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Characterising Cold-Dry and Cold-Wet Compound Events in the United Kingdom

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ABSTRACT

Compound cold extreme weather events—co-occurring multivariate events—have been defined as either cold-dry (CD) or cold-wet (CW) depending on the absence or presence of heavy precipitation. Both event types induce varying levels of social and economic impacts across multiple sectors such as health, transport and energy depending on which type of event is experienced. In this study, we characterise these CD and CW events in the United Kingdom (UK) using a location-specific percentile approach and assess their relationship with a set of 30 UK-specific weather patterns to determine the event drivers. The results show that there are up to 14 CD days per winter season in the west of the study region compared to 4–8 CD days in the east. The inverse is shown for CW with 0–1 days per winter season in the west and 2–3 days in the east. CD events are predominantly driven by anticyclonic weather patterns (which are classified in the negative North Atlantic Oscillation regime), and CW days are driven by cyclonic weather patterns. This study provides evidence that a location-specific approach alongside weather pattern analysis could be adopted as a tool for impact-based forecasting at a medium-range lead time to forecast CD and CW events.

1 | Introduction

Extreme cold events are projected to occur throughout the 21st century despite a warming climate (Kodra et al. 2011; Räisänen and Ylhäisi 2011). Cold events are characterised by locally low temperatures, which deviate from the seasonal average (Huang et al. 2020). Cold events impact infrastructure in numerous ways by putting a strain on public health, transportation, water and energy services (Charlton-Perez et al. 2019; Palin et al. 2016). Cold conditions have significant impacts on energy, from driving demand and affecting price volatility to impacting power plant operations (Añel et al. 2017). Low temperatures trigger an increase in energy demand as people turn on their heating. During a cold, windless event, this demand can be difficult to meet if the event is being driven by high pressure (i.e., a wind drought) (Hall and Hanna 2018). Cold events can have severe impacts on the agriculture sector, causing crops to freeze (Koumoutsaris 2019) and loss of livestock through hypothermia (Ecosulis 2019). Snowy and icy conditions can lead to airport and road closures (Palin et al. 2016), and rail services can experience delays and cancellations due to ice formation and/or snow on any moveable piece of equipment (Doll et al. 2014). When considering human health, cold temperatures are known to aggravate respiratory and cardiovascular conditions which can ultimately lead to death (Psistaki et al. 2020). The cascading impacts include disruption to the delivery of public services, such as school closures and the breakdown of supply chains (UKHSA 2023). The winter of 2010 effectively demonstrates how extreme cold events can still occur as the climate continues to warm, when the

United Kingdom (UK) experienced record-breaking low temperatures (Prior and Kendon 2011). There is, therefore, a need to understand what causes these cold events, their associated impacts and how warnings can be more effectively communicated to end-users.

Although extreme cold events are still predicted to occur throughout the next century (Kodra et al. 2011; Räisänen and Ylhäisi 2011) observations and climate models have indicated that there has been and will continue to be a global decrease in cold events (Wu et al. 2021; Ballester et al. 2008). Yan et al. (2002) found that over Europe and China there was a 7% decrease in the annual frequency of cold extremes per century. In turn, society may become more vulnerable to these events when they do occur, as they will become rarer and therefore potentially more impactful. Eisenberg and Warner (2005) found that in the United States, the number of road accidents that cause fatality is higher during the first snowfall of the season compared to non-first snowfalls. Hitchens (2022) carried out a similar study that supports the findings of Eisenberg and Warner (2005) suggesting that the first (and perhaps only) extreme cold event of the season could incur more serious impacts due to a lack of familiarity and resilience.

Up until now, cold extreme events have largely been viewed as a singular hazard. Drawing from the growing body of research, however, these cold events can be categorised as 'compound events'. The International Panel on Climate Change (IPCC) Special Report on Climate Extremes (SREX) in 2012 defined compound events as the combination of weather and/or climate events which lead to an extreme impact (IPCC 2012). Since SREX, there has been a notable uptake in research in compound events across the discipline (Brett et al. 2024). Cold events can be classified specifically as multivariate compound events that is, when one event is accompanied by another extreme meteorological phenomenon (Zscheischler, Martius, et al. 2020). As discussed by Zscheischler, van den Hurk, et al. (2020), the addition or absence of precipitation can amplify a 'hot' event; here we apply this to 'cold' events. Precipitation coupled with air temperatures of between 0°C and 2°C can lead to heavy snowfall. The absence of heavy precipitation and cloud cover can allow the air temperature to reach sub-zero. This is because clouds act as a terrestrial radiation insulator (Spiridonov and Ćurić 2021a). Cold compound events have received considerably less attention than heat-related events (Brett et al. 2024), but are still important considering the severity of associated impacts.

Several methods have been used to examine multivariate compound events including the copula method (Li et al. 2024), multivariate statistical models (Feng and Hao 2020), quantiles (Wu et al. 2021) and hazard indices (Ridder et al. 2020). Compound event indices are used to define modes of hot-dry, hot-wet, cold-dry and cold-wet and typically use combinations of the 25th and 75th percentile of temperature and precipitation (see Table 1 for previous studies). The temporal resolution and methodology vary across studies. Observed extreme compound cold events have been researched in China (Wu et al. 2019; Peng et al. 2023) and Eastern Europe (Vyshkvarkova and Sukhonos 2022) and have used a coarse spatial resolution of meteorological data and quantile indices to define compound cold events (25th percentile of temperature/25th percentile of precipitation for cold-dry, 25th percentile of temperature/75th percentile of precipitation for cold-wet) based on the methodology of Beniston (2009) which uses quantiles to define modes of temperature and precipitation combinations. There has been limited research that seeks to characterise these compound cold events at a high spatial resolution and that uses more extreme indices than quantiles. This method would allow for a local characterisation of these extreme events and ensures that only impactful events are captured. This methodology could then be used for impact-based forecasting. We use the UK as a study area as it is a climatically diverse country that has historically been impacted by extreme cold weather events. Using a local characterisation of compound cold events would provide a tailored approach to how future compound weather alerts are issued and could be utilised across other sectors such as energy, agriculture and transport. The impact alerts of extreme cold events are currently issued at short lead times (i.e., 1–5 days ahead) but could potentially be extended to medium range by employing weather pattern analysis.

Weather patterns have been used to support several medium-range forecasting applications, due to their predictability out to 15 days lead time (Neal et al. 2016). The Met Office 30 weather patterns (MO30) have been utilised across a range of operational applications such as forecasting potential periods of coastal flood risk (Neal et al. 2018) serving as an early forecast system for fluvial flooding (Richardson et al. 2018), and forecasting impacts such as lightning activity (Wilkinson and Neal 2021), volcanic ash flow (Harrison et al. 2022), and power outages (Souto et al. 2024). In this study, we explore the link between cold compound events and weather patterns to identify which patterns drive these events. Associating these events with weather patterns will potentially enable impact-based forecasting at a longer lead time and, in turn, reduce the associated impacts.

This study characterises compound cold-dry and cold-wet events in the UK and assesses their relationships with weather patterns to determine the event drivers and understand how singular hazards can be classified as compound events and the associated impacts can be attributed to synoptic conditions. This is executed through defining indices for cold-dry and cold-wet events to characterise locally occurring compound cold events; identifying the spatial distribution of these events across the study region using a high-resolution dataset to provide a localised understanding of how these events occur; analysing the temporal variation of these events using observations; and exploring how these events are linked to weather patterns and regimes. This paper is structured as follows: Section 2 describes the data and methodology used; Section 3 presents the results of the spatial and temporal distribution and the link to weather patterns; in Section 4 we discuss the results, and finally in Section 5 we draw conclusions of the work.

2 | Data and Methodology

2.1 | Data

The Met Office HadUK-Grid gridded climate observations dataset, available through the Centre for Environmental Data Analysis (CEDA) archive, was used in this study (Met

TABLE 1 | A selection of previous studies which have investigated compound cold-dry and cold-wet events.

Publication	Dataset	Resolution	Extreme index used (percentiles)	Qualifying period for compound event
Yang et al. (2024)	SSP2-4.5 scenario in CMIP6	0.5°×0.5°	25th and 75th percentile of daily min/max temperature and precipitation of each year	Within the same day
Peng et al. (2023)	Gridded data set CRU TS v4.04	0.5°×0.5°	25th and 75th percentile of temperature and precipitation for each month	Within the same month
Vyshkvarkova and Sukhonos (2022)	Reanalysis E-obs 20.0	0.25°×0.25°	25th and 75th percentile of temperature and precipitation for each season	Within the same day
Wu et al. (2021)	Gridded data set CRU TS v4.03; CMIP6 GCMs	1°×1°	10th and 90th percentile of temperature and precipitation for each month	Within the same month
Wu et al. (2019)	Observations	0.5°×0.5°	25th and 75th percentile of temperature and precipitation for each month	Within the same month
Hao et al. (2013)	Observations; CMIP5 historical simulations	2°×2°	25th and 75th percentile of temperature and precipitation for each month	Within the same month
Beniston (2009)	Observations; RCMs	0.5°×0.5°	25th and 75th percentile of temperature and precipitation for each month	Within the same month

Note: The dataset used, resolution, extreme index and qualifying period for a compound event are displayed.

Office 2023). HadUK-Grid was chosen for this study because it provides daily values of minimum air temperature and precipitation covering the entire spatial extent of the UK at a high resolution of 5 km from 1960 to 2022. HadUK-Grid provides gridded values of several land surface variables including maximum, minimum and mean air temperature, rainfall, and ground frost spanning the period of 1836–2022 (the start date is variable dependent). The dataset was produced through interpolation of in situ land surface observations from climate observing stations across the UK (Hollis et al. 2019).

2.2 | Definition of Cold Weather Compound Event Indices

Days were classified as compound event days when percentile thresholds of both variables (daily minimum temperature and daily precipitation) were met. The following indices were chosen to define compound cold events:

- Cold-dry (CD): ≤15th percentile of daily minimum temperature AND ≤15th percentile of daily precipitation.
- Cold-wet (CW): ≤15th percentile of daily minimum temperature AND ≥85th percentile of daily precipitation.

These indices have been selected to represent extreme compound events for the UK based on rigorous sensitivity testing. The selection of more extreme thresholds (e.g., 5th or 95th percentiles) was discarded as these produced a very low number of compound events, making it difficult to analyse any changes in the study period. Wu et al. (2021) use extreme indices of the 10th and 90th percentiles; however, these thresholds must only be observed within the same month (rather than day) to qualify as a compound event (Table 1). Combinations of the 5th, 10th, 15th, 20th, 80th, 85th, 90th and 95th percentiles were all trialled for both CD and CW events but were ultimately discarded as they produced either too many events (therefore not representing an extreme event) or too few events (therefore not providing enough data points). Previous studies have used less extreme percentiles (e.g., the 25th and 75th percentiles) (Wu et al. 2019; Vyshkvarkova and Sukhonos 2022; Peng et al. 2023). These indices were trialled but not used in this study as they did not represent inherently cold temperatures in the UK; for example, in parts of southwest England, the average seasonal 25th percentile of minimum temperature is > 4°C.

Percentile values have been calculated using an ordered time series of winter (December, January, February, DJF) days over a 30-year period of 1993–2022 for each HadUK-Grid land grid-square as this is standard practice for climatology calculations (Kendon et al. 2023). The precipitation time series has been masked to only include days when the precipitation value was ≥ 0.2 mm. This research is intended to support impact-based forecasting and therefore using the most recent 30 years provides percentiles that are more realistic in the present and near future. For every day in DJF from 1960 to 2022, the percentile thresholds were applied to each land grid-square in the UK. The resulting number of days above or below the threshold was averaged over the 63-year period to provide an average number of CD and CW days per winter season. Only single-day occurrences of compound events were considered in this study. Multi-day events were not considered to avoid confusion when referring to 'events' and 'days'. Subsequent discussion of cold compound events refers to single days.

Glasgow, Belfast, Newcastle, London and Plymouth were chosen to provide regional representative cities across the UK. The geographical centre point of each city was identified, and the closest grid square was selected. The qualifying percentile thresholds for each city can be found in Table 2. Qualifying threshold values for the rest of the UK can be found in Figure 1 of the Supporting Information.

2.3 | Weather Classifications

The MO30 weather patterns were used to identify the weather pattern present on the days that a compound CD or CW event was observed. The MO30 weather patterns were created using a

TABLE 2 | Percentile thresholds for compound cold events for the cities of Belfast, Glasgow, Newcastle, London and Plymouth.

City	15th percentile min temp (°C)	15th percentile precipitation (mm)	85th percentile precipitation (mm)
Belfast	−0.48	0.56	8.91
Glasgow	−1.53	0.62	10.54
Newcastle	−0.86	0.41	5.25
London	−0.16	0.48	6.91
Plymouth	0.27	0.64	12.12

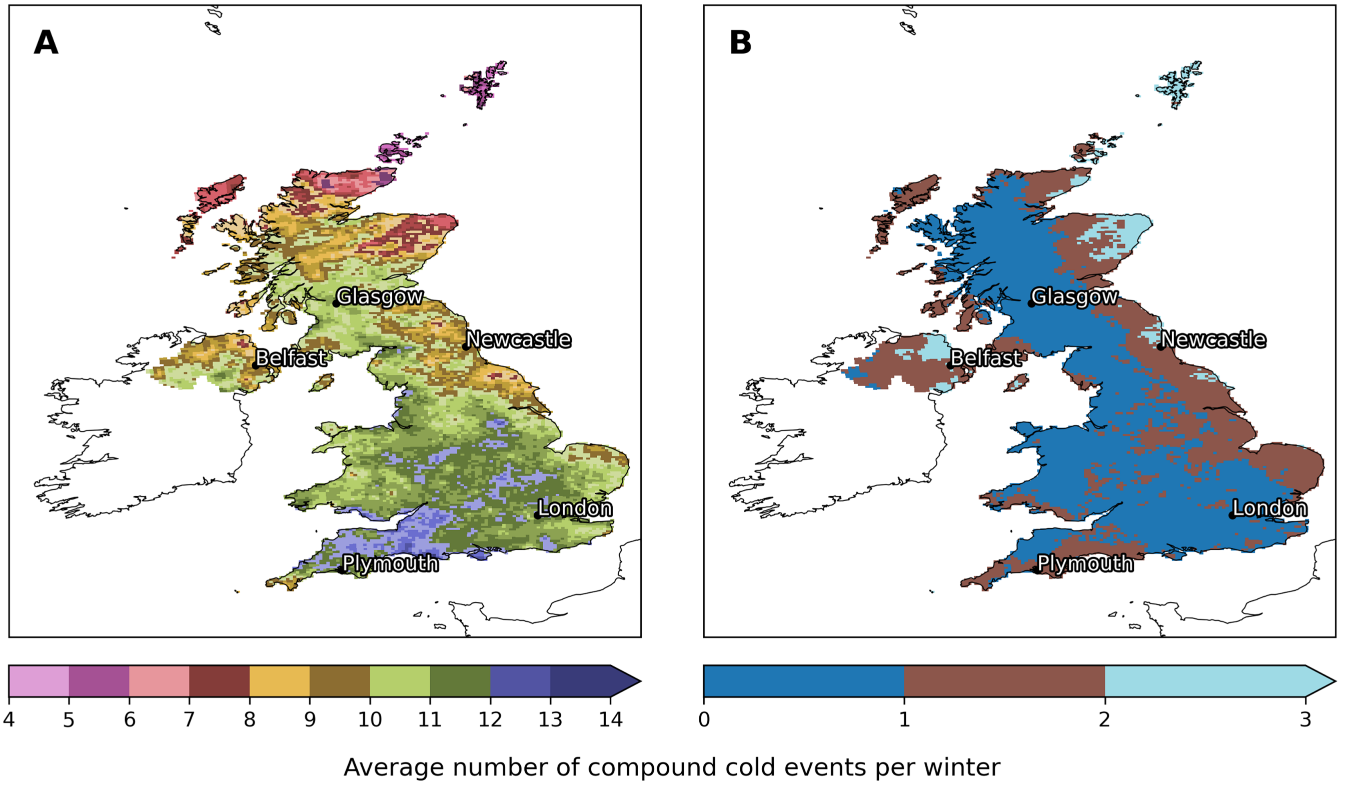

FIGURE 1 | Study area of the UK, showing the winter average compound CD (A) and CW (B) days calculated using location-specific percentile thresholds. The results are expressed as a yearly average from 1960 to 2022. [Colour figure can be viewed at wileyonlinelibrary.com]

simulated annealing variant of the *k*-means clustering analysis method (Philipp et al. 2007) and applied to the European-North Atlantic mean sea level pressure dataset (Ansell et al. 2006) over the North Atlantic and European region for the period of 1850–2003. The MO30 weather patterns are categorised into eight weather regimes: North Atlantic Oscillation (NAO) negative, NAO positive, northwesterly, southwesterly, Scandinavian high, high pressure centred over the UK, low close to the UK and Azores high (Neal et al. 2016). Regimes are circulation patterns which cover a larger geographical region than patterns and tend to be more persistent in nature (Büeler et al. 2021). For every CW or CD day, the weather pattern and regime for that day were recorded. Table 3 shows a breakdown of the eight regimes into the 30 weather patterns. A flow description of each weather pattern can be found in Table 1 of the Supporting Information.

3 | Results

3.1 | Spatial Distribution of Observed Cold-Dry and Cold-Wet Events

The mean observed annual (DJF) spatial distribution of CD and CW days across the UK is shown in Figure 1 (calculated from the period 1960–2022). For CD events, the results show high levels of geographical variation across the UK from west to east and north to south, ranging from a minimum of 4 days in all locations to a maximum of 14 days in central south and southwest England. Areas with the lowest number of CD days include the Outer Hebrides, northeast Scotland, and the Shetland Isles, with up to 8 CD days. Regions in the west of the UK generally show the highest CD days per year, with over 10 days in central and southwest Scotland and southern and southwest England. Eastern regions such as northeast Northern Ireland and the east coast of England show between 7 and 10 CD days per year. On average, between 0 and 3 compound CW days occur per winter. Central and western Scotland and areas of high ground display the lowest number of CW days, with up to 1 day per winter. Aberdeenshire, Newcastle and the north of Northern Ireland show 2–3 CW days per year, and the rest of the UK shows 1–2 CW days per year. Across mainland UK, CW days present a west to east spatial distribution, with the lowest occurrence in the west of the country (except for the southwest peninsula of England) and the highest occurrence at eastern coastal regions. A similar pattern can be observed for Northern Ireland, with an increase in CW days moving eastward across the country.

TABLE 3 | MO30 eight weather regimes and weather patterns in each regime.

Regime	Weather pattern number
NAO Negative	6, 9, 11, 19, 25, 27, 28
NAO Positive	4, 8, 20, 23, 26, 30
Northwesterly	1, 13, 14, 24
Southwesterly	2, 12, 15, 21
Scandinavian High	5, 16, 17, 22
High Pressure Centred Over UK	3, 18
Low Close to UK	7, 29
Azores High	10

The west of the UK is wetter than the east due to the topography of the country with several orographic features in the west. Weather systems that move off the Atlantic Ocean towards the UK produce rainfall in the west (where there is higher ground) through mechanisms such as orographic rainfall (Spiridonov and Ćurić 2021b). The east is known to be drier as this region is in the rain shadow of the west and is subject to dry easterly winds from the continent (Met Office 2023). Figure 1 presents a counterintuitive result for both CD and CW days, with a higher number of CD days in the west and CW in the east. This emphasises the importance of considering extreme cold events as compound events as the joint interaction of temperature and precipitation does not present an intuitive result in this scenario. The results presented here show that the east of the country is more likely to experience CW days—events in which extreme low temperatures and extreme precipitation are observed simultaneously.

3.2 | Temporal Variation of Observed Cold-Dry and Cold-Wet Events

Figure 2A shows the number of CD days per winter season from 1960 to 2022 across five representative cities. The highest annual peak for Newcastle, Glasgow, London and Plymouth is observed in 1963 with 27, 42, 43 and 49 CD days respectively. Belfast observed the highest number of CD days in 2010 at 30 CD days. Throughout the study period, there are several peaks and troughs which emphasise the interannual variability of events. London shows the highest number of CD days historically—a total of 717 over the study period. London experienced 7 years that had a CD day count of over 20 days. Belfast shows 5 years with a CD count exceeding 20 days, Glasgow and Plymouth both displaying 4 years, and Newcastle only showing 2 years with a CD count above 20 days. This suggests that London is in a region susceptible to localised persistent CD events.

From the 1990s and throughout the rest of the study period, there is an observed decrease in the number of CD days each winter. The most notable year in the 21st century is 2010, when cities located in the west of the UK saw an increased number of CD days. During 2010, Glasgow observed 37 CD days, Plymouth 32 CD days and Belfast 30 CD days. This winter saw the coldest December temperatures in the UK in over 100 years and suggests that cities in the west are more susceptible to experience a higher number of localised CD days during this kind of event. Following the winter of 2010 and up until 2022, there are generally less than 12 CD days per winter in all five cities (except for London in 2012 with 17 CD days). The winter of 2010 is an anomaly in an otherwise decreasing number of CD occurrences; however, this does not suggest that these types of events will cease to exist (Räisänen and Ylhäisi 2011).

In contrast, the number of CW days per year (Figure 2B) does not show the same level of temporal variation as the CD days. By our definition, CW days require the precipitation observed to meet or exceed the local 85th percentile. The presence of

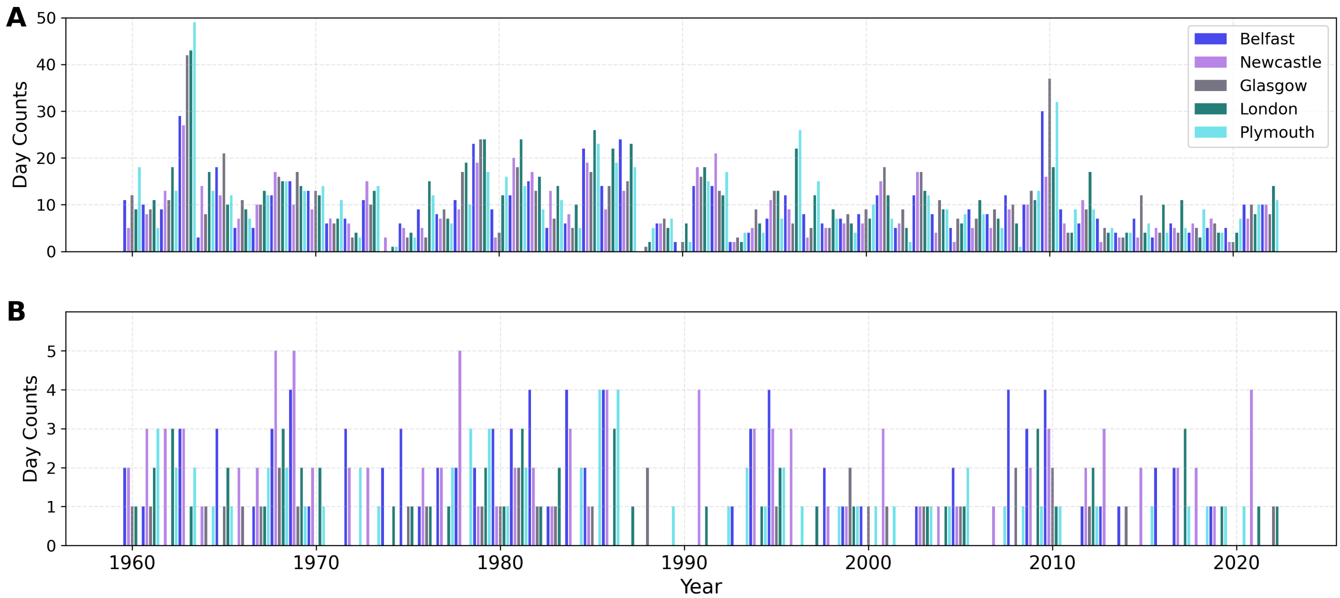

FIGURE 2 | Timeseries of the observed number of CD (A) and CW (B) days per year from 1960 to 2022 in HadUK-Grid 5 km. [Colour figure can be viewed at wileyonlinelibrary.com]

precipitation and therefore clouds prevents the air temperature from reaching extreme lows (Spiridonov and Ćurić 2021a). This is why we see a lower number of CW days, as meeting both the temperature and precipitation thresholds to qualify for a CW day is an extremely rare case. The results shown in Figure 2B display values ranging from 0 to 5. Since 1990, only Belfast and Newcastle show years that exceed 3 CW days within a year, suggesting that locations on eastern coasts are more susceptible to localised CW events. Belfast is situated in the west of the UK but sits on the eastern coast of the island of Ireland. This unique positioning indicates that Belfast is liable to experience both localised CD and CW days.

3.3 | Linking Observed Events With Weather Patterns and Regimes

Figure 3A shows that the highest number of CD days occurs under the NAO− regime. Cities in western parts of the UK show a higher occurrence under anticyclonic patterns 25 (anticyclonic northerly with high pressure over Northern Ireland) and 27 (anticyclonic easterly with high pressure over the Norwegian Sea), for example, Plymouth shows a 16% occurrence for pattern 27, compared to Newcastle (in the east) which displays a 4% occurrence for this pattern. The NAO− regime contains four anticyclonic weather patterns within it (6, 9, 25 and 27) which can be characterised as persistent compared to the cyclonic patterns (Neal et al. 2016). This persistence of high pressure allows the air temperature to reach extreme lows under a cloudless sky and calm conditions.

NAO+ is comprised of cyclonic patterns and shows less than 2% across the cities. Other notable weather patterns are 12 (anticyclonic south-south-westerly with high pressure over Poland) in the Southwesterly regime and 17 (anticyclonic east-south-easterly with a high pressure centre over Denmark) in the Scandinavian High regime. Both patterns show the highest occurrence for all cities within their respective regimes, both showing Newcastle has the highest occurrence at 7% and 9% respectively.

Compared to CD days, CW days occur under a wider variety of weather conditions, which can be seen in Figure 3B by the larger range of weather patterns during which these events are experienced. This figure demonstrates that CW days are driven by different patterns depending on what region of the UK the city is located in. For pattern 28 (cyclonic south-easterly with low pressure southeast of the UK) within NAO-, London, Newcastle, and Plymouth display their highest CW occurrence at 20%, 18%, and 16%, respectively. Newcastle is the city located furthest to the east and is the only city that has CW days under pattern 25 (anticyclonic northerly with high pressure over Northern Ireland). Belfast, Glasgow, London, and Plymouth show the highest occurrence under cyclonic weather patterns. In general, cities show the lowest level of occurrence under unbiased or anticyclonic patterns, that is, pattern 9, 25, 4, 15, 17, 3 and 10. The city analysis suggests that in the broadest terms, CD events are predominantly driven by anticyclonic patterns and CW by cyclonic patterns. Cyclonic patterns tend to move quickly and do not remain stationary. This explains why a lower number of CW days are shown in Figures 1B and 2B, as the driving weather patterns of CW days do not persist for as long as those that drive CD days.

NAO− and Scandinavian High regimes show the highest percentage of CD days, with > 60% of CD days on parts of the west coast occurring under NAO− (Figure 4A,E). This is in agreement with Hanna et al. (2017) who found a link to cold events and NAO− in the UK and Hall and Hanna (2018) who found that NAO− brings cold and dry conditions to the UK. NAO− (Figure 4A) displays striations running from west to east with decreasing percentages of occurrence. The regions with the highest percentage of occurrence (> 60%) are coastal areas of western Scotland, western Northern Ireland, south Wales and southwest England. The occurrence value decreases from 50%

FIGURE 3 | Percentage of CD (A) and CW (B) days under the eight weather regimes (NAO−, NAO+, Northwesterly, Southwesterly, Scandinavian High, High Pressure Centred Over UK, Low Close to UK and Azores High) for five representative cities (Belfast, Newcastle, Glasgow, London and Plymouth). [Colour figure can be viewed at wileyonlinelibrary.com]

in the west of the UK down to 30% on the east coast. Each grid square in the study area has a value of at least 29% for CD occurrences under NAO−. Scandinavian High (Figure 4E) shows 20%–30% on the northeast coast of Scotland and 10%–20% for most of the UK. The regimes NAO+ (Figure 4B), High Pressure Centred Over the UK (Figure 4F), Low Close to UK (Figure 4G) and Azores High (Figure 4H) generally report less than 10% CD occurrence. Northwesterly (Figure 4C) shows 10%–20% for much of Scotland and north England, while Southwesterly (Figure 4D) shows 10%–20% down the eastern coast of England. These findings align with the city results, suggesting that CD days are predominantly driven by anticyclonic patterns.

The occurrence of CW days shows more spatial variation across the regimes in comparison to CD days for the period of 1960–2022. NAO− (Figure 4A) occurrence varies greatly across the country with the highest percentages of 40%–60% in parts of northeast and eastern England and less than 10% in inland areas of western Scotland. NAO+ (Figure 4B) shows occurrences of 20%–40% down the western half of Scotland and north and central England, while the rest of the country shows 10%–20% with less than 10% in northeast England and the southwest peninsula. Northwesterly (Figure 4C) and Southwesterly (Figure 4D) both exhibit 10%–20% in central southern England but show differing spatial patterns in the north. Northwesterly shows 20%–40% in northeast Scotland and less than 10% in the west of Scotland, whereas Southwesterly shows the inverse of this with 20%–40% in the west of Scotland and less than 10% in northeast Scotland. Scandinavian High (Figure 4E) and Low Close to the UK

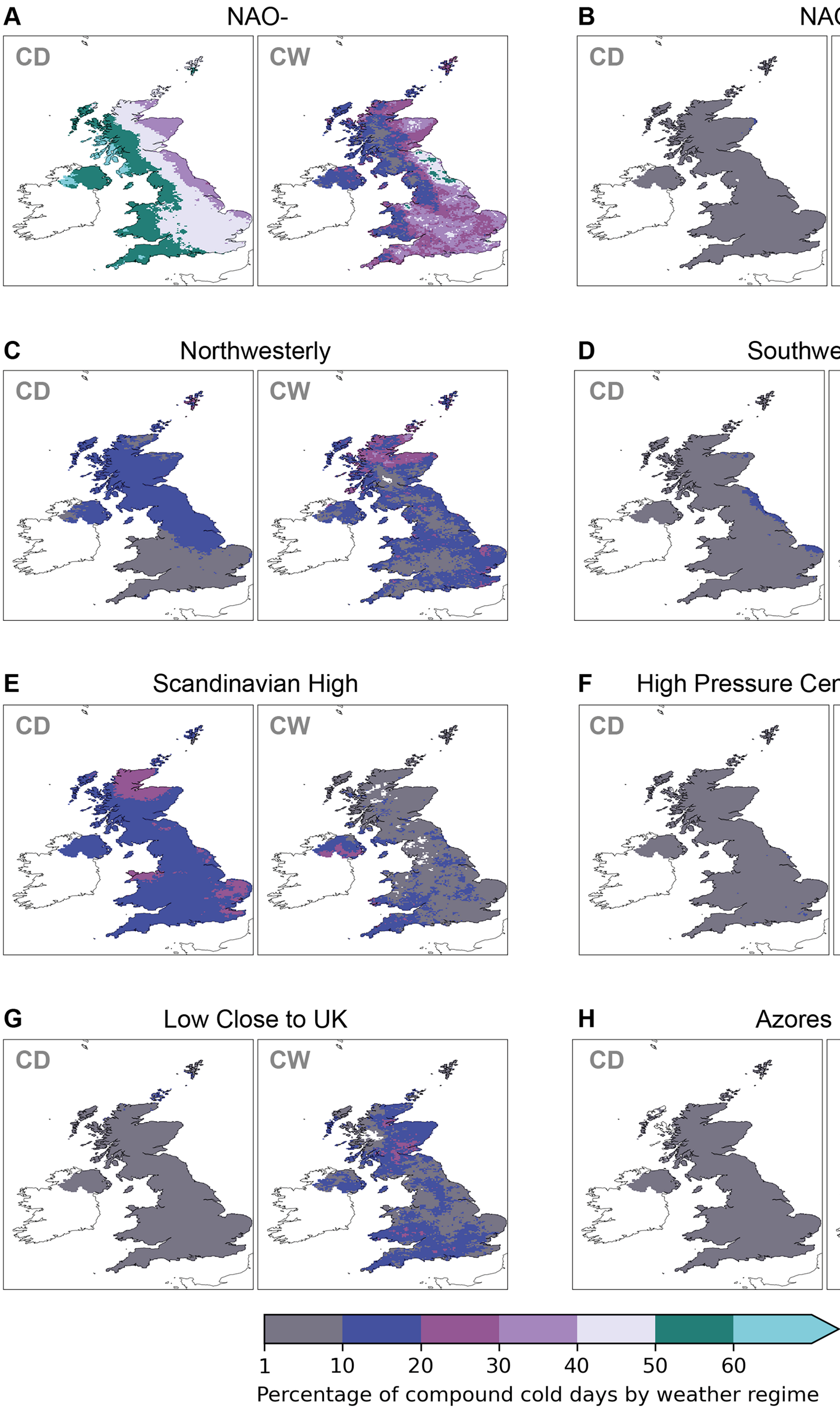

FIGURE 4 | Percentage of CD and CW day occurrence under eight weather regimes. (A) NAO−, (B) NAO+, (C) Northwesterly, (D) Southwesterly, (E) Scandinavian High, (F) High Pressure Centred Over the UK, (G) Low Close to UK, (H) Azores High. [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 4G) both show 10%–20% across differing regions of the country. Scandinavian High shows 10%–20% in parts of southwest and central England and 10%–30% in Northern Ireland. In contrast, Low Close to the UK shows 10%–20% in south and east Scotland, southern Wales, and southern England. High Pressure Centred Over UK (Figure 4F) and Azores High (Figure 4G) express the lowest percentage of CW days, with most of the UK displaying less than 10%.

4 | Discussion

This study has shown that, in the UK, CD events are more likely to be observed on the west coast of the country and are driven by anticyclonic weather patterns. Conversely, we have shown that CW events are more likely to be observed on the east coast and are driven by cyclonic weather patterns. This results from using location-specific percentile thresholds to define the CD/

CW indices. Previous studies have used qualifying thresholds derived from a ~27 km grid (Vyshkvarkova and Sukhonos 2022). We chose to use a high-resolution observation dataset (HadUK-Grid, 5 km) coupled with grid-specific thresholds to capture location-specific geographical differences in minimum temperature and precipitation. Both variables are influenced by topography, proximity to bodies of water, and terrain. By using a 5 km grid we can demonstrate how these influences affect the thresholds set for the CD/CW indices, thereby providing a highly localised characterisation of these events. The associated impacts of CD and CW events could be forecast at a much higher resolution by adopting this method. We have demonstrated the spatial differences in these events across the UK and have shown that specific regions of the UK are influenced by specific weather patterns and regimes. This knowledge could be adopted by a range of sectors (e.g., public health, agriculture, tourism, etc.) to forecast the local impacts incurred by these events. The UK Health Security Agency (UKHSA) currently operates an early weather-health alerting system informed by short-range forecasts (up to 5 days) (UKHSA 2024). This system previously received stakeholder feedback that using a static temperature threshold (2°C) can be problematic due to the differing climatology across the UK, that is, the threshold is either too high or too low depending on the region (Roberts et al. 2022; PHE 2013). A percentile-based method of defining extreme compound events would provide a tailored approach to how these hazards are characterised in different regions of the study area.

Historically, the number of observed CD and CW days has decreased in the period 1960–2022 across the representative cities. These findings are in agreement with other studies on compound cold events (Vyshkvarkova and Sukhonos 2022; Li, Jiang, et al. 2022; Li, Liu, et al. 2022; Vyshkvarkova and Sukhonos 2022; Wu et al. 2019; Qian et al. 2014). This, however, does not detract from the level of impact of these events. The winters of 2010 and 2018 saw widespread impacts across the UK, including travel disruption, school closures and weather-related deaths (Prior and Kendon 2011; Galvin et al. 2019). The decreasing frequency of events suggests that the ramifications may, in fact, be more impactful as the events become less common, and therefore there will be less resilience to them. Current climate change and adaptation plans in the UK focus on resilience towards a warming climate and an increase in extreme weather events such as extreme precipitation associated with thunderstorms (Burnett 2023). CD and CW events are extreme weather events and therefore should be considered serious hazards in the changing climate.

The investigation of CD and CW event occurrence by weather pattern (for representative cities) and regimes (for the entire UK) offers insight into the synoptic drivers. We found a strong relationship between the NAO− regime and CD events, particularly for the western coast of the UK. Huang et al. (2020) found that persistent NAO− events lasting at least 5 days had over a 30% chance of including a day with a UK-wide excess mortality above the seasonal 95th percentile. Based on our findings, any CD day in the UK has a minimum 29% chance of being driven by the NAO− regime. The persistent nature of these events allows for impacts to temporally compound. A spell of CD days in which the temperature does not exceed 0°C would induce multiple ice-related impacts. For example, black ice on roads, ice on rail equipment (thereby preventing electricity conduction), or ice on walkways (increasing the number of slips and falls). CD days can be particularly impactful as they occur in the absence of snow and are therefore not always recognised or taken seriously despite being associated with significant risks (Roberts et al. 2022).

Associating the occurrence of CD and CW days with weather patterns provides means to forecast the impacts at a local level. Using the MO30 weather patterns to forecast compound cold events would provide a longer lead time (up to 15 days) which would reduce the level of impacts felt across different sectors (Ireland et al. 2024). The MO30 weather patterns have been used in a range of operational applications and in the future could be adopted to forecast the impacts associated with CD and CW events.

5 | Conclusions

This study used a location-specific approach to characterise multivariate compound CD and CW events in the UK, analyse the spatial distribution and temporal variation, and establish the relationship between these events and weather patterns/regimes. A methodology was developed to define these events based on previous studies of compound cold events. A location-specific percentile approach was provided as an example of how this methodology could support the future development of impact-based forecasting at a local level. This could alleviate issues such as alert fatigue and cognitive overload by ensuring that alerts are only issued when a locally extreme event is forecast. Using this methodology, we found that CD events are more common on the west coast of the country and are predominantly driven by anticyclonic weather patterns and more broadly NAO− and Scandinavian High regimes. CW events are less common (on average 0–3 days per winter season) with the highest number of events occurring on the east coast. CW events were found to be driven by cyclonic weather patterns that varied across the NAO−, NAO+, Northwesterly and Southwesterly regimes.

The findings of this study highlight that cold events can be classified into combinations of multivariate cold compound events and are driven by different weather patterns. This is relevant when considering how to incorporate compound events into impact-based forecasting systems. By understanding which weather patterns influence CD and CW events across different regions of the country, these cold events could be forecast at a longer lead time of up to 15 days.

The benefit of this approach is that it considers the local climatology and level of resilience and preparedness of different locations across the study area. The location-specific approach coupled with impact-based forecasting has the possibility of reducing impacts felt at a local level. Incorporating the use of weather pattern analysis could extend the forecast of these events from short range to medium range, which would allow necessary preparations to be made across various sectors. The findings of this paper are relevant for future planning of extreme cold weather events, as the methodology used here could be implemented in other impacted locations. As this study has only considered single-day events, future work could consider longer events from multi-day up to several week-long events and further explore the applicability of how to utilise weather pattern analysis to incorporate compound cold events into an impact-based forecasting system.

Author Contributions

Kanzis L. Mattu: conceptualization, formal analysis, methodology, writing – original draft, writing – review and editing, visualization. **Christopher J. White:** conceptualization, formal analysis, supervision, writing – review and editing, methodology. **Hannah Bloomfield:** conceptualization, methodology, formal analysis, supervision, writing – review and editing. **Joanne Robbins:** conceptualization, methodology, formal analysis, supervision, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The HadUK-Grid Gridded Climate Observations on a 5 km grid over the UK, v1.2.0.ceda dataset was used in this study. This dataset is publicly available through the UK Met Office Centre for Environmental Data Analysis (CEDA) Archive: https://catalogue.ceda.ac.uk/uuid/adf1a6cf830b4f5385c5d73609df8423/ (last accessed on 6/12/24).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.