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Interactions between apparently 'primary' weather-driven hazards and their cost: Supplementary Material

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Here we provide further information on the current extent of knowledge about the linkages (e.g., FL↔SS) that can be postulated for four hazards (SS, FL, WS, FT) that are arguably the UK's main source of risk (i.e., losses)[1,2]. Possible inter-relationships can be conceptualized as linked risk and hazard systems which, as they are primarily weather-driven, are underpinned by the climatic system (Fig. 1). Risks associated with a hazard in the financial system are denoted with a prime (e.g., FL').

Understanding hazards in terms of physical processes associated with climate or weather is extremely well studied[3–11], even if more work is usually called for[12,13]. Hazard-risk conversions for three 'primary' UK perils (i.e., for FL, WS and SS) have received extensive consideration independently[3,8,14–20]. In particular, they have had science-driven probabilistic exposure based 'catastrophe model' of them constructed for insurers (e.g., by AIR, RMS, EQECAT, SwissRe)[21–24]. Thus these vertical bars on Fig. 1 are marked as bold arrows. Such well-established conversions are a strong indicator that that linkages between perils in one system will reflect the other; namely if FL↔SS is demonstrated then FL'↔SS' is to be expected to behave consistently with it. Also note that, within a peril (e.g., FL), it is not unusual for studies to consider the whole pathway from climate system to impact and its management[3,8,25–27]. Periods of extreme cold in the UK and Europe have been studied[11,28], and the physics of pipes splitting by freeze-thaw has been modelled[29], but the focus of analysis for damaging (e.g., Dec 2010) is mainly confined to infrastructural pipes[30–32]. Thus published considerations of domestic UK freeze-thaw (FT') risk are embryonic[33], and catastrophe models do not currently exist[34]. However, this review focuses, to the extent that it is possible, on the less-studied inter-hazard linkages and inter-risk linkages.

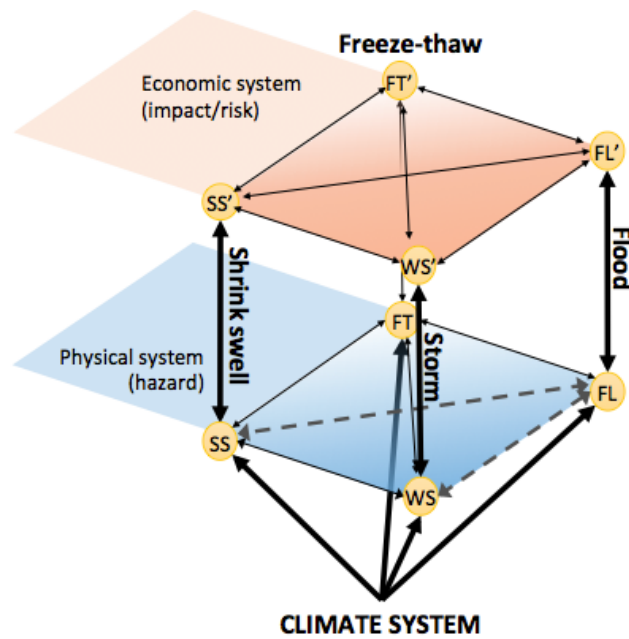


Fig 1: State of investigation into potential inter-relationships between the climate system, hazards (e.g., FL) and impacts (denoted with a prime, e.g., FL') in the UK. Bold arrows indicate previously well-studied links, such as the conversions from each hazard to risk (i.e., vertical bars such as $SS \leftrightarrow SS'$). Dashed grey arrows indicate interactions for which there is related study, but no previous suggestion of a systematic intra-annual linkage. Other potential interactions between the hazards (e.g., $FL \leftrightarrow SS$) or risks (e.g., $FL' \leftrightarrow SS'$) are much more poorly understood[35] (thin lines).

A recent review[36] collates global evidence for links between hazards, inter-hazard links (e.g., a primary hazard triggering a secondary one), spatial overlap and the temporal likelihood of triggering relationships. However, the review identifies no pertinent studies for 'primary' hazards in the UK. Storm surge following a storm[5] is modelled in the UK[22], but the major hazards (e.g., WS, FL, SS) are typically considered separately, and are thus considered here as 'primary'. Heatwaves, storms and precipitation have been considered in the same model (PRUDENCE study)[13], but their interaction was not considered. Illustrative examples (e.g., 2013/4 storms)[37] and modelling exist for some postulated interactions, but robust, long-term and systematic linkages have not been demonstrated observationally.

For the $FL \leftrightarrow WS$ linkage flash floods, pluvial flooding, and floods small catchments can be generated by single storms[26,38]. Sequences of cyclones such as in the winter of 2013/2014 have been suggested to lead to conditions (e.g., saturated soil) favouring flooding in larger catchments[37], perhaps via associated atmospheric rivers[39] or fronts[40]. However, anecdotally, events that cause major wind damage do not tend to be the same ones that cause flooding, presumably because fast moving systems do not loiter to deposit high levels of spatially concentrated precipitation. Despite this, there is no systematic evidence of an interaction within meteorological years between events that cause wind damage and those that dispense major (i.e., large scale) flooding.

In the context of major risks to the UK, the postulated $FL \leftrightarrow SS$ linkage refers to a spatially coherent effect across a large area (e.g., 100 km), and is therefore not related to the limited work on the shrink-swell of ground within single floodplains[41]. Equally, it is not driven by water escaping from pipes[9,27]. Both FL and drought have been evaluated together[10,42], but not in terms of their intra-annual interaction, and focusing on other aspects of drought (e.g., a deficit of water for use) rather than shrink-swell. Interestingly, European heatwaves (1901-2005) have found to be preceded by a winter moisture deficit[43,44]. So, meteorologically, we can postulate seasonal-scale modulating factors

consistent with less flooding in the winter preceding SS. No suggestions, however, of a SS↔WS linkage were found. Thus, we believe that it is reasonable to say that these links are relatively unstudied.

Relationships between FT and the other hazards (i.e., FL, SS, WS) do not appear to have been investigated directly. Multiple studies, however, have created links with multi-decadal modes of climate variability such as the North Atlantic Oscillation (NAO). Both extreme heat and cold have been shown to be associated with blocking anti-cyclones[45,46], but promoted by positive[47,48] and negative[11,28] phases of the NAO respectively. Thus, some inverse relationship might be expected through this modulation. Similarly, cold events in the UK typically involve easterly advection of cold air masses (e.g., from the Arctic, Russia, Greenland)[45], whilst extreme winter storms arrive from the west[49]. Since these are opposing wind directions, years may favour one or the other and a tendency may exist for windy and wet years to not be so cold.

A review was conducted of grey- and peer-review literature for analyses relating to inter-risk relationships (e.g., FL'-WS'), but very little was found, even in resilience reviews[42] and reviews that favour its incorporation into modelling[36,50]. This is consistent with interactions being considered a key unknown in the next UK National Climate Change Risk Assessment that was missing from the first one[35]. In industry, multi-risk and multi-hazard models are considered to be in their infancy[51]. A partial exception is AIR's US and China 'Multiple Peril Crop Insurance' model[52], where an 'Agricultural Weather' index is constructed from multiple hazards (e.g., temperature, precipitation, soil conditions), then probabilistic impact footprints created using the index. This, however, does not explicitly consider the interactions, and is not for UK. Thus, risk interactions are essentially unstudied either for themselves or to gain insights into the driving hazards.

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