

**COLD-DRY AND COLD-WET COMPOUND
EVENTS IN THE UNITED KINGDOM:
HAZARD CHARACTERISATION, AND
IMPACT-BASED FORECASTING FOR THE
SCOTTISH RAIL NETWORK**

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Paper 1 (presented as Chapter 3 in this thesis): Published in the International Journal of Climatology

Citation: Mattu, K.L., White, C.J., Bloomfield, H. and Robbins, J. (2025), Characterising Cold-Dry and Cold-Wet Compound Events in the United Kingdom. *Int. J. Climatol.*, e8859. <https://doi.org/10.1002/joc.8859>

Status: Published in the *International Journal of Climatology*. First submission 8 July 2024; revised submission 30 January 2025; manuscript accepted 24 March 2025

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Paper 2 (presented as Chapter 4 in this thesis): Published in Meteorological Applications

Citation: Mattu, K.L., White, C.J., Bloomfield, H. and Robbins, J. 2026. “Compound Cold Events, Impacts and Weather Patterns: A Case Study of the Scottish Rail Network.” *Meteorological Applications* 33, no. 5: e70242.
<https://doi.org/10.1002/met.70242>.

Status: Published in *Meteorological Applications*. First submission 10 December 2025; revised submission 8 July 2026; manuscript accepted 3 September 2026

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Paper 3 (presented as Chapter 5 in this thesis): In preparation for submission

Title: Developing a bespoke impact-based forecasting framework for the Scottish rail network

Status: In preparation for possible submission to *npj Natural Hazards*

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ACKNOWLEDGEMENTS

I'm not a runner, so undertaking a PhD is the closest I'll come to doing a marathon. I can see the faces of my biggest supporters cheering for me to cross the finish line. A kaleidoscope of emotion and experiences have gone into this PhD, which aren't included in the words written in the following pages. This endeavour has truly been a journey that has pushed me far outside my comfort zone and through that I have travelled to new countries, overcome my fear of public speaking, received prestigious accolades and most importantly met some exceptionally wonderful humans.

Much gratitude is due to the people who have supported me through this journey. To my supervisors, Chris, Hannah, and Jo: I cannot thank you enough for your academic guidance, invaluable feedback and continued belief in me. Jo – a special thank you for hosting me at the Met Office on several occasions and affording me opportunities to interact with your talented colleagues.

A special thank you to the Royal Meteorological Society for enabling me to join the wider meteorological community within the UK and partake in various events and groups that have significantly contributed to my growth as a researcher and individual.

To my friends and teammates: thank you for listening to me explain how the weather works and recognising my passion for the subject. I am honoured to be your weather woman, and I am blessed to have so many cheerleaders in my corner. James, Megan, Chey, Claire, and Kirsty: thank you for lifting me up, going for a wee coffee, picking up the phone, and providing unwavering support through the highs and lows. Lou: your camaraderie and encouragement through the years won't soon be forgotten.

To my family: thank you for believing in me, even when things were exceptionally tough. I am grateful each day for the lengths you have gone to in supporting me in my biggest academic pursuit and I owe so much of my success to you. Liam: thank you for showing up for me, day in, day out. I wouldn't be here without you.

To Loki, the whippet: thank you for staying by my side through it all, you really are the best boy.

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LIST OF ABBREVIATIONS

<i>CD</i>	Cold-dry
<i>CNI</i>	Critical national infrastructure
<i>CW</i>	Cold-wet
<i>ECMWF</i>	European Centre for Medium-Range Forecasting
<i>HRP</i>	High-risk pattern
<i>IbFW</i>	Impact-based forecasts and warnings
<i>MHEWS</i>	Multi-hazard early warning system
<i>MO30</i>	Met Office 30 weather patterns
<i>MSLP</i>	Mean sea level pressure
<i>NAO</i>	North Atlantic Oscillation
<i>WMO</i>	World Meteorological Organization
<i>WP</i>	Weather pattern

ABSTRACT

Compound events arise from the interaction of multiple climate hazards and/or drivers, often resulting in impacts that exceed those of individual extremes and driving some of the most severe disruptions to society and infrastructure. While compound events have in recent years become a focal point in climate science, research has disproportionately emphasised heat-related hazards relative to cold weather events. Compound cold events remain comparatively underexplored despite their capacity to generate significant impacts across society and critical infrastructure. Even as climate projections indicate a decline in extreme low temperatures, compound cold events represent a critical low-frequency high-impact hazard that warrants systematic investigation.

This thesis addresses this gap by developing an end-to-end framework for understanding, detecting, and forecasting compound cold events in the United Kingdom (UK), demonstrated here through a case study of the Scottish rail network. The research defines two types of compound cold events based on co-occurring meteorological conditions: cold-dry (CD) events, characterised by locally low temperatures in the absence of heavy precipitation, and cold-wet (CW) events, where low temperatures coincide with heavy precipitation.

This research first establishes the climatological characteristics of compound cold events in the UK using location-specific percentile thresholds applied to gridded observations. A clear spatial pattern emerges: CD events occur more frequently in the west of the UK (up to 14 days per winter) while CW events are more common in the east of the country (2-3 days per winter). By linking compound cold events to a set of 30 weather patterns, this thesis identifies the large-scale atmospheric drivers responsible for the observed regional differences. CD events are predominantly associated with anticyclonic patterns such as those associated with the negative phase of the North Atlantic Oscillation, whereas CW events are driven by transient conditions associated with cyclonic patterns.

The research then examines how these compound cold events translate into real-world consequences. Analysing over 10,500 Scottish rail incidents spanning the winters of 2006 to 2023, the thesis shows that high-impact days (i.e., those causing extreme service disruption or customer delays) are strongly associated with compound cold conditions. Critically, many severe disruption incidents occurred on days without heavy snowfall, highlighting the role of snow persistence and event sequencing. When a CW event deposits snow followed by a CD event with sub-zero temperatures, hazardous conditions can persist for multiple days and prolong periods of disruption. This demonstrates that impact severity does not always align with meteorological extremes alone and highlights the importance of adopting an impact-led approach when identifying hazardous weather risks.

The final stage of this research builds on these insights to develop a tiered operational forecasting framework that bridges the gap between atmospheric predictability and infrastructure decision-making. The framework provides early indication of heightened risk at extended lead times using a set of “high-risk” weather patterns and dynamically evolving spatial probabilities of CD and CW events. Within this framework, weather patterns serve as a crucial link connecting large-scale atmospheric circulation, compound hazard occurrence, and ultimately infrastructure impacts. This enables predictability to propagate from synoptic-scale patterns through to sector-specific risk information. The framework’s performance demonstrates that actionable forecasts of compound cold events are achievable at operationally relevant lead times. Weather pattern forecasts successfully identify windows of elevated risk up to 10 days in advance of major disruption events, while the spatial probability forecasts capture the location-specific nature of CD and CW hazards across Scotland’s rail network.

This thesis makes three principal contributions. First, it establishes weather patterns as effective diagnostic and prognostic tools for compound cold events, revealing systematic relationships between synoptic-scale circulation and regional hazard occurrence. Second, it demonstrates that compound cold events are the primary driver of high-impact disruption days to the Scottish rail sector, and that the sequencing of these events is critical to understanding how impacts unfold. Third, it provides a methodological pathway for operationalising compound event science

within impact-based forecasting systems, with transferability beyond the rail sector to other weather-sensitive infrastructure and services. As climate variability continues to challenge infrastructure resilience, such frameworks offer a template for developing multi-hazard early warning systems that anticipate not just what weather will occur, but what consequences it will bring.

INTRODUCTION

1.1 Background and motivation

Anthropogenic climate change is fundamentally reshaping weather extremes, intensifying both their variability and severity, with increasingly disruptive consequences observed globally (IPCC, 2023a). In the United Kingdom (UK), these changes are not limited to increasing temperatures, but are evident in changes in the frequency, intensity, and variability of weather events (Hanlon *et al.*, 2021). Despite observed warming and an increase in extreme temperatures in the UK (Kendon *et al.*, 2025), extreme cold events are still predicted to occur (Hanna *et al.*, 2024). For example, in January 2026, a cold snap in Scotland resulted in widespread disruption to transport and school services due to unprecedented snowfall (Kendon, 2026). Another notable cold event in the UK is the low-temperature record-breaking December of 2010 where snowfall and sustained low temperatures resulted in widespread disruption across sectors affecting the daily operations of transport, emergency, and utility services (Prior and Kendon, 2011).

The warming climate means that society will be less prepared to deal with cold events therefore making them more impactful when they do occur. Even though there is a decrease in the frequency of cold events (Kendon *et al.*, 2025), this does not translate to reduced risk, therefore the challenges these events pose to society and infrastructure should be considered. Furthermore, the weakening and possible collapse of the Atlantic Meridional Overturning Circulation (AMOC) in the future could lead to an increase in observed cold events in the UK (Bouwer *et al.*, 2022).

Traditionally, cold weather has been considered as a singular hazard. However, the most disruptive events often arise from the interaction of multiple meteorological conditions. The co-occurrence of multiple climate extremes is referred to as a compound event (Zscheischler *et al.*, 2018). Compound events have been shown to produce impacts that are greater than those associated with individual hazards alone. For example, the impacts associated with cold weather can vary significantly depending on whether low temperatures coincide with heavy precipitation conditions

or dry conditions. The Third UK Climate Change Risk Assessment (CCRA3) identifies compound events as a key risk to critical infrastructure systems and highlights that previous assessments have likely underestimated risk by considering hazards in isolation (Jaroszweski, Wood and Chapman, 2021).

There is a growing body of literature focused on compound events, particularly in relation to their physical drivers (Brett *et al.*, 2024). However, comparatively few studies examine how these events translate into real-world impacts on society and infrastructure (Fehlman *et al.*, 2025). This disconnect highlights a critical knowledge gap, especially for low-frequency, high-impact hazards such as compound cold events, which may occur less often in a warming climate but continue to cause significant disruption when they do arise. Moreover, the interaction of multiple hazards across different spatial scales presents challenges for prediction, as traditional forecasting approaches are typically designed to consider hazards in isolation (Zscheischler, Sillmann and Alexander, 2022).

Forecasting practices have traditionally focused on predicting the likelihood of a hazard occurring, often without explicitly considering the consequences of that hazard. In response, the World Meteorological Organization (WMO) has advocated a global shift towards impact-based forecasting (IbF) (World Meteorological Organization, 2015; Bazo *et al.*, 2021) which emphasises what the weather *will do* rather than just what the weather *might be* (World Meteorological Organization, 2015). This approach is particularly relevant for decision-making across sectors, where actions are triggered by anticipated impacts rather than meteorological thresholds alone. Despite this shift, current IbF implementations remain largely centred on single hazards, with limited consideration of compound events and the risks that emerge from their combined impacts on exposed and vulnerable systems (Lumbroso *et al.*, 2025). For example, the UK Met Office operates an IbF warning system that issues warnings for single hazards such as snow, wind, and rain, but does not explicitly account for the combined occurrence of these hazards. This presents a critical limitation as many of the most disruptive weather impacts arise from the interaction of multiple hazards rather than from isolated extremes. This is particularly relevant for transport systems such as the rail network, which is highly sensitive to weather

conditions (Network Rail, 2024b). Cold-related hazards including snowfall, ice and low temperatures can disrupt services, damage infrastructure, and pose safety risks (Lotfi *et al.*, 2023). It is therefore critical to develop reliable and impact-based forecasting systems for operational decision-making.

One approach that can be used to potentially bridge this gap is the use of weather pattern classifications. Weather pattern classification aims to classify the variability of the atmosphere, using techniques such as k-means clustering or self-organising maps (SOMS), into a manageable set of atmospheric circulation types that can be used to understand the driving conditions related to different high-impact weather events and their impacts. By providing a physically coherent representation of the atmospheric drivers that can lead to multiple interacting hazards, weather pattern analysis enables the identification of atmospheric set-ups conducive to compound events observed at the surface. For example, Neal *et al.* (2016) developed a set of 30 weather patterns over the north Atlantic and European domain that is used operationally by the UK Met Office. Weather patterns themselves are not forecasting systems but provide a diagnostic framework that can be applied to both historical data and numerical weather prediction outputs. Large-scale circulation is predictable at longer lead times than individual surface variables such as temperature or precipitation, therefore presenting opportunities for medium-range forecasting (up to 15 days ahead) (Ferranti, Corti and Janousek, 2015; Strommen, Christensen and Bloomfield, 2025). Previous studies have successfully applied weather pattern analysis to single hazards (Richardson *et al.*, 2018), and more recently to compound events (Bloomfield *et al.*, 2024), demonstrating through historical and diagnostic analyses that specific circulation patterns are conducive to particular hazard combinations. However, the potential for weather patterns to act as a link between compound hazard occurrence and IbF remains largely unexplored.

Taken together, these strands highlight a critical gap in current research and practice. While compound events are increasingly recognised as a significant source of risk, particularly for infrastructure systems, there remains a lack of approaches that explicitly link large-scale atmospheric drivers, compound hazard occurrence, and real-world impacts within a forecasting context. Existing forecasting systems largely

operate on a single-hazard basis, limiting their ability to capture the interacting processes that drive the most disruptive events. Furthermore, while weather pattern analysis has demonstrated value in understanding hazard occurrence, its potential to translate atmospheric predictability to impact-relevant forecasting remains underdeveloped. Addressing this gap is essential for advancing forecasting beyond hazard prediction towards decision-relevant, impact-based approaches. This thesis seeks to address this challenge by developing a framework that integrates compound event characterisation, impact data, and weather pattern-informed forecasting to support infrastructure decision-making.

1.2 Aim of the thesis and guiding research questions

This research aims to bridge the gap between atmospheric predictability and operational resilience by integrating large-scale weather patterns with the compound meteorological drivers of rail impacts. This will provide a workflow to transform raw forecasts into actionable, network-wide impact intelligence at medium-range forecast lead times. To achieve this, the thesis first characterises the occurrence of compound cold events across the UK and examines their relationship with large-scale atmospheric drivers. It then investigates how these hazards translate into real-world impacts on critical infrastructure, using the Scottish rail network as a case study. Building on these insights, the research develops and demonstrates a tiered forecasting framework that integrates hazard characterisation, impact data, and atmospheric predictability to support operational decision-making. In doing so, this work contributes to bridging the gap between compound event science and impact-based forecasting and provides a pathway for applying these concepts to critical national infrastructure.

This thesis is structured around five research questions (RQs) (Table 1.1), which progress from a general understanding of compound cold events and their drivers (RQs 1-2) to sector-specific impact analysis (RQs 3-4) and finally to the development of a transferable forecasting framework (RQ5).

Table 1.1 Guiding research questions used in this thesis

RQ1	What is the spatial and temporal distribution of compound cold events in the UK?	Addressed in Chapter 3
RQ2	Is there a relationship between compound cold events and weather pattern occurrence?	Addressed in Chapter 3
RQ3	To what extent do compound cold events impact the Scottish rail network?	Addressed in Chapter 4
RQ4	Is there a relationship between impacts on the Scottish rail network and weather pattern occurrence?	Addressed in Chapter 4 and 5
RQ5	Can an impact-based forecasting framework be developed to predict compound cold events?	Addressed in Chapter 5

1.3 Thesis structure

The thesis is divided into six chapters, comprising a background review (Chapter 2), the main analysis and results are presented in Chapters 3, 4 and 5 which are written as peer-reviewed journal articles (as stated in the Statement of Co-Authorship) and therefore contain their own independent abstract, introduction, discussion, conclusions and acknowledgment sections, followed by a synthesis discussion and conclusions (Chapter 6). The focus and contents of each chapter are as follows:

Chapter 2 provides an overview of the key research components underpinning this thesis: compound events, weather patterns, and impact-based forecasting and identifies the research gaps. It introduces compound events before focusing on compound cold events including their physical characteristics, quantification methods, and associated impacts. The chapter then reviews forecasting approaches, progressing from traditional hazard-based forecasting to large-scale circulation analysis, and concludes with impact-based forecasting and the challenges associated with forecasting compound events.

Chapter 3 presents a localised percentile-based methodology for characterising the occurrence of compound cold events in the UK. This chapter provides the first detailed assessment of their historical spatial and temporal distribution in the UK and establishes their link to weather patterns. It forms the foundation for this thesis by linking compound hazard occurrence to large-scale atmospheric circulation.

Chapter 4 utilises an impact dataset from Network Rail to examine how compound cold events affect the Scottish rail network. An impact-led approach is applied to identify the most disruptive rail incident types and find a link to compound cold events. Building on Chapter 3, weather pattern analysis is used to link these impacts to large-scale atmospheric drivers, providing a pathway towards impact-based forecasting.

Chapter 5 develops a forecasting framework that integrates the findings from Chapters 3 and 4. A set of “high-risk” weather patterns specific to the Scottish rail network is identified and combined with multiple forecast inputs to produce a tiered suite of information to support operational decision-making. The framework is demonstrated through three case studies of highly disruptive days to the rail network between 2010 and 2021.

Chapter 6 synthesises the findings across Chapters 3-5, with weather pattern analysis used as a consistent framework linking hazard characterisation, impact analysis, and forecasting development. The results are discussed in the context of the original research questions, alongside key limitations, directions for future research and concluding remarks.

CHAPTER 2 BACKGROUND REVIEW

2.1 Compound events

2.1.1 Defining compound events

In 2012, the International Panel on Climate Change (IPCC) Special Report on Climate Extremes formally introduced the concept of “compound events” which was defined as a combination of weather and/or climate events which lead to an extreme impact (IPCC, 2012). At that time research on compound events had received little attention in the literature and was very much still in its’ infancy. Since then, there has been a profound uptake in research in the compound events space (Brett *et al.*, 2024). Key papers have sought to more accurately define compound events (Leonard *et al.*, 2014), classify compound events (Zscheischler *et al.*, 2020a), develop a global event typology (Ridder *et al.*, 2020) and consider compound events under the influence of climate change (AghaKouchak *et al.*, 2020; Hao and Singh, 2020). A schematic showing the elements of a compound event are displayed in Figure 2.1.

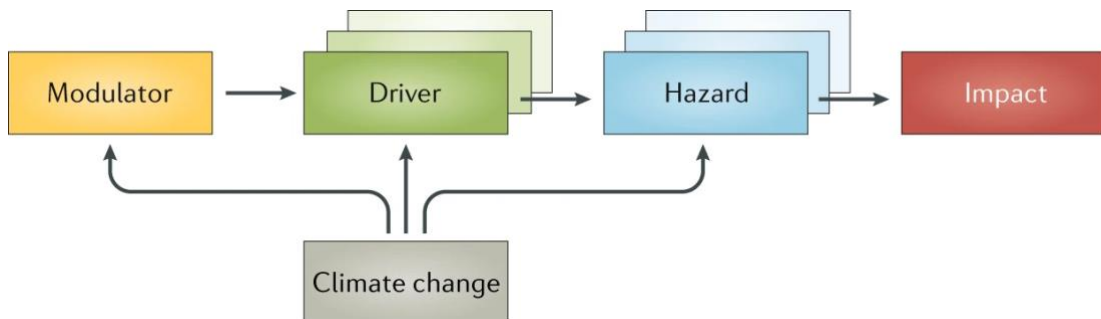


*Figure 2.1 Elements of a compound event showing how modulators (e.g., ENSO) influence climate drivers (green) and hazards (blue) that lead to impacts (red), with climate change affecting all components. Arrows indicate causal relationships. (adapted from Zscheischler *et al.*, 2020a).*

Compound events are also known as correlated, interacting, or complex extremes (Zscheischler *et al.*, 2020a). To advance the growing field of compound events, Zscheischler *et al.* (2020a) developed a typology to classify the events using four classifications: pre-conditioned, multivariate, temporally compounding, and spatially compounding. Pre-conditioned events occur when a hazard causes an amplified

impact due to a pre-condition (for example, heavy rainfall on already saturated soil leading to a landslide); multivariate refers to multiple variables in the form of drivers and/or hazards causing an impact; a sequence of hazards is known as temporally compounding and spatially co-occurring hazards can be classified as spatially compounding.

Compound events are observed around the globe across a range of spatial and temporal scales. A notable example of preconditioning was demonstrated by Hurricane Helene in the United States of America in 2024. The large-scale atmospheric set up of Hurricane Helene was conducive to excessive rainfall in the Appalachian Mountains where up to 300 mm of rainfall fell 24-36 hours ahead of the hurricane's arrival (Zscheischler *et al.*, 2025). The antecedent precipitation preconditioned the landscape prior to Hurricane Helene, amplifying the impacts of subsequent heavy rainfall and contributing to over \$100 billion US dollars in flood and landslide damages across Virginia, North Carolina, and Tennessee (Zscheischler *et al.*, 2025). A more recent example of preconditioning took place in Türkiye, when a false spring was triggered by +3°C above average temperatures in March 2025 and followed by a severe cold spell in April. This resulted in >50% losses in fruit crops that caused economic stress for farmers and consumers alike (Raymond *et al.*, 2026).

In the UK, a storm triplet caused cumulative damage through rapid temporal succession. Storm Henk (02/01/2024) brought strong winds and heavy rain leading to 38,000 properties experiencing power outages with road and rail infrastructure services also disrupted (Zscheischler *et al.*, 2025). These impacts were compounded by the arrival of Storms Isha and Jocelyn (21-24/01/2024) which prompted the Met Office to issue a rare red weather warning for wind in parts of Scotland (Zscheischler *et al.*, 2025). Storm Éowyn is a prominent example of a multivariate event that affected Scotland in January 2025 that brought co-occurring high winds, heavy snow and heavy rain (Raymond *et al.*, 2026). Critical national infrastructure including power, telecommunications and transportation was affected by the storm directly from high winds and coastal flooding and indirectly through snowdrifts and felled trees (Cha *et al.*, 2025).

Zscheischler *et al.* (2018) published a seminal perspective that highlighted how traditional risk assessment underestimates risk by only considering one driver/hazard at a time. They propose a paradigm shift towards a “bottom-up” approach that starts with analysing the impacts to assess the causal meteorological hazard(s). This approach aims to capture the impacts of compound events rather than considering extreme hazards in isolation. To successfully employ this shift Zscheischler *et al.* (2018) emphasise the need for interdisciplinary collaboration between climate scientists, engineers, social scientists, impact modellers and decision-makers.

2.1.2 Compound events in a changing climate

As the climate continues to change under global warming, weather and climate events have increased in frequency and severity. Anthropogenic greenhouse gas emissions are responsible for this, alongside land use changes which have interrupted the hydrological cycle (Zakeri and Olsson, 2018; Ebi *et al.*, 2021).

Compound events have received more attention in the literature over the past decade due to the nonstationarity of the climate system, the increased capability of complex climate models (Leonard *et al.*, 2014), and growing evidence that certain types of compound events may become more frequent under a warming climate (AghaKouchak *et al.*, 2020). However, these projected changes are not uniform across all compound event types. Many studies demonstrate the increase in compound events that will accompany climate change. Most notably there is evidence that there will be changes in extreme temperature- and precipitation-related compound events with an increase in observed hot-dry events (Manning *et al.*, 2019; Bevacqua *et al.*, 2022; Tabari and Willems, 2023). In an increasingly warm world, there will be a higher occurrence of compound events driven by extremely high temperatures such as concurrent heatwaves, hot-dry events and wildfires (Zscheischler *et al.*, 2025).

In the UK specifically, there is limited research that quantifies how compound event occurrence may change under current global warming levels. While there is strong evidence for changes in individual hazards in the UK, these are seldom considered in the context of compound events. Heat extremes are intensifying (McCarthy *et al.*,

2019; Hanlon *et al.*, 2021; Kendon *et al.*, 2024), with the July 2022 record 40°C event made six times more likely by climate change. Conversely, cold extremes are declining with 2024 recording the lowest number of ground frost days (Kendon *et al.*, 2025).

Some recent work has begun to explore compound hazards in the UK context. Bloomfield *et al.* (2023) identified a substantial increase in extreme compound wind-flood events under future climate scenarios, with extreme events projected to increase threefold by 2061-2080. In a similar vein, Manning *et al.* (2024) found that wind-rainfall extremes were 3.6 times more likely over the same period. Despite these advances, research on interacting hazards remains limited in scope and is largely focused on wind and flooding. In particular, compound cold events remain absent from UK literature, despite the UK Natural Hazards Partnership (Ciurean *et al.*, 2018; Hemingway and Gunawan, 2018) identifying multi-hazard research as critical for climate adaptation.

In addition to becoming more frequent and severe, the impacts associated with these events are becoming more extreme due to an increase in exposure (from growing populations and rapid urbanization) coupled with an increase in vulnerability (from aging populations and poor infrastructure). The extent of the impact of each pair of hazards is dependent on the exposure and vulnerability of the affected population (Ebi *et al.*, 2021). A severe storm could be less impactful to a resilient and prepared community, compared to a moderate storm hitting an underprepared community with poor infrastructure.

2.2 Cold compound events: drivers, metrics, and trends

Over Europe the typical weather regimes that result in cold near-surface temperatures are associated with periods of atmospheric blocking. The term “blocking” describes persistent anticyclones (i.e., large stationary regions of high surface pressure) that disrupt the usual westerly flow, lasting on average 7-10 days and in extreme cases 2-3 weeks (Kautz *et al.*, 2022; Hauser *et al.*, 2023). Under blocking conditions, low temperatures develop through persistent clear-sky conditions that enable strong radiative cooling at night (Kautz *et al.*, 2022). Cold events are characterised by locally

low temperatures which deviate from the seasonal average (Huang *et al.*, 2020). Absolute cold events can be quantified using frost days and icing days which represent days when the daily minimum temperature is below 0°C and days when the daily maximum temperature does not exceed 0°C, respectively (Hanlon *et al.*, 2021).

When considering compound events, cold events can be further classified as multivariate compound events when accompanied by another hydrometeorological element (Zscheischler *et al.*, 2020a). In the context of compound cold events, the presence or absence of precipitation can provide an important distinction between cold-wet and cold-dry conditions. However, defining compound cold events is not straightforward particularly because the relevant meteorological conditions do not necessarily occur simultaneously. For example, precipitation coupled with temperatures near freezing can lead to snow, sleet or freezing rain (Met Office, 2023a), while subsequent low temperatures can cause accumulated moisture to freeze. Conversely, persistent dry conditions can allow temperatures to fall below freezing and contribute to the development or persistence of snow and ice. Consequently, the interaction between temperature and precipitation may occur simultaneously or sequentially, meaning that the temporal window used to define a compound event can influence whether conditions are classified as a single event or as separate hazards.

A limited number of studies have investigated compound cold events at a daily resolution. A common approach used is to categorise the events using percentiles to represent a level of 'extreme'. The percentile used is often driven by the length of the data record available to retain enough data to conduct reasonable statistics. Vyshkvarkova and Sukhonos (2022) investigate compound extremes of air temperature and precipitation in eastern Europe by examining four indices including cold-wet and cold-dry events. Using reanalysis data, they use the daily average surface air temperature and precipitation values from 1950-2018 on a 25 km grid. Cold-wet days were calculated as the number of days where the average temperature was below the 25th percentile and the daily precipitation exceeded the 75th percentile, while cold-dry days used the indices of daily air temperature and precipitation values below the 25th percentile. The study describes the choice of percentile thresholds as

“moderate extremes”. Their results indicate an increasing trend for cold-wet compound events and decrease in cold-dry compound events. More recently, Polychroni *et al.* (2026) applied a similar quantile-based approach over the Mediterranean region and found significant annual negative trends for both event types and demonstrate that atmospheric circulation patterns are key drivers for compound event variability. In these studies, the definition of a compound cold event does not require that both temperature and precipitation extremes occur simultaneously. At a daily resolution, a cold-wet event can encompass heavy precipitation followed by low temperatures or low temperatures followed by heavy precipitation, provided that both extremes occur within the defined temporal window of one day. This introduces an important temporal consideration when defining compound events, as the choice of the temporal window determines which interactions are classified as compound rather than single hazards.

Other studies have considered compound cold events over longer temporal scales. Wu *et al.* (2021b) used global observations and CMIP6 simulations to examine compound extremes of monthly temperature and precipitation. Thresholds used in this study were the 10th and 90th percentiles of monthly temperature and precipitation over a 30-year period, and a compound event was classified as when both thresholds were met within the same month. The study concluded that there was an overall global decrease in cold-dry events excluding parts of North and South America, parts of the Middle East and parts of Asia. Additionally, a decreasing trend was found for cold-wet events except for the southern USA, west Australia, and the Middle East, where the trend was increasing. Lemus-Canovas (2022) investigated monthly temperature and precipitation extremes over the Mediterranean, using the 25th and 75th percentiles for air temperature and precipitation, found that there was a decrease in cold-wet and cold-dry events in this region. These studies demonstrate that the temporal scale over which compound events are defined can vary considerably, from daily to monthly timescales, depending on the specific research objective and potential application being investigated.

Within the context of compound cold events, the concept of precipitation extremes presents an additional definition challenge. Throughout this thesis, the term *heavy*

precipitation is used to describe precipitation conditions that are unusually high relative to the local climatology, rather than implying a universal absolute precipitation amount. This distinction is important when differentiating between cold-dry and cold-wet conditions. A lower precipitation percentile (e.g., the 25th percentile as used in the aforementioned studies) used to define cold-dry events does not necessarily represent the absence of precipitation altogether; in wetter regions the lower quantile of daily precipitation could still amount to several millimetres. Consequently, defining cold-dry conditions simply as “dry” should not be interpreted as meaning that no precipitation is present. In contrast, cold-wet events represent cold conditions occurring alongside precipitation above a higher climatological threshold, thereby distinguishing relatively wet conditions from the lower precipitation conditions associated with cold-dry events. The terminology *heavy precipitation* is therefore used throughout this thesis to distinguish these relatively wet conditions from the lower end of the precipitation distribution, rather than to imply a static rainfall amount.

2.3 Impacts of compound cold events

Cold events in the UK can affect society through a range of impacts across critical services and infrastructure including public health, transportation, water, and energy (Palin *et al.*, 2016; Charlton-Perez *et al.*, 2019). To the author’s knowledge, at the time of writing this thesis, no studies have explicitly investigated the impact of compound cold events on society or infrastructure in the UK. Given the limited literature on compound cold events specifically, the following studies provide a baseline for understanding the types of impacts that can result from cold conditions across public health, transportation and energy. Where appropriate, the examples given have been categorised according to compound cold event type to distinguish the different impacts associated with cold-dry and cold-wet events.

There is an established relationship between ambient temperature and adverse health effects, with human health considered optimal between 15-25°C and health risks rising progressively outside this range (Rudge and Gilchrist, 2007). Cold weather can aggravate respiratory and cardiovascular conditions, potentially leading to death (Hughes and Natarajan, 2019; Psistaki, Paschalidou and McGregor, 2020). These

impacts are often delayed, with mortality impacts peaking 2-3 days after a cold event and persisting for up to three weeks (Rudge and Gilchrist, 2007; Charlton-Perez *et al.*, 2019; Psistaki, Paschalidou and McGregor, 2020). Physiological impacts can begin at temperatures of approximately 5-6°C (Charlton-Perez *et al.*, 2019), with the elderly, children, and those with compromised health most vulnerable (Psistaki, Paschalidou and McGregor, 2020). Cold and icy conditions can result in an increase in injury due to slips and falls (Curtis *et al.*, 2017). The cascading health effects associated with cold events are an increase in GP and A&E visits due to the delayed onset of physiological impacts, therefore putting pressure on the NHS (Curtis *et al.*, 2017; Hughes and Natarajan, 2019).

Cold events can additionally affect health through their impacts on living conditions. The World Health Organisation advises that households maintain a minimum temperature of 18°C to avoid cold-related health effects (World-Health-Organization, 2018). Cold housing can contribute to high blood pressure, increased risk of influenza and asthma, and reduced resistance to infections. Further impacts can include mould growth, damp and condensation which further exacerbate health conditions (Boomsma *et al.*, 2017). UK dwellings are known to have poor thermal efficiency, therefore leaving millions susceptible to the impacts of cold events (Hughes and Natarajan, 2019). These human health impacts in turn result in pressure on the NHS following a cold event.

As a weather sensitive sector, low temperatures can cause considerable impacts on the energy network. This includes strongly influencing electricity supply and demand which in turn affects price volatility (Añel *et al.*, 2017). During winter, low temperatures and shorter days increases the energy demand for lighting and heating. Lower solar irradiance coupled with calm conditions can result in renewable energy shortfalls. For example, during a cold windless event the demand can be difficult to meet if the event is being driven by high pressure (i.e., a wind drought)(Hall and Hanna, 2018). In November 2024 this type of event occurred, whereby a period of cold and cloudy conditions increased the energy demand across the UK and as a result electricity prices increased across the month (Hutchins *et al.*, 2025).

Transport links including road, rail and aviation are affected by cold events. The main impact is disruption to normal services of transportation links, but the specific mechanisms differ between cold-dry and cold-wet conditions. Snowy, icy, and foggy conditions can lead to airport and road closures (Palin *et al.*, 2016). During cold-dry events, the major hazard to be considered is the formation of ice. Roads must be gritted to counteract the formation of ice and speed restrictions may be put in place as braking distances are increased tenfold in the presence of ice (The Highway Code, 2025).

Cold-wet events introduce the additional hazard of potential snowfall, sleet and freezing rain which can have costly impacts by causing major road-network disruptions (Department for Transport and Met Office, 2025). A study by Pejovic *et al.* (2009) found the presence of snow to increase the chance of flight delays by 25%, in a case study at Heathrow Airport. Heavy snowfall on railway lines and runways can cause cancellations of train and aviation services, respectively (Palin *et al.*, 2016). When heavy precipitation is followed by a rapid temperature drop during a cold-wet event, the temporal sequencing creates the optimal conditions for black ice formation which is often widespread and challenging to detect and treat (Chapman, Thornes and Bradley, 2001; DTN, 2026). In contrast, snowfall followed by sub-freezing temperatures can produce compacted ice and snow layers that can persist for days. The temporally compounding effects within a single cold-wet event can produce more severe disruption than either extreme phenomenon occurring in isolation.

This thesis specifically investigates the impacts of compound cold events on the rail network in Scotland. The following studies give an overview of how cold conditions can affect different parts of railway infrastructure. Figure 2.2 demonstrates how weather hazards translate into railway infrastructure impacts. Railway services can be disrupted due to the formation of ice on movable track equipment and powerlines and are susceptible to speed restrictions in extreme cold weather which further increases delays (Network-Rail, 2023). During a cold-dry event the presence of extreme low temperatures can negatively impact railway infrastructure by causing the tracks to become brittle and possibly separate (Xia *et al.*, 2013) and potential clear-sky conditions can produce severe radiative cooling at night (Kautz *et al.*, 2022),

leading to persistent ice formation and thawing inhibition. On the other hand, a cold-wet event could lead to accumulated snowfall, of which 5cm or more on railway tracks can have significant impacts on tracks and can potentially cause derailment (Xia *et al.*, 2013). The rail network therefore represents critical infrastructure that has the potential to be severely impacted by cold-related hazards.

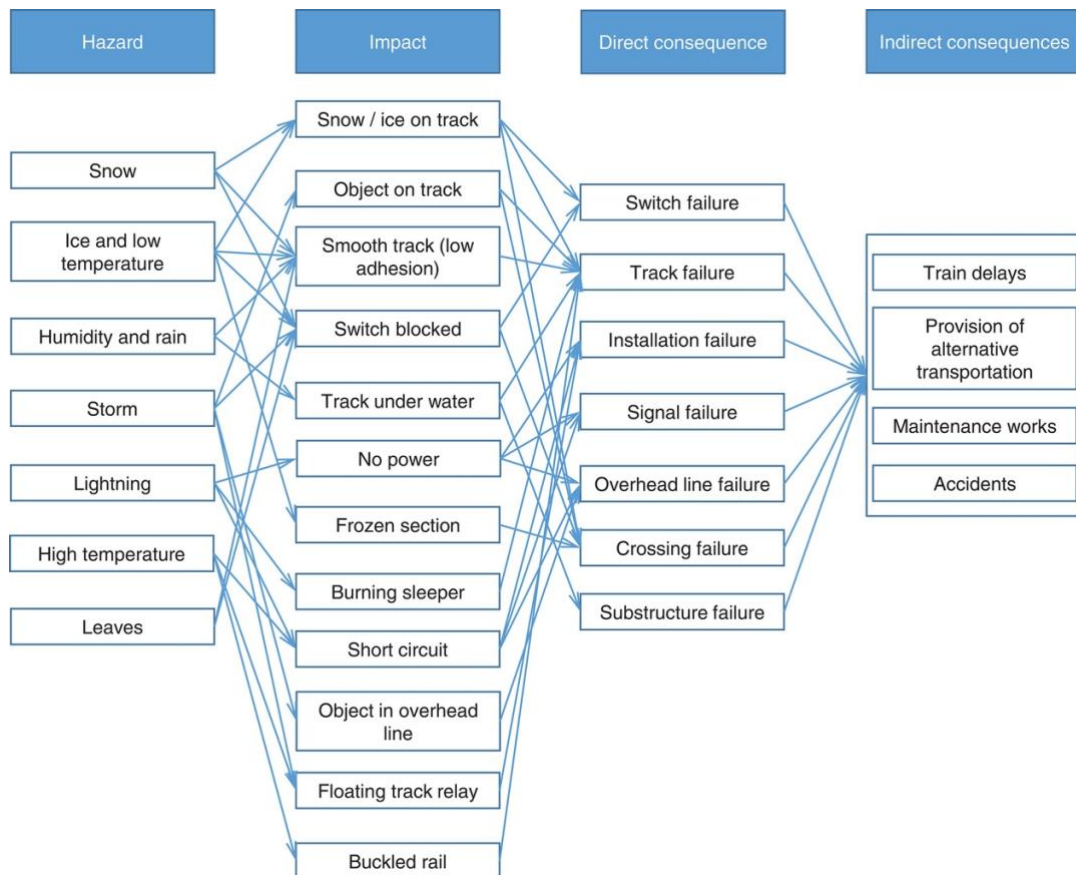


*Figure 2.2 Illustration of the complex relationships linking weather hazards to railway infrastructure impacts and their direct and indirect consequences (adapted from Palin *et al.*, 2021).*

2.4 Forecasting extremes: from hazards to decision-support

2.4.1 Ensemble forecasting

The evolution of forecasting practices has been accompanied by the increasing use of ensemble forecasting. Unlike deterministic forecasts that provide a single outcome,

ensemble forecasting adopts a probabilistic approach by running several numerical weather prediction (NWP) models with slightly perturbed initial conditions. As the ensemble members evolve independently, they sample a range of possible future states of the atmosphere (Figure 2.3). The range of possible outcomes allows the forecast uncertainty to be quantified. For example, if 25 out of 50 members indicated that there would be rain then there would be a 50% chance of rain for that forecast.

Ensemble forecasts are widely used in operational meteorology due to their enhanced predictive skill and their ability to represent uncertainty (Mylne, 2026). Beyond simple probabilities, ensemble output can be used to derive percentiles (Figure 2.3), uncertainty bounds, most-likely outcomes, alternative scenarios, and plausible worst-case conditions (Mylne *et al.*, 2025). As a result, major forecasting centres including the UK Met Office and the European Centre for Medium-Range Weather Forecasts (ECMWF) have transitioned toward ensemble-based forecasting systems, reflecting a broader shift from deterministic to probabilistic forecasting (Mylne *et al.*, 2025).

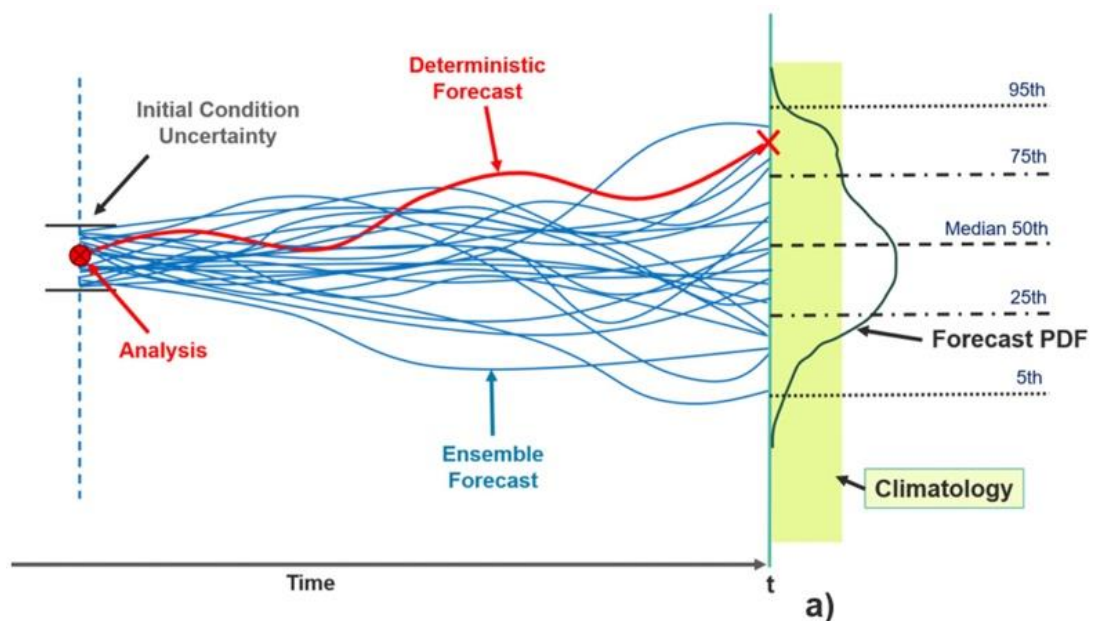


Figure 2.3 Representation of ensemble forecasting methodology: individual ensemble members (blue lines) capture the range of possible outcomes, contrasted with a single deterministic forecast (red line). Percentile applications demonstrate how ensemble spread can be translated into probabilistic forecast products (adapted from Mylne, 2026).

2.4.2 Hazard-based forecasting limitations

Traditional meteorological hazard-based forecasting has predominantly focused on predicting the physical characteristics associated with weather hazards such as temperature, precipitation amounts, and wind speeds and how these hazards may present spatially and temporally. For example, on Tuesday 10mm of rain is forecast to fall in X location. This is a hazard-centric approach that provides essential information about what the weather *will be* but does not give any further context about the potential impacts of that hazard and more importantly what the weather *might do* (World Meteorological Organization, 2015; Harrowsmith *et al.*, 2020). Hazard-based forecasts traditionally operate using fixed thresholds to trigger hazard warnings: if rainfall exceeds X mm in Y hours, or if temperatures fall below Z °C, a warning would be issued without considering the exposure and vulnerability of the affected population (Potter *et al.*, 2021).

The hazard-based approach has been effective to a degree in raising awareness of severe weather events, but it carries several limitations. Firstly, broadly defined hazard thresholds do not account for spatial differences in vulnerability (Potter, Harrison and Kreft, 2021; Harrison *et al.*, 2022a). The same hazard can have different impacts depending on the affected location. For example, a given snowfall accumulation may be routinely managed in northern cities such as Aberdeen, where infrastructure and services are adapted to winter conditions, but may cause significant disruption in southern cities such as London, where such events are less frequent and systems are less resilient. Secondly, hazard-based warnings are reliant on the end-user correctly interpreting and acting upon the warning information given. In many instances the end-user lacks the expertise or local knowledge to contextualise how that hazard will affect their specific situation (Otto *et al.*, 2018). Thirdly, the hazard-based approach is primarily for single individual hazards and does not consider compound and cascading events where impacts may emerge from the interaction of multiple hazards or the sequencing of hazards (Zscheischler *et al.*, 2020).

2.4.3 Large scale predictability and circulation regimes

Forecasting at extended lead times remains challenging due to the reduced predictability of surface variables such as temperature and precipitation. One route to providing relevant forecast information is by leveraging the skill in large-scale circulation patterns and weather regimes. Weather patterns are circulation types defined over a specific geographic region that have distinct meteorological characteristics and can vary at a daily timescale (James, 2006; Neal *et al.*, 2016). Using large-scale synoptic typing has long been used to relate circulation to surface weather and associated impacts. This paradigm was first established by the classical Grosswetterlagen (GWL) circulation types (Hess and Brezowsky, 1969) and Lamb weather types (Lamb, 1972). More recently, classification approaches have been developed for operational use. The UK Met Office developed a set of 30 weather patterns (MO30) over the North Atlantic-European domain (Figure 2.4) primarily for use in their operational tool “Decider” which provides probabilistic forecasts of pattern occurrence at a 15-day lead time (Neal *et al.*, 2016).

While deterministic forecasts of specific surface variables such as temperature and precipitation become increasingly uncertain with lead time, large-scale circulation features often retain greater predictability (Strommen *et al.*, 2025). Forecasting weather pattern occurrence therefore enables informed assumptions to be made about temperature and precipitation conditions associated with specific regimes and patterns, effectively extending the temporal horizon of useful relevant forecasting information (Ireland *et al.*, 2024). Relating the most impactful local surface weather conditions to large-scale weather patterns is useful in an operational impact-based forecasting setting as weather patterns can be skilfully predicted out to 10 days lead time in the UK (Neal *et al.*, 2016), providing valuable time for preparatory action to be taken.

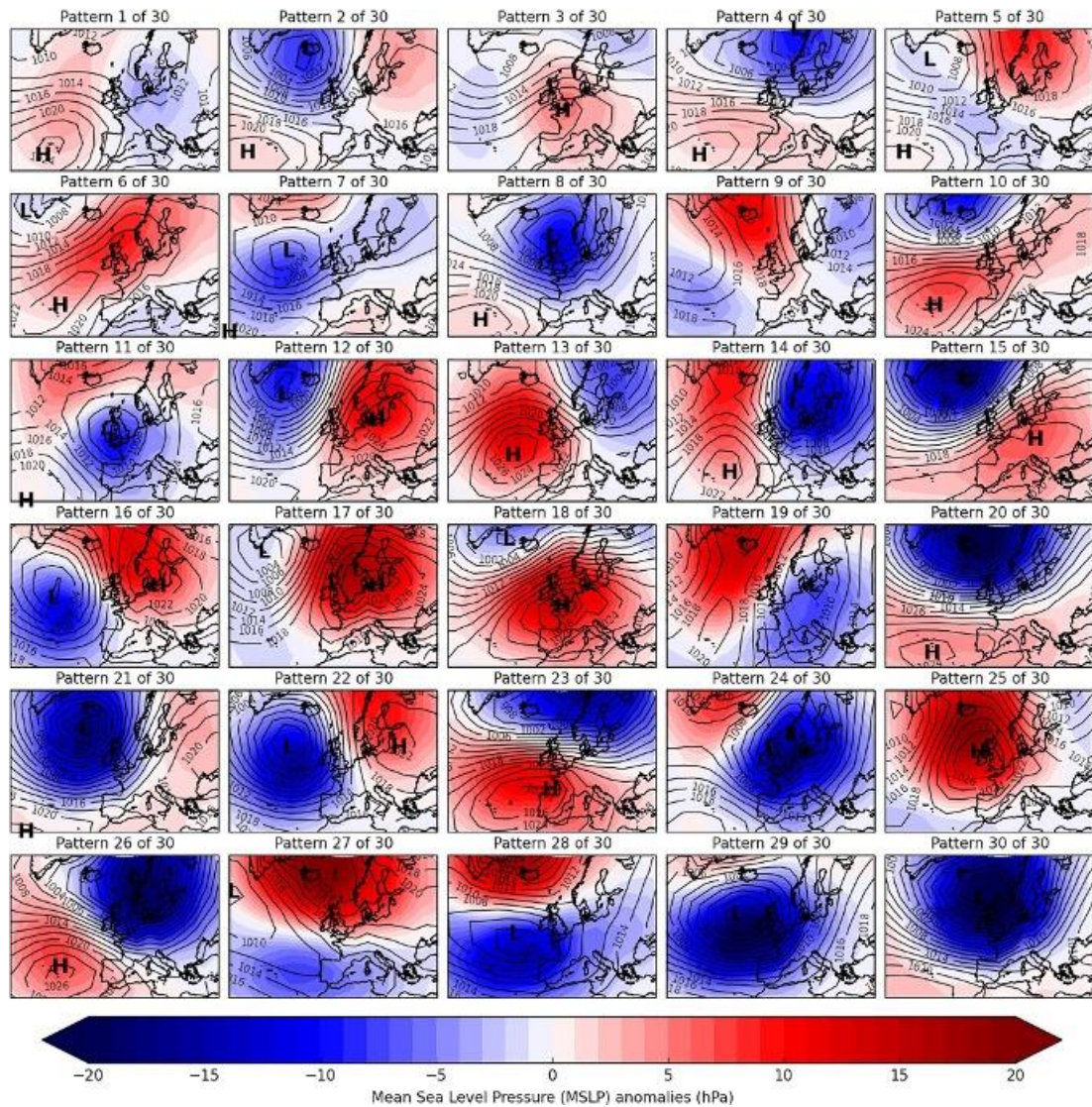


Figure 2.4 The set of 30 weather patterns developed by Neal *et al.* (2016). The colours indicate the location of areas of high and low pressure, demonstrating the different flow characteristics of each pattern. An accompanying flow description can be found in Table A1.1 of Appendix 1.

Weather patterns have been applied across a wide range of sectoral forecasting contexts. The MO30 classifications alone have been used in historical studies exploring coastal flooding risk (Neal *et al.*, 2018a), drought risk (Richardson *et al.*, 2018; Richardson *et al.*, 2020), urban mobility (Brown *et al.*, 2019), lightning risk (Wilkinson and Neal, 2021b), energy network power outages (Souto *et al.*, 2024), wildfire risk (Little *et al.*, 2026) and volcanic ash flow (Harrison *et al.*, 2022b). In

addition to their potential predictive value, weather pattern frameworks can provide an interpretable representation of forecast information for non-technical users, supporting their integration into operational decision-making (Strommen, Christensen and Bloomfield, 2025). To support the accurate use of weather patterns, several studies have been carried out to demonstrate the forecast skill in different situations and across several timescales (Ferranti, Corti and Janousek, 2015; Bloomfield, Brayshaw and Charlton-Perez, 2019; Büeler *et al.*, 2021; Osman *et al.*, 2023).

A limited number of studies have sought to link compound events with large-scale circulations, demonstrating that such events have predictable atmospheric drivers. Examples include compound wind-flood events in Great Britain (Bloomfield *et al.*, 2024), rainfall-wave events in the Mediterranean (Sanuy *et al.*, 2024) and cold and snowy compound events in Italy (D'Errico *et al.*, 2022). These studies demonstrate that the synoptic set up can be conducive to the occurrence of compound events, and establishing a link can enable forecasting into the medium range. However, at present, these relationships remain largely diagnostic with no translation into operational forecasting frameworks designed to support real-world decision making.

2.4.4 Impact-based forecasting

The weather is an integral part of everyday life and influences many of the decisions made on a day-to-day basis. It may influence what clothing choices or if the heating or air-conditioning should be switched on. For these types of decisions, the weather forecast can be simple: will it be wet or dry, will it be cold or hot. When considering more impactful weather such as storms, heatwaves, and snowfall, it is necessary to have more information than just the meteorological forecast alone. As the weather can impact lives, livelihoods, health, and infrastructure, there needs to be a shift in consideration to what the weather *will do*, rather than simply what the weather *might be* (World Meteorological Organization, 2015). Despite timely weather warnings being issued, there are still billions of US dollars of socioeconomic losses and a high number of fatalities worldwide following severe weather events (Potter, Harrison and Kreft, 2021). This need for improved interpretability of weather forecasts has led to a

paradigm shift from hazard-based to impact-based forecasts (Lee, 2017; Taylor, Kox and Johnston, 2018).

Changes in global demographics, such as population growth and aging populations, coupled with climate change, has resulted in the impact of weather events becoming more costly (Potter, Harrison and Kreft, 2021). Impact-based forecasts (IbF) provide additional information to the end user which are intended to limit socioeconomic losses and assist individuals with decision making. This comes from a need to make weather forecasts and warnings more “people centred” (Potter, Harrison and Kreft, 2021). IbF takes into account the elements of exposure and vulnerability to calculate risk rather than solely providing information of the physical hazard such as the intensity, and spatial and temporal reach (Merz *et al.*, 2020).

The 2015 UNISDR Global Assessment Report on Disaster Risk Reduction (UNISDR, 2015) highlights that for early warning systems to be successful, the warnings issued must contain information which considers the exposure and vulnerability of the impacted region. This is a step change in how early warning systems operate, as traditionally they use set thresholds of weather phenomena to warrant a warning being issued (e.g., if the wind speed exceeds X km/hr, or if snow depth exceeds X mm)(Potter, Harrison and Kreft, 2021). These impact-based warnings aim to trigger an action by the end-user (e.g., general public, emergency services, civil protection) which will reduce socioeconomic loss. Additionally in 2015, the World Meteorological Organization released the “WMO Guidelines on Multi-Hazard Impact-based Forecasts and Warning Services” (World Meteorological Organization, 2015). These guidelines articulate the definition of IbF and confirm the need to incorporate this approach into national meteorological and hydrological services.

Several studies have been published that underscore the need for IbF systems to be implemented to reduce the impacts incurred by hydrometeorological hazards. Rogers et al, (2019), for example, discuss the paradigm shift from hazard-based to impact-based forecasts with respect to hydrometeorological hazards which occurred during the Covid-19 pandemic and lessons which can be learned from this type of multi-hazard event. They recommended that early detection and early warning was the

most successful way to limit the impact on respective populations. Kox *et al.* (2018) investigated the emergency service response to severe weather events in Germany and found that there was a need to focus on the importance of communicating the associated impacts rather than just the hazard alone. They also found that there was a lack of understanding of the behaviour of key responders and how they use and communicate weather information. Otto *et al.* (2018) uses a case study where major casualties occurred, despite a weather warning being issued, due to a public misunderstanding of the term “storm surge”. This study stresses the need to move to impact-based forecasts and warnings so that the general public are able to make decisions based on their individual circumstance. Moving forward they recommended that IbF warning services incorporate aspects of vulnerability information, development of an information sharing system, and extensive training at community and professional level. Despite these advances in IbF methodology, compound events present unique challenges that existing frameworks have not fully addressed.

2.4.5 Challenges for compound event forecasting

Operational forecasting frameworks designed specifically for compound events are rare despite the growing recognition of the disproportionate impacts of compound events. There are several challenges associated with integrating compound events into impact-based forecasting. For example, most forecasting systems are set up to predict a singular hazard at a time. Forecasting compound events would require the accurate prediction of multiple variables simultaneously. Standard forecast verification metrics focus on single variables, making it challenging to assess skill in predicting co-occurring or sequentially occurring extremes (Zscheischler *et al.*, 2018). For compound cold-wet and cold-dry events, this would require the prediction of temperature and precipitation alongside the prediction of if they will occur within an operationally relevant time window.

While univariate extremes can often rely on climatological percentiles, compound events require joint probability distributions that account for the dependence structure between variables (Leonard *et al.*, 2014). Moreover, impact-relevant thresholds may differ from climatological extremes. A “moderate” cold spell combined with “moderate”

precipitation may produce severe infrastructure impacts if they occur simultaneously, even though neither variable meets an extreme threshold (van der Wiel *et al.*, 2020). This creates the need for bespoke, sector-specific compound event definitions that reflect operational realities rather than purely statistical extremes.

2.5 Forecasting compound events: emerging approaches

Current IbF systems are predominantly designed for single hazards rather than compound events, which could present as multivariate, pre-conditioned, spatially compounding, or temporally compounding (Zscheischler *et al.*, 2020a). This single-hazard focus is increasingly recognised as inadequate (Van Den Hurk *et al.*, 2015), particularly given that climate change has already increased the frequency and intensity of some types of compound events (Section 2.1.2). As a result, there is a growing consensus that IbF systems must evolve to account for interacting hazards in order to effectively anticipate impacts.

A key limitation in advancing compound event IbF is the scarcity of impact data linking meteorological conditions to real-world consequences. Several studies highlight that relatively few investigations explicitly quantify the impacts of compound events (Merz *et al.*, 2020; de Brito *et al.*, 2021), which constrains the development of operational warning systems. Without empirical evidence it is challenging to define the thresholds and triggers required for IbF implementation. Recent methodological advances such as the integrated network analysis and data mining approach proposed by de Brito (2021) for compound droughts, demonstrate potential pathways forward, but remain limited in application.

Beyond data limitations operational challenges also impede the implementation of compound event IbF systems. Existing systems often rely on predefined thresholds that may not adequately capture dynamic vulnerability whereas more flexible approaches that incorporate real-time decision-making require sustained human input and associated costs (Boult *et al.*, 2022). This highlights the need for hybrid systems that balance automation with expert judgement, an approach also emphasised in earlier work on forecast-based action (Coughlan de Perez *et al.*, 2015). At the policy level, there is an increasing recognition of the need for multi-hazard approaches, as

reflected in initiatives such as the WMO's "Early Warnings for All" initiative (2022-2027) (WMO, 2022a) which explicitly calls for multi-hazard early warning systems (MHEWS). Similarly, Van Den Hurk *et al.* (2023) propose a framework for embedding compound events across the disaster risk reduction cycle. However, operational implementation of such approaches remains limited particularly outside humanitarian contexts and in sectors such as critical infrastructure and transport systems.

2.6 Summary

While compound events research has grown globally (Brett *et al.*, 2024), UK-specific studies remain limited, with most research focusing on individual hazards (Kendon *et al.*, 2024) or hot and dry compound events in other regions (e.g., Bevacqua *et al.*, 2022; Shi *et al.*, 2023). Compound cold events remain comparatively understudied, partly due to the observed decline in cold extremes under a warming climate. However, climate warming does not eliminate cold extremes; rather, it alters the variability and distribution of weather extremes. As a result, severe cold events remain plausible in the present and near future. It is therefore necessary that critical infrastructure continues to include cold-related hazards such as compound cold events in weather resilience and climate adaptation planning. Despite growing recognition of the disproportionate impacts of compound events and policy-level calls for MHEWS, no operational IbF systems are known to currently exist for compound events (Lumbroso *et al.*, 2025).

Weather pattern analysis has been applied extensively to understand and predict single hazards (Neal *et al.*, 2018b; Brown *et al.*, 2019; Wilkinson and Neal, 2021b; Souto *et al.*, 2024; Little *et al.*, 2026) and a small number of studies have begun to link weather patterns to compound event occurrence (D'Errico *et al.*, 2022; Bloomfield *et al.*, 2024; Sanuy *et al.*, 2024). However, these streams of research remain largely separate. To date, no study has combined weather pattern analysis, compound event characterisation, and integration into an impact-based forecasting framework. This gap is particularly important given the subseasonal forecast skill available through weather pattern approaches (Bueler *et al.*, 2021; Osman *et al.*, 2023), which would enable impact-based warnings at lead times sufficient for preparedness actions.

Chapter 3 CHARACTERISING COLD-DRY AND COLD-WET COMPOUND EVENTS IN THE UNITED KINGDOM

3.1 Preface

This chapter (excluding this preface) has been published in the International Journal of Climatology. Numberings of chapters and figures have been adapted for consistency of the overall thesis, and references have been compiled at the end of the thesis.

Corresponding publication: Mattu, K.L., White, C.J., Bloomfield, H. and Robbins, J. (2025), Characterising Cold-Dry and Cold-Wet Compound Events in the United Kingdom. Int J Climatol e8859.

Corresponding DOI: <https://doi.org/10.1002/joc.8859>

This chapter directly addresses the following research questions (posed in Chapter 1.2 – Table 1.1):

- RQ 1. What is the spatial and temporal distribution of compound cold events in the UK?*
- RQ 2. Is there a relationship between compound cold events and historical weather pattern occurrence?*

Chapter 3 is the first of three science chapters presented in this thesis. Chapter 3 initiates this research pathway by presenting a hazard-based characterisation of compound cold events in the UK so that Chapters 4 and 5 can subsequently examine the impacts associated with these events and propose a framework for forecasting them. Chapter 3 addresses RQs 1 and 2 by developing a localised percentile-based methodology for characterising the occurrence of compound cold events in the UK. It provides the first detailed assessment of their historical spatial and temporal distribution in the UK and establishes their link to weather patterns. In doing so, it forms the foundation for this thesis by linking compound hazard occurrence to large-scale atmospheric circulation. While not explicitly discussed in Chapter 3, multi-day

events were considered in the initial development of methodology for defining compound cold events. Ultimately single-day events were retained as the focus of research to follow a similar approach of previous studies that have investigated compound cold events at a daily resolution (Vyshkvakova and Sukhonos, 2022; Polychroni *et al.*, 2026). This is discussed further in Section 6.3.

3.2 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.

Keywords: compound events, cold-dry, cold-wet, impact-based forecasting, weather patterns

3.3 Introduction

Extreme cold events are projected to occur throughout the 21st Century despite a warming climate (Kodra, Steinhäuser and Ganguly, 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 (Palin *et al.*, 2016; Charlton-Perez *et al.*, 2019). Cold conditions have significant impacts to 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, Paschalidou and McGregor, 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 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, Steinhäuser and Ganguly, 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 (Ballester, Douville and Chauvin, 2008; Wu *et al.*, 2021b). 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 which cause fatality are higher during the first snowfall of the season compared to non-first snowfalls. Hitchens (2022) carried out a similar study which 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, i.e., when one event is accompanied by another extreme meteorological phenomena (Zscheischler *et al.*, 2020a). As discussed by Zscheischler *et al.* (2020b), 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 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.*, 2021b) 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 3.1 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 which 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 which 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.

Table 3.1 A selection of previous studies which have investigated compound cold-dry and cold-wet events. The dataset used, resolution, extreme index and qualifying period for a compound event are displayed.

Publication	Dataset	Resolution	Extreme index used (percentiles)	Qualifying Period for Compound Event
(Yang <i>et al.</i> , 2024)	SSP2-4.5 scenario in CMIP6	0.5° × 0.5°	25 th and 75 th percentile of daily min/max temperature and precipitation of each year	Within the same day
(Peng <i>et al.</i> , 2023)	Gridded data set CRU TS v4.04	0.5° × 0.5°	25 th and 75 th percentile of temperature and precipitation for each month	Within the same month

(Vyshkvarkova and Sukhonos, 2022)	Reanalysis E-obs 20.0	$0.25^{\circ} \times 0.25^{\circ}$	25 th and 75 th percentile of temperature and precipitation for each season	Within the same day
(Wu <i>et al.</i> , 2021b)	Gridded data set CRU TS v4.03; CMIP6 GCMs	$1^{\circ} \times 1^{\circ}$	10 th and 90 th percentile of temperature and precipitation for each month	Within the same month
(Wu <i>et al.</i> , 2019)	Observations	$0.5^{\circ} \times 0.5^{\circ}$	25 th and 75 th percentile of temperature and precipitation for each month	Within the same month
(Hao, AghaKouchak and Phillips, 2013)	Observations; CMIP5 historical simulations	$2^{\circ} \times 2^{\circ}$	25 th and 75 th percentile of temperature and precipitation for each month	Within the same month
(Beniston, 2009)	Observations; RCMs	$0.5^{\circ} \times 0.5^{\circ}$	25 th and 75 th percentile of temperature and precipitation for each month	Within the same month

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.*, 2018b) serving as an early forecast system for fluvial flooding (Richardson *et al.*, 2018), and forecasting impacts such as lightning activity (Wilkinson and Neal, 2021a), volcanic ash flow (Harrison *et al.*, 2022b), 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 understating 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 3.4 describes the data and methodology used; Section 3.5 presents the results of the spatial and temporal distribution and the link to weather patterns; in Section 3.6 we discuss the results, and finally in Section 3.7 we draw conclusions of the work.

3.4 Data and methodology

3.4.1 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 Office *et al.*, 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 to 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).

3.4.2 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): $\leq 15^{\text{th}}$ percentile of daily minimum temperature AND $\leq 15^{\text{th}}$ percentile of daily precipitation
- cold-wet (CW): $\leq 15^{\text{th}}$ percentile of daily minimum temperature AND $\geq 85^{\text{th}}$ 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., 5^{th} or 95^{th} 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.* (2021b) use extreme indices of the 10^{th} and 90^{th} percentile, however, these thresholds must only be observed within the same month (rather than day) to qualify as a compound event (see Table 3.1). Combinations of the 5^{th} , 10^{th} , 15^{th} , 20^{th} , 80^{th} , 85^{th} , 90^{th} and 95^{th} 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 25^{th} and 75^{th} 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, e.g., in parts of southwest England the average seasonal 25^{th} percentile of minimum temperature is $>4^{\circ}\text{C}$.

Percentile values have been calculated using an ordered time series of winter (December, January, February, DJF) days over a 30-year period of 1993 to 2022 for each HadUK-Grid land grid-square as this is standard practise for climatology calculations (Kendon *et al.*, 2023). The precipitation time series has been masked to only include days when the precipitation value was $\geq 0.2\text{mm}$. This research is intended to support impact-based forecasting and therefore using the most recent 30 years provides percentiles which 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.

Table 3.2 Percentile thresholds for compound cold events for the cities of Belfast, Glasgow, Newcastle, London, and Plymouth.

City	15 th percentile min temp (°C)	15 th percentile precipitation (mm)	85 th 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

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 3.2. Qualifying threshold values for the rest of the UK can be found in Figure A1.1 of Appendix 1.

3.4.3 Weather classifications

Table 3.3 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 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 simulated annealing variant of 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 was recorded. Table 3.3 shows a breakdown of the eight regimes into the 30 weather patterns. A flow description of each weather pattern can be found in Table A1.1 of Appendix 1.

3.5 Results

3.5.1 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 3.1 (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 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.

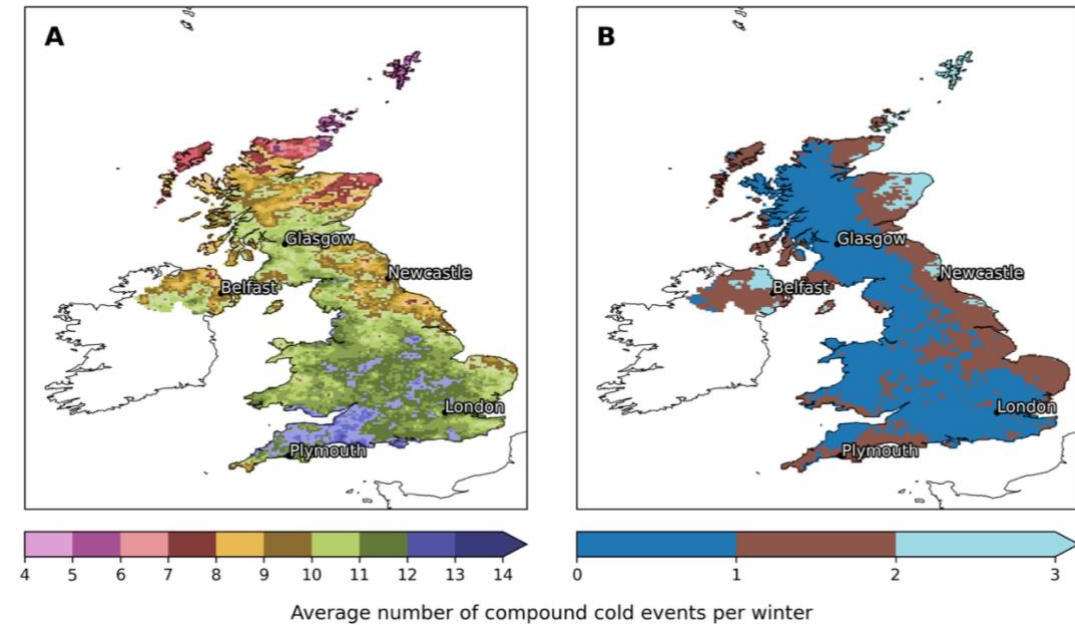


Figure 3.1 Study area of the UK, showing the winter average compound CD (A) and CW (B) days calculated using location-specific percentile thresholds. The results are expressed as a yearly average from 1960 to 2022.

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 which 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 wind from the continent (Met Office, 2023b). Figure 3.1 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 emphasizes 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.

3.5.2 Temporal variation of observed cold-dry and cold-wet events

Figure 3.2A 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 which 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.

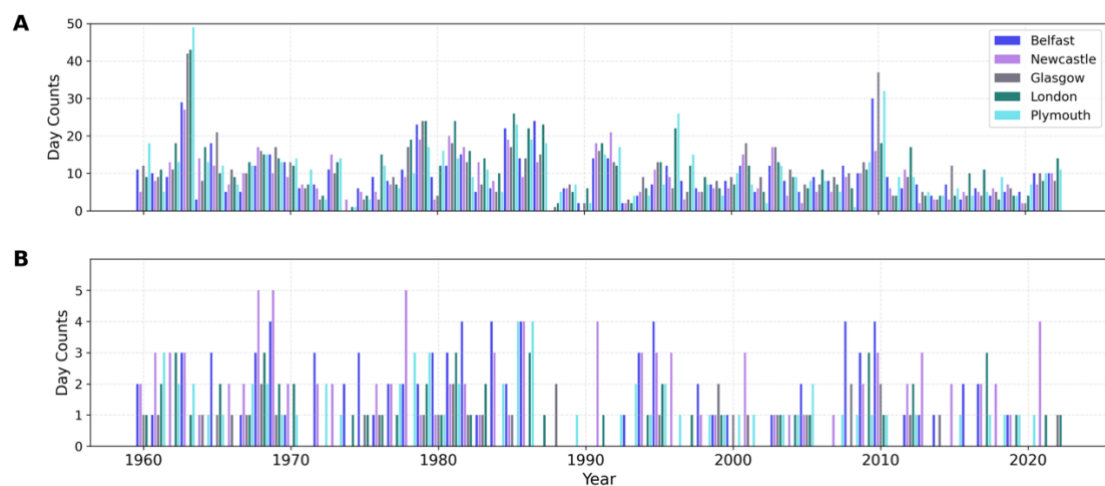


Figure 3.2 Timeseries of the observed number of CD (panel A) and CW (panel B) days per year from 1960 to 2022 in HadUK-Grid 5km.

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 3.2B) do 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 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 3.2B display values ranging from 0 to 5. Since 1990 only Belfast and Newcastle show years which 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.

3.5.3 Linking observed events with weather patterns and regimes

Figure 3.3A shows that the highest number of CD days occur 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), e.g., 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, 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.

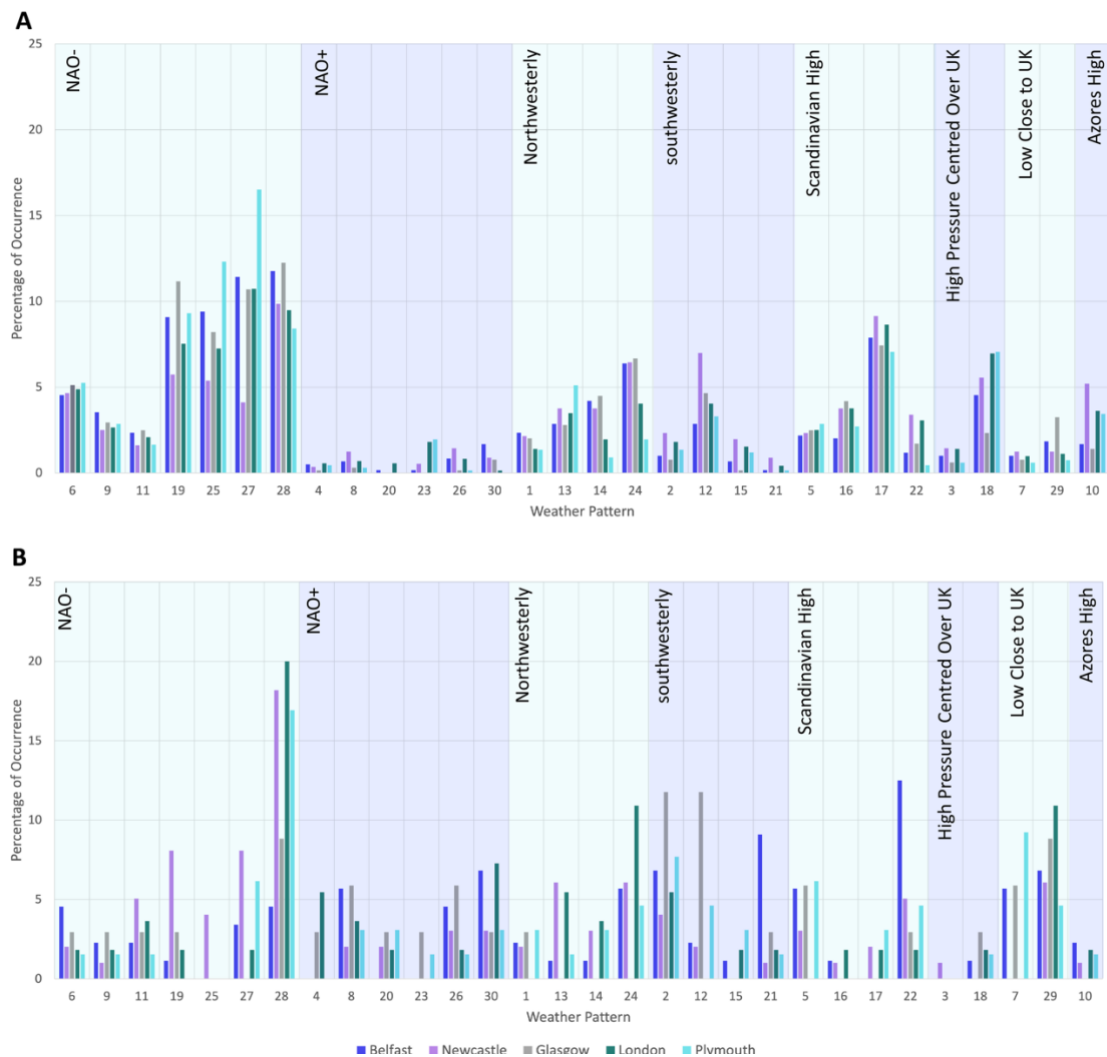


Figure 3.3 Percentage of CD (panel A) and CW (panel B) days under the eight weather regimes (NAO-, NAO+, Northwesterly, Southwesterly, Scandinavian High, High Pressure Centred Over UK, Low Close to UK, and Azores High) for five representative cities (Belfast, Newcastle, Glasgow, London and Plymouth).

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 regime, 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 3.3B 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 which 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 i.e., 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 Figure 3.1B and Figure 3.2B as driving weather patterns of CW days do not persist for as long as those which 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 3.4A, 3.4E). This is in agreement with (Hanna, Hall and Overland, 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 3.4A) 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% 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 3.4E) shows 20-30% on the northeast coast of Scotland and 10-20% for most of the UK. The regimes NAO+ (Figure 3.4B), High Pressure Centred Over the UK (Figure 3.4F), Low Close to UK (Figure 3.4G) and Azores High (Figure 3.4H) generally report less than 10% CD occurrence. Northwesterly (Figure 3.4C) shows 10-20% for much of Scotland and north England, while Southwesterly (Figure 3.4D) 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 3.4A) 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 3.4B) shows occurrences of 20-40% down the western half of Scotland and north and central England while the rest of the country show 10-20% with less than 10% in northeast England and the southwest peninsula. Northwesterly (Figure 3.4C) and Southwesterly (Figure 3.4D) 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 3.4E) and Low Close to the UK (Figure 3.4G) 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 3.4F) and Azores High (Figure 3.4G) express the lowest percentage of CW days with most of the UK displaying less than 10%.

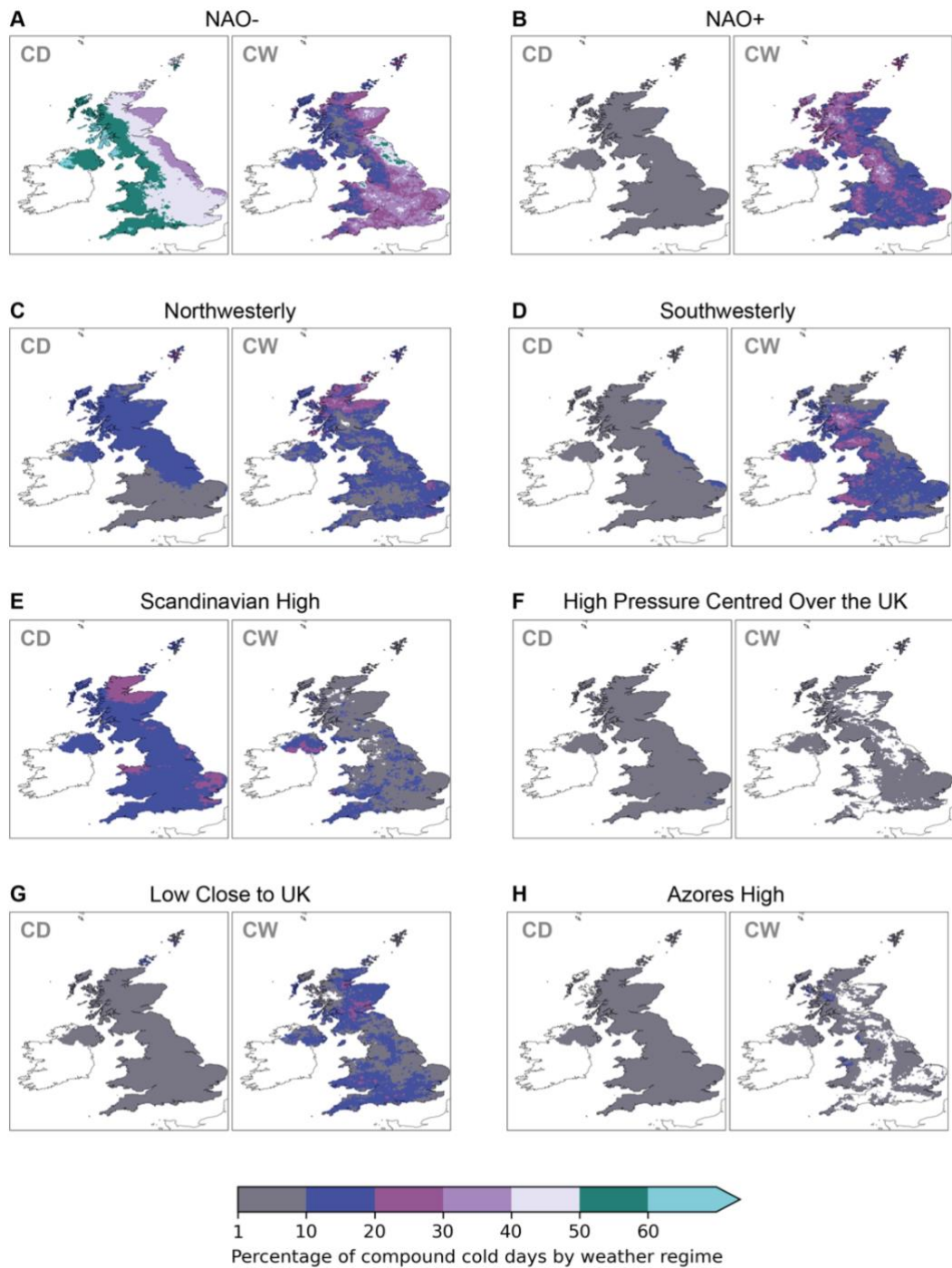


Figure 3.4 Percentage of CD and CW day occurrence under eight weather regimes. (A) NAO-, (B) NAO+, (C) Northwesterly, (D) Southwesterly, (E) Scandinavian High, (F) High Pressure Centred Over the UK, (G) Low Close to UK, (H) Azores High.

3.6 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, 5km) 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 5km grid we can demonstrate how these influences affect the thresholds set for the CD/CW indices, thereby providing a highly localized 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 operate 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 i.e., the threshold is either too high or too low depending on the region (PHE, 2013; Roberts *et al.*, 2022). 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 to 2022 across the representative cities. These findings are in agreement with other studies on compound cold events (Qian *et al.*, 2014; Wu *et al.*, 2019; Li *et al.*, 2022a; Li *et al.*, 2022b; Vyshkvarkova and Sukhonos, 2022). 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, Kendon and McCarthy, 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 an insight to 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 five days had over 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 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.

3.7 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 to provide 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 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.

3.8 Acknowledgements

CJW was supported by the European Union's Horizon Europe 'Multi-hazard and risk informed system for enhanced local and regional disaster risk management (MEDiate)' project under grant agreement no. 101074075. HB was supported by the Newcastle University Academic Track Fellowship (NUAcT) scheme.

CHAPTER 4 COMPOUND COLD EVENTS, IMPACTS, AND WEATHER PATTERNS: A CASE STUDY OF THE SCOTTISH RAIL NETWORK

4.1 Preface

This chapter (excluding this preface) has been published in the journal *Meteorological Applications*. Numberings of chapters and figures have been adapted for consistency of the overall thesis, and references have been compiled at the end of the thesis.

Corresponding publication: Mattu, K.L., White, C.J., Bloomfield, H. and Robbins, J. 2026. "Compound Cold Events, Impacts and Weather Patterns: A Case Study of the Scottish Rail Network." *Meteorological Applications* 33, no. 5: e70242.

Corresponding DOI: <https://doi.org/10.1002/met.70242>

This chapter directly addresses the following research questions (posed in Chapter 1.2 – Table 1.1):

RQ 3. To what extent do compound cold events impact the Scottish rail network?

RQ 4. Is there a relationship between impacts on the Scottish rail network and weather pattern occurrence?

Chapter 3 provides a baseline for understanding historical compound cold event occurrence across the UK over the period 1960-2022. This analysis also explores the relationship between these events and large-scale atmospheric drivers, providing an initial understanding of the spatial clustering of compound cold events under different weather regimes. This hazard-based analysis forms a foundation to explore how compound cold events translate into impacts on society and therefore motivates a shift towards an impact-based perspective.

As described in Chapter 2, several sectors across the UK can be affected by compound cold events. The initial focus of this research was to examine the relationship between compound cold events and the health sector; however, access to appropriate health-impact data presented challenges that meant this avenue could not be pursued within the scope of the thesis. Other sectors that were considered included transport infrastructure such as road and rail. An appropriate impact dataset was identified for the rail sector, providing an opportunity to examine the relationship between compound cold events and disruption to the Scottish rail network. Rail represents an important case study given the dual relationship between the sector and climate change: decarbonisation of the railway is crucial for reducing greenhouse gas emissions, while the infrastructure itself is vulnerable to the impacts of extreme weather. The critical and interconnected nature of the rail network therefore provides a valuable case study for investigating the relationship between weather hazards, observed impacts and large-scale atmospheric drivers.

Chapter 4 therefore builds on Chapter 3 by moving from understanding when and where compound cold events occur towards understanding when these events are associated with consequential impacts and how those impacts relate to their meteorological drivers. Weather pattern analysis is applied to link observed rail impacts and compound cold events to large-scale atmospheric drivers, providing a pathway towards impact-based forecasting. This forecasting application is developed further in Chapter 5.

4.2 Abstract

Winter weather events disrupt critical national infrastructure, with rail networks particularly vulnerable to blocked tracks, mechanical faults, and frozen infrastructure leading to service delays and cancellations. The impacts of these cold weather events can be amplified by the compounding effect of another meteorological variable, particularly whether heavy precipitation is present or absent, with subsequent impacts dependent on the nature of the cold event. For example, a ‘compounding’ cold-wet event could incur heavy snowfall, whereas a cold-dry event could result in extreme low temperatures and icy conditions. Despite their prevalence, such compound cold extremes remain understudied compared to compound heat extremes. In this study, we analyse 10,500 Scottish rail incidents (2006-2023, October to March) using Network Rail impact data, the set of Met Office 30 weather patterns (MO30), and HadUK-Grid observations to link incidents with compound cold events. We identify high-impact days based on two classifications: (1) days exceeding the 99th percentile of aggregated daily incidents; (2) days exceeding the 99th percentile of daily customer minutes lost. The majority of high-impact days were snow-related, occurring under cold-dry or cold-wet conditions with the definition depending on whether snow was falling or lying. These findings highlight the importance of considering co-occurring cold hazards, as real-world impacts may diverge from traditional hazard-based detection. This provides useful insight for compound cold early warning systems.

4.3 Introduction

As the climate continues to change under anthropogenic forcing an increase in the frequency and severity of extreme weather events has been observed across the globe (IPCC, 2023b). These events can be particularly damaging to critical national infrastructure (CNI) and lead to multi-sectoral service disruption. Transport is a key part of CNI, underpinning all major service delivery. Impacts to the transport network can have cascading impacts across other sectors such as energy, water and health with issues such as lack of accessibility, delayed service delivery and community isolation (Blainey and Preston, 2016). During winter, the United Kingdom’s (UK) rail network is subjected to impactful hazards including snow, ice, windstorms and

flooding (Network Rail, 2024a). Network Rail is the owner and operator of the Great British railway network including track, signalling, bridges, tunnels and stations. Train operating companies (for example ScotRail in Scotland) run passenger services. The Scottish rail network includes 362 stations, 2668 miles of track and operates ~2500 daily passenger and freight services (Network Rail, 2025). Network Rail owns and manages all rail infrastructure in Scotland including tracks and Scotland's busiest stations Glasgow Central and Edinburgh Waverley. As part of Scotland's CNI, thousands of people depend on the railway for business and leisure every day, making any service delays or cancellations exceptionally impactful.

The complex management of the rail network (Network Rail owning infrastructure that train operating companies run services on) has implications for decision-making. There are multiple organisations working to make effective decisions and therefore multiple dependencies between organisations which means more time is needed to both communicate upcoming risks and to take mitigating actions to reduce impacts. Uncertainties in weather forecasting can result in reduced lead time warning, but by leveraging the skill of different forecasts (e.g., weather patterns) there is the possibility to extend impact-based forecast and warning (IbFW) lead times for those working in complex decision-making environments. In addition to increased lead times, it is important to provide forecast information in a way that can be contextualised within other dynamic processes (i.e., beyond the hazard) and that are relevant to the decision-maker. This is particularly important for stakeholders managing complex networks where impacts can be driven by not only hazard magnitude but organisational, behavioural and context-based decision-making.

One route to overcome the challenge of increasing lead time for decision-makers is by identifying the hazard types that are most impactful and understanding the associated meteorological and synoptic drivers for these impactful events. Severe impacts are not always caused by the most meteorologically extreme events and can arise from the combination of moderate conditions co-occurring (van der Wiel *et al.*, 2020). Establishing the relationship between hazard(s) and impacts provides the foundation for IbFW systems (Bazo *et al.*, 2021) which can be used to effectively communicate risk. Together with a shift towards IbFW, there is a growing research

focus on advancing the understanding and quantification of compound events (Brett *et al.*, 2025). Compound events are classified as multi-hazards that co-occur or interact to varying extents. This may present as a pre-conditioned hazard, hazards in succession (temporally compounding), related hazards in different geographic regions (spatially compounding) or two hazards occurring simultaneously (multivariate) (Zscheischler *et al.*, 2020a). Compound events have been shown to result in more severe impacts than single hazards (Ridder *et al.*, 2020; Lee *et al.*, 2024; Manning *et al.*, 2024). Forecasting compound events can be challenging due to their multivariate nature (Su *et al.*, 2025) and therefore, there could be benefits in leveraging weather pattern forecasts that can identify the driving atmospheric set-up for particular compound hazards. Stakeholders such as Network Rail could possibly benefit from increased lead time forecasts to communicate and act on potentially impactful weather.

Within the literature several studies have investigated the relationship between weather hazards and impacts to railway infrastructure. These hazards range from extreme high temperatures (Ferranti *et al.*, 2018) and high wind events in the UK (Fu and Easton, 2018), to cold climate in Sweden (Stenström *et al.*, 2012), and heavy precipitation in China (Liu, Wang and Zhou, 2021). Cold-related hazards specifically have been shown to have damaging impacts to rail infrastructure (Doll *et al.*, 2013). Within the Nordic region notable studies have explored the impact of snowfall and low temperature. Persistent low temperatures coupled with snowfall and high winds were found to significantly impact freight punctuality during 2010 in Sweden, Norway, Poland, and Switzerland (Ludvigsen *et al.*, 2013). Additionally, in Sweden, high snow depths and low temperatures were found to be the dominant driver of passenger service delays and cancellations (Ochsner, Ivina and Palmqvist, 2023). Ochsner *et al.* (2024) investigated the impact of daily average wind speed, precipitation, snow depth and temperature on Swedish rail infrastructure supporting previous findings: the track is vulnerable across all four weather variables and switches are most impacted by low temperatures and snow depth. While these studies have established the vulnerability of railway infrastructure to individual weather hazards, relatively little attention has been given to the influence of compound cold events or how their

associated impacts relate to large-scale atmospheric circulation. Addressing this gap has the potential to support impact-based forecasting for the rail sector.

Weather patterns are a circulation type defined over a specific geographic region that have distinct meteorological characteristics and can vary at a daily timescale (James, 2006; Neal *et al.*, 2016). Relating the most impactful local surface weather conditions to large-scale weather patterns is useful in an operational impact-based forecasting setting as weather patterns can be skilfully predicted out to 10 days lead time (Neal *et al.*, 2016), providing valuable time for preparatory action to be taken. The UK Met Office developed a set of 30 weather patterns (MO30) over the North Atlantic-European domain (Neal *et al.*, 2016) that are used operationally in a range of forecasting applications. This has been accomplished by identifying and linking specific hazards and impacts with the historical occurrence of different weather patterns. This has been used in forecasting applications for coastal flooding (Neal *et al.*, 2018a), meteorological droughts (Richardson *et al.*, 2018; Richardson *et al.*, 2020), London bike hire (Brown *et al.*, 2019), risks associated with lightning activity (Wilkinson and Neal, 2021b), and energy network power outages (Souto *et al.*, 2024).

This study analysed the interrelationship between reported rail incidents (impacts), large-scale weather patterns (MO30) and compound cold events across the Scottish rail network. By taking an impact-led approach, the analysis identified periods of heightened disruption from the Network Rail incident dataset, examined the occurrence and spatial distribution of compound cold events on those days, and assessed how these relate to prevailing weather patterns. This study aims to provide insight that could inform the development of a medium-range forecasting prototype for operational decision-making within the rail sector by: (i) identifying the relationship between rail incidents and compound cold hazards; and (ii) linking these high-impact hazard conditions to the large-scale weather patterns that drive them. While prototype design is beyond the scope of this paper, the discussion interprets the results through the lens of future usability. This chapter is structured as follows: Section 4.4 describes the data and methodology used; Section 4.5 presents the results of the relationship between weather patterns and rail incidents, the incidents prevalent on high-impact

days on the rail network and the relationship to compound cold events; Section 4.6 discusses the results and applications, and Section 4.7 concludes the work.

4.4 Data and Methodology

4.4.1 Data

Network Rail incident data

An impact dataset was acquired from Network Rail through a Freedom of Information request (reference number: FOI2024/00624). The dataset includes all weather-related incidents on the rail line recorded in Scotland for the period of October to March for years 2006 to 2023 (inclusive). The dataset comprises 10,533 incidents. Each incident contains information on the incident date, incident description, incident reason, incident rail section (spatial location), section name and PfPI (process for performance improvement) minutes (number of minutes trains were delayed). A full list of terminology and definitions used throughout the study can be found in Table 1. Incident descriptions and reasons can be found in Table 4.2, and the distribution of weather-related incident reasons is displayed in Figure 4.1.

Table 4.1 Terminology and definitions used throughout the study.

Term	Definition
Incident	A singular logged report of an incident impacting the service of the rail network.
Incident day	A calendar day in which a minimum of one incident was reported.
High-impact day	An incident day which surpassed the high-impact threshold (99 th percentile) of an impact metric i.e., days with the most extreme impacts. For daily aggregated

	incidents the 99 th percentile is >51 incidents, for daily accumulated PfPI minutes the 99 th percentile is >23010 minutes.
PfPI minutes	Delay minutes attributed to an incident which affect a passenger train service under the “Process for Performance Improvement” regime(Network Rail, 2019).
CD/CW event	A day in which the localised percentile threshold for CD/CW has been met for a given grid cell (in this study, the HadUK-Grid at 5km resolution).

Table 4.2 Incident reason descriptors for the Network Rail incident dataset (adapted from Network Rail incident descriptions), including all weather-related incidents that were reported in Scotland within the period October to March in years 2006 to 2023.

Incident Reason Name	Incident Reason Description
FLOODING	Flooding not due to exceptional weather
FOG/SNOW	Special Working for fog and falling snow conditions
HEAT SPEED	Critical Rail Temperature speeds, (other than buckled rails)
HIGH WIND	Severe weather not snow affecting infrastructure the responsibility of Network Rail

ICING	Ice on conductor rail/overhead line equipment (OLE)
INF WEATHER	Non severe - Snow/Ice/Frost affecting infrastructure equipment
KRS / BLKT	Blanket speed restriction for extreme heat or high wind in accordance with the Group Standards
LIGHTNING	Lightning Strike - damage to protected systems
MISC OBS	Miscellaneous items on line (incl trees) due to effects of weather responsibility of Railtrack (RT)
PNTS SNOW	Points failure caused by severe snow where heaters are working as designed
SEV FLOOD	Severe flooding beyond that which could be mitigated on Network Rail infrastructure
SEV SNOW	Severe snow affecting infrastructure the responsibility of Network Rail
SPL WRKING	Visibility in semaphore signalled areas, or special workings for fog and falling snow implemented by Network Rail - in all signalling areas
WEATHER	Severe weather other than snow affecting infrastructure the responsibility of infrastructure maintenance contractor (IMC)

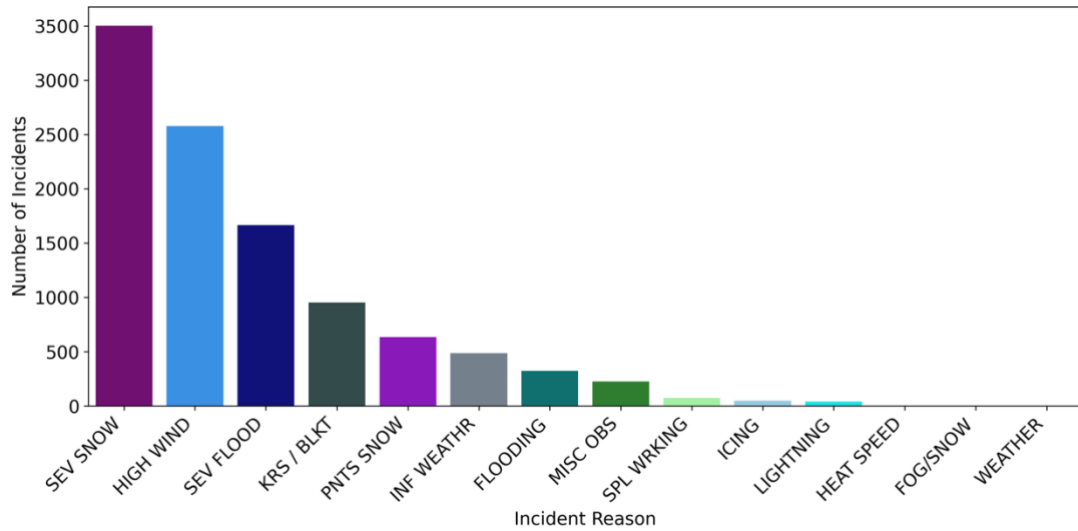


Figure 4.1 Histogram of incident type distribution of Network Rail impact dataset for Scotland from October to March in years 2006 to 2023. Incident descriptors can be found in Table 4.2.

HadUK-Grid

HadUK-Grid Gridded Climate Observations dataset at 5km resolution were used to calculate compound cold event occurrence. These data are accessed via the Centre for Environmental Data Analysis archive (Met Office *et al.*, 2024). Daily minimum air temperature and daily rainfall accumulation were used to calculate compound cold event occurrence. This dataset was selected as it provides these variables at a high spatial resolution making it preferable for investigating local impacts. The dataset was derived from interpolated in situ land surface observations collected at climate monitoring stations across the UK (Hollis *et al.*, 2019).

Weather pattern classifications

To understand the driving weather patterns that result in compound cold events and rail incidents, the MO30 weather pattern classifications (Neal *et al.*, 2016) have been used. These classifications were developed using a simulated annealing variant of the k-means clustering method (Philipp *et al.*, 2007) applied to the European-North Atlantic mean sea level pressure dataset (Ansell *et al.*, 2006) covering the North Atlantic and European region from 1850 to 2003. The MO30 are grouped into eight

broader 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). These regimes present large-scale circulation types that are spatially larger and more temporally persistent than individual patterns (Büeler *et al.*, 2021). A description of the flow associated with each weather pattern can be found in Table A1.1 of Appendix 1.

4.4.2 Methodology

NR impact data aggregation

To match the temporal resolution of the weather pattern data rail incidents were aggregated to daily resolution using the incident report date. The aggregation resulted in 1,729 incident days out of 3,094 days in the study period, showing that 55% of all days experienced a weather-driven incident. Not all weather-driven incidents are problematic for the rail network; this study therefore focuses on a high severity subset. These high severity days were identified by filtering the daily aggregated dataset to produce two sets of high-impact days: (1) incident days that met or exceeded the 99th percentile of daily aggregated incident counts, and (2) incident days that met or exceeded the 99th percentile of daily accumulated PfPI minutes, where a PfPI minute is defined as delay minutes attributed to an incident which affect a passenger train service under the “Process for Performance Improvement” regime (Network Rail, 2019). The two impact metrics produced two sets of 18-days (with seven days in common) which are collectively referred to as “high-impact days”. Figure 4.2 shows the set of high impact days using impact metric 1, while Figure 4.3 shows the high impact days using impact metric 2.

Compound event occurrence

To determine the meteorological hazard, this study adopted the methodology used in Mattu *et al.* (2025) to calculate compound event occurrence cold-dry (CD) and cold-wet (CW) events using the following indices:

- cold-dry (CD): $\leq 15^{\text{th}}$ percentile of daily minimum temperature AND $\leq 15^{\text{th}}$ percentile of daily precipitation
- cold-wet (CW): $\leq 15^{\text{th}}$ percentile of daily minimum temperature AND $\geq 85^{\text{th}}$ percentile of daily precipitation.

Following Mattu *et al.* (2025), percentile threshold values were calculated using an ordered time series of winter (December, January, February) days over a 30-year period of 1994-2023 for each HadUK-Grid land grid-square. A localised percentile framework was used to make the compound event indices more relevant to local climatology. A detailed methodology, sensitivity analysis, and indices calculation can be found in Mattu *et al.* (2025).

Meteorological conditions on high-impact days

Daily snapshots of minimum temperature and daily rainfall accumulation were analysed to assess the compound event occurrence for high-impact days (Figure 4 and Figure 5). Using the indices defined in Section 2.2.2, spatial maps of compound CD and CW events were calculated. In addition to mapping compound cold event occurrence, the plots also identified where the individual minimum temperature ($\leq 15^{\text{th}}$ percentile) and precipitation ($\leq 15^{\text{th}}$ or $\geq 85^{\text{th}}$ percentile) thresholds were met independently, to show locations experiencing single-variable extremes that did not coincide to produce a CD or CW event. These plots take inspiration from previous studies which have used ‘footprints’ to display the maximum wind gusts associated with damaging windstorms (Roberts *et al.*, 2014). Unlike wind footprints, which show maximum gusts over multi-day events, this study analysed each day in isolation to maintain consistency in temporal resolution across the different datasets used.

Linking incidents to weather patterns

Each incident in the rail impact database was assigned one of the 30 MO30 weather patterns based on the dominant pattern on the day the incident was reported. Incidents were then aggregated according to the weather pattern which they occurred under. For each weather pattern, the frequencies of all associated incident types were

summed, and the proportion of each incident type was calculated by normalising these counts. This approach allowed the relative prevalence of different incident types under each weather pattern to be examined and provided a holistic view of how weather patterns related to winter rail impacts in Scotland. The method assigned weather patterns to the reported incident day only and did not incorporate potential reporting delays or the geographic location of incidents.

A hit rate was calculated to quantify the likelihood of an incident occurring on any given day under each of the MO30 weather patterns. The hit rate is defined as the proportion of days on which at least one incident was reported, expressed as a percentage of the total number of days the regime occurred during the study period (October to March, 2006-2023). This was first performed across all incident reasons combined, $P(\text{any incident} \mid \text{weather pattern } Y)$, and then broken down into individual incident types, $P(\text{incident type } X \mid \text{weather pattern } Y)$. The hit rates for individual incident types are independent conditional probabilities and are not additive components of the overall hit rate. Since multiple incident types can occur on the same day, the individual hit rates will not sum to the overall hit rate.

4.5 Results

Figure 4.1 shows the distribution of weather-related incident types for all incidents reported from October to March in years 2006 to 2023. A description of incident types can be found in Table 4.2. The three incident types with the highest occurrence are: *severe snow* with 3,501 incidents, *high wind* with 2,577 incidents and *severe flood* with 1,666 incidents. These incident counts correspond to 33.2%, 24.4% and 15.8% of the total incident counts respectively. The inclusion of incident type *points failure-related severe snow* adds a further 635 incidents attributed to snow, bringing the snow-related incident total to 4,136 incidents (39.2% of the total incident counts). Similarly, including *flooding* alongside *severe flood* brings the flood-related total to 1,989 incidents (18.8% of the total incident counts). This demonstrates that the Scottish rail network is most impacted by snow-, wind- and precipitation-related hazards during winter. Having identified the dominant weather-related incident types

across the dataset, the following section focuses on the subset of exceptionally disruptive days to the rail network.

4.5.1 High-Impact Days

Out of 1,759 incident days analysed, 18 days exceed the 99th percentile of the total daily number of incidents (>51 incidents reported in a single day). By this metric, the top 1% of incident days account for 13.5% of all incidents. Within this set of high-impact days the values range from 52 incidents to a maximum of 152 incidents reported on 29/11/2010. Figure 4.2 shows the scaled incident reasons for each high-impact incident day. Out of this set, only one day (09/01/2015) does not include *severe snow* as an incident reason. For the first 15 days in the set of high-impact days the predominant incident reason is *severe snow*. These 15 high-impact days all occurred within the years 2009 and 2010. Post-2010 there have been notable extreme cold events such as “Beast from the East” in late February 2018 that resulted in cross-sectoral disruption across the UK (Met Office, 2018), including 21 rail incidents reported in Scotland on 28/02/2018. Similarly, in December 2022 the UK experienced a cold-wave that brought low temperatures and ice (Met Office, 2023c); both hazards affected rail services in Scotland with 27 incidents reported on 12/12/2022. Although these more recent examples were impactful, they did not cause as many rail incidents as the winters of 2009 and 2010. The dry, powdery snow that fell in December 2010 was drawn in by train traction motors causing widespread speed restrictions and cancellations. Following this event the train traction motors were updated to better cope with heavy snowfall conditions (B. Haddock pers. comm, 11/09/25). This demonstrates how network vulnerability is represented in impact and incident reporting but not specifically reported as part of the incident reporting process.

Using the PfPI minutes impact metric, the top 1% of incident days represents 31.5% of all PfPI minutes over the study period. Figure 4.3 shows the set of 18 days exceeding the 99th percentile of daily accumulated PfPI minutes, with values ranging from 23,459 (30/12/2015) to 107,579 (28/02/2018). Similarly to the incident reasons displayed in Figure 4.2, *severe snow* is the most common incident reason up to and including the year 2010. As previously stated, the update of the train traction motors

improved the network's ability to cope with snow events and from 2011 onwards incident reasons are more diverse with an increase in incidents due to *high wind*. Figure 4.3 shows how considering another metric, such as PfPI minutes, can be insightful to understanding consequential meteorological hazards. In Figure 4.3, the second-highest high-impact day (03/01/2012) has a value of 101,481 PfPI minutes but only three reported incidents. Therefore, this date is not present in Figure 4.2 which uses the 1st impact metric focused on incident numbers. One possible explanation for the difference between the two high-impact datasets is that wind-related hazards can affect a larger spatial extent than snow-related hazards or wind-related hazards affecting more operationally critical parts of the network (e.g., if a tree falls on an overhead line this may lead to power distribution issues that could render entire sections of the railway inoperable). However, the available dataset does not contain sufficient operational information to determine the specific mechanism responsible for the exceptionally high PfPI value on 03/01/2012. Additionally, 03/01/2012 was a public holiday in Scotland and reduced service frequency together with altered passenger demand may have influenced the observed PfPI minutes relative to the number of reported incidents. Although this cannot be confirmed from the available dataset, it highlights how operational factors alongside meteorological conditions can influence the severity of observed impacts. This contrast (between PfPI minutes and number of incidents) demonstrates the importance of considering the intended end use when developing a forecasting tool: for decision-makers, the key question is whether it is more beneficial to predict the likely number of incidents or their associated operational impacts. The following analysis examines whether these high-impact days coincide with the occurrence of compound cold events.

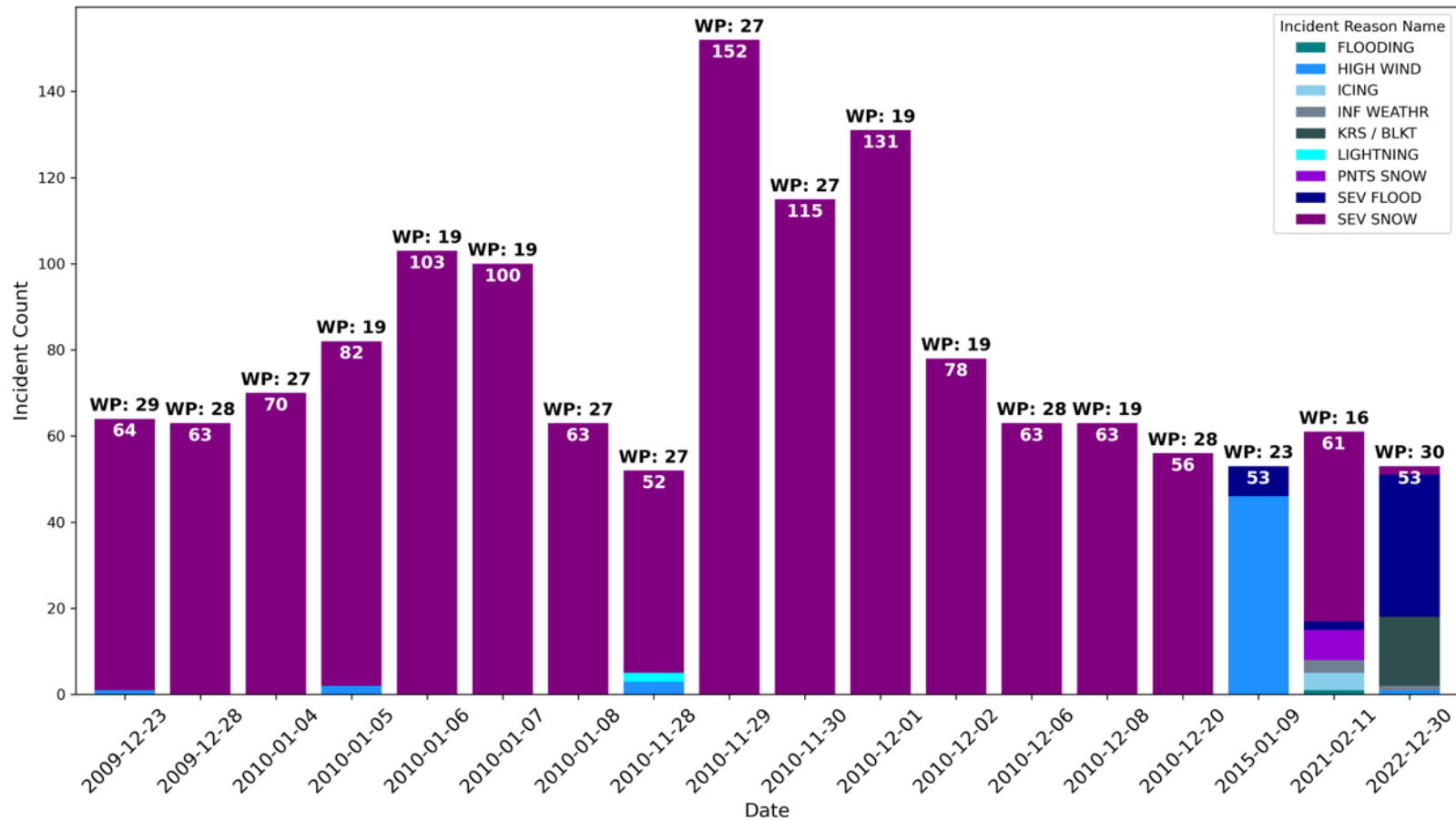


Figure 4.2 The 99th percentile of incident days by number of daily reported incident, i.e., days exceeding 51 reported incidents from the Network Rail incident dataset for Scotland covering the period October to March in years 2006 to 2023. White numbers at the top of the bars express the number of incidents reported that incident day and the black number above the bar shows the weather pattern on that incident day.

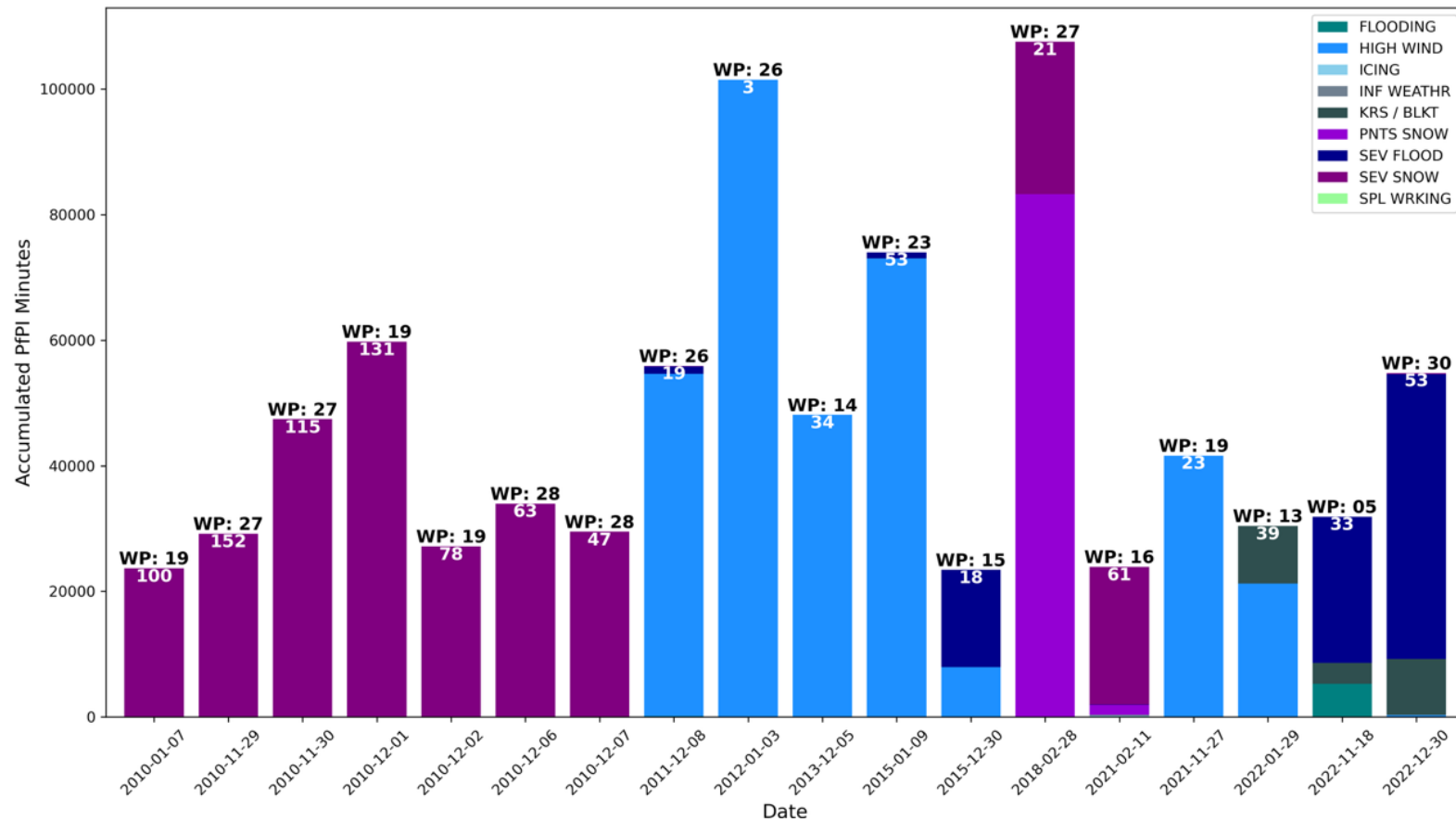


Figure 4.3 The 99th percentile of incident days by accumulated daily PfPI minutes, i.e., day exceeding 23010 PfPI minutes total from the Network Rail incident dataset for Scotland covering the period October to March in years 2006 to 2023. White numbers at the top of the bars express the number of incidents reported that day and the black number above the bar shows the weather pattern on that incident day.

4.5.2 High-Impact Days and Compound Events

To establish a relationship between rail incidents and meteorological drivers the occurrence of compound cold events on both sets of high-impact days was analysed. High-impact days determined by the daily aggregated incidents impact metric are presented first. A graphical illustration can be found in Figure A2.1 of Appendix 2 Material. Of the 18 high-impact days shown in Figure 4.2, 16 coincide with CD events at several locations within Scotland. CD events across these days have a broad spatial distribution with a greater prevalence in the west and centre of Scotland. CW events occurred on 13 of the 18 days and are generally more localised in comparison to CD events. Although these high-impact days represent a subset of the compound events examined in Mattu *et al.* (2025), their spatial characteristics – CD events concentrated in the west and CW events occurring in the north and east – are consistent with the broader hazard-based assessment. This alignment indicates that the compound events associated with the most disruptive rail-impact days reflect the general climatological patterns identified in Mattu *et al.* (2025).

Figure A2.2 in Appendix 2 provides a graphical illustration of compound cold event occurrence on high-impact days using the PfPI minutes metric. Out of the 18 high-impact days, only half (nine) show the occurrence of compound cold events. Of the other nine days, some show that the precipitation threshold has been met (>85th percentile) indicating that a high precipitation event occurred on these days. These high-precipitation days are only captured in the high-impact days when using the PfPI minutes impact metric. This suggests that delays on the network may only aggregate significantly when more of the network intersects with a widespread hazard. This could also increase the likelihood for vulnerable parts of the network to be exposed to the hazard spatial footprint, increasing potential consequences.

To explore the spatial evolution of high-impact days, Figure 4.4 shows the occurrence of CD and CW events across Scotland on 28/11/2010 to 02/12/2010. On 28/11/2010, 52 incidents were reported (see Figure 4.2). These incidents are spatially clustered under an area of CW in eastern Scotland. The succeeding day, 29/11/2010, reports the highest number of incidents recorded within the dataset at 152 incidents (note this

is not a cumulative event count, but new events reported on this date). The areas with reported incidents meet the percentile threshold for minimum temperature but not for precipitation to be classified as either CD or CW. There are regions of CD and CW events to the south and east of the clustered incident location, respectively. Over the next three days there was a continuous elevated number of reported incidents (see Figure 4.3). Coincident with the incident reporting is a persistence of the CD event covering the west of the country and a slow movement of CD event occurrence from west to east. The results suggest that the prolonged disruption was associated with the sequential occurrence of an initial CW event followed by persistent CD conditions. This sequence would allow snowfall generated during the CW event to persist under sustained low temperatures therefore extending hazardous conditions beyond the initial precipitation event. This example demonstrates a temporal offset between the occurrence of the CW event and the peak in reported incidents, highlighting that impacts can be experienced and/or recorded after the initial hazard occurs. During this time the NAO- regime is dominant; within this regime there is a transition from weather pattern 27 to 19 on 01/12/2010. This transition represents a change in position of high pressure from sitting centrally over the UK (weather pattern 27) to moving to the west of the UK (weather pattern 19). This case study illustrates how the sequencing of compound cold events, modulated by the large-scale circulation, contributed to one of the most impactful periods within the rail incident dataset.

Two named storms appear in the top 1% of days for accumulated PfPI minutes: Storm Frank (29-30/12/2015) and Storm Arwen (26-27/11/2021). Both storms brought widespread heavy precipitation and strong winds to Scotland (Met Office, 2016; Kendon, 2021). Wind gusts in excess of 70 mph associated with Storm Arwen caused severe impacts to energy distribution networks with over 100,000 homes in northern Scotland without electricity for several days (SEN Distribution, 2024). More than half of the PfPI minutes reported on 30/12/2015 (Storm Frank) were associated with *severe flood*, whereas all the incidents reported on 27/11/2021 (Storm Arwen) were associated with *high wind*.

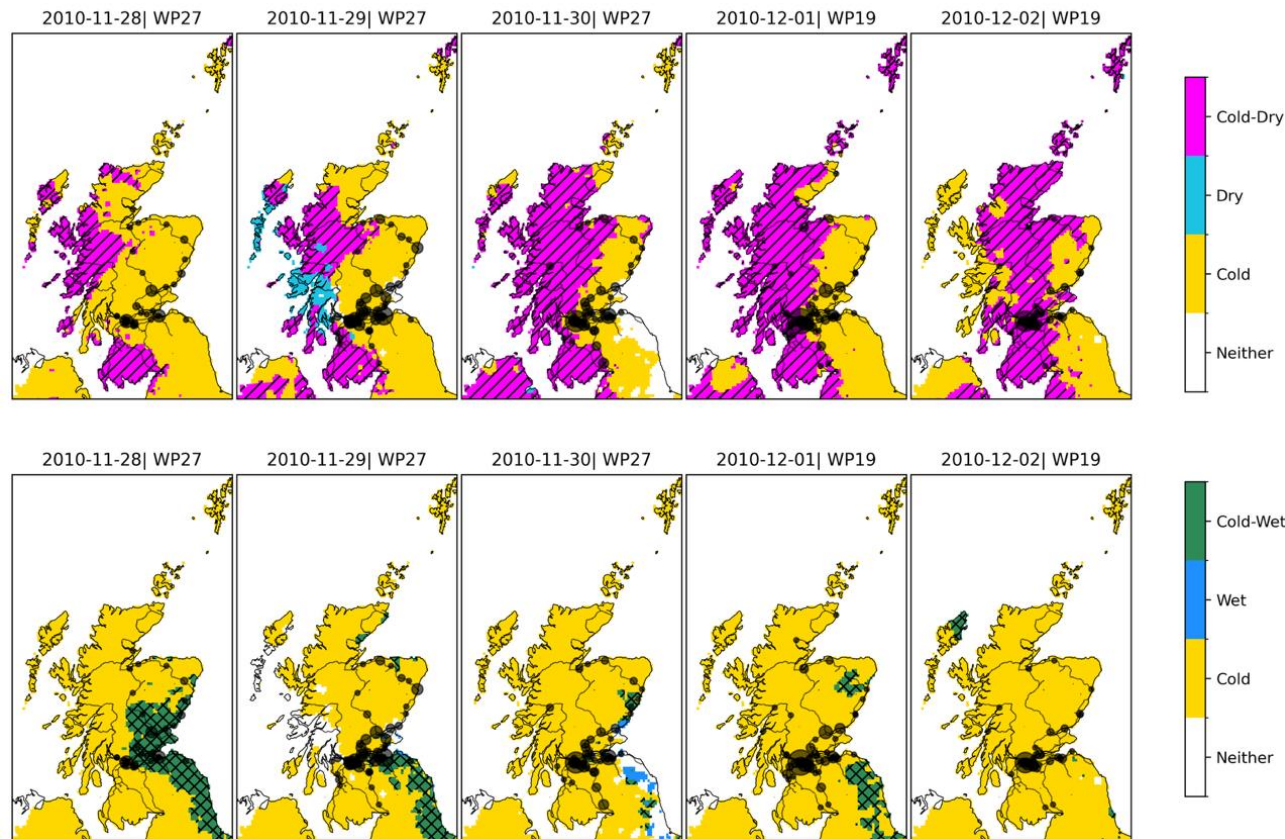


Figure 4.4 Daily occurrences of high-impact days 28/11/2010 – 02/12/2010 showing occurrence of compound CD and CW events and temperature and precipitation threshold (thresholds are noted in S4.4.2). The black line illustrates the rail line in Scotland. The black markers indicate the location and number of reported rail incidents. The prevailing weather pattern on that day is expressed as “WPx” in the panel titles.

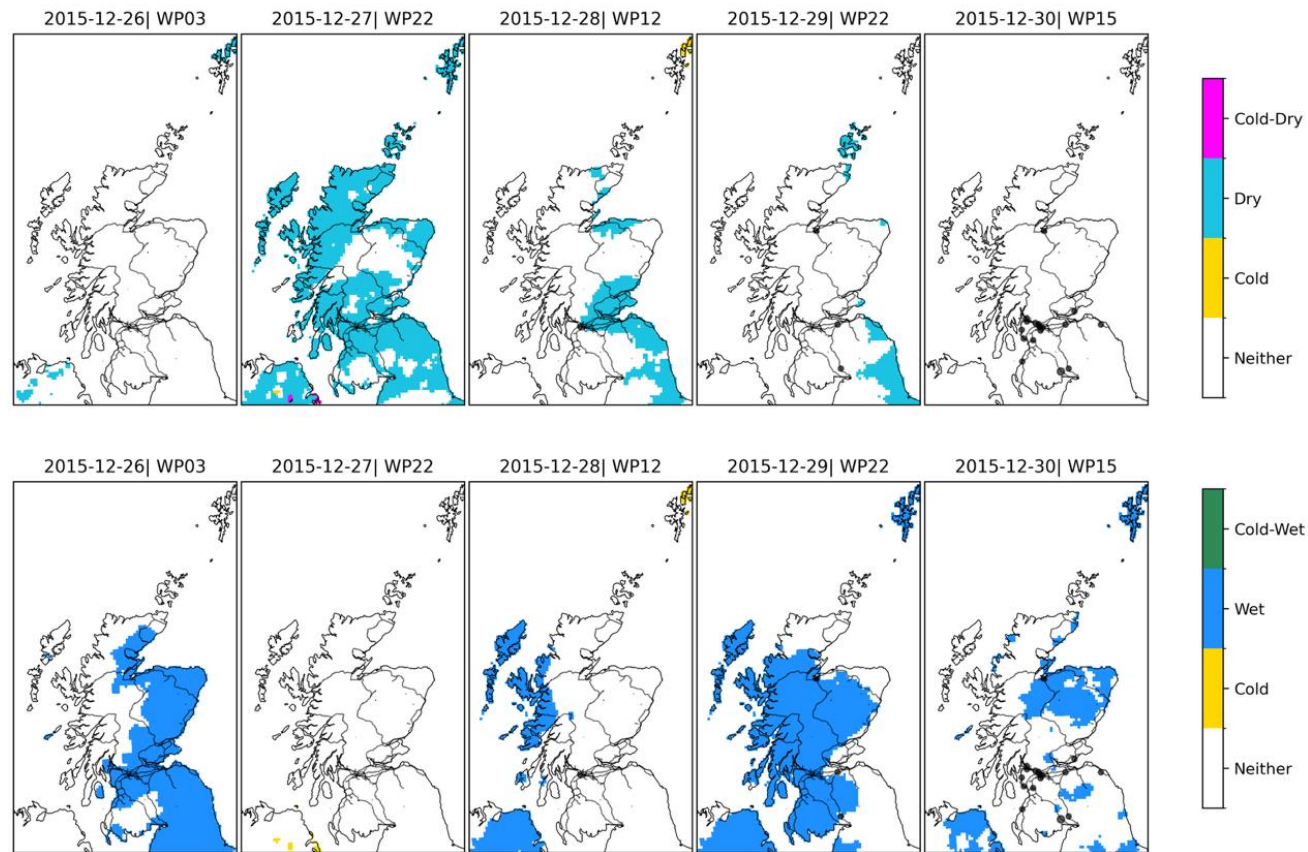


Figure 4.5 Daily snapshots of Storm Frank (29-30/12/2015) and the days preceding showing occurrence of compound CD and CW events and temperature and precipitation threshold (thresholds are noted in Section 2.2.2). The black line illustrates the rail line in Scotland. The black markers indicate the location and number of reported rail incidents. The prevailing weather pattern on that day is expressed as "WPx" in the panel titles.

Figure 4.5 displays the occurrence of CD and CW events on the high-impact day associated with Storm Frank (30/12/2015) and the conditions on the four preceding days. No compound cold events were observed in this period, however, the 85th percentile of precipitation was consistently met over large areas of Scotland in the lead up to the high-impact day. This highlights the importance of preconditioning and the sequencing of hazards (e.g., heavy precipitation on saturated ground) as these antecedent conditions can exacerbate impacts.

4.5.3 Weather patterns and rail incidents

Having established the relationship between compound cold events and high-impact rail disruption, the final analysis presented in this section investigates the large-scale atmospheric circulation associated with these incidents by examining their relationship with the MO30 weather patterns across the full incident dataset. The proportions of each rail incident type per weather pattern are shown in Figure 4.6. This shows the proportion under all 30 weather patterns that have been grouped into eight regimes (Section 4.4.2) and ordered in descending number of reported incidents per pattern. The entire dataset has been included in this analysis (1,729 incident days). Table A1.1 in Appendix 1 shows a flow description of each weather pattern and Table 3.3 shows which weather patterns from the set of 30 fall into each of the eight regime categories. To complement the frequency analysis, a hit rate analysis (Figure A2.3 in Appendix 2) was undertaken to quantify the conditional probability of each incident type for each of the 30 weather patterns.

Results show considerable variation in both the frequency and conditional probability of incidents between weather patterns. The weather pattern with the highest number of reported incidents is weather pattern 27 in the NAO- regime, with 1,022 incidents over 59 incident days, representing 9.7% of all incidents and 11.1% of all PfPI minutes. This weather pattern represents an anticyclonic easterly flow, with high pressure over the Norwegian Sea (Richardson *et al.*, 2018). Under weather pattern 27, 86.4% of the incidents reported are attributed to *severe snow* with a further 5% attributed to points failure-related severe snow. The hit-rate analysis (Figure A2.3 in Appendix 2) shows that 37.7% of all weather pattern 27 days within the study period

are associated with *severe snow*, indicating that this weather pattern is conducive to disruptive snow-related incidents. Moreover, this demonstrates that the incident-weather pattern relationship is not simply a consequence of weather pattern 27 occurring frequently. Although weather pattern 27 contributes to the greatest number of *severe snow* incidents, weather pattern 28 exhibits the highest conditional probability of *severe snow* occurrence (42.7%), illustrating that weather pattern frequency and conditional probability provide complementary measures of disruption potential. More broadly within the NAO- regime (patterns 6, 9, 11, 19, 25, 27, 28), four patterns (patterns 27, 19, 28, 25) are linked to >50% of *severe snow* rail incidents. Weather pattern 20 is responsible for the highest number of incident days, totalling 967 incidents over 129 incident days, representing 9.1% of all incidents and 9.5% of all PfPI minutes. This weather pattern represents a cyclonic westerly with a deep centre of low pressure near Iceland (Richardson *et al.*, 2018). This pattern sits within the NAO+ regime (patterns 4, 8, 20, 23, 26, 30), where *high wind* is the leading incident reason. Five of the weather patterns (patterns 4, 20, 26, 30, 23) within this regime attribute >30% of incidents to *high wind*. Consistent with this, weather patterns within the NAO+ regime exhibit some of the highest hit rates for wind- and flood-related incidents, i.e. 58.7% for weather pattern 20 and 50.1% for weather pattern 26. *Severe flood* is another prominent incident reason within this regime with four of the patterns (patterns 20, 30, 8, 4) attributing >20% to this reason. This is further supported by *severe flood* conditional probabilities exceeding 24% for weather patterns 4, 8, 20, 26 and 30. The NAO+ regime has previously been shown to bring mild and wet conditions to the UK (Simpson *et al.*, 2024), aligning with the main incident reasons that occur under this regime.

The Northwesterly (patterns 1, 13, 14, 24) and Southwesterly (patterns 2, 12, 15, 21) regimes show a strong association with high wind incidents across their respective patterns but differ in the occurrence of snow-related incidents. The Northwesterly regime shows three patterns (patterns 1, 13, 24) with >24% of *severe snow* related incidents whereas most patterns within Southwesterly show <10% for incidents attributed to *severe snow*. The hit-rate analysis supports this distinction with Northwesterly weather patterns exhibiting substantially higher conditional probabilities of *severe snow* occurrence (8-35%) than those within the Southwesterly regime (1-

9%). This difference is likely due to the flow associated with each of these regimes. The Northwesterly regime is characterised by a neutral north-westerly with high pressure to the southwest of the UK and low pressure to the northeast whereas the Southwesterly regime is characterised as a cyclonic south-westerly with low pressure centred near Iceland (Richardson *et al.*, 2018). As the Northwesterly regime brings with it northerly winds and moisture i.e., a polar maritime air mass, this would support the occurrence of more snow-related incidents. The Southwesterly regime shows a higher occurrence of flood-related incidents than the Northwesterly regime, with all patterns in the Southwesterly regime (patterns 2, 12, 15, 21) reporting >20% summed for *flooding* and *severe flood*.

High Pressure Close to the UK (patterns 3, 18) is dominated by *high wind* incidents. Weather pattern 3 within this regime reports 68% for *high wind* across 20 incident days; this is the highest occurrence of *high wind* incidents across all 30 weather patterns. Weather pattern 3 is characterised by an anticyclonic south-westerly with a ridge over northern France (Richardson *et al.*, 2018). The pressure gradient created by this flow can lead to strong wind events in Scotland, particularly the central belt (between Glasgow and Edinburgh). Together, the frequency and hit-rate analyses demonstrate that different large-scale circulation patterns are associated with distinct disruption mechanisms therefore providing a physically meaningful foundation for anticipating the types of rail incidents most likely to occur under different synoptic condition

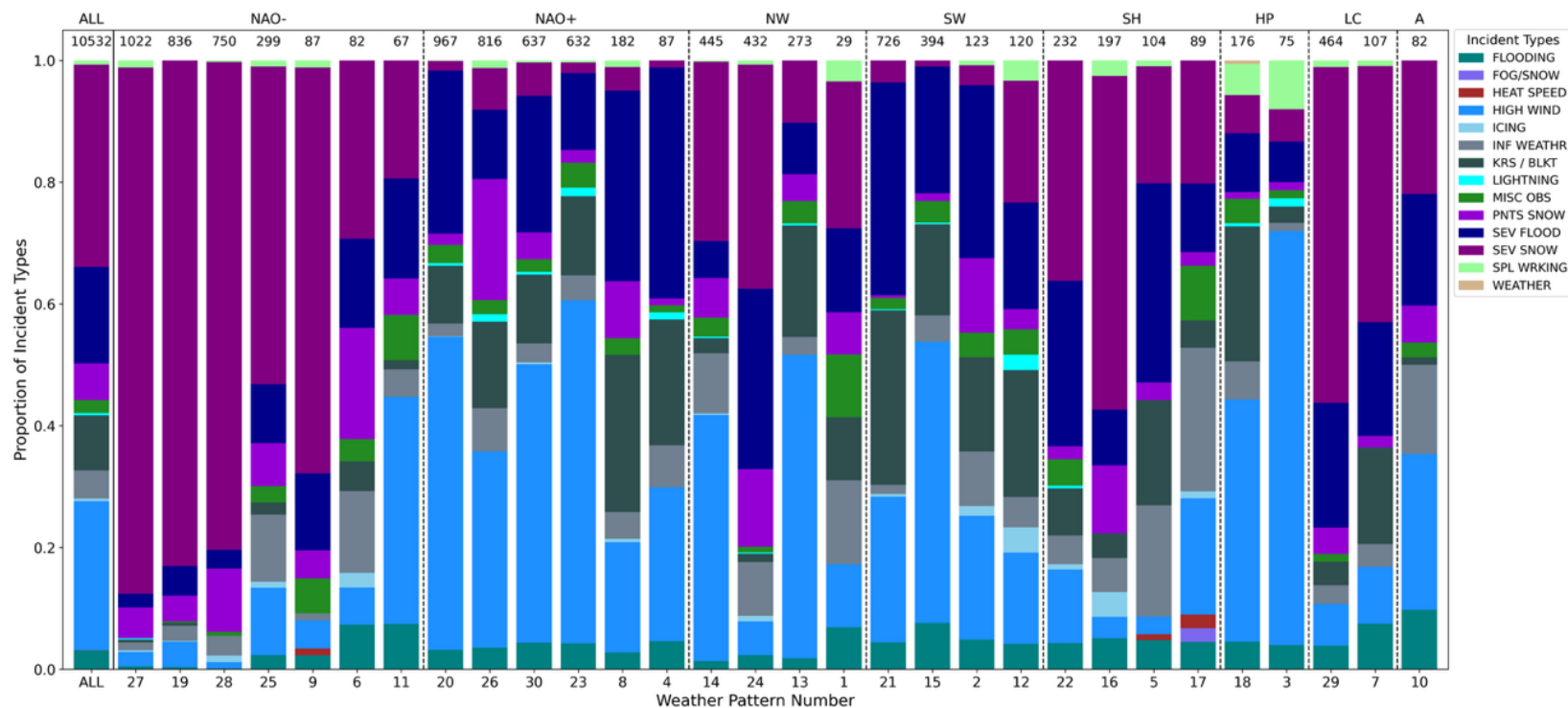


Figure 4.6 Rail incident types - from the Network Rail incident dataset for Scotland from October to March in years 2006 to 2023 per weather pattern (MO30). Black dotted line represents regime groups from left to right: all weather patterns, NAO-, NAO+, Northwesterly, Southwesterly, Scandinavian High, High Pressure Centred Over UK, Low Close to UK and Azores High. See Appendix 1 Table A1.1 for descriptions of the different patterns. The number of reported incidents for each weather pattern is shown at the top of each bar.

4.6 Discussion

In the context of the Scottish rail network, this study has identified snow-, wind- and precipitation-related hazards as the primary drivers of winter rail disruption between the years of 2006 and 2023. Snow-related incident types dominate when using both impact metrics: (1) total daily incidents and (2) daily accumulated PfPI minutes. The results show how a subset of high-impact days (18 days within each set that met the respective 99th percentile of the given impact metric) contribute disproportionately to overall disruption, particularly when compound cold events or sequential compound events occur. The following discussion explores how these findings align with the MO30 weather patterns and compound cold event dynamics and considers the implications for developing possible forecasting applications.

The results demonstrate how different weather patterns and regimes are conducive to certain incident types on the rail network. While the frequency analysis identifies the weather patterns responsible for the greatest proportion of incidents, the accompanying hit-rate analysis demonstrates that not all weather patterns are equally informative from an operational perspective. For example, weather pattern 27 contributes the greatest number of severe snow incidents, whereas weather pattern 28 exhibits the highest conditional probability of severe snow occurrence, therefore illustrating that frequency and conditional probability provide complementary measures of disruption potential. The strong correspondence between large-scale atmospheric circulation and locally observed rail impacts provides confidence that weather patterns capture physically meaningful drivers of disruption. Mattu *et al.* (2025) showed that CD and CW events are prevalent under different weather regimes in different parts of the UK. This is reflected in the contrasting incident types associated with the positive and negative NAO phases (Figure 4.6). The NAO- regime is predominantly associated with snow-related rail incidents, whereas NAO+ is typically associated with wind- and precipitation-related rail incidents. This aligns with previous work describing NAO- as cold and dry (Hanna, Hall and Overland, 2017; Hall and Hanna, 2018) and NAO+ as wet and windy (West, Quinn and Horswell, 2019). Understanding this relationship between large-scale weather patterns and local impacts can support the identification of periods of heightened risk to rail assets and

customers, which could be leveraged to enable rail impacts to be forecast at lead times of up to 15 days ahead, and skilfully up to 10 days ahead (Neal *et al.*, 2016) .

Previous studies have found that low temperatures and snow can have damaging impacts on rail operations (Doll *et al.*, 2013). Compound cold events present an additional challenge for decision-makers because (1) information/forecasts about compound cold events are not routinely available, and (2) the joint occurrence of meteorological variables with different temporal and spatial scales increases the difficulty of assessing potential impacts. CW events are particularly rare because they require the co-occurrence of extreme low temperatures coupled with extreme precipitation (see Section 4.4.2), whereas CD events are more common. Under the event definition (Section 4.4.2) CW criteria can be met when heavy precipitation and low temperatures occur in sequence within the same 24-hour period; even though not simultaneous, this combination can still generate issues such as freeze-thaw cycles, ice formation and freezing rain. Persistent CD events can lead to prolonged icing which does not thaw creating issues for overhead lines and movable infrastructure components (Zakeri and Olsson, 2018; Lotfi and Virk, 2023).

The impacts of a CD event can be exacerbated if preceded by a CW event. Figure 4.4 illustrates this sequencing for 28/11/2010 – 02/12/2010, where precipitation (may that be freezing rain, sleet or snow) from an initial CW event in eastern Scotland (28/11/2010 – 29/11/2010) was prevented from thawing by a subsequent, persistent widespread CD event (30/11/2010-02/12/2010). For this reason, high-impact days were assessed alongside adjacent days rather than independently, exposing some of the complexities surrounding compound events. The analysis indicates that the hazards interact in a twofold manner: (1) the interaction of single hazards i.e., temperature and precipitation to produce CD/CW events, which can lead to prolonged icing on overhead lines and refreezing on movable infrastructure components, and (2) how the compound events interact both spatially and temporally, as demonstrated by the CW to CD transition in late November 2010. Both types of interaction should be considered when planning for winter weather on the Scottish rail network.

This study has identified periods of heightened risk to the Scottish rail network rather than single points of failure. Weather hazards can inflict severe consequences on rail infrastructure due to their inherent interconnectedness and integrated nature. Palin *et al.* (2021) demonstrate this by highlighting how a single hazard does not result in a single impact but a range of interconnected impacts to the rail network, making incident attribution incredibly challenging. These interdependencies also introduce uncertainties, influenced by factors such as the characteristics of the weather hazard, the condition of the affected infrastructure and the relationship between asset performance and the magnitude of the hazard (Palin *et al.*, 2021).

To address these complexities, an impact-driven approach was applied in this study to identify the most consequential type of winter weather across two impact metrics, rather than focusing solely on days with the most extreme meteorological conditions. Two impact metrics were applied to provide a more thorough analysis of the impact dataset (see Section 4.4.2). The objective of focusing on the 99th percentile subset was not to characterise routine winter operations but to isolate the meteorological conditions associated with the most severe operational disruption. Sensitivity testing demonstrated a marked increase in both the incident count and PfPI distributions at the 99th percentile, indicating the presence of a distinct subset of exceptionally disruptive events. Van der Wiel *et al.* (2020) discuss how the most extreme weather does not always result in the most extreme impacts and using an impact-driven approach can improve risk estimates. As stated in Section 4.5.1, the top 1% of incident days (by the incident count metric) account for 13.5% of all incidents, whereas the top 1% of incident days (by the PfPI minutes) metric account for 31.5% of all PfPI minutes. This disparity highlights how network-wide consequences can be disproportionate across the rail system. Using a hazard-based approach of exclusively analysing meteorological extremes may omit such findings. The identification of this disparity provides decision-makers with vital information when planning for disruptive weather. This distinction underscores the benefit of an impact-driven approach, which in this study revealed that high-impact days coincide with the occurrence of compound cold events across both impact metrics, indicating that this type of compound hazard is particularly disruptive to the rail network in Scotland.

The initial dataset provided by Network Rail was a filtered ‘weather-related’ incident list, however Wyatt *et al.* (2023) and Gall *et al.* (2009) have shown that where impact observations are collected for a specific organisational purpose, valuable information that is important for the type of analysis conducted in this study, can be missing or error prone. This has potential implications for the analysis. In this work, careful data cleaning was undertaken, and methodological decisions were made to account for known uncertainties in the data (i.e. reporting date/time is often lagged from the true incident date/time). The impact dataset reflects impacts recorded to meet internal and regulatory reporting requirements (Office of Rail and Road, 2025), and therefore does not contain enough detail for risk modelling (as it has not been collected exclusively for that application)(Robbins *et al.*, 2022). Relevant biases in this context include hazard selection bias (as only one incident reason can be selected, see Table 4.1, this makes it more challenging to identify compound events), recorder perception bias (misleading reporting of incident cause due to the recorder’s understanding of the impact) and geographic bias due to the most heavily trafficked part of the Scottish rail line existing between Glasgow and Edinburgh, with the majority of passenger services operating in the central belt region.

This assessment has used the incident report day and taken the weather pattern assignment for that day; future work could investigate weather pattern assignment on days preceding the reported incidents to provide a more accurate representation of the relationship with weather patterns and incidents. Figures 4.4 and 4.5 provide an example of how the meteorological conditions and weather patterns transition in the lead up to a high-impact day. If this method was applied to all impact days, then patterns may appear for which locations of the line are susceptible to CD/CW events and what weather pattern transitions signal that a high impact event is probable. Furthermore, in this work we consider an “event” as a single day for each grid cell, future work may look at multi-day events (this would be most appropriate for persistent CD events that occur under the same weather pattern). This study uses the methodology from Mattu *et al.* (2025) as a demonstration for defining compound cold events but employing industry-specific thresholds may be more appropriate in an operational setting. While the hit-rate analysis provides a high-level assessment of the operational relevance of individual weather patterns, future work should evaluate

forecast performance through verification metrics including false alarm ratios and forecast skill when integrated within an operational forecasting system.

The relationships identified in this study demonstrate how knowledge of large-scale atmospheric circulation can be translated into information that supports impact-based forecasting for the Scottish rail network. The frequency and hit-rate analyses demonstrate that a subset of weather patterns is both responsible for a large proportion of disruption and exhibits elevated conditional probabilities of specific incident types. In an operational setting, forecasts of these weather patterns could provide an early indication of an elevated-risk window several days in advance. This information could then be combined with forecasts of temperature and precipitation to identify the likelihood of compound cold event occurrence, therefore allowing decision-makers to move from a high-level awareness towards more targeted operational planning as forecast lead time decreases. The combination of identified weather patterns, associated compound events and observed impacts forms a predictive triad that demonstrates the feasibility of a forecasting prototype. Future work should focus on translating these relationships into an operational decision-support tool through identification of high-risk weather patterns specific to the Scottish rail network, refinement of infrastructure-specific compound cold event thresholds, and the evaluation of forecast performance using operational verification metrics. Such a framework would provide decision-makers with additional lead time to coordinate staff, resources and contingency measures ahead of potentially disruptive winter weather. By linking forecasts of large-scale atmospheric circulation with compound cold event likelihood and historical impact relationships, this approach provides a clear pathway to anticipating not only the temporal and spatial aspects of compound event occurrence, but also their likely consequences for the rail network.

4.7 Conclusions

This study demonstrates the interrelationship between compound cold events, large-scale weather patterns and impacts on the Scottish rail network. Traditionally a hazard-based approach would be used by assessing the impacts associated with the most extreme meteorological variables, however, in this study, an impact-based

approach was adopted to identify the most impactful hazard types (that are not necessarily the most extreme). This approach was chosen to better support potential impact-based forecasting applications. The analysis showed that compound cold events are key drivers of the highest impact days, and the sequencing of the event types can produce prolonged and widespread impacts. Weather pattern analysis showed that patterns under the NAO- regime are predominantly associated with snow-related rail incidents whereas patterns under the NAO+ regime tend to produce wind and precipitation-related rail incidents. Relating these large-scale circulation patterns to local-level impacts provides the basis for a predictive framework as the patterns can be used to anticipate which types of rail disruptions are likely. The output of this study has laid the foundation for a possible future forecasting prototype that could guide operational decision-making and potentially reduce the consequential impacts of winter weather on the Scottish rail network.

4.8 Acknowledgements

We acknowledge and thank Brian Haddock (former Head of Weather Resilience at Network Rail) for his valuable inputs. We also thank Robert Neal (Met Office) for his support in the provision of data that enabled this work to take place. HB was supported by Newcastle University Academic Track Fellowship (NUAcT) scheme. CJW acknowledges support from the European Union Horizon Europe 'Multi-hazard and risk informed system for enhanced local and regional disaster risk management (MEDiate)' project under grant agreement no. 101074075, and the 'Towards enhanced coordination of disaster risk management and governance through a holistic framework for multi-level and cross-sectoral interaction and communication (TOGETHER)' project under grant agreement no. 101226137.

Chapter 5 DEVELOPING A BESPOKE IMPACT-BASED FORECASTING FRAMEWORK FOR THE SCOTTISH RAIL NETWORK

5.1 Preface

This chapter (excluding this preface) has been prepared for submission to npj Natural Hazards. Numberings of chapters and figures have been adapted for consistency of the overall thesis, and references have been compiled at the end of the thesis.

This chapter directly addresses the following research question (posed in Chapter 1.2 – Table 1.1):

RQ 5. Can an impact-based forecasting framework be developed to predict compound cold events?

Chapter 5 is the final science chapter presented in this thesis and represents the culmination of the hazard-based and impact-based analyses undertaken in Chapters 3 and 4. Chapter 5 addresses RQ 5 by developing a forecasting framework that builds on the hazard characterisation presented in Chapter 3 and the relationships between compound cold events, weather patterns and observed rail impacts established in Chapter 4. Chapter 5 therefore investigates how these relationships can be translated into a forecasting framework.

The analysis for this work was carried out at Met Office headquarters while embedded within the Weather Impacts team, providing an opportunity to explore how the findings of this research could be translated towards an operational forecasting context. This work was inspired by the Met Office weather pattern forecasting tool “Decider” that produces weather pattern forecasts at a 15-day lead time. Building on the relationships identified in Chapter 4, Chapter 5 identifies weather patterns associated with an elevated risk of compound cold events across the Scottish rail network and combines these with multiple forecast inputs to develop a tiered impact-based forecasting framework. The framework is designed to translate forecasts of large-

scale atmospheric circulation and compound cold event occurrence into information relevant to potential disruption of the Scottish rail network, thereby demonstrating the potential for an impact-based forecasting approach to compound cold events. The framework is demonstrated through three case studies of highly disruptive days to the Scottish rail network between 2010 and 2021.

5.2 Abstract

There is a growing recognition that effective weather forecasts for decision-making require a shift from predicting hazardous weather to anticipating their potential impacts. However, current impact-based forecasting approaches remain largely focused on single hazards and do not account for the interacting and compounding nature of weather extremes. This study develops a bespoke forecasting framework for compound cold events affecting the Scottish rail network by integrating impact data with large-scale atmospheric and surface level meteorological information. Rail incident data from a national rail infrastructure operator and gridded climate observations are used to identify high-risk weather patterns, while weather pattern classifications and ensemble forecasts are combined to produce probabilistic forecasts across multiple lead times from 0 – 15 days. Results show that weather pattern forecasts provide early indication of periods of heightened disruption risk up to 10 days in advance, while compound cold event forecasts give spatial detail into the likely occurrence of cold-dry and cold-wet events. These findings demonstrate how the framework can provide both early-warning and location-specific risk information, supporting anticipatory decision-making in the rail sector. More broadly, this work highlights how compound event science can be operationalised within impact-based forecasting systems, with applicability to other weather-sensitive sectors.

5.3 Introduction

In Scotland, the rail network operates approximately 2,500 services and serves around 295,000 passengers daily (Network Rail, 2025). These services are highly susceptible to disruption from severe weather, particularly during the winter operating period from October to March. During these months, Scotland frequently experiences high-impact weather events including storms associated with high winds, heavy precipitation, snowfall, fog and ice. These hazards often occur simultaneously, with their joint occurrence exacerbating impacts on rail operations (Mattu *et al.*, 2026). For example, high winds combined with snowfall can result in blizzard conditions, while heavy rain during periods of low temperatures can lead to sleet and widespread icing.

Prolonged periods of extreme low temperature, even in the absence of precipitation, can extend the impact of accumulated snow and ice.

Such compound and sequential hazards can significantly disrupt rail service delivery, with consequences ranging from delays and cancellations to risks to passenger and staff safety (Lotfi *et al.*, 2023). As transport infrastructure underpins wider societal and economic activity, mitigating weather-related disruption is a critical operational challenge. However, forecasting hazards such as precipitation and snowfall can be challenging leading to higher forecast uncertainties that can make decision-making difficult. This is exacerbated where decision-makers require longer lead times to prepare for high-impact weather, as uncertainties typically increase with lead time. The framework being proposed here aims to overcome this challenge by leveraging medium-range weather pattern forecasts (out to 15 days ahead) together with spatial hazard footprints for increasingly localised information on potential impacts to the rail network.

Compound events have received increasing attention since the Intergovernmental Panel on Climate Change Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC, 2012), with subsequent studies highlighting the importance of studying multi-hazards and compound events due to their significant socioeconomic impacts (Zscheischler *et al.*, 2018; UK Natural Hazards Partnership, 2019; Zscheischler *et al.*, 2020). To date, much of the research has focused on heat-related hazard combinations such as hot-dry and hot-wet events (Mukherjee, Ashfaq and Mishra, 2020; Bevacqua *et al.*, 2022; Sauter *et al.*, 2023). More recently, Mattu *et al.* (2025) undertook the first study of compound cold-dry (CD) and cold-wet (CW) events in the United Kingdom (UK). These studies demonstrated a higher prevalence of CD events relative to CW events, reflecting underlying dynamical processes, and identified distinct spatial patterns with CD events more likely in western regions of Scotland and CW events more likely in the east of the UK. Mattu *et al.* (2025) also established a link between compound cold events and large-scale circulation with CD events more likely to occur under anticyclonic regimes such as North Atlantic Oscillation negative (NAO-) and CW events under cyclonic regimes such as North Atlantic Oscillation positive (NAO+).

Although there has been significant research on the physical drivers of compound events (Zscheischler *et al.*, 2018; Zscheischler *et al.*, 2020; Ridder *et al.*, 2020; AghaKouchak *et al.*, 2020) there remains a lack of studies that translate compound event research into operational forecasting frameworks. Existing operational frameworks for compound events remain largely conceptual (World Meteorological Organization, 2015; Gill & Malamud, 2016), focus on combining separate hazard models (Láng-Ritter *et al.*, 2022), or propose multi-hazard integration for the weather service value chain (Su *et al.*, 2025). Zscheischler *et al.* (2022) state “Forecasting is an important tool to reduce damages of extreme events. However, to date, typical postprocessing tools are not tailored to multivariate events...”, highlighting the existing gap in research of forecasting tools for compound events. Although the World Meteorological Organisation (WMO) has promoted the adoption of impact-based forecasting to better detect and reduce the impacts of co-occurring hazards (World Meteorological Organization, 2015; Bazo *et al.*, 2021), operational examples addressing compound hazards remain limited, particularly within the transport sector.

One potential pathway for bridging this gap lies in the use of synoptic weather pattern or weather regime classifications. Weather patterns are a circulation type defined over a specific geographic region that have distinct meteorological characteristics and can vary at a daily timescale (James, 2006; Neal *et al.*, 2016). Synoptic weather patterns have been used extensively to establish relationships between specific pattern occurrence and societal impacts thereby creating a pathway to effectively forecast impacts, skilfully so at a 10-day lead time in the UK for weather patterns (Neal *et al.*, 2016) and out to 13 days for European-scale weather regimes (Cassou, 2008). Weather regime based approaches have been used comprehensively to investigate weather-dependent variables impacting the European and (Grams *et al.*, 2017; Bloomfield, Brayshaw and Charlton-Perez, 2020; Garrido-Perez *et al.*, 2020; Mockert *et al.*, 2023) and American (Millin, Furtado and Malloy, 2024) energy sector.

In the UK, the Met Office has developed a set of 30 weather patterns (herein referred to as MO30) over the North Atlantic-European domain that are used in their operational tool “Decider” which provides probabilistic forecasts of pattern occurrence out to 15-days ahead (Neal *et al.*, 2016). While individual surface variables like

temperature and precipitation show limited skill beyond 5-7 days, large-scale atmospheric circulation patterns remain predictable at longer lead times (Ferranti *et al.*, 2015; Strommen *et al.*, 2025). The MO30 classification have been applied to a wide range of impact-focused studies including coastal flooding (Neal *et al.*, 2018a), drought (Richardson *et al.*, 2018; Richardson *et al.*, 2020), urban mobility (Brown *et al.*, 2019), lightning risk (Wilkinson and Neal, 2021b), energy network power outages (Souto *et al.*, 2024), wildfire occurrence (Little *et al.*, 2026) and compound cold events affecting the Scottish rail network (Mattu *et al.*, 2026). These studies demonstrate the value of linking large-scale circulation patterns to local impacts, providing a basis for enhancing predictability at medium-range timescales.

A small number of studies have explicitly linked compound events and synoptic weather patterns, demonstrating that specific regimes are conducive to compound event occurrence. Bloomfield *et al.* (2024) studied compound wind-flood events in Great Britain, while Sanuy *et al.* (2024) examined rainfall-wave events in the Mediterranean. Compound cold events have been investigated by D'Errico *et al.* (2022) in Italy and Mattu *et al.* (2025) in the UK. Despite this research, there are no current examples of operational impact-based forecasting frameworks to support decision-making.

Impact-based forecasting focuses on communicating what the weather *might do* rather than simply what the weather *will be* (World Meteorological Organization, 2015). Following WMO guidance (World Meteorological Organization, 2015; Bazo *et al.*, 2021) meteorological agencies globally have begun to transition to impact-based forecasting to help reduce damages associated with extreme weather events. For example, in the UK, the Met Office issue impact-based warnings for a number of hazards (Met Office, 2018). These warnings integrate the magnitude of the hazard in conjunction with exposure and vulnerability in the affected region to communicate risk more effectively. However, impact-based forecasting systems are typically developed for single hazards rather than compound events.

Although there is a growing body of research on compound events, synoptic weather patterns and impact-based forecasting, no study to date has sought to integrate these

elements into an operational impact-based forecasting framework tailored for decision-makers in a specific sector. By combining these three components, the proposed framework provides a novel methodological contribution demonstrating how large-scale predictability can be translated into anticipatory, impact-based information suitable for operational use. To support anticipatory decision-making, the proposed framework is designed around a sequence of diagnostic questions that progressively link large-scale predictability to local-scale impacts. At longer lead times synoptic weather patterns provide an initial indication of elevated risk. When high-risk weather patterns are identified, spatial information on historically associated compound events is then used to assess whether critical sections of the rail network may be affected. Finally, shorter range probabilistic forecasts provide an indication of likelihood of compound event occurrence. A schematic overview of this workflow is shown in Figure 5.1.

This chapter is structured as follows: Section 5.4 and 5.5 describe the data and methodology used; Section 5.6 presents the results of developing high-risk weather patterns, weather pattern forecasts and dynamic compound cold event forecasts; Section 5.7 discusses the results, applications, and future work; and Section 5.8 concludes the work.

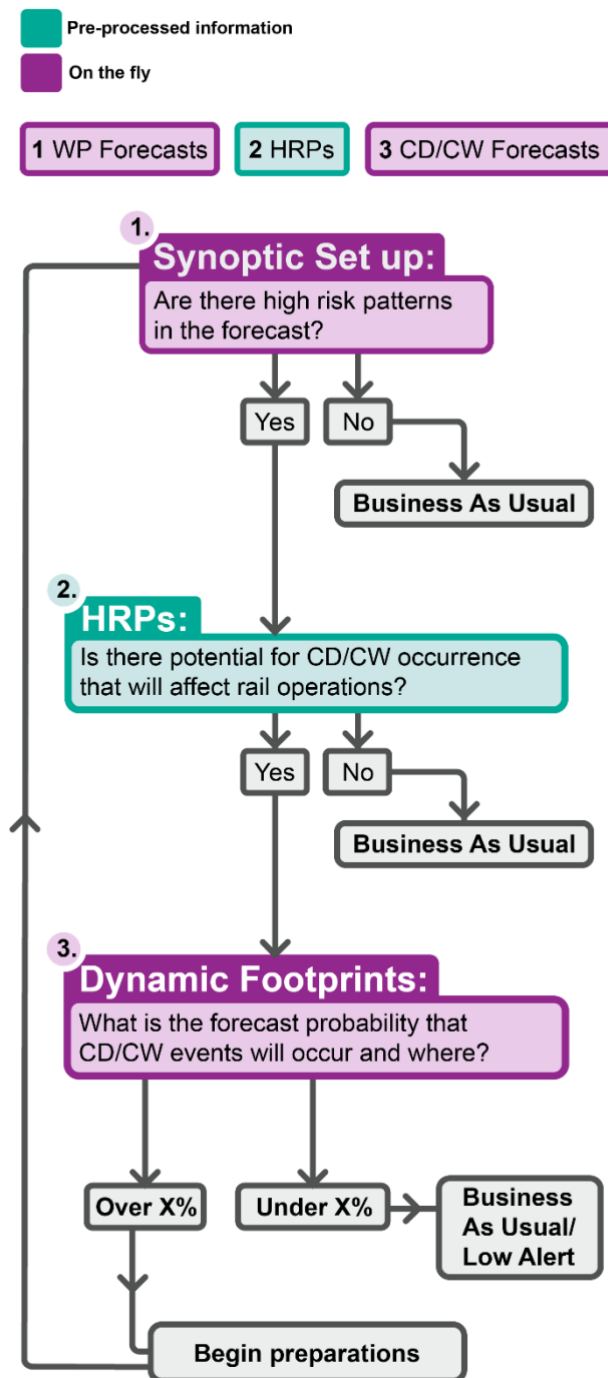


Figure 5.1 Schematic overview of the proposed impact-based forecasting framework. The workflow illustrates how synoptic-scale weather pattern forecasts are linked to dynamic, spatially explicit compound cold event probability forecasts, progressing from early situational awareness at longer lead times to localized impact relevance at shorter lead times. The framework is structured around the key decision-making questions addressed at each stage.

5.4 Data

5.4.1 Network Rail incident data

An impact dataset was obtained from Network Rail via a Freedom of Information request (reference: FOI2024/00624). The dataset records all weather-related rail incidents reported in Scotland during the winter operating season (October to March) from 2006 to 2023 inclusive, comprising a total of 10,533 incidents. For each incident, information is provided on the date of occurrence, incident description, incident reason, rail section (spatial location), section name, and passenger delay minutes (PfPI); Table 4.2 displays the incident names and definitions.

5.4.2 HadUK Grid

Gridded daily temperature and precipitation data from the HadUK-Grid dataset at 5 km spatial resolution were used to identify compound cold event occurrence. The data were accessed through the Centre for Environmental Data Analysis archive (Met Office *et al.*, 2024). HadUK-Grid was selected because it provides high-resolution land-surface variables, including minimum near-surface air temperature and precipitation, making it well suited for the analysis of local-scale hazards and impacts. The dataset is constructed from interpolated in situ observations collected at climate monitoring stations across the UK (Hollis *et al.*, 2019). HadUK-Grid was chosen over the ERA5 reanalysis (Hersbach *et al.*, 2020) because ERA5 is known to underestimate extreme precipitation events (Lavers *et al.*, 2022), whereas HadUK-Grid is derived directly from quality-controlled station observations (Hollis *et al.*, 2019) and provides a more accurate representation of UK precipitation extremes.

5.4.3 Weather pattern classifications

The Met Office 30-pattern (MO30) weather pattern classification (Neal *et al.*, 2016) was used to characterise the large-scale atmospheric conditions under which different incident types occurred. The MO30 classification was developed using a simulated annealing variant of the k-means clustering algorithm (Philipp *et al.*, 2007), applied to mean sea level pressure fields from the European–North Atlantic dataset (Ansell *et*

et al., 2006) spanning the period 1850–2003. The 30 individual weather patterns are grouped into eight broader circulation regimes: negative North Atlantic Oscillation (NAO-), positive North Atlantic Oscillation (NAO+), northwesterly, southwesterly, Scandinavian high, high pressure centred over the UK, low pressure close to the UK, and Azores high (Neal *et al.*, 2016). These regimes represent circulation states that are spatially extensive and more temporally persistent than individual weather patterns (Büeler *et al.*, 2021). Descriptions of the flow characteristics associated with each weather pattern are provided in Table A3.1 of Appendix 3.

The MO30 classification act as a static circulation dataset within the forecasting framework. Ensemble forecasts of mean sea level pressure from the European Centre for Medium Range Forecasting (ECMWF) ensemble prediction system (ENS) are compared to the MO30 patterns and assigned to the closest matching pattern for each ensemble member. This enables the probability of each weather pattern occurring to be estimated at different forecast lead times. The historical daily classification is additionally used to support the identification of high-risk weather patterns and compare their occurrence to climatology (Section 3.3) and to provide the observed circulation for the case study analysis.

5.4.4 ECMWF forecast model

The ECMWF ENS was used to calculate the dynamic probability of compound cold event occurrence, and to derive probabilistic forecasts of weather pattern occurrence. The dynamic probability of compound cold event occurrence is defined here as the time-evolving, ensemble-derived likelihood that event conditions are met based on the proportion of ensemble members satisfying the CD/CW thresholds at each forecast lead time. Archived ECMWF ensemble forecast data were accessed from the ECMWF Meteorological Archival and Retrieval System. Three forecast variables were utilised within the framework: (1) mean sea level pressure (MSLP) forecasts to assign weather patterns and determine the probabilities of each weather pattern occurring, (2) near-surface temperature forecasts, and (3) total precipitation forecasts to determine the probabilities of compound-cold events. These variables were used to produce two output forecasts: (1) daily weather pattern probability forecasts and (2)

daily gridded forecasts of CD and CW compound event occurrence, calculated following the methodology described in Section 5.5.2.

Weather pattern forecasts were obtained from the Met Office Decider system, which produces probabilistic forecasts of the MO30 weather pattern classifications. These forecasts are archived by the Met Office and provide, for each forecast initialisation, the probability of occurrence of each weather pattern across the ensemble forecast period. These archived forecasts were used to undertake the high-risk pattern (HRP) forecasting component of the framework.

The ECMWF ENS comprises 51 ensemble members, consisting of one control member and 50 perturbed members designed to sample forecast uncertainty arising from initial condition and model error. Forecasts initialised at 00 UTC were selected to reduce data volume and computational overhead (six-hourly outputs are available if more frequent updates are required for an application). Ensemble forecasts were extracted for lead times of 3, 5, and 10 days ahead of the selected case study events. Total precipitation and minimum near-surface temperature were extracted for all ensemble members from T+48 hours to T+252 hours at 6-hourly temporal resolution and covering a UK domain at a horizontal resolution on $0.2^\circ \times 0.2^\circ$. Although this does not reflect the native resolution of the ECMWF model, all forecasts were re-gridded to this common grid to ensure spatial consistency across the case studies. This was necessary because the operational ECMWF model resolution has evolved over the study period, with the selected case studies spanning forecasts from 2010, 2018, and 2021. For each forecast initialisation, only the time window corresponding to the relevant lead time (3, 5, or 10 days ahead of the event) was retained for analysis. All 51 ensemble members were retained for probabilistic analysis.

5.5 Methodology

5.5.1 NR impact data cleaning

The rail incidents were aggregated to daily resolution by the incident report date to maintain temporal consistency across all datasets used. The aggregation resulted in

1,729 incident days out of 3,094 days in the study period, showing that 55% of all days experienced a weather-driven incident.

5.5.2 Compound event occurrence

This study adopts the methodology developed in Mattu *et al.* (2025) to calculate compound cold event occurrence for high-impact days. Cold-dry (CD) and cold-wet (CW) events are defined using the following indices:

- cold-dry (CD): $\leq 15^{\text{th}}$ percentile of daily minimum temperature AND $\leq 15^{\text{th}}$ percentile of daily total precipitation
- cold-wet (CW): $\leq 15^{\text{th}}$ percentile of daily minimum temperature AND $\geq 85^{\text{th}}$ percentile of daily total precipitation.

Percentile threshold values were calculated using an ordered time series of winter (December, January, February; DJF) days over a 30-year period of 1994-2023 for each HadUK-Grid land grid-square. The DJF period was selected as it represents the climatological winter season and captures most cold-related hazards in the UK, which are most relevant for infrastructure impacts. Extending the time series to a broader season (e.g. ONDJFM) would reduce the sensitivity of thresholds to extreme cold events. The percentile approach was used to make the compound event indices more relevant to local climatology. A detailed methodology of the sensitivity analysis and indices calculation can be found in Mattu *et al.* (2025).

5.5.3 Defining a set of “high-risk” weather patterns

The Network Rail impact dataset was used to identify a set of “high-risk” weather patterns (HRPs) specific to the Scottish rail network. This dataset contains 1,729 incident days (days where at least one weather-related incident was reported). PfPI minutes are a performance metric used by Network Rail that reflects the scale of delay associated with incidents and are used here as an indicator of disruption severity.

Each incident day was assigned to a corresponding weather pattern (one of the MO30) that occurred on that day using the daily historical weather pattern data (1850-

2003). A subset of the incident days was then selected based on weather pattern correlation and PfPI minutes. Weather pattern correlation is defined as the spatial correlation between the mean sea level pressure (MSLP) field on a given day and the corresponding idealised MO30 pattern, providing a measure of how closely the observed atmospheric state matches the predefined circulation pattern. Correlation values range between -1 and 1, with higher values indicating a stronger agreement between the observed MSLP field and the idealised pattern (Wilks, 2011).

The following filters were applied: days with pattern correlation greater than 0.6 and >25th percentile of PfPI minutes were counted as high-risk days. These filters were applied to select days with reliable weather pattern assignment and to exclude days that caused minimal disruption. The subset produced 1,035 incident days. The number of incident days that occurred under each weather pattern can be found in Table A3.1 of Appendix 3. Only one pattern, WP3, did not have any incident days assigned to it. For each of the subset incident days the occurrence of CD and CW events was produced, using the methodology described in Section 5.5.2. A composite was generated for each of the 30 weather patterns, representing the most frequently occurring spatial footprint of compound cold events under each pattern (e.g., if there were 3 CW and 5 CD events the composite would record CD). Figure A3.1 in Appendix 3 displays the composite for each weather pattern. Weather patterns were subsequently ranked on the spatial extent of CD and CW occurrence within these composites, defined as the proportion of grid cells exhibiting dominant compound event conditions. Patterns with the greatest spatial extent of CD event occurrence were retained as high-risk patterns (HRPs). Across all 30 weather pattern composites no patterns exhibited sufficiently consistent or spatially extensive CW event occurrence to meet this criterion and therefore no HRPs were identified for CW events. This analysis represents an offline (historical) step used to identify weather patterns associated with elevated impact risk, which are then applied within the forecasting framework. It demonstrates the spatial variability of CW events relative to CD events for high-risk events.

5.5.4 Selecting case studies

Three case study days were selected to demonstrate the application of the proposed forecasting framework. Each case study corresponds to a day associated with severe impacts on the Scottish rail network linked to compound cold events. The selected dates are 29/11/2010, 28/02/2018, and 11/02/2021. Figure 5.2 shows the number of incidents and accumulated PfPI minutes for each of the selected case study days.

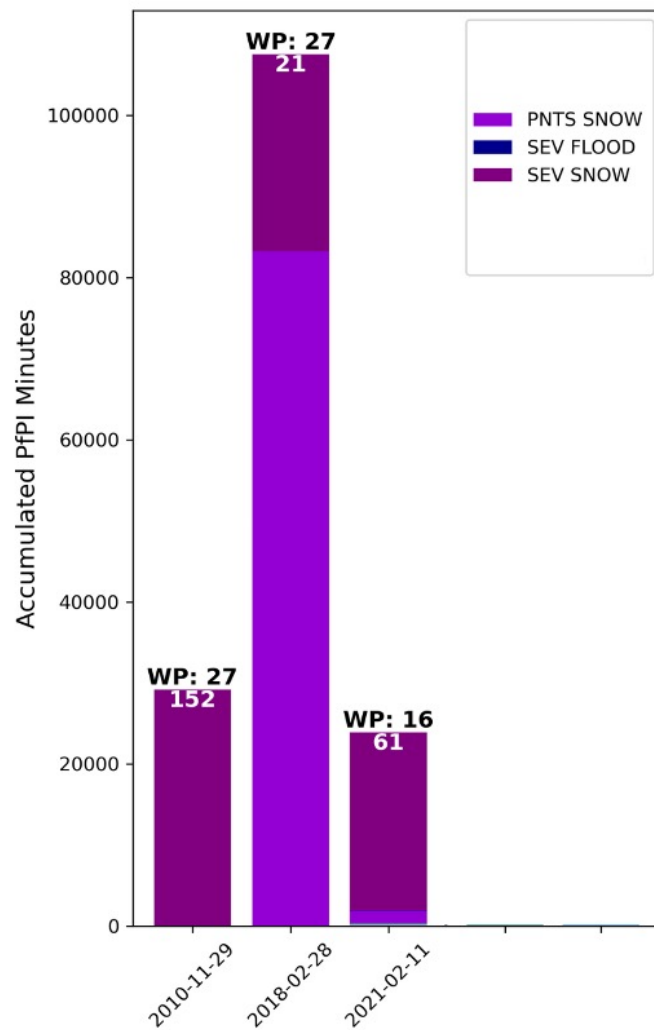


Figure 5.2 Overview of the selected case study days showing the total number of weather-related rail incidents and the accumulated passenger delay minutes (PfPI) recorded in the Network Rail impact dataset. The prevailing Met Office weather pattern (WP) on each case study day are also indicated.

All three case studies are characterised by snow-related incident types, although the nature and severity of impacts vary between events. On 29/11/2010, all reported incidents were classified as severe snow (SEV SNOW), with a total of 152 incidents recorded. This represents the highest number of incidents reported on a single day across the entire impact dataset.

The second case study, 28/02/2018, corresponds to the most impactful day of the “Beast from the East” event, during which easterly flow associated with a persistent cold air mass interacted with Storm Emma to produce widespread blizzard conditions across the UK (Adekola, Renaud and Hill, 2021). Although only 21 incidents were reported on this day, approximately 70% were classified as snow resulting in a points failure (PNTS SNOW), with the remainder recorded as severe snow. Despite the lower incident count, the accumulated passenger delay minutes (PfPI) exceeded 100,000 minutes, the highest value observed in the dataset, indicating severe network-wide disruption.

For both 29/11/2010 and 28/02/2018, Weather Pattern 27 (WP27) was the dominant synoptic pattern. The final case study, 11/02/2021, is also characterised by snow-related incidents, primarily as severe snow (SEV SNOW), with a smaller proportion of PNTS SNOW and a limited number of incidents attributed to severe flooding (SEV FLOOD). A total of 61 incidents were recorded on this day, with accumulated PfPI minutes of ~21000. On this day, Weather Pattern 16 (WP16) occurred.

5.5.5 Development of the forecasting framework

Weather pattern forecasts (Stage 1: synoptic set up)

15-day probabilistic weather pattern forecasts were produced using the ECMWF ENS (see Section 5.4.4), comprising 51 ensemble members. For each ensemble member, forecast MSLP fields were compared to the MO30 weather pattern classification, and assigned to the closest matching pattern. This enabled the probability of each of the 30 weather patterns occurring to be estimated at each forecast lead time.

Forecasts were initialised 10-, 5-, and 3-days ahead of each case study date (29/11/2010, 28/02/2018, and 11/02/2021). For example, the initialisation dates corresponding to the first case study are 19/11/2010 (10-day), 24/11/2010 (5-day), and 26/11/2010 (3-day). In total, nine forecasts were produced, comprising three for each case study.

High-risk weather pattern probabilities (Stage 2: HRP identification)

A subset of weather patterns associated with elevated disruption risk, HRPs, was identified using the methodology described in Section 5.5.3. The probabilities of individual HRPs were combined to produce an overall probability of a HRP occurring at each lead time. HRP probabilities were evaluated relative to their climatological frequency. The climatological probability represents the baseline likelihood of HRP occurrence derived from the historical MO30 classification. Periods where forecast probabilities exceed this climatological baseline are interpreted as windows of elevated risk, while probabilities below climatology indicate comparatively quiescent conditions. This provides a simple threshold to support decision-making within the forecasting framework (Figure 5.1).

Dynamic compound cold event forecasts (Stage 3: HRP spatial footprints)

Probabilistic forecasts of compound CD and CW events were produced using ECMWF ensemble forecasts of temperature and precipitation. Percentile thresholds derived from HadUK-Grid (Section 5.3.2) were applied to the forecast fields at lead times of 10-, 5-, and 3-days for each case study.

The percentile thresholds correspond to the conditions defining CD/CW events: 15th percentile of daily minimum temperature, 15th and 85th percentile of daily precipitation. These thresholds were originally produced in HadUK-Grid's native resolution of 5 km and subsequently re-gridded to 22 km to match the resolution of the ECMWF forecast grid. This was completed using linear interpolation as this method is optimal for continuous fields such as temperature and precipitation (National Centre for Atmospheric Research, 2014; Cornes *et al.*, 2018)

Gridded forecast probabilities were generated by assessing, for each ensemble member, whether the CD/CW criteria were met at each grid square in the domain and then dividing by the total number of ensemble members (51). This provides spatially explicit “dynamic footprints” of compound cold event likelihood, representing the final stage of the forecasting framework (Figure 5.1).

A sensitivity analysis was conducted using ERA5 reanalysis data in place of HadUK-Grid observations for threshold calculation. This comparison showed a high degree of spatial agreement in the identification of CD and CW events between ERA5 and HadUK-Grid, indicating that the choice of HadUK-Grid as the observational reference does not materially affect the identification of compound cold events. Given HadUK-Grid’s higher spatial resolution and closer alignment with surface observations it was retained for the main analysis.

5.6 Results

5.6.1 Identifying high-risk weather patterns

Weather patterns (WPs) 19, 27, and 28 were retained as high-risk patterns (HRP), see Figure 5.3. The flow characteristics of these patterns are shown in Figure 2.3, and flow descriptions are shown in Table A1.1 in Appendix 1. These HRPs were derived from a historical analysis of the full Network Rail impact dataset and represent patterns associated with elevated disruption risk across all incident days, rather than being specific to the case studies examined later. The spatial distribution of the dominant CD event composite is displayed in Figure 5.3. Each HRP is characterised by a predominance of CD event occurrence in western Scotland with distinct spatial differences between them. No consistent spatial signal of CW events was identified in the modal composites, reflecting the greater spatial variability of these events; this is further explored in Section 5.7.

WP19 (Figure 5.3) exhibits CD events primarily across the Western Isles, Ayrshire, Dumfries and Galloway, and parts of the central belt. WP27 extends these surface impacts further north, with CD events reaching the Isle of Skye and inland towards

Fort William. For both WP19 and WP27 the CD event occurrence remains largely confined to the western regions of Scotland.

In contrast, WP28 displays a more spatially homogenous distribution across southern and central Scotland. CD events are evident across the Southern Uplands, with a pronounced concentration in Argyll and Bute, while coverage over Ayrshire and Dumfries and Galloway is reduced relative to WP19 and WP27. Notably, WP28 also includes regions in eastern Scotland, with CD event occurrence extending into areas such as Fife and East Lothian.

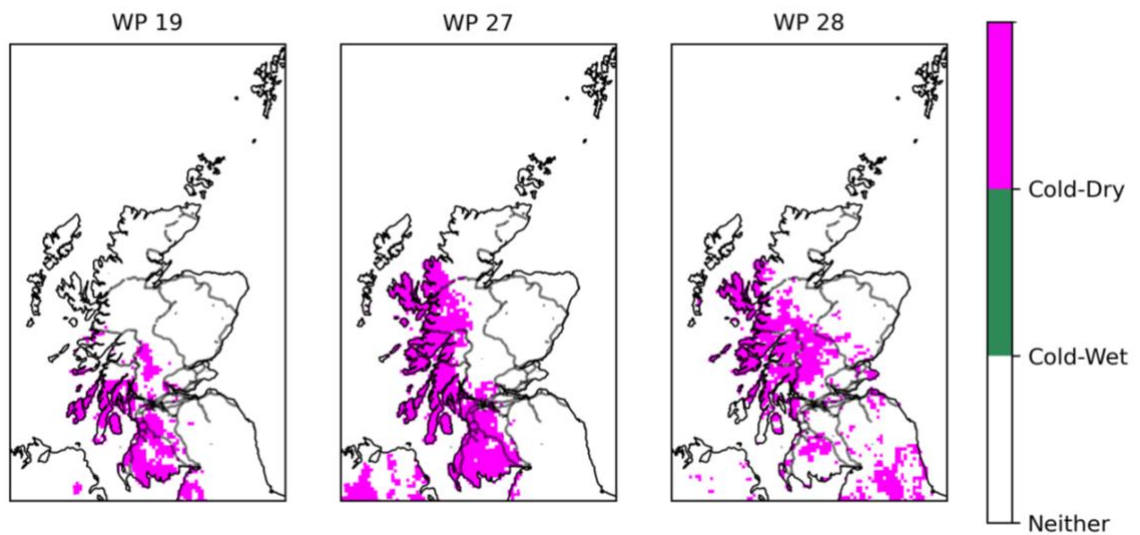


Figure 5.3 Spatial distribution of modal compound cold event occurrence for the retained high-risk weather patterns (HRPs), derived using HadUK-Grid observations. Shading indicates the modal occurrence of CCE under each HRP. The Scottish rail network is shown by the black line for reference.

5.6.2 Case study demonstration of the forecasting framework

The following case studies are presented in accordance with the forecasting framework outlined in Figure 5.1, progressing from large-scale synoptic conditions to high-risk weather pattern identification, and finally to spatially resolved compound cold event probabilities.

29 November 2010

Synoptic set up: identification of a high-risk period

At a 10-day lead time (Figure 5.4a), the forecast indicates a heightened risk window as probabilities significantly exceed climatology. There is a combined 69% probability of a high-risk weather pattern (HRP, Figure 5.3) occurring on 29/11/2010, comprising 8% for WP19, 20% for WP27, and 42% for WP28. Across the preceding nine days, the forecast shows persistently elevated HRP probabilities exceeding 80%, illustrating a clear window where HRPs conducive to compound cold events had the potential to cause rail disruption. Between 20/11/2010 and 22/11/2010, WP27 dominates with 100% probability, before a gradual increase in the contribution from WP19 from 23/11/2010 onwards. From 26/11/2010, the overall HRP probability decreases, alongside an increasing contribution from WP28.

At a 5-day lead time (Figure 5.4b), the probability of an HRP on 29/11/2010 increases to 100%, with WP27 accounting for 73%, WP19 for 20%, and WP28 for 8%. The forecast for the preceding days shows a more pronounced alternation between WP27 and WP19, with 24/11/2010 and 25/11/2010 characterised by 100% probability of WP19. From 27/11/2010 onwards, the forecast shifts back towards WP27, which exceeds 90% probability on both 27/11/2010 and 28/11/2010. Dynamically, these patterns represent closely related circulation states as they are both grouped within the NAO- regime, therefore the transition between WP19 and WP27 reflects a subtle displacement of a blocking high-pressure system from northwest of the UK towards the Norwegian Sea.

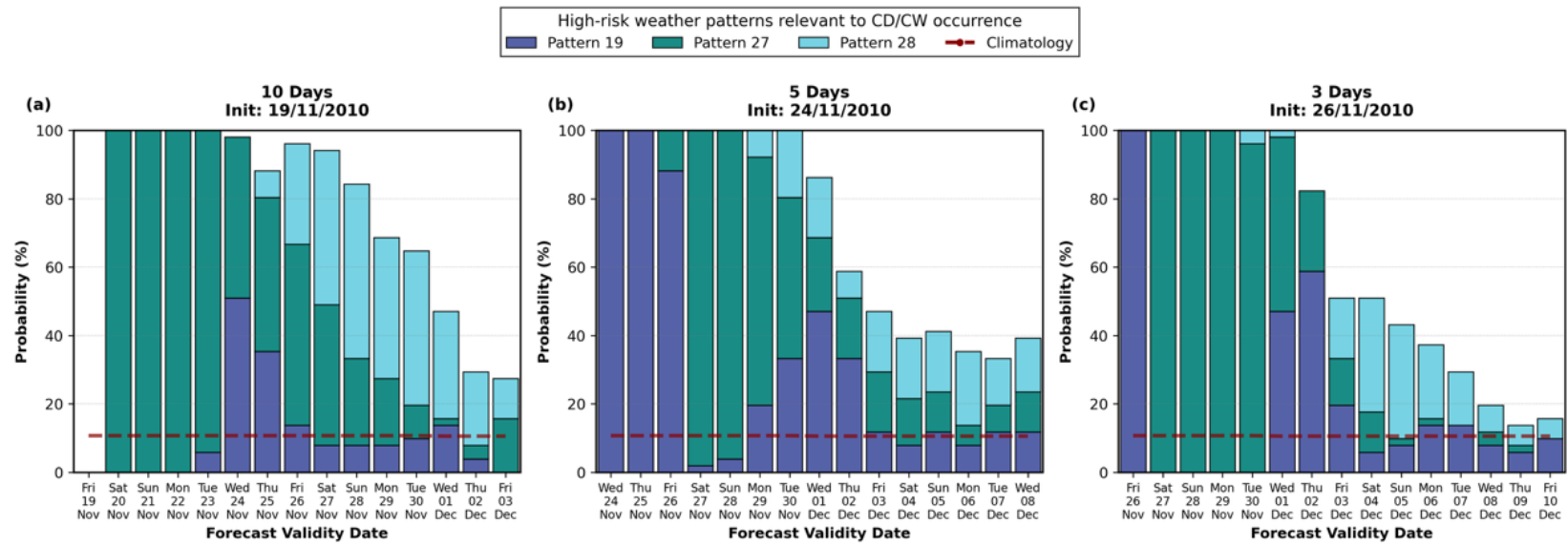


Figure 5.4 Forecast probability of high-risk weather pattern (HRP) occurrence for Case Study 1 at 10-day (a), 5-day (b), and 3-day (c) lead time, derived from weather pattern classification forecasts.

At a 3-day lead time (Figure 5.4c), the forecast converges on WP27, with a 100% probability assigned to this pattern on 29/11/2010. WP28 briefly dominates on 26/11/2010 before a definitive transition to WP27 from 27/11/2010 through to the event day. Observations confirm that WP27 was present on 29/11/2010.

High-risk weather patterns: likelihood of compound cold event occurrence

The persistence of HRPs over the forecast period indicates a high likelihood that compound cold events would occur under these weather patterns. WP27 and WP19 contribute substantially to the overall HRP probability across multiple lead times. Figure 5.3 indicates the spatial distribution of compound cold events likely to occur under these weather patterns.

Dynamic footprint: spatial probability of compound cold event occurrence

At a 10-day lead time (Figure 5.5a), the forecast probability of cold–dry (CD) events show a spatially diffuse signal across Scotland, with probabilities ranging from 0–80% and no cohesive footprint of elevated likelihood. In contrast, the cold–wet (CW) forecast at this lead time (Figure 5d) exhibits more spatial structure, with three distinct regions of enhanced probability: Aberdeenshire, East Lothian, and the southern Scottish Borders. Within these regions, clustered probabilities of 20–60% are evident, while surrounding areas generally show weaker signals below 10%.

By 5 days lead time (Figure 5.5b), the CD signal becomes more spatially organised. A region of high probability (>80%) emerges along the north-west coast, with decreasing probability bands extending eastward to values below 10%. Across southern Scotland, probabilities are more heterogeneous, ranging between 1–60%. The CW signal weakens substantially at this lead time (Figure 5.5e), with only two isolated grid cells exhibiting probabilities of 10–20%, located in northern Aberdeenshire and East Lothian.

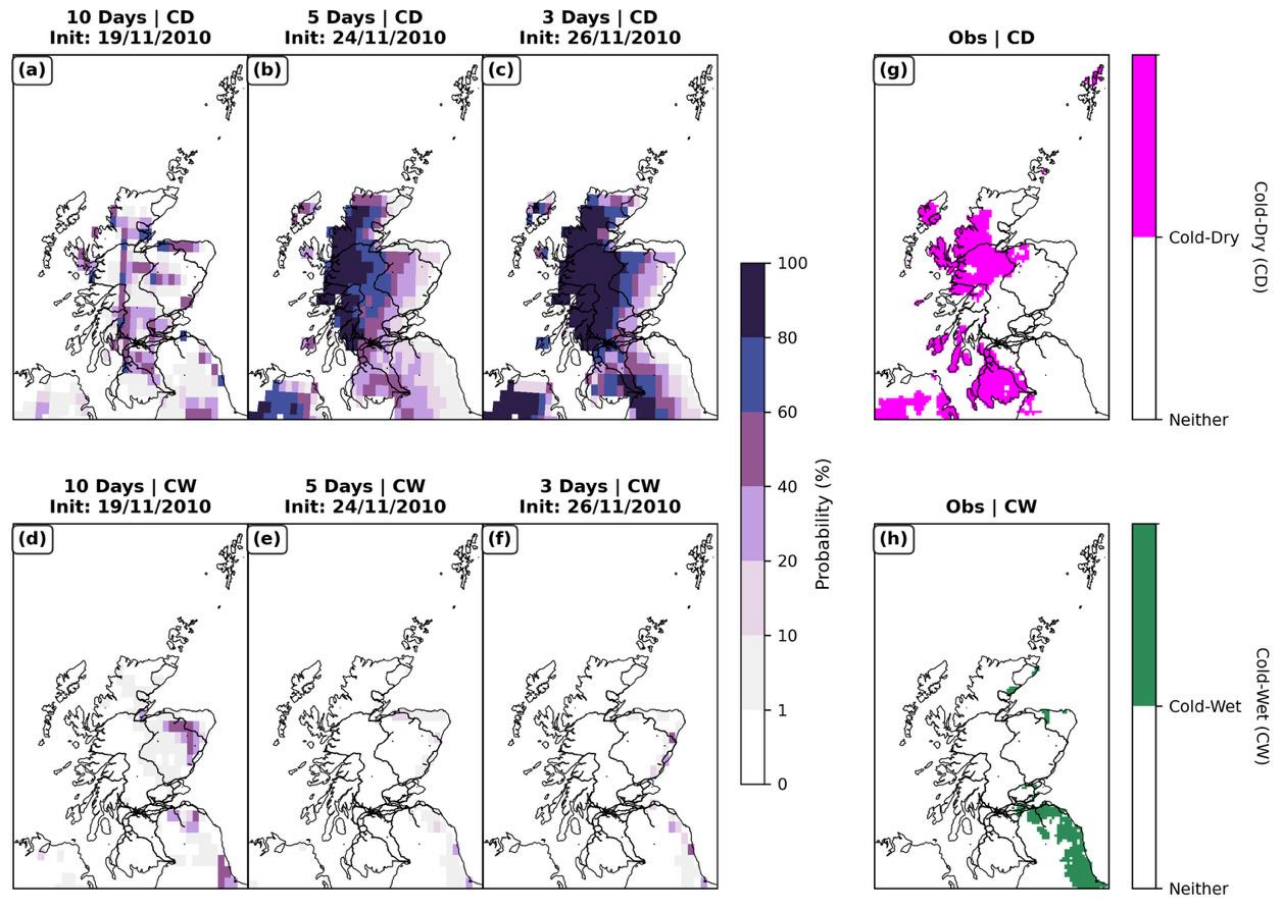


Figure 5.5 Dynamic probabilistic forecasts of compound cold-dry (CD; top row) and cold-wet (CW; bottom row) event occurrence for Case Study 1 at 10-day (a;d), 5-day (b;e), and 3-day (c;f) lead times, derived from the ECMWF ensemble forecasts. Ensemble-based probabilities are shown alongside observed CD (g)/CW (h) occurrence from HadUK-Grid. The Scottish rail network is shown by the black line for reference.

At a 3-day lead time (Figure 5.5c), the CD forecast resolves into two spatially distinct regions of elevated probability. The first encompasses the west and southern Highlands, Argyll and Bute, Stirling, and western Perth and Kinross, while the second is located in Dumfries and Galloway. In both regions, probabilities decrease incrementally away from the areas of maximum likelihood. The CW forecast shows renewed spatial variability (Figure 5.5f), with several grid cells along the east Aberdeenshire coast and the south-eastern coastline exhibiting probabilities between 10–60%.

Comparison with observed events

Observed compound cold events on this day show two spatially distinct CD regions, located in the north-west and south-west of Scotland, separated by an area where no CD events were recorded (Figure 5.5g). Observed CW events are more limited in extent, occurring in the north-east around Golspie and Wick, along the north coast of Aberdeenshire, and more widely across Edinburgh, East Lothian, and the south-east coast (Figure 5.5h).

28 February 2018

Synoptic set up: identification of high-risk period

At a 10-day lead time (Figure 5.6a), the combined probability of an HRP occurring on 28/02/2018 exceeds climatology at 76.47%, with contributions from WP27 (59%) and WP28 (18%), while WP19 does not feature. HRP probabilities increase progressively from 18/02/2018, rising from near-zero values to exceed 60% by 25/02/2018. Elevated probabilities persist through to the event day, ranging between 60% and 76%.

At a 5-day lead time (Figure 5.6b), the forecast assigns a 100% probability of an HRP on 28/02/2018, entirely attributed to WP27. This dominance of WP27 extends across the preceding days, which also exhibit 100% probability. In the days following the event, HRP probabilities remain elevated, with a gradual shift towards WP28. Dynamically, this represents a transition from a persistent anticyclonic easterly flow to a more cyclonic south-easterly flow.

At a 3-day lead time (Figure 5.6c), the forecast remains unchanged for the event day, with WP27 retaining 100% probability. The preceding days continue to show full dominance of WP27, while the days following the event show a marked transition towards WP28. Observations show that WP27 occurred on 28/02/2018.

High-risk weather patterns: likelihood of compound cold event occurrence

The persistent dominance of WP27 across all lead times indicates conditions highly conducive to compound cold event occurrence. Reference to Figure 5.3 shows the most likely location of observed compound cold events under this weather pattern.

Dynamic footprints: spatial probability of compound cold events

At a 10-day lead time (Figure 5.7a), the forecast indicates a widespread probability of CD event occurrence across Scotland. Probabilities increase incrementally from east to west, with the lowest values (1–10%) in eastern regions and the highest probabilities (>80%) in western areas. At a 10-day lead time (Figure 5.7d), the CW forecast shows a weak signal confined to eastern Scotland. Both north-eastern and south-eastern regions exhibit probabilities of up to 10%, with isolated pockets reaching 20%.

By 5 days lead time (Figure 5.7b), the spatial distribution of CD probability becomes more concentrated. Probabilities increase in western regions, where areas previously exhibiting up to 60% probability now show values of 60–80%. Conversely, probabilities in eastern regions decrease, with areas that previously showed up to 20% probability dropping to below 10%. For CW event probability (Figure 5.7e) the signal remains weak but persists in eastern areas. An increase in probability is evident in the south-east, where values reach up to 40%.

At a 3-day lead time (Figure 5.7c), the spatial pattern tightens further while broadly maintaining the distribution observed at 5 days. Very high probabilities (>80%) are evident across the Western Isles, the southern Highlands, and Argyll and Bute. Moving eastwards away from this region, probabilities decrease sharply, reaching 0% in areas around Stirling and Moray. Elevated probabilities (>60%) persist in parts of

South Ayrshire. At a 3-day lead time (Figure 5.7f), the forecast indicates increased confidence in CW event occurrence in the south-east, although the precise location remains spatially diffuse. Several clustered grid cells exhibit probabilities ranging from 10–80%. Along the north-east coast, a coastal grid cell in southern Aberdeenshire exceeds 60% probability and forms part of a broader cluster south of Aberdeen with probabilities of 10–40%. Additional elevated probabilities of up to 40% are evident around Golspie on the north-east Highland coast.

Comparison with observed events

Observed CD events on this day (Figure 5.7g) were spatially limited and occurred in the north-east of Scotland, Argyll and Bute, the southern Highlands, and the Western Isles, including the Outer Hebrides. Additional isolated events were recorded along the Ayrshire coast and in Orkney. Observed CW events (Figure 5.7h) occurred in two main regions: a narrow band along the north-east coast between Golspie and Dunbeath, and a larger area encompassing much of East Lothian and the Scottish Borders.

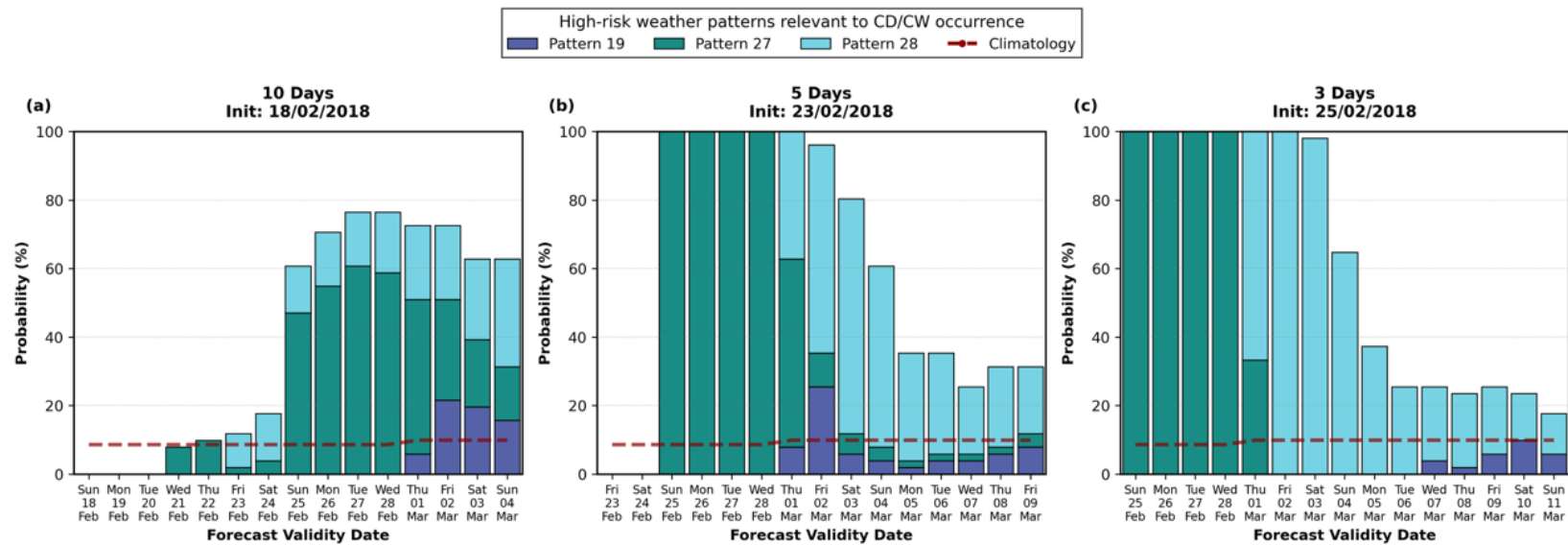


Figure 5.6 Forecast probability of high-risk weather pattern (HRP) occurrence for Case Study 2 at 10-day (a), 5-day (b), and 3-day (c) lead time, derived from weather pattern classification forecasts.

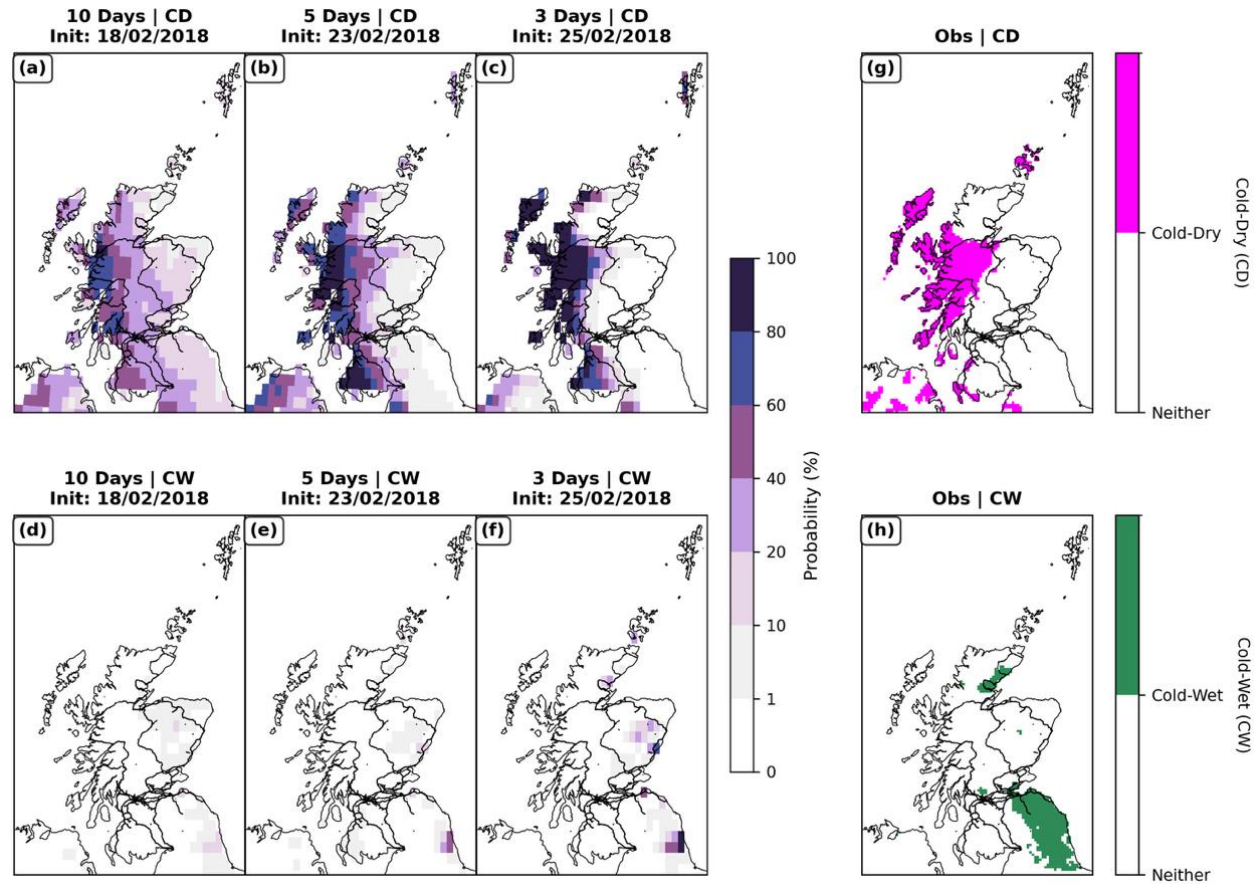


Figure 5.7 Dynamic probabilistic forecasts of compound cold-dry (CD; top row) and cold-wet (CW; bottom row) event occurrence for Case Study 1 at 10-day (a,d), 5-day (b,e), and 3-day (c,f) lead times, derived from the ECMWF ensemble forecasts. Ensemble-based probabilities are shown alongside observed CD (g)/CW (h) occurrence from HadUK-Grid. The Scottish rail network is shown by the black line for reference.

11 February 2021

Synoptic set-up: identification of a high-risk period

At a 10-day lead time (Figure 5.8a), the forecast assigns a relatively low combined probability of 16% for an HRP on 11/02/2021, composed of 4% for WP19, 10% for WP27, and 2% for WP28. In contrast, the seven days preceding the event show consistently elevated HRP probabilities exceeding 45%, with probabilities greater than 90% between 03/02/2021 and 09/02/2021. WP27 is the dominant contributor during this period.

At a 5-day lead time (Figure 5.8b), the combined HRP probability on 11/02/2021 increases slightly to 22%, solely represented by WP27. Although relatively low, this probability exceeds the climatological baseline, indicating that conditions are elevated above typical background risk. The five preceding days exhibit high confidence in HRP occurrence, with the first four days showing 100% probability. During this period, the forecast indicates a transition from WP27 towards WP28 on 08/02/2021 and 09/02/2021.

At a 3-day lead time (Figure 5.8c), the HRP probability on the event day decreases to 4%, entirely attributed to WP27. However, the preceding three days continue to show 100% probability of an HRP, with a further increase in the contribution from WP28. Observations show that WP16 occurred on 11/02/2021.

High-risk weather patterns: likelihood of compound cold event occurrence

The persistence of HRPs in the days leading up to the event indicates conditions conducive to compound cold event occurrence prior to 11/02/2021. Despite an HRP not being forecast on 11/02/2021, Figure 5.3 can still be utilised to understand the most likely location of compound cold events ahead of the high-impact day itself.

Dynamic footprints: spatial probability of compound cold events

At a 10-day lead time (Figure 5.9a), the forecast indicates a widespread probability of a cold–dry (CD) event across Scotland. Probabilities increase gradually from east to west, with the lowest values (1–10%) in eastern regions and the highest probabilities

(>80%) in western Scotland. In contrast, the cold–wet (CW) signal is weak at this lead time and confined to eastern areas (Figure 5.9d). Both north-eastern and south-eastern Scotland show probabilities of up to 10%, with isolated pockets reaching 20%, indicating low confidence in CW event occurrence.

By 5 days ahead (Figure 5.9b), the CD signal becomes more consolidated in the west of the country. Probabilities increase in western regions, with areas that previously exhibited up to 60% probability now showing values of 60–80%. At the same time, probabilities in eastern Scotland decrease, with regions that previously indicated up to 20% probability dropping to below 10%. The CW signal remains weak overall but persists in eastern Scotland (Figure 5.9e). An increase in probability is evident in the south-east, where values reach up to 40%, while probabilities elsewhere remain low.

At a 3-day lead time (Figure 5.9c), the spatial distribution of CD probability tightens further while broadly maintaining the west–east gradient observed at earlier lead times. Very high probabilities (>80%) are evident across the Western Isles, the southern Highlands, and Argyll and Bute. Probabilities decrease sharply moving eastward from this region, reaching 0% in areas around Stirling and Moray, while elevated probabilities (>60%) persist in parts of South Ayrshire. For CW (Figure 5.9f), the forecast shows increased confidence relative to earlier lead times, particularly in the south-east, although the spatial distribution remains diffuse. Clusters of grid cells range from 10–80% probability, with elevated probabilities also present along the north-east coast, including a coastal grid cell in southern Aberdeenshire exceeding 60%, and probabilities of up to 40% around Golspie on the north-east Highland coast.

Comparison with observed events

Observed CD events on this day were spatially limited and occurred in the north-east of Scotland, Argyll and Bute, the southern Highlands, and the Western Isles, including the Outer Hebrides (Figure 5.9g). Additional isolated CD events were recorded along the Ayrshire coast and in Orkney. Observed CW events occurred in two main regions: a narrow band along the north-east coast between Golspie and Dunbeath, and a larger area encompassing much of East Lothian and the Scottish Borders (Figure 5.9h).

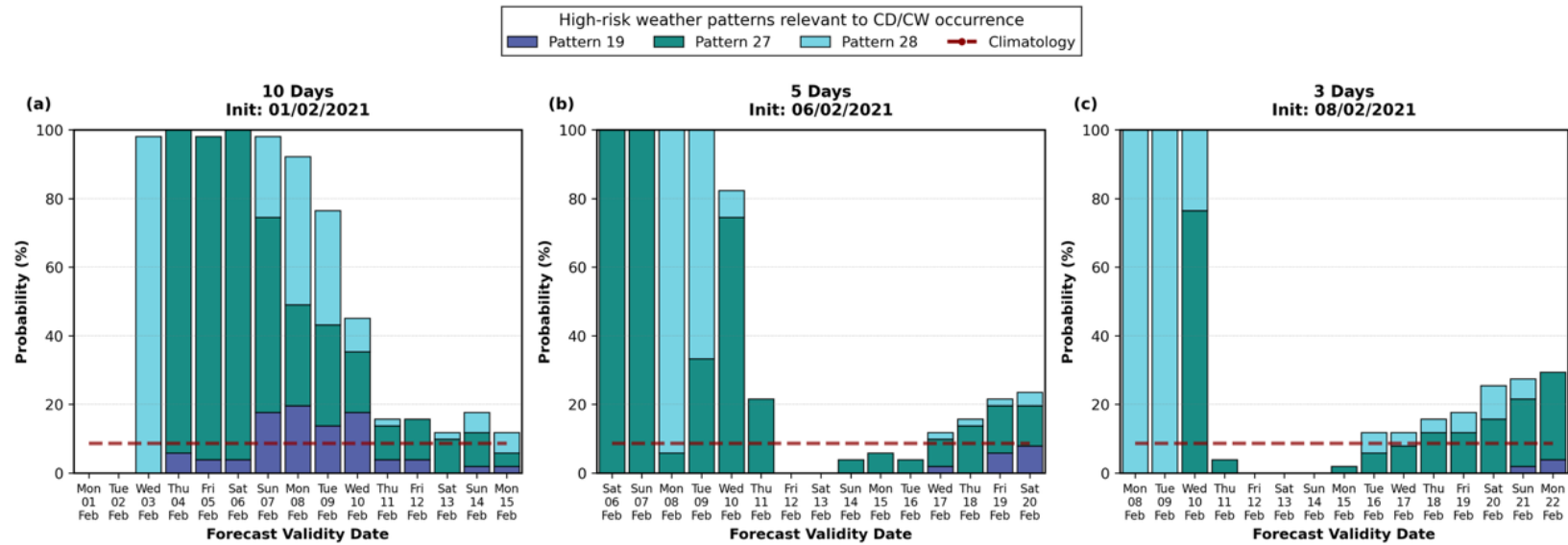


Figure 5.8 Forecast probability of high-risk weather pattern (HRP) occurrence for Case Study 3 at 10-day (a), 5-day (b), and 3-day (c) lead time, derived from weather pattern classification forecasts.

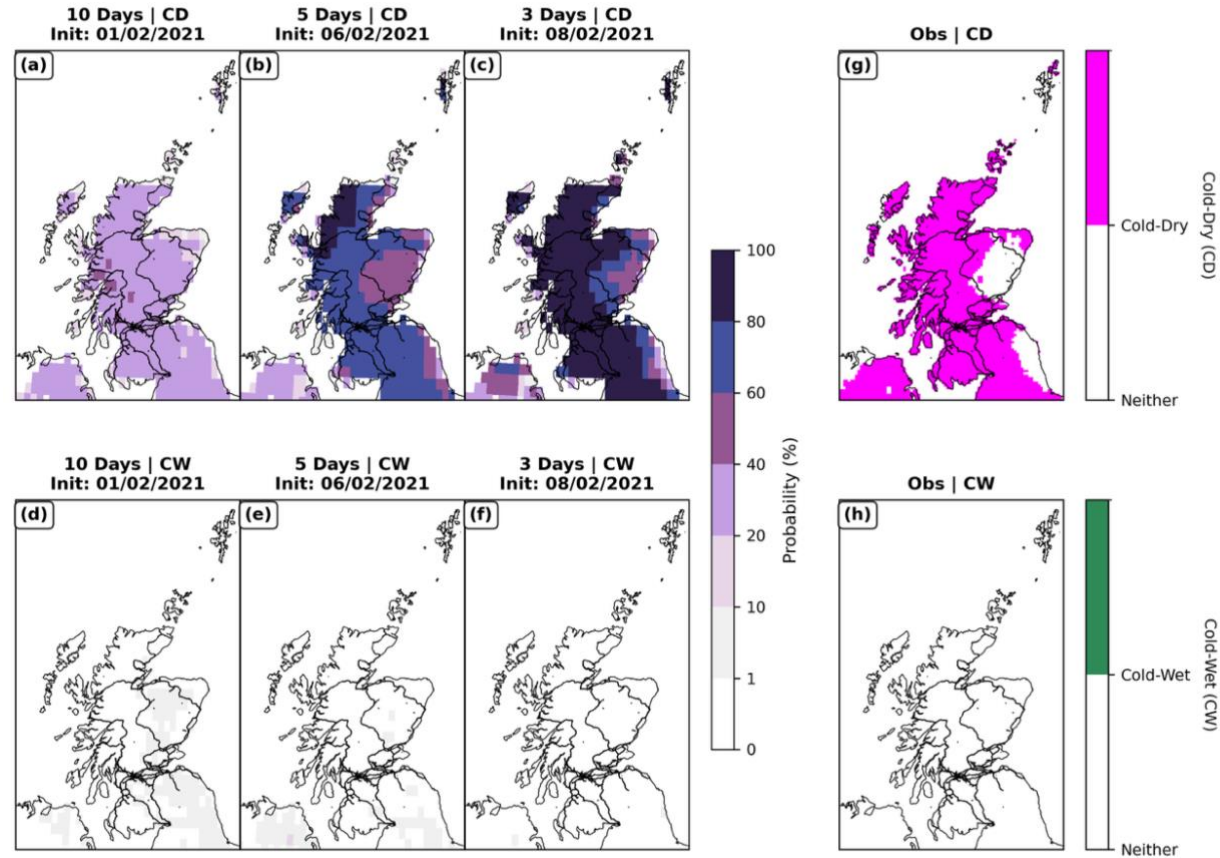


Figure 5.9 Dynamic probabilistic forecasts of compound cold-dry (CD; top row) and cold-wet (CW; bottom row) event occurrence for Case Study 1 at 10-day (a;d), 5-day (b;e), and 3-day (c;f) lead times, derived from the ECMWF ensemble forecasts. Ensemble-based probabilities are shown alongside observed CD (g)/CW (h) occurrence from HadUK-Grid. The Scottish rail network is shown by the black line for reference.

5.6.3 Cross-case summary

Across the three case studies, the forecasting framework consistently demonstrates how different layers of information contribute to identifying and refining periods of risk. At the synoptic set-up stage (Figure 5.1, question 1), two of the three case studies were characterised by high-impact days occurring under the NAO- regime, reinforcing the role of persistent anticyclonic conditions in producing prolonged cold and snow-related impacts. In the third case study, the high-impact day itself did not occur under an HRP or NAO- regime; however, the preceding days were dominated by HRPs, highlighting the importance of antecedent circulation and event sequencing in identifying high-risk periods.

At the HRP stage (Figure 5.1, stage 2), elevated HRP probabilities provided early indication of heightened impact potential at extended lead time (up to 10-15 days). Across all case studies forecast confidence in the dominant HRP increased as lead time decreased with the strongest signal emerging at 5- and 3-day lead times. At the dynamic footprint stage (Figure 5.1, stage 3), compound cold event probabilities added spatial detail to the large-scale signal. CD events were forecast with greater confidence and clearer spatial location than CW events across all case studies reflecting both the conditional rarity of CW events and the limitations of medium-range precipitation forecasts. Dynamic compound cold event footprints added spatial specificity to the regime-based signal allowing a bridge between large-scale circulation predictability and localised impact relevance for the Scottish rail network.

In conclusion, the combination of regime-level forecasts and dynamic event probabilities consistently provided more operationally relevant information than considering the components in isolation, therefore demonstrating the value of a tiered forecasting approach that progresses from an early heads-up to spatially explicit risk information.

5.7 Discussion

This study develops a tiered forecasting framework for compound cold events affecting the Scottish rail network, integrating impact data, weather pattern analysis

and ensemble-based forecasts to translate large-scale atmospheric predictability into decision-relevant information. The framework is designed as a tiered suite of outputs that correspond to the key questions posed in Figure 5.1. Each level of the framework operates at a different temporal and spatial resolution aimed to support different parts of the decision-making chain. This tiered structure is designed to progressively narrow attention from a broad-scale heads-up to localised event probability, reducing the need for decision-makers to interpret high-resolution forecasts at longer lead times. The intent is that this framework is displayed in a way that it would be accessed and interpreted by someone without forecasting expertise i.e., a decision-maker within an organisation responsible for national critical infrastructure facilities. Forecast lead times of 10-, 5- and 3-days were selected to align the impact data provider's (Network Rail) operational timescales for weather-related decision-making. The Met Office offer rail-specific 10-day forecasts for medium-term planning and resource allocation (Met Office, 2024). Network Rail contracts 2–5-day forecasts for tactical response and recovery operations (Haddock, 2022) and is developing predictive models that use 3–4-day forecasts to deploy engineers for proactive maintenance of at-risk assets (Higgins, 2026). A conceptual design of the framework can be found in Appendix 3 (Figures A3.2 to A3.5.). As a demonstration the case studies were chosen retrospectively as impactful days to the Scottish rail network (Section 5.5.4) and the lead-times for the dynamic CD/CW forecasts display the changing probability solely for the high-impact day. In an operational version this information would be available for all 15 days present in the HRP forecast window, enabling continuous evaluation of individual days and potential sequencing of CD/CW events that may further compound or prolong impacts (Mattu *et al.*, 2026). The dynamic component of the forecast displays the evolution of probabilities over the heightened risk period.

Across the three case studies, the large-scale circulation was consistently dominated by the NAO- regime, with high probabilities above climatology forecast for HRP occurrence during the high-impact periods. Within the framework (Figure 5.1), this corresponds to the initial identification of a high-risk synoptic set-up, providing an early heads-up of a potentially disruptive period. In all case studies, confidence in the dominant HRP increased as the lead time shortened. For case study 1 and 2 at a 10-day lead time, there is ~70% probability that a HRP will occur on the high-impact day,

increasing to 100% probability at a 3-day lead time. This level of confidence would provide a clear signal for decision-makers to transition from a heads-up phase to active preparation.

The dominance of HRPs, particularly WP27, reflects a persistent blocking configuration associated with cold-air advection over the UK. As noted by Pope *et al.* (2021), WP27 is characterised by a pressure anomaly pattern that promotes the advection of very cold air and the potential for snow showers over eastern regions of the UK. This highlights that while HRPs are defined primarily through CD event occurrence they can still support localised CW conditions where cold air interacts with moisture-bearing flows. Therefore, the absence of CW signals in the HRP composites does not preclude their occurrence on individual high-impact days but rather reflects their greater spatial variability.

For the final case study there is an accurate probability (0%) that an HRP will occur as WP16 occurred on that high-impact day. However, the preceding days were characterised by persistent HRPs, which would still trigger earlier stages of the framework and indicate a period of elevated risk. This emphasises the importance of temporal sequencing within the framework, where persistent HRPs in preceding days may influence impacts even if the event day itself does not meet HRP criteria. As shown by Mattu *et al.* (2026), such sequencing can prolong impacts under persistent conditions, reinforcing the need for decision-making to consider both the event day and preceding risk signals.

Generally, the ECMWF model-derived spatial probability forecasts captured the broad location of compound cold events when compared with HadUK-Grid observations (Figure 5.1, stage 3). This was particularly evident for CD event occurrence, where the dynamic footprint forecasts showed strong and spatially coherent probability signals. High probabilities were often observed alongside clear spatial structure indicating consistency in both the likelihood and location of CD event occurrence. This behaviour reflects the established relationship between compound cold events and anticyclonic weather patterns within NAO- regime. This physical consistency between large-scale circulation and surface conditions provides a source of

predictability that is captured by the forecasting framework. Previous studies (Hall and Hanna, 2018; Mattu *et al.*, 2025) have shown that NAO- regime conditions bring cold and dry weather to the UK, with persistent high pressure supporting snow retention and limited thaw. The strong CD event signals observed in the spatial forecasts are therefore consistent with the high probabilities of HRPs identified at the synoptic stage of the framework, where prolonged anticyclonic conditions are present. It is important to note that the case studies examine here represent high-impact events and are therefore associated with particularly strong and persistent signals in both the HRP and spatial forecasts. As such, the high probabilities observed in the CD forecasts are not unexpected but instead reflect the selection of events characterised by large-scale atmospheric drivers.

In contrast, CW events exhibit weaker and more variable signals in the dynamic footprint forecasts (Figure 5.1, stage 3). This likely reflects both the conditional rarity of CW events (Section 5.4.2) and the inherent challenges of representing precipitation in medium-range forecasts. Accurate rainfall forecasting requires the use of a higher resolution model that can capture both frontal rain and rain associated with convective processes (Becker, Bechtold and Sandu, 2019). However, it is important to consider that decision-makers may already have access to rainfall forecasts from higher-resolution models at shorter lead times. In this context the added value of the framework proposed here lies in the early identification of elevated risk through the HRP forecasts. While uncertainty in precipitation increases with lead time, the persistence and predictability of weather patterns provide a more stable signal at extended lead times. Within the framework (Figure 5.1), HRP forecasts therefore act as an early heads-up of conditions conducive to compound cold events, even when the precise location and intensity of precipitation remain uncertain. The dynamic footprint forecasts then provide additional spatial detail as lead time decreases. Together, these components enable a progression from early awareness to more targeted preparation, enhancing decision-making beyond what would be possible using rainfall forecasts alone.

Taken together, these results demonstrate the value of combining circulation-based predictability with dynamically evolving surface-level forecasts. Each step of the

framework provides progressively refined insight that can support the decision-making process. The regime-level forecasts provide useful foresight as they present an indication as to whether there may be a period of heightened risk. In this context, probabilistic uncertainty remains informative in a risk-based forecasting context. Possessing forecast information alone does not always guarantee that action will follow. Da Costa *et al.* (2026) underscore the importance that institutions are enabled to interpret probabilistic forecasts as actionable signals. This speaks to the increased lead time available with the HRP forecasts. At a 15-day lead time this forecast can begin to signal if a period of heightened risk may be approaching and thereby increase response capability (Šakić Trogrlić *et al.*, 2022). Da Costa *et al.* (2026) elaborate on this, noting that this kind of awareness is especially useful in situations when deterministic thresholds have not yet been exceeded. The HRP forecast hence provides a heads-up of what *could* occur. Leveraging these forecasts lends itself to a flexible system that prioritises early decision-making based on consistent risk-indicators (high probability of HRP occurrence), rather than waiting for formal confirmation of hazard occurrence (Da Costa *et al.*, 2026). Furthermore, the HRPs also give a spatial indication of where compound cold events are most likely to occur under those given conditions. Historically in Scotland snow-, rain-, and wind-related hazards have resulted in the highest number of incidents being reported in winter (Mattu *et al.*, 2026). The ability to identify where these events are most likely to occur at lead times of up to 15 days gives decision-makers valuable lead time to coordinate anticipatory action and highlights the added temporal value of the framework.

The proposed framework offers a solution to some of the most difficult challenges associated with predicting impacts that typically arise from the need to incorporate local environmental and societal variables, to consider compounding and cascading events and to utilize a diverse set of data sources (Reichstein *et al.*, 2025). To address these challenges the framework has used a location-specific percentile methodology for calculating compound events (Mattu *et al.*, 2025), utilised an impact dataset from Network Rail that by its nature incorporates elements of vulnerability and exposure which leads to the HRPs already leveraging this information in their presentation, and has considered the sequential nature of compound events (Mattu *et al.*, 2026).

This study demonstrates how a forecasting framework can be developed to support impact-based forecasting for specific hazards and infrastructure systems, in this case compound cold events and the Scottish rail network. By integrating impact data, synoptic-scale weather pattern forecasts, and dynamic compound cold event probabilities, the framework provides a structured approach to linking large-scale circulation to localised impacts. This study has also detailed the value in combining a range of lead times and forecast types to enable better decision-making by providing a heads-up and ground-level knowledge of the associated impacts.

As with any forecasting framework, this study is subject to methodological assumptions, which are common to compound event and impact-based forecasting approaches. The current study builds on assumptions established in Mattu *et al.* (2025) regarding the definition of compound event indices and in Mattu *et al.* (2026) in relation to the Network Rail impact dataset used. The framework is constrained by the quality of the impact data used. There may be a disparity between when an incident occurred and when it was reported, introducing uncertainty in the temporal alignment between the causal hazard and the recorded impact. This limitation is examined in detail in Mattu *et al.* (2026).

CW event occurrence is largely absent from the modal composites used to define HRPs, and where present in the case studies exhibits considerable spatial variability. This contrasts with CD events which display more spatially coherent and persistent patterns. This disparity highlights a key challenge in applying weather pattern-based approaches to compound events. While the MO30 classification has demonstrated skill in representing large-scale circulation conducive to temperature-driven extremes, its ability to capture the localised and transient nature of precipitation associated with CW events appears more limited. This is reflected in both the weaker forecast signals for CW events and the absence of CW-dominated HRPs within the historical analysis. The conditional nature of CW events that requires both low temperatures and high precipitation further compounds this challenge, as it depends on the interaction between large-scale circulation and smaller-scale processes that may not be well resolved within the classification framework. These findings suggest that while the HRP-based approach provides a robust foundation for identifying CD-related risks,

additional refinement may be required to better capture CW events. Addressing the limitation represents an important avenue for future work, particularly given the potential for CW events to generate highly disruptive yet spatially heterogeneous impacts on infrastructure systems.

A key priority for future work is a comprehensive assessment of forecast skill across a larger sample of events. This framework demonstrated here is based on a small number of high-impact case studies, and while these provide valuable insight into its potential application, a systematic evaluation is required to determine its robustness and reliability. Building on this, future developments could enhance the framework capabilities by incorporating high-resolution model output at a 2-day lead time. Ideally this would be presented as a seamless blend with the coarser resolution model and follow on from the current dynamic CD/CW footprint forecasts. Including a higher resolution model would provide clarity on the probability and location of CW events which could lead to better decision-making outcomes. An expansion of the current framework could include a “best case” and “worst case” scenario for the dynamic CD/CW event footprints by showing ensemble member outliers and the ensemble median; here we have used the ensemble average to demonstrate the probability. The resulting interface could then give the user additional information on how the forecast event may unfold. Such information may be particularly valuable for risk-averse operational decisions where low-probability, high-impact outcomes must be considered. Depending on the desired application, future iterations of this framework could use variable thresholds when calculating CD/CW events dependent on the exposure and vulnerability of the given location.

While demonstrated here for compound cold events and the Scottish rail network, the framework is fundamentally transferable. The methodology could be extended to other compound hazards and sectors, including heat- and precipitation-related impacts on rail infrastructure, as well as applications in energy, transport and public health. This study therefore provides a practical and scalable pathway for integrating compound event science with operational impact-based forecasting systems to enhance preparedness for high-impact weather.

5.8 Conclusions

This study demonstrates how impact data can be used to identify high-risk weather patterns associated with compound cold events and to translate large-scale atmospheric predictability into actionable, impact-focused forecast information. By integrating rail incident records from Network Rail with HadUK-Grid observations, MO30 weather pattern classifications and ECMWF ensemble forecasts, a tiered forecasting framework has been developed that spans from synoptic-scale foresight to localised, dynamic compound event probabilities. The application of the framework to three high-impact case studies of severe disruption on the Scottish rail network provides a robust, real-world demonstration of its capability, reinforcing confidence in its ability to capture both the timing and spatial characteristics of compound cold events.

This framework provides a pathway for linking large-scale circulation to sector-specific impacts. Weather pattern forecasts offer an early indication of periods of heightened risk, often with high confidence up to 10 days in advance, while dynamic compound cold event footprints refine this signal by identifying where impacts are most likely to occur. Together, these complementary components demonstrate how probabilistic forecast information can be translated into progressively more actionable insight, supporting anticipatory decision-making rather than reliance on single-hazard or deterministic thresholds.

The findings from this study advances the integration of compound events science, weather pattern analysis, and impact-based forecasting demonstrating how these components can be combined to improve preparedness for low-frequency, high-impact weather events and support more effective decision-making across critical infrastructure systems.

Chapter 6 DISCUSSION

6.1 Significance and wider implications of the results

6.1.1 Compound cold events as operationally critical hazards

The research was motivated by two related gaps identified in the background literature (Section 2.6): the limited understanding of compound events in the UK, and the separation between research on compound event occurrence, weather pattern analysis and impact-based forecasting. This thesis addresses these gaps by progressing from the characterisation of compound cold events, through examination of their relationship with sector-specific impacts, to the development of an impact-based forecasting framework. The findings presented here therefore demonstrate how understanding an understudied compound hazard can be progressively translated from hazard characterisation, through impact relevance, towards forecasting information. This progression is important for decision-making as it provides a pathway towards generating information at lead times that can support preparedness for high-impact weather events.

In a warming climate, cold extremes are expected to become lower-frequency but potentially high-impact hazards. To address RQ1 (Table 1.1), Chapter 3 evidences the historical occurrence of compound cold events across the UK using high-resolution (5 km) gridded climate observations and a percentile-based methodology to account for regional climatological variability. Temporally, both CD and CW events exhibit substantial interannual variability but show an overall decline in frequency from 1960 to 2023, particularly from the 1990s onwards, as demonstrated by the five cities (Figure 3.2). Across all cities, the number of observed CD and CW events decreases in the period 1960-2022, consistent with other studies on compound cold events (Vyshkvarkova and Sukhonos, 2022; Li *et al.*, 2022a; Li *et al.*, 2022b; Wu *et al.*, 2019; Qian *et al.*, 2014).

Despite their decreased frequency, compound cold events are still high-impact weather events that have significant impacts across society and infrastructure

including public health, energy and transportation systems. Consideration of such events should be built into weather resilience and climate change adaptation plans as the reduced frequency of these events does not necessarily translate into reduced risk. Current climate change adaptation policy in the UK often prioritises hazards projected to increase in frequency such as extreme precipitation (Burnett, 2023). However, sector-specific adaptation strategies adopt a more risk-based perspective. For example, Network Rail's *Scotland's Railway Climate Ready Plan* (2024b) explicitly acknowledges that while cold weather hazards such as frost and snow are projected to decline in frequency, they will continue to occur and retain the potential to cause significant disruption.

Historical events reinforce this perspective. The winters of 2010 and 2018 demonstrate how compound cold events can act as high-impact low-frequency hazards bringing widespread snow-related impacts including travel disruption, school closures and weather-related deaths (Prior and Kendon, 2011; Galvin, Kendon and McCarthy, 2019). This is reflected in Figure 3.2 with western cities of Belfast, Glasgow and Plymouth seeing a sharp rise in CD events in 2010 compared to relative years. More recently, in January 2026, Scotland experienced extreme snowfall described as "comparatively unusual, particularly in the UK's warming climate" (Kendon, 2026). This event led to communities being isolated, school and college closures, and suspension of flight operations at Aberdeen airport (Kendon, 2026). These examples highlight that declining frequency does not equate to reduced risk and underline the importance of incorporating cold-related hazards into climate resilience and adaptation planning for critical infrastructure systems.

To address RQ3 (Table 1.1), Chapter 4 provides evidence of the operational significance of CD and CW events by examining their coincidence with disruptive rail incidents in Scotland. Using two impact metrics, compound cold events were found to coincide with 88% of weather-related high-impact days (in October to March 2006 to 2023) when defined by total incident count, and 50% of high-impact days when defined by accumulated delay minutes. This indicates that compound cold events are a dominant driver of frequent disruption, while other hazard types may contribute to more widespread but less frequent network-wide impacts.

The findings also highlight several complexities in defining and characterising compound cold events. First, the identification of an event is sensitive to the thresholds used to define the variables of minimum temperature and precipitation. The percentile-based approach adopted in this thesis accounts for regional climatological variability but means that the same meteorological conditions may not be classified as a compound event across all locations. Second, temporal resolution introduces an important limitation. At a daily resolution the co-occurrence of low temperature and heavy precipitation is identified within the same daily window and does not confirm that the two hazards occurred simultaneously. The specific sequence of precipitation and low temperature within a CW event therefore cannot be resolved using the available data.

The results further demonstrate the importance of temporal sequencing of individual compound events. The November-December 2010 case study illustrates this clearly (Figure 4.4), where a CW event preceded several days of persistent CD conditions, during which the absence of thawing allowed the impacts of the initial snowfall to persist. This sequence resulted in one of the most severe disruption periods in the dataset (Figure 4.2). The peak in reported incidents occurred after the initial hazard (CW event), highlighting a temporal lag between hazard occurrence and realised impact. This suggests that the operational significance of a compound cold event may depend not only on whether individual hazards meet their respective thresholds but also on their sequencing, persistence and antecedent conditions. Similarly, CD events may occur in temporal clusters meaning that the impact of an individual day can be influenced by conditions occurring before and after it.

Another complexity concerns spatial extent. The spatial distribution of compound cold events varies considerably with CD conditions generally more widespread across Scotland and CW conditions spatially constrained, reflecting the spatial climatological patterns identified in Chapter 3 (Figure 3.1). This spatial structure suggests that disruption is driven not only by hazard intensity but by the interaction between hazard occurrence and network exposure. In particular, the concentration of rail infrastructure in the Central Belt, between Glasgow and Edinburgh, likely amplifies the impacts of hazards occurring in this region, as a greater proportion of the network is exposed to

these conditions. Compound cold events therefore represent operationally critical hazards for the rail sector, particularly where sequential hazards can generate persistent or compounding disruption. This temporal complexity adds a layer of difficulty with forecasting, as the potential impact of an event may depend not only on the occurrence of compound cold events but on their sequence and persistence. Chapter 5 then addresses RQ5 (Table 1.1) by proposing a solution to this challenge through a tiered forecasting approach (Figure 5.1) that would give decision-makers an insight to the sequencing of compound cold events. Taken together, these findings highlight that compound cold events remain operationally significant hazards despite their declining frequency, and that their sequencing and predictability is critical for effective infrastructure resilience planning.

6.1.2 Moving from hazard severity to impact relevance

Using compound cold events, this thesis demonstrates why a paradigm shift from hazard-centric to impact-centric forecasting is necessary when considering high-impact weather events. Additionally, the findings presented in this research support a shift towards impact-led risk assessment. It may not always be the most meteorologically severe hazards that lead to the most significant impacts, but rather the joint occurrence of two meteorologically moderate extremes (van der Wiel *et al.*, 2020). This strongly aligns with the increasing academic and policy-driven focus on compound events (Jaroszweski, Wood and Chapman, 2021) where the joint occurrence of two or more hazards can be more impactful than the sum of their parts (Zscheischler *et al.*, 2018). Chapter 4 reflects this through the analysis of an impact dataset from Network Rail in which an impact-driven approach was applied to identify the most consequential weather patterns, rather than using the most extreme hazards and then analysing the associated impacts.

These findings reinforce the principles of impact-based forecasting, where the focus shifts from predicting meteorological elements in isolation to anticipating the societal consequences of weather events. The example provided in Chapter 4 is a key finding for RQ3 (Table 1.1) which demonstrates how incorporating impact data can reshape

hazard understanding, revealing that moderate meteorological conditions can contribute disproportionately to overall network disruption.

For interconnected infrastructure systems such as rail networks, the persistence of disruption may therefore depend less on the magnitude of a single hazard and more on the sequencing of meteorological conditions that prevent response and recovery processes. This also raises the possibility that the impacts of subsequent events may be influenced by the effects of preceding events through mechanisms such as failure harvesting (Ferranti *et al.*, 2016). This occurs when vulnerable components fail during an initial event and are subsequently repaired or replaced. The concentration of high-impact days within the December 2009 – January 2010 and November – December 2010 periods (Figure 4.2) demonstrates the potential importance of considering temporal dependencies. However, the available impact dataset does not contain sufficient asset-specific information to determine whether earlier failures affected subsequent network vulnerability.

6.1.3 Using weather patterns as a bridge to predictability

A central theme of this thesis is the use of weather pattern analysis as a mechanism for translating large-scale atmospheric predictability into information relevant for impact-based forecasting. This addresses RQ2 and RQ4 (Table 1.1) by examining the relationship between large-scale atmospheric circulation, compound cold event occurrence and observed impacts on the Scottish rail sector. This thesis builds on previous research demonstrating that compound events are modulated by large-scale atmospheric circulation (D'Errico *et al.*, 2022; Bloomfield *et al.*, 2024; Sanuy *et al.*, 2024), while extending this approach by considering how circulation patterns relate not only to compound cold event occurrence but also to sector-specific impacts. These relationships provide a basis for exploiting the extended predictability of large-scale circulation within an impact-based forecasting framework, which is explored through RQ5 (Table 1.1) in Chapter 5.

The MO30 weather patterns were selected for analysis in this thesis over broader circulation regime classifications (e.g., Michelangeli *et al.*, 1995; Cassou, 2008) due to their UK-specific domain and greater number of patterns which allow for a more

nuanced representation of day-to-day variability relevant to local-scale impacts. While larger-scale regime classifications may offer slightly extended predictability, the MO30 weather patterns enable a more detailed linkage between circulation and surface-level hazard occurrence, making it better suited to capturing the spatial characteristics of compound cold events.

To answer RQ2 (Table 1.1), Chapter 3 demonstrates a clear relationship between compound cold event occurrence and large-scale atmospheric circulation over the period 1960 to 2022. CD events are predominantly associated with anticyclonic weather patterns, with the strongest signal arising from weather patterns associated with the negative phase of the NAO. The anticyclonic nature of many of the weather patterns within the NAO- regime that typically bring clear skies, stable conditions and sustained low temperatures conducive to CD event occurrence are prone to persistence and can therefore enable temporal compounding of CD events over a number of days. This finding is relevant for public health applications as 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. In contrast, CW events are associated with a broader range of weather patterns and exhibit greater spatial variability. These events are primarily linked to cyclonic regimes, particularly the NAO+ regime which is known to bring wet and windy conditions to the UK (West, Quinn and Horswell, 2019). Unlike CD events, CW events are driven by transient low-pressure systems, which limits their persistence and contributes to their lower overall frequency. Together these findings establish that compound cold events are strongly modulated by large-scale circulation regimes thereby providing a physical basis for predictability.

However, within each regime there is considerable circulation variability, therefore the exact weather patterns of interest may depend on the location that impact information is required for across the UK. For example, although NAO- is predominantly comprised of anticyclonic weather patterns (i.e., 6, 9, 25, 27), some are cyclonic (i.e., 11, 28) or unbiased (i.e., 19) in nature. The synoptic set up of weather pattern 27 within the NAO- regime is conducive to conditions that advect cold air over the UK and can result in snowfall in eastern regions (Pope *et al.*, 2021). As a result, this

pattern can give rise to both CD and CW events depending on the geographical location within the UK and the availability of moisture. This is evident in Figures 5.5 and 5.7, where both CD and CW events are forecast to occur under WP27. The observations verify that both events did occur under the same weather pattern in different regions of the country. This spatial variability provides an explanation for the lack of a CW signal in the HRP composites (Figure 5.3), as CW events are more spatially heterogeneous and dependent on smaller-scale processes.

To address RQ4 (Table 1.1), Chapter 4 extends the circulation analysis from compound event occurrence to observed disruption on the Scottish rail network. Building on previous studies that have linked historical hazard occurrence to the MO30 classifications (Neal *et al.*, 2018a; Richardson *et al.*, 2018; Brown *et al.*, 2019; Richardson *et al.*, 2020; Wilkenson and Neal, 2021a; Harrison *et al.*, 2022b; Souto *et al.*, 2024; Little *et al.*, 2026), Chapter 4 demonstrates a clear and systematic relationship between large-scale circulation patterns and rail impacts in Scotland. Substantial variation is observed in both the frequency and type of incidents across the MO30 weather patterns (Figure 4.6). The results demonstrate that different circulation regimes are associated with distinct incident types, with anticyclonic NAO- regime conditions favouring snow-related disruption and cyclonic NAO+ regime conditions favouring wind- and flooding-related incident types. This reflects the underlying physical drivers of each regime, with the NAO- regime associated with cold and stable conditions conducive to snow accumulation and, importantly, the persistence of snow cover. While some snowfall may still occur under these conditions, the results suggest that many snow-related incidents arise not solely from active snowfall but from prolonged presence of snow and ice on the ground. This is consistent with the dominance of CD conditions during high-impact periods which act to preserve hazardous surface conditions following preceding snowfall events associated with earlier CW event conditions.

The results also demonstrate the importance of considering both the frequency and conditional probability of impacts. WP27, within the NAO- regime, is associated with the highest number of reported incidents, of which 86% are attributed to *severe snow*. Of all the WP27 days within the study period, 37% were associated with a severe

snow incident. Although WP27 contributes to the greatest number of *severe snow* incidents, WP28 exhibits the highest conditional probability of *severe snow* occurrence (42.7%), illustrating that weather pattern frequency and conditional probability provide complementary measures of disruption potential. More broadly, multiple patterns within the NAO- regime show a strong dominance of snow-related incidents, with several patterns (including WP19, WP25, WP27, and WP28) attributing over 50% of incidents to severe snow. In contrast, weather pattern 20, within the NAO+ regime, is associated with the highest number of incident days (967 incidents across 129 incident days) and is dominated by wind- and precipitation-related incident types. Across the NAO+ regime multiple patterns attribute over 30% of incidents to high wind and over 20% to flooding-related incidents. Consistent with this, weather patterns within the NAO+ regime exhibit some of the highest hit rates for wind- and flood-related incidents, i.e. 58.7% for weather pattern 20 and 50.1% for weather pattern 26. The consistency of these relationships across multiple weather patterns highlights the potential to use large-scale circulation as a forecasting tool, providing a pathway for anticipating infrastructure disruption based on forecast weather pattern occurrence.

6.1.4 Translating science into operational forecasting

This thesis demonstrates a pathway from cold-weather hazard characterisation towards operational forecasting by progressing from event characterisation (Chapter 3) to impact assessment (Chapter 4), and finally to the construction of a forecasting framework (Chapter 5) by answering the research questions posed in Table 1.1. The aim has been to build on previous work within the research areas of compound events, weather patterns and impact-based forecasting to demonstrate how an end-to-end hazard assessment can be developed with specific application to sector-specific decision-making. Many studies focus on a single component of this chain – be it the hazard (Zscheischler *et al.*, 2018), the impact (Noone *et al.*, 2025), or the forecasting element (Coughlan de Perez *et al.*, 2015). This is consistent with recent findings that impact-based forecasting systems remain largely hazard-specific and struggle to account for interacting multi-risk events (Lumbroso *et al.*, 2025). In contrast, this thesis links all three elements through the use of weather pattern

analysis as a common framework. This provides a methodological strategy for advancing impact-based forecasting of compound hazards, responding to recent calls for integrated multi-hazard approaches (Van den Hurk *et al.*, 2023; Reichstein *et al.*, 2025).

By addressing RQ5 (Table 1.1), Chapter 5 exploits this potential by developing a set of high-risk weather patterns (HRPs) (Figure 5.3) that are specific to disruptive compound cold event occurrence on the Scottish rail sector and demonstrates how they can enable anticipatory action. Central to the forecasting framework is the identification of high-risk weather patterns (HRPs), specifically weather patterns 19, 27, and 28 (Figure 5.3) from the MO30 (Figure 2.3), which are consistently associated with widespread cold-dry conditions and elevated disruption risk. Additionally, these patterns display an elevated conditional probability for the occurrence of snow-related rail incidents (Figure A2.3 in Appendix 3). Cold-dry events are chosen as the focus here due to their persistence, and therefore largest potential for predictability in an IbF framework. The HRPs provide an early indication of heightened risk at extended lead times, forming the first tier of the forecasting framework (Figure 5.1, question 1 and 2).

Chapter 5 demonstrates how the findings of Chapter 3 and 4 could be used in an operational setting through identifying periods of heightened risk for the Scottish rail network to address RQ5 (Table 1.1). The framework was designed this way rather than identifying single points of failure as having a high-level awareness of risk at an increased lead time allows for advanced preparatory decision-making (Šakić Trogrlić *et al.*, 2022). This aligns with how infrastructure operators make decisions in relation to resource allocation and staff readiness when there is a risk of a high-impact weather event. Due to the interconnected nature of the rail network, anticipating risk windows is more useful than pinpointing exactly where failures may occur, particularly at longer lead times where uncertainties are greater and the spatial and temporal characteristics of an event are prone to evolve.

The results demonstrate that forecasting value emerges from combining complementary sources of predictability rather than relying on a single forecast

product, consistent with the principles of ensemble-based forecasting (Mylne *et al.*, 2025). The framework is presented in a tiered format (Figure 5.1) to further support different levels of decision-making, with the HRP forecast designed to support decisions at an extended lead time of up to 15 days ahead and give an overview of the synoptic situation (i.e., windows of risk). The dynamic footprints are then valuable when an HRP is confirmed by adding spatial specificity to the pattern-based signal, enabling the identification of regions most likely to experience CD and CW events, i.e. event likelihood. This reflects broader findings that large-scale circulation provides a source of extended predictability, while local-scale detail emerges closer to the event (Ferranti *et al.*, 2015). This demonstrates how forecasting should be viewed as a suite of complementary, ensemble-derived information, rather than a single deterministic prediction as the different forecast products serve different decision horizons.

While this thesis focuses on compound cold events and their impacts on the Scottish rail sector, the methodology presented here could be applied to other relevant compound hazards and sectors, such as compound wind-rain events (Manning *et al.*, 2024; Bloomfield *et al.*, 2024). The current framework could be extended to include compound hot events by following the methodology used for hazard characterisation, subsequent impact analysis and identifying associated HRPs for integration into the forecasting framework. Heat-related impacts on rail infrastructure are strongly influenced by both large-scale circulation and local persistence, making them well suited to a weather pattern approach. The core idea presented here of linking large-scale circulation to hazard clustering and then to infrastructure vulnerability aligns with emerging multi-risk frameworks that seek to integrate hazards, exposure and vulnerability within operational forecasting systems (Van den Hurk *et al.*, 2023). Taken together, the results demonstrate how linking atmospheric circulation, compound hazard occurrence, and sector-specific vulnerability can provide a practical pathway for advancing impact-based forecasting in complex infrastructure systems.

6.2 Assumptions and limitations

This thesis brings together three research areas (compound events, weather patterns, and impact-based forecasting). To achieve this integration, there are assumptions

and limitations of this work which are detailed in each of the science chapters (3, 4 and 5). These are discussed below.

The first assumption made in this thesis and carried throughout chapters 3, 4 and 5 pertains to the definition of compound cold events in time and space. Within the compound events literature there are several approaches to defining compound events varying both spatially and temporally. Some studies consider a compound event to be the co-occurrence of extreme hazards within the same month or season (Hao, AghaKouchak and Phillips, 2013; Wu *et al.*, 2019; Wu *et al.*, 2021a; Peng *et al.*, 2023) whereas others consider the co-occurrence at a daily timescale (Vyshkvarkova and Sukhonos, 2022; Polychroni *et al.*, 2026). This challenge is widely acknowledged in the literature as many studies apply their own compound event definition relevant to their study (Bevacqua *et al.*, 2021; Brett *et al.*, 2024). This extends to the spatial definition of compound events in terms of where the extreme hazards co-occur geographically. For temperature and precipitation joint occurrence a range of spatial resolutions have been employed from ~11 km (Doshi *et al.*, 2023) to ~55 km (Wu *et al.*, 2021a), where both variable thresholds must be met within the same grid cell to qualify as a compound event. Most of the aforementioned studies have sought to identify compound events for hazard attribution and predictability purposes. This thesis aims to build on hazard characterisation and predictability while also considering providing information relevant for local operational implementation. This decision was primarily inspired by how the UKHSA operate their weather-health alerting system (UKHSA, 2024), which originally used a static temperature threshold but now considers local climatic differences to account for the different climatology across England (Roberts *et al.*, 2022).

The second assumption this thesis worked to is the choice of compound cold event indices. The decision to use the chosen indices of $\leq 15^{\text{th}}$ percentile of minimum temperature and $\leq 15^{\text{th}}$ percentile of precipitation for cold-dry and $\leq 15^{\text{th}}$ percentile of minimum temperature and $\geq 85^{\text{th}}$ percentile of precipitation is discussed in detail in Chapter 3. Given that a high-resolution dataset of 5 km was being used, significant sensitivity analysis was undertaken to appoint indices which represented locally relevant compound cold events across the entirety of the UK (Figure A1.1, Appendix

1). Previous studies have used quantiles of the 25th and 75th percentiles (Beniston, 2009; Vyshkvarkova and Sukhonos, 2022), but this thesis sought to characterise more extreme events. The chosen indices were found to provide a moderate extreme of temperature and precipitation whilst also providing a sufficient number of data points for analysis. This approach of using a high-resolution dataset coupled with the chosen indices provides a highly localised characterisation of compound cold events in the UK that considers how variables are influenced by topography, proximity to bodies of water, and terrain.

The analysis presented in this thesis is informed by impact data acquired from Network Rail (Chapters 4 and 5) therefore the output is limited by the quality of the data supplied. Chapter 4 discusses the assumptions and uncertainties of working with impact data that has not been recorded for the reason it has been used for in this context. The main limitation associated with this piece of work is the temporal mismatch between the reporting date and incident date of the rail incidents. In Chapter 4, relationships are drawn between the occurrence of rail incidents and presiding weather patterns and the occurrence of compound cold events. The date used for analysis is the incident report date; however, there is no way to confirm if this is truly the day that the incident occurred as there may be a delay between the incident occurring and the reporting date. As the weather patterns fluctuate on a daily timescale this limitation could significantly impact the results. However, this limitation is likely to be less pronounced for CD events, which are often associated with persistent high-pressure systems. In such cases the prevailing weather pattern and surface conditions may remain relatively stable across consecutive days therefore reducing the sensitivity of the results to any temporal offset in reporting. Despite this, the limitation remains important especially for transient conditions, such as those conducive to CW events, and cannot be resolved given the current structure of the dataset and associated reporting procedures.

Other considerations in this thesis include forecast and model limitations. This is specifically pertinent to Chapter 5 where the ECMWF medium range ensemble model has been employed to produce compound cold event forecasts at a 10-, 5-, and 3-day lead time. The results are bound to the spatial resolution of the model (re-gridded

to 22 km to account for changing resolution since 2010) and therefore precipitation processes are less well represented at this resolution. This likely contributes to the weaker cold-wet event signal compared to cold-dry events.

Finally, the forecasting framework proposed in Chapter 5 assumes that: (1) the end-user possesses an institutional capacity to interpret the forecast probabilities and associated uncertainties output, (2) there is a willingness for anticipatory action, and (3) integration into existing operational workflows is possible.

6.3 Recommendations for future research

This research demonstrates hazard characterisation, links to impacts and how a forecasting framework might operate. Future research priorities emerging from the foundations laid in this thesis relate broadly to (1) extending compound events science, (2) enhancing forecast system capabilities, and (3) operational integration of compound events into impact-based forecasting as follows:

1. **Expanding compound hazard types.** This research has focused on compound cold events, but the methodology presented here can be applied to other compound hazard types. Other combinations of temperature and precipitation (hot-dry, hot-wet) could be analysed using the same methodological set-up demonstrated here. Future research could also add an additional hazard such as wind to investigate compound cold-wet-windy events; however, it is noted that this would require a long historical period to maintain enough extremes for rigorous statistics.
2. **Application to other sectors.** The focus of this thesis is compound cold event impacts on the rail network in Scotland. The methodology that has been developed here has been done so with the future application to other sectors in mind. In the early development stages of the current research the health sector was strongly considered as a point of interest. Several epidemiological studies exist that investigate the health impacts associated with cold events (Rudge and Gilchrist, 2007; Charlton-Perez *et al.*, 2019; Psistaki, Paschalidou and McGregor, 2020) and some that explore the relationship between health outcomes and large-scale circulation patterns (Huang *et al.*, 2022). The

volume of available literature on the health sector therefore provided a viable starting point to investigate the health implications associated with compound cold events. However, this was ultimately not pursued due to difficulties surrounding data access. This decision was reached following conversations with health-data experts at the Met Office who indicated that due to the sensitivity and sparsity of health data that specific training had to be undertaken to handle the data. The time constraints associated with the thesis timeline required the use of a readily available dataset. Through conversations with other researchers working within the infrastructure impact space, a relevant rail impacts dataset was identified that was more readily available than the health data. This decision shaped the thesis and focused the research on the Scottish rail network. The methodology proposed here of defining a compound event, establishing its historical and spatial occurrence, relating it to the MO30 and then investigating the relationship to an impact dataset could be applied to other sectors and then used to develop a bespoke impact-based forecasting framework as has been done in this thesis.

3. **Multi-day compound events.** In the context of this thesis, a compound “event” was considered a single day event as the analysis has been carried out at a daily temporal resolution (Chapter 3). Previous studies investigating compound cold events at a daily resolution have similarly defined events on a daily basis (e.g., Vyshkvarkova and Sukhonos, 2022; Polychroni *et al.*, 2026). This approach was therefore adopted to maintain consistency with existing research and provide a clear and comparable first characterisation of CD and CW events across the UK, without introducing the complexity defining event onset, duration and termination. However, multi-day compound events were considered during the development of the methodology and represent an important area for future research. Future work might consider investigating multi-day compound events to better understand the temporal characteristics of compound cold events. This may be specifically useful when considering the dynamics and predictability of compound cold events which have been shown here to be driven by persistent weather regimes such as the NAO- and can last multiple days (Chapter 3). Conversely, cold-wet events tend to be

much shorter-lived so using higher temporal resolution data e.g., hourly, may be more insightful to understanding the joint occurrence of this particular compound hazard.

4. **Forecast system development.** The forecasting framework (Chapter 5) has been designed using a medium range ensemble model with a spatial resolution of approximately 22 km. Future research could incorporate a high-resolution model output at a 2-day lead time to enhance the framework capabilities and enable seamless multi-model blending. Higher resolution ensemble models, such as MOGREPS-UK (UK Met Office Ensemble Forecast Model) (~2 km resolution), are available and offer improved representation of precipitation processes, although only at shorter lead times (up to 5 days). Within the tiered forecasting framework proposed in this study (Figure 5.1), such models could be integrated to complement the medium-range forecasts. For example, coarser resolution ensemble forecasts (e.g., ECMWF ENS) can provide early indication of large-scale circulation and high-risk weather patterns at extended lead times, while higher resolution models can refine the spatial and temporal characteristics of CD and CW event footprints at shorter lead times. In this way, the framework can leverage the strengths of different ensemble systems to provide appropriately skilful information across decision horizons, enhancing its operational relevance.
5. **Verification and user testing.** A critical next step from this work is to explore co-production of the forecasting framework with operational forecasters and end-users such as industry decision-makers. This would enable operator-specific thresholds to be implemented early in the workflow and ensure appropriate action at necessary decision-making trigger points. Co-production would result in a robust forecasting framework that was scientifically sound whilst also being operationally relevant and useful.
6. **Impact datasets as dynamic inputs to forecasting systems.** This thesis has demonstrated how impact data can be used to identify high-risk atmospheric conditions by linking historical impacts to specific weather patterns, which are then exploited within a forecasting framework (Chapter 5). Future work could build on this by continuously integrating new impact data

into the framework, allowing the identification of high-risk patterns and associated compound event characteristics to be iteratively refined over time. In this way, the forecasting system would evolve alongside the impact dataset and become increasingly tailored to observed vulnerabilities within the rail network. This would enable forecast outputs to become more targeted and context-specific therefore moving beyond static definitions of risk towards a more adaptive and impact-informed forecasting approach. Such an approach could also be extended to incorporate cross-sector impact datasets that would support the development of forecasting systems that are responsive to a broader range of infrastructure and societal needs.

7. **Climate change and adaptation.** This work is based on historical occurrence of compound events to deduce the relationship with weather patterns (Chapter 3). Future work could extend this analysis using climate projections to quantify how both compound cold events and their relationship to weather patterns could change in a plausible future climate. Recent studies (e.g., Pope et al, 2021) suggest a projected decrease in winter occurrence of weather patterns within the NAO- regime (including patterns 11, 19, 27, and 28) alongside an increase in occurrence of patterns within the NAO+ regime (including patterns 4, 20, 23, 26, and 30). This implies a potential reduction in compound CD events linked to persistent high-pressure systems, but a possible shift towards more transient and precipitation-driven CW events. While the overall frequent of compound cold events may decline, their characteristics and associated impacts may change. Understanding how these relationships evolve will be critical for infrastructure-specific climate change adaptation planning.

6.4 Concluding remarks

Taken together, this thesis addresses the gaps identified in the background literature (Section 2.6) by bringing together compound event characterisation, climate impact analysis, and impact-based forecasting using the Scottish rail sector as a case study. By addressing the research questions outlined at the outset (Table 1.1), this work advances understanding of compound cold events in the UK, their physical drivers, and their relevance for forecasting impacts on critical infrastructure. The research

demonstrates that compound cold events remain relevant to infrastructure resilience despite their declining historical frequency and that their significance arises not only from the occurrence of individual meteorological extremes but also from their spatial distribution, persistence and temporal sequencing.

This thesis demonstrates that weather pattern analysis can act as a unifying framework linking atmospheric circulation, compound hazard occurrence, and infrastructure impacts. This represents a methodological advance in impact-based forecasting, showing how compound event science can be operationalised to provide earlier and more actionable risk information. More broadly, this work highlights the importance of moving beyond hazard-centric perspectives towards impact-led approaches that account for compound and sequential events. While focused on compound cold events and the Scottish rail network, the framework and methodology presented here are transferable to other compound hazards and infrastructure systems. By leveraging the predictability of large-scale circulation, there is significant potential to enhance early warning systems, support anticipatory action, and improve resilience to high-impact weather in a changing climate.

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APPENDICES

Appendix 1 – Chapter 3 Appendices

Appendix 1 has been submitted as the Supplementary Material of the publication “Characterising cold-dry and cold-wet compound events in the United Kingdom” (presented as Chapter 3 in this thesis).

Table A1.1 Flow description of the MO30 weather patterns. (Richardson et al., 2018)

Weather pattern number	Flow description
1	Neutral north-westerly
2	Cyclonic south-westerly
3	Anticyclonic south-westerly with a ridge over France
4	Neutral westerly
5	Neutral southerly with a centre of high pressure over Scandinavia
6	Anticyclonic with a high pressure centre over Azores
7	Cyclonic south-westerly with a centre of low pressure west-north-west of Ireland
8	Cyclonic westerly with a low pressure centre near the Shetland Islands
9	Anticyclonic with high pressure over Iceland

10	Anticyclonic westerly with high pressure over the Azores
11	Cyclonic with a low pressure centre over southern Britain
12	Anticyclonic south-south-westerly with high pressure over Poland
13	Anticyclonic north-westerly with high pressure over south-west of Ireland
14	Cyclonic north-north-westerly with low pressure centred over southern Sweden
15	Neutral south-westerly
16	Anticyclonic south-south-easterly with high pressure near Denmark
17	Anticyclonic east-south-easterly with a high pressure centre over Denmark
18	Anticyclonic south-westerly with high pressure over northern France
19	Neutral northerly
20	Cyclonic westerly with a deep centre of low pressure near Iceland
21	Cyclonic south-westerly with a deep low south of Iceland
22	Cyclonic southerly with low pressure west of Ireland
23	Neutral westerly with high pressure north of Spain

24	Cyclonic northerly with low pressure centred over the North Sea
25	Anticyclonic northerly with high pressure over Northern Ireland
26	Cyclonic north-westerly with low pressure centred near Norway
27	Anticyclonic easterly with high pressure over the Norwegian Sea
28	Cyclonic south-easterly with low pressure southeast of the UK
29	Cyclonic south-south-westerly with a deep low centre of pressure west of Ireland
30	Cyclonic west-north-westerly with deep low pressure southeast of Iceland

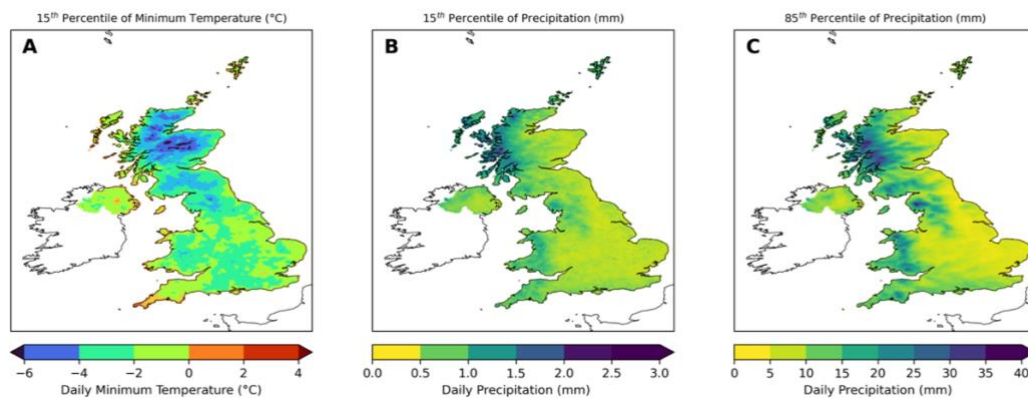


Figure A1.1 Qualifying percentile thresholds for CD/CW events across the UK. From left to right (A) 15th percentile of daily minimum temperature; (B) 15th percentile of daily precipitation; (C) 85th percentile of daily precipitation. Calculated over winter (DJF) for the period 1993-2022 using HadUK-Grid 5km.

Appendix 2 – Chapter 4 Appendices

Appendix 2 has been submitted as the Supplementary Material of the manuscript under review “Compound cold events, impacts, and weather patterns: a case study of the Scottish rail network” (presented as Chapter 4 in this thesis).

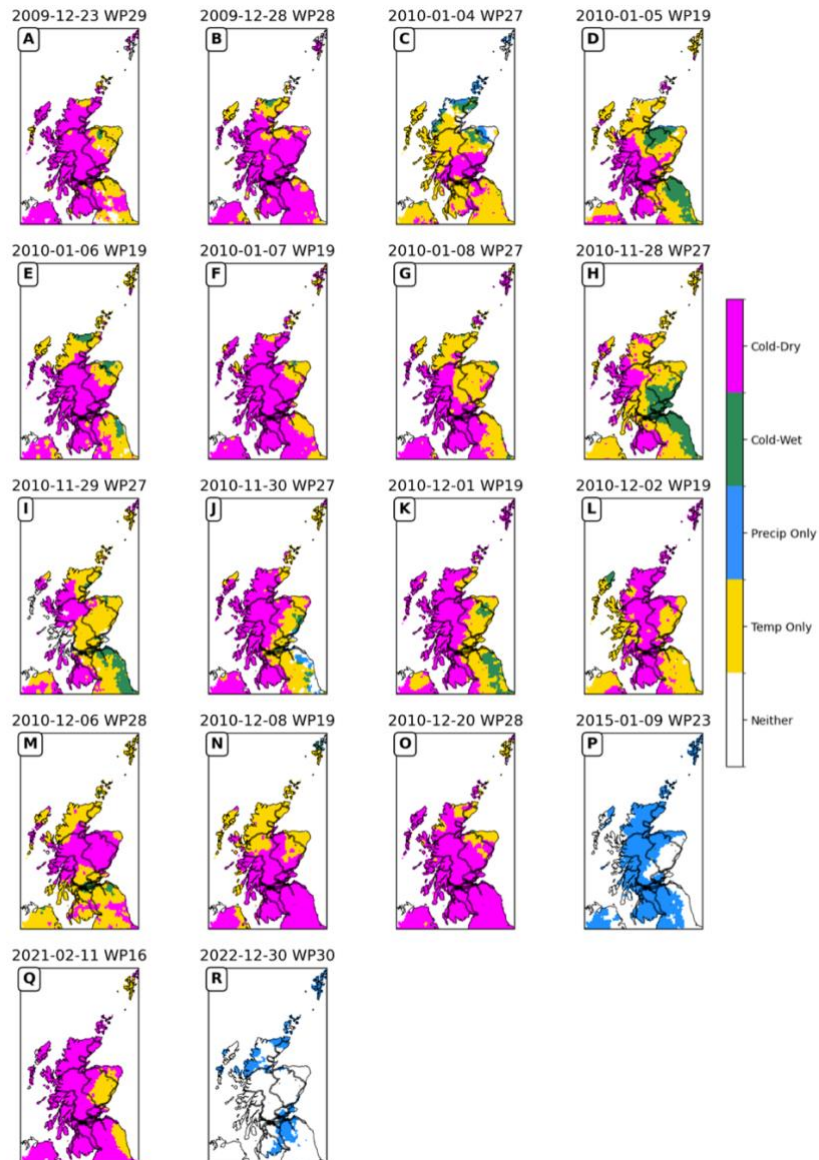


Figure A2.1 High-impact days (by the metric of daily aggregated incident count) showing occurrence of compound CD and CW events and temperature and precipitation threshold (thresholds are noted in Section 2.2.2). The black lines represent the Scottish railway line.

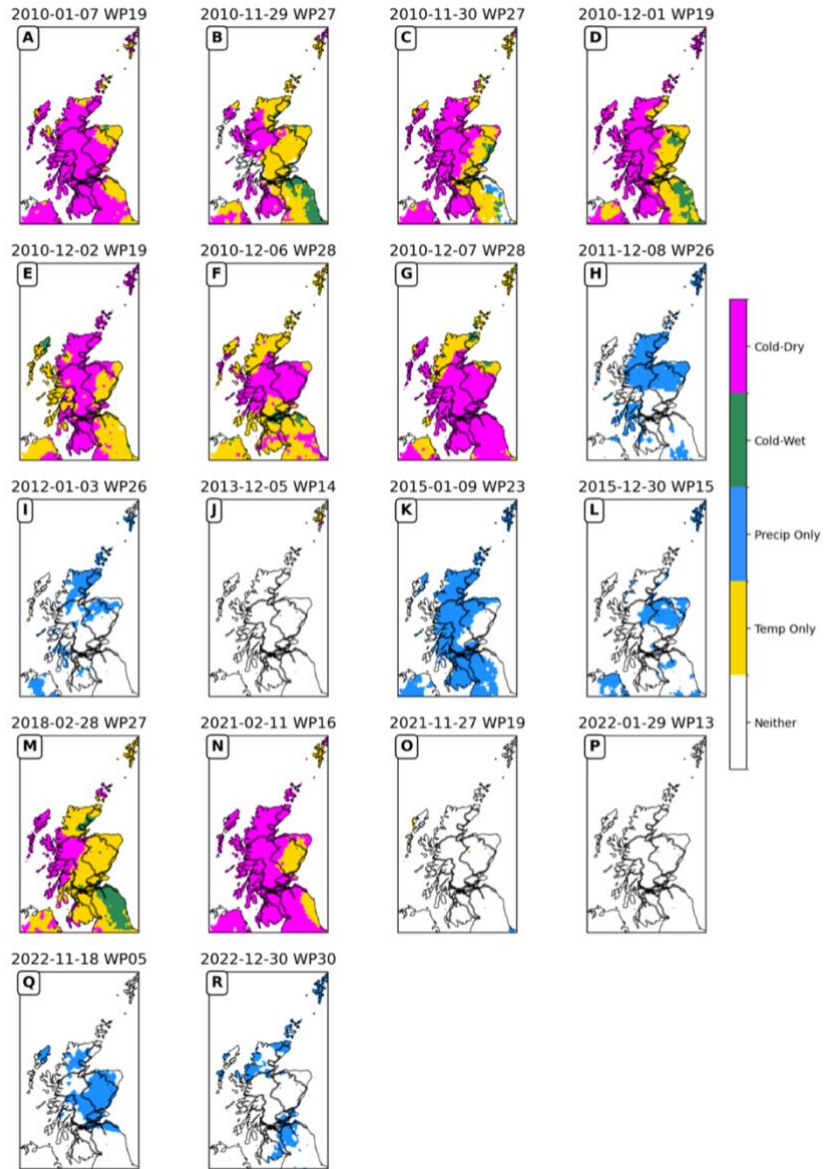


Figure A2.2 High-impact days (by the metric of daily accumulated PfPI minutes) showing occurrence of compound CD and CW events and temperature and precipitation threshold (thresholds are noted in Section 2.2.2). The black lines represent the Scottish railway line.

		All Incidents	FLOODING	FOG/SNOW	HEAT SPEED	HIGH WIND	ICING	INF WEATHR	KRS / BLKT	LIGHTNING	MISC OBS	PNTS SNOW	SEV FLOOD	SEV SNOW	SPL WRKNG	WEATHER
NAO-	WP6	35.90%	6.41%	0.00%	0.00%	6.41%	1.28%	7.69%	1.28%	0.00%	3.85%	7.69%	12.82%	12.82%	0.00%	0.00%
	WP9	43.48%	4.35%	0.00%	2.17%	8.70%	0.00%	2.17%	0.00%	0.00%	6.52%	4.35%	17.39%	21.74%	2.17%	0.00%
	WP11	51.22%	7.32%	0.00%	0.00%	14.63%	0.00%	4.88%	0.00%	0.00%	2.44%	4.88%	19.51%	12.20%	0.00%	0.00%
	WP19	52.14%	2.56%	0.00%	0.00%	7.69%	0.85%	12.82%	3.42%	0.00%	0.85%	11.11%	14.53%	28.21%	0.00%	0.00%
	WP25	36.90%	2.38%	0.00%	0.00%	8.33%	1.19%	10.71%	1.79%	0.00%	4.17%	5.95%	8.33%	14.88%	1.19%	0.00%
	WP27	51.75%	2.63%	0.00%	0.00%	9.65%	2.63%	8.77%	2.63%	0.88%	0.00%	8.77%	7.89%	37.72%	7.89%	0.00%
NAO+	WP28	68.00%	1.33%	0.00%	0.00%	9.33%	2.67%	13.33%	0.00%	0.00%	4.00%	17.33%	8.00%	42.67%	2.67%	0.00%
	WP4	44.44%	5.56%	0.00%	0.00%	30.56%	0.00%	11.11%	11.11%	2.78%	2.78%	2.78%	27.78%	2.78%	0.00%	0.00%
	WP8	59.15%	7.04%	0.00%	0.00%	25.35%	1.41%	4.23%	9.86%	0.00%	7.04%	2.82%	23.94%	5.63%	2.82%	0.00%
	WP20	74.42%	13.37%	0.00%	0.00%	58.72%	0.58%	7.56%	6.98%	2.33%	8.72%	5.23%	31.98%	6.98%	0.58%	0.00%
	WP23	58.15%	8.70%	0.00%	0.00%	39.67%	0.00%	10.33%	3.80%	2.72%	8.15%	4.89%	15.22%	4.89%	1.09%	0.00%
	WP26	75.33%	12.00%	0.00%	0.00%	50.67%	0.00%	16.67%	7.33%	4.67%	8.00%	20.67%	24.00%	19.33%	4.67%	0.00%
NW	WP30	69.68%	13.55%	0.00%	0.00%	49.68%	0.65%	10.32%	7.74%	1.94%	6.45%	7.10%	27.10%	13.55%	1.29%	0.00%
	WP1	45.71%	5.71%	0.00%	0.00%	8.57%	0.00%	11.43%	5.71%	0.00%	5.71%	5.71%	11.43%	11.43%	2.86%	0.00%
	WP13	45.65%	2.17%	0.00%	0.00%	24.64%	0.00%	4.35%	7.25%	0.72%	7.25%	4.35%	8.70%	7.97%	0.00%	0.00%
	WP14	68.00%	4.00%	0.00%	0.00%	39.00%	1.00%	20.00%	4.00%	0.00%	8.00%	15.00%	13.00%	23.00%	1.00%	0.00%
SW	WP24	76.09%	7.61%	0.00%	0.00%	13.04%	3.26%	19.57%	2.17%	0.00%	3.26%	22.83%	38.04%	34.78%	3.26%	0.00%
	WP2	44.93%	8.70%	0.00%	0.00%	11.59%	1.45%	11.59%	4.35%	0.00%	5.80%	5.80%	13.04%	2.90%	1.45%	0.00%
	WP12	43.00%	5.00%	0.00%	0.00%	13.00%	1.00%	4.00%	7.00%	2.00%	4.00%	2.00%	15.00%	9.00%	4.00%	0.00%
	WP15	61.64%	13.70%	0.00%	0.00%	39.04%	0.00%	3.42%	10.27%	0.68%	4.79%	1.37%	22.60%	1.37%	0.00%	0.00%
SH	WP21	68.00%	14.67%	0.00%	0.00%	36.00%	2.00%	6.67%	21.33%	0.67%	6.00%	2.00%	34.00%	7.33%	0.00%	0.00%
	WP5	36.11%	8.33%	0.00%	2.78%	8.33%	0.00%	13.89%	5.56%	0.00%	0.00%	5.56%	13.89%	16.67%	2.78%	0.00%
	WP16	36.99%	12.33%	0.00%	0.00%	5.48%	5.48%	8.22%	4.11%	0.00%	0.00%	6.85%	15.07%	12.33%	5.48%	0.00%
	WP17	36.00%	3.20%	1.60%	1.60%	11.20%	0.80%	10.40%	0.80%	0.00%	6.40%	8.00%	8.00%	8.00%	0.00%	0.00%
HP	WP22	52.03%	5.69%	0.00%	0.00%	13.01%	1.63%	6.50%	4.07%	0.81%	5.69%	2.44%	18.70%	15.45%	0.00%	0.00%
	WP3	43.18%	6.82%	0.00%	0.00%	25.00%	0.00%	2.27%	2.27%	2.27%	2.27%	2.27%	9.09%	6.82%	4.55%	0.00%
	WP18	35.03%	3.05%	0.00%	0.00%	17.77%	0.00%	4.06%	3.05%	0.51%	3.55%	1.02%	5.08%	4.06%	3.05%	0.51%
LC	WP7	52.54%	11.86%	0.00%	0.00%	13.56%	0.00%	3.39%	11.86%	0.00%	0.00%	1.69%	22.03%	15.25%	1.69%	0.00%
	WP29	58.26%	14.78%	0.00%	0.00%	16.52%	0.00%	6.96%	1.74%	0.00%	5.22%	5.22%	20.87%	13.91%	3.48%	0.00%
AH	WP10	35.96%	7.87%	0.00%	0.00%	12.36%	0.00%	11.24%	1.12%	0.00%	2.25%	2.25%	10.11%	6.74%	0.00%	0.00%

Figure A2.3 Hit rate table showing the conditional probability of each rail incident type occurring on any given day under each of the MO30 weather patterns (WPs), organised by synoptic regime grouping: North Atlantic Oscillation negative (NAO-), North Atlantic Oscillation positive (NAO+), Northwesterly (NW), Southwesterly (SW), Scandinavian High (SH), High Pressure Centred Over UK (HP), Low Close to UK (LC), and Azores High (AH). The 'All Incidents' column represents $P(\text{any incident} | \text{weather pattern})$ and is calculated independently as the proportion of days given a WP was active that resulted in at least one recorded incident of any type. Individual incident type hit rates are independent conditional probabilities and are not additive components of the 'All Incidents' column, as multiple incident types may co-occur on the same day. The study period covers October to March, 2006-2023. Incident type descriptors can be found in Table 4.2 of the main text. WP flow descriptions can be found in Table A1.1 in Appendix 1.

Appendix 3 – Chapter 5 Appendices

Appendix 3 has been prepared as the Supplementary Material of the manuscript in preparation “Developing a bespoke impact-based forecasting framework for the Scottish rail network” (presented as Chapter 5 in this thesis).

Table A3.1 Flow description of the MO30 weather patterns (Richardson et al., 2018) and the number of incident days per weather pattern after subset conditions were applied (see Section 5.5.3).

Weather pattern number	Flow description	Number of incident days per pattern
1	Neutral north-westerly	2
2	Cyclonic south-westerly	13
3	Anticyclonic south-westerly with a ridge over France	0
4	Neutral westerly	7
5	Neutral southerly with a centre of high pressure over Scandinavia	3
6	Anticyclonic with a high pressure centre over Azores	8
7	Cyclonic south-westerly with a centre of low pressure west-north-west of Ireland	16
8	Cyclonic westerly with a low pressure centre near the Shetland Islands	20
9	Anticyclonic with high pressure over Iceland	10
10	Anticyclonic westerly with high pressure over the Azores	17
11	Cyclonic with a low pressure centre over southern Britain	10
12	Anticyclonic south-south-westerly with high pressure over Poland	17
13	Anticyclonic north-westerly with high pressure over south-west of Ireland	37

14	Cyclonic north-north-westerly with low pressure centred over southern Sweden	45
15	Neutral south-westerly	62
16	Anticyclonic south-south-easterly with high pressure near Denmark	17
17	Anticyclonic east-south-easterly with a high pressure centre over Denmark	17
18	Anticyclonic south-westerly with high pressure over northern France	33
19	Neutral northerly	41
20	Cyclonic westerly with a deep centre of low pressure near Iceland	100
21	Cyclonic south-westerly with a deep low south of Iceland	78
22	Cyclonic southerly with low pressure west of Ireland	43
23	Neutral westerly with high pressure north of Spain	80
24	Cyclonic northerly with low pressure centred over the North Sea	54
25	Anticyclonic northerly with high pressure over Northern Ireland	31
26	Cyclonic north-westerly with low pressure centred near Norway	95
27	Anticyclonic easterly with high pressure over the Norwegian Sea	46
28	Cyclonic south-easterly with low pressure southeast of the UK	40
29	Cyclonic south-south-westerly with a deep low centre of pressure west of Ireland	40
30	Cyclonic west-north-westerly with deep low pressure southeast of Iceland	86

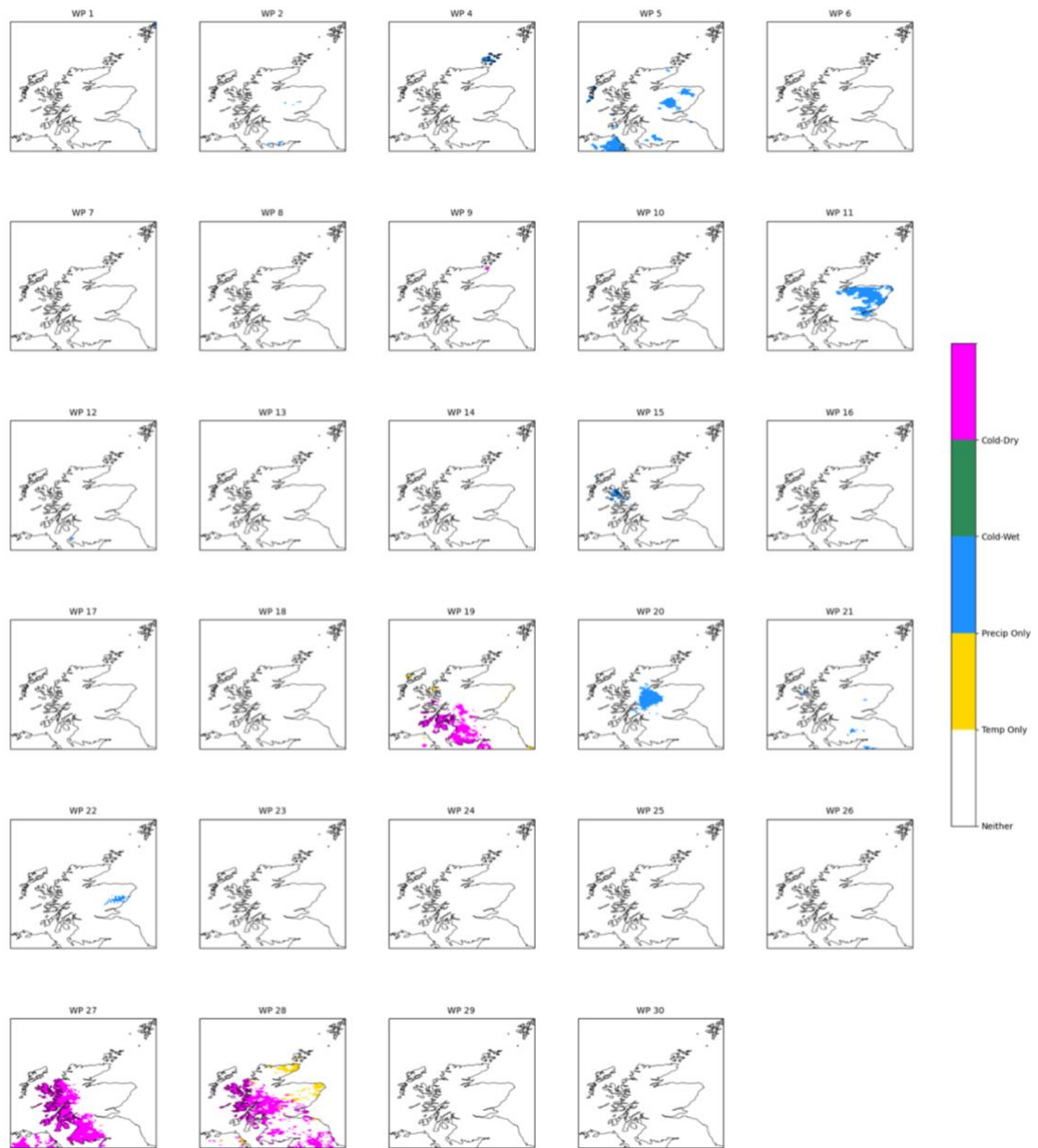


Figure A3.1 Compound cold event composites for the MO30 weather patterns (WP3 not included as no incidents were recorded under this weather pattern). Cold-dry and cold-wet occurrence are indicated by pink and green, respectively. The wet and dry percentiles (>85th percentile and <15th percentile of total daily precipitation) are indicated by blue and yellow, respectively.

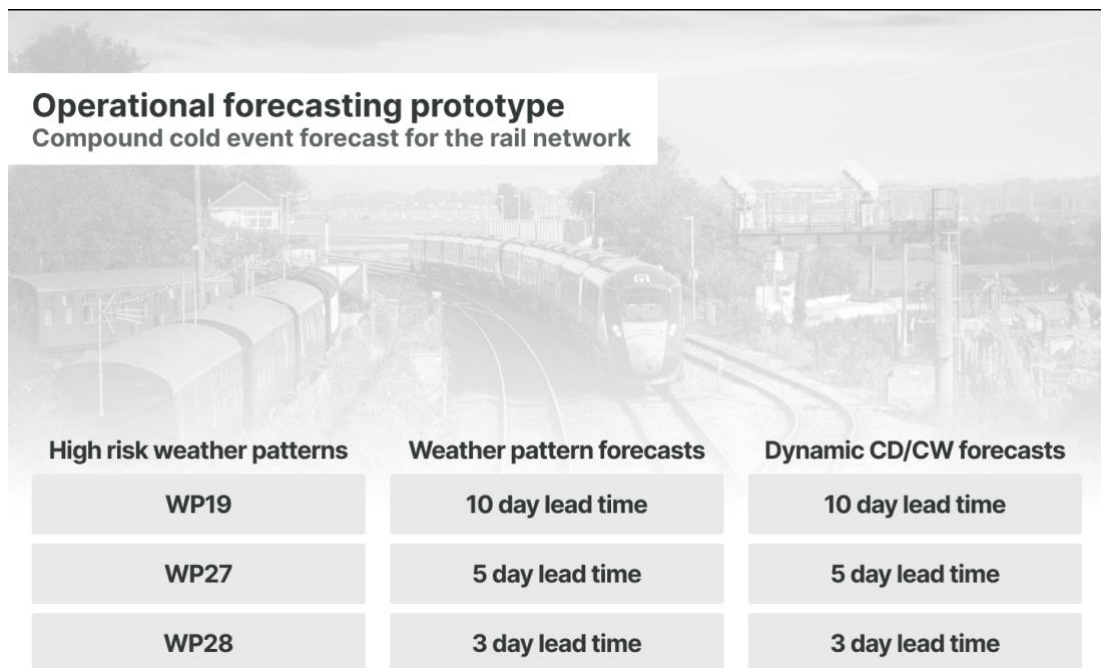


Figure A3.2 Illustrative demonstration of a homepage of an operational forecasting tool interface. This shows how HRPs, WP forecasts and CD/CW forecasts can be used collectively at different lead times.

home

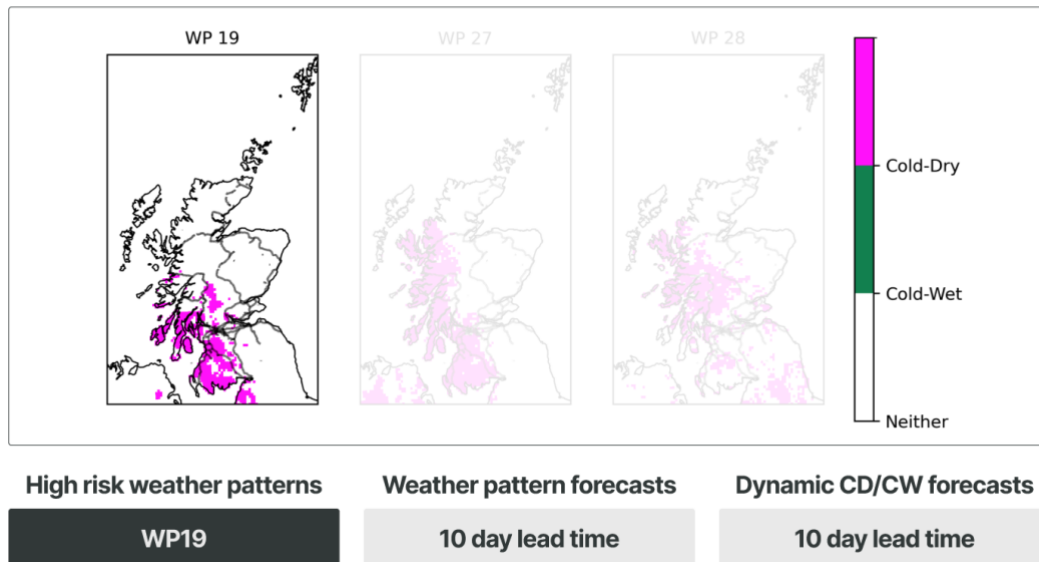


Figure A3.3 Illustrative demonstration of HRP display showing the spatial extent of CD/CW events under each of the HRPs (19, 27 and 28).

home

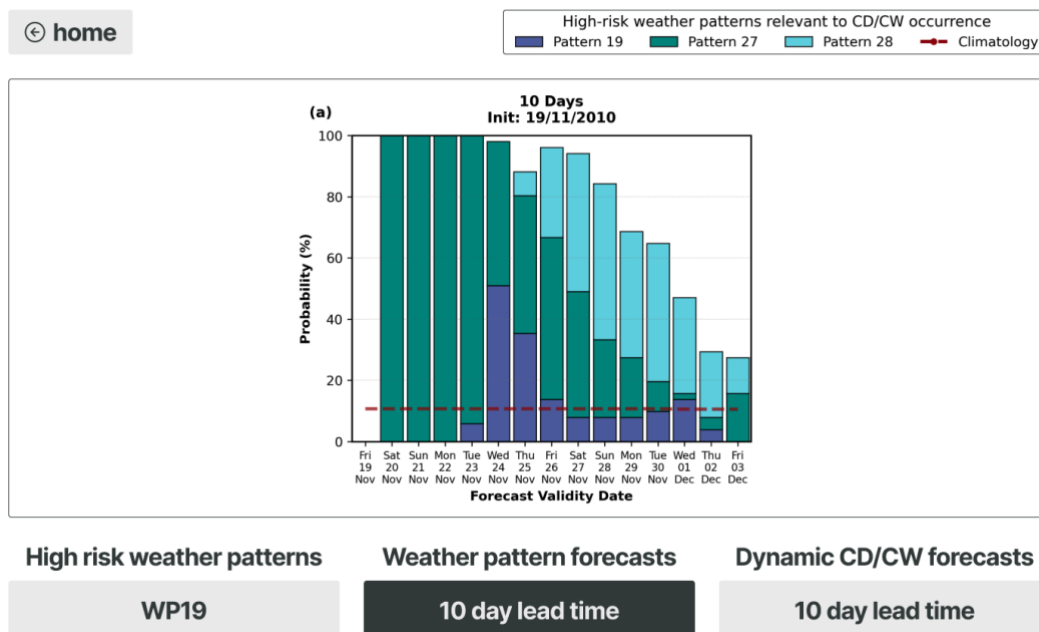


Figure A3.4 Illustrative demonstration of HRP forecast displaying a 15-day window of the probability of a HRP occurring.

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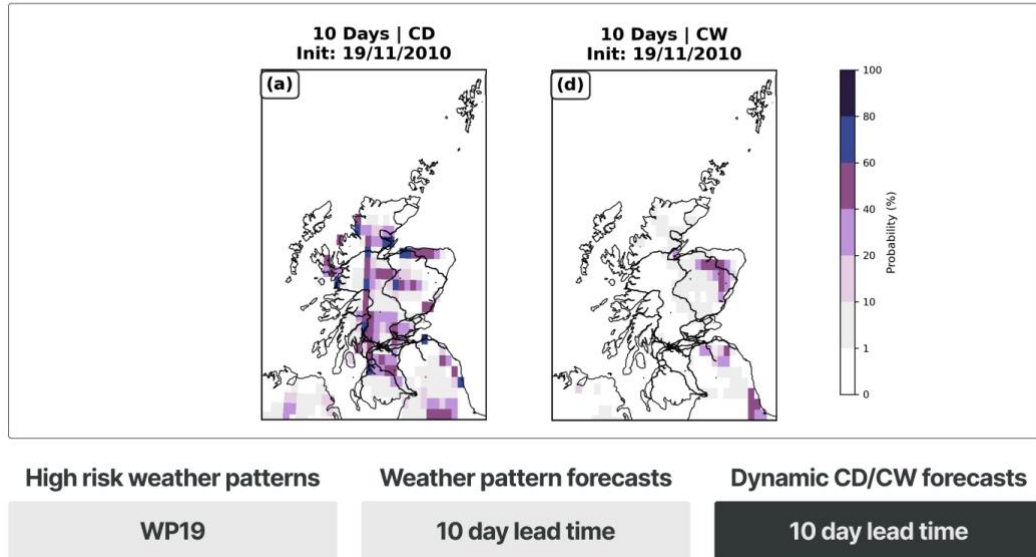


Figure A3.5 Illustrative demonstration of CD/CW footprint dynamic forecast at a 10-day lead time.