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Climate Chronicles: Compound weather and climate events in 2024

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Standfirst | 2024 saw multiple high-impact compound events. Record-breaking global temperatures combined with regional weather variability to create compound floods, spatially compounding droughts and heatwaves, and hazard sequences with often devastating impacts.

Key points:

1) Spatially compounding marine heatwaves and droughts hit the global ocean and southern Africa, respectively, causing widespread impacts on ecosystems and human societies
2) Wet soils preconditioned landscapes in the US and Nepal, amplifying impacts caused by extreme rainfall events
3) Sequences of hazards, such as droughts or heatwaves followed by heavy rainfall and the rapid succession of storms, led to large impacts in China, Australia and the UK

Compound weather and climate events refer to multiple drivers and hazards that combine to cause impacts on ecosystems and society[1]. These drivers and hazards can combine in various ways—across time (preconditioned and temporally compounding events), across space (spatially compounding events), and/or across multiple climate variables (multivariate events)—giving rise to a myriad of possible events[2]. Owing to their complex nature, compound events can result in particularly severe impacts as multiple adverse conditions can interact and amplify. Systematic monitoring of when, where and how these events occur enhances understanding of their dynamics and helps mitigate the risks associated with their impacts.

Here, we examine compound events that occurred in 2024 around the globe (**Fig. 1**). Given the vast number of individual occurrences, we focus on a selection of particularly impactful episodes across the different compound event types.

[H1] Spatially compounding events

Spatially compounding events describe those in which multiple connected locations experience the same or different hazards in a short time period[2]. In the ocean, a prominent spatially-compounding event was the widespread occurrence of marine heatwaves during 2023-2024, mainly in the North Atlantic, western Indian Oceans, and southwest and eastern Pacific. Indeed, during the 2023-2024 summer months, the number of marine heatwave days was 2.4 times higher than in any other year of the instrumental record[3]. In 2024, 21% of ocean areas experienced record-breaking annual mean temperatures. These hot temperatures impacted coral reefs worldwide, with heat-stressed corals being bleached throughout the tropics, impacting economies, livelihoods and food security.

Devastating spatially concurrent extremes also occurred over land, as epitomised by drought through much of southern Africa. Driven by the 2023 El Niño and subsequent decreased moisture fluxes, Mozambique, Zimbabwe, southern and central Zambia, Botswana, south-eastern Angola, Namibia, southern Malawi and parts of South Africa all experienced widespread drought during their austral summer wet season[4,5]. Rainfall deficits were particularly severe from January to April, with some regions receiving only 20-30% of their normal rainfall. Given that the region is home to approximately 135 million people, this spatially-extensive drought had considerable impact: crop failure and subsequent severe food shortages, limited access to clean water, disease outbreaks, and loss of livestock. However, as the event was forecasted, some of the worst impacts were mitigated.

Other 2024 spatially-compounding events include: concurrent widespread floods from Storm Boris in mid-September affecting countries include Austria, Czech Republic, Poland, Romania, Slovakia, Germany and Hungary; and extensive river and wetland flooding across northern South Sudan.

[H1] Preconditioned and multivariate events

Preconditioned events are those where pre-existing conditions amplify the impact of a subsequent hazard[2]. They can combine with multivariate events, which refer to those where multiple drivers or hazards combine to cause or exacerbate an impact. Such events were seen across South America in 2024. Widespread record-breaking high temperatures co-occurred with extremely dry conditions, with strong winds and available fuel subsequently supporting devastating fires in many regions. For instance, fast-moving fires in central and southern Chile in February were characterized as a 1 in 30-year event[6], affecting 40,000 people, destroying 7,000 homes and killing 130—the worst natural disaster in the country since the 2010 earthquake. In Bolivia, the country's most uncontrolled fire season ever recorded burned over 15 million hectares, releasing around 100 megatons of carbon and affecting more than 65,000 families, including traditional and Indigenous populations. In the Brazilian Pantanal, the largest wetlands in the world, exceptional wildfire conditions occurred in June rather than mid-September, burning 440,000 hectares (fifty times the historical average) in that month—an event expected to occur once every 35 years (refs [6,7]).

Notable preconditioning can also occur on the opposite end of the hydroclimatic spectrum. Indeed, several factors compounded to make September 2024's Hurricane Helene a >US$100-billion disaster and the deadliest mainland-US tropical cyclone since 2005 (ref[8]). In the days leading up to landfall, a stalled cold front plus orographic forcing drew tropical moisture northward, leading to heavy antecedent precipitation (100-250mm) and saturated soil moisture over the southern Appalachian Mountains. Hurricane Helene's passage over the region 24-36 hours later caused an additional 150-300mm of rain

to fall across inland portions of North Carolina, Virginia and Tennessee, a multi-day precipitation total whose estimated recurrence interval is more than 1,000 years. The sequence triggered record-breaking fluvial flooding along with landslides and debris flows. Extensive damage to the infrastructure network in narrow flood-stricken valleys complicated evacuation, response and recovery efforts, and entirely isolated some communities. Emphasizing the unexpectedness and accentuating the toll of this combination of hazards[9], uptake of flood- and earth-movement insurance in the most affected inland areas was <1% of homes.

There are various other examples of preconditioned and multivariate compound events in 2024: wet soils at the end of the monsoon season combined with extreme rainfall on September 26-28, causing flash floods in Nepal; and Cyclone Chido, which entered the Mozambique Channel on 14 December, featured compound wind and precipitation extremes impacting Mozambique, Mayotte and Malawi.

[H1] Temporally compounding events

Temporally compounding events involve a sequence of multiple hazards, exacerbating effects compared to a single hazard[2]. A rapid succession of storms is one such example[10], as in the UK during 2024. In January, for instance, there was a cluster of three storms: Storms Henk, Isha and Jocelyn. Storm Henk brought strong winds with gusts up to 81mph and heavy rain on 2 January (compounding an already wet period from late 2023) causing power outages for 38,000 properties, and severe road and rail transport disruptions from flooding. Storms Isha and Jocelyn (21–24 January) then arrived in quick succession, driven by a powerful jet stream, with Isha with gusts up to 99mph prompting extensive amber warnings and a rare overnight red warning for wind in Scotland. An additional storm cluster also occurred in late November and early December with Storms Bert, Conall and Darragh. Storm Bert (22–25 November) was the UK's first designated 'multi-hazard' storm, bringing strong winds, heavy rain and snow, with over 150mm of precipitation falling in the wettest upland areas resulting in localised flooding and fatalities. Storm Darragh followed just two weeks later, worsening flood concerns, causing multiple deaths, and leaving 2.3 million customers without power.

Temporally compounding events also include hazard sequences that swing from one extreme to the opposite, as with heavy rainfall to heavy drought--so-called whiplash events[10]. This sequencing was observed in major cropland regions between the Yellow River and Huai River in China during early summer 2024. In May-June, the regions received less than 50% of their normal precipitation, with many meteorological stations observing record low levels since 1961. These drought-hit regions were suddenly inundated with 400-600mm rain during the first 20 days of July (a doubling to quadrupling of the average precipitation). This drought-heavy rainfall combination overwhelmed the coping capabilities of farmers, with maize and rice yields amongst the most affected. Such whiplashes between dry and wet conditions are expected to intensify with climate change[11].

Temporally compounding hazards can also consist of different hazard types. For example, increased atmospheric instability and moisture availability during some heatwaves can subsequently intensify extreme rainfall[12]. This temporal sequence was observed in south-eastern Australia toward the end of 2024, affecting the major cities of Sydney, Melbourne and Canberra. The region witnessed heatwave conditions in November followed by an outbreak of severe storms with heavy rainfall and damaging wind gusts. The event was most severe over eastern New South Wales where the heatwave persisted from 23-29 November, with five consecutive days above 35˚C in Penrith, peaking at 39.9˚C. Heavy rainfall (>97th percentile) followed on 30 November-1 December, with Sydney Airport receiving

79.4mm on 30 November. The event also affected the state of Victoria, but with a shorter heatwave (21-24 November) and less severe rainfall (27 November). Property damage occurred due to flooding and strong winds.

Other temporally-compounding events include: sequences of heavy rainfall during different stages of the growth cycle causing drops in crop production in many parts of Europe; two tropical cyclones making landfall in Shanghai within only 4 days (16-19 September) the first being the strongest hitting Shanghai and Jiangsu Province in the past 75 years; and successive rounds of thunderstorms across the US Upper Midwest in June leading to flooding and a partial dam failure.

[H1] Summary

Compound weather and climate events were ubiquitous in 2024. To varying extents, they were driven by extremely high temperatures at the global scale, high atmospheric moisture capacity (and related vapor-pressure deficit) and a decaying strong El Niño. 2024 was the hottest year on record and a harbinger of a 1.5°C world[13]. Compound events that feature extremely high temperatures as one of the drivers or hazards – like spatially concurrent heatwaves, compound hot-dry events and widespread wildfires – are more likely to occur under such conditions. Continuing climate change will lead to even more such events in the future, while a generally-intensified hydrological cycle will also render co-occurrences and sequences with other hazards more likely, such as heavy precipitation and widespread drought. The diversity in scales, involved variables, and relevant interactions, as well as the devastating impacts, highlights the urgent need to better understand, model and project compound events in a changing climate.

References

1. Zscheischler, J. *et al.* Future climate risk from compound events. *Nat. Clim. Change* **8**, 469–477 (2018).
2. Zscheischler, J. *et al.* A typology of compound weather and climate events. *Nat. Rev. Earth Environ.* **1**, 333–347 (2020).
3. Smith, K. E. *et al.* Ocean extremes as a stress test for marine ecosystems and society. *Nat. Clim. Change* 1–5 (2025) doi:10.1038/s41558-025-02269-2.
4. Kimutai, J. *et al.* El Niño key driver of drought in highly vulnerable Southern African countries. (2024) doi:10.25561/110770.
5. Manatsa, D., Mushore, T. & Lenouo, A. Improved predictability of droughts over southern Africa using the standardized precipitation evapotranspiration index and ENSO. *Theor. Appl. Climatol.* **127**, 259–274 (2017).

6. Kimutai, J. *et al.* Despite known coastal cooling trend, risk of deadly wildfires in central Chile increasing with changing land management in a warming climate. (2024) doi:https://doi.org/10.25561/109375.
7. Barnes, C. *et al.* Hot, dry and windy conditions that drove devastating Pantanal wildfires 40% more intense due to climate change. (2024) doi:https://doi.org/10.25561/113726.
8. Thiem, Haley & Lindsey, Rebecca. Hurricane Helene's extreme rainfall and catastrophic inland flooding. https://www.climate.gov/news-features/event-tracker/hurricane-helenes-extreme-rainfall-and-catastrophic-inland-flooding (2024).
9. Heinrich, D., Stephens, E. & Coughlan de Perez, E. More than Magnitude: Towards a multidimensional understanding of unprecedented weather to better support disaster management. *Water Secur.* **23**, 100181 (2024).
10. de Ruiter, M. C. *et al.* Why We Can No Longer Ignore Consecutive Disasters. *Earths Future* **8**, e2019EF001425 (2020).
11. Swain, D. L. *et al.* Hydroclimate volatility on a warming Earth. *Nat. Rev. Earth Environ.* **6**, 35–50 (2025).
12. Sauter, C., Catto, J. L., Fowler, H. J., Westra, S. & White, C. J. Compounding Heatwave-Extreme Rainfall Events Driven by Fronts, High Moisture, and Atmospheric Instability. *J. Geophys. Res. Atmospheres* **128**, e2023JD038761 (2023).
13. Bevacqua, E., Schleussner, C.-F. & Zscheischler, J. A year above 1.5 °C signals that Earth is most probably within the 20-year period that will reach the Paris Agreement limit. *Nat. Clim. Change* 1–4 (2025) doi:10.1038/s41558-025-02246-9.

End matter

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Competing interests

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Figure 1. **Compound events in 2024.** Select examples of spatially-compounding, temporally-compounding, and preconditioned or multivariate compound events that occurred in 2024.