

Off-season extreme events under climate change

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Anthropogenic climate change has increased extreme weather and climate events (e.g., heatwaves, droughts, and floods) worldwide.¹ These events have exerted tremendous impacts on both natural and human-managed systems, not only causing illnesses and deaths, but also triggering a range of challenges in food, water, energy, and ecology.¹ Climate change has shifted the spatial and temporal distributions of the environmental conditions that favour extreme events, thus allowing extreme events to occur outside the typical seasons in which they are expected. Such off-season or unseasonal events can have unexpected or underestimated impacts on societies and ecosystems which are often less prepared (Figure 1).

Off-season extremes differ from shifts in the seasonal timing of conventional in-season extremes. The latter reflects an advance or delay in the temporal window of extreme events, whereas off-season extremes represent contrasting extremes occurring in the opposite season. This distinction extends beyond timing, as season-dependent atmospheric circulation, surface energy budgets, and land-atmosphere interactions can alter processes and impacts of these events. Off- and in-season extremes may share large-scale climate drivers, and both respond to climate change. However, the behaviors, impacts, and mitigations of off-season extremes remain largely unknown. Despite occasional sporadic public news and reports, emerging challenges of off-season events have not received adequate attention, especially from academic and policy aspects. Here we discuss these concerns and highlight potential strategies for better understanding, predicting, and mitigating off-season events in a warming world.

Typical off-season extremes include winter heatwaves, summer cold spells, rainy-season droughts, dry-season intense precipitation, and tropical cyclones occurring outside their typical season. These events can be identified relative to their local climatology. For example, a winter heatwave is defined as at least three consecutive days when daily mean temperature exceeds the local 90th percentile in the coldest three-month period.² Off-season extremes have been increasingly documented across different regions. For example, winter warm spells (or winter heatwaves) occur widely over global land areas but exhibit pronounced regional differences. During 1979–2023, tropical regions experienced more frequent and longer-lasting winter warm spells (average annual occurrence of 2.26 events and 10.62 participating days), compared with global averages of 1.92 events and 8.73 days.² In major tropical cyclone basins, the timing of intense tropical cyclone activity has advanced since the 1980s, at rates of 3.7 and 3.2 days per decade in the Northern and Southern Hemispheres, respectively.³

IMPACTS OF TYPICAL OFF-SEASON EXTREME EVENTS

Off-season events are of particular concern given the high vulnerability of both human and nature, especially challenging for communities and ecosystems unprepared for extreme hazards occurring outside their typical or expected seasons. Temperature extremes outside their usual seasons provide a typical example. Winter heatwaves and summer cold spells can increase the risks of temperature-related morbidity and mortality. Winter heatwaves can also accelerate snowmelting, thereby shifting streamflow timing and increasing snowmelt-induced flood risks. They may also favour wildfire activity and disrupt dormant ecosystems by advancing phenology and exposing vegetation to subsequent cold damage when low temperatures return. Reduced snowpack and earlier snow loss can lower spring soil moisture and increase the likelihood of hot-dry extremes in the subsequent warm season, providing a pathway through which anomalous conditions in winter propagate into summer drought and heat stress.

Hydrological off-season extremes can also pose severe risks. For example, dry-season extreme precipitation can trigger flash floods and landslides because dry or crusted soils often favour rapid runoff and limited infiltration. Rainy-season drought signals an opposite characteristic, which can disrupt agricultural production by reducing water availability during crop growth stages. The 2002 rainy-season drought in India illustrates the scale of these impacts: ~56% of the country's area experienced drought conditions, affecting ~300 million people and 150 million cattle, causing USD ~8.7 billion in crop

losses.⁴ Tropical cyclones outside their prime months can amplify risks by exposing coastal regions to storm hazards when warning systems and infrastructure operations are less prepared for unexpected occurrences.

Off-season extremes may also have impacts that extend far beyond the region in which they occur originally. For instance, rapid winter Arctic warming and sea ice loss have been linked to changes in mid-latitude circulation, and have been proposed as one pathway influencing winter cold extremes in Eurasia and persistent summer hot-dry extremes in the mid-latitudes. These teleconnections suggest that off-season events can develop more broadly and may have cascading impacts across spatial and temporal regimes.

Potential benefits of off-season extremes should also be acknowledged. Winter heatwaves may temporarily reduce heating demand of human beings, and summer cold spells may provide brief relief from ambient hot conditions. Off-season tropical cyclones and extreme rainfall can replenish soil moisture and water storage, thus alleviating dry conditions. Occasional dry-season rainfall may also support vegetation growth and partially mitigate drought stress. However, these benefits are often outweighed by hydrological, ecological, and infrastructural disruptions that arise when the events occur outside the typical seasons in which natural and human systems are organized.

POSSIBLE DRIVERS OF OFF-SEASON EXTREME EVENTS

Off-season extremes can be triggered by processes that are similar to those for in-season extremes, but the former occurs when the window favourable for those processes extends beyond its typical range. For example, winter heatwaves are often associated with the same synoptic conditions that drive summer ones, including anomalous ridging, subsidence, and warm air advection.² In the Swiss Alps, winter heatwaves have been linked to the North Atlantic Oscillation, while the February 2019 European heatwave was associated with a narrow ridge that advected warm subtropical air into the mid-latitudes. Evidence further indicates that winter heatwaves in the tropics are mainly driven by enhanced shortwave radiation under clearer and drier conditions, and non-tropical events by enhanced downward longwave radiation.² These findings suggest that winter heatwaves arise from the combined influences of synoptic forcing, local surface-atmosphere interactions, and large-scale climate variability.

A similar combination of drivers is likely to play a role in hydrological extremes and tropical cyclones. Rainy-season droughts show that the rainy season may still arrive, yet no longer function as a wet season, because longer dry spells, more dry days, and monsoon breaks can intensify droughts even without a substantial rainfall decrease. In monsoon regions, the timing and persistence of these interruptions are also strongly influenced by short-term climate variations. Dry-season intense precipitation may occur when circulation and moisture transport temporarily resemble those of the typical rainy season, as documented by the extraordinary January 2021 storm in Andes. Tropical cyclones outside their prime season months point toward a similar shift in favourable conditions. In the North Atlantic, earlier tropical cyclone activity has been linked to more favourable spring thermodynamic conditions, driven by warming western Atlantic sea surface temperatures.³

CHANGES IN OFF-SEASON EXTREME EVENTS

Climate warming is likely altering the occurrence and persistence of many off-season extremes. Winter heatwaves over global lands have become more frequent (0.224 events per decade) and longer-lasting (0.134 days per decade) since 1979, suggesting that anomalous warmth is increasingly extending into the cold season.² Off-season tropical cyclones have also increased in several ocean basins. Rainy-season droughts are likewise projected to intensify. In India, flash droughts occur predominantly during the rainy season, and events comparable to the 1979 flash drought will likely become ~7–8 times more frequent by the end of the 21st century.⁵

These long-term changes in off-season extremes reflect influences from both internal variability and external forcings. For example, El Niño–Southern Oscillation and the Indian Ocean Dipole have effects on rainfall variability and can influence rainy-season dry spells. For off-season tropical cyclones,

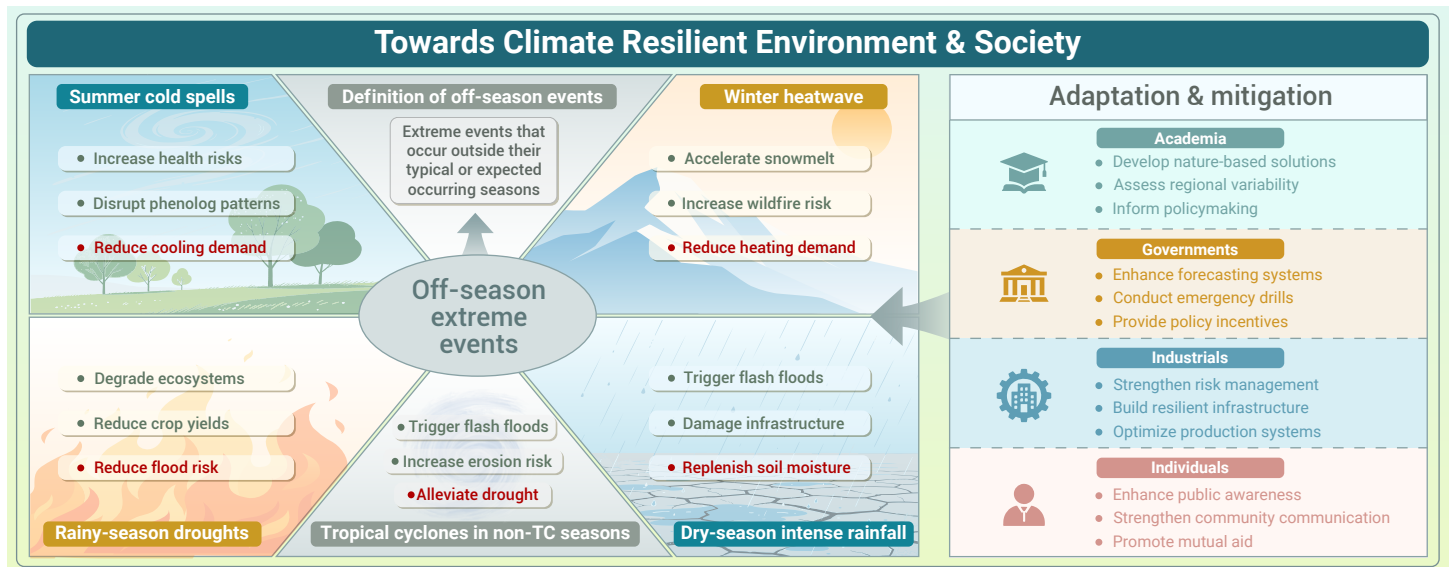


Figure 1. Impacts, adaptation, and mitigation of typical off-season extreme events.

changes in sea surface temperature, near-surface air temperature, and cloud cover explain a substantial fraction of the increasing frequency. External forcing is also evident in model experiments for rainy-season drought. Anthropogenic climate warming increases the risk of concurrent hot-dry extremes during the Indian monsoon season, with the risk ratio between the anthropogenic forcings and no-greenhouse-gas experiments reaching ~16–18 by the end of the century.⁵ These risks of off-season extremes will become more widespread under future warming. Earth system model simulations project delayed wet season and longer dry spells across parts of the extended tropics, while in northern mid- and high-latitude extreme precipitation is projected to occur more often in colder seasons. Off-season extremes will likely become a more prominent component of climate risk under future warming.

ADAPTATION AND MITIGATION OF OFF-SEASON EXTREME EVENTS

With off-season extremes becoming more frequent and more intense, more adaptation and mitigation are needed to address a fundamental mismatch between increasing climate risks and season-based management (Figure 1). Adaptation is needed to reduce vulnerability to events that are already occurring or cannot be fully avoided, particularly because many existing management systems remain organized around historical seasonal patterns, including crop calendars, reservoir operations, snowmelt and flood preparedness, and heat health plans. Mitigation addresses the longer-term development of these risks by reducing greenhouse gas emissions and enhancing carbon sinks, thereby limiting future warming and the associated changes in the occurrence of off-season extremes.

For the academia, adaptation-oriented research should improve understanding of vulnerability to off-season extremes and evaluate whether existing management and response measures stay effective when hazards occur outside their expected seasons. Greater attention is needed to forecast and project at decision-relevant spatio-temporal scales so that adaptation strategies can be adjusted to regional differences in event timing and impacts. Mitigation-oriented research should quantify how the behaviours and impacts of off-season extremes respond to different emission pathways and climate warming levels. Such analyses can help determine how much future risk could be avoided under stronger mitigation and provide a clearer basis for linking emission reductions with changes in off-season extremes.

At the policy level, adaptation measures are encouraged to incorporate off-season extremes into routine risk planning rather than relying solely on historical seasonal calendars. Multi-scale climate information should be integrated into decision-making, including short-term forecasts for early warning and emergency response, seasonal-to-interannual predictions for resource management and preparedness, and long-term projections for infrastructure design and land use planning. Mitigation measures should focus on reducing greenhouse gas emissions and strengthening carbon sinks to limit future warming and prevent further increases in off-season climate risks.

At the public and industrial level, adaptation should strengthen awareness, preparedness, and operational flexibility in sectors exposed to off-season extremes. Improved risk communication and public education are needed so that warnings outside conventional hazard seasons are recognized and acted

upon in time. Climate-sensitive sectors such as agriculture, water resources, energy, and infrastructure should adjust management practices that depend strongly on historical seasonal conditions. Mitigation requires a broader participation in low-carbon transitions, including reducing greenhouse gas emissions from energy use, production, and other sectoral activities.

CONCLUSION

Off-season (or unseasonal) extremes are emerging as an increasingly important climate risk. As climate change makes extreme events more likely to occur outside their typical seasons, relying solely on historical seasonal patterns for preparedness and response will become increasingly inadequate. Future risk frameworks should explicitly account for changes in when extreme events occur, rather than treating seasonal boundaries as fixed. This will require improved detection and prediction of off-season extremes, better assessment of their cross-season impacts, and adaptation strategies that are sufficiently flexible to respond to hazards occurring outside conventional planning periods. Also, mitigation remains essential for limiting future warming and constraining further increases in off-season extremes. Incorporating off-season extremes into climate science, policy, and risk management will therefore be critical for reducing emerging blind spots in climate preparedness and strengthening resilience under continued climate change.

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AUTHOR CONTRIBUTIONS

M.L. initiated, designed and supervised the study. S.W. and M.S. drafted the manuscript. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.