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PAPER

Future precipitation whiplash over Belgium from a high-resolution regional climate model

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Abstract

Precipitation whiplash events, characterized by rapid transitions between dry and wet extremes, are expected to intensify under climate change. However, current understanding of these events relies largely on coarse-scale climate models that cannot adequately resolve the physical processes driving abrupt hydroclimatic shifts. This study presents a high-resolution assessment of precipitation whiplash in Belgium using convection-permitting simulations from the ALARO regional climate model under three Representative Concentration Pathways scenarios (2.6, 4.5, and 8.5). We analyze both dry-to-wet and wet-to-dry transitions, focusing on projected changes in frequency, duration, transition speed, and seasonal timing. Results reveal increasing frequency and duration of both transition types, alongside shorter transition periods, indicating more abrupt shifts. Seasonal timing also changes, with a growing concentration of events, particularly dry-to-wet transitions, during spring and summer months. These projected changes pose heightened risks for climate-sensitive sectors, including agriculture, water management, and infrastructure, underscoring the need to consider the compound and abrupt nature of future hydroclimatic extremes in adaptation planning.

1. Introduction

Droughts and floods are among the most damaging natural hazards (WMO, 2021), each posing substantial threats to society by disrupting water supply, weakening ecosystem resilience, reducing agricultural productivity, and jeopardizing public health (Tabari, 2021, Hosseinzadehtalaei *et al* 2025). However, it is not only the individual occurrence of these extremes that poses a risk. Sudden transitions between them such as a dry spell followed by intense rainfall can result in disproportionately large impacts (Tan *et al* 2023, Facincani Dourado *et al* 2024). These rapid shifts, often referred to as precipitation whiplash or drought-to-downpour events, can amplify damages beyond what would be expected from droughts or floods in isolation (Intergovernmental Panel on Climate Change (IPCC), 2021; Fang and Lu, 2023; Zhu *et al* 2024; Lai *et al* 2025; Mullens and Engström, 2025).

Such transitions can trigger cascades of interconnected hazards, exacerbating risks well beyond those posed by the individual extremes. For instance, rainfall following drought can stimulate rapid vegetation growth, which in turn provides abundant fuel for wildfires during subsequent dry periods (Tan *et al* 2023, Puxley *et al* 2024). Drought-hardened soils often develop surface crusts that inhibit infiltration, increasing surface runoff and elevating the risk of flash floods, landslides, and soil erosion during subsequent heavy rainfall events (Fang and Lu, 2023, Tan *et al* 2023). Furthermore, the abrupt onset of intense rainfall following drought can accelerate nitrogen leaching from agricultural soils into water bodies, thereby degrading water quality (Loecke et al 2017, Tan et al 2023). These examples reflect the nature of compound events, where the co-occurrence or rapid succession of extremes leads to more severe consequences than when such events occur in isolation (Zscheischler et al 2018, 2020, Tabari and Willems, 2023a). As climate extremes intensify, precipitation whiplash is receiving increasing attention in both scientific research and public discourse (Chen et al 2022, Francis et al 2022, Cheng et al 2025). Understanding the drivers and projected future behavior of these events is critical for developing effective adaptation strategies and mitigating associated risks.

Precipitation whiplash cannot be fully explained by individual meteorological or hydrological variables alone. Its occurrence and intensification are fundamentally tied to a combination of large-scale atmospheric and dynamical drivers, with land–atmosphere interactions playing a particularly crucial role at the regional scale (He and Sheffield, 2020, Rezvani et al 2023). Global warming is intensifying the hydrological cycle, resulting in substantial changes in precipitation characteristics. These include longer and more severe droughts (Hosseinzadehtalaei et al 2023, Pinto et al 2023, Tabari and Willems, 2023b), more intense precipitation extremes, and increased precipitation variability (Ingram, 2016, Tabari et al 2019, Tabari, 2021, Le Gall et al 2024, Zhu et al 2024). Across a range of emission scenarios, climate models project a rise in the frequency of precipitation whiplash events (Chen and Wang, 2022, Tan et al 2023, Mullens and Engström, 2025). Notably, the response of post-drought precipitation to warming is more pronounced than that of mean precipitation, with projected increases of 4.5%–4.7% per degree of warming. This amplified response is attributed to the atmosphere's increased moisture-holding capacity and stronger vertical motion during the recovery phase following drought (Zhu et al 2024).

To date, most projections of precipitation whiplash events have relied on simulations from general circulation models (GCMs) (e.g. Chen and Wang, 2022, Tan et al 2023, Zhu et al 2024). GCMs are indispensable for global-scale climate projections and for representing large-scale atmospheric circulation. However, their spatial resolutions are insufficient to explicitly resolve convective processes, which typically require grid spacing finer than 4 km (Prein et al 2015, Tabari et al 2016, Akinsanola et al 2023). As a result, GCMs tend to smooth out localized extremes and underrepresent the intensity, frequency, and spatial heterogeneity of high-impact precipitation events that are central to the dynamics of precipitation whiplash (Kendon et al 2017, Prein et al 2017).

In contrast, convection-permitting models (CPMs) offer substantial advantages by explicitly resolving deep convection and capturing high-intensity, short-duration precipitation events (Prein et al 2015, Kendon et al 2017, Ban et al 2021). This capability allows for more accurate representation of the timing, magnitude, and sequencing of rapid dry-to-wet or wet-to-dry transitions. In addition, high-resolution models better capture land–atmosphere interactions, including soil moisture feedbacks, evapotranspiration dynamics, and heterogeneous land surface processes (Tabari et al 2016, Ban et al 2021). They also improve the simulation of mesoscale phenomena such as convective storms, mesoscale convective systems, and atmospheric blocking, and better represent changes in moisture convergence and local circulation that drive extreme precipitation variability (Kendon et al 2017, Berthou et al 2020).

Despite these clear advantages, the application of CPMs to the study of precipitation whiplash remains limited, largely due to the computational costs associated with long-term high-resolution simulations and the relatively recent availability of CPM-based climate projections (Kendon et al 2021). Expanding the use of CPMs is thus essential for advancing our understanding of the physical mechanisms, regional characteristics, and projected trajectories of these increasingly consequential events (Ban et al 2021, Fosser et al 2024). Improved CPM-based projections will be critical for informing regional adaptation strategies, infrastructure design, and risk management in the face of intensifying hydroclimatic extremes.

To address this gap, the present study investigates how precipitation whiplash events, specifically both wet-to-dry and dry-to-wet transitions, are projected to evolve under climate change in Belgium. We use high-resolution, convection-permitting simulations from the ALARO regional climate model (RCM) to resolve fine-scale atmospheric processes relevant to these rapid transitions. The analysis focuses on projected changes in the frequency, duration, and timing of whiplash events under three future climate scenarios, offering a detailed assessment of how these extremes may intensify or shift in a warming climate.

2. Materials and methods

2.1. Data

The ALARO model is a high-resolution RCM developed by the Royal Meteorological Institute of Belgium (Termonia et al 2018). Built on the foundation of the Aire Limitée Adaptation Dynamique

Développement International numerical weather prediction system, ALARO incorporates several enhancements tailored specifically for regional climate applications. Its physics parameterization package is optimized for resolutions between 3 and 8 km. A key component of this package is the Modular Multiscale Microphysics and Transport (3MT) scheme, which is specifically designed to support convection-permitting simulations.

The data used in this study consist of high-resolution daily precipitation simulations over Belgium, generated using the ALARO model at a spatial resolution of 4 km. These simulations are driven by the global climate model CNRM-CM5 (ensemble member r1i1p1) and cover the period from 1976 to 2100. To assess the potential impacts of different greenhouse gas trajectories on future precipitation whiplash events, this study considers three Representative Concentration Pathways (RCPs). RCP2.6 represents a stringent mitigation scenario in which greenhouse gas emissions peak early and decline substantially, consistent with limiting global warming to well below 2 °C in line with the Paris Agreement. RCP4.5 describes an intermediate scenario where emissions stabilize by mid-century, reflecting moderate mitigation efforts. In contrast, RCP8.5 represents a high-emissions, business-as-usual pathway with continuously rising emissions throughout the 21st century (Van Vuuren *et al* 2011). Future climate projections are analyzed over a 30 year period (2071–2100) and compared to a 30 year historical baseline (1976–2005) to examine changes in the characteristics of precipitation whiplash events.

The ALARO model has been widely evaluated for Belgium, demonstrating a high capability for simulating precipitation. Its performance in reproducing the regional precipitation climatology and the mean seasonal cycle has been firmly established (De Troch *et al* 2013). Regarding extreme precipitation, the model shows a marked improvement in reproducing summer rainfall extremes compared to coarser-resolution models (De Troch *et al* 2013, Tabari *et al* 2016), a capability confirmed over multidecadal simulations at convection-permitting scales (Saeed *et al* 2017). Crucially, the model's physical representation of the processes driving heavy rainfall events has been specifically validated, demonstrating skillful simulation of the dynamical and hydrological mechanisms responsible for intense precipitation (Giot *et al* 2016). This robust skill across both the general precipitation climate and its most intense manifestations provides strong confidence in the suitability of ALARO for analyzing precipitation whiplash events in Belgium.

2.2. Methodology

Precipitation whiplash events are characterized using daily precipitation data by identifying rapid transitions between wet and dry extremes. It begins by calculating cumulative precipitation, using a 30 d rolling sum of daily precipitation across the entire study period (Tan *et al* 2023). One of the key advantages of this method, based on a rolling sum of daily data, is the ability to capture a more nuanced and robust picture of the temporal distribution of whiplash events. To remove the influence of seasonality, these rolling sums are standardized by computing the long-term mean and standard deviation for each calendar day and grid cell. This standardization is based on the combined data from the historical (1976–2005) and future (2071–2100) periods for each RCP. Standardized precipitation anomalies are then derived by subtracting the climatological mean and dividing by the standard deviation for each corresponding day and location (equation (1)–,

$$P'_{ij} = \frac{P_{ij} - \bar{P}_j}{\sigma_j} \tag{1}$$

where P_{ij} is the cumulative precipitation total for the jth Julian day in year i, $\bar{P}_j$ is the long-term mean precipitation for the jth Julian day, and σ_j is the standard deviation of precipitation for the jth Julian day.

Based on these standardized anomalies, threshold values for extremes are established using the 10th and 90th percentiles derived from the historical reference period. A dry-to-wet whiplash event is defined as a transition from a dry extreme (anomaly $\leqslant$10th percentile) to a wet extreme (anomaly $\geqslant$ 90th percentile) within 30 d (figure 1). Conversely, a wet-to-dry event is marked by the opposite sequence (figure 2). Only transitions occurring within this 30 d window are considered true whiplash events, as longer gaps would indicate independent events rather than a rapid switch. To evaluate the suitability of the thresholds to define dry and wet events, we conducted a sensitivity analysis. Using more stringent thresholds (5th/95th) produced country-average counts of 6 dry-to-wet and 4 wet-to-dry events in the historical period, with no wet-to-dry events in some grid cells. Results using the 15th/85th percentiles (figure S1, supplementary information) were broadly consistent with those obtained using the 10th/90th percentiles. Considering the trade-off between sample size and the extremity of events, we selected the 10th/90th percentiles as a balanced choice and present these results in the main text.

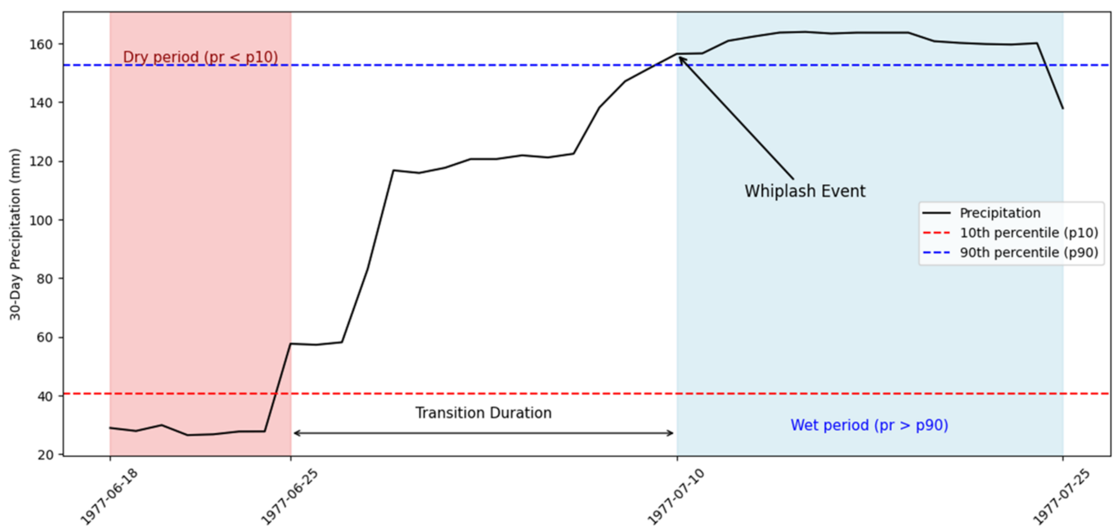

Figure 1. Illustration of a dry-to-wet transition on July 10th, 1970, based on ALARO simulation data. If the 30 d cumulative precipitation values (black line) fall below the 10th percentile (red dashed line), this is labeled as a dry period. If the 90th percentile (blue dashed line) is exceeded, a wet-period occurs. The transition period is the time between the end of the dry period and the start of the wet period. If this transition duration is lower than 30 d, a whiplash event happens.

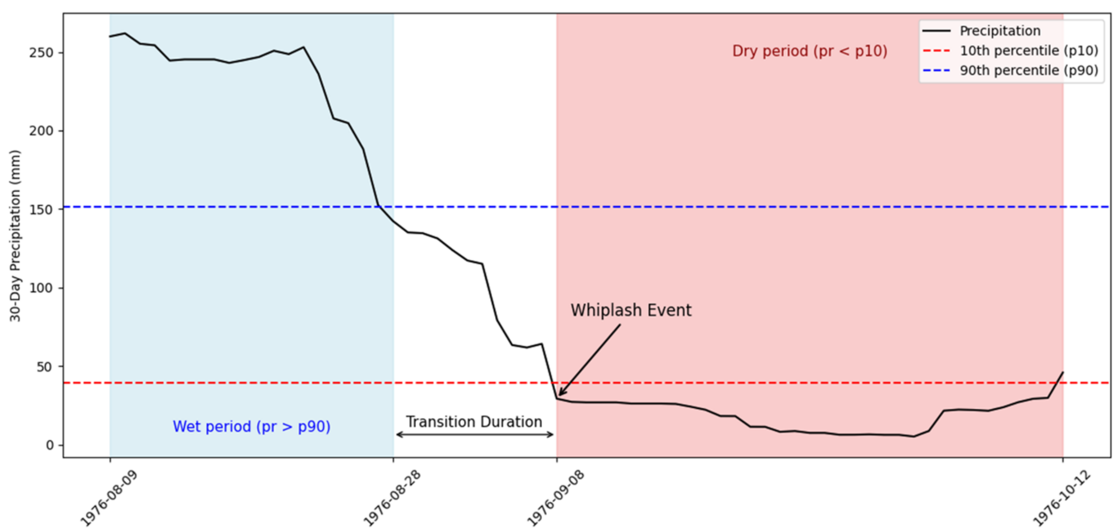

Figure 2. Illustration of a wet-to-dry transition on September 8th, 1976, based on ALARO simulation data. If the 30 d cumulative precipitation values (black line) fall below the 10th percentile (red dashed line), this is labeled as a dry period. If the 90th percentile (blue dashed line) is exceeded, a wet-period occurs. The transition period is the time between the end of the wet period and the start of the dry period. If this transition duration is lower than 30 d, a whiplash event happens.

In addition to the daily rolling-window approach used here to identify whiplash events, another common method defines dry periods at the monthly scale (Chen and Wang, 2022, Zhang *et al* 2023, Zhu *et al* 2024). We tested this monthly approach (see text S1 and figure S2 of the supplementary information for methodological details). It yields broadly consistent spatiotemporal patterns but differs in magnitude (figure S3), primarily due to the reduced number of events identified at the coarser temporal scale. By contrast, the continuous daily rolling-window method provides a more realistic view of when events occur throughout the year. Therefore, we report only the daily rolling-window results in the main text and summarize the monthly-based results in the supplementary information.

For each event, the start and end dates of both the dry and wet period are recorded. This method allows for the analysis of key characteristics, including event frequency, the duration of the transition phase, total event length, and the Peak Month Index (PMI). The occurrence frequency refers to the total count of dry-to-wet or wet-to-dry whiplash events detected at each grid point during each study period. The transition duration represents the number of days between the final day of the initial extreme (dry or wet) and the first day of the following opposite extreme. The overall duration captures the combined length of both the dry and wet periods that make up the whiplash event. The statistical significance of differences in total frequency, average duration, and average transition duration between historical and future periods (figures 3, 5, and 7) was assessed using the Mann–Whitney test, applied separately to Belgian grid cells showing increasing and decreasing signals.

Additionally, the PMI identifies the time of year when whiplash events most frequently occur. The calculation of the PMI is based on the study by Luo *et al* (2025). This method uses circular statistics, treating calendar days as angles on a unit circle (i.e. a circular calendar), to determine the mean direction or dominant timing of events across a year. For each grid cell, the day D_i on which each whiplash event occurs, is converted to an angular value θ_i, using equation (2). An angular value θ_i of zero radians corresponds to January 1st and December 31st corresponds to 2π radians. In equations (3) and (4), these angular values are converted into cosine and sine components and averaged, followed by the mean angle $\bar{D}$, which is mapped back to a calendar day (equation (6)). Finally, the PMI is the month in which $\bar{D}$ falls. This value reflects the month where whiplash events are most likely to occur,

$$\theta_i = D_i \cdot \frac{2\pi}{m_i},\ 0 \leqslant \theta_i \leqslant 2\pi \tag{2}$$

$$\tilde{x} = \frac{1}{n}\sum_{i=1}^{n}\cos(\theta_i) \tag{3}$$

$$\tilde{y} = \frac{1}{n}\sum_{i=1}^{n}\sin(\theta_i) \tag{4}$$

$$\tilde{m} = \frac{1}{n}\sum_{i=1}^{n} m_i \tag{5}$$

$$\bar{D} = \begin{cases} \tan^{-1}\left(\frac{\tilde{y}}{\tilde{x}}\right)\cdot\frac{\tilde{m}}{2\pi}, \tilde{x} > 0, \tilde{y} \geqslant 0 \\ \left[\tan^{-1}\left(\frac{\tilde{y}}{\tilde{x}}\right) + \pi\right]\cdot\frac{\tilde{m}}{2\pi}, \tilde{x} \leqslant 0 \\ \left[\tan^{-1}\left(\frac{\tilde{y}}{\tilde{x}}\right) + 2\pi\right]\cdot\frac{\tilde{m}}{2\pi}, \tilde{x} > 0, \tilde{y} < 0 \end{cases} \tag{6}$$

where D_i is the day of the year of the event, m_i is the total number of days in that year (365 or 366), θ_i is the corresponding angle in radians, n is the total amount of whiplash events at the grid, and $\tilde{m}$ is the mean number of days per year.

3. Results

The spatial distribution of whiplash events across Belgium, as shown in figure 3, highlights distinct differences in the frequency of these events between the historical baseline (1976–2005) and future projections (2071–2100) under the three RCP scenarios. For dry-to-wet events, future frequencies increase substantially across the country, with future-to-historical ratios exceeding two in some areas. Depending on the scenario, 61%–86% of Belgian grid cells exhibit an increase, and those increases are statistically significant ($p < 0.001$). Wet-to-dry changes broadly mirror the dry-to-wet response under RCP 2.6 and RCP 8.5, though with slightly larger increases. Under these two scenarios, 13%–16% of grid cells are expected to experience a $\geqslant$50% increase in the frequency of dry-to-wet events, while 20%–30% of grid cells are expected to experience a $\geqslant$50% increase in wet-to-dry events. In contrast, RCP 4.5 stands out, with 58% of grid cells showing a decrease in wet-to-dry frequency. Both the increasing and decreasing signals for wet-to-dry events are statistically significant ($p < 0.001$).

The temporal characteristics of whiplash events over Belgium under future climate change scenarios reveals clear intra-annual variations and scenario-dependent responses (figure 4). From April to July, both transition types show an overall increase in frequency, with RCP 2.6 exhibiting the most consistent and widespread rise. For dry-to-wet events, the increase extends into late summer and autumn (August–November), particularly under RCP 8.5, which displays the highest medians and upper percentiles during these months. An additional increase under RCP8.5 is also evident in December. In contrast, wet-to-dry events display an increase during February and March across any of the scenarios.

The impact of precipitation whiplash events depends not only on their frequency and timing but also on their duration, which influences how long extreme conditions persist and, consequently, their

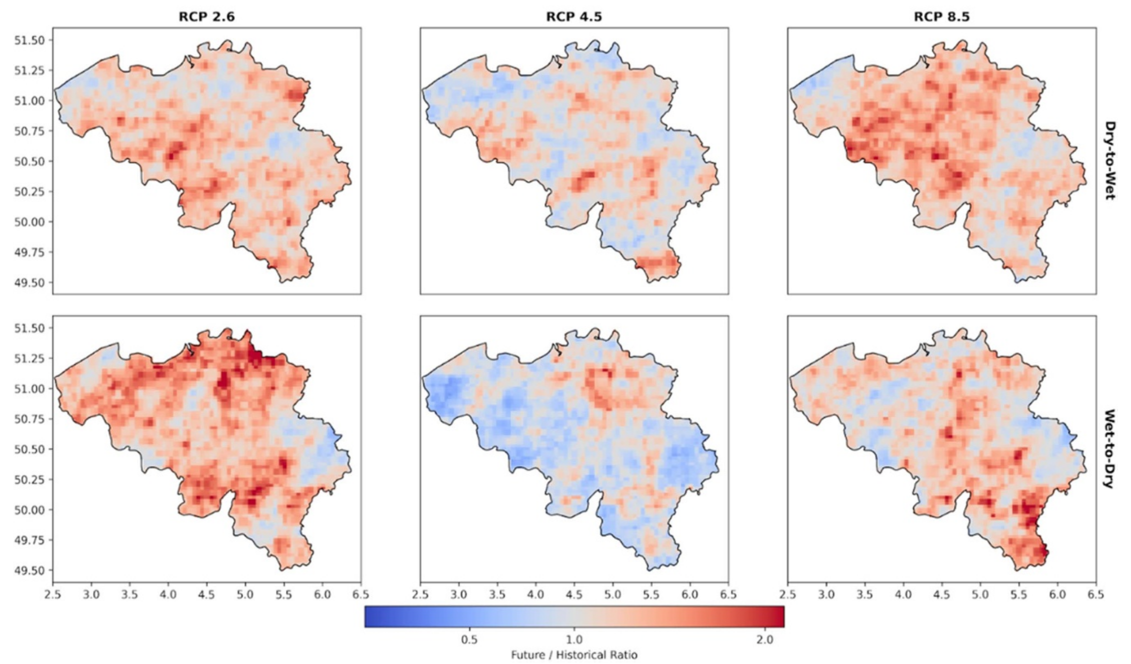

Figure 3. Ratio of the frequency of dry-to-wet and wet-to-dry events in the future period (2071–2100) to the historical baseline period (1976–2005) under three climate scenarios: RCP2.6, RCP4.5, and RCP8.5.

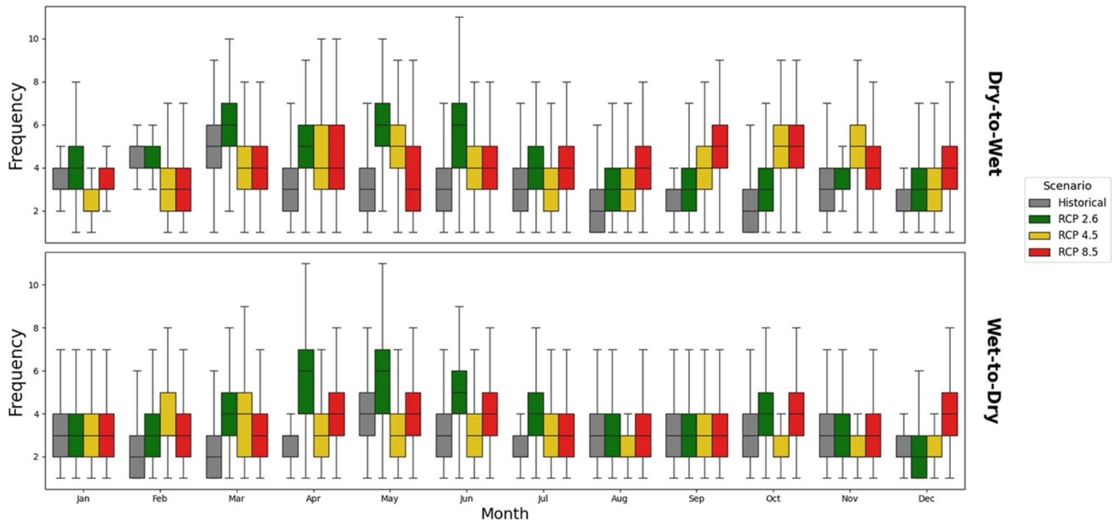

Figure 4. Monthly distribution of dry-to-wet and wet-to-dry frequency by scenario. Box plots indicate the median (horizontal black line), interquartile range (box from 25th to 75th percentile), and whiskers extending to the most extreme values within 1.5 times the interquartile range.

potential to cause disruption. For dry-to-wet events (figure 5), RCP 4.5 and RCP 8.5 indicate a widespread increase in duration (74%–79% of grid cells), with several regions exhibiting a ⩾50% increase in duration. In contrast, RCP 2.6 presents a mixed pattern, with reduced duration across about half of the country (53% of grid cells). Wet-to-dry events generally display increasing durations (61%–66%, depending on scenario). The spatial pattern of projected duration changes varies across emission scenarios, and there is no clear trend in the magnitude of change with increasing scenario intensity. For both dry-to-wet and wet-to-dry events, the increases and decreases in duration across Belgian grid cells are statistically significant ($p < 0.001$).

These spatial patterns are further summarized in figure 6, which presents average event durations for each scenario and transition type. For dry-to-wet events, both RCP 4.5 and RCP 8.5 show an increase in median duration and an expansion in the range of values, with some events extending beyond 60 d.

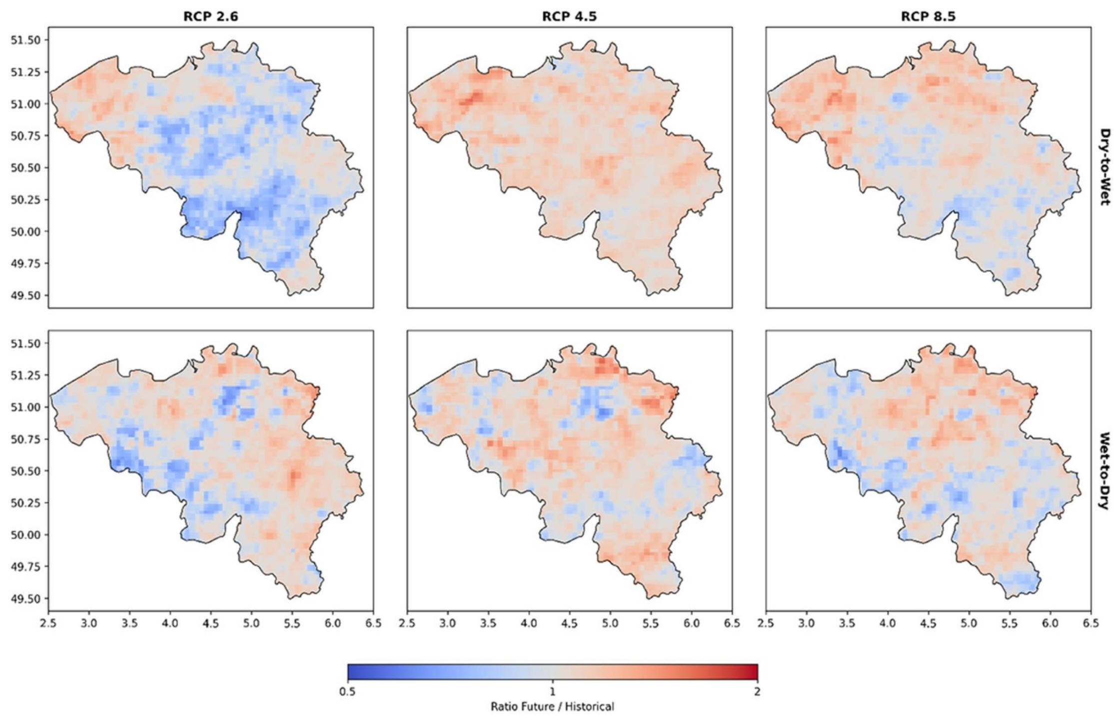

Figure 5. Spatial distribution of the ratio of average event duration between future RCP scenarios (2071–2100) and the historical baseline (1976–2005) for dry-to-wet and wet-to-dry events.

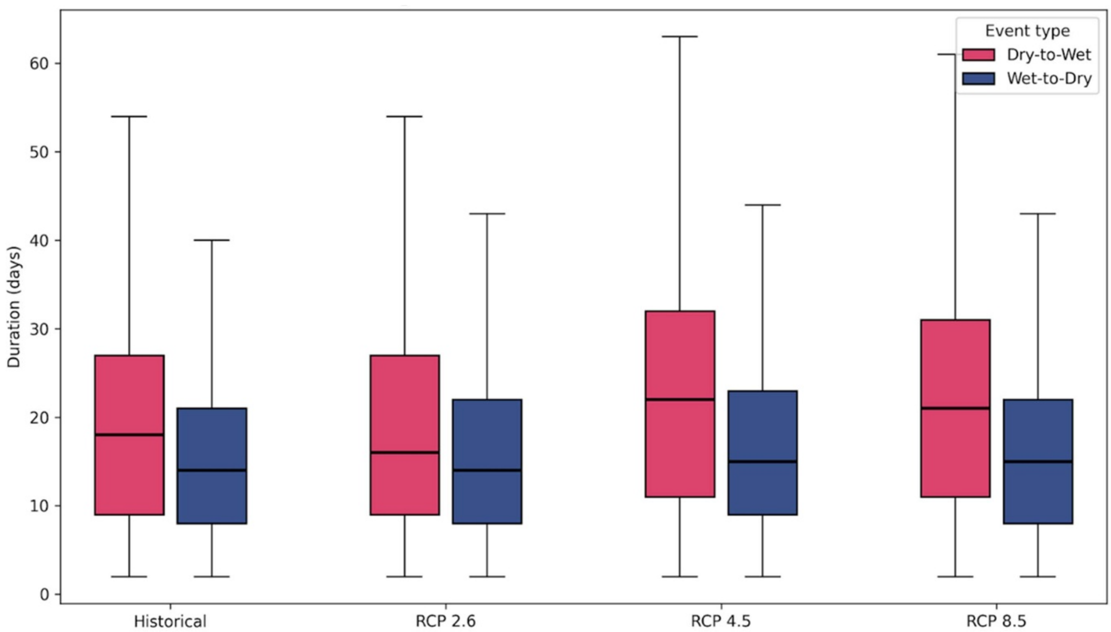

Figure 6. Average event duration for dry-to-wet and wet-to-dry events during the historical baseline period (1976–2005) and three future climate scenarios (2071–2100) under RCP 2.6, RCP 4.5, and RCP 8.5. Box plots display the median (horizontal black line), interquartile range (box from the 25th to 75th percentile), and whiskers extending to the most extreme values within 1.5 times the interquartile range.

This increase is particularly pronounced under RCP 4.5, suggesting longer-lasting episodes of consecutive dry and wet extremes. In contrast, wet-to-dry events exhibit more modest changes. RCP 2.6 shows a slight decrease in median duration compared to the historical period, while RCP 4.5 and RCP 8.5 reveal only marginal increases in variability without a clear shift in median values. Notably, across all scenarios, wet-to-dry transitions are consistently shorter in duration than dry-to-wet events. This indicates that

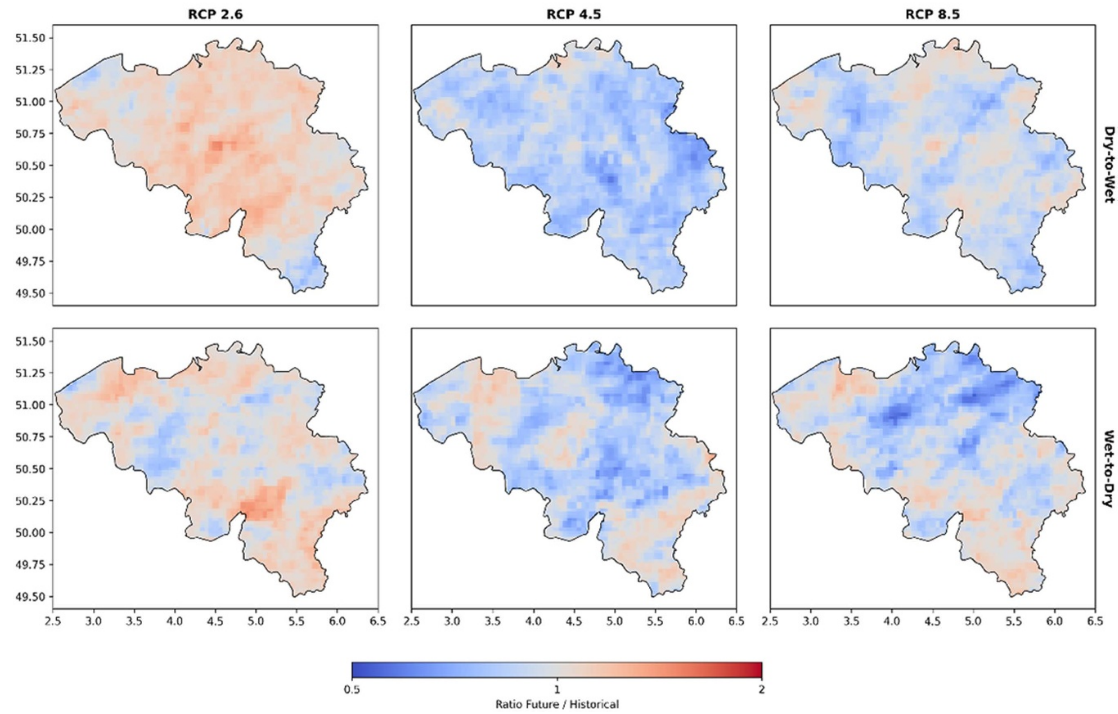

Figure 7. Spatial distribution of the ratio of average transition duration between future RCP scenarios (2071-2100) and the historical baseline (1976–2005) for dry-to-wet and wet-to-dry events.

dry spells followed by wet conditions tend to be more prolonged, either due to more persistent antecedent dryness or longer-lasting subsequent wet periods, whereas wet-to-dry transitions are comparatively abrupt or less persistent.

Another critical characteristic in assessing compound precipitation events is the transition duration, which is the time interval between the end of the first extreme (dry or wet) and the onset of the second. Shorter transition durations increase the risk of adverse impacts, as they allow less time for adaptation, preparedness, or recovery between successive extremes (Tan *et al* 2023). Figure 7 illustrates the spatial distribution of changes in transition duration under future climate scenarios relative to the historical period. Under RCP 4.5 and RCP 8.5, transition durations generally shorten across Belgium for both dry-to-wet and wet-to-dry events, and these decreases are statistically significant ($p < 0.001$): 57%–78% of grid cells for dry-to-wet and 62%–63% for wet-to-dry. In contrast, RCP 2.6 shows an opposite trend, with longer transition durations in most Belgium (76% of grid cells for dry-to-wet and 65% for wet-to-dry), which is statistically significant ($p < 0.001$), suggesting more time between the end of one extreme and the onset of the next.

These spatial patterns are confirmed in figure 8, which presents boxplots of transition duration by scenario and event type. Under RCP 2.6, both dry-to-wet and wet-to-dry events exhibit higher median transition durations compared to the historical baseline, and the distributions show fewer short-duration transitions. RCP 4.5 stands out with the lowest median values for both transition types, reflecting the most rapid succession of extremes. For RCP 8.5, a decrease in transition duration is evident for wet-to-dry events, although the change is less marked than in RCP 4.5, and no clear shift is observed for dry-to-wet events. Across all scenarios, wet-to-dry transitions consistently have shorter median transition durations than dry-to-wet events. This systematic difference suggests that dry conditions tend to set in more abruptly following wet periods, whereas transitions into wet extremes may occur more gradually. These results underline the importance of considering not only the frequency and duration of compound events but also the speed at which one extreme transitions into another when evaluating future hydroclimatic risks.

An additional key dimension in the analysis of whiplash events is their seasonal timing, which has significant implications for climate-sensitive sectors such as agriculture, water management, and infrastructure planning. To examine when these transitions most frequently occur, the PMI was applied. Figure 9 displays the spatial distribution of PMI values across Belgium for both dry-to-wet and wet-to-dry events under the historical baseline and future projections across the three RCP scenarios.

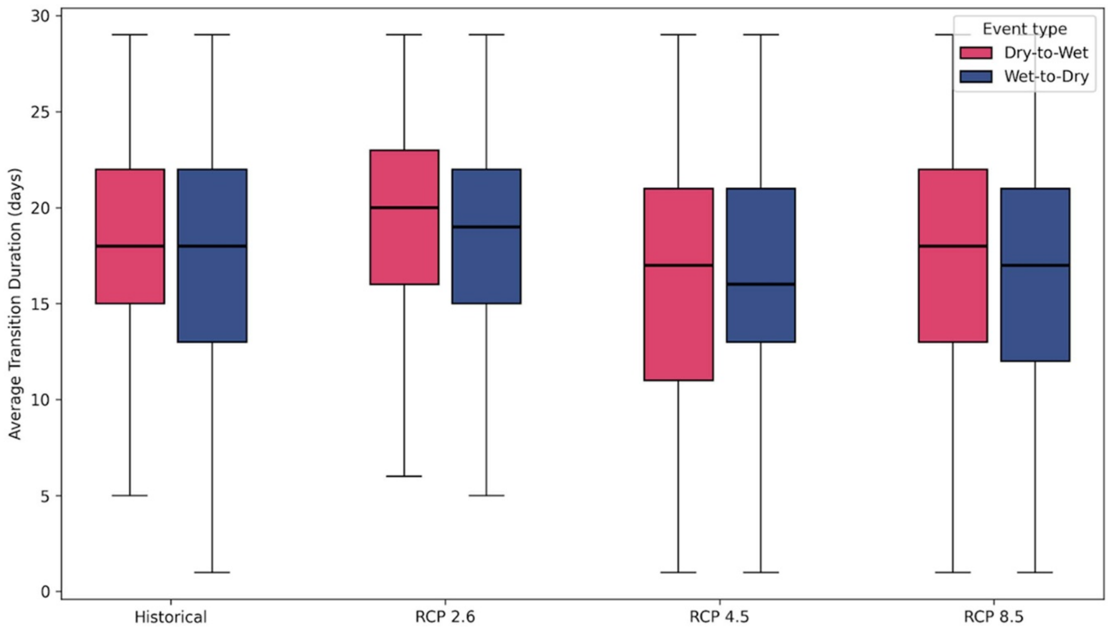

Figure 8. Average transition duration for dry-to-wet and wet-to-dry events under the historical baseline period (1976–2005) and three future climate scenarios (2071–2100) based on RCP 2.6, RCP 4.5, and RCP 8.5. Box plots indicate the median (horizontal black line), interquartile range (box from 25th to 75th percentile), and whiskers extending to the most extreme values within 1.5 times the interquartile range.

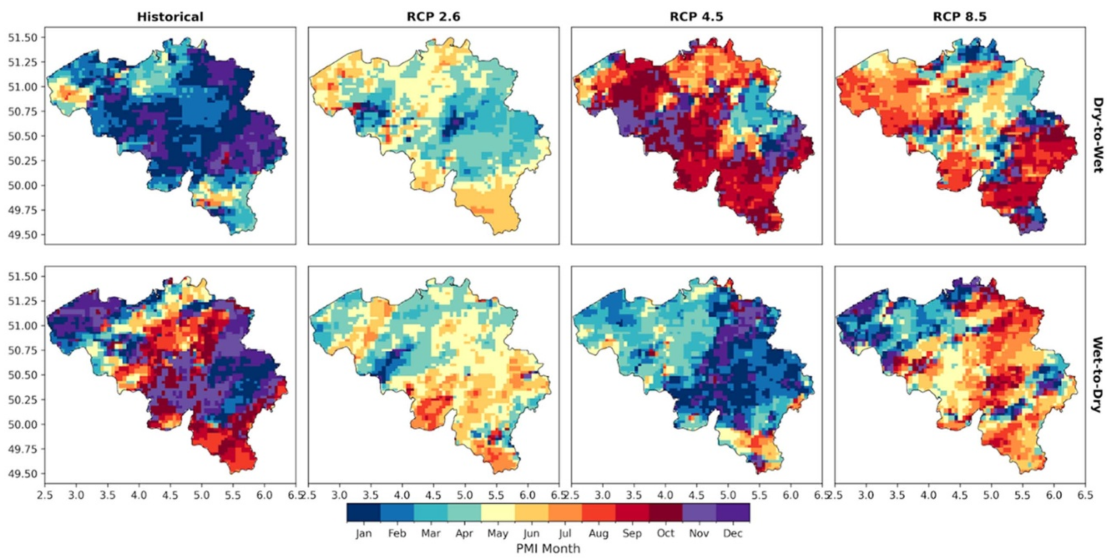

Figure 9. Spatial distribution of Peak Month Index (PMI) for dry-to-wet (top) and wet-to-dry (bottom) events for four scenarios.

During the historical period (1976–2005), dry-to-wet events most commonly peak in the winter months (November–February), especially in central and eastern regions, while wet-to-dry events are concentrated in the autumn (September–December). Under RCP 2.6, a clear shift toward earlier seasonal timing is observed, with both event types increasingly peaking in spring months, particularly March, April, and May. This pattern aligns with the earlier increase in event frequency seen during spring (as shown in previous figures), indicating that more transitions may occur during the onset of the growing season in a low-emissions future. Under RCP 4.5, timing patterns diverge further. Dry-to-wet events are projected to shift toward autumn, peaking primarily between September and November. Wet-to-dry events under this scenario display a more temporally diffuse distribution, with peak months occurring in both spring and winter, suggesting increased variability in seasonal timing. The most pronounced changes appear under RCP 8.5. Dry-to-wet events are expected to peak mainly during summer and early autumn (June–October), marking a substantial shift away from winter-dominated transitions. Wet-to-dry events also occur more frequently in summer across most of the country, though winter and early spring peaks persist in coastal regions. These shifts suggest that under high-emissions conditions, Belgium may experience an elevated risk of abrupt wet and dry transitions during critical periods for vegetation growth and agricultural activity, potentially amplifying impacts on crop yields, soil moisture dynamics, and water supply systems.

4. Discussion

Our results indicate that precipitation whiplash events are projected to occur more frequently under climate change, in line with findings from other regions worldwide (Chen and Wang, 2022, Tan *et al* 2023, Mullens and Engström, 2025). The increase in dry-to-wet transitions with rising global temperatures can be attributed to a combination of thermodynamic and dynamic changes in the climate system (Li and Li, 2015, Swain *et al* 2018, Zhang *et al* 2021, Rezvani *et al* 2023). At the global scale, changes in hydroclimate volatility are fundamentally driven by thermodynamic processes; however, dynamical effects become important regionally by modulating the influence of moisture increases (Mishra *et al* 2021, Tan *et al* 2023, Swain *et al* 2025).

Thermodynamic changes play a central role. As the atmosphere warms, its capacity to hold water vapor increases exponentially, following the Clausius–Clapeyron (CC) relationship (Allen and Ingram, 2002, Trenberth *et al* 2003, Ingram, 2016, Tabari, 2020). Future projections for extreme rainfall intensity over Belgium generally follow this CC scaling, showing an average increase of 7% per additional degree of global warming (Brajkovic *et al* 2025). This aligns with broader European projections of more intense precipitation extremes, particularly under high-emission scenarios (Hosseinzadehtalaei *et al* 2019, Steensen *et al* 2025). The enhanced moisture availability increases the likelihood of intense post-drought rainfall, accelerating transitions between dry and wet conditions (Chen and Wang, 2022, Zhu *et al* 2024).

While thermodynamics provide the background intensification of extremes, circulation changes determine how these extremes manifest regionally, particularly in mid-latitude Europe. Atmospheric blocking systems, characterized by quasi-stationary anticyclones, strongly influence droughts and heatwaves in Europe by inducing subsidence and suppressing precipitation (Kautz *et al* 2022). Similarly, weakened storm track activity and reduced baroclinic instability—caused by a declining meridional temperature gradient—limit cyclonic activity over mid-latitudes, lengthening dry spells (Lehmann and Coumou, 2015, Swain *et al* 2018, Zhang *et al* 2021). When storm systems return, however, the accumulated atmospheric moisture can be rapidly released in the form of intense downpours, favoring abrupt dry-to-wet transitions.

Finally, large-scale climate variability may itself become more volatile or persistent under global warming, enhancing interannual swings and the likelihood of successive, contrasting extremes (Rezvani *et al* 2023). The strong influence of large-scale circulation on European precipitation extremes has been widely documented (Tabari and Willems, 2018), highlighting the need to consider both thermodynamic intensification and dynamical modulation when interpreting the projected rise in whiplash over Belgium.

Our findings also reveal a notable asymmetry in future whiplash behavior. Dry-to-wet transitions increase consistently across Belgium under all emission scenarios, reflecting the thermodynamic intensification of the hydrological cycle. Wet-to-dry transitions also increase under most scenarios, though with less consistency in magnitude, suggesting that their evolution is more sensitive to regional atmospheric dynamics. Circulation features such as North Atlantic storm track activity, jet stream shifts, and persistent atmospheric blocking in spring and summer (Pfahl *et al* 2017, Kautz *et al* 2022, Köhler *et al* 2024) can accelerate the onset of dry periods following wet extremes. The projected frequency and duration of such regime shifts remain uncertain, but their modulation by large-scale circulation helps explain why wet-to-dry transitions display more variability across scenarios compared to dry-to-wet events (Fabiano *et al* 2021, Müller *et al* 2025).

Beyond changes in frequency, our results show that the duration of both dry-to-wet and wet-to-dry events increases under moderate and high emission scenarios. We also find that these longer whiplash events are accompanied by shorter transition periods between extremes. This pattern is consistent with previously observed (Tan *et al* 2023) and projected (Chen and Wang, 2022) accelerations in wet–dry transitions. The reduced transition duration leaves less time for preparedness and decision-making, thereby amplifying the risk of catastrophic consequences (Sloat *et al* 2018, Tan *et al* 2023).

Importantly, our analysis highlights that the timing of compound events is also shifting. Dry-to-wet transitions show a clear increase across seasons, particularly in spring and summer, with pronounced late-season peaks under RCP 8.5. Wet-to-dry events, however, display greater variability across scenarios and seasons, with less uniform trends. The PMI analysis confirms a shift in event timing from winter and autumn in the historical period toward spring and summer under future scenarios. Under RCP 8.5, both transition types increasingly coincide with the growing season (June–October), posing heightened risks to agriculture and water resources. Seasonal shifts in post-drought precipitation peaks using CMIP6 models were reported, noting a shift toward autumn rather than summer under high-emission scenarios (SSP5-8.5) in many regions (Zhu *et al* 2024). While regional differences exist, the seasonal reorganization of whiplash events appears to be a robust feature of future hydroclimate extremes.

Collectively, these findings underscore the need to move beyond frequency-based assessments of compound events. Transition speed, event duration, and seasonal timing are equally critical, as they determine the impact pathways and the windows of opportunity for adaptation. As the climate continues to warm, the compound nature of hydroclimatic extremes is expected to intensify, with more abrupt, prolonged, and ill-timed transitions between wet and dry extremes. These dynamics will pose growing challenges for managing water systems, sustaining agricultural productivity, and protecting vulnerable communities.

5. Summary and future directions

This study provides new insights into the projected evolution of precipitation whiplash events in Belgium under climate change, based on high-resolution, convection-permitting simulations from the ALARO RCM. By analyzing both dry-to-wet and wet-to-dry transitions across three climate scenarios, we offer a multi-dimensional characterization of future whiplash dynamics, including projected changes in event frequency, duration, transition speed, and seasonal timing.

The results indicate a robust increase in both the frequency and duration of dry-to-wet and dry-to-wet events. Both event types are also projected to become more abrupt, with shorter transition periods between opposing extremes. Both event types are projected to become more abrupt, with shorter transition periods between opposing extremes. These accelerated shifts reduce the time available for preparedness and response, thereby increasing the potential for adverse impacts across multiple sectors. In addition, we find clear changes in seasonal timing, with a growing alignment of compound events, particularly dry-to-wet transitions, with the agricultural growing season under high-emission scenarios such as RCP 8.5. This seasonal reorganization raises critical concerns for crop production, water availability, and ecological resilience.

Taken together, these findings underscore the importance of expanding beyond frequency-based metrics when assessing compound climate extremes. Transition speed, event duration, and timing are crucial dimensions that determine the severity and sectoral relevance of these events. As the climate continues to warm, future adaptation strategies must explicitly consider the growing complexity, intensity, and seasonal dynamics of hydroclimatic variability.

The projected intensification and seasonal reorganization of precipitation whiplash also carry sectoral consequences. More frequent and abrupt dry-to-wet transitions during spring and summer coincide with the growing season, heightening agricultural risks through both water stress and flood damage. Shorter transition times compress the window for operational response in water management, challenging reservoir operations, urban drainage, and groundwater recharge. Wet-to-dry shifts in late summer and autumn may further stress drinking water supply. Urban areas and infrastructure face compounding threats, as antecedent drying can weaken soils and structures while subsequent intense rainfall elevates pluvial and fluvial flood hazards. These implications underline that whiplash intensification is not only a hydroclimatic issue but also a socio-economic challenge that warrants targeted adaptation in Belgium's agriculture, water resources, and infrastructure planning.

While this study is among the first to apply convection-permitting regional climate simulations to assess precipitation whiplash, several important research directions remain. First, our analysis defines wet extremes using daily precipitation thresholds. However, sub-daily extremes are expected to intensify more rapidly under warming (O'Gorman *et al* 2015, Hosseinzadehtalaei *et al* 2020), and may exert greater influence on short-term impacts such as flash flooding. Future work should explore how whiplash behavior evolves when wet events are defined at sub-daily timescales, particularly given the ability of high-resolution models to resolve convective processes (Kendon *et al* 2017). These refinements would also support more integrated impact modeling across flood risk, infrastructure, and emergency response planning.

Second, most existing studies on precipitation whiplash have focused primarily on trend detection, with limited attention given to the underlying physical drivers or the fidelity of their representation in climate models (Francis *et al* 2023). Whiplash events typically result from a combination of thermodynamic amplification, atmospheric circulation shifts, and land–atmosphere feedbacks, which may not be equally well captured across models. Advancing our understanding of these mechanisms and improving their representation in regional high-resolution frameworks such as ALARO is essential to enhance the robustness and physical realism of future projections.

Finally, this study relies on a single ALARO simulation driven by one GCM member; consequently, internal (natural) variability and structural model uncertainty are not fully sampled. The forthcoming CORDEX.be II projections will provide a stronger basis to assess these uncertainties. In addition to new ALARO simulations based on SSP scenarios, CORDEX.be II will deliver ensembles from two other limited-area models widely used in Belgium (COSMO-CLM and MAR). These multi-model, SSP-consistent simulations will enable direct comparison with our RCP-based results, thereby improving assessments of model robustness and scenario sensitivity for precipitation whiplash.

Data availability statement

Climate model data from the ALARO simulations can be accessed via: https://ac.ngi.be/catalogue?language=en&openpath=GeoBePartners-open%2FBelgianClimateCentre&tab=dataaccess&auth=false&open=true&accesscode=A9DO3Cfh1fQpxxu3XS5J.

The data that support the findings of this study are openly available at the following URL/DOI: https://ac.ngi.be/catalogue?language=en&openpath=GeoBePartnersopen%2FBelgianClimateCentre&tab=dataaccess&auth=false&open=true&accesscode=A9DO3Cf h1fQpxxu3XS5J.

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