European windstorm triplets in UKCP18, present and future

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1 ABSTRACT

In wintertime, infrastructure and property in NW Europe are threatened by multiple meteorological hazards, co-occurring in stormy episodes that last days to weeks. Storm sequence (Dudley, Eunice, Franklin) is a classic example, bringing a mixture of disruptive extremes including damaging winds and flooding that caused losses of €3.8 billion over 7-10 days in Feb 2022. Yet, triplets containing three distinct events are rarely studied systematically. Great Britain (GB) is selected here as it is a sentinel location for weather that later tracks into NW Europe. Adaptively positioned time windows of length Δt are used to group events as a stakeholder might, placing maximum potential loss within each window. A wind event set (n = 3,426, Hillier et al, 2025) from the 12km regional UK Climate projections (1981-1999, 2061-2079) is matched to high-flow events (n = 14,400, Griffin et al, 2023) using windows of Δt = 21 days. Using statistical simulation modelling, triplet events are shown to increase in future climates (p < 0.05). Illustratively, (1981-1999, Δt = 21, 95th percentile) the return period of 2 widespread floods and 1 extreme wind event is x10 lower than the expectation of independence, namely 100 vs 1,000 years! This has implications in terms of planning and preparedness for (re)insurers and wider society (e.g. infrastructure providers).

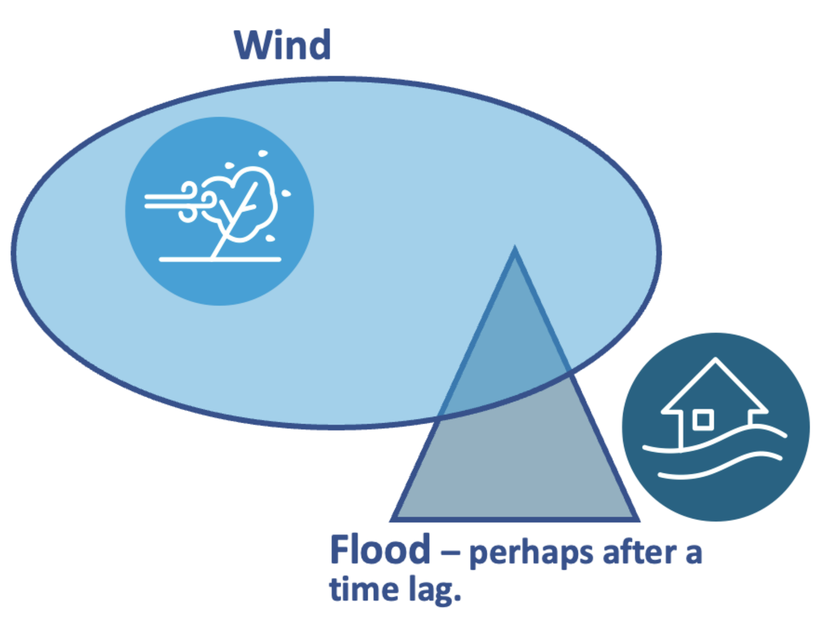

FIG 1: Illustration of how two perils - flooding and extreme wind - may co-occur, highlighting some points to note. (1) The oval and triangle are footprints - or area impacted - for an 'event', which may last 1 or serveral days. (2) Footprints may be different sizes, shapes and in different places. (3) There may be a time-lag between the events of the same or different types, combining into what we call a multi-hazard *episode*.

2 EVENT SETS

A wind event set (n = 3,426) is created from the 12km regional UK Climate projections (1981-1999, 2061-2079) to match previously created high-flow events (Griffin et al, 2023). Fig. 2 demonstrates the expected pattern that wind events are brief and widespread, whilst floods are of smaller extent by longer duration, with rainfall somewhere in between. This is similar for the two time periods, indeed the only statistically significant change is +18% for flooding events.

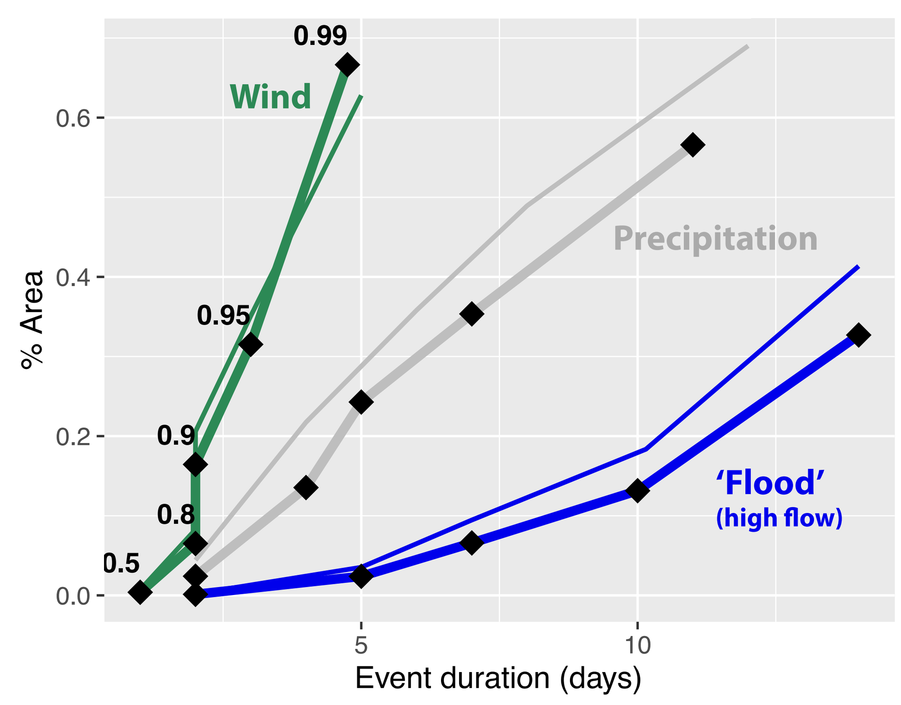

FIG 2: Size and duration of events created for Wind, Precipitation and Flood. 'Flood' events are high-flow events created by Griffin et al (2023). Percentiles are shown from 50th to 99th, calculated separately for duration and area (i.e. this is **not** a joint distribution as it's for illustrative purposes only). Present (thick lines) anf future (thin lines) are similar.

3 METHOD - Overview

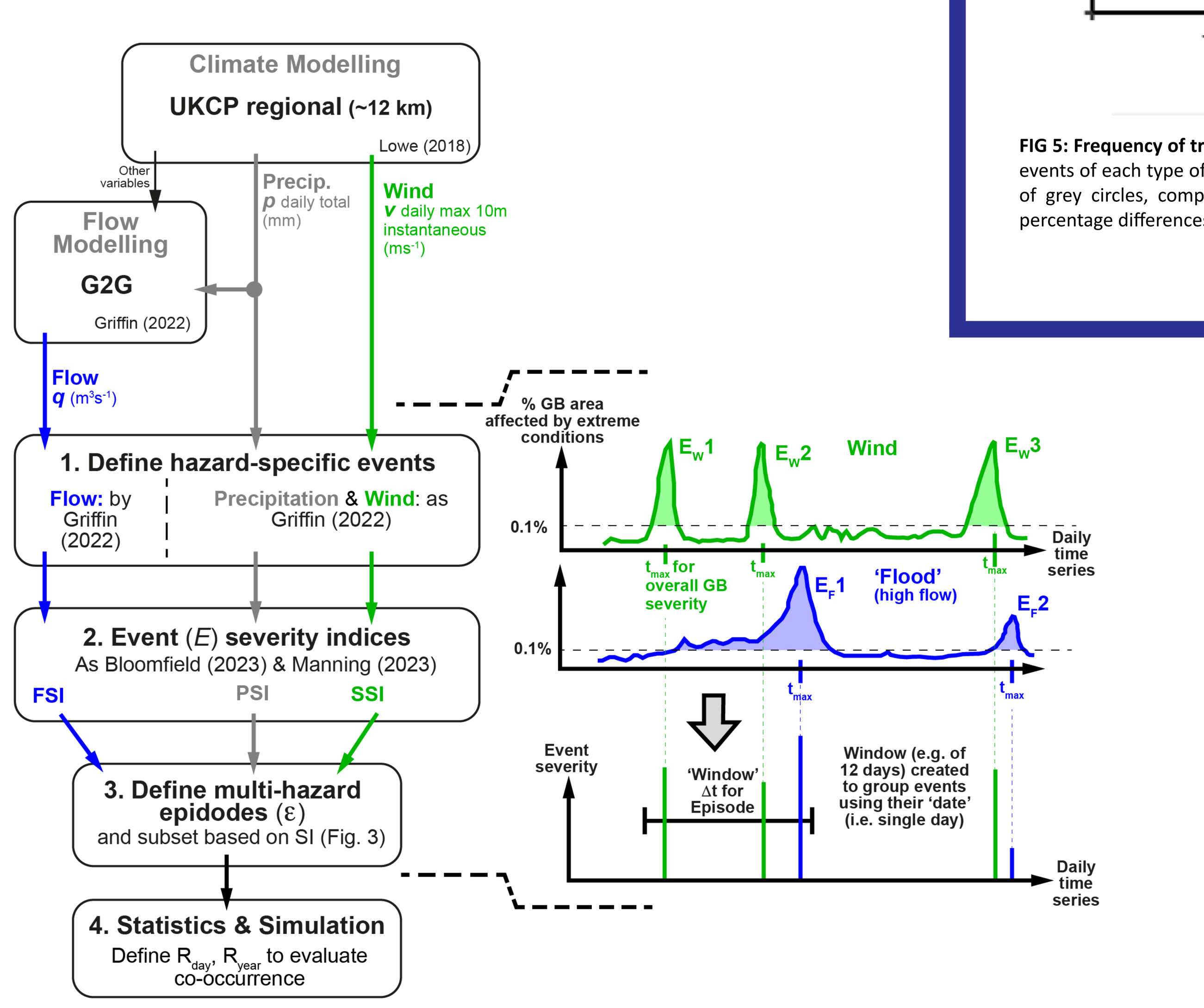

FIG 3: Workflow used in this analysis, including definitions for some of the variables. Details in Hillier et al (2025). For the flow data from Grid-to-Grid (G2G) (Griffin et al., 2022a), 0.1% of the river network is ~20 cells, or > ~20 km2. For the UKCP18r data on wind gusts and precipitation 0.1% is of the GB land area is >=2 cells or ~300 km2. To find the largest SI to create episodes, FSI and SSI are normalized so that their 95th percentile values are equal (ratio = 1.0). In reality, rare storms might have twice the impact of floods (e.g., Hillier et al., 2024), but sensitivity testing shows that ratios of 0.5 and 2.0 have minimal effect on the episodes defined. Time series are illustrative, not real data. Precipitation is included for completeness.

4 RESULTS - Sequence of events during episodes (i.e. n >= 2)

- Wind and precipitation event occurrence peaks at t = -2, a perfectly sensible duration of up to 48h for flooding to occur after a storm.
- No evidence of position of second wind event is anything but random (i.e. most severe one could be first, middle or last).
- Exclusion around the peak extends beyond 1 day buffer required by event definition, due to duration of events, and is asymmetrical (i.e. there are more before events before the main peak than afterwards, $p < 0.05$).
- This is due to flow in a flood event peaking early then tailing off, and possibly also a tendency for wetting up during an episode (i.e. soil saturates).
- So, **the relative timing of secondary events** within a longer multi-hazard episode, aside from the short term Δt = 3 linkage, **is essentially random. This demonstrates that persistence of conditions conducive to storm formation is critical to the most costly triplet episodes.**

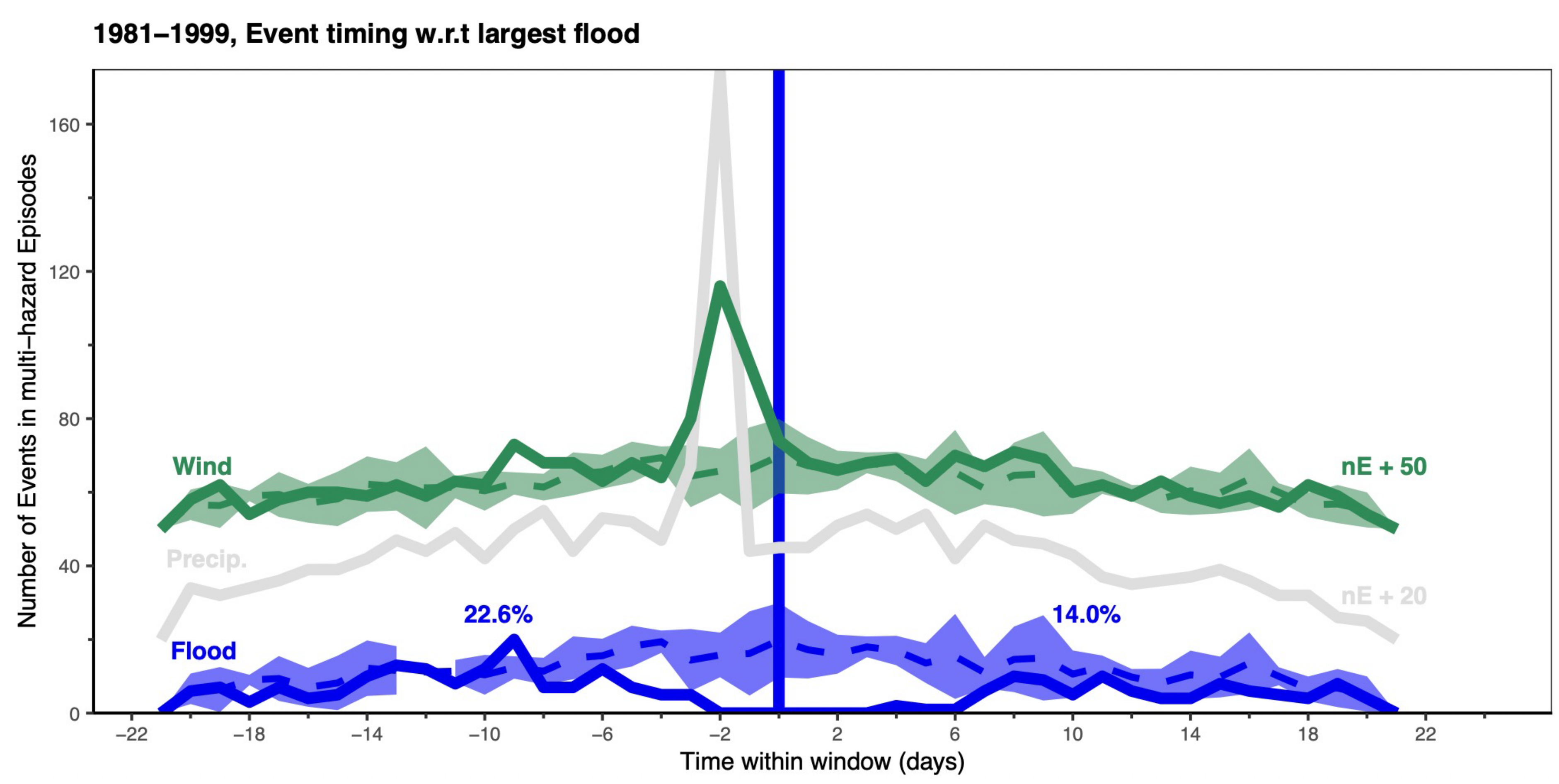

FIG 4: Anatomy of flood-wind episodes in terms of a frequency plot of their time-sequence during a 21-day window, in the recent historical time period in UKCP18 (i.e. 1981-1999). All events are stacked around the most severe flood (i.e. largest FSI). Solid lines are directly from UKCP18. Dotted lines represent a null hypothesis, created from realisations where the same events have had their year randomised and thus any sequencing within events originating in UKCP18 weather eliminated.

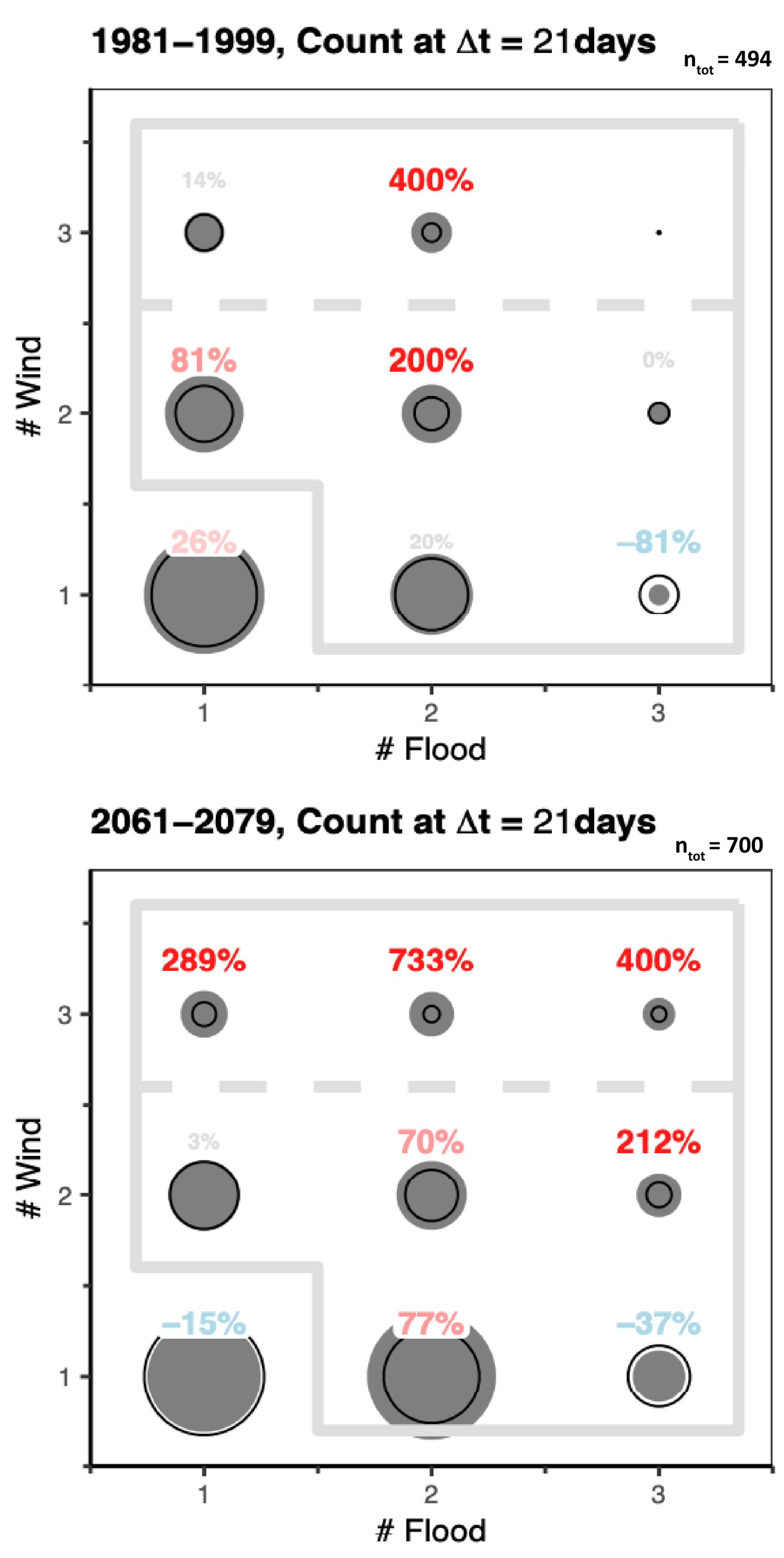

FIG 5: Frequency of triplet occurrece (Δt = 21 days, 75th percentile) in terms of the number of events of each type of they contain. a) Number of episodes in 1981-1999, proportional to area of grey circles, compared to the independent case (black open circles). Numbers are the percentage differences, coloured according to magnitude and sign. b) as a) for 2061-2079.

5 RESULTS - Triplet occurrence

Multi-hazard episodes involving flooding and extreme winds co-occur more frequently than by chance, driven i) on short timescales by individual ETCs having some tendency to cause both flooding and extreme wind and ii) on longer timescales of 1-3 weeks by processes related to the jet stream that govern their seasonality (see Fig. 6, Hillier et al, 2025). The detail of this is not yet well understood, particularly for episodes containing event triplets (or indeed n>3). However, it is clear that they occur more than would be expected by chance and become more frequent in the future (Fig. 5)

- In the UKCP18 'present' (1981-1999 i.e. TS1, Δt = 21, 95th percentile) **the return period of 2 FL and 1 WS is x10 lower than the expectation of independence** (i.e. business as usual simulation with independent catastrophe models), 114 *vs* 1,140 years! (p = 0.00084). This threshold is 3yr RP for wind events and a 1yr RP for floods.
- In the future (TS3), this is 76 *vs* 540 years RP.
- At the 75th percentile level, the effect is smaller, roughly halving RPs i.e. 7.2 > 4.8 yrs for 2 FL & >= 1 WS for TS1, and 4.0 -> 2.2 yrs for TS3 (p < 0.001 for both). This is consistent with two event episodes (Bloomfield et al, 2023).
- RP of x3WS is much reduced in TS3, from 81.4 to 16.3 yrs. As overall numbers of wind events are similar in TS1 and TS3, increased seasonality plays a large role.

6 SOME OUTSTANDING QUESTIONS

1. Do the largest losses occur from multiple jointly occurring events in a 21-day window, or isolated extreme events? i.e. Do triplet storms matter?
2. Was DEF an exception, or something to be expected? i.e. in type and return period.
3. What is the anatomy of a flood-wind triplet? (i.e. how many of what type, and how are they sequenced)
4. Can triplet episodes be explained by Weather Patterns?
5. Can triplet episodes be explained by ETCs? i.e. Are there always storms present, and how many?
6. Can triplet episodes by explained by the jet stream? Is there a feature of it that distinctively causes them?
7. What do the most severe triplet events look like?
8. What does the seasonality of triplet events look like?

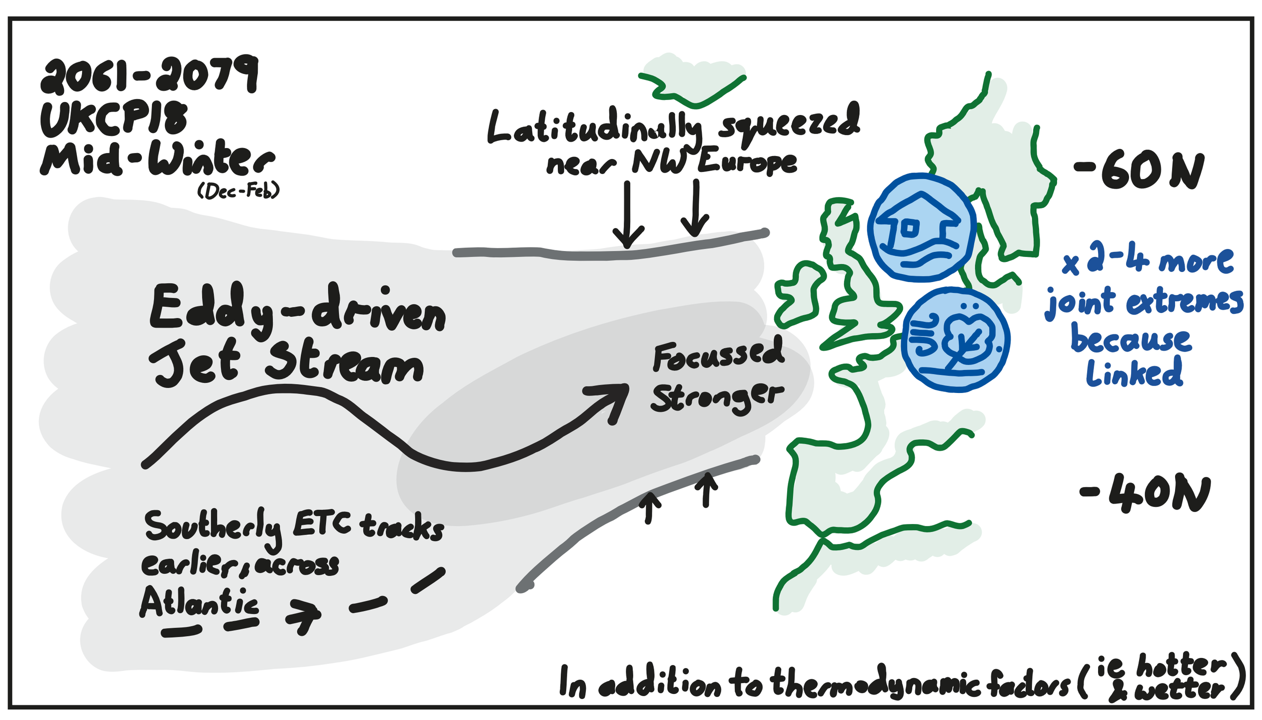

FIG 6: Summary cartoon of the factors causing flood-wind co-occurrence to increase in future (Hillier et al, 2025). Thermodynamic effects (i.e. hotter therefore wetter) lead to more flood events. But, this is insufficient to explain the whole increase in co-occurrence. Joint extremes are 2-4 times more likely due to dynamic factors over and above this (blue). On longer time-scales, from monthly to seasonal this is probably due to storms being squeezed into mid-winter, and being latitudinal squeezed, with this found in UKCP and CMIP ensembles; future jets causing storms with joint extremes are stronger and pointed straight at us in UK, Germany, Northern France! Lastly, the character of the jet likely matters (e.g. track further south collecting moisture and thenmoving north and strengthen as it impacts).

MAIN CITATIONS

Bloomfield, H. et al. (2023) Co-occurring wintertime flooding and extreme wind, *Weather Clim. Extremes*, **39**, https://doi.org/10.1016/j.wace.2023.100550.
Griffin, A., (2024) Widespread flooding dynamics under climate change, *Hydrol. Earth Syst. Sci.*, **28**, 2635–2650, https://doi.org/10.5194/hess-28-2635-2024.
Hillier, J. K (2024) Open R-code to communicate the impact of co-occurring natural hazards, Geosci. Comm., https://doi.org/10.5194/egusphere-2023-2799.
Hillier, J. (2025) Increasingly Seasonal Jet Stream Raises Risk of Co-Occurring Flooding and Extreme Wind, *Intl J. Climatology*, https://doi.org/10.1002/joc.8763.