Stratospheric modulation of the large-scale circulation in the Atlantic–European region and its implications for surface weather events

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Abstract
Extreme states of the stratospheric polar vortex can have long-lasting impacts on extratropical circulation patterns, such as the North Atlantic Oscillation (NAO). This provides windows of subseasonal predictability beyond the typical weather forecast horizon of about 10 days. Subseasonal forecasts of surface weather are of significant interest in weather-dependent socio-economic sectors. For example, demand and supply for electricity and gas are weather dependent and therefore accurate forecasts are important for the energy industry and energy trading. Here we investigate the subseasonal impact of stratospheric conditions on surface weather events relevant to the energy industry in five subregions of Europe in winter. We use a definition of seven Atlantic–European weather regimes to describe the variability of the large-scale circulation on subseasonal time scales. Results indicate that weather events are often associated with more than one preferred weather regime. In turn, some weather regimes project onto a specific NAO phase, while others are independent of the NAO. As expected, anomalous stratospheric polar vortex states predominantly modulate the occurrence of regimes related to the NAO and affect the likelihood of their associated weather events. In contrast, the occurrence of weather regimes which do not project well onto the NAO is not affected by anomalous stratospheric polar vortex states. These regimes provide pathways to unexpected weather events in extreme stratospheric polar vortex states. For example, weak stratospheric polar vortex states enhance the likelihood of negative NAO. High wind events in Central Europe predominantly occur during the zonal regime, strongly projecting onto positive NAO. However, these events also occur during the Atlantic trough regime, which is unaffected by anomalous stratospheric polar vortex states and thus provides a pathway to Central European high wind events during weak stratospheric polar vortex states. A correct NAO prediction alone is therefore not sufficient to correctly predict surface weather after extreme stratospheric polar vortex states. Moreover, weather regime life cycles independent of the NAO also need to be forecast accurately.

KEYWORDS
energy, midlatitude, stratosphere, teleconnections (AO, NAO, MJO, ENSO, SSW, ONI, ADO, MJO), weather regimes
1 | INTRODUCTION

Extreme weather conditions have significant impacts on a number of industries and markets around the world (Subak et al., 2000; Lazo et al., 2011). The energy sector is arguably among the most strongly affected (White et al., 2017; Staffell and Pfenninger, 2018). Both the supply of and the demand for energy are influenced by weather; therefore prices on energy markets (for electricity, natural gas, coal and oil, for example) are strongly weather dependent. On spot and forward markets energy is traded on many different time horizons (from hours to days, weeks, months and even multiple calendar years ahead). Thus, weather and weather forecasts have an influence on energy markets on various time scales. The sensitivity of the balance of energy supply and demand to weather, particularly in electricity markets, has increased significantly in recent years due to a substantial increase in the installed capacity of renewable energy generation, notably wind and solar power (Pfenninger and Staffell, 2016; Staffell and Pfenninger, 2016). This is due to the high variability of wind and solar power output, along with prevailing weather conditions, and poses a significant challenge for the European energy sector (Brouwer et al., 2014).

Of particular importance are periods when energy supply or demand, and therefore also market prices, are strongly driven by anomalous weather conditions, such as during a windy period affecting northwestern Europe or during a cold spell affecting Central Europe. Due to the substantial weather impacts, participants of the energy markets are in great need of weather information and weather forecasts on various time horizons. Because of the direct impact of the expectation of future weather development on market prices, the energy industry is quasi-advanced in the use and interpretation of subseasonal (10 to 60 days ahead) forecasts (White et al., 2017). Despite some progress in recent years, numerical weather forecast models still have a low skill level for surface weather in Europe on the subseasonal scale (White et al., 2017). Therefore, a better understanding of the factors influencing surface weather on subseasonal time scales, and in particular of windows of enhanced subseasonal predictability for Europe, is needed. An extensive body of research has suggested that extreme states of the stratospheric polar vortex provide extended-range predictability. Extreme states of the stratospheric polar vortex modulate the probabilities for large-scale weather patterns on subseasonal time scales (e.g., Baldwin and Dunkerton, 2001; Tripathi et al., 2015a; Beerli et al., 2017). For example, there is an enhanced probability of a positive (negative) North Atlantic Oscillation (NAO) following strong (weak) stratospheric polar vortex conditions (Baldwin and Dunkerton, 2001). The surface weather impacts of such weather patterns in turn provide potential extended-range predictability for surface weather.

This study provides a detailed perspective on surface weather impacts related to the energy sector in Europe depending on different states of the stratospheric polar vortex. We address the following research questions.

- What are the prevailing large-scale flow conditions during different types of surface weather events?
- How does the occurrence frequency of weather regimes relate to different states of the stratospheric polar vortex?
- How do extreme states of the stratospheric polar vortex affect the occurrence of surface weather events?
- What are the dynamical pathways for unexpected weather events after extreme stratospheric polar vortex events?

We continue with more background on weather regimes, the NAO and stratosphere–troposphere interactions in Section 2. Section 3 introduces the data and methods used. We then discuss the large-scale flow situation during the different weather events (Section 4) followed by an in-depth investigation of the modulation by the stratosphere (Section 5). Section 6 summarises our main findings.

2 | BACKGROUND

2.1 | Weather regimes

Persistent, quasi-stationary and recurrent circulation patterns, known as weather regimes, explain most of the large-scale flow variability in the extratropics on subseasonal time scales (e.g., Wallace and Gutzler, 1981; Vautard, 1990; Michelangeli et al., 1995). Weather regimes can be viewed as “low-frequency envelopes” of synoptic weather variability (Cassou, 2008), with lifetimes ranging from several days to a few weeks. At the same time, regimes are accompanied by typical surface weather conditions and enhance the likelihood of large-scale weather extremes (e.g., Yiou and Nogaj, 2004; Della-Marta et al., 2007; Stefanon et al., 2012; Ferranti et al., 2018; Schaller et al., 2018; Vigaud et al., 2018).

Weather regimes are commonly identified using clustering techniques applied to geopotential height. Most studies suggest the existence of four dominant regimes in the Atlantic–European region (Vautard, 1990; Michelangeli et al., 1995; Cassou, 2008): a regime with enhanced zonal flow (a large-scale flow configuration consistent with strong positive NAO), a regime with preferred blocking over Greenland (consistent with strong negative NAO), a regime with a ridge over the eastern North Atlantic and a regime with preferred blocking over Europe and Scandinavia.

Only a few studies use year-round regime definitions with seven or eight regimes, which reflect the seasonal variability in the regime patterns. Here we employ the seven year-round Atlantic–European weather regimes of Grams et al. (2017), which are based on standardised 500-hPa geopotential height.
anomalies. These seven regimes include the “standard” four winter regimes but also allow us to distinguish important variants that occur year-round, albeit with varying seasonal frequencies. A similar result was obtained by Santos et al. (2016), who found eight regimes based on k-means clustering of mean sea-level pressure. Grams et al. (2017) demonstrated the usefulness of their seven regimes to describe the impact of large-scale flow variability on the energy sector, since different regimes strongly modulate the potential for wind electricity generation (and, to a lesser degree, solar photovoltaics and electricity demand) in different regions of Europe. Thus the seven regimes represent a useful compromise between simplification (by reducing the degrees of freedom of the atmosphere to seven regimes) and complexity (the seven regimes allowing a more detailed analysis of regional impacts than the standard four regimes or the NAO alone; cf. Zubiate et al., 2017) in characterising the large-scale flow and its energy-relevant surface weather impacts in Europe.

2.2 North Atlantic Oscillation

Several previous studies (e.g., Brayshaw et al., 2011; Clark et al., 2017; Correia et al., 2017; Grams et al., 2017; Zubiate et al., 2017) have also used the North Atlantic Oscillation (NAO) to describe the impacts of the large-scale atmospheric flow on energy supply and demand. The NAO is associated with fluctuations in the strength and position of the North Atlantic jet stream. The positive phase of the NAO (NAO+) generally corresponds to a stronger-than-normal and rather zonally oriented jet displaced to the north, while the negative phase (NAO−) corresponds to a weaker-than-normal and rather wavy jet displaced to the south. The surface weather variability related to the NAO is most pronounced in winter. Periods with a positive (negative) NAO are associated with milder, windier, and wetter (colder, calmer, and drier) than normal conditions in northern Europe and vice versa in the Mediterranean region. In this study we will use both the weather regime definition of Grams et al. (2017) and the NAO in order to describe the large-scale atmospheric flow conditions.

Recent research has found intriguing evidence that the NAO could be predictable on subseasonal-to-seasonal (S2S) time scales and perhaps even 1–2 years ahead (Scaife et al., 2014; Dunstone et al., 2016). There is still considerable debate in the scientific community about the validity of the more optimistic estimations of the skill of numerical models in predicting the NAO on S2S time scales, since the intrinsic predictability of the NAO might depend on interdecadal variability (e.g., Weisheimer et al., 2017, 2018). Still, capabilities of S2S predictions of the NAO with state-of-the-art numerical models have improved considerably over the past decade (e.g., Vitart, 2014; Clark et al., 2017). However, as will be shown in this study, a significant portion of surface weather variability and anomalous surface weather conditions occurs independently from the phase of the NAO. For example, Hurrell et al. (2013) showed that the NAO only accounts for 30% of interannual winter temperature variability in the Northern Hemisphere. Hence, extended-range forecasts of the NAO, although skilful, need to be interpreted with care in order to determine their implications for surface weather and ultimately energy supply and demand in a specific region.

2.3 Stratosphere–troposphere interactions

One of the most important sources of predictability for the extratropical troposphere in winter is the polar stratospheric circulation, especially when its state is far from its climatological mean conditions (Tripathi et al., 2015a). Baldwin and Dunkerton (1999, 2001) showed that anomalous states of the stratospheric polar vortex can lead to persistent anomalies in the troposphere that shift the probability density function of the NAO. Weak (strong) stratospheric polar vortex events can thereafter contribute to large-scale flow anomalies in the troposphere that are consistent with the negative (positive) phase of the NAO for up to 2 months. Since this discovery, a large number of studies have shown that these observed anomalies are the result of a two-way interaction between the stratospheric polar vortex and the jet stream in the upper troposphere, which are coupled through the vertical propagation of Rossby waves (see Kidston et al., 2015 and Tripathi et al., 2015a for more details on the different proposed coupling mechanisms).

Despite uncertainties about the importance of different suggested coupling mechanisms, the scientific community today regards weak and strong polar vortex events, as described by Baldwin and Dunkerton (2001), as periods when the large-scale flow evolution in the troposphere and stratosphere are coupled and mutually affect each other. Since the stratosphere is dynamically evolving more slowly than the troposphere, the state of the stratospheric flow induces memory, leading to quasi-persistent tropospheric NAO anomalies on monthly time scales.

The life cycle of weak (also known as sudden stratospheric warmings; SSWs) and strong stratospheric polar vortex events was studied in detail by Limpasuvan et al. (2004, 2005). They showed that the dynamical evolution of weak and strong vortex events is fundamentally different. Strong polar vortex events tend to build up continuously over time, that is, the polar vortex spins up gradually until it is anomalously strong, due to the below-normal activity of vertically propagating low wavenumber Rossby waves in the stratosphere. In contrast, SSWs happen by a fast breakdown of the stratospheric polar vortex without significant weakening prior to the event, due to strongly increased activity of vertically propagating low wavenumber Rossby waves in the stratosphere or internal stratospheric variability (e.g., Albers and Birner, 2014).
Both SSWs and strong polar vortex events are associated with long-lasting significant geopotential height anomalies in the troposphere (about 40 days, starting from the central date of the stratospheric polar vortex event), which project onto the NAO– and NAO+ phases, respectively. Recently, Domeisen et al. (2019) showed that the switch of the NAO phase and NAO persistence is a reasonable indicator of SSW events. Despite the evidence that strong (weak) polar vortex events on average lead to prolonged positive (negative) NAO periods, there are a number of examples of such events that did not lead to the expected prolonged NAO response. Karpechko et al. (2017) classified SSWs into “propagating” (SSWs with a clear negative NAO response) and “non-propagating” cases (SSWs with no NAO response after the event). They argued that the main discriminating factor between propagating and non-propagating events is the lower-stratospheric circulation. White et al. (2019) confirmed this result and additionally showed that propagating SSW cases are preceded by stronger tropospheric wave activity and a stronger Siberian high than their non-propagating counterparts. Kretschmer et al. (2018) additionally showed, by applying a clustering technique to the lower-stratospheric circulation, that SSWs are linked to two main clusters in the lower-stratospheric circulation: SSWs that lead to a negative NAO response are dominated by their cluster 5 in the stratosphere, which exhibits a strong lower-stratospheric anticyclonic anomaly centred over the North Pole. However, if their cluster 4 lower-stratospheric circulation anomaly is dominant during an SSW (the anticyclonic anomaly is shifted towards the Bering Strait), the tropospheric circulation response resembles the negative North Pacific Oscillation pattern. This pattern is characterised by a strong ridge over Alaska and a somewhat weaker but statistically significant signal for a trough in the North Atlantic—a pattern that resembles the Atlantic trough regime of Grams et al. (2017). Finally, focusing on the Atlantic–European region, Charlton-Perez, Ferranti, and Lee (2018) and Papritz and Grams (2018) provided the first evidence that only weather regimes related to the NAO are modulated by stratospheric conditions, while the occurrence frequency of weather regimes that do not project onto the NAO is not affected by strong or weak stratospheric polar vortex events.

The existence of a stratosphere–troposphere link in winter that leads to long-lasting circulation anomalies in the troposphere has been known of since the study of Baldwin and Dunkerton (2001), and various aspects of this link have been discussed in recent decades (see Tripathi et al., 2015a for an overview). The goal of this study is to provide a detailed overview for which areas of Europe and surface weather variables relevant to the energy industry (e.g., temperature, wind, precipitation) the stratosphere is potentially a good source of predictability. We also aim to explain the differences in the significance of the stratospheric impact between different subregions of Europe and surface weather variables by their link to weather regimes and the NAO index.

3 DATA AND METHODS

3.1 Data

The basic dataset used for this study is the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis “ERA-Interim” interpolated to a horizontal grid of 1° resolution (Dee et al., 2011). The temporal resolution is 6 hr, from which we computed daily means unless otherwise stated. In order to compute anomalies from long-term means, we used a 30-day running mean for each calendar day as a reference climatology.

We used the daily NAO index of the Climate Prediction Center (CPC) at the National Oceanic and Atmospheric Administration (NOAA) to analyse the state of the NAO for weather events and regimes (retrieved from http://www.cpc.noaa.gov/products/precip/CWlink/pna/nao.shtml on December 6, 2016). It is based on rotated empirical orthogonal function (EOF) analysis of normalised 500-hPa geopotential height anomalies (Barnston and Livezey, 1987). This version of the NAO index uses the seasonal varying patterns of the first EOF, valid for each calendar month and weighted for the respective date.

The study focuses on winter as defined by the months December, January and February (DJF). For investigating extreme states of the stratosphere we focus on an extended winter season covering the months November to April (NDJFMA).

3.2 Weather regime definition

Weather regimes are obtained from a k-means clustering in the phase space spanned by the first seven EOFs of 6-hourly 10-day low-pass filtered normalised 500-hPa geopotential height anomalies (Z500') in the Euro-Atlantic sector (80°W–40°E, 30°N–90°N; Grams et al., 2017). Geopotential height anomalies are defined with respect to the 90-day running mean of the climatology for the respective date. In addition, weather regime life cycles are objectively identified based on the normalised projection of each 6-hourly Z500' into the cluster mean (Grams et al., 2017), which enables time steps that do not exhibit a well-established regime (“no regime”; about 23% of all days in winter) to be filtered out. Note that in contrast to the bimodal NAO and Arctic Oscillation (AO), which are typically derived from the first EOF explaining about 20–25% of the variance, weather regimes are based on the seven leading EOFs explaining about 76% of the variance, and thus cover almost the full range of large-scale flow variability in the Euro-Atlantic sector.

Three of the seven regimes are dominated by a negative Z500' and enhanced cyclonic activity (Figure 1a–c).
These are the “Atlantic Trough” (AT) regime, with a trough extending towards western Europe, the “Zonal” (ZO) regime, with cyclonic activity around Iceland, and the “Scandinavian Trough” (ScTr) regime, with a trough shifted towards the east. In winter these three cyclonic regimes cause mild and windy conditions in large parts of Europe, extending from western Europe and the Iberian Peninsula across the North Sea region to the Baltic Sea, depending on the specific cyclonic regime (see Grams et al., 2017, supplementary information).

The remaining four regimes are characterised by positive Z500' centred at different locations and are thus referred to as “blocked regimes” (Figure 1d–g). These are the “Atlantic Ridge” (AR) regime, with a blocking ridge over the eastern North Atlantic and an accompanying trough extending from Eastern Europe into the central Mediterranean, the “European Blocking” (EuBL) regime, with a blocking anticyclone extending from western Europe to the North Sea, “Scandinavian Blocking” (ScBL), with high-latitude blocking over Scandinavia, and “Greenland Blocking” (GL), with a blocking ridge over the Greenland/Icelandic region. The blocked regimes overall go hand-in-hand with calm and rather cold surface weather in winter; however, peripheral regions adjacent to the blocking anticyclone experience enhanced cyclonic activity and thus more wind and precipitation (Grams et al., 2017). The ZO and GL regimes correspond to the positive and negative phases of the NAO, respectively (Table 1 and Figure 2a). The ScTr and (to a lesser extent) AT regimes also project onto mean positive NAO. The blocked EuBL regime is also weakly NAO+ in the mean. The remaining blocked AR and ScBL regimes project onto weakly mean negative NAO. Still, it is noteworthy that all regimes span a wide range of NAO projections (Figure 2a).

3.3 Surface weather event definition

The definition of surface weather events reflects surface weather conditions with a particularly strong impact on the European energy system. We split Europe into five subregions, which represent interconnected subdivisions of the European electricity system (e.g., Rodriguez et al., 2014, their
TABLE 1 Mean NAO index during the seven weather regimes and frequencies (in %), both for winter (DJF).

| Weather Regime | Frequency  |
|----------------|------------|
| AT             | 13.1%      |
| ZO             | 13.8%      |
| ScTr           | 11.3%      |
| AR             | 9.75%      |
| EuBL           | 10.9%      |
| ScBL           | 6.5%       |
| GL             | 11.7%      |
| No regime      | 23.0%      |

AT = Atlantic Trough; ZO = zonal; ScTr = Scandinavian trough; AR = Atlantic ridge; EuBL = European blocking; ScBL = Scandinavian blocking; GL = Greenland blocking. NAO = North Atlantic Oscillation.

**FIGURE 2** Distribution of daily North Atlantic Oscillation (NAO) indexes for (a) all winter days (DJF) attributed to one of the seven weather regimes or no regime, (b) all winter days (DJF) attributed to the strong, neutral or weak stratospheric polar vortex conditions, and (c) the average of the 40 days following a strong or weak vortex event as described in the text. The violin plots represent histograms of the NAO values, while the black and red lines indicate the mean and the median, respectively.

**FIGURE 3** Subregions used to study surface weather events. These regions approximately reflect the European energy market structure.

In order to define the events, the variables of interest (temperature, wind speed and precipitation) are averaged spatially for the subregions throughout the ERA-Interim record (1979–2014). Wind speeds are interpolated to 100 m above the ground from the two closest vertical levels of ERA-Interim. Precipitation is accumulated to daily aggregated precipitation. Before applying the event definition procedure, a cubic trend (following the approach of Gastineau and Frankignoul, 2015) is removed from the raw data in order to eliminate signals from long-term trends.

From the time series for these three quantities (daily mean 2-m temperature, daily mean 100-m wind speed and daily aggregated precipitation), we define weather events as exemplified for wind events in the following and as illustrated in Figure S1 in the supporting information. First, we compute thresholds for low and high wind events specific to each calendar day, defined by the 7% percentile (low) and the 93% percentile (high), respectively. The choice of these percentiles is motivated by the yield (on average) of about 5–6 events per year (1–2 per season). Due to the rather low sample size of 36 years, the raw thresholds vary quite strongly from calendar day to calendar day. Therefore, we further smooth the raw percentile-based threshold values by a 90-day low-pass Lanczos filter (Duchon, 1979). The filter width (90 days) represents a season. High (low) wind events are then defined as periods of at least 3 days when the wind speed is higher (lower) than the smoothed 93% percentile (and lower than the smoothed 7% percentile). Since wind is a highly variable quantity, we allow brief variations below (above) the daily threshold. If the event threshold is exceeded (undercut) on a given day, then that day is considered the start of an event if the sum of the deviations on that day and at least two more consecutive days is higher than the summed threshold values on those days. For wind and temperature we define both high
and low events, while for precipitation we define only heavy precipitation events and no dry events.

The weather events as derived by the methodology described above are multi-day periods of at least 3 days, when either wind, temperature or precipitation deviate strongly from the climatological mean for the respective time of year. Due to this particular methodology they occur all year round. By definition, however, there is some seasonal variability in event counts since the number of events in one month or one season is not directly constrained by the methodology. Per event type, region and season, the methodology detects between 33 and 52 events (Table S2 in the supporting information).

3.4  |  SPV Stratospheric polar vortex event definition

To identify extreme states of the stratospheric polar vortex we use a slightly altered version of the “polar vortex intensification events” of Limpasuvan et al. (2005) and the SSWs of Limpasuvan et al. (2004). They defined a strong (weak) polar vortex event, when the 15-day low-pass filtered first principal component of the zonal wind north of 60°N is below (above) one standard deviation on five consecutive days. We use the polar-cap average north of 60°N of the geopotential height anomaly at 50-hPa ($\phi \cdot \text{PC}_{50}$) instead of the first principal component of the zonal wind. This choice is supported by the findings of Baldwin and Thompson (2009), who showed that polar-cap averaged geopotential height is a useful quantity to investigate lead–lag relationships of the Northern Annular Mode in the troposphere and the stratosphere.

3.5  |  Statistical significance testing

Most results dealing with sets of selected time steps from the ERA-Interim reanalysis period are tested for significance with a bootstrapping method that creates sample sets of 1,000, 2,000 or 10,000 time steps for each original set and determines at each grid point whether the respective percentile score of the original set undercuts the 2.5% or lies above the 97.5% percentile of the random samples. We then state significance at the 95% level. Seasonality is considered by randomly selecting time steps in a time window of ±7 days around the original time step for each sample set and assigning a random year excluding the original year. Specific details are given in the respective figures and tables.

4  |  THE LARGE-SCALE FLOW DURING WEATHER EVENTS

In this section we characterise the tropospheric large-scale flow conditions during weather events affecting the European energy sector. Since the NAO is commonly used to describe the large-scale circulation in the Atlantic–European region, we first explore the mean NAO index during the different event types and regions (Table 2). In the northern European regions (Central Europe, Nordics and Eastern Europe) the mean NAO qualitatively varies similarly for different event types: high wind, high temperature and precipitation events tend to occur during mean positive NAO conditions except for precipitation events in Eastern Europe, which occur during mean neutral NAO conditions. Low temperature events tend to occur during mean negative NAO and low wind events during mean neutral NAO conditions. However, for most events the amplitudes are relatively low; only for high wind events in Central Europe and the Nordics is the mean NAO amplitude notably high, exceeding 0.9. In the southern European regions (Mediterranean and Balkans), weather events occur during mean neutral NAO conditions, indicating that these events are less directly affected by the NAO. Only low wind events tend to occur during moderately positive mean NAO conditions. While the actual distribution of the NAO during the different weather event categories somewhat reflects the mean NAO characteristics, a broad variability becomes apparent, suggesting that weather events might practically occur during any NAO state (Figure S2 in the supporting information). In essence, the exploration of the NAO during the different weather event categories suggests that the large-scale conditions during weather events are not simply characterised by their NAO projection, especially for regions that are farther away from the Atlantic such as Eastern Europe, the Mediterranean and the Balkans.

Maps of the mean 500-hPa geopotential height anomalies, which are exemplified for high and low wind events in Figure 4, shed more light on the large-scale flow conditions accompanying weather events in the different regions. Consistent with the mean positive NAO, high wind events in Central Europe, the Nordics and Eastern Europe are associated with a dipole of negative geopotential height anomalies to the north and positive geopotential height anomalies to the south of the respective region. This configuration indicates an anomalous westerly flow. It reaches a maximum at the strongest gradient of the geopotential height anomaly field which occurs just over the centre of these regions (Figure 4a–c) and enhances the climatological mean westerly flow (cf. Figure 1h). The position of the geopotential height anomaly differs across the regions. For Central European high wind events, the negative anomaly and thus the cyclone activity extends from southern Greenland towards the North Sea. This configuration also projects most strongly onto the NAO (Table 2) and resembles a superposition of the signature of the cyclonic AT, ZO and ScTr regimes (cf. Figures 1a–c and 4a). For the Nordics, the negative anomaly shifts poleward and eastward over the Nordic Seas, more closely resembling the ZO and ScTr
regimes (cf. Figures 1b,c and 4b). For Eastern Europe the negative geopotential height anomaly is centred over Scandinavia resembling the ScTr regime (cf. Figures 1c and 4c), consistent with weaker NAO+ conditions (Table 2). The pattern differs for the Mediterranean and the Balkans (Figure 4d,e). Here, a single negative geopotential height anomaly dominates and is located slightly to the north of the respective region, accompanied by weaker positive anomalies upstream and less closely resembling a specific regime.

For low wind events in Central Europe, the Nordics and Eastern Europe a positive geopotential height anomaly is located to the north of the respective region and resembles the blocked EuBL, GL and ScBL regimes, respectively (cf. Figures 1e–g and 3f–h). For the Mediterranean and the Balkans a positive geopotential height anomaly is centred over the respective region accompanied by negative anomalies up- and downstream, so that the pattern resembles to some degree the cyclonic ZO (Mediterranean) and AT (Balkans) regimes (cf. Figures 1a,b and 4i,j). Such differing patterns are also found for low and high temperatures and for precipitation events (Figure S3 in the supporting information). The amplitude of geopotential height anomalies is roughly half of that of a specific regime (cf. Figures 1 and 4), suggesting variability in the large-scale conditions causing the weather event, and corroborating the earlier finding, based on the NAO, that a weather event type in a specific region might occur during various different weather regimes.

A quantitative analysis of the weather regime frequencies during the different event types and regions (Figure 5) confirms that weather events occur during several preferred regimes. For example, high wind events in Central Europe preferably occur during the AT or ScTr regime, whereas in the Nordics and Eastern Europe high wind events occur most often during ZO or ScTr. In the Mediterranean high wind events mostly occur during the cyclonic AT regime, but also during the ScTr and the blocked GL regime. In the Balkans more than 40% of all high wind events occur during blocked regimes, but none of the regimes is clearly preferred. Low wind events in Central Europe most often (>65%) occur during EuBL. Also, in the Nordics and Eastern Europe the blocked EuBL, ScBL, and GL regimes dominate for low wind events. In contrast, low wind events preferentially occur during the ZO and AT regimes in the Mediterranean and the Balkans, respectively. For brevity, we do not discuss temperature and precipitation events here, but note that for each region and category weather events occur during a few preferred weather regimes. In addition, for most event types unusual (i.e., “no regime”) conditions are slightly less frequent than in the winter mean (<23%).

In summary, it is important to note that most of the weather event types in European regions do not exclusively occur in distinct NAO conditions. Rather, weather events take place during a few specific large-scale patterns which are reflected in weather regimes. The preferred regimes differ according to the event category and the considered region. Thus, via the large-scale conditions established through these regimes, there exist different pathways to a similar regional impact. Therefore, we conclude that weather regimes provide useful additional insights (as compared to only considering the NAO) to characterise the large-scale flow conditions during surface weather events. In the next section we explore how stratospheric conditions affect weather regimes which might modulate the different pathways to weather events and their frequency.

5 | STRATOSPHERIC INFLUENCES ON THE LARGE-SCALE FLOW AND ASSOCIATED WEATHER EVENTS

In winter the stratospheric polar vortex can affect the tropospheric circulation in the North Atlantic region, in particular the prevailing NAO state. For strong stratospheric polar vortex conditions the probability density function of the NAO shifts towards positive values and for weak stratospheric polar vortex conditions it shifts towards negative NAO values (Baldwin and Dunkerton, 2001). In Section 4 we described how surface weather events occur during different weather regimes, which are not necessarily directly related to the NAO (see the discussion of Figure S2a and Table 1 in Section 3). Here we explore how stratospheric conditions modulate the occurrence of weather regimes (Section 5.1) and weather events (Section 5.2). Furthermore, we discuss the impacts of extreme states of the stratosphere such as sudden stratospheric warmings (SSWs; Section 5.3).

| Region         | High wind | Low wind | High temp. | Low temp. | Precipitation |
|----------------|-----------|----------|------------|-----------|---------------|
| Central Europe | 1.01      | 0.05     | 0.57       | −0.46     | 0.58          |
| Nordics        | 0.92      | −0.15    | 0.77       | −0.33     | 0.85          |
| Eastern Europe | 0.69      | −0.05    | 0.61       | −0.26     | 0.01          |
| Mediterranean  | 0.12      | 0.68     | −0.03      | −0.1      | −0.25         |
| Balkans        | 0.08      | 0.40     | 0.04       | 0.08      | 0.06          |

TABLE 2 Mean NAO index during the different weather events
5.1 Modulation of weather regimes by the stratosphere

Based on the upper, middle and lower terciles of daily normalised 50-hPa polar-cap averaged geopotential height anomalies, we classify all winter days as either strong, neutral or weak stratospheric polar vortex states. Figure 2b shows the distribution of daily NAO conditions for the three terciles. Generally, the NAO distribution shifts towards positive values for strong stratospheric polar vortex states and to negative values for weaker stratospheric polar vortex states. There is, however, a strong overlap of NAO conditions during different stratospheric polar vortex states, and positive NAO conditions also occur in weak polar vortex states and vice versa. Moreover, weak stratospheric vortex conditions and SSW events feature rather neutral NAO conditions in the mean (right violin plots in Figure 2b,c).

Figure 6 shows weather regime frequencies for the different stratospheric conditions. It is striking that frequencies for regimes that project strongly onto the NAO (ZO, ScTr and GL, with mean NAO values of 1.01, 0.88 and −0.84, respectively; Table 1 and Figure 2a) are strongly modulated...
in different stratospheric conditions. Consistent with the shift towards positive NAO conditions during a strong stratospheric polar vortex, the cyclonic ZO and ScTr regimes are about twice as frequent (27% and 20%; left bars in Figure 6) as during the winter mean (13% and 11%; Table 1). During weak stratospheric conditions these regimes are very rare (4% and 1%; right bars in Figure 6). Consistent with its negative NAO projection, the GL regime behaves in the opposite way, with a doubling of its frequency during weak stratospheric polar vortex conditions (24% compared to 12% in the winter mean) and a suppression during strong stratospheric conditions (3%). The modulation of regime frequencies for the ZO, ScTr and GL regimes corroborates earlier studies that report a modulation of the NAO dependent on stratospheric conditions in winter (Baldwin and Dunkerton, 2001; Papritz and Grams, 2018; Domeisen, 2019; Figure 2b). The remaining regimes, AT, AR, EuBL, ScBL and the “no regime” category, occur during a broader range of either NAO state (Figure 2a). These four regimes show only little variability in frequency depending on the stratospheric conditions. The AR and ScBL regimes tend to be less frequent during strong stratospheric conditions and are slightly more frequent during neutral or weak stratospheric conditions (Figure 6). The cyclonic AT and the blocked EuBL regimes, however, show hardly any modulation in either strong or weak stratospheric conditions. These regimes always occur for about 10% of all winter days independently of the state of the stratospheric circulation. The robustness of the AT and EuBL regimes against stratospheric modulation is very important regarding the fact that the cyclonic (AT, ZO and ScTr) and blocked (AR, EuBL, ScBL and GL) regimes generally result in quite different weather conditions in Europe (Section 4). Thus an AT regime during weak stratospheric polar vortex conditions or a EuBL regime during strong stratospheric polar vortex conditions might result in unexpected weather conditions if one relied only on the favouring of GL (NAO– conditions) or ZO and ScTr (NAO+ conditions) regimes.

Before we investigate this in more detail with relation to weather event modulation, we discuss the time-lagged
response of weather regime occurrence to stratospheric conditions. Figure 7 shows the lagged frequency of weather regimes after a day in the strong (Figure 7a), normal (Figure 7b) and weak (Figure 7c) terciles of the climatological distribution of the polar vortex strength. The time lags are not independent, since stratospheric conditions often remain in a tercile for several consecutive days. However, this is taken into account by the design of the significance test (see the description in the caption of Figure 7). The frequency of ZO (GL) is already higher (lower) than its climatological frequency about 40 days before a day in the strong vortex tercile. Statistically significantly enhanced (reduced) frequencies are present from around lag $-25$ days to lag $25$ days (Figure 7a). The modulation of ScTr occurs more suddenly with an abrupt increase by 10% from lag $-5$ days to lag 0 days, reaching statistically significantly enhanced frequencies until lag 20 days and gradually declining thereafter. Other regimes show no strong time-lagged modulation. Likewise, neutral stratospheric conditions do not significantly modulate the frequency of any weather regime (Figure 7b). Weak stratospheric polar vortex conditions favour GL from about 20 days before to 30 days after a day in the tercile of weak polar vortex strength, with a statistically significant frequency modulation from about lag $-10$ days to lag $25$ days (Figure 7c). ScTr occurs less frequently in about the same time window. The suppression of ZO begins earlier (at about lag $-40$ days), with significantly reduced frequencies from lag $-20$ to lag $25$ days, but remaining less frequent ($-5\%$ compared to the winter mean) beyond lag $50$ days. We conclude that, due to the longevity of stratospheric conditions, the modulation of the ZO, ScTr and GL regimes has a memory of roughly $\pm 25$ days. Our results are consistent with the increased persistence of and enhanced transition probability into NAO$^+$ or NAO$^-$ during strong or weak stratospheric polar vortex states, respectively (Charlton-Perez et al., 2018). Thus a modulation of the frequency of the ZO, ScTr and GL regimes likely arises from changes in both the duration of the regime life cycle and the transition probabilities. Next we focus on a weather-event perspective and investigate how stratospheric conditions modulate surface weather events.

5.2 Modulation of weather events by the stratosphere

Different weather event types in European subregions occur to some degree during specific NAO states (Section 4 and Table 2). Thus, in the first instance one would expect stratospheric conditions to favour those weather events that are related to the NAO.

Figure 8 shows the frequency of stratospheric conditions during the different weather event categories. Event categories that project strongly onto NAO$^+$ (high wind events in all the northern European subregions, high temperature in Eastern Europe and the Nordics, and precipitation in the Nordics; cf. Table 2) preferentially occur during strong polar vortex conditions (blue colours in Figure 8a–c). The reverse is less evident. Low wind and low temperature events in northern European regions tend to preferentially occur during weak polar vortex conditions, but frequencies are only statistically significantly above climatology (one third) for low wind events in Eastern Europe and the Nordics (dark red colours in Figure 8a–c). This is not surprising, since low wind and low temperature events in northern European regions project less strongly onto negative NAO conditions than high wind and high temperature events onto positive NAO conditions (Table 2).

For the Mediterranean and the Balkans, stratospheric conditions only have a weak effect on weather event occurrence, which in most cases is not statistically significant. Mediterranean high wind and low wind events tend to occur more often during strong polar vortex conditions (around 40%; blue
colors in Figure 8d), while low temperature and precipitation events in both regions tend to prefer weak polar vortices (also around 40%; red colours in Figure 8d,e).

The stratospheric modulation of the prevailing NAO conditions indeed modulates the occurrence of surface weather events, particularly in those categories that show a stronger connection to the NAO. However, all weather event categories also occur independently of the stratospheric conditions. We now explore the detailed large-scale flow conditions for weather events during different stratospheric conditions using the weather regime perspective. Central European high wind events occur in the cyclonic AT, ZO or ScTr regimes (Figure 5). During strong stratospheric polar vortex conditions, the ZO or ScTr regimes are strongly favoured (Figure 6) and these then also account for more than 70% of all Central European high wind events (lag 0 days; Figure 9a). The AT regime accounts only for about 20% of these events during strong stratospheric polar vortex conditions—half the climatological frequency (cf. Figure 5a). In contrast, during weak stratospheric polar vortex conditions when ZO and ScTr are strongly suppressed (Figure 6), the AT regime accounts for almost all Central European high wind events (Figure 9c). Thus, the AT regime that is unaffected by stratospheric modulation (Figure 6) provides a pathway to Central European high wind events during weak stratospheric conditions, when one would not typically expect strong cyclonic activity and associated high wind speeds.

We found different preferred regimes for most of the weather event categories depending on the stratospheric conditions (Table 3). This link is consistent with the reported two to three preferred regimes for each category (Figure 5) and their stratospheric modulation (Figure 6). In the following, key findings are discussed based on Table 3. High wind events in Eastern Europe alternate between the ZO and AT regimes during strong and weak stratospheric conditions. In the Mediterranean this alternation is between ScTr and GL, while in the Balkans high wind events dominantly occur during the AT, AR and EuBL regimes, which are not constrained by the state of the stratosphere. High temperature events in the northern regions (Nordics, Central Europe and Eastern Europe) occur in westerly flow patterns. Thus, in strong vortex conditions they occur during ZO (which is enhanced during strong vortex conditions), while during neutral and weak vortex conditions high temperature events preferentially occur during AT (Table 3), since AT is not suppressed by weak vortex conditions (in contrast to ZO). In the southern European regions high temperature events mainly occur during AT and GL regimes. The EuBL regime occurs similarly frequently in all stratospheric conditions (Figure 5) and is responsible for low wind events in Central Europe, irrespective of the stratospheric conditions. Likewise, it provides a pathway to low wind events in Eastern Europe during strong polar vortex conditions and in the Mediterranean when the stratospheric polar vortex is weak. For most regions, the GL
FIGURE 9 Lagged weather regime frequencies for Central European high wind events that occur during strong, neutral and weak (top, middle, and bottom) stratospheric polar vortex conditions in winter (DJF). The x-axis indicates lag in days, with lag 0 corresponding to the start of the high wind event. The frequencies are computed for a 5-day period and are shown daily centred on the respective 5-day period. Bold lines indicate statistically significant values at the 95% level from the distribution of 10,000 random sample sets of time steps. As for the original set, we compute the mean regime frequency for a 5-day period centred around each random date of the sample set.

regime is the preferred pathway to produce low temperature events during a weak stratospheric polar vortex, but the AR and EuBL regimes sometimes cause low temperature events during strong stratospheric polar vortex conditions. Also, for precipitation events in all regions we see a consistent link between the different weather regime pathways and their stratospheric modulation.

Overall, of the 25 event/region combinations in Table 3, 23 have different regime pathways in different stratospheric conditions. The two exceptions are low wind events in Central Europe and high wind events in the Nordics. Low wind events in Central Europe are dominated by EuBL, a regime that occurs with the same frequency during all stratospheric conditions; thus the occurrence frequency of low wind events is not constrained by the stratospheric conditions. High wind events in the Nordics, on the other hand, occur very favourably during ZO and are thus very rare during weak polar vortex conditions. In the few instances where they did occur in weak polar vortex conditions (only 3 out of 52), they happened during the rare instances where a ZO regime occurred in weak vortex conditions.

We conclude that weather regimes are essential in establishing the large-scale flow conditions in which surface weather events occur. Each weather event category has several preferred weather regimes. The occurrence of these preferred regimes is modulated differently by the prevailing stratospheric conditions and some are unaffected by stratospheric modulation. The existence of multiple pathways to a weather event type, via the preferred regimes and their opposing stratospheric modulation, explains why extreme weather events can occur during any stratospheric condition.

5.3 Pathways to unexpected weather events following extreme SPV states

We finish with an investigation of the weather regime and weather event occurrence around extreme states of the stratosphere. These are thought to provide a window of extended-range predictability in the troposphere (Baldwin and Dunkerton, 2001) and are therefore of particular interest for subseasonal weather forecasting (Tripathi et al., 2015b). Extreme states are identified following Limpasuvan et al. (2004, 2005), as described in Section 2. While the foregoing analysis was based on the core winter months (DJF) we now investigate the extended winter period from November to April (NDJFMA) in order to enlarge our sample size. In total we identified 44 strong and 33 weak extreme SPV events. It should be noted that the relatively small sample size might hide some stratosphere–troposphere coupling; nevertheless we focus on statistically significant signals in the following discussion.

Strong polar vortex events tend to go hand-in-hand with mean positive NAO conditions and weak events with mean neutral-to-negative NAO conditions. However, the NAO distribution during extreme polar vortex events spans a broad range of positive and negative values (Figure 2c). Figure 10 shows the composite polar global average (north of 60°N) of normalised geopotential height as a time–height plot centred on extremely strong (negative geopotential height) SPV events. Already 40 days prior to the strong vortex event, an anomaly emerges in the stratosphere coupled with the troposphere (Figure 10a). In that time window we see slightly enhanced frequencies of the ZO regime (Figure 10b). At the time of the strong vortex event there is a strong downward penetration of the negative anomaly into the troposphere that becomes weaker at around 15 days and strengthens again from lag 20 to 35 days. From about lag −10 days to lag 35 days the ZO regime is statistically more frequent, reaching 30% at lag 0 days. From lag 0 to 10 days and again from lag 20 to 40 days the ScTr regime is also statistically significantly enhanced, such that these cyclonic regimes together reach frequencies of 40–50%. The GL regime is suppressed from
TABLE 3 Summary of the most frequent weather regimes occurring during weather events in the three climatological terciles of the polar-cap averaged geopotential height anomaly at 50 hPa

| Stratospheric/SPV state | High wind | Low wind | High temp | Low temp | Precipitation |
|------------------------|-----------|----------|-----------|----------|---------------|
| **Central Europe**     |           |          |           |          |               |
| Strong                 | ScTr (30) | EuBL (14)| ZO (20)   | GL (4)   | ScTr (19)     |
| Neutral               | AT (11)   | EuBL (12)| AT (10)   | ScBL (15)| AT (17)       |
| Weak                  | AT (9)    | EuBL (17)| AT (16)   | GL (16)  | AT (16)       |
| **Nordics**           |           |          |           |          |               |
| Strong                 | ZO (27)   | AR (7)   | ZO (21)   | AR (5)   | ScTr (34)     |
| Neutral               | ZO (12)   | AT (17)  | AT (10)   | GL (20)  | ScTr (7)      |
| Weak                  | ZO (3)    | GL (22)  | AT (10)   | GL (20)  | AT (8)        |
| **Eastern Europe**    |           |          |           |          |               |
| Strong                 | ZO (17)   | EuBL (10)| ZO (20)   | AR (9)   | AR (13)       |
| Neutral               | ScTr (14) | GL (6)   | AT (7)    | ScBL (14)| GL (21)       |
| Weak                  | AT (5)    | GL (25)  | AT (12)   | GL (13)  | GL (14)       |
| **Mediterranean**     |           |          |           |          |               |
| Strong                 | ScTr (22) | ZO (21)  | AT (11)   | AR (15)  | AR (12)       |
| Neutral               | GL (13)   | ZO (16)  | GL (17)   | AR (11)  | ScBL (16)     |
| Weak                  | GL (16)   | EuBL (11)| GL (16)   | GL (18)  | GL (20)       |
| **Balkans**           |           |          |           |          |               |
| Strong                 | AT (13)   | ZO (15)  | AT (11)   | EuBL (7) | AR (15)       |
| Neutral               | AR (17)   | AT (16)  | AT (14)   | ZO (15)  | ScTr (8)      |
| Weak                  | EuBL (14) | AT (10)  | GL (18)   | EuBL (18)| GL (20)       |

Note: “Strong” corresponds to the tercile of days with the most negative 50-hPa geopotential height anomalies, “weak” to the tercile with the most positive 50-hPa geopotential height anomalies and “neutral” to the tercile between the strongest and weakest polar vortex conditions.

In contrast to strong events, the geopotential height anomalies during extremely weak SPV events occur abruptly (Figure 11a). The positive geopotential height anomalies emerge in the upper stratosphere around lag −5 days and coincide with a surface signal within a few days. In the troposphere there are weak positive geopotential height anomalies that are already intermittently present from about lag −40 days before anomalies in the stratosphere emerge at around lag −20 days. Also, starting from lag −40 days the occurrence of the GL regime is enhanced to a frequency of about 20%. From lag −15 days before the event, the ScBL and AT regimes become more frequent, peaking at 20% at lag −5 days and lag 0 days, respectively. The positive geopotential height anomaly then persists in the stratosphere for 50 days. From about lag 0 to 30 days and again from about lag 40 to 50 days geopotential height is also anomalously high in the troposphere. These episodes of strong stratosphere–troposphere coupling go hand-in-hand with a significant increase in the frequency of the GL regime, peaking at 28% around lag 30 days. In the period lag 30–40 days the tropospheric signal vanishes and the AT and EuBL regimes become more frequent, before GL re-emerges as the most frequent regime together with the second period of stratosphere–troposphere coupling from lag 40 to 50 days.

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**TABLE 4**  Frequency of days assigned to a weather event in the 40 days following a strong stratospheric polar vortex event with respect to the expected frequency by chance

| Strong polar vortex events | Central Europe | Nordics | Eastern Europe | Mediterranean | Balkans |
|---------------------------|----------------|---------|----------------|---------------|---------|
| High wind                 | 1.8*           | 1.9*    | 1.4            | 1.1           | 0.8     |
| Low wind                  | 0.8            | 0.5*    | 0.9            | 1.5*          | 1.1     |
| High temp.                | 1              | 1.4     | 1.2            | 0.8           | 0.7     |
| Low temp.                 | 0.6*           | 0.9     | 1.1            | 1.1           | 0.9     |
| Precipitation             | 0.9            | 1.6*    | 0.8            | 0.7           | 1.3     |

Note: A value of 1 means that a weather event occurred as frequently as expected by chance after a strong vortex event. A value of 0.5 means that the weather event only occurred half as frequently as expected by chance. A value of 1.8 means that a weather event occurred 80% more frequently than expected by chance. Bold numbers accompanied by an asterix are statistically significantly more or less frequent than expected by chance on a 95% confidence level, according to the following bootstrapping method. In 10,000 repetitions we sampled as many 40-day periods in the extended winter period (November–April [NDJFMA]) as there were strong polar vortex events (44). In the same repetition we also randomly sampled as many periods as there were weather events of a certain type with the same duration distribution as the weather events. From these samples we derived both the expected frequency by chance and the statistical significance thresholds of weather events in the 40-day period following the polar vortex events.

**FIGURE 10**  (a) Composite of standardised mean polar-cap averaged (north of 60°N) geopotential height anomalies shown as a time–pressure height diagram for strong SPV events. The geopotential height anomalies are divided on each level by the 95% significance threshold based on the Student’s t-test. Anomalies greater (smaller) than 1 (−1) are thus statistically significant. The x-axis shows the time lag with respect to the start of the polar vortex event. (b) Lagged weather regime frequencies with respect to the start of the polar vortex events (lag 0), computed for a 5-day period and shown daily centred on that period. Bold lines indicate statistical significance at the 95% level. Statistical significance is tested as in Figure 9.

Variability in surface weather has strong impacts on weather-dependent socio-economic activities. This study focuses on unusual larger-scale surface weather conditions and their potential impacts on the European energy sector in winter, and investigates how such regional weather events are affected by large-scale circulation patterns and the stratosphere.

Five weather event types are defined based on area-averaged surface weather variables for five European subregions that reflect the regional energy markets. For each region, high/low temperature, high/low wind and precipitation events are identified if the area average exceeds/undercuts the climatological daily 97%/3% percentile (smoothed by a 90-low-pass filter) for at least 3 consecutive days.

We find that only a few event types in specific regions prefer a distinct NAO phase (such as low wind events in the Mediterranean and the Balkans and high wind events in Central Europe during NAO+). In fact, all weather event types in the different regions occur within a broad range of prevailing NAO conditions, such that the NAO alone is a rather weak indicator of the probability of specific weather events. The different weather event types in each region occur during several (one to three) specific large-scale flow patterns that are well captured by a definition of seven year-round Atlantic–European weather regimes. These provide different physical pathways to a specific event type. Two of the seven regimes, the zonal (ZO) and Scandinavian trough (ScTr)
regimes, clearly project onto NAO+, while only Greenland blocking (GL) is predominantly NAO−. The remaining four regimes (Atlantic trough [AT], Atlantic ridge [AR], European Blocking [EuBL] and Scandinavian blocking [ScBL]) have a weak relation to the NAO.

It is known that the probability density function of the NAO shifts with the intensity of the SPV (Baldwin and Dunkerton, 2001). We consistently found a strong increase (decrease) in the frequency of the ZO and ScTr regimes and the reverse for the GL regime during strong (weak) SPV conditions. However, the frequency of the AT, AR, EuBL and ScBL regimes, which show no clear projection on either NAO phase, also varies less under different stratospheric conditions. These regimes can thus provide pathways to unexpected weather events during different stratospheric vortex states. For example, Central European high wind events prefer the AT, ZO and ScTr regimes. Although ZO and ScTr are strongly suppressed and GL is strongly enhanced during weak SPV states, high wind events in Central Europe might still occur due to an AT regime. This behaviour is particularly relevant after extreme weak SPV states (such as sudden stratospheric warmings), which have received a lot of attention recently (particularly from the energy industry) as a potential window of extended-range predictability. Our results suggest that the simple reasoning that after an SSW event we should expect a negative NAO period with below-normal temperatures is potentially misleading, because AT is the second most abundant weather regime after an anomalous weak SPV, and AT is actually milder, windier and wetter than normal for northwestern Europe.

We conclude that understanding the connection between stratospheric conditions and the NAO, as well as an improved forecast skill for predicting the NAO, are not sufficient to correctly predict surface weather conditions across all of Europe on subseasonal to seasonal time scales. To fully exploit sources of subseasonal predictability, such as the stratosphere, large-scale flow variability imposed by weather regimes and its modulation by climate modes needs to be predicted accurately. Therefore, we need a better understanding of and improved numerical weather forecasts for weather regime life cycles which might also help to better predict regional surface weather conditions on subseasonal time scales.

**Figure 11** As Figure 10, but for weak SPV events

**Table 5** As Table 14, but for weak polar vortex events

| Weak polar vortex events | Central Europe | Nordics | Eastern Europe | Mediterranean | Balkans |
|--------------------------|----------------|---------|----------------|--------------|--------|
| High wind                | 0.7            | 0.5*    | 0.4*           | 1            | 0.9    |
| Low wind                 | 0.9            | 1.8*    | 1.5*           | 0.5*         | 1.1    |
| High temp.               | 1.2            | 0.7     | 1              | 1            | 1.3    |
| Low temp.                | 0.9            | 1.4     | 1              | 0.9          | 0.9    |
| Precipitation            | 1.1            | 0.5*    | 0.9            | 1.3          | 1.2    |
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Additional supporting information may be found online in the Supporting Information section at the end of this article.

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