Huth et al. (2008b). ~~of approximately 50 years in length.~~ We removed 3 years following large volcanic eruptions as they can have a significant influence on climate (e.g., Robock, 2000). The three groups of solar activity are therefore of different sizes (see Table 2). The list of volcanic eruption was taken from Arfeuille et al. (2014). A resampling method was used to test the significance of the ratios The weather type series (for each period) was resampled 10000 times. The computed ratio is considered as significant when below (above) the 250th (9750th) value of the resample elements. Another series of histogram (not shown) was computed using only days ~~weather types~~ having a probability (to be correctly classified) superior to 75%. We also computed the ratios with a 1, 2 and 3-year lag for the 1763-2009 period.

2.4 Within-type differences

In addition to the change in the weather types occurrences, we investigate the within-type difference of atmospheric fields between low and high solar activity levels for each of the 7 weather types. For this, we computed composites for each weather type in order to identify changes in their mean circulation pattern over Europe and the North Atlantic under low and high solar activity. Composites of slp, z500 and t850 of each type were computed for the previously defined high and low solar activity classes for the period 1958-2009 (JFM). Additionally to these parameters, the mean blocking frequency was also computed for each composite (see Section 2.5). From these composites, differences were calculated by subtracting the high activity from the low activity composites. ERA-40 (January 1958-March~~August~~ 2002) and ERA-Interim (~~September~~ January 2003~~2~~-March 2009) were used as the original CAP types were computed based on the ERA-40 and ERA-Interim mean slp field. The reanalysis data were remapped to 1° x 1° to be combined. The within-types analysis can therefore only be made over the period 1958-2009 and cannot be extrapolated back to 1763.

2.5 Blocking Frequency

Blockings are defined as reversal of the meridional geopotential height gradient at 500 hPa. We follow the approach of Tibaldi and Molteni (1990) and extended the blocking algorithm to find blockings in a two dimensional field following the procedure of Scherrer et al. (2006). The algorithm flags a certain longitude and latitude as blocked, if two criteria are fulfilled:

1. GPH gradient towards the pole

$$GPHG_P = Z500(\varphi + 14) - \frac{Z500(\varphi)}{\varphi+14-\varphi} < -10\,\frac{\text{gpm}}{°\text{lat}} \quad (1)$$

2. GPH gradient towards the equator

$$GPHG_E = Z500(\varphi) - \frac{Z500(\varphi-14)}{\varphi-\varphi-14} > 0\,\frac{\text{gpm}}{°\text{lat}} \quad (2)$$

The latitude φ varies from 36° to 76° in 2° intervals. ERA-40 data is bilinearly interpolated to a 2°x2° before computation. Only blockings with a minimum lifetime of 5 days and spatial overlap larger than 70% between each time step are considered here.

2.6 Model simulations

~~In the last part of this paper, we used model simulations to complete the previous analysis on the mean differences between low and high solar activity. The SOCOL-MPIOM model (Muthers et al., 2014) was used for this analysis. The SOCOL (Solar Climate Ozone Links) chemistry-climate model is coupled to the ocean-sea-ice model MPIOM. SOCOL is based on the middle atmosphere model MA-ECHAM5 version 5.4.01 (Roeckner et al., 2003) and a modified version of the chemistry model MEZON (Model for Evaluation of oZONe trends, Egorova et al., 2003). Several major external forcings were applied in the transient simulations. It includes radiative forcing from major greenhouse gases (CO2, CH4, N2O and CFCs). The volcanic forcing is computed as global annual mean aerosol optical depth in the visible band. The TSI was calculated from the SSI reconstruction of Shapiro et al. (2011). In addition, the upper envelope of the uncertainty range was taken as moderate solar activity (smaller amplitude forcing) in the simulation. This reconstruction differs from previous ones (Schmidt et al., 2012) because of its larger amplitude. It has the advantage to be a predominant forcing in the model with visible impacts in the simulations. The Sunspot Number is one of the proxies used in this reconstruction. In addition to the impact of the high frequency (11-year cycle), we can use the model also to look at effects of low frequency solar activity (prolonged periods of low and high solar activity) by comparing simulations in which only the low-frequency component of the solar forcing changed. The results can then be compared back to those obtained from reanalysis data. We want to see of the model reproduce similar changes in the tropospheric weather in Europe (slp and t850) linked to the 11-year cycle. Also we can compare the impact of the 11-year cycle (Fig. 3) to the impact of the low frequency of the solar activity (i.e. grand minimum, Fig. 4). For more information on the SOCOL-MPIOM model see Muthers et al. (2014).~~

In the last part of this paper we have employed the Coupled Atmosphere-Ocean-Chemistry Climate Model (AOCCM) simulations carried out with SOCOL-MPIOM (see, Muthers et al. 2014). The SOCOL (Solar Climate Ozone Links) chemistry-climate model is coupled to the ocean-sea-ice model MPIOM. The SOCOL is based on the middle atmosphere model MA-ECHAM5 version 5.4.01 (Roeckner et al., 2003) and a modified version of the chemistry model MEZON (Model for Evaluation of oZONe trends, Egorova et al., 2003). The model has a horizontal resolution of T31 (3.75° × 3.75°) with 39 irregular vertical pressure levels (L39) from 1000 hPa to 0.01 hPa. The horizontal resolution of the ocean component

(MPIOM) is 3° varying between Greenland (22 km) and tropical Pacific (350 km). The SOCOL-MPIOM cannot reproduce the Quasi-Biennial-Oscillation (QBO), thus nudged to QBO reconstruction from Brönniman et al. (2007). The MA-ECHAM5 (MPIOM) component calculates the dynamical processes in every 15 (144) minutes and atmosphere-ocean coupling takes place in every 24 hours (Anet et al. 2013a, b; Muthers et al. 2014). Muthers et al. 2014 employed SOCOL-MPIOM to carry out four transient simulations (namely L1, L2, M1, and M2) over the period AD 1600-1999 with all major forcings (i.e. greenhouse gases, volcanic eruptions, aerosols, and solar spectral irradiance), and interactive ozone chemistry. The SOCOL-MPIOM was forced with six bands of Solar Spectral Irradiance (SSI) reconstruction of Shapiro et al. (2011) over the Ultraviolet (UV), visible, and near infrared ranges. The L1 (M1) and L2 (M2) simulations were forced with large (small) mean solar amplitude of 6 (3) W/m2 with different ocean initial conditions for both runs. For more details of the model the reader is referred to Muthers et al. 2014. The model is well capable of simulating the top-down (stratospheric-tropospheric coupling) and bottom-up (coupled ocean-atmosphere response) mechanisms as proposed by Meehl et al. (2009). For more information on the SOCOL-MPIOM model see Muthers et al. (2014).

We used the four model simulations (M1, M2, L1 and L2) and ~~covering the period 1600-1999, two with a large solar activity amplitude (L1 and L2, different initial conditions, Shapiro reconstruction) and two with a moderate amplitude (M1 and M2, different initial conditions) which correspond to the upper bound of the Shapiro reconstruction uncertainty. For the analysis, we~~ removed again 3 years following large volcanic eruptions (Arfeuille et al., 2014). ~~Note that many of the important eruptions occur during a solar minimum.~~ The 11-year solar cycle was analysed similarly as for the weather types (33rd and 66th percentile thresholds of the sunspot number) since the sunspot number was used in the Shapiro et al. (2011) reconstruction. The period 1958-1999 was selected ~~Two periods were selected, 1958-1999 –~~ for comparison with the reanalysis data (1958-2009). ~~– and 1763-1999~~. ~~The low frequency solar activity (Shapiro, Fig. 4) was again divided again using the 33rd and 66th percentile threshold (with respect to the period 1600-1999).~~ High and low solar activity composites were computed for slp and t850, and the low minus high activity difference was calculated. TSI forcing is correlated with the anthropogenic forcing (carbon dioxide - CO2, methane - CH4, nitrogen dioxide - N2O and chlorofluorocarbons CFCs) with an increase over the 19th and 20th century. These anthropogenic forcings were taken from the PMIP3 database (Etheridge et al., 1996, 1998; Ferretti et al., 2005; MacFarling-Meure et al., 2006). Both forcings (solar and anthropogenic) reach their highest values at the end of the 20th century (see Muthers et al., 2014). We removed the anthropogenic forcing by applying a linear regression:

$$y_i = \alpha + \beta x_i + \varepsilon \tag{3}$$

where y is the predicted value and x the predictor (radiative forcing, CO2, CH4, N2O and CFCs), α the intercept, β the regression coefficient and ε the residual.

3. Results

3.1 Mean difference

The differences computed between low and high solar activity with ERA-40 and ERA-Interim for 1958-2009 (Fig. 4~~5~~) show a reduced zonal flow over Europe under low solar activity relative to high activity. The slp is higher between Iceland and Scandinavia, and lower over Southern Europe and the Mediterranean Sea. The z500 differences have a similar pattern but with higher values which extend more to the west over Greenland. The blocking frequency is also higher over this region under low solar activity especially between Iceland, the northern British Isles and western Scandinavia where it is significant on the 95% level. The higher values extend also to the south-western part of Europe. The t850 is reduced over most of the European continent and North Africa, and higher between Greenland, the northern British Isles and Scandinavia.

3.2 Solar signal in the occurrence of the weather types

The frequencies of occurrence of CAP7 weather types for different solar activity levels for JFM are shown in Fig. 5~~6~~. The size of the groups (number of months) is displayed in Table 2. The histograms display the ratios computed between the low, moderate and high solar activity frequencies and the long-term mean frequency. Histograms (a) and (b) correspond to a 123 and 122-year period (1763-1886 and 1887-2009). ~~Histograms (a) to (e) correspond each approximately to a 50-year period (1763-1807, 1808-1857, 1858-1907, 1908-1957, 1958-2009) and histogram (f) to the whole time series (1763-2009).~~ Histogram (c~~e~~) (1958-2009) correspond to the reanalysis period and roughly to the period (1950-2002) analysed in (Huth et al., 2008b). Histogram (d) shows the whole period (1763-2009). For these last 50 years (c), the Northerly (N), North-Easterly (NE) and Easterly (E)~~Westerly flow over Southern Europe (WC)~~ types have the highest ratios under low solar activity but only the Northerly type ratio is significantly different from 1. At the same time, the West South-Westerly (WSW) and High Pressure (HP) types have the lowest ratios (significant for HP) ~~(non-significant)~~. Under high solar activity, the Easterly (E) and Northerly (N) types have a ratio ~~significantly~~ lower than 1 (significant for N). Under medium activity, no ratio is significantly different than 1.

For the other sub-periods of time (a) and (b) ~~(sub-periods (a) to (e))~~ the ratios do not all show a similar signal~~have a large variability in-between them~~. For example, ~~in none of them~~ the Northerly (N) type ratio is slightly lower than 1 for the sub-period (a) but higher than 1 for sub-period (b) under low solar activity.~~significantly higher than 1~~. This kind of variability is visible in most of the weather types. Another example is the High Pressure (HP) type with a ratio significantly higher (lower) than 1 under low (moderate) solar activity in sub-period (a) but no signal in sub-period (b).~~the North-Easterly (NE) type under low solar activity where the ratio is lower (higher) than 1 in sub-periods (b) and (c) ((a) and (d))~~. ~~There are only two~~ Some weather types ~~which~~ have~~s~~ ~~stable ratios over time~~similar ratios in both (a) and (b). For example, ~~U~~under low solar activity the Westerly (W) and West South-Westerly (WSW) types ratios are lower than 1~~ in four of the five sub-periods~~.

Although it can be difficult to deduce a general structure (similar ratios under the same solar activity level) in the weather types occurrences between the different sub-periods (a),~~ to~~ (b~~e~~) and (c), there are some significant changes in the mean occurrence of some of the types over the whole time series (1763-2009, (d~~f~~)). Under low solar activity, we observe significantly lower ratios of West South-Westerly (WSW) and Westerly (W) types, and significant higher ratios of ~~High Pressure~~Easterly (E~~HP~~) type. Under moderate and high solar activity the higher ~~West South-Westerly (WSW) and~~ Westerly (W) type~~s~~ ratios are significant~~, as well as the lower High Pressure (HP) type ratio~~. Under moderate solar activity the Easterly (E) and High Pressure (HP) types ratios are significantly lower than 1 as well as for the Northerly (N) type under high solar activity. ~~Finally, under high solar activity the higher Westerly (W) type ratio and is significant.~~

Ratios ~~in Fig. 7 were~~ computed only with days with a probability (to be correctly classified) higher than 75% (not shown), allowing us to omit some potentially erroneous weather type data, show similar results as in Fig. 5. The potential misclassified days have therefore no significant impact on our results.~~ Again there is a large variability in-between the different sub-periods. Over the period 1763-2009, minor changes appear compared to Fig. 6. The higher ratio in the Easterly type (E) under low solar activity is significant. Under moderate solar the higher West South-Westerly (WSW) type ratio is not significant. Hence the ratio for the same type (WSW) is higher than 1 (but not significant) under high solar activity~~.

~~The sub-period (a) (1763-1807) shows some of the largest differences between the three solar activity classes (Figs. 6 and 7). The sub-period 1763-1807 is shorter than all other ones and therefore contains fewer days (especially for Fig. 6). It is also the period in which the weather types' reliability is the lowest.~~

The decrease in the occurrence of the Westerly type (W) is also visible with a 1, 2 and 3-year lag (Fig. 6~~not shown~~), as for the West South-Westerly (WSW) it is only visible with a 1 year lag. The increase in the occurrence of these two types under high solar activity is visible with a 1 and 2-year lag but disappear with a 3-year lag. It is even significant for the 2-year lag. The signal found in the Northerly ~~type~~ (N) and Easterly (E) types is inverted with a 2 and 3-year lag with a reduction ~~(increase)~~ in the occurrence under low ~~(high)~~ solar activity. The increase in the occurrence of the High Pressure type (HP) type under low solar activity is the strongest with a 3 year lag.

The main occurrence differences for the period 1763-2009 can be summarised as follows: The occurrence of Westerly and West-South Westerly types decreases significantly under low solar activity~~ relative to high activity~~. At the same time, we observe a significant higher occurrence of~~ High Pressure, Northerly and~~ Easterly type~~s~~. The occurrences of the Westerly type increases significantly under moderate and high solar activity. The occurrence of the Easterly and High Pressure (Northerly) types is significantly lower under moderate (high) solar activity.~~under moderate activity are similar to those observed under high activity. The number of days with a Westerly and West-South Westerly (High Pressure and Easterly) type increases (decreases).~~

3.3 Solar signal in weather types – within-type differences

The inter-type analysis is completed with a within-type analysis of their composites (Fig. 7~~8~~ & 8~~9~~). Difference composites were computed by subtracting the high from the low solar activity class composites. They were computed for the period 1958-2009 with ERA-40/-Interim and are therefore not representative of the whole 1763-2009 period. Fig. 7~~8~~ displays the z500 and blocking frequency differences. Fig. 8~~9~~ displays the slp and t850 differences. The weather types were originally computed with the slp over the Alpine region; thus the smallest slp differences are expected to be observed over this region. However, differences appear in the position and intensity of the high and low pressure centres, this can influence the general flow and thus the temperatures over Europe and the Alpine region.

With Fig. 7~~8~~ and 8~~9~~ we can identify the influence of the solar activity on each weather type and from this try to deduce a general influence on the tropospheric weather over Europe. The following descriptions always refer to the low solar activity class composite relative to the high activity one. The mean JFM weather types slp and z500 composites are shown in Fig. 3~~2~~.

1 (NE): The low pressure system south of Greenland extends more to the south and less from Iceland to Scandinavia. The anticyclone is weaker over Western Europe but extends more towards Scandinavia. The low pressure system over Italy is slightly deeper. The blocking frequency is higher from Greenland to Scandinavia but lower further south over the Atlantic. These changes in the pressure pattern lead to lower temperature over the whole European continent.

2 (WSW): The low pressure system located between Iceland and Scotland is less pronounced over Northern Europe. The mean z500 is higher between the British Isles and Scandinavia, and lower over Eastern Europe and the Mediterranean. The same pattern is visible in the temperature differences. Small differences in the blockings with higher frequencies over Scandinavia are also visible

3 (W): The pressure over Iceland is reduced whereas the Azores anticyclone is more pronounced over the Atlantic, the pressure gradient is tighter. The pressure is higher over Scandinavia and the anticyclone is more present over Southern Europe with a higher blocking frequency. Temperatures are therefore lower over most parts of Europe.

4 (E): The pressure is higher between Greenland and Scandinavia as well as the blocking frequency. The anticyclone extends more over Europe and the pressure is lower over the Mediterranean Sea. The temperature is reduced over all Europe except Scandinavia.

5 (HP): The pressure and z500 are higher over most of the North Atlantic and Northern Europe, whereas lower over Southern Europe and Northern Africa. The blocking frequency is higher over all Europe. The temperature is reduced over Europe especially in the eastern part.

6 (N): The pressure and z500 are higher over Scandinavia and lower over the Western Mediterranean Sea and Eastern Atlantic. The flow is more oriented north-easterly than north-westerly over Central Europe with reduced temperature.

7 (WC): The Azores anticyclone is more pronounced and the low pressure system between the British Isles and Scandinavia is weaker but extend more towards the Mediterranean Sea. The temperatures are reduced over South-Eastern Europe and Northern Africa, whereas warmer over North-Eastern Europe.

Similar patterns can be observed among the weather types. Types 1 (NE), 4 (E) and 6 (N) all have an enhanced easterly flow over central Europe under low solar activity and thus lower temperatures, All three types also have more frequent Scandinavian Blockings. Types 2 (WSW) and 3 (W) have a slightly reduced westerly flow over Central Europe. On average (ALL on Figs. 7~~8~~ & 8~~9~~, also Fig. 4~~7~~) we see a higher pressure between Iceland and Scandinavia, and lower pressure over the Mediterranean Sea under low solar activity. The blocking frequency is higher between Iceland and Scandinavia too. This leads to a weaker pressure gradient and westerly flow over Europe. Following this reduction in the zonal flow, temperatures tend to be lower over Europe (except Scandinavia). Outside Europe we note an increase in temperature over the high latitude in all cases especially around Greenland.

3.4 Solar signal in model simulations

The model simulations are used to complete the analysis of the weather types and the reanalysis data. The differences between low and high solar activity obtained by four simulations (M1, M2, L1, L2) for the period 1958-1999 are displayed in Fig. 9. ~~10, 11 and 12. In Fig. 10 and 11 t~~The low and high solar activity classes corresponds again to the 11-year solar cycle (Fig. 1~~3~~). ~~In Fig. 12 the classes correspond to extended periods of weak and strong activity (Fig. 4). M1 and M2 are the simulations with a moderate solar activity amplitude whereas L1 and L2 correspond to the simulations with a large amplitude (Fig. 3). Again the high solar activity is subtracted from the low activity and the slp and t850 differences are shown.~~

The difference plots in Fig. ~~10~~ 9 should be comparable to Fig. 4~~5~~ as well as the “ALL” plot in Fig. 7~~9~~. However, none of the four simulations display a similar difference pattern as the reanalysis data. There is a lower pressure over the North Atlantic (M1), Scandinavia (L1), and Eastern Atlantic/Western Europe (L2) under low solar activity, whereas M2 shows a higher pressure and temperature over Europe. Only M1 have extended lower temperature over Europe, but the slp differences do not fit with the reanalyses data.

~~Over the period 1763-2000 (Fig. 11) the differences between low and high solar activity are similar but less pronounced as in Fig. 10. One exception is the L1 simulation which has a higher pressure over Scandinavia under low solar activity. Lower temperatures over Eastern Europe can also be seen. This pattern resembles that the mean slp difference in the reanalyses (Fig. 5 and “ALL” in Fig. 9).~~

~~In Fig. 12 (low frequency solar influence), all four simulations have a similar pattern of differences. M1 shows higher pressure values between Iceland and Scandinavia. The pressure is reduced over the Atlantic between 25° N and 50° N. M2 is similar with a pattern shifted to the north-west with positive differences extending more towards Greenland and negative~~

~~differences covering part of Europe. L1 is similar to M2 over the Atlantic and Western Europe with larger values. Finally L2 is very similar to M1 with positive values between Greenland and Europe and slightly negative values over the Atlantic. M1 and L2 have a similar slp pattern as found in the reanalyses data (Fig. 5 and ALL in Fig. 9). 850 hPa temperatures are cooler under low solar activity over all Europe except around the Iberian Peninsula. We see also that this reduced westerly flow has consequent cooler temperature over Europe. The reduction in temperature is probably a combination between changes in circulation and reduced solar radiations.~~

4. Discussion

The reduced zonal flow and colder temperatures over Europe under low solar activity (Fig. 4) are consistent with other studies (e.g., Brugnara et al., 2013; Ineson et al., 2011; Sfîca et al., 2015; Sirocko et al., 2012; Woollings et al., 2010). The differences over Europe resembles a more negative (positive) NAO pattern under low (high) solar activity. This kind of pattern was ~~suggested~~ found in several studies (e.g., Ineson et al., 2011; Sfîca et al., 2015; Thiéblemont et al., 2015). As suggested in Thiéblemont et al. (2015) there is no direct correlation between solar activity and the NAO but a synchronisation following the downward propagation of the solar signal from the stratosphere to the troposphere. However, our results over the North Atlantic correspond more to a positive NAO under low solar activity relative to high activity with a lower slp south of Greenland and a stronger Azores high pressure system. So it seems that the 11-year cycle does not directly modulate the NAO but projects ~~shows~~ more onto~~a~~ west-east pattern between the Labrador Sea and Western Russia. Other studies corroborate this pattern with a solar signal extending toward Eurasia (Brugnara et al., 2013; Woollings et al., 2010). For Brugnara et al. (2013) the Eurasian index is more linked to the 11-year cycle than the NAO. The differences in the blocking~~s~~ index confirm the reduced zonal flow under low solar activity with a higher blocking frequency over the Norwegian Sea and Scandinavia. Similarly, Barriopedro et al. (2008) found an increase in the blocking frequency over the Eastern Atlantic under low solar activity. They also found that Atlantic blockings are located further east under low solar activity which corresponds to our result with a higher blocking frequency towards the east of the Atlantic. ~~They also found an increase in the blocking frequency under high solar activity over the Western Atlantic which we did not find in our results.~~

The differences in weather type occurrences over the period 1958-2009 (Fig. 5 (c)) correspond well ~~with~~ to the results of Huth et al. (2008b). It is especially the case for the West South-Westerly type with a decrease in ~~their~~ its occurrence under low solar activity. The Northerly type shows also the same pattern ~~in Fig. 4 and 5~~ as in Huth et al. (2008b) with an increase (decrease) in the occurrence under low (high) solar activity. The differences in these two types (WSW and N) are also confirmed in the long-term ~~(1763-2009)~~ differences in our results (1763-2009, Fig. 5 (d)). Under low (high) solar activity the frequency of occurrence of Westerly and West-South Westerly types decreases (increases). This consecutively results in an increase in the frequency of Easterly, ~~and~~ High Pressure and Northerly types under low solar activity. The reduction (increase) in the occurrence of Westerly and West South-Westerly (Easterly) types is the largest difference in the ratios between one solar activity class and the long-term mean that we observe and is visible over ~~almost all the shorter periods of time~~both sub-periods (1763-1886 and 1887-2009). ~~There is however a large variability in the variations in the occurrences.~~ However, c~~C~~ertain types (e.g. North-Easterly) do not have the same signal under both sub-periods ~~show a large variability in their occurrence across time and no mean pattern can be identified over the whole period analysed~~. These types could be more sensitive to internal variability or to the influence of others forcings. As a counterexample it is interesting to see that in ~~almost all cases~~both sub-periods we observe a decrease in the occurrence of the Westerly type under low solar activity but it is not the case for the 1958-2009 period. This persistence of this signal over time supports the hypothesis that the 11-year solar cycle has an influence on the occurrence of European weather types.

A reduction (increase) in the occurrence of westerly types under low (high) solar activity as well as an increase in the occurrence of easterly types under low activity (Fig. 5) leads to a decrease (increase) in temperature observed in Fig. 4. ~~In addition, t~~These changes in the occurrence ~~pattern~~ of weather types ~~occurrences~~ are consistent with a weaker (stronger) zonal flow over the North Atlantic and Europe, and a negative (positive) NAO-like phase pattern under low (high) solar activity as it was suggested in several studies (e.g., Ineson et al., 2011; Sfîca et al., 2015).

A lagged response of the NAO following a solar maximum was suggested in Gray et al. (2013) and Thiéblemont et al. (2015). Our results with a 1 and 2-year lag (Fig. 6) showing a higher occurrence of westerly types under high solar activity also support the hypothesis of a delayed signal. However, we do not observe any signal with 3-year lag (Fig. 6 (c)) under high solar activity. Under low solar activity the weather types occurrences are similar at with no lag and a 1 year (reduction in ~~w~~Westerly and ~~w~~West ~~s~~South-~~w~~Westerly types, slight increase in ~~e~~Easterly~~,~~ ~~northerly~~ and ~~h~~High ~~p~~Pressure types~~.~~). The signal found in the Northerly type with no lag is inverted with a 2 and 3-year lag (reduction in the occurrence under low solar activity). ~~Although for the westerly and high pressure types the signal is still visible with a 2 and 3 years lag, it gets inverted for the westerly, northerly and high pressure types~~ However, our results do not support previous findings suggesting that the strongest solar signal over Europe is visible with a lag.

The mesoscale circulation variations can explain the changes in the frequency of occurrence of the Easterly and Westerly weather patterns over Central Europe. A weaker zonal flow as seen in Fig. 4 leads to a reduction of the occurrences of westerly types and thus to an increase in the occurrence of easterly types (continental flow). These pattern changes are also consistent with a higher blocking index over Scandinavia under low solar activity. Blockings over high European latitudes are often responsible for the establishment of an easterly flow over Central Europe. We also observe – from 1958 to 2009 – not only a change in the weather types occurrences but also on the slp patterns of each weather type (Fig. 7 and 8). For the Westerly and West South-Westerly types we observe a reduction in the slp between Greenland and Iceland under low solar activity. Similarly to the mean difference (no weather type discrimination, Fig. 4), it resembles more to a positive NAO phase which is in contradiction with previous studies (e.g., Ineson et al., 2011; Thiéblemont et al., 2015). However, further east (toward Scandinavia) the pressure is higher under low solar activity which is synonym of a reduced oceanic flow over Central Europe and lower temperatures. So it seems that the 11-year cycle does not directly modulate the NAO but shows more a west-east pattern between the Labrador Sea and Western Russia. As mentioned above, other studies corroborate this pattern with a solar signal extending toward Eurasia (Brugnara et al., 2013; Woollings et al., 2010).

As mentioned above, an increase in slp and blockings over Scandinavia as well as a decrease in slp over the Mediterranean Sea are synonym of an enhanced continental flow over Central Europe. We notice a double effect with an increase in the occurrence of Easterly and Northerly types (inter-type) under low solar activity but also a stronger mean easterly flow based on their composites for the period 1958-2009 (within-type). The same holds for Westerly and West South-Westerly types, which are less frequent and the associated zonal flow to these patterns is also slightly weaker over Central Europe. The stronger (weaker) continental (zonal) flow under low solar activity brings cold air from the Eurasian continent and diminishes the influence of the warm oceanic air over Central Europe. Following these circulations changes we estimate that there is a higher (lower) probability to have cold winter during the weak (strong) phase of the 11-year solar cycle. Other studies (Lockwood et al., 2010; Sirocko et al., 2012) found similar results with cold European winters being often linked to weak solar activity.

The comparison with model simulations does not ~~(or only partially)~~ confirm our observation-based results on the mean slp over the North Atlantic and Europe. The response of the slp and t850 to the 11-year solar cycle does not display any clear pattern, each simulation having a different response. Although the model is forced with six bands of SSI, there is no agreement in-between the four simulations on a solar signal on the surface pressure over Europe. The low amplitude of the 11-year cycle in the Shapiro reconstruction (compared to the large amplitude of the low frequency activity) ~~TSI~~ combined with the relatively coarse resolution of the model could explain the difficulty of the model to capture changes over a specific region. ~~Also, during phases of grand minima the 11-year cycle almost vanishes. Even if the 11-year solar cycle is visible after 1958, the simulations do not show any signal in slp similar to the reanalysis data. The differences between grand minima and maxima (low frequency) are closer the reanalysis data (high frequency, 11-year cycle differences). The model captures well the general cooling linked to the reduced solar forcing but also displays slp differences which are similar to ERA-40/-Interim with higher slp over the North Atlantic/Scandinavia and therefore a weaker zonal flow under low solar activity.~~

5. Conclusion

We have used a new weather types classification to analyse the impact of the 11-year solar cycle on European weather in late winter. The monthly sunspot number was used as a measure of solar activity and the daily weather types were retrieved from the CAP7 classification. We have analysed changes in the frequency of occurrence of the CAP7 weather types under three different solar activity levels (low, moderate, high) from 1763 to 2009 and analysed as well ~~as~~ the within-type differences between low and high solar activity from 1958 to 2009 in reanalyses data. The mean difference in the sea level pressure and 850 hPa temperature was then compared with four model simulations.

The strongest solar signal visible in the occurrence of the CAP7 weather types is a reduction in the number of days with westerly and west south-westerly flow under low solar activity. Consequently, ~~we observe an increase in~~in the number of days with a northerly, easterly flow and high pressure increases. Conversely, the occurrence of both westerly and west south-westerly types increases under moderate and high solar activity. The analysis of within-type differences under low and high solar activity phases confirms that ~~N~~not only the frequency of occurrence of some weather types respond to change in the solar activity, but also the mean patterns of these types are slightly different. The zonal flow characteristic of westerly types is reduced under low solar activity as the continental flow for easterly and northerly types is enhanced. ~~We observe on average a weaker zonal flow over Europe under low solar activity for westerly types and a stronger continental flow for easterly, north-easterly and northerly types.~~ This is also confirmed by the higher blocking frequency over Scandinavia under low solar activity. The sea level pressure differences observed in the reanalysis data are not supported by the SOCOL-MPIOM model simulations. ~~But we estimate that the SOCOL-MPIOM~~The coarse resolution of the model is not ~~ideal~~ suited for an analysis of the 11-year solar cycle impact on tropospheric weather. ~~However, we suggest that the differences between prolonged period of low and high solar activity are similar to the 11-year response.~~

The 247-year long analysis of the 11-year solar cycle impact on late winter European weather patterns suggest a reduction in the occurrence of westerly flow types linked to a reduced mean zonal flow under low solar activity. Following these observation, we estimate the probability to have cold conditions in winter over Europe to be higher under low solar activity than under high activity. ~~Also similar conditions can occur during periods of prolonged reduced total solar irradiance.~~

Acknowledgments. This work was funded by the Swiss National Science Foundation through the Sinergia FUPSOL II (Number 147659). We thank ECMWF for providing ERA-40 and ERA-Interim data. We also thank the World Data Center (WDX-SILSO, Royal Observatory of Belgium, Brussels) for the production, preservation and dissemination of the international Sunspot Number.

References

Andersson, M. E., Verronen, P. T., Rodger, C. J., Clilverd, M. A. and Seppälä, A.: Missing driver in the Sun-Earth connection from energetic electron precipitation impacts mesospheric ozone., Nat. Commun., 5(May), 5197, doi:10.1038/ncomms6197, 2014.

Arfeuille, F., Weisenstein, D., MacK, H., Rozanov, E., Peter, T. and Brönnimann, S.: Volcanic forcing for climate modeling: A new microphysics-based data set covering years 1600-present, Clim. Past, 10(1), 359–375, doi:10.5194/cp-10-359-2014, 2014.

Barriopedro, D., García-Herrera, R. and Huth, R.: Solar modulation of Northern Hemisphere winter blocking, J. Geophys. Res. Atmos., 113(14), 1–11, doi:10.1029/2008JD009789, 2008.

Brugnara, Y., Brönnimann, S., Luterbacher, J. and Rozanov, E.: Influence of the sunspot cycle on the Northern Hemisphere wintertime circulation from long upper-air data sets, Atmos. Chem. Phys., 13(13), 6275–6288, doi:10.5194/acp-13-6275-2013, 2013.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., Mcnally, A. P., Monge-Sanz, B. M., Morcrette, J. J., Park, B. K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J. N. and Vitart, F.: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Q. J. R. Meteorol. Soc., 137(656), 553–597, doi:10.1002/qj.828, 2011.

Etheridge, D., Steele, L., Langenfelds, R., Francey, R., Barnola, J., and Morgan, V.: Natural and anthropogenic changes in atmospheric CO2 over the last 1000 years from air in Antarctic ice and firn, J. Geophys. Res., 101, 4115–4128, doi:10.1029/95JD03410, 1996.

Etheridge, D. M., Steele, L. P., Francey, R. J., and Langenfelds, R. L.: Atmospheric methane between 1000 A.D. and present: Evidence of anthropogenic emissions and climatic variability, J. Geophys. Res., 103, 15979–15993, doi:10.1029/98JD00923, 1998.

Ferretti, D. F., Miller, J. B., White, J. W. C., Etheridge, D. M., Lassey, K. R., Lowe, D. C., Meure, C. M. M. F., Dreier, M. F., Trudinger, C. M., Van Ommen, T. D., and Langenfelds, R. L.: Unexpected changes to the global methane budget over the past 2000 years, Science, 309, 1714–1717, doi:10.1126/science.1115193, 2005.

Gimeno, L., de la Torre, L., Nieto, R., García, R., Hernández, E. and Ribera, P.: Changes in the relationship NAO-Northern hemisphere temperature due to solar activity, Earth Planet. Sci. Lett., 206(1–2), 15–20, doi:10.1016/S0012-821X(02)01090-7, 2003.

Gray, L. J., Beer, J., Geller, M., Haigh, J. D., Lockwood, M., Matthes, K., Cubasch, U., Fleitmann, D., Harrison, G., Hood, L., Luterbacher, J., Meehl, G. a., Shindell, D., van Geel, B. and White, W.: Solar influence on climate, Rev. Geophys., 48(2009), RG4001, doi:10.1029/2009RG000282, 2010.

Gray, L. J., Scaife, A. A., Mitchell, D. M., Osprey, S., Ineson, S., Hardiman, S., Butchart, N., Knight, J., Sutton, R. and Kodera, K.: A lagged response to the 11 year solar cycle in observed winter Atlantic/European weather patterns, J. Geophys. Res. Atmos., 118(24), 13405–13420, doi:10.1002/2013JD020062, 2013.

Hood, L. L., Misios, S., Mitchell, D. M., Rozanov, E., Gray, L. J., Tourpali, K., Matthes, K., Schmidt, H., Chiodo, G., Thiéblemont, R., Shindell, D. and Krivolutsky, A.: Solar signals in CMIP-5 simulations: The ozone response, Q. J. R. Meteorol. Soc., 141(692), 2670–2689, doi:10.1002/qj.2553, 2015.

Huth, R., Bochníček, J. and Hejda, P.: The 11-year solar cycle affects the intensity and annularity of the Arctic Oscillation, J. Atmos. Solar-Terrestrial Phys., 69(9), 1095–1109, doi:10.1016/j.jastp.2007.03.006, 2007.

Huth, R., Beck, C., Philipp, A., Demuzere, M., Ustrnul, Z., Cahynová, M., Kyselý, J. and Tveito, O. E.: Classifications of atmospheric circulation patterns: Recent advances and applications, Ann. N. Y. Acad. Sci., 1146, 105–152, doi:10.1196/annals.1446.019, 2008a.

Huth, R., Kyselý, J., Bochníček, J. and Hejda, P.: Solar activity affects the occurrence of synoptic types over Europe, Ann. Geophys., 26, 1999–2004, 2008b.

Ineson, S., Scaife, A. a., Knight, J. R., Manners, J. C., Dunstone, N. J., Gray, L. J. and Haigh, J. D.: Solar forcing of winter climate variability in the Northern Hemisphere, Nat. Geosci., 4(11), 753–757, doi:10.1038/ngeo1282, 2011.

Lockwood, M.: Solar Influence on Global and Regional Climates, Surv. Geophys., 33(3–4), 503–534, doi:10.1007/s10712-012-9181-3, 2012.

Lockwood, M., Harrison, R. G., Woollings, T. and Solanki, S. K.: Are cold winters in Europe associated with low solar activity?, Environ. Res. Lett., 5(2), 24001, doi:10.1088/1748-9326/5/2/024001, 2010.

Van Loon, H. and Meehl, G. A.: Interactions between externally forced climate signals from sunspot peaks and the internally generated Pacific Decadal and North Atlantic Oscillations, Geophys. Res. Lett., 41(1), 161–166, doi:10.1002/2013GL058670, 2014.

MacFarling-Meure, C., Etheridge, D., Trudinger, C., Steele, P., Langenfelds, R., Van Ommen, T., Smith, A., and Elkins, J.: Law Dome CO2, CH4 and N2O ice core records extended to 2000 years BP, Geophys. Res. Lett., 33, L14810, doi:10.1029/2006GL026152, 2006.

Martin-Puertas, C., Matthes, K., Brauer, A., Muscheler, R., Hansen, F., Petrick, C., Aldahan, A., Possnert, G. and van Geel, B.: Regional atmospheric circulation shifts induced by a grand solar minimum, Nat. Geosci., 5(6), 397–401, doi:10.1038/ngeo1460, 2012.

Matthes, K., Kodera, K., Haigh, J. D., Shindell, D. T., Shibata, K., Langematz, U., Rozanov, E. and Kuroda, Y.: GRIPS Solar Experiments Intercomparison Project: Initial results, Pap. Meteorol. Geophys., 54(2), 71–90, doi:10.2467/mripapers.54.71, 2003.

Matthes, K., Langematz, U., Gray, L. J., Kodera, K. and Labitzke, K.: Improved 11-year solar signal in the freie universitat Berlin climate middle atmosphere model (FUB-CMAM), J. Geophys. Res., 109, 1–15, doi:10.1029/2003JD004012, 2004.

Misios, S., Mitchell, D. M., Gray, L. J., Tourpali, K., Matthes, K., Hood, L., Schmidt, H., Chiodo, G., Thi??blemont, R., Rozanov, E. and Krivolutsky, A.: Solar signals in CMIP-5 simulations: Effects of atmosphere-ocean coupling, Q. J. R. Meteorol. Soc., 142(695), 928–941, doi:10.1002/qj.2695, 2016.

Mitchell, D. M., Misios, S., Gray, L. J., Tourpali, K., Matthes, K., Hood, L., Schmidt, H., Chiodo, G., Thieblemont, R., Rozanov, E., Shindell, D. and Krivolutsky, A.: Solar signals in CMIP-5 simulatioms: she stratospheric pathway, Q. J. R. Meteorol. Soc., 141, 2390–2403, doi:10.1002/qj.2530, 2015.

Moffa-Sánchez, P., Born, A., Hall, I. R., Thornalley, D. J. R. and Barker, S.: Solar forcing of North Atlantic surface temperature and salinity over the past millennium, Nat. Geosci., 7(April), 275–278, doi:10.1038/NGEO2094, 2014.

Muthers, S., Anet, J. G., Stenke, A., Raible, C. C., Rozanov, E., Brönnimann, S., Peter, T., Arfeuille, F. X., Shapiro, A. I., Beer, J., Steinhilber, F., Brugnara, Y. and Schmutz, W.: The coupled atmosphere-chemistry-ocean model SOCOL-MPIOM, Geosci. Model Dev., 7(5), 2157–2179, doi:10.5194/gmd-7-2157-2014, 2014.

Oldenborgh, G. J. Van, Laat, a. T. J. De, Luterbacher, J., Ingram, W. J. and Osborn, T. J.: Claim of solar influence is on thin ice: are 11-year cycle solar minima associated with severe winters in Europe?, Environ. Res. Lett., 8(2), 24014, doi:10.1088/1748-9326/8/2/024014, 2013.

Päivärinta, S. M., Seppälä, A., Andersson, M. E., Verronen, P. T., Thölix, L. and Kyrölä, E.: Observed effects of solar proton events and sudden stratospheric warmings on odd nitrogen and ozone in the polar middle atmosphere, J. Geophys. Res. Atmos., 118(12), 6837–6848, doi:10.1002/jgrd.50486, 2013.

Philipp, A., Bartholy, J., Beck, C., Erpicum, M., Esteban, P., Fettweis, X., Huth, R., James, P., Jourdain, S., Kreienkamp, F., Krennert, T., Lykoudis, S., Michalides, S. C., Pianko-Kluczynska, K., Post, P., Álvarez, D. R., Schiemann, R., Spekat, A. and Tymvios, F. S.: Cost733cat - A database of weather and circulation type classifications, Phys. Chem. Earth, 35(9–12), 360–373, doi:10.1016/j.pce.2009.12.010, 2010.

Philipp, A., Beck, C., Huth, R. and Jacobeit, J.: Development and comparison of circulation type classifications using the COST 733 dataset and software, Int. J. Climatol., 36(7), 2673–2691, doi:10.1002/joc.3920, 2014.

Robock, A.: Volcanic eruptions and climate, , 38(2), 191–219, doi:10.1029/1998RG000054, 2000.

Rozanov, E., Calisto, M., Egorova, T., Peter, T. and Schmutz, W.: Influence of the Precipitating Energetic Particles on Atmospheric Chemistry and Climate, Surv. Geophys., 33(3–4), 483–501, doi:10.1007/s10712-012-9192-0, 2012.

Scherrer, S. C., Croci-Maspoli, M., Schwierz, C. and Appenzeller, C.: Two-dimensional indices of atmospheric blocking and their statistical relationship with winter climate patterns in the Euro-Atlantic region, Int. J. Climatol., 26(2), 233–249, doi:10.1002/joc.1250, 2006.

Schwander, M., Brönnimann, S., Delaygue, G., Rohrer, M., Auchmann, R. and Brugnara, Y.: Reconstruction of Central European daily weather types back to 1763, Int. J. Climatol., doi:10.1002/joc.4974, 2017.

Seppälä, A., Matthes, K., Randall, C. E. and Mironova, I. a: What is the solar influence on climate? Overview of activities during CAWSES-II, Prog. Earth Planet. Sci., 1(1), 24, doi:10.1186/s40645-014-0024-3, 2014.

Sfîca, L., Voiculescu, M. and Huth, R.: The influence of solar activity on action centres of atmospheric circulation in North Atlantic, Ann. Geophys., 33(2), 207–215, doi:10.5194/angeo-33-207-2015, 2015.

Sirocko, F., Brunck, H. and Pfahl, S.: Solar influence on winter severity in central Europe, Geophys. Res. Lett., 39(16), 2–6, doi:10.1029/2012GL052412, 2012.

Sitnov, S. A.: Influence of the 11-year solar cycle on the effects of the equatorial quasi-biennial oscillation, manifesting in the extratropical northern atmosphere, Clim. Dyn., 32(1), 1–17, doi:10.1007/s00382-007-0362-6, 2009.

Solomon, S., Crutzen, P. J. and Roble, R. G.: Photochemical coupling between the thermosphere and the lower atmosphere:

1. Odd nitrogen from 50 to 120 km, J. Geophys. Res., 87, 7206, doi:10.1029/JC087iC09p07206, 1982.

Stevens, M. J. and North, G. R.: Detection of the climate response to the solar cycle, J. Atmos. Sci., 53(18), 2594–2608, doi:10.1175/1520-0469(1996)053<2594:DOTCRT>2.0.CO;2, 1996.

Thiéblemont, R., Matthes, K., Omrani, N.-E., Kodera, K. and Hansen, F.: Solar forcing synchronizes decadal North Atlantic climate variability, Nat. Commun., 6, 8268, doi:10.1038/ncomms9268, 2015.

Tibaldi, S. and Molteni, F.: On the operational predictability of blocking, Tellus A, 42(3), 343–365, doi:10.1034/j.1600-0870.1990.t01-2-00003.x, 1990.

Uppala, S. M., Kallberg, P. W., Simmons, A. J., Andrae, U., Bechtold, V. D., Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Van De Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Holm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., McNally, A. P., Mahfouf, J. F., Morcrette, J. J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljevic, D., Viterbo, P. and Woollen, J.: The ERA-40 re-analysis, Q. J. R. Meteorol. Soc., 131(612), 2961–3012, doi:10.1256/qj.04.176, 2005.

Weusthoff, T.: Weather Type Classification at MeteoSwiss - Introduction of new automatic classification schemes, Arbeitsberichte der MeteoSchweiz, (235), 46, 2011.

White, W. B., Lean, J., Cayan, D. R. and Dettinger, M. D.: Response of global upper ocean temperature to changing solar irradiance, J. Geophys. Res., 102(C2), 3255–3266, doi:10.1029/96JC03549, 1997.

Woollings, T., Lockwood, M., Masato, G., Bell, C. and Gray, L.: Enhanced signature of solar variability in Eurasian winter climate, Geophys. Res. Lett., 37(20), 1–6, doi:10.1029/2010GL044601, 2010.

Table 1: CAP7 weather types numbers, abbreviations and names

Index	Abbreviation	Full Name
1.	NE	North-East, indifferent
2.	WSW	West South-West, cyclonic, flat pressure
3.	W	Westerly flow over Northern Europe
4.	E	East, indifferent
5.	HP	High Pressure over Europe
6.	N	North, cyclonic
7.	WC	Westerly flow over Southern Europe, cyclonic

Table 2: Size (number of months) of each solar activity level and periods analysed

	1763-1886	1887-2009	1958-2009	1763-2009
low	98	99	38	195
moderate	108	102	35	211
high	106	105	47	212

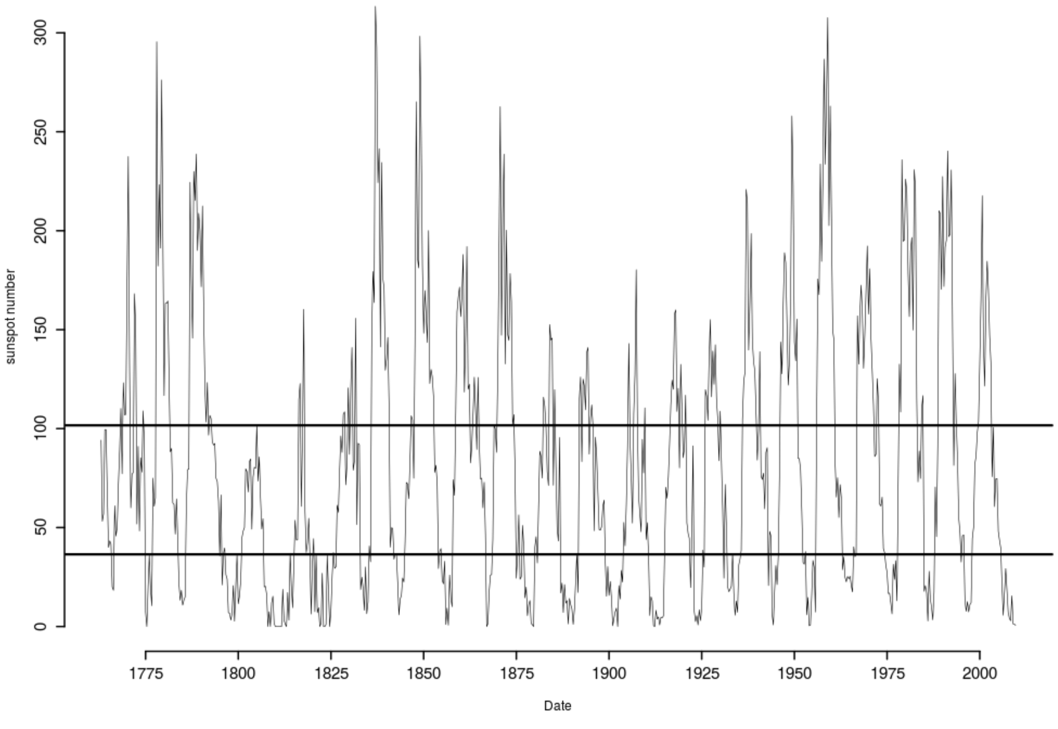

Figure 1: 1763-2009 JFM monthly sunspot number with 33rd and 66th precentile thresholds.

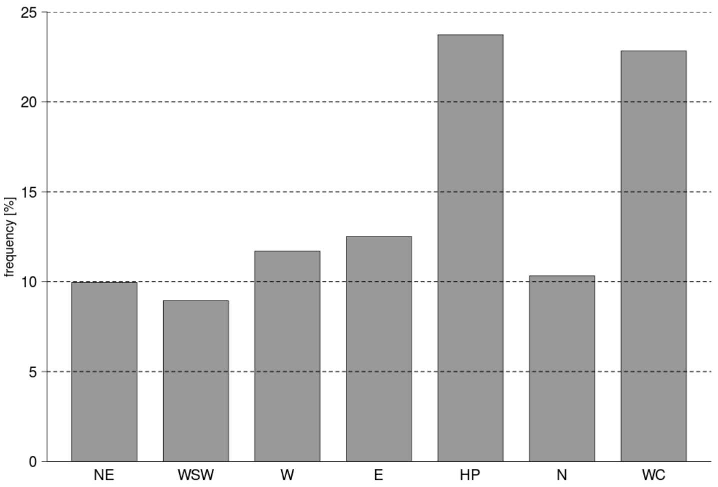

Figure 2: CAP7 1763-2009 JFM mean frequency of occurrence.

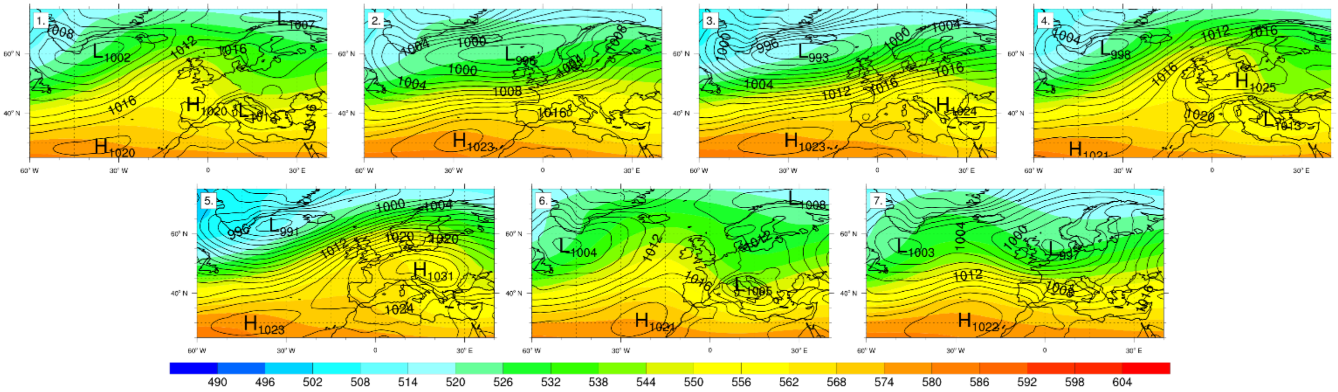

Figure 3: CAP7 1958-2009 500 hPa geopotential height (color) and sea level pressure (contours) JFM composites.

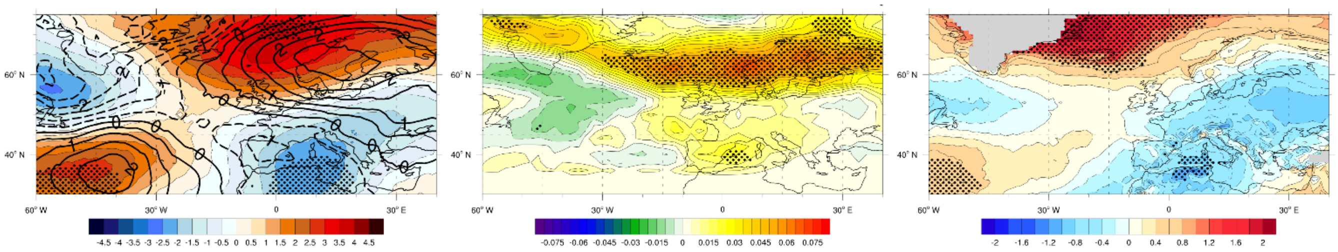

Figure 4: 1958-2009 low minus high solar activity differences computed with ERA-40/-Interim. Left: 500 hPa geopotential height (color) and sea level pressure (contour). Centre: blocking frequency. Right 850 hPa temperature. The 95% significance level is indicated with stippled areas.

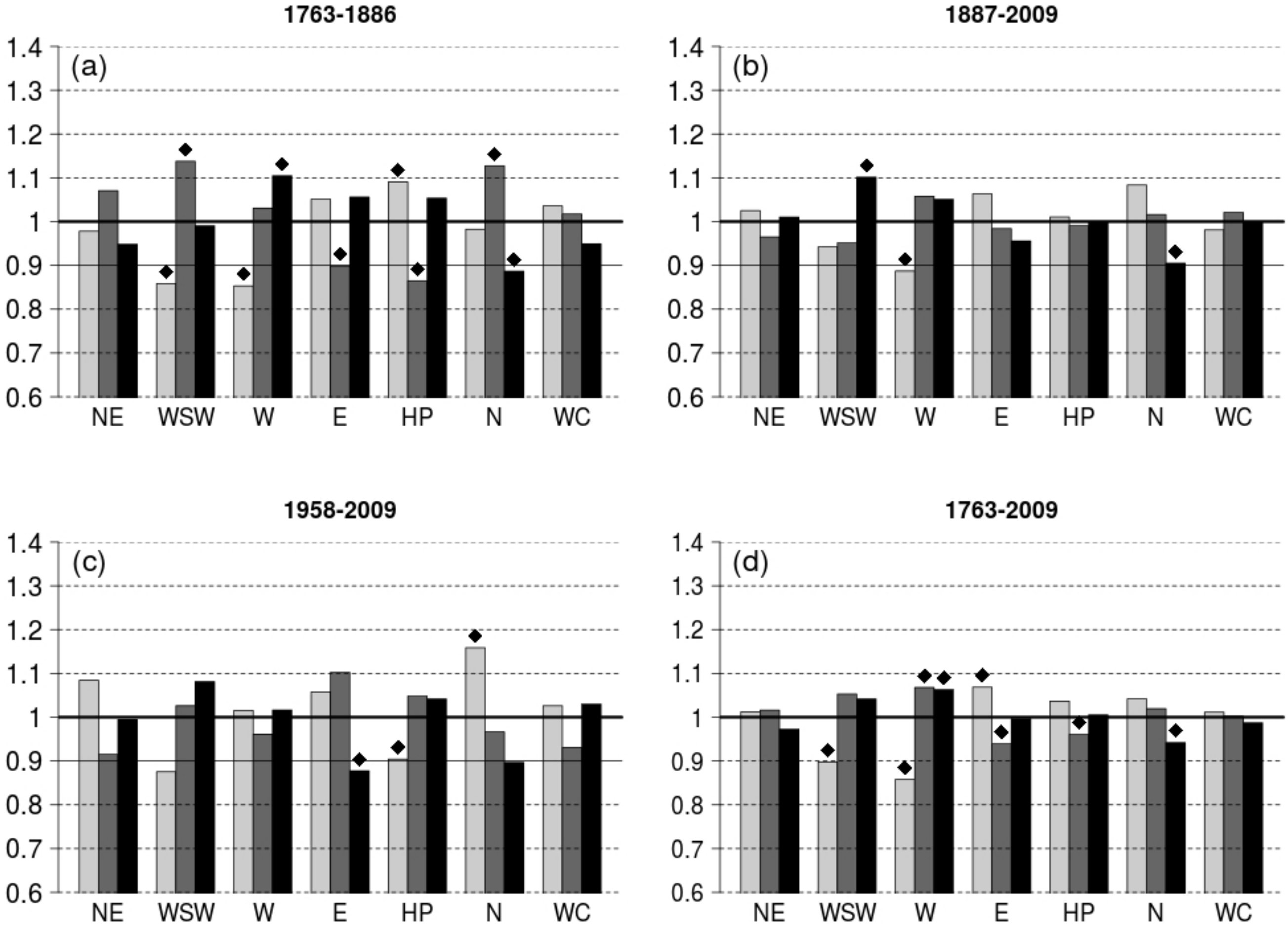

Figure 5: Ratios of the frequency for the low (light grey), moderate (grey) and high (black) solar activity classes for different periods. Dots correspond to statistical significance of the ratios at the 95% level.

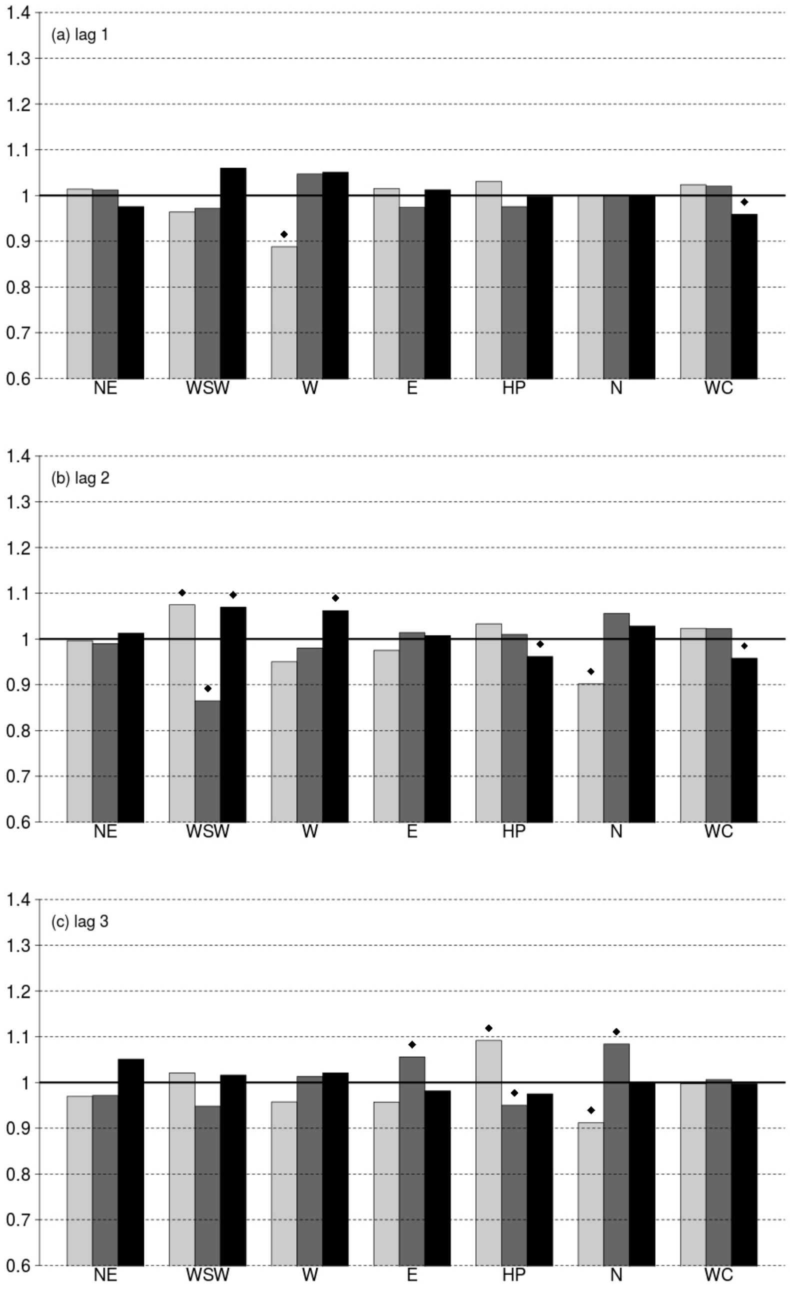

Figure 6: Ratios of the frequency for the low (light grey), moderate (grey) and high (black) solar activity classes for 1 (a), 2 (b) and 3 (c) years lags. Dots correspond to statistical significance of the ratios at the 95% level.

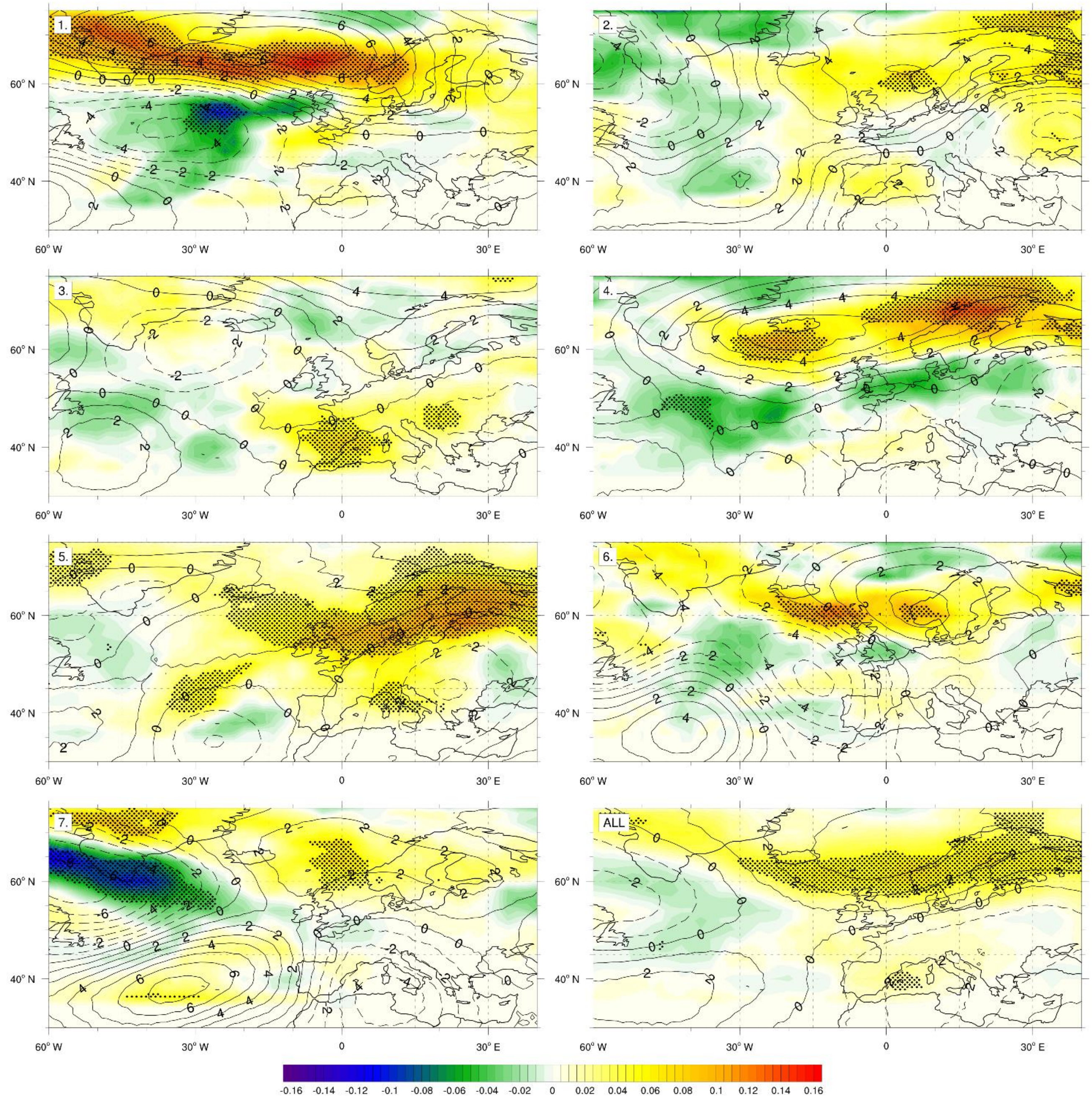

Figure 7: CAP7 (1 to 7) and mean (ALL) JFM blocking frequency (color) and 500 hPa geopotential height (contour) difference between low and high solar activity (low minus high) computed with ERA-40/-Interim for 1958-2009. The 95% significance level is indicated with stippled areas.

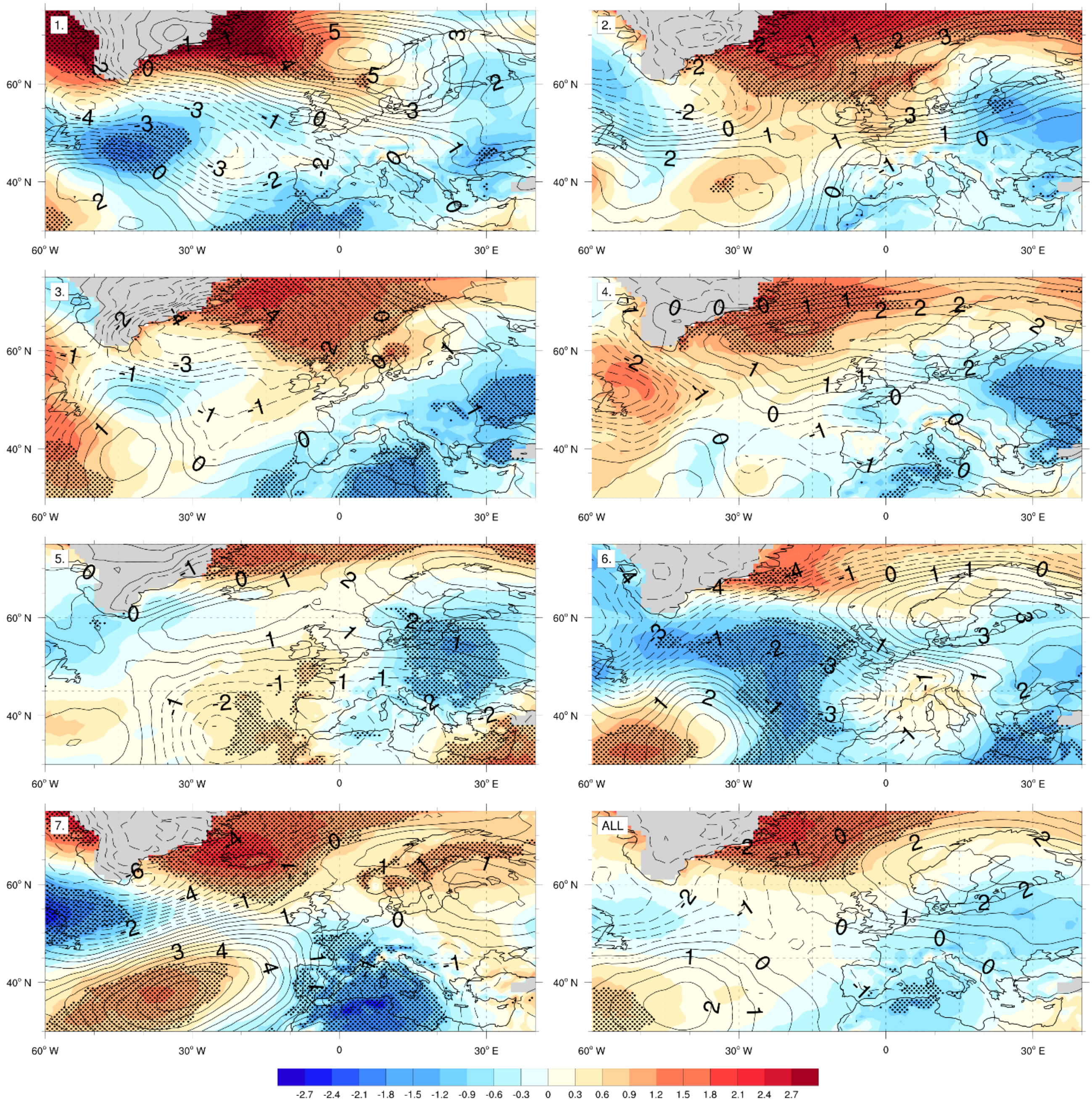

Figure 8: CAP7 (1 to 7) and mean (ALL) JFM sea level pressure (contour) and 850 hPa temperature (colour) difference between low and high solar activity (low minus high) computed with ERA-40/-Interim for 1958-2009. The 95% significance level is indicated with stippled areas.

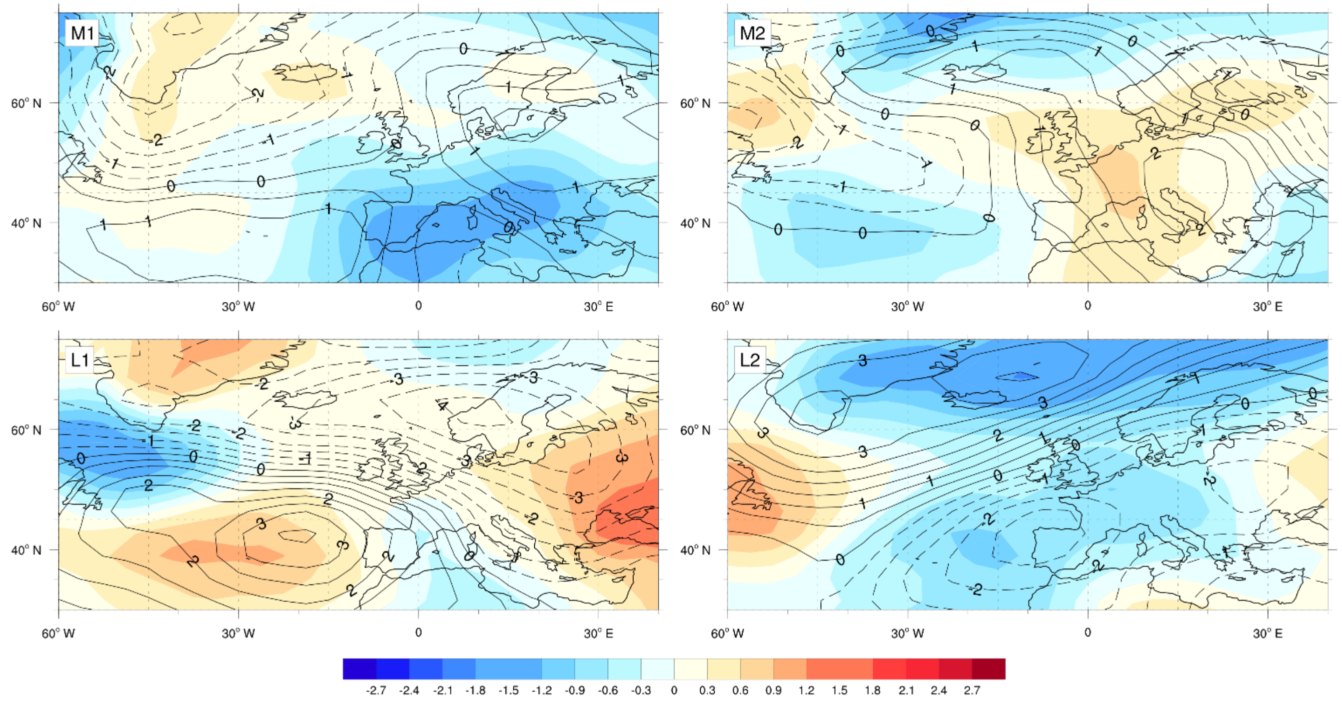

Figure 9: JFM sea level pressure (contour) and 850 hPa temperature (colour) difference between 11-year cycle low and high solar activity (high frequency) computed with the model simulations for 1958-1999.