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Surface hazards in North-west Europe following sudden stratospheric warming events

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Abstract
Sudden stratospheric warmings (SSWs) have been linked to surface temperature anomalies, but how these connect to changes in the likelihood of specific weather extremes and their associated weather patterns remains uncertain. While, on average, it is true that cold surface temperatures follow SSW events, particularly in Northern Europe, there is considerable event-to-event variability. Over the British Isles and Central Europe, only around 45% of SSWs are followed by a colder than average period and a negative phase of the North Atlantic Oscillation, cautioning against an over-generalised approach to surface anomalies associated with SSWs. Focussing on more hazardous weather, which in winter is associated with cold extremes, we use reanalysis data to consider how SSWs impact temperature-related hazards; namely the frequency of snowy days, frost days and spells of extreme cold weather in 12 major European cities. In general, SSWs are associated with an increased risk of snow across most of western Europe, and that this is particularly significant in milder, more maritime locations such as London where in reanalysis, snowfall days are 40% more likely after an SSW. However, there is considerable variation in surface temperature anomalies between SSW events; the third of SSWs with the warmest surface anomalies are statistically more likely to have a decreased risk of snow, frost and persistent cold spells compared with non-SSW time periods. These warmer events are associated with a different temperature anomaly pattern, which is consistent in both reanalysis data and large ensemble CMIP6 models. We further show that these warm surface temperature anomaly SSWs are becoming more frequent, a trend which is consistent with background global warming. The varied surface anomalies associated with SSWs highlights the need to study their impacts in a probabilistic sense, and motivates further work to enable better prediction of the impacts of a given event.

1. Introduction

Cold winter weather extremes over Northern Europe can be driven by subseasonal variability in the stratosphere (e.g. Domeisen and Butler 2020). During winter a stratospheric polar vortex develops over the Arctic, with cold air surrounded by strong westerly winds. However, the vortex can break down, with rapid warming (up to 50 K in a few days, e.g. Butler *et al* 2017), and the winds may reverse in the zonal mean. Such events are known as sudden stratospheric warmings (SSWs; Scherhag 1952, Butler *et al* 2015, Baldwin *et al* 2021). This pattern of anomalies can influence the surface over a period of a month or so (Baldwin and Dunkerton 2001), and may result in prolonged severe cold weather in certain regions (Domeisen and Butler 2020, Hall *et al* 2022), particularly at higher latitudes over Eurasia (Kolstad *et al* 2010), as the eddy-driven jet and North Atlantic storm track shift southwards, with a more negative North Atlantic Oscillation (NAO) (Kidston *et al* 2015). The storm track shift can result in increased likelihood of storms entering the Mediterranean region, with consequent flooding (Afargan-Gerstman et al 2020). In reanalysis data and model output, around 40%–50% of winter European cold spells were preceded by stratospheric dynamical disturbances (Kolstad et al 2010, Tomassini et al 2012).

The most recent SSW occurred in January 2021 (Lee 2021, Wright et al 2021) and was followed by snow over Athens, and the lowest UK temperature since 1956 (−23 °C at Braemar, Scotland (www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2021/2021-a-year-in-weather-a-review)). Prior to this, the SSW in February 2018 was associated with cold, snowy weather over Europe in early March (Karpechko et al 2018, Overland et al 2020). Such extreme cold events have significant societal impacts, disrupting transport systems, affecting energy supply and demand (Beerli and Grams 2019) and increasing cold-related mortality (Charlton-Perez et al 2021). The 2018 event resulted in a large peak in UK insurance claims during the first quarter of the year (£328 million, of which £193 million resulted from water escape such as burst pipes) (Association of British Insurers 2019, p8).

However, it would be incorrect to assume that SSW will always result in extreme cold conditions in Europe. For example, the January 2019 event is less well-known than the 2018 SSW, and was followed by much weaker surface anomalies (e.g. Butler et al 2020). Indeed, about one third of SSWs are associated with a more poleward shift in the jet (Afargan-Gerstman and Domeisen 2020), or have been identified as having no tropospheric signature (Karpechko et al 2017, Domeisen 2019).

In a warming world, European winters are projected to become wetter and milder (e.g. King and Karoly 2017) and it is crucial to understand whether SSWs will continue to have the same surface impacts in future. Climate change can affect SSW surface impacts in two ways; (1) more or less frequent SSWs affecting the frequency of surface impacts or (2) changes in the surface response to SSWs. There is considerable uncertainty regarding point 1 (e.g. Kim et al 2017, Ayarzaguena et al 2018, 2020), and average surface impacts have been found not to change under a range of future scenarios (Ayarzaguena et al 2020, Rao and Garfinkel 2021). However, these recent studies are limited to studying changes in tropospheric impacts that are identified solely from circulation changes, such as sea-level pressure (SLP) and zonal winds.

In this study we examine the European winter season surface anomalies associated with SSWs in reanalysis and assess the robustness of the results with data from the historical simulations of the Coupled Model Intercomparison Project 6 (CMIP6; Eyring et al 2016) models with a relatively large number of ensemble members. We also compare several climate indices and changes in weather patterns following SSWs to provide estimates of the likelihood of severe conditions after an SSW. We build on recent studies by focussing on the probability of different surface weather following an SSW, not just the mean anomalies, as well as by studying impact-relevant metrics such as surface temperature extremes and snowfall.

2. Methods and data

We use the new ERA5 reanalysis (Hersbach et al 2020), including a preliminary extension back to 1950. SSWs are identified following Charlton and Polvani (2007), with the onset identified as the date of zonal-mean zonal wind reversal at 10 hPa, 60°N. In addition, 20 consecutive days of westerlies are required between events, and final warmings are not considered. The SSWs identified in ERA5 mostly correspond to the events listed in the Sudden Stratospheric Warming Compendium (Butler et al 2017), with the addition of five 'new' events prior to 1958 and additional SSWs in March 2018, January 2019 and 2021, giving a total of 47 events.

We repeat some of the analysis with CMIP6 models where data are available for more than ten ensemble members. Here we use the UK Earth System Modelling Project (UKESM1-0-LL), Centre National de Recherches meteorlogiques (CNRM-CM6-1) and the Institut Pierre Simon Laplace (IPSL-CM6A-LR) models, taking the historical simulations (1850–2014) from each ensemble member, and combining them to find mean values of a large sample of SSWs, identified following Charlton and Polvani (2007). SSW frequencies in models and reanalysis are summarised in table 1. These data are obtained from the Centre for Environmental Data (CEDA) repository for UKESM and from the Pangeo cloud-storage repository in the case of the other two models. At the time of this study, these were the only models providing the necessary data across a large number of ensemble members.

We use SLP and 2 m temperature (2 mT) fields to assess patterns associated with surface impact of SSWs and calculate daily anomalies from climatology (1951–2000). We also use daily snowfall to analyse the number of days with snow in specific locations. Snow schemes in reanalysis are sensitive to model-simulated precipitation and do not account for important processes such as snow-vegetation interactions and blown snow (Mortimer et al 2020) so results should be treated with caution. Frost and ice days are defined as days on which the daily minimum and maximum temperatures respectively are less than 0 °C. We use the cold spell duration index (CSDI) from the expert team on climate change detection and indices (Peterson 2005), to identify any changes in persistent cold spells following SSWs. The CSDI is the frequency of days within a defined period (in this case the 61 days post-SSW or in a winter season) where for at least six consecutive days, the daily minimum temperature falls below the tenth

Table 1. Summary of SSW frequencies in CMIP6 models and ERA5.

Model	Members used	Total SSWs	SSWs/decade
UKESM	16	1413	5.38
CNRM-CM6-1	28	2758	6.00
IPSL-CM6A-LR	31	4016	7.90
ERA5	NA	47	6.62

percentile for that particular day of the year, based on 1951–2000 climatology. The NAO index is calculated as the first empirical orthogonal function of daily SLP over 20–80°N, 90°W–40°E, from November to May (Hurrell 1995).

While the NAO explains around 40% of the variance of SLP over this region, it is also the case that different weather patterns with different impacts can be associated with other indices of atmospheric variability (Hall and Hanna 2018). We therefore identify changes in more detailed weather patterns associated with SSWs. The UK Met Office identifies 30 daily weather patterns over Europe and the North Atlantic based on a k-means clustering of SLP anomalies (Neal *et al* 2016). These patterns have been grouped by similarity into eight aggregated patterns which indicate broader-scale flow regimes. See Neal *et al* (2016) for details of the methods used. Each day of the period is assigned to a specific weather pattern, based on a distance measure (the grid-point average-sum-of-squares difference between the reanalysis field and the weather patterns). We assess changes in frequency of the eight aggregated weather patterns over the 61 day window from SSW onset, compared with non-SSW days. This 61 day window is used throughout for assessing SSW associations with 2 mT, SLP, snowfall, CSDI, minimum and maximum temperatures.

We use the relative risk ratio (RR) to quantify the changes in probability of a range of conditions following an SSW. If the probability of an event occurring in non-SSW days is $P_0 = p(\text{event} \mid \text{no SSW})$ and the probability of the event after an SSW is $P_1 = p(\text{event} \mid \text{SSW})$, then the RR of the event occurring after an SSW is P_1/P_0.

Significance is assessed for composites using a bootstrap method. Resampling is taken from all winter years, selecting a start date for a window of 61 consecutive days, to represent an event, 47 'events' being selected, or in the case of warm and cold terciles, 16 events. The resampling process is completed 1000 times for each month. For spatially averaged quantities, 95% confidence intervals are applied using the Agresti–Coull correction of the Wald confidence interval for proportions (Agresti and Coull 1998), which is more stable than the standard Wald method.

3. Results

Following SSW onset, there is considerable inter-event variability in daily 2 mT anomalies averaged over the British Isles, with mean anomalies ranging from −1.64 K to 1.78 K (figure 1(b)). To better analyse these inter-event differences in surface anomalies, SSW terciles are created based on the ranking of the mean 2 mT temperature anomaly for each SSW over the 61 day window over the British Isles. The upper and lower terciles (hereafter warm-anomaly and cold-anomaly events) each contain 16 events, with 15 events in the central tercile (figure 1). The nomenclature illustrates an association between SSWs and subsequent warm or cold anomalies, without implying causation. Indeed, we note that any surface temperature anomaly following an SSW will be comprised of both a component forced by the SSW and unrelated internal variability. Qualitatively very similar results are obtained if the terciles are derived by averaging over NW Europe (tables S1 and S2). Results for averaging over Scandinavia and Central Europe are presented in figure S1. While 21 SSWs have mean negative temperature anomalies over the British Isles post-onset (figure 1(b)), 26 are followed by mean positive temperature anomalies, which confounds the popular expectation that SSWs are followed by cold extremes. Averaging over the British Isles, cold-anomaly events are associated with a more negative NAO after SSW onset (mean NAO, −0.5), while warm-anomaly events have both positive and negative NAO phases (figure 1(b)) and do not therefore project strongly onto the NAO (mean NAO, 0.05). For the British Isles and Central Europe, only 45% of SSWs are associated with both a negative NAO and lower temperatures (figure 1(b)) (for Scandinavia it is 51%), cautioning against an over-generalised approach to surface anomalies associated with SSWs. The warm-anomaly events do not show the hemispheric features associated with SSWs (warm anomalies over the Middle East and Baffin Bay, cold anomalies over Eurasia and the eastern United States). Instead there are warm temperature anomalies across most of the hemisphere (not shown). Furthermore, split and displacement SSWs, defined using the method of moments (Seviour *et al* 2013, Gerber *et al* 2022) are evenly distributed between warm- and cold-anomaly events (tables S1 and S2). We find no association between the strength and duration of the 10 hPa zonal wind anomaly and the nature of associated surface impacts (not shown).

Fourteen out of 16 cold-anomaly events are pre-1990, while warm-anomaly SSWs increase in frequency after 1990 (figure 1(a), tables S1 and S2) and there are significant ($p < 0.05$) positive trends in the 2 mT anomalies associated with SSW events over all three regions (figure S2). These are very close to the trend in winter temperature anomalies over the same period, which is largely driven by anthropogenic climate change (not shown). Detrending the temperature data provides a more even distribution of cold-and warm-anomaly events through time (figure 1(c)).

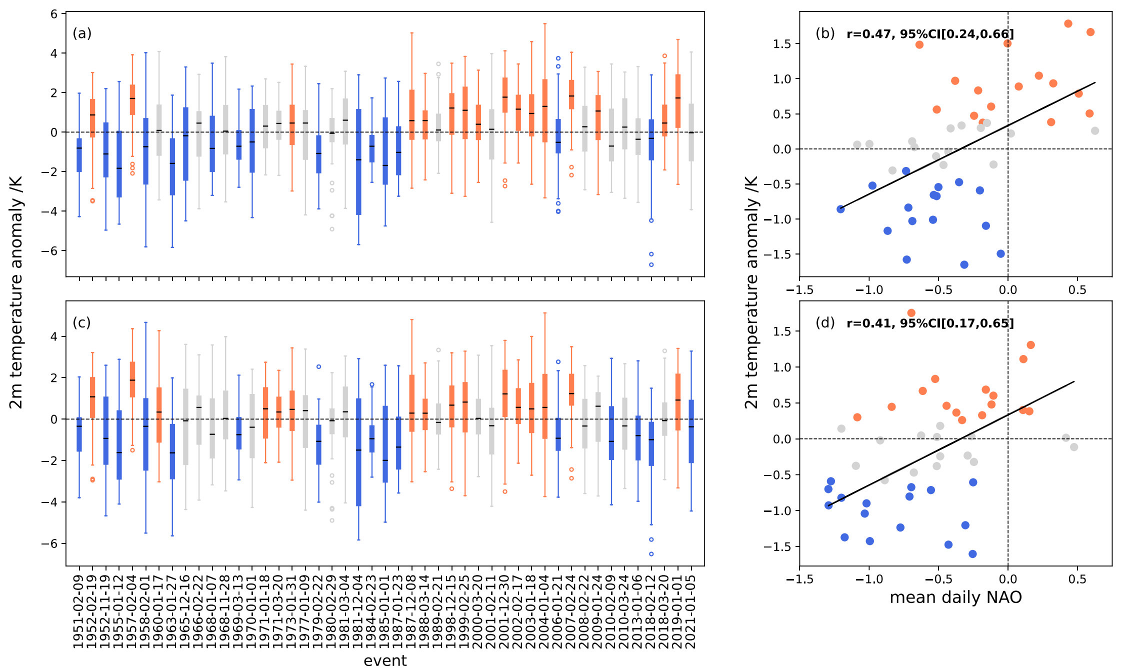

Figure 1. (a) Boxplot of daily mean 2 m temperature anomalies over the British Isles region (−11–2° E, 50–60° N) in the 61 day window from onset date to 60 d after SSW onset, for each SSW from 1950–2021. Solid horizontal line in each box indicates the median, box limits are at the first (Q1) and third (Q3) quartile. (b) Scatter plot of mean 2 mT against mean NAO averaged over the 61 day window from SSW onset. Correlation confidence intervals calculated by a bootstrap method with 10 000 resamples. (c) and (d) as for (a) and (b), but using data where a linear trend is removed.

The three CMIP6 models show a similar increase in warm-anomaly events over time, which is particularly marked from 2000 onwards (figure 2). The large number of historical simulations for each model (table 1) reduces the impact of internal variability. A quadratic detrending is used for the CMIP6 models (figures 2(d)–(f)), due to the longer time-period and the more recent emergence of the global warming signal. This produces a more even temporal distribution of the SSW terciles similar to detrending the reanalysis. These results indicate that the temporal distribution of warm- and cold-anomaly events is related to the mean change in winter temperatures attributable to anthropogenic climate change.

To further investigate the inter-event variability of anomalies, we now examine the spatial patterns of temperature anomalies associated with SSWs. For all SSW events in reanalysis and the three CMIP6 models, the strongest negative temperature anomalies are over Scandinavia (figure 3), while to the south and west milder conditions prevail, with weakly positive temperature anomalies over Spain and the Mediterranean, in agreement with King *et al* (2019). SLP anomalies resemble the negative NAO (e.g. Hurrell and Deser 2010). The signal is weak in reanalysis, with no significant temperature anomalies for all SSW (figure 3(a)).

The cold-anomaly events (figure 3(b)) are characterised by an intensification and eastward extension of the negative NAO-like SLP anomaly differences seen for all SSWs, with much stronger significant negative temperature anomalies stretching westwards from northern Europe and Scandinavia to the British Isles, also evident in the CMIP6 models (figures 3(e), (h) and (k)). However, the patterns for warm-anomaly events are not mirror-images of the cold-anomaly events, suggesting an asymmetric surface response, as can be seen from the different NAO responses shown in figure 1(c). The SLP anomaly fields shows weak anomalously low pressure further north in the North Atlantic, so that warm air is advected from the southwest, creating warmer conditions than usual over most of Europe, with the centre of positive temperature anomalies shifted south and west compared with that for cold-anomaly events (figure 3(c)). In reanalysis the warm temperature anomalies are centred over Denmark and western Norway, compared with a more central European location in the CMIP6 models (figures 3(f), (i) and (l)), with CNRM also showing stronger positive temperature anomalies over Iceland and the Norwegian Sea.

In previous studies, (Karpechko *et al* 2018, Domeisen 2019) several SSW have been identified as having no surface impact, using circulation-based metrics such as the NAO or norther annular mode (NAM). Most of these are warm-anomaly events, but have no surface signal by definition, as a surface

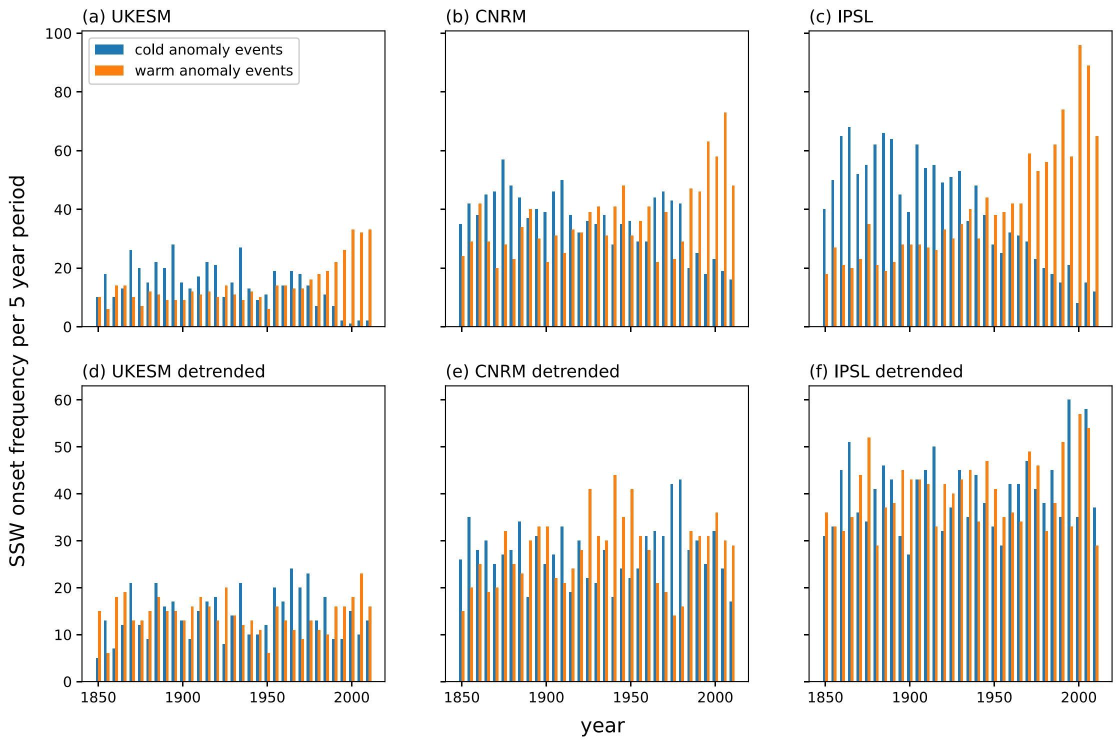

Figure 2. (a)–(c) Frequency of warm- and cold anomaly events occurring in five year periods in three CMIP6 models. (d)–(f) repeated with data detrended using a second-order polynomial.

impact is defined as a negative NAO or NAM. However, here we show that these events are associated with significant warm temperature anomalies, which are also evident in CMIP6 models.

It is notable that the detrended anomaly pattern for all SSWs (figure 3(m)) shows broader significant cold anomalies over northern Europe, once the signal of anthropogenic climate change is removed. The surface anomaly patterns for warm- and cold-anomaly SSWs are very similar when detrended ERA5 data are used (figures 3(n) and (o)). This suggests that the distinctive temperature anomaly pattern associated with warm-anomaly events is not a result of climate change. This is confirmed by examining 2 mT anomaly patterns for different 50 year periods in the UKESM model (figure S3). While Ayarzaguena *et al* (2018), Ayarzaguena *et al* (2020) and Rao and Garfinkel (2021) find no consensus as to future changes in tropospheric circulation anomalies associated with SSWs, here by comparing ERA5 data (figures 3(a)–(c)) with detrended ERA5 data (figures 3(m)–(o)) the climate change signal manifests as an increased magnitude of temperature anomalies for warm-anomaly events, with cold-anomaly events and all SSW impacts decreasing in magnitude, although the spatial patterns remain broadly similar.

Given that warm temperatures during the UK winter are largely not hazardous to society, we next analyse a range of indicators of cold weather hazards associated with SSWs for 12 representative European cities, as weather disruption to urban areas will be significantly more costly than in rural settings. Data are obtained from a 1° grid cell containing the city, and so while we use the term ‘city’ we really mean city and surrounding area. Due to the trapping of heat in cities, known as the urban heat island effect, the temperatures in the city will be warmer and fewer instances of snow, frost and ice days will be experienced, although this effect is poorly represented in ERA5 (e.g. Nogueira *et al* 2022).

In ERA5, SSWs are associated with changes in frost, ice and snow days, and changes in the CSDI (figure 4) and are summarised in table 2.

Snow, frost and ice days occur independently of SSWs across much of Europe with more continental and northern locations having more frequent snow, frost and ice days irrespective of modulation by SSWs (figures 4(a)–(c)) compared with cities that are further south (Rome, Barcelona) or west (Dublin, Glasgow, London, Paris). Significant increases in snow day frequency after SSWs occur across much of Europe, with the exceptions of Rome, Barcelona and Vienna (the more southerly cities) and Glasgow. The greatest relative RR of snow days after SSWs occurs in the more western cities, where winters are milder; snowy days are around 30% more likely (RR = 1.3) in Dublin and London compared with non-SSW days. SSWs are associated with the westward extension of cold temperature anomalies, which when encountering the warmer maritime air results in increased snowfall.

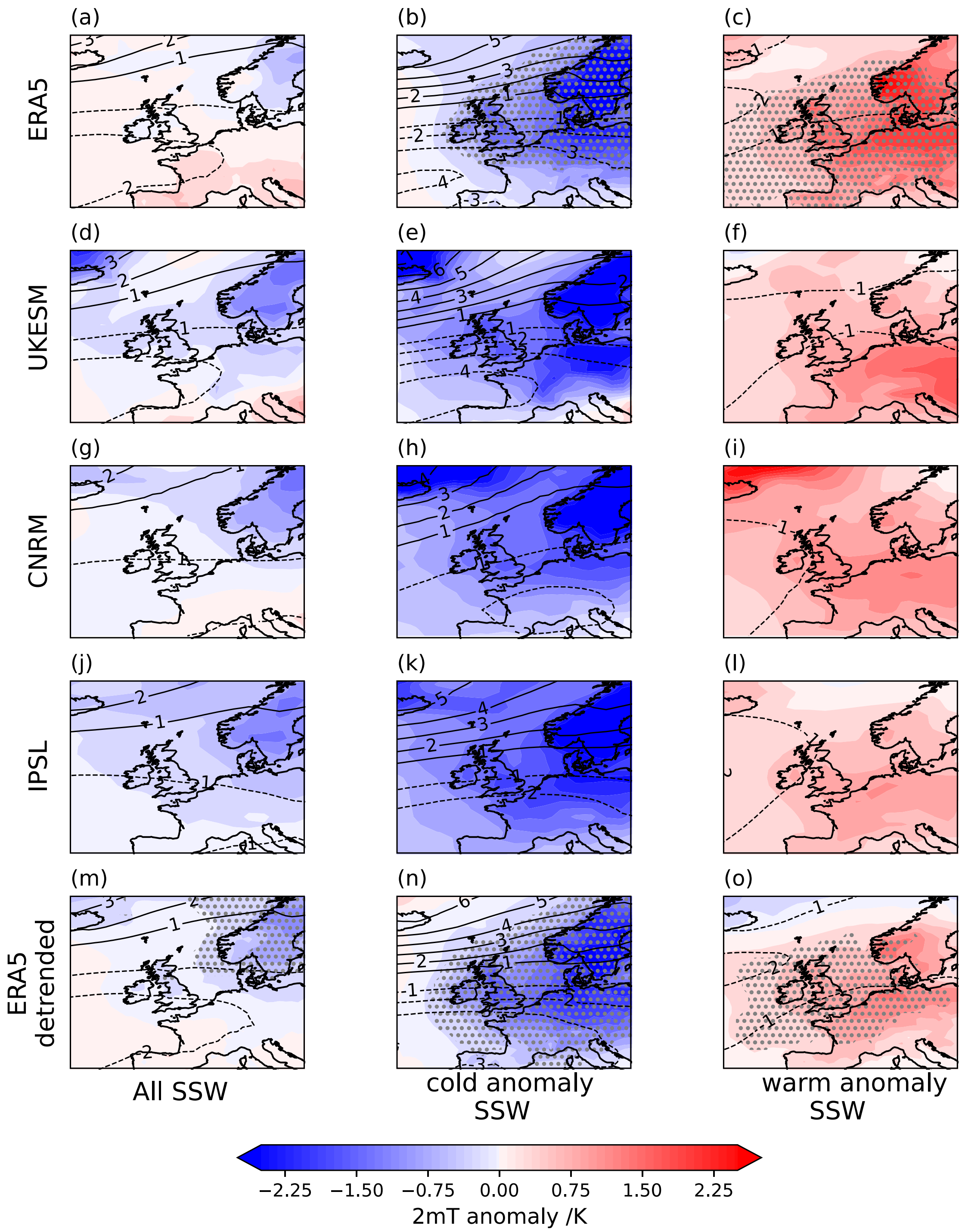

Figure 3. SSW 2 m temperature (shading) and SLP (contours) anomalies averaged over 61 day windows from SSW onset, for all SSW events and cold and warm terciles, for UKESM, CNRM and IPSL models compared with ERA5, and detrended ERA5 data. For SLP, negative anomaly contours are dotted, the zero contour is omitted and contours are at 1 hPa intervals. For ERA5, anomalies that are significant ($p < 0.05$) are shown as stippling. Significance is not shown for the CMIP6 models as the very large sample sizes result in widespread significance.

There are significant increases in frost day frequency after SSWs in the more northern cities (Glasgow, Copenhagen, Oslo, Stockholm), together with London and Berlin although the RR are relatively low (1.08–1.24) (figure 4(b), table 2). The only significant increases in ice days after all SSWs occur in Scandinavia (figure 4(c)), where the temperature anomalies associated with SSWs are the most negative (figure 3). The RR of ice days for these cities is much higher than for frost days (1.18–1.52; table 2) suggesting a greater impact on daily maximum rather than daily minimum temperatures.

Impacts of SSWs on the CSDI are more widespread (figure 4(d)), as the index is not based on an absolute threshold but on local climatology and the RR of persistent cold spells is quite high (1.53–4.67;

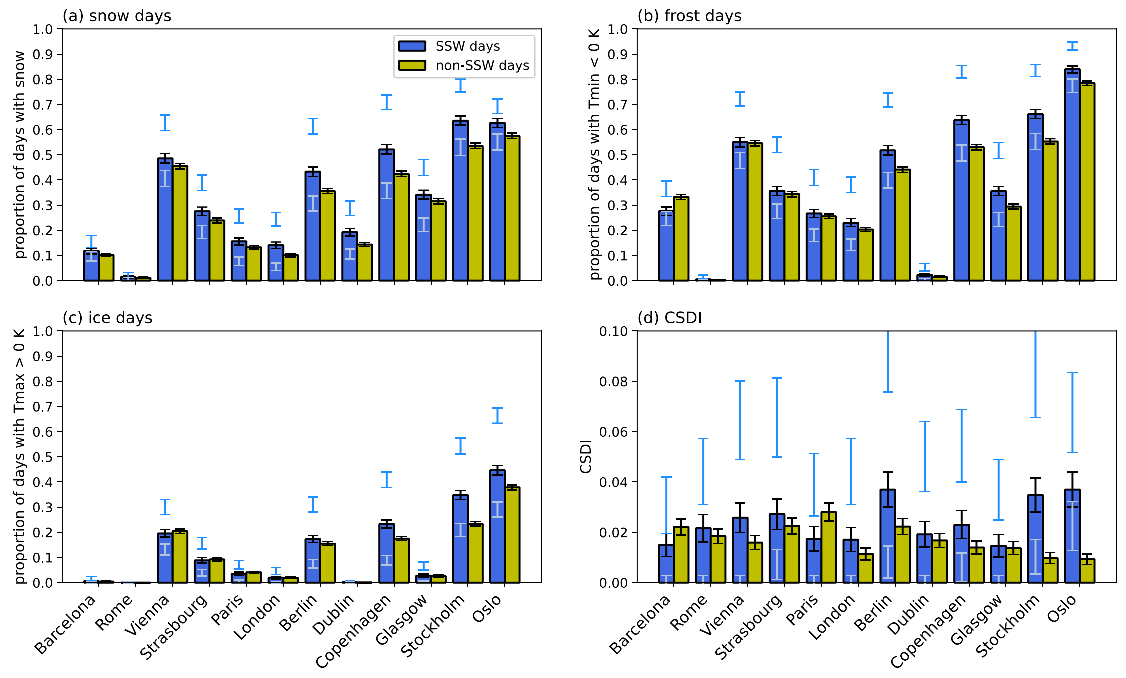

Figure 4. Frequency of snow, frost and ice days, and the proportion of days in the CSDI, for 12 European cities, for SSW and non-SSW days, using ERA5 data. SSW days occur in a 61 day window following the onset, including the onset date. Non-SSW days are the remaining winter days. Blue (light blue) CI bars above (within) the SSW days bars show the 95% confidence intervals for cold-impact (warm-impact) events for each city. Data are taken from a 1° × 1° grid box containing the city. Cities are arranged in order of increasing latitude.

Table 2. Relative risk ratios for snow, frost and ice days and CSDI for 12 European cities, for cold, all and warm SSW events. Only significant values are shown, determined from the 95% CI in figure 3. Values greater than 1 indicate increased likelihood following the SSW, while values less than 1 indicate a decreased likelihood.

	Barcelona	Rome	Vienna	Strasbourg	Paris	London	Berlin	Dublin	Copenhagen	Glasgow	Stockholm	Oslo
Snow days												
All				1.17	1.23	1.4	1.19	1.36	1.24		1.19	1.09
Cold	1.6	2	1.4	1.63	2	2.4	1.69	2.07	1.69	1.41	1.44	1.19
Warm			0.91	0.79	0.62	0.6	0.86	0.79	0.86	0.69		
Frost days												
All	0.85					1.15	1.18		1.21	1.24	1.2	1.08
Cold			1.31	1.59	1.58	1.9	1.64	2.5	1.57	1.79	1.51	1.19
Warm	0.76		0.87	0.79	0.69	0.7	0.91	0		0.83		
Ice days												
All									1.35		1.52	1.18
Cold			1.5	1.78	1.75	2.5	2.07		2.41	2.33	2.35	1.74
Warm			0.65	0.44	0.25	0	0.47		0.53			0.76
CSDI												
All			1.625		0.61	1.73	1.91		1.53		3.5	4.67
Cold	1.68	2.32	4.06	2.87	1.39	4	4.95	3.11	3.6	2.93	8.3	8.2
Warm	0	0	0	0.30	0	0	0.36	0	0.4	0		2.56

table 2). For Paris and Barcelona, the CSDI decreases after SSW, consistent with the milder temperatures associated with SSWs to the south and west (figure 3).

Cold-anomaly events have a much wider impact across Europe than all SSW events. All cities have significant increases in snow day frequency (figure 4(a)), with the greatest RR (⩾2) being for the more peripheral cities (Rome, Paris, London, Dublin, table 2). There are significant increases in frost days everywhere apart from Rome and Barcelona (figure 4(b)), with the greatest RR again being London and Dublin (1.9 and 2.5; table 2). Ice days increase for all cities

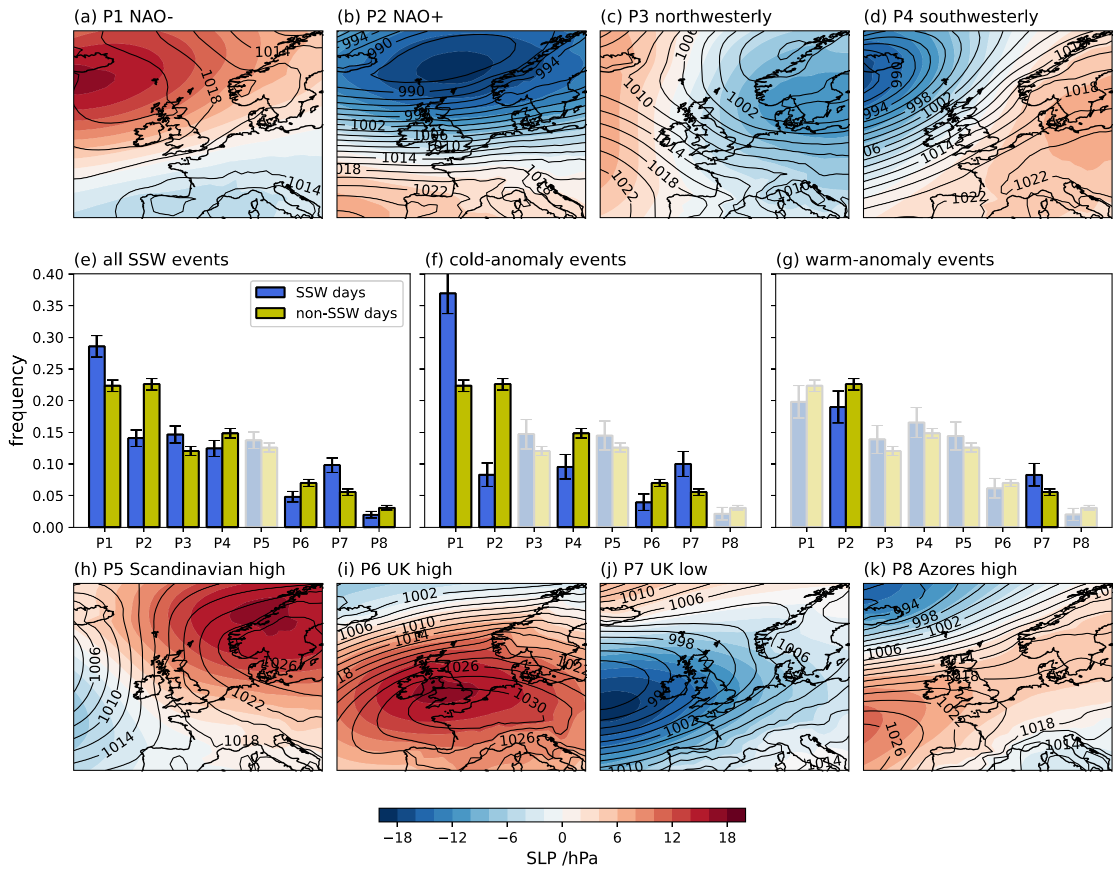

Figure 5. Weather patterns for all winter days ((a)–(d), (h)–(k)), with mean SLP (contours, interval 2 hPa) and SLP anomalies from climatology (shading) and the frequency of weather pattern occurrence for extended winter (DJFMA), post SSW and non-SSW days (e–g). Errorbars show the 95% confidence intervals. Patterns where the frequencies are significantly different post-SSW compared with non-SSW days are shown in darker colours. Note that the 2021 SSW is not included. November days post-SSW are excluded as there are so few.

apart from those further south and west (Rome, Barcelona and Dublin; figure 4(c)). There is a significant increase in the CSDI for all cities after a cold-anomaly event (figure 4(d)), with the greatest RR for Oslo and Stockholm (>8; table 2).

Warm-anomaly events are associated with significant decreases in all metrics across much of Europe (figures 4(a)–(d)). Notably, for Stockholm, which is located to the east of the warmest temperature anomalies associated with warm-anomaly events, there are no significant decreases compared with non-SSW days and Oslo shows only a modest decrease in RR of ice days (table 2), and the CSDI actually increases after warm-anomaly events (figure 4(d)).

To understand the atmospheric drivers behind these results, we now examine weather patterns associated with the events (figure 5). All weather patterns apart from the Scandinavian high (pattern 5, figure 5(h)) show a significant change in frequency following an SSW, compared to non-SSW days (figure 5(e)). Patterns that increase in frequency following an SSW are the NAO−, northwesterly and UK-low regimes (figure 5(a), (c) and (j)), while those that decrease are NAO+, UK-high, Azores-high (figures 5(b), (i) and (k)). Charlton-Perez *et al* (2018) find the primary impact of SSWs is on the frequency of occurrence of the positive and negative phases of the NAO. This is broadly in agreement with results here as they use a 4-regime pattern (NAO+, NAO−, Atlantic ridge, Scandinavian Blocking) and most of the patterns that increase post-SSW fall into their NAO− category, while those that decrease fall within their NAO+ definition. The UK-low (pattern 7, NAO− in the 4-regime cluster) increases in frequency across all SSW categories. However, this pattern is associated with milder temperatures over England, Wales and NW Europe more generally, indicating that the NAO− associated with many SSWs is not linked to uniformly cold weather patterns.

Cold-anomaly events have a strong association with NAO phase, with large increases in NAO− frequency and decreases in NAO+ frequency compared with all SSWs (figure 5(f)). However, warm-anomaly events only favour northwesterly (pattern 3) and UK-low (pattern 7), with a significant decrease in both NAO+ (pattern 2) and NAO− (pattern 1), with all other changes being insignificant, confirming that warm-anomaly events do not project strongly onto the NAO (figure 5(g)).

This impact on weather patterns is important information for contingency planners. Two sub-patterns of NAO−, identified as Patterns 27 and 28 in Neal *et al* (2016), are associated with the lowest negative temperatures (figure S4), and have been linked to significant excess cold-related mortality (Huang *et al* 2020). For cold-anomaly events, the likelihood of patterns 27 or 28 occurring is 2.57 times greater, compared with all SSWs (not shown) and these patterns tend to be more persistent (Neal *et al* 2018). The cold-anomaly events pose a significant health risk through the increase in patterns 27 and 28 and the associated persistent cold anomalies, and this highlights the importance of being able to predict the magnitude and sign of the surface impact well in advance.

4. Summary and key points

We have examined surface impacts over North-west Europe associated with SSWs in ERA5 reanalysis and compared the results with large ensembles of historical simulations from three CMIP6 models, to assess the robustness of conclusions that can be drawn from reanalysis.

1. There is large inter-event variability in surface anomalies following SSWs. For the British Isles and central Europe, for the non-detrended data, 44.7% of SSWs are followed by a mean negative temperature anomaly and 55.3% by a mean positive temperature anomaly. For Scandinavia the figures are 51.1% and 42.5% respectively, with some neutral temperature SSWs. Warm-anomaly events are characterised by warmer-than-usual temperature over NW Europe, with no consistent NAO sign, whereas cold-anomaly events are associated with negative temperature anomalies and a more negative NAO. This inter-event variability is also evident in CMIP6 models and does not appear to be related to aspects of SSW morphology, such as splits or displacements, or the duration or magnitude of zonal wind reversal in the stratosphere.
2. In both reanalysis (1950–2021) and CMIP6 (1850–2014) warm-anomaly events are becoming more frequent, while cold-anomaly events become less common. This change is likely to be associated with warming linked to anthropogenic climate change, with the rate of SSW surface temperatures increasing at the same rate as UK winter temperatures.
3. Warm-anomaly events have a surface temperature anomaly pattern that is distinct from the cold-anomaly events. This is also evident in detrended data and from different time periods in CMIP6 models, and is therefore a robust feature independent of climate change, although the magnitude of the anomalies is affected by the climate change signal.
4. SSWs are associated with significant increases in snowfall days, particularly in the milder western locations. In the London, Dublin and Paris regions, snow days are around 1.3 times more likely following SSWs. The main increase in frost and ice days and the CSDI is over Scandinavia. However, for cold-anomaly events, all regions of Europe see significant increases in these metrics, except for Dublin in the far west and Rome in the south. Warm-anomaly events are associated with widespread reduction in frost, snow and ice days, and the CSDI, compared with non-SSW days.
5. SSWs are associated with specific weather patterns, consistent with the main influence of SSWs being on the NAO. The occurrence of weather patterns that are similar to the negative NAO, but associated with milder temperatures helps to explain why the negative NAO is not consistently associated with low temperatures. P27 and P28, sub-patterns of the negative NAO associated with strongly negative temperature anomalies are around twice as common during cold-anomaly events, compared with non-SSW days. This has significant implications for health contingency planners as these patterns are linked with increased cold-related mortality.

Significant surface anomalies are associated with SSWs, as well as the large variability between surface anomalies following different SSW events. Future SSW impacts must, in addition, be understood in the context of background climate warming, which can significantly affect both the temperature and circulation anomalies. The extent to which the diverse surface anomalies found following SSWs are related to either the nature of the individual SSW, or to unrelated internal variability remains an open question and should be the focus of future study.

Data availability statement

ERA5 data are available from the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/). CMIP6 data were accessed at the Centre for Environmental Analysis (CEDA) archive at JASMIN (www.jasmin.ac.uk/) but are also freely available from the Earth System Grid Federation (ESGF) (https://esgf-index1.ceda.acuk/projects/esgf-ceda/).

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