

Multi-hazard dependencies can increase or decrease risk

In risk analysis, it is recognized that hazards can often combine to worsen their joint impact, but impact data for a rail network show that hazards can also tend to be mutually exclusive at seasonal timescales. Ignoring this overestimates worst-case risk, so we therefore champion a broader view of risk from compound hazards.

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The interplay among natural hazards affects risk globally, and this is expected to evolve as climate changes (for examples, see refs. 1–3). Conventional modelling has focused on impacts from each hazard in isolation^{4,5}, but this is being transcended by a ‘compound event’ paradigm for multi-hazards^{3,6}. Over meteorological timescales (hours to weeks), hazards like wind and precipitation extremes can combine to exacerbate total risk^{7–9}. However, infrastructure operators, government agencies, (re)insurance and health services are also interested in aggregated risk over climatological timescales (seasonal to annual). Using Australia and Great Britain

as examples, we illustrate that, from this perspective, some hazards tend to be mutually exclusive due to low-frequency modes of variability. Pairwise views of a multi-hazard environment that target instances where risk is exacerbated^{7–9} might therefore overestimate worst-case risk. This complication is one reason for the ongoing development of multi-variate statistical frameworks to better model hazardous extremes^{10–13}, but cases are under-reported. Thus, we highlight the need for a broader and more holistic view of multi-hazard risks applied at spatial scales meaningful to stakeholders, which include the climatological timescales relevant to them. From this standpoint, it becomes

clear that hazards can be influenced by modes of atmospheric variability in ways that reduce the likelihood of some hazard combinations, thereby moderating tail-end (that is, worst-case) risk (Fig. 1). How such risk moderation works is explained using an analogy of rolling dice and by relating hazards to climate modes, such as the El Niño/Southern Oscillation (ENSO).

El Niño example

Consider weather-related hazards in Australia. During summer, El Niño tends to reduce the likelihood of tropical cyclones² and flooding⁸, but enhances drought¹⁴ and wildfire¹⁵ risk, whereas La Niña drives the

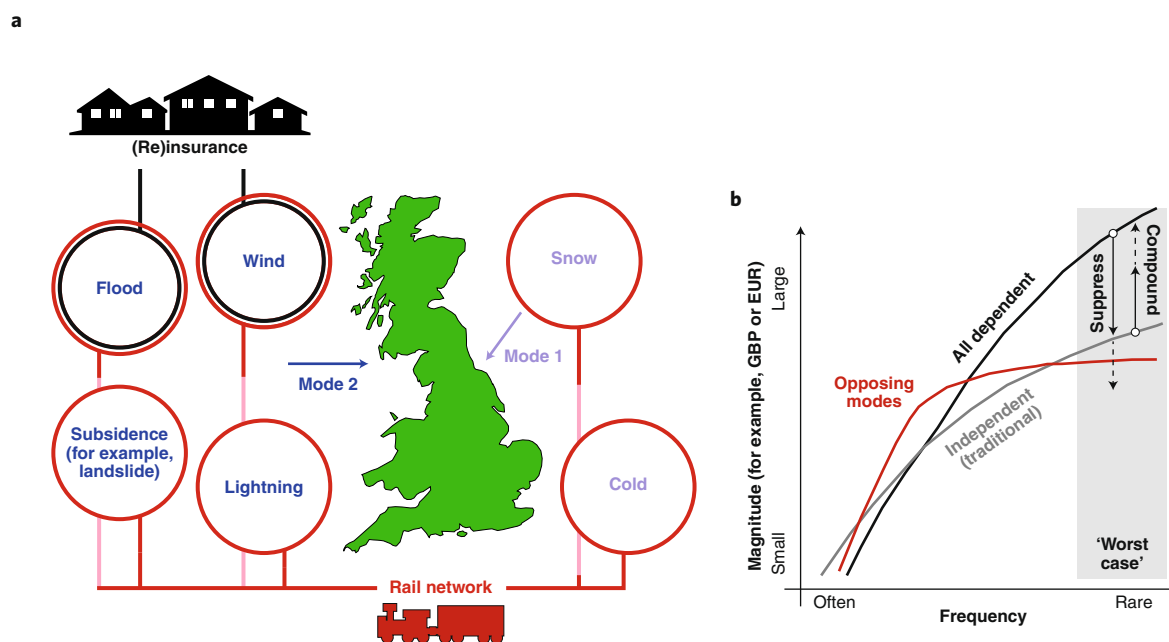


Fig. 1 | Illustration of plausible effects when the activity of hazard(s) switches between climatologically controlled modes of behaviour, based on Great Britain. a, Impact-centric^{1,3} conceptualization of the multi-hazard system. Two hazard modes, each associated with a dominant wind direction (blue arrows), drive six hazards (circles). Rail infrastructure (red) is exposed to all six hazards, while (re)insurance (black) is primarily concerned with only two hazards in Mode 2. **b**, Losses in terms of magnitude and frequency, with rare ‘worst cases’ on the right-hand side (grey band). A conventional view that does not consider dependencies (grey) might underestimate risk if two hazards (for example, flood and wind) compound. However, where exposed assets are subject to hazards driven by two opposing modes (red), compounding effects are suppressed, so care is needed to avoid overestimating risk. Solid arrows represent effect magnitudes seen within the Network Rail loss data (Fig. 2 and Box 1), with dashed lines indicating plausible stronger effects.

Box 1 | A case study of compound risk in Great Britain

A case study of weather-related impacts (Fig. 2a and Supplementary Discussion 1) on the rail network in Great Britain illustrates that interactions may suppress tail-end (worst-case) risk, mitigating pairwise compound effects (Fig. 2d). Here, impact is expressed as delays to trains which, when monetized, cost Network Rail an estimated £64.6 million annually. Most (72.5%) of these costs occur in the 'winter' half-year (October–March). Thus, winter is selected as our temporal domain for a seasonal-scale analysis, which in Great Britain is hydro-meteorologically distinct from summer (see Supplementary Fig. 1).

From a narrow (bivariate) multi-hazard perspective, the largest losses (13-yr return period) for flooding and wind damage (Wi) compound substantially (+28%), as shown in Fig. 2d. Simulation modelling^{1,10} is conducted to demonstrate that this observation (dark blue line) is not due to chance ($P < 0.05$) by breaking all hazard inter-relationships. In the simulation (see Supplementary Discussion 1), this was achieved by shuffling the years in which losses occur independently for each hazard,

and 10,000 of these random realizations are used (dashed line).

However, a wider (multivariate) view yields a distinctly different outcome. When one set of hazards in Great Britain is active, the other main group is typically not. The categories of loss may be, visually or otherwise, grouped into subsets that tend to coincide (that is, are correlated; Fig. 2b). Specifically, when flooding and wind damage incidents are prevalent, impacts due to cold and snow are muted. When summed in pairs (snow + cold and flooding + wind damage), there is no overlap between the years in which each pair's top five losses occur ($P = 0.024$, χ^2 test), and an inverse correlation is evident (Fig. 2e). In Fig. 2d, this mutual avoidance expresses itself as the largest losses (that is, a 13-yr return period) being suppressed to the level of entirely random selection (dashed line), even as each of the pairs is demonstrated to compound (blue lines). This new observation adds to growing evidence of a seasonal scale flooding–wind damage association for Great Britain^{1,7,18}.

We propose the term 'hazard modes' for subsets of partially associated hazards (Fig. 2b). For Great Britain, we hypothesize a simple westerly versus north-easterly driver of the hazard modes (wind damage + flooding; westerly, or snow + cold: north-easterly; Fig. 2c). Low pressure systems (named storms) are associated with westerly and cyclonic synoptic-scale atmospheric patterns¹⁸, and although individual storms are typically viewed as either causing flooding or wind damage^{4,16}, some cause both (for example, Storm Desmond); particular seasons have also been identified as notably 'wet and stormy'¹⁸. Opposing this behaviour, episodes of extreme wintertime cold or snow in Great Britain are typified by advection of cold air from the north and east, and 'blocking' anticyclonic circulation^{5,19}. The wintertime frequency of mobile westerly and cyclonic flows are known to trade off against more stable anticyclonic conditions²⁰. Here, we show that the North Atlantic Oscillation is a useful metric to capture these behaviours through its correlations with the hazard modes (Fig. 2f,g).

opposite conditions. Under the present climate there are then two regimes or modes of hazard behaviour which are unlikely to co-occur. Concurrent impacts from both cyclone- and drought-related hazards are unlikely when either mode is active, making severe aggregate impacts from all four hazards less likely than might be expected if the two hazard modes were independent. This creates the possibility that, if a tendency for hazard modes to be mutually exclusive exists but is not accounted for, a focus on damaging extremes that compound to worsen impacts (individually^{5,15,16} or in pairs/triplets^{7–9}) may overestimate risk. Numerous oscillatory climate modes (for example, ENSO and the North Atlantic Oscillation (NAO)) have been related to the activity level of hazards^{2,16}, meaning that cases similar to this Australian example may not be unusual.

Illustration using dice

A probabilistic configuration of multi-hazards that protects against worst-case combinations can be illustrated by rolling dice. Imagine that flooding and wind damage happen if a six is rolled on a standard die. In traditional risk analysis¹⁷, flooding and extreme winds are treated as independent phenomena so would have a

die each. A 'worst case' scenario is when both occur (two sixes), on average 1-in-36 throws. If flooding and wind always happen together, however, only one die is needed and both hazards occur if a six is thrown (1-in-6 rolls). Thus, assessing such hazards independently underestimates risk^{7,9,17}. Flooding and wind damage in a tropical cyclone are strongly related⁸ and thus close to this specific case. To replicate a situation where flooding and wind never happen together, a rule is introduced that rolling a six on one die dictates (somehow) that the other die must score a one; two sixes are not allowed. Hence, neglecting a relationship in which states are mutually exclusive overestimates worst-case risk.

Where there is a weaker tendency for phenomena to occur together, such as for flooding and wind in extratropical cyclones¹⁷ (Box 1), two similarly loaded dice is a more apt analogy. Both would tend to score high or low such that the chance of two sixes is greater, perhaps 1-in-12. On the other hand, hazards (for example, flooding and wildfire in Australia) might tend to be mutually exclusive over a season or year. Then the loading of the dice would be such that if a six is rolled on the first die, the chance of a second six is reduced. This lowers the probability of

two sixes, a worst-case impact, to perhaps 1-in-60 throws on average. Supplementary Discussion 3 describes a series of exercises using standard dice that can be used to illustrate and verify these statistical assertions. These arguments apply to ENSO-driven hazard modes in Australia and to impactful winter weather in Great Britain.

Great Britain case study

Given that risk relates to potential for loss, an impact-centric approach^{1,3} is essential. The holistic view advocated here requires consideration of multi-hazards and their dependencies at timescales relevant to stakeholders for their hazard-specific exposure (that is, assets at risk; Fig. 1a). For instance, wintertime weather-related impacts on the rail network in Great Britain (2006–2018) quantitatively show how such interactions can suppress tail-end risk, mitigating pairwise compound effects (detailed in Box 1). In a narrow (bivariate) multi-hazard view, based on the idea that storms might drive concurrent flooding and wind damage^{7,8}, the largest losses for these hazards compound substantially, increasing by 28% above those simulated when assuming that the damage types are independent (Fig. 2d). This view is

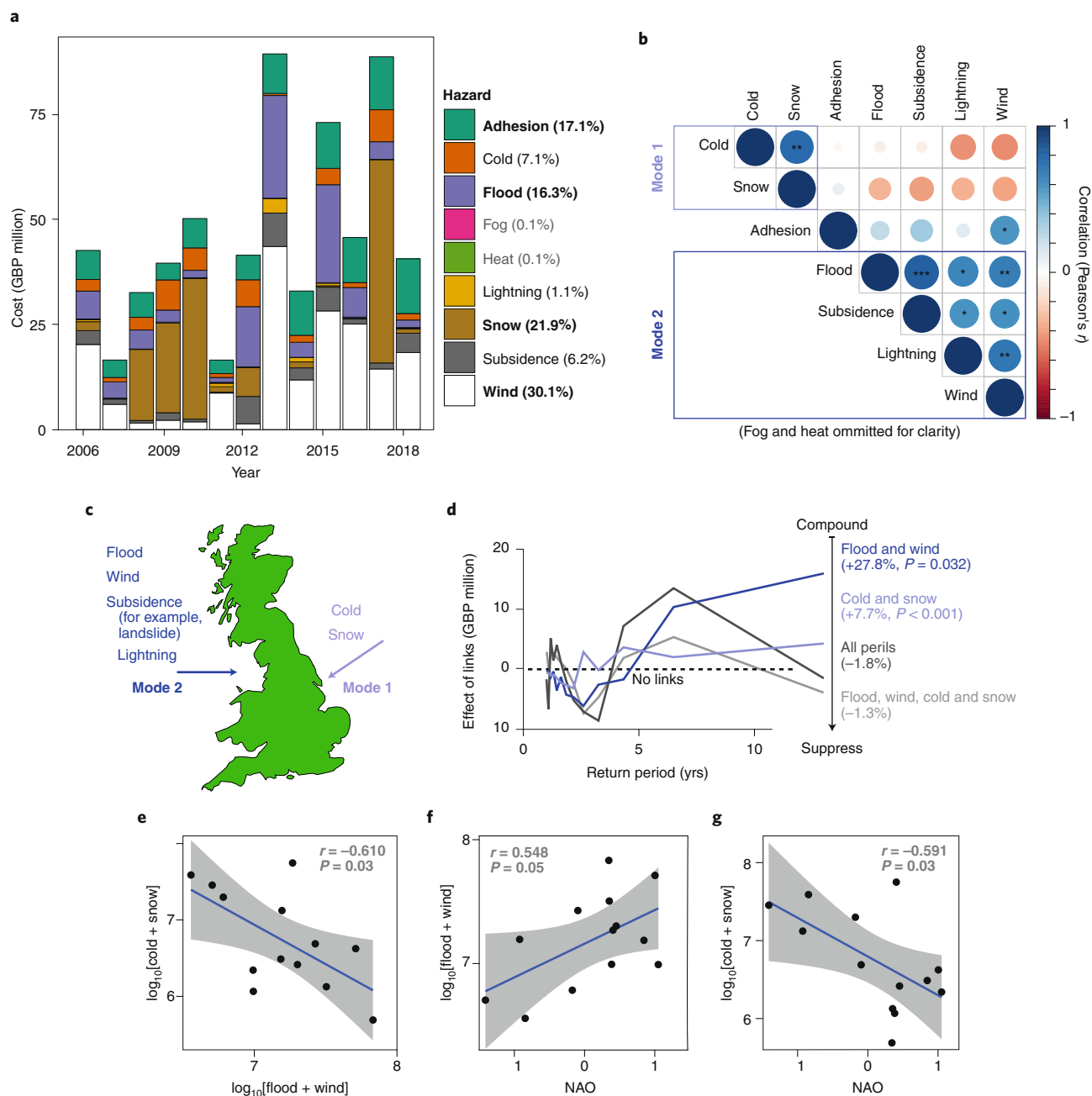


Fig. 2 | Winter multi-hazard impacts in Great Britain. **a**, National total winter (October–March) losses for nine hazards affecting Network Rail, of which seven are substantive, namely <0.1% of total losses. **b**, Correlations between the loss classifications. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$. **c**, Illustration of the proposed ‘hazard modes’. **d**, The effect of interdependencies between hazards upon seasonal loss totals calculated as the difference between observations (solid lines), and simulation modelling in which randomization has been used to break any process-based linkages between hazards (dashed line). Larger, rarer losses have greater return periods in this exceedance probability plot. Loss values greater than zero indicate that selected hazard combinations compound, or alternatively negative values show that combined impacts are suppressed. Statistical significance of the tendency to compound is computed using the AEP method¹ and simulation. Details of data and simulation methods are provided in Supplementary Discussion 1. **e–g**, Scatter plots showing correlations between paired categories of losses, and between these pairs and the NAO. Pearson's r and its statistical significance are displayed, and the grey shading represents the 95% confidence interval for the trend line.

appropriate for domestic property (re) insurance where these two hazards dominate¹. However, Network Rail is also exposed to substantial cold and snow impacts, which themselves compound

by +8% during winter. Assuming now that hazards are paired, but the pairs are independent given that no published study explicitly suggests otherwise, yields a simulated increase in overall loss of

+17%. However, these calculations would overestimate risk. This is demonstrated by simulating the total effect of all dependencies acting together on these four hazards, which results in little net effect

(approximately –1%; Fig. 2d). This occurs because when flooding and wind incidents are prevalent, impacts due to cold and snow are muted. Therefore, a broad multi-hazard approach evidently leads to a very different conclusion from bivariate view(s) (Fig. 1b).

Mutual exclusivity is not self-evident. Storm Ciara (8–10 February 2020) led to disruption from snow, flooding and wind damage. However, some hazards are more likely under particular synoptic-scale conditions^{16,18,19} (weather types²⁰), so if the frequency of a weather type is high over the season, the damage from its associated hazards will also be high. Mutual exclusivity arises as the frequency of different weather types trade off against one another²⁰. The greater the difference in hazard likelihood between weather types and the clearer the seasonal trade-off in their frequency, the stronger this effect will be.

For Great Britain, wintertime frequencies of cyclonic (flood and wind damage^{7,18}) and anticyclonic or north-easterly (cold and snow damage^{5,19}) weather types show strong compensation²⁰, explaining the emergence of ‘hazard modes’ (Box 1). These modes, however, may not persist in a future climate. Even if the trade-off in circulation types persists, air masses associated with cold and snow hazards may warm sufficiently to no longer yield damage, reducing annual average losses by ~30% (Fig. 2a). To resolve the effect of such dependencies and to test simplified hypotheses like this, statistical frameworks for multivariate extremes^{10–13} and/or climate models are needed.

A broader view of compound risk

In summary, dependencies between causative hazards can both compound and suppress risk (for examples, see refs. ^{1,3,9}; Figs. 1b and 2d). Both over and under-estimation of risk is problematic for the systems and people affected. To neither waste resources nor to be underprepared, scientists, society and decision-makers need to be alert to both. To date, however, the focus of the modelling community (especially within climate science) has been on those aspects of dependency that

make outcomes worse. Our contribution highlights that the opposite can also be true (Fig. 1b). We therefore advocate a broad view of compound risk — a refinement of the established ‘compound event’ viewpoint that might better serve hazard and risk management communities.

The term ‘compound’, as applied to risks, developed from its meaning ‘make (something bad) worse; intensify the negative aspects of’^{23,6,17} (see Supplementary Discussion 2). Recently, the definition has been expanded^{3,6}, but only rarely is a beneficial side effect³ or reduction of risk noted as a caveat²¹, and the importance of these tends to be downplayed. We believe that this wider description, including such positive connotations, is viable, as the word compound also means to ‘mix or combine constituents’ (in this case, a mix of hazards). An ‘event’, however, is an occurrence rooted in a specific time and place. Thus, perhaps the phrase ‘compound event risk’ could be explicitly kept narrow. Conversely, we advocate that ‘compound risk’ be applied more holistically and used to accommodate compound events^{3,6} that increase impact severity, but also used to include those impacts that combine within extended timeframes and those that combine in ways that are mutually exclusive.

Based on the examples above, situations are likely to be common globally where multi-hazard risk is systematically suppressed with respect to selected narrow (for example, bivariate or pairwise) configurations. We suspect that these are under-diagnosed due to (1) lack of systematic collection and analysis of impact data; (2) difficulties in comparing hazards (for example, time lags between extreme events, different hazard metrics^{1,17} and time lags between end-member conditions, like El Niño/La Niña); and lastly (3) a need for greater awareness that such situations should be identified. The subtle balance between hazards is also non-stationary as climate changes^{2,3}, so diagnosis is needed for future climates. Moreover, dependencies are not only between causative hazards but are also embedded in vulnerability

and how impacts cascade³. Broad, holistic, stakeholder-relevant assessments of compound risk for multi-hazard environments are therefore needed to improve assessments of current and future risk. □

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Additional information

Supplementary information is available for this paper at <https://doi.org/10.1038/s41558-020-0832-y>.