Current methods of assessing multiple hazard risks

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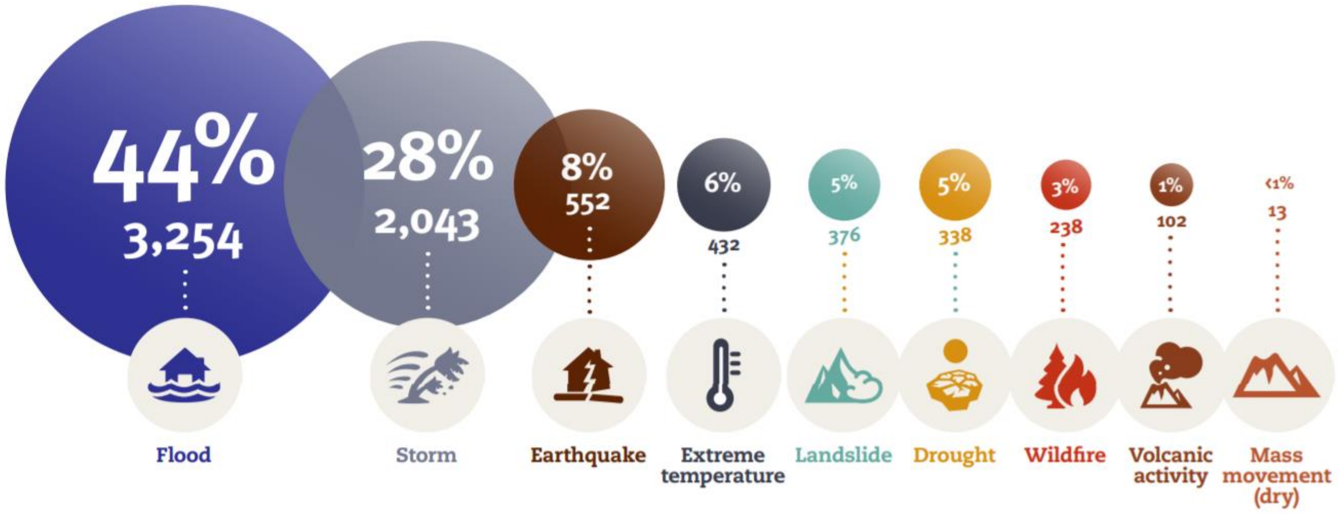
Extreme events, natural hazards and disasters

- Natural hazard: a severe or extreme event which occurs naturally anywhere in the world (UNDRR, 2020)



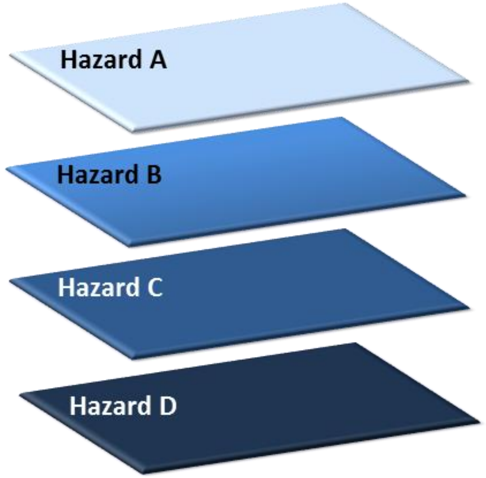
Percentage of occurrences of disasters by disaster type (2000-2019). From CRED and UNDRR: The human cost of disasters: an overview of the last 20 years (2000-2019)., 2020.

- Globally and yearly, individual hazards and hazard interrelations have the potential to result in socio-economic losses.

Multi-hazard: definition(s)

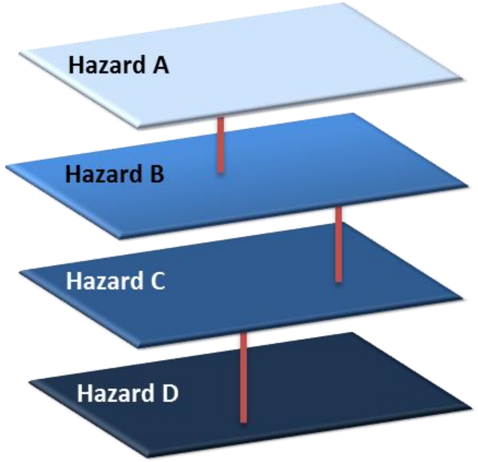
- **More-than-one-hazards-in-a-place** (multi-layer single hazard)

- Discrete
- Independent



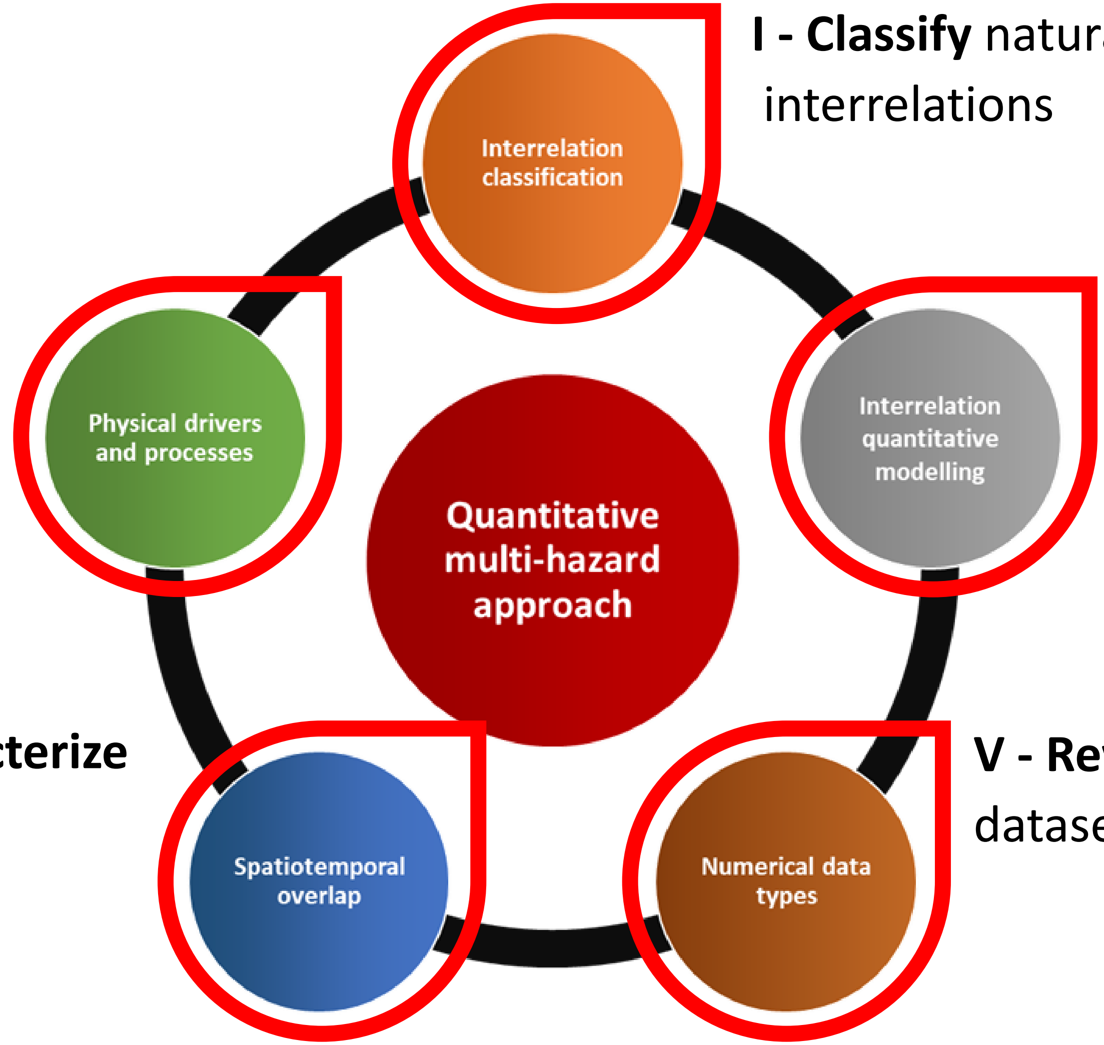
- **Holistic Approach** (multi-hazard)

- Interconnected
- Interacting
- Interrelationships



- **Multi-hazard approach:** considering more than one hazard in a given place and the interrelations between these hazards

Quantitative multi-hazard approach



I - Classify natural hazard interrelations

II - Evaluate methods to **model interrelations** between hazards

III - Define and characterize compound hazards in **time and space**

IV - Identify relevant Hazard interrelations for a given region

V - Review freely available datasets for multiple hazards

Natural hazard interrelation types

Interrelation types	Definition
(1) Independence	Combinations of independent phenomena
(2) Triggering	One hazard triggers another hazard
(3) Change conditions	One hazard alters the disposition of a second hazard by changing environmental conditions
(4) Compound hazards	Different hazards are the result of the same overarching event
(5) Mutual exclusion/Negatively dependent	Two natural hazards are negative dependence or be mutually exclusive

From Tilloy et al. (2019) Earth Sci. Rev.

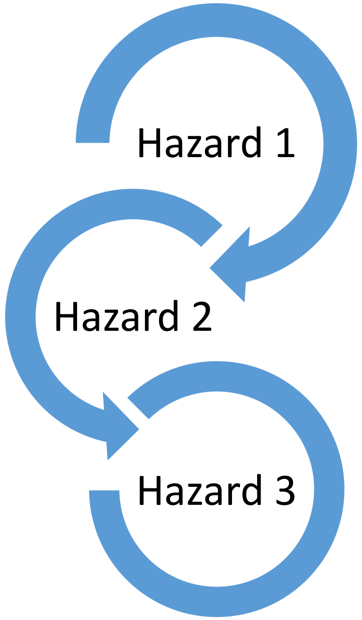
Triggers

From classification to modelling

Interrelation class
(1) Independence
(2) Triggering
(3) Change conditions
(4) Compound hazards
(5) Mutual exclusion/Negatively dependent

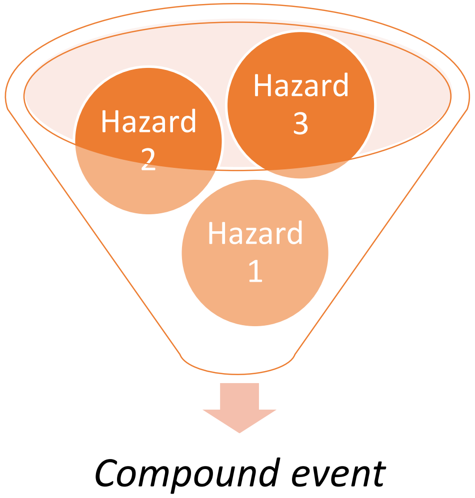
Cascading hazards

- A series of hazards that occur sequentially



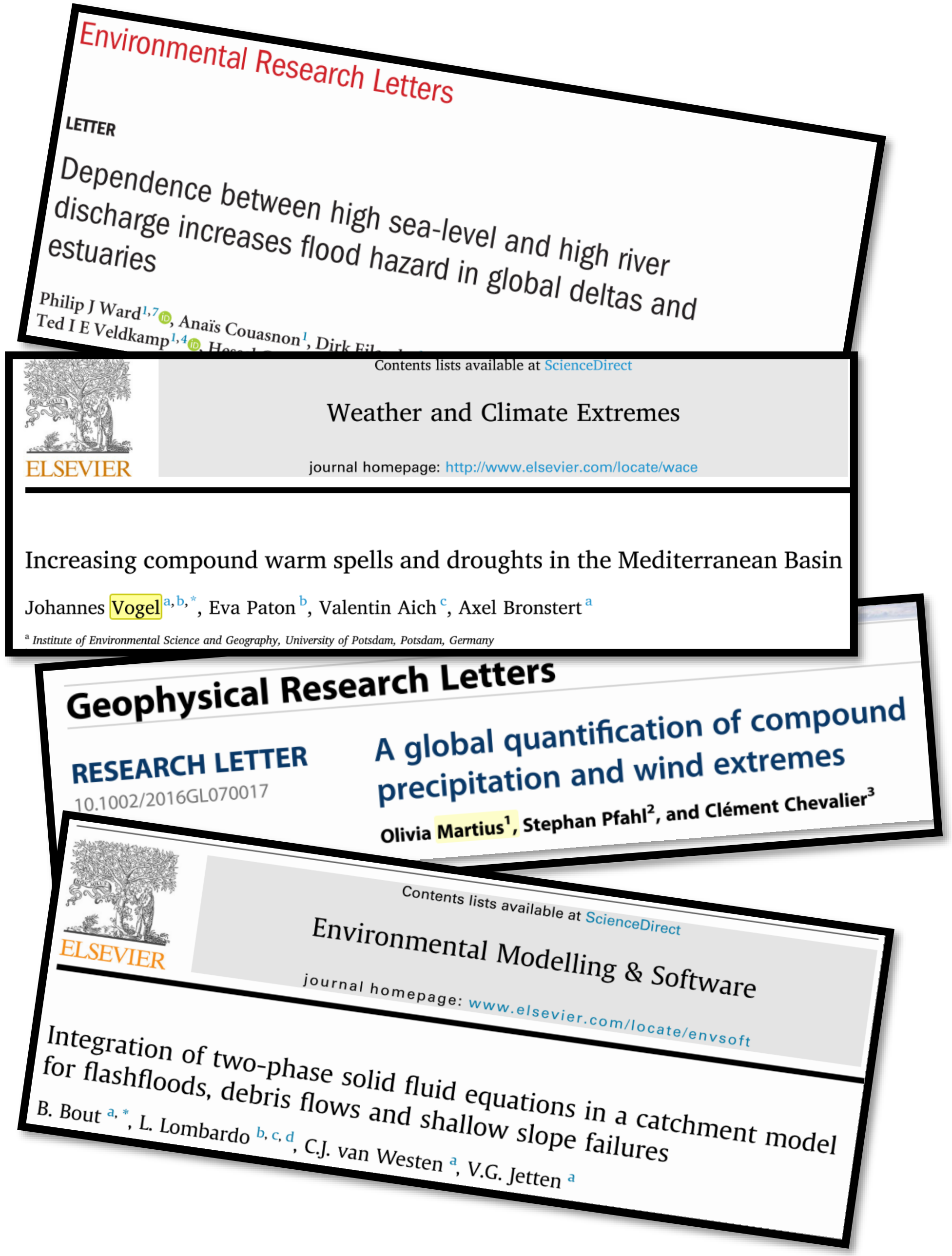
Compound hazards

- Several hazards act together above a threshold



Prominent hazard pairs

- Compound flooding
  (sea surge-river flooding)
- Compound hot and dry
  (heatwave-drought)
- **Compound precipitation and wind**
  (extreme precipitation-extreme wind)
- Precipitation-triggered landslides
  (extreme precipitation-landslides)


Environmental Research Letters
LETTER
Dependence between high sea-level and high river discharge increases flood hazard in global deltas and estuaries
Philip J Ward[1,7], Anaïs Couasnon[1], Dirk Eil...
Ted I E Veldkamp[1,4], ...

Contents lists available at ScienceDirect
Weather and Climate Extremes
journal homepage: http://www.elsevier.com/locate/wace
ELSEVIER
Increasing compound warm spells and droughts in the Mediterranean Basin
Johannes Vogel[a,b,*], Eva Paton[b], Valentin Aich[c], Axel Bronstert[a]
[a] Institute of Environmental Science and Geography, University of Potsdam, Potsdam, Germany

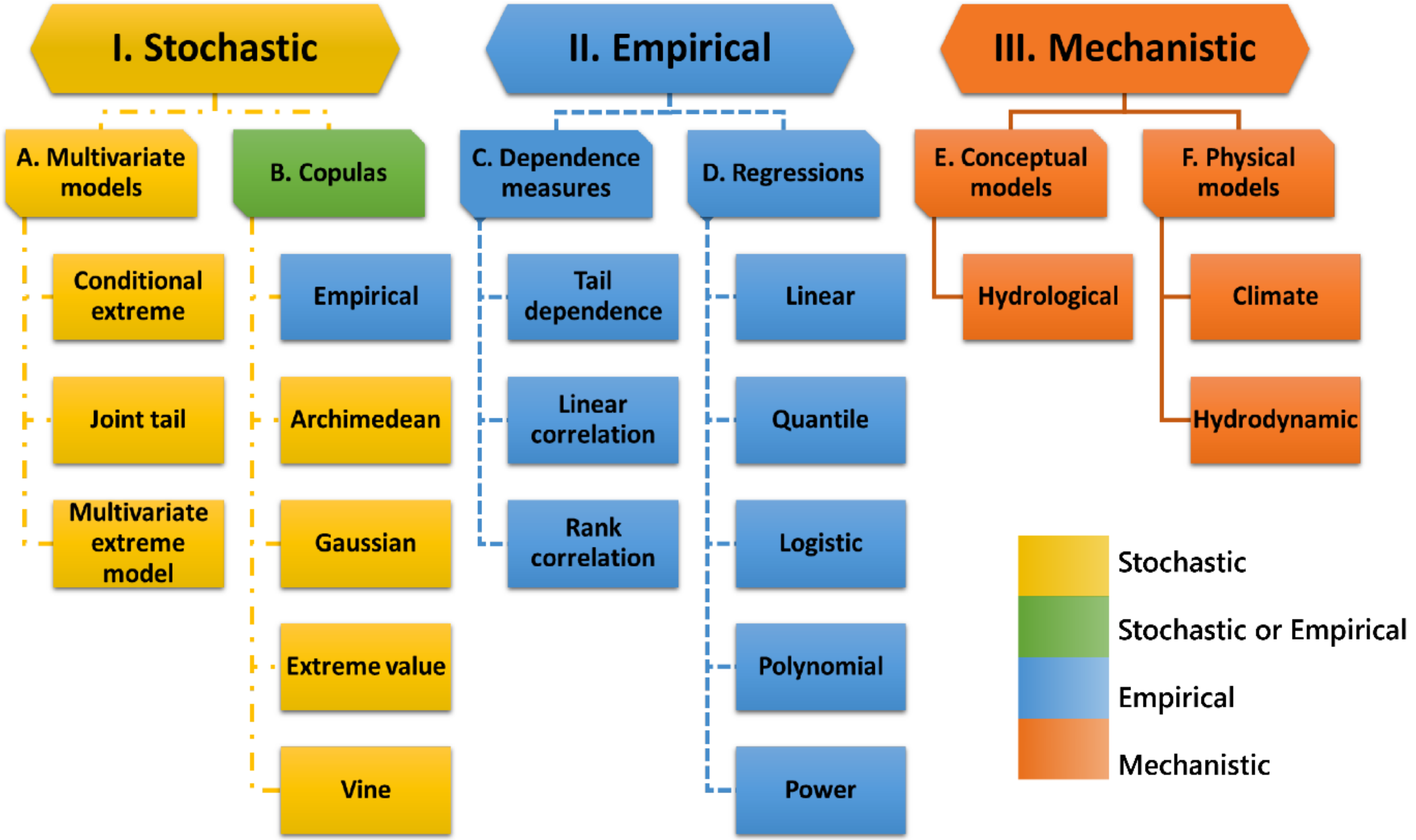
Geophysical Research Letters
RESEARCH LETTER
10.1002/2016GL070017
A global quantification of compound precipitation and wind extremes
Olivia Martius[1], Stephan Pfahl[2], and Clément Chevalier[3]

Contents lists available at ScienceDirect
Environmental Modelling & Software
journal homepage: www.elsevier.com/locate/envsoft
ELSEVIER
Integration of two-phase solid fluid equations in a catchment model for flashfloods, debris flows and shallow slope failures
B. Bout[a,*], L. Lombardo[b,c,d], C.J. van Westen[a], V.G. Jetten[a]

Hazard interrelation models framework

- Approaches, families and modelling methods
- 13 natural hazards from three categories:

1 Geophysical hazards
2 Atmospheric hazards
3 Hydrological hazards



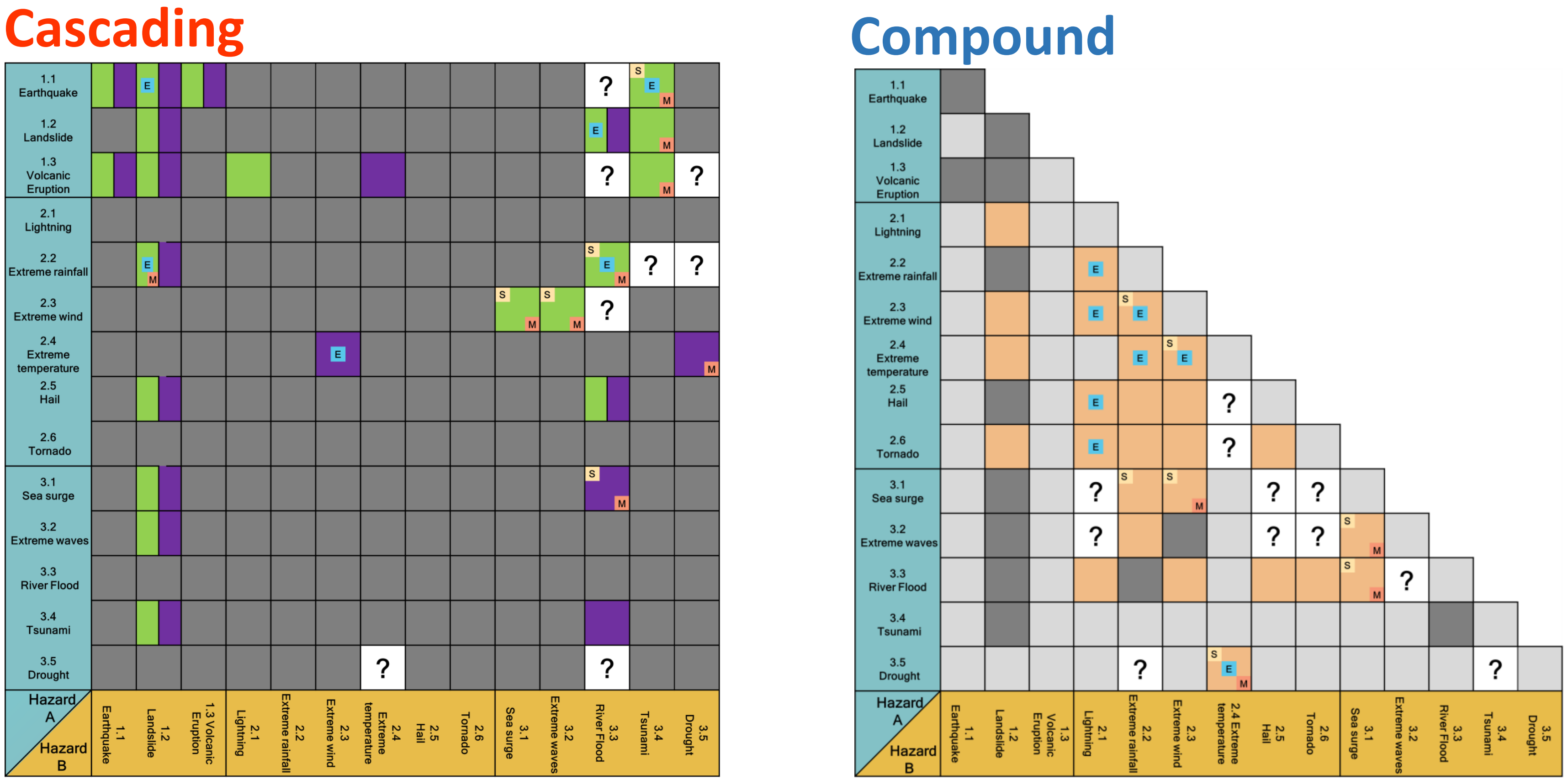
Natural hazard interrelationship models based on a review of 70 references from 1980 to 2018. From Tilloy et al. (2019) Earth Sci. Rev.

Interrelation Matrices

Interrelation types

- *(1) Independence*
- *(2) Triggering*
- *(3) Change conditions*
- *(4) Compound hazards*
- *(5) Mutual exclusion/Negatively dependent*
- ***(?)** debatable*
- *Not cascading / not compound*

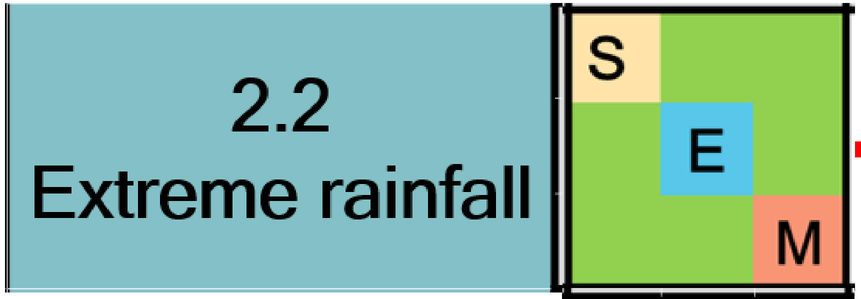
- S = Stochastic
- E = Empirical
- M = Mechanistic



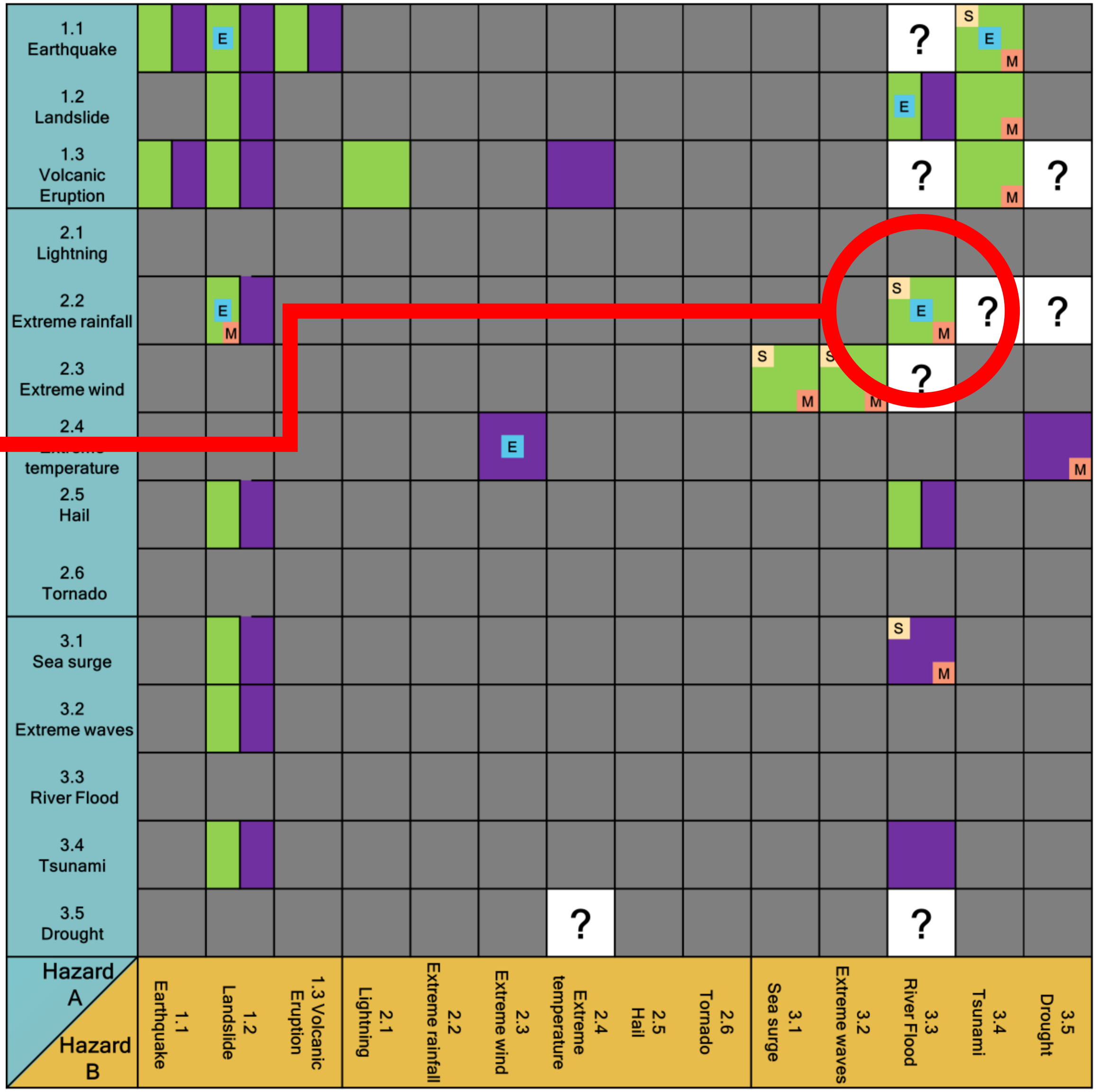
Cascading and compound hazard interrelation matrices for the considered hazards. Matrices based on 70 references and the modelling approach applied. Figure from: Tilloy, Malamud, Winter, Joly-Laugel (2019).

- **Cascading** and **compound** hazards cannot be analysed in the same way
- Each **cell** is filled with **evidence** (e.g., peer-review paper)

Modelling Matrices (example)

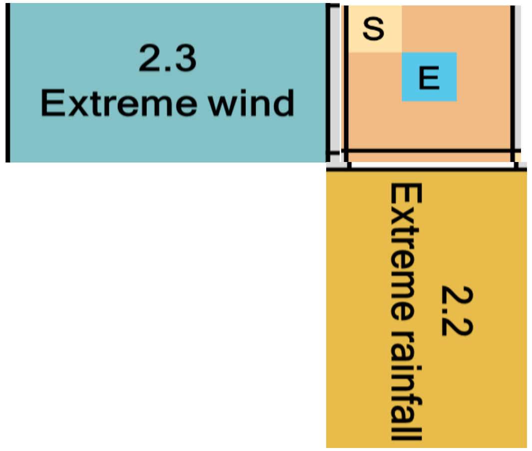


Matrices are associated to a **database** containing more information about the method used and complete references.

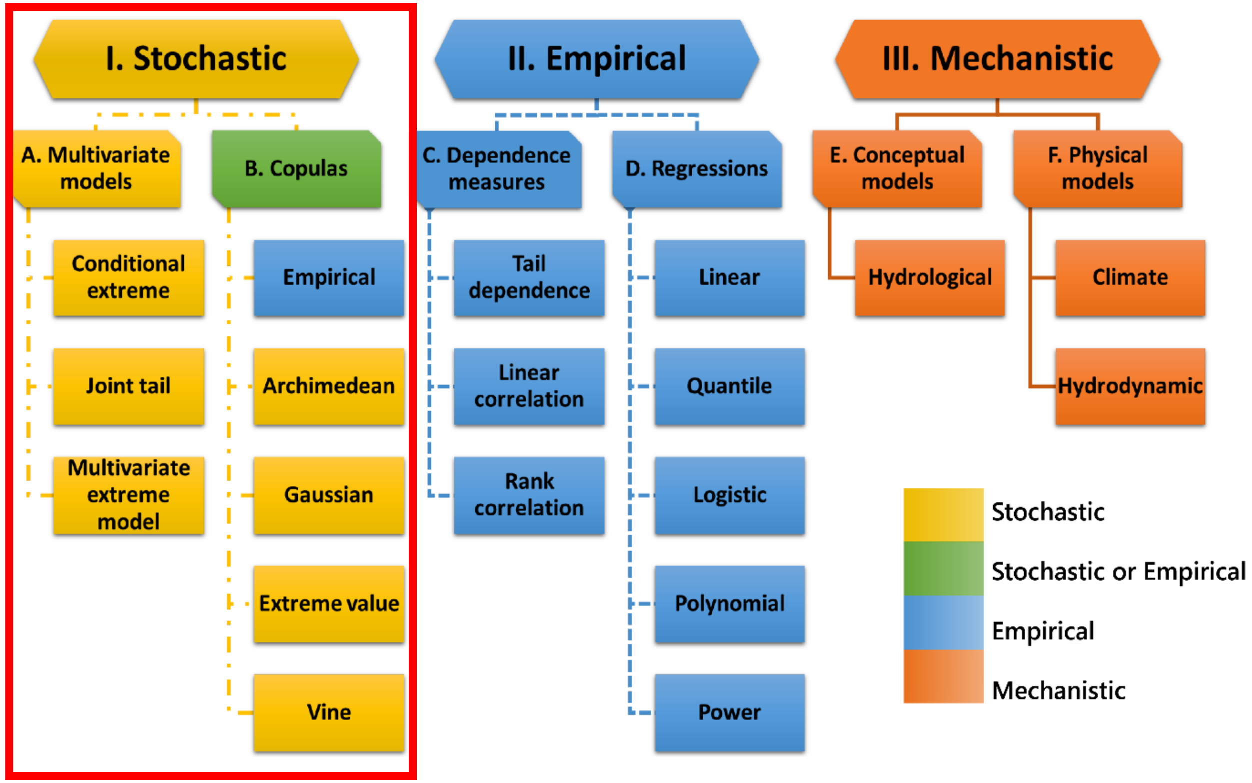


Bivariate modelling of hazard interrelations

- **Systematic** selection of the most suitable **quantitative model** for a given hazard interrelation.
- Application to compound extremes:



What is the **probability** of having a multivaria **extreme wind**?



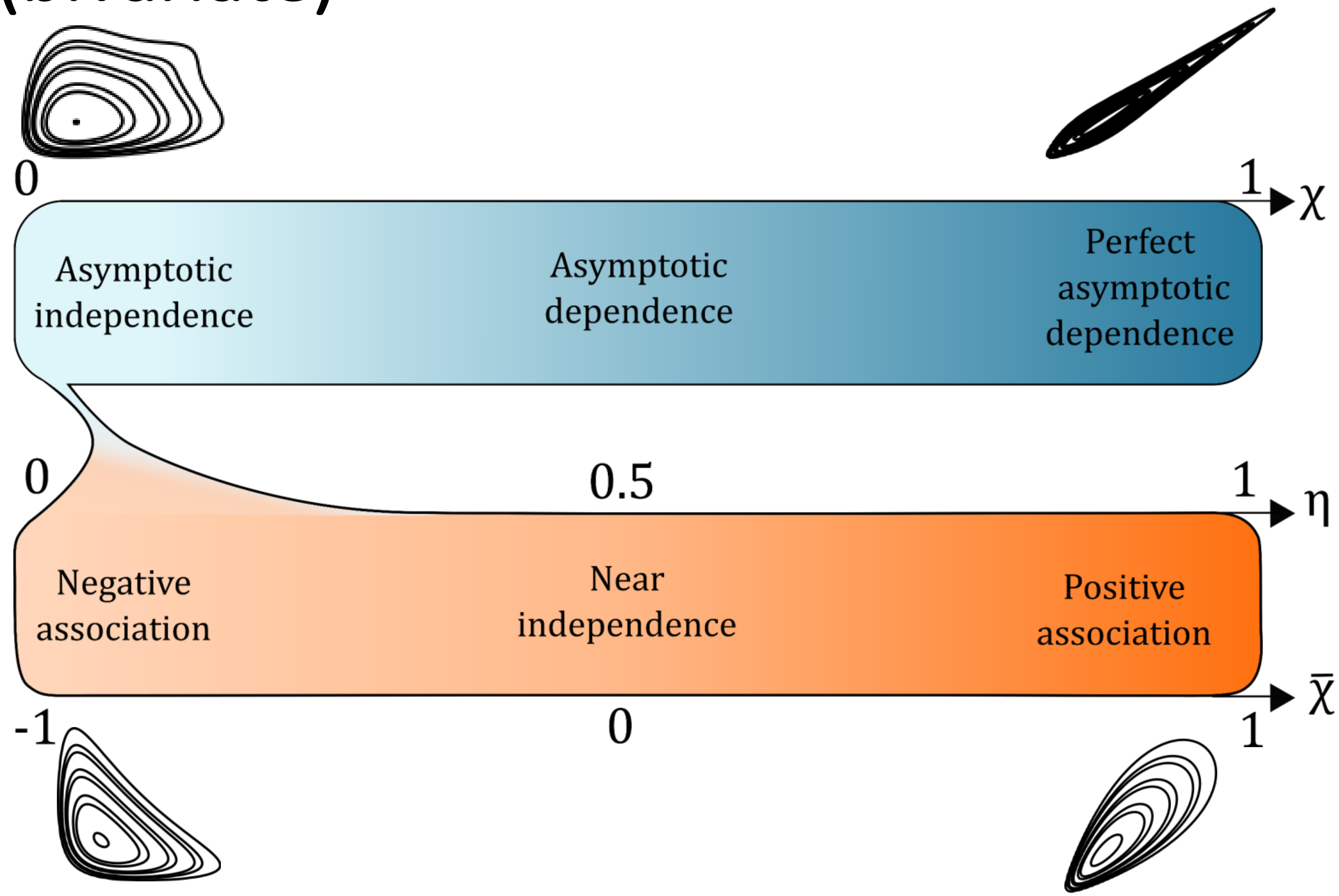
Natural hazard interrelationship models based on a review of 70 references from 1980 to 2018. From Tilloy et al. (2019)

Extremal dependence (bivariate)

- Dependence in the tail can be different to the dependence in the bulk
- Two types of asymptotic dependences
- Dependence measures:

$$\chi(x) = P(X_1 > x \mid X_2 > x)$$
with $\lim_{x \to x^*} (x) = \chi$

$$P(Z_1 > z, Z_2 > z) \sim \mathcal{L}(z)(P(Z_1 > z))^{1/\eta}$$



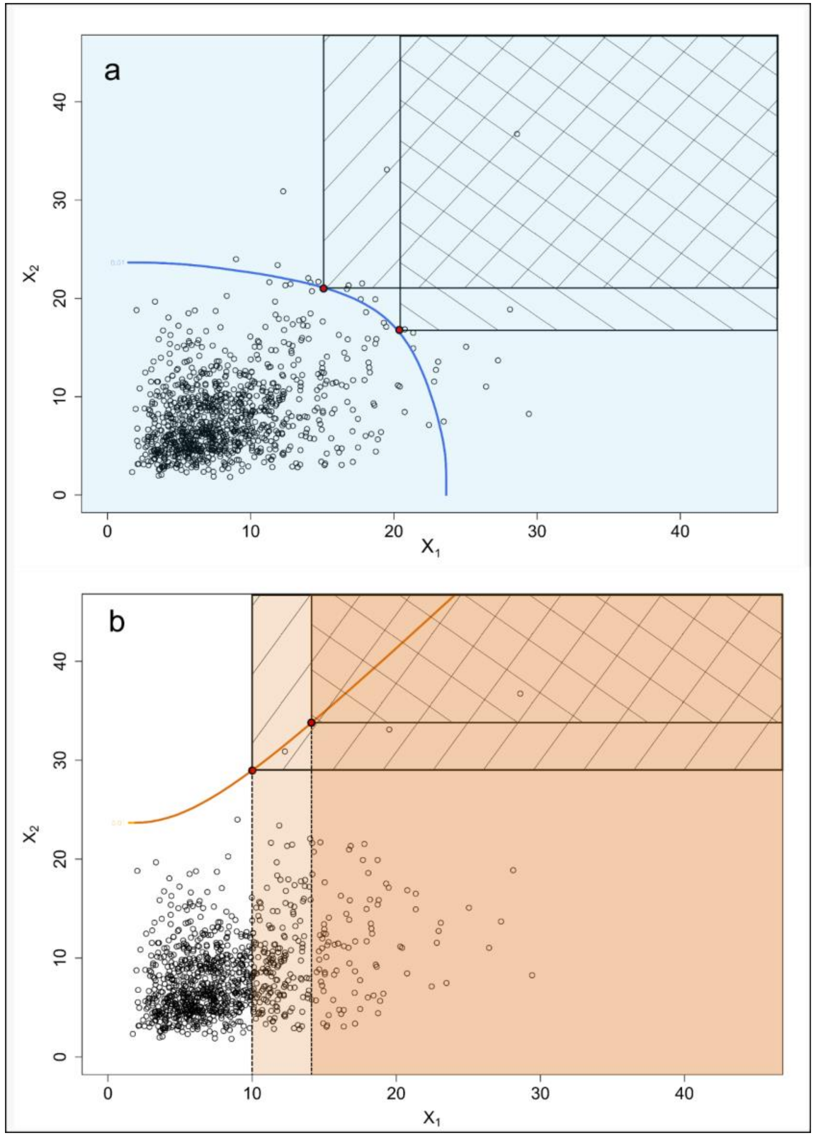
Three coefficients used to assess the dependence between two variables at an extreme level. From Tilloy et al. (2020), Nat. Haz. Earth. Sys. Sciences.

Bivariate return period

- X_1 and X_2 are two variable of interest
- Bivariate return periods are visualized as **curves**

- Several **types of probability** associated to **types of interrelation** between hazards

Compound hazards	**a.** $P_{AND} = P(X_1 > u \cap X_2 > v)$
Triggering **Change conditions**	**b.** $P_{COND} = P(X_1 > u \mid X_2 > v)$

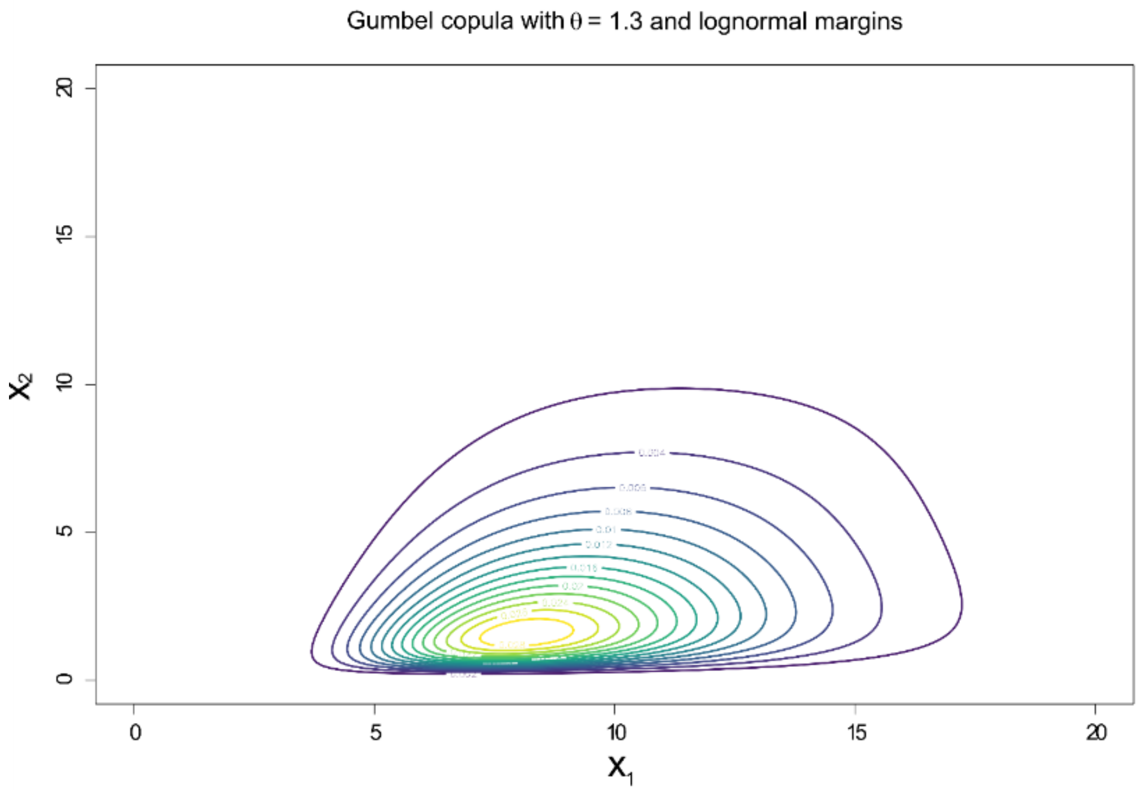


Graphical representation of two bivariate (X_1, X_2) probabilities of exceedance: (a) P_{AND} probability and (b) P_{COND}. From Tilloy et al. (2020), Nat. Haz. Earth. Sys. Sciences.

Bivariate models

- *Parmetric: Copula*
  - Gumbel (AD)
  - Galambos (AD)
  - FGM (AI)
  - Normal (AI)
- *Semi-parametric*
  - Conditional extremes model (Heffernan and Tawn, 2004)
  - Joint tail + kernel density estimator (Cooley et al., 2019)

- Need for common metric for comparison

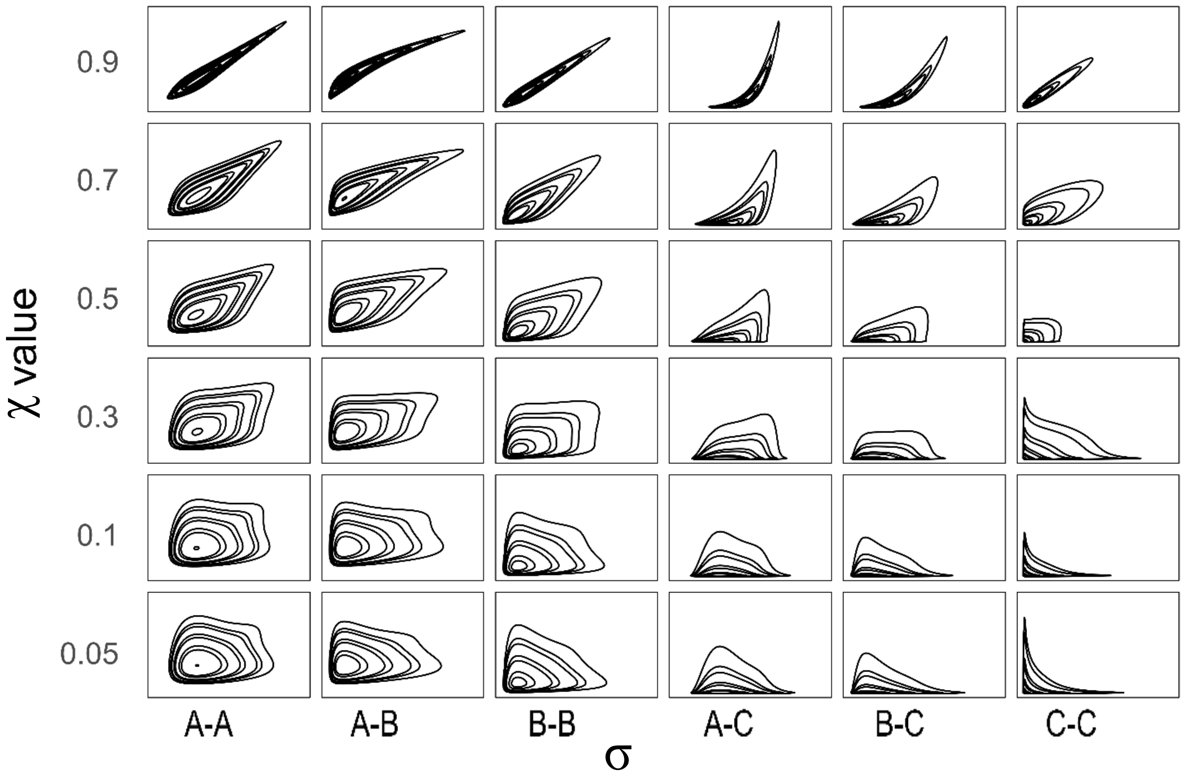


Fonction de densité d’une copule de Gumbel bivariée

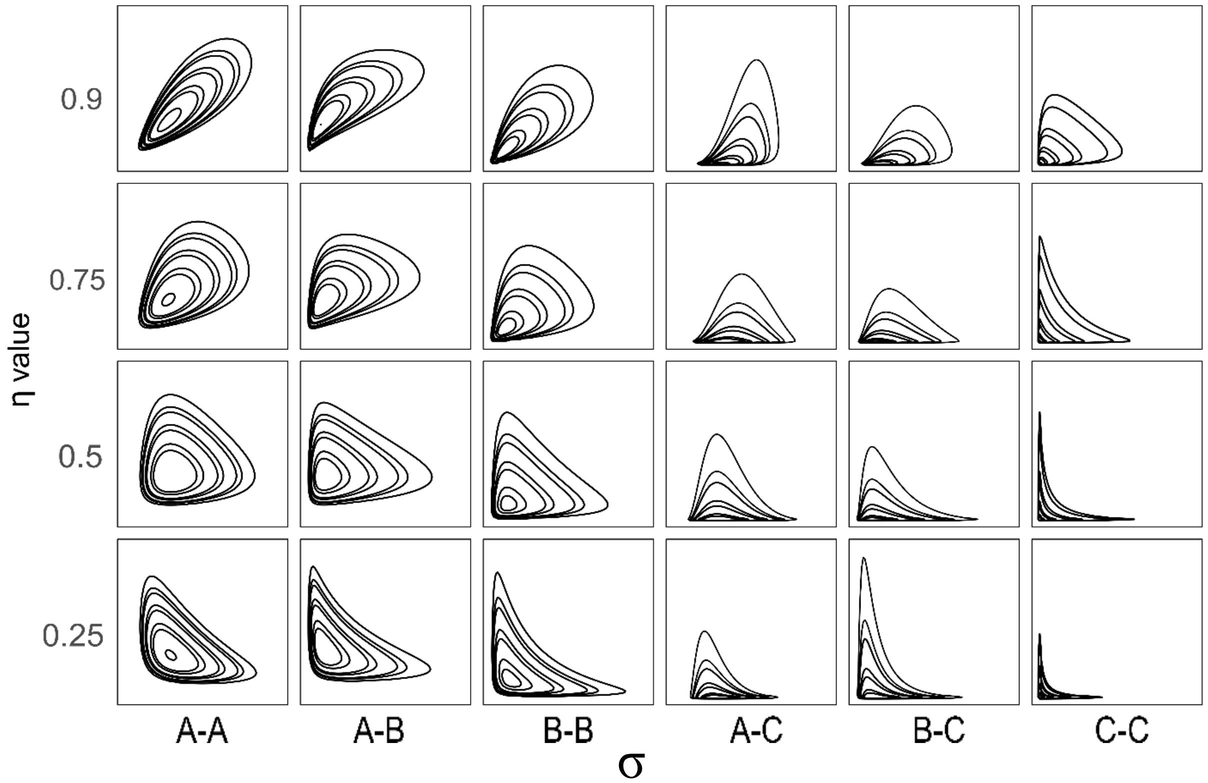
Assessing diverse bivariate extreme models abilities with synthetic data

- Marginal distributions: **log-normal** |Dependence functions: Gumbel copula & Normal copula
- Two varying parameters: shape of marginal distribution σ (A=0.25, B=0.5, C=1.5) | strength and type of asymptotic dependence

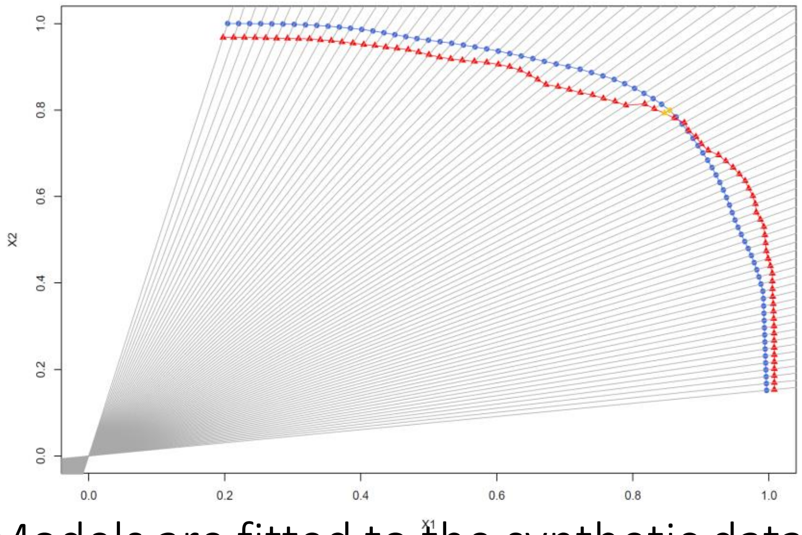
36 datasets for Asymptotic dependence



24 datasets for Asymptotic independence



Models abilities heatmap



- Models are fitted to the synthetic datasets (replicated 100 times) to estimate **the joint probability** p=0.001

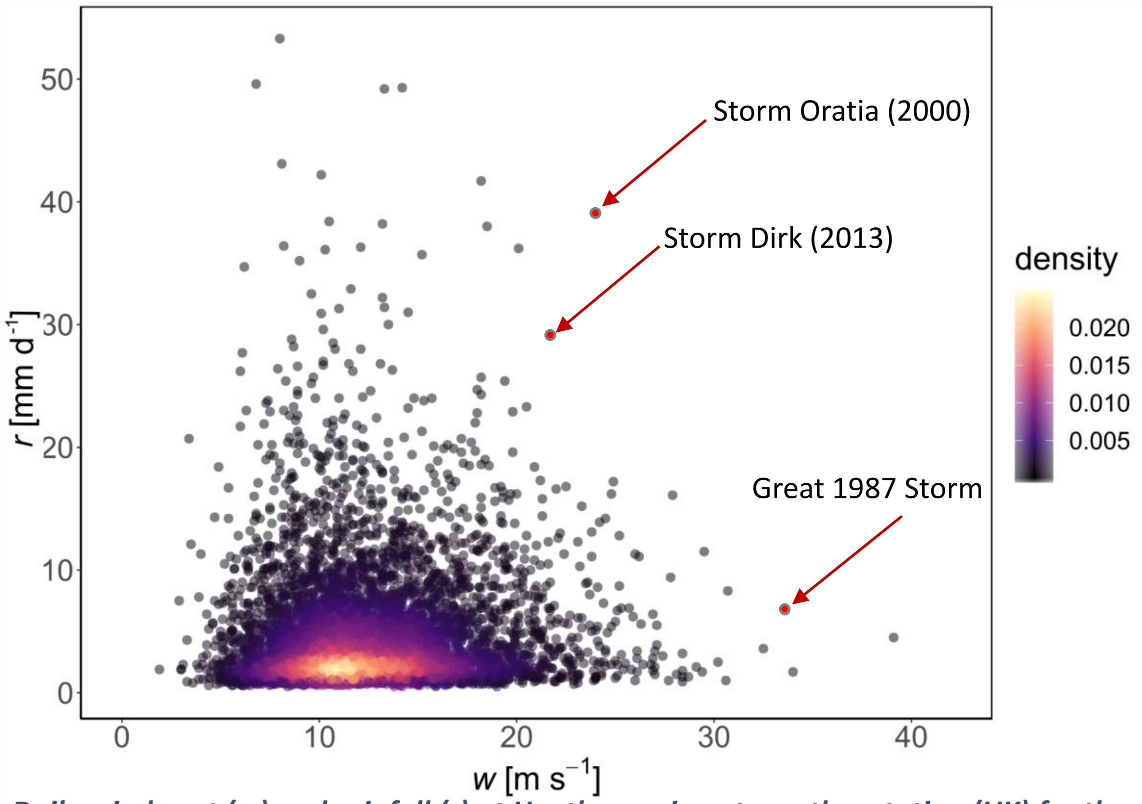
- Weighted normalized Euclidean distance (*wd*) between each estimated level curve and a reference curve.
    - Value & colours = median
    - thickness of borders= Confidence interval

Mean Weighted Euclidean distance (wd) between modelled and synthetic level curve. From Tilloy et al. (2020), Nat. Haz. Earth. Sys. Sciences.

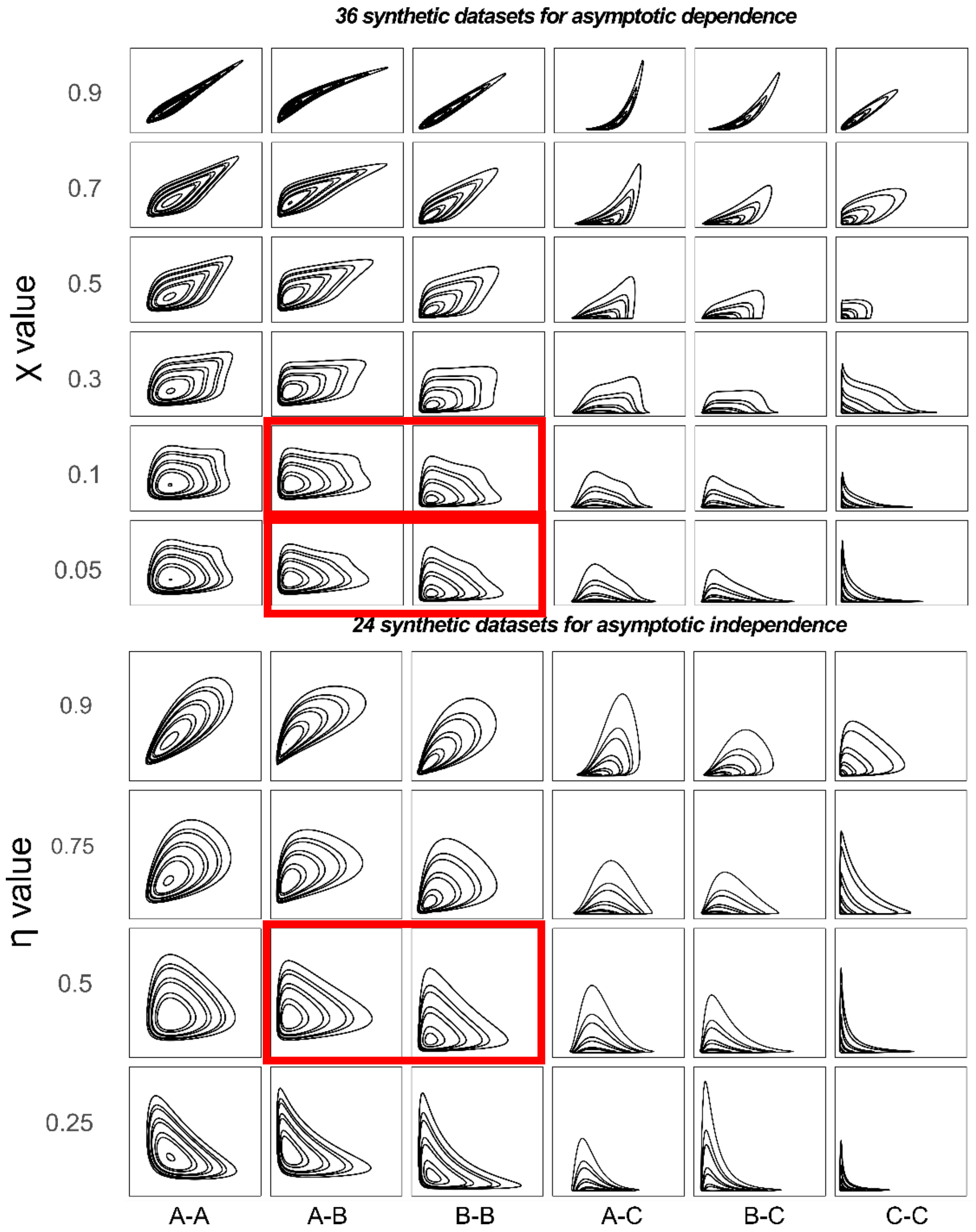
Application to wind and rainfall in Heathrow Airport

Extreme wind and extreme rainfall are compound hazards (Tilloy *et al*. 2019)

➔ P_{AND} return period



***Daily wind gust (w) and rainfall (r) at Heathrow airport weather station (UK) for the period 1971 – 2018**. Data from: Met Office (Wind gust) & E-OBS (Daily rainfall). From Tilloy et al. (2020)*



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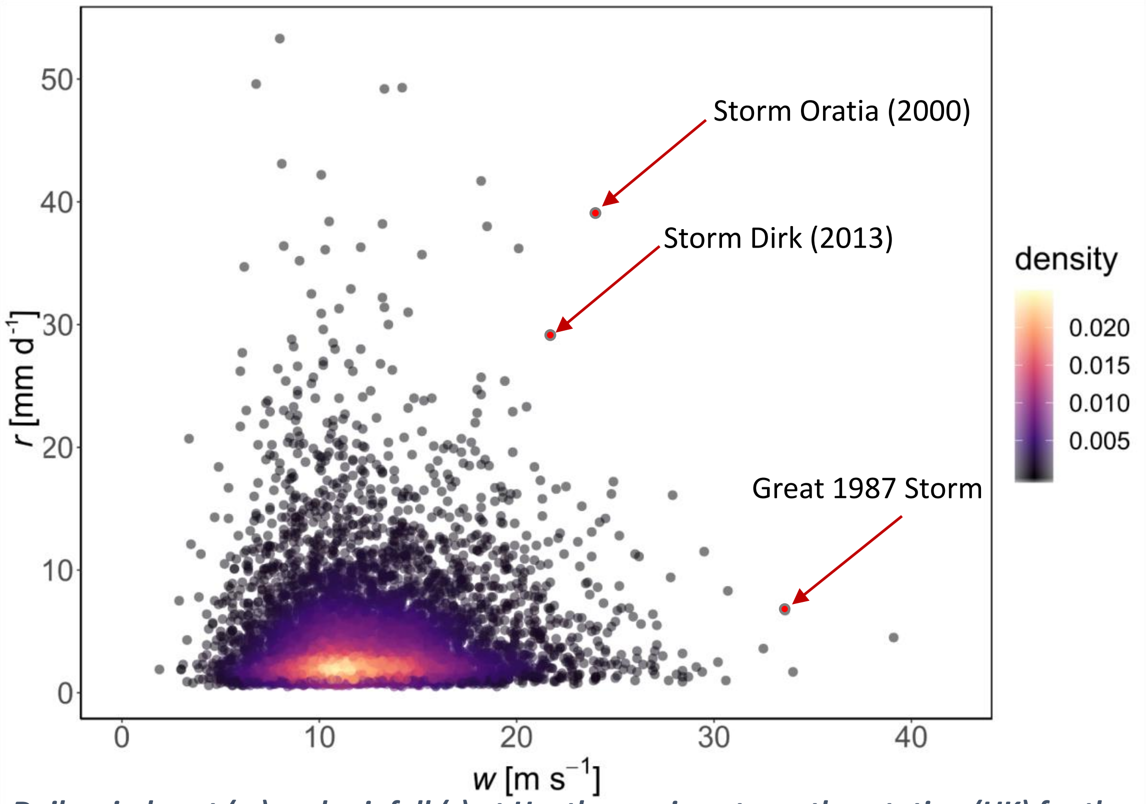
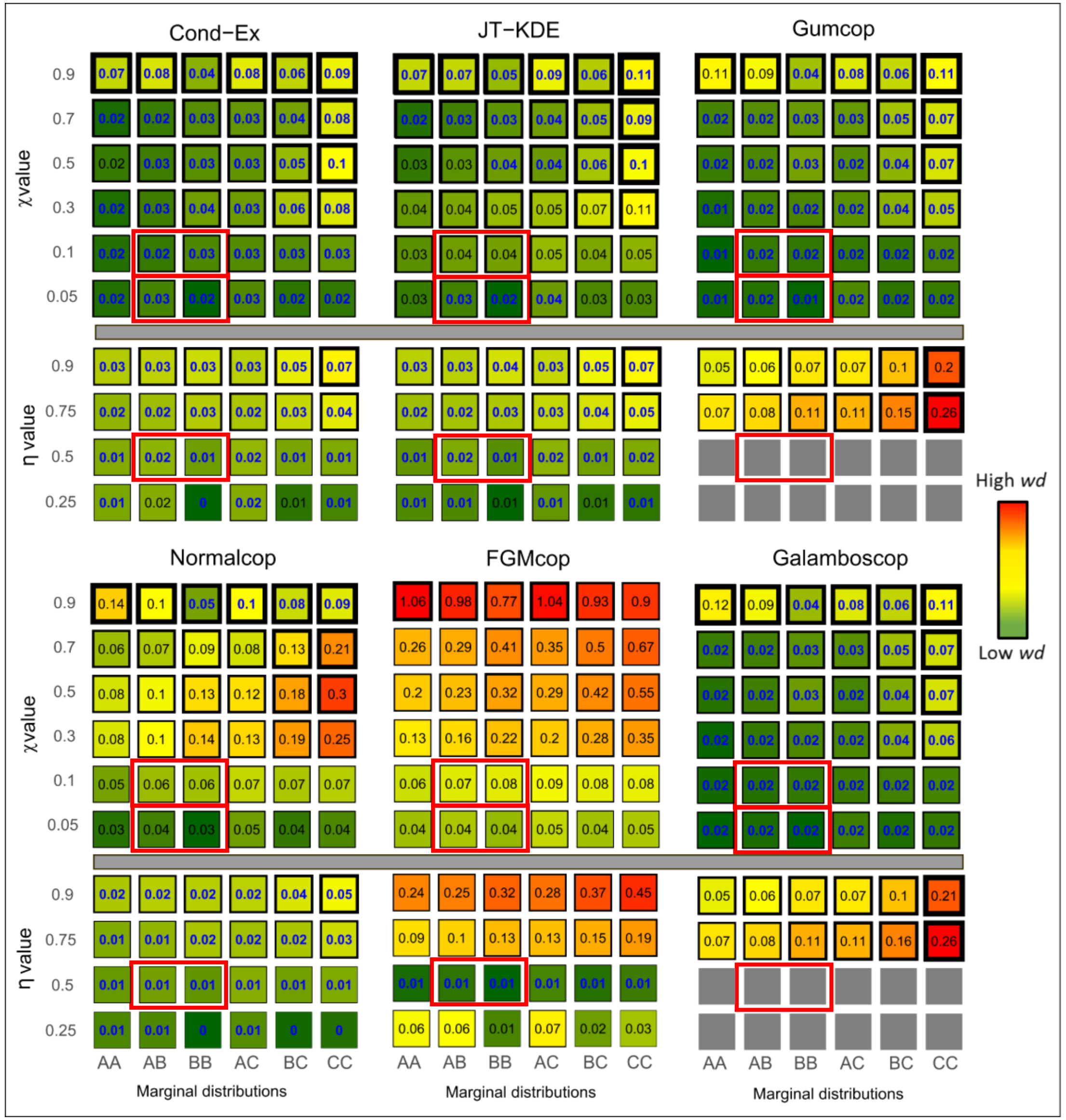




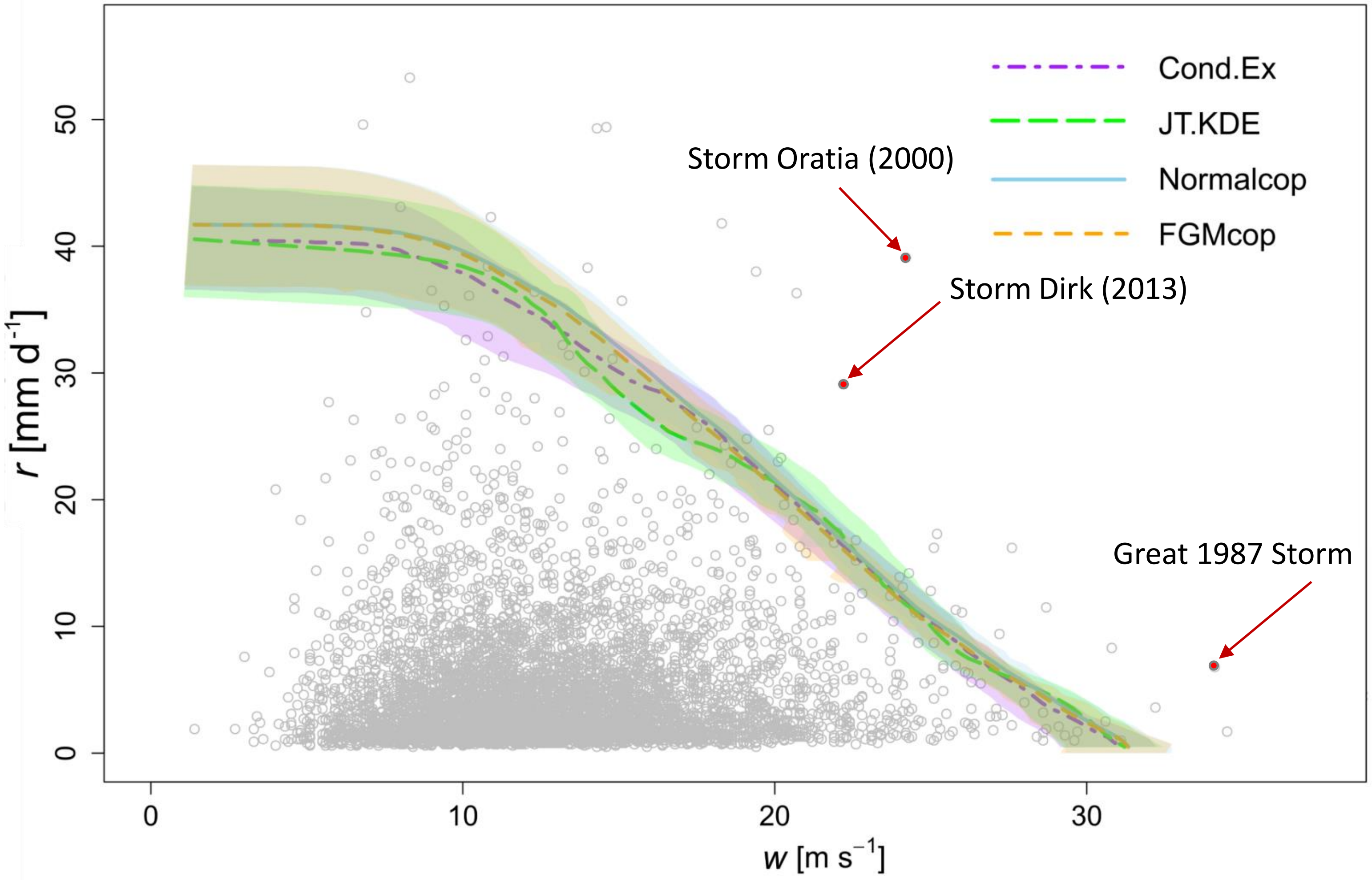
Daily wind gust (w) and rainfall (r) at Heathrow airport weather station (UK) for the period 1971 – 2018*. Data from: Met Office (Wind gust) & E-OBS (Daily rainfall). From Tilloy et al. (2020)*

Application to wind and rainfall in Heathrow Airport

- **Daily maximum wind gust** and **daily accumulated rainfall** at Heathrow Airport

- Level curves (with 95% CI) from four selected models for a joint probability $\boldsymbol{P_{AND}}$ = 0.001*

*8 years joint return period

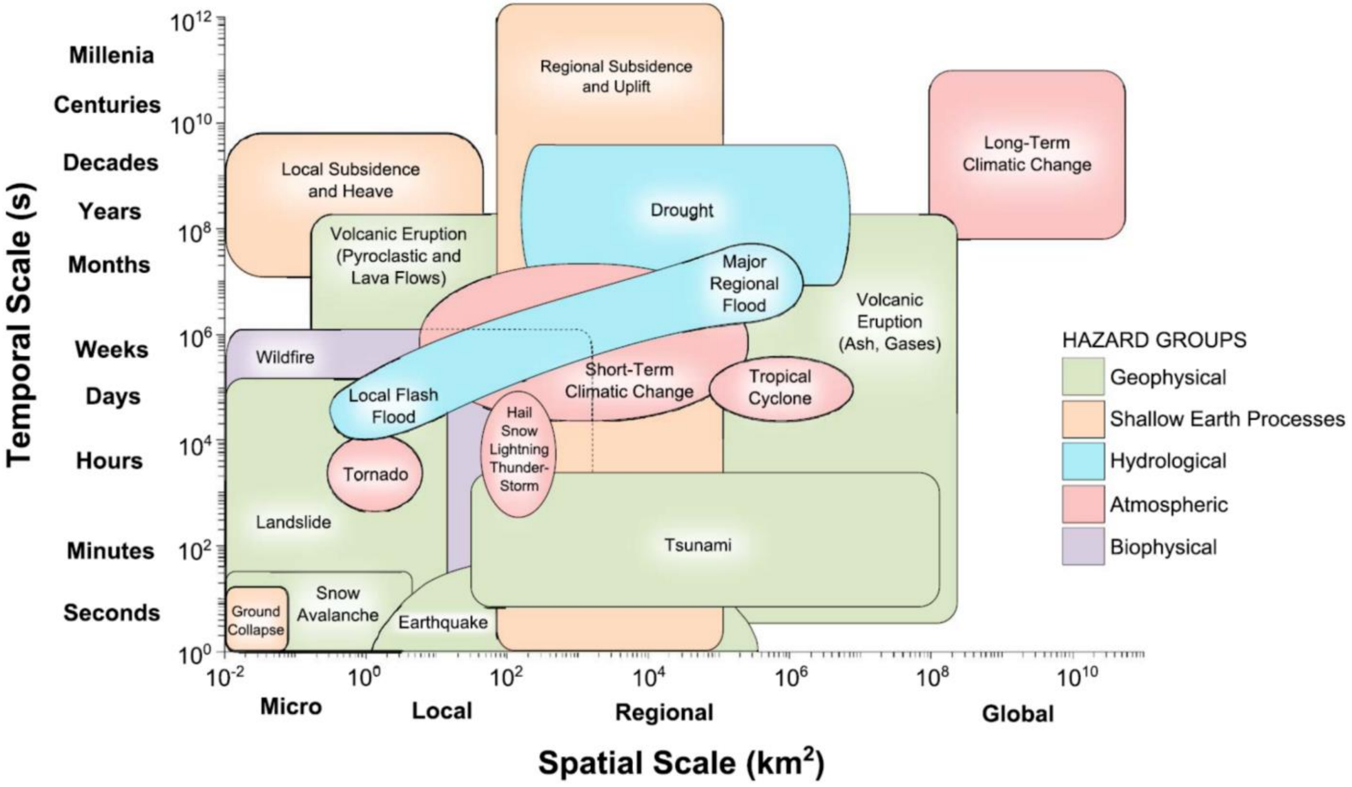


Level curves for a P_{and} joint probability p = 0.001 of daily wind gust (w) and daily rainfall (r) at Heathrow airport (London, UK). From Tilloy et al. (2020)

Compound hazards in space and time

Natural hazards can occur different spatial and Temporal scale

- Hazard event: a **cluster** in space and time representing the **footprint** of a **singular phenomenon**
- **Compound hazards**: two or more associated hazard events **occurring** the **same time and place**.



Spatial and temporal scales of different natural hazards. From Gill and Malamud (2014)

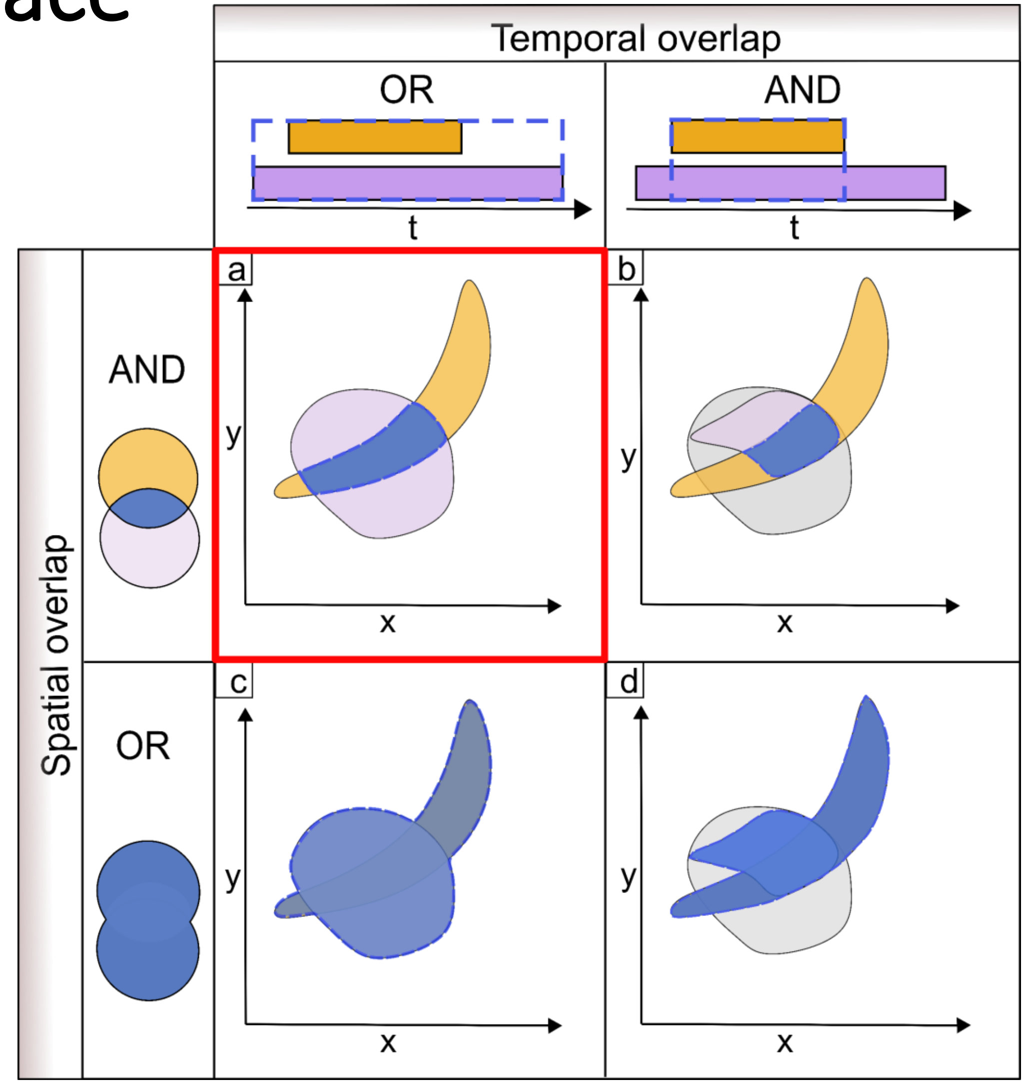
Application to compound wind and precipitation extremes in Great Britain

Defining compound hazards in space and time

Spatiotemporal Compound hazards : different hazards occur on the **same area** during the **duration** of **an event.**

- (a) spatial overlap in aggregated time (AND-OR)
- (b) spatiotemporal overlap (AND-AND)
- (c) aggregated time and space (OR-OR)
- (d) temporal overlap on aggregated space (OR-AND)

Spatiotemporal **footprint**: Area impacted by two(or more) hazards during the aggregated duration of a event (AND-OR).

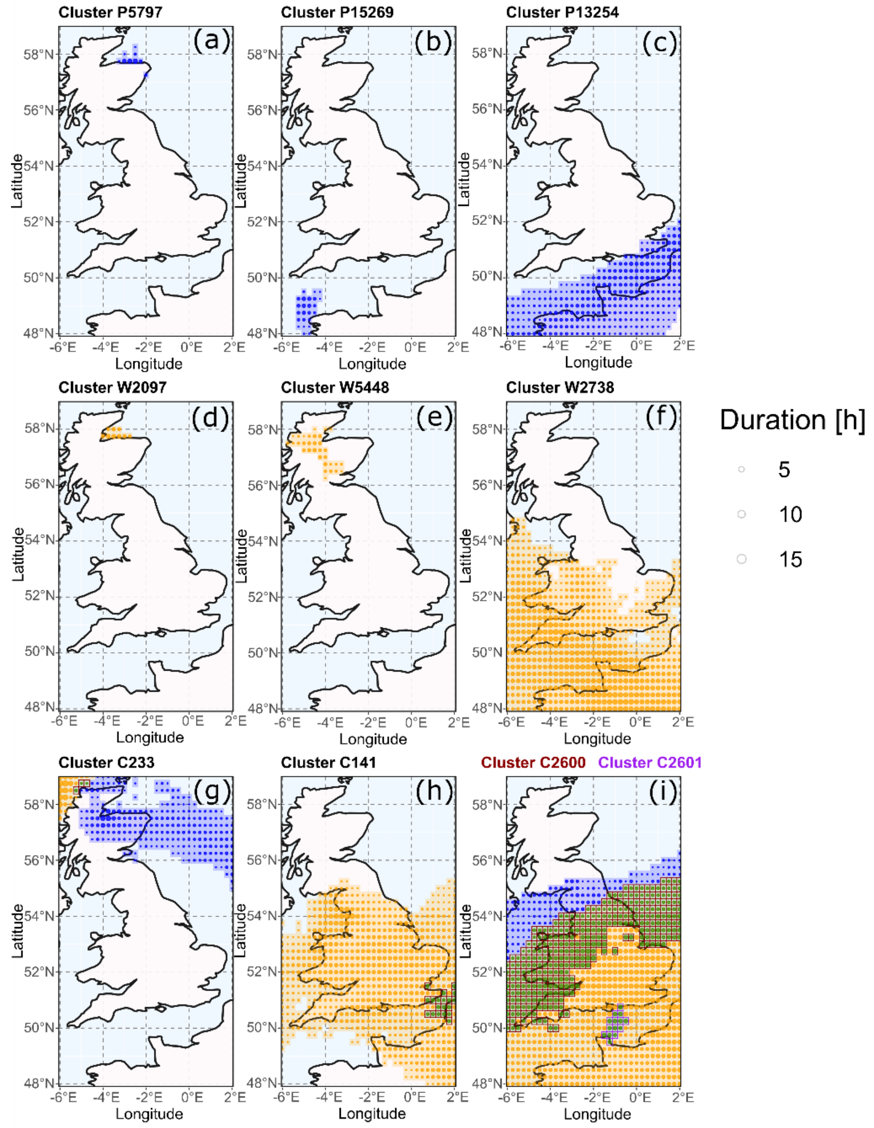


Different spatial and temporal scales considered to define compound hazard events with each case representing a combination of spatial and temporal overlap..

Cluster identification

- **Extremes** are **point objects** with coordinates in space (latitude and longitude) and time (date)
- Clustering algorithm: Density Based Spatial Clustering of Applications with Noise (**DBSCAN**)
- Extremes are clustered in time and space
- Each cluster has attributes

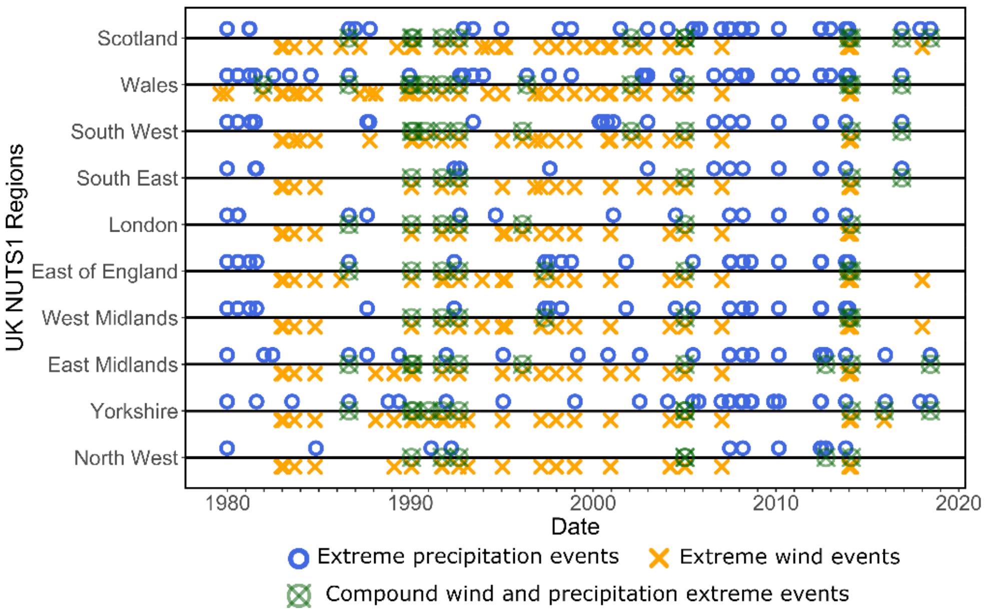
	Attribute	Wind clusters	Precipitation clusters	Compound wind–precipitation clusters
Intensity	p_a (mm)		✓	✓
	w_g (m s^{-1})	✓		✓
Scales	Footprint (%)	✓	✓	✓
	Duration (h)	✓	✓	✓
Historical	Start time (h)	✓	✓	✓
	End time (h)	✓	✓	✓
	Location (cells involved)	✓	✓	✓



Footprints of ten example natural hazard clusters over Great Britain.

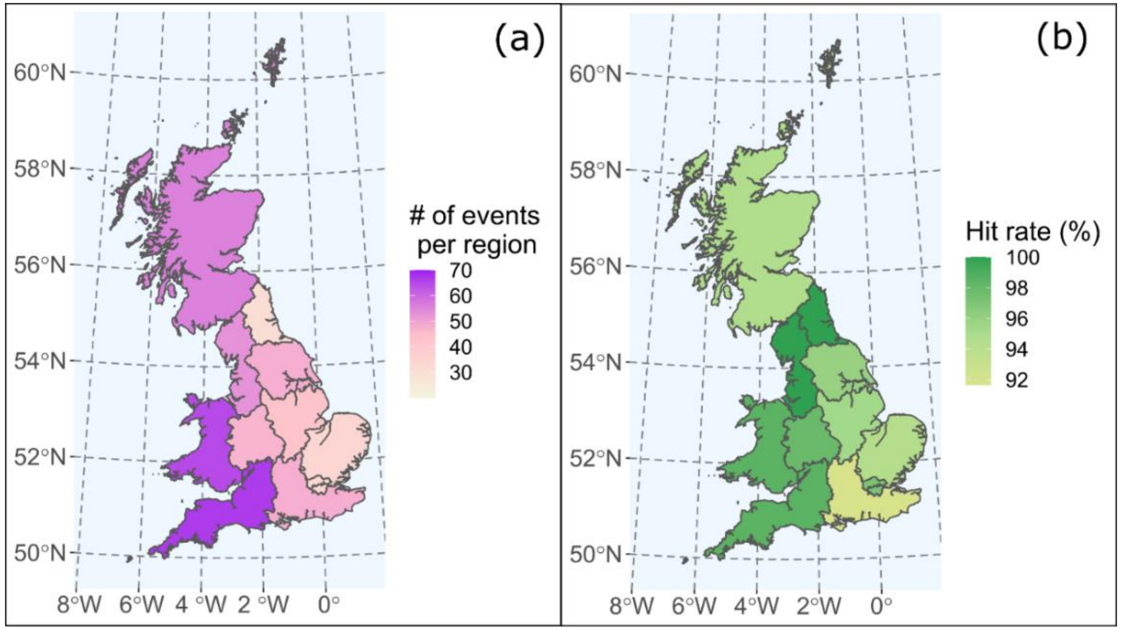
Confrontation with significant events

- *"Great Britain Significant Weather Events Catalogue 1979–2019"* consisting of **157 significant Great Britain weather events.**



Timeline of 157 events in the Great Britain Significant Weather Events Catalogue 1979–2019

- *"Database of **4555 compound hazard clusters for Great Britain** (1979-2019)"*
- **Hit rate** (# of events with corresponding clusters / total # of events).
- Over Great Britain, **hit rate = 93.4%.**

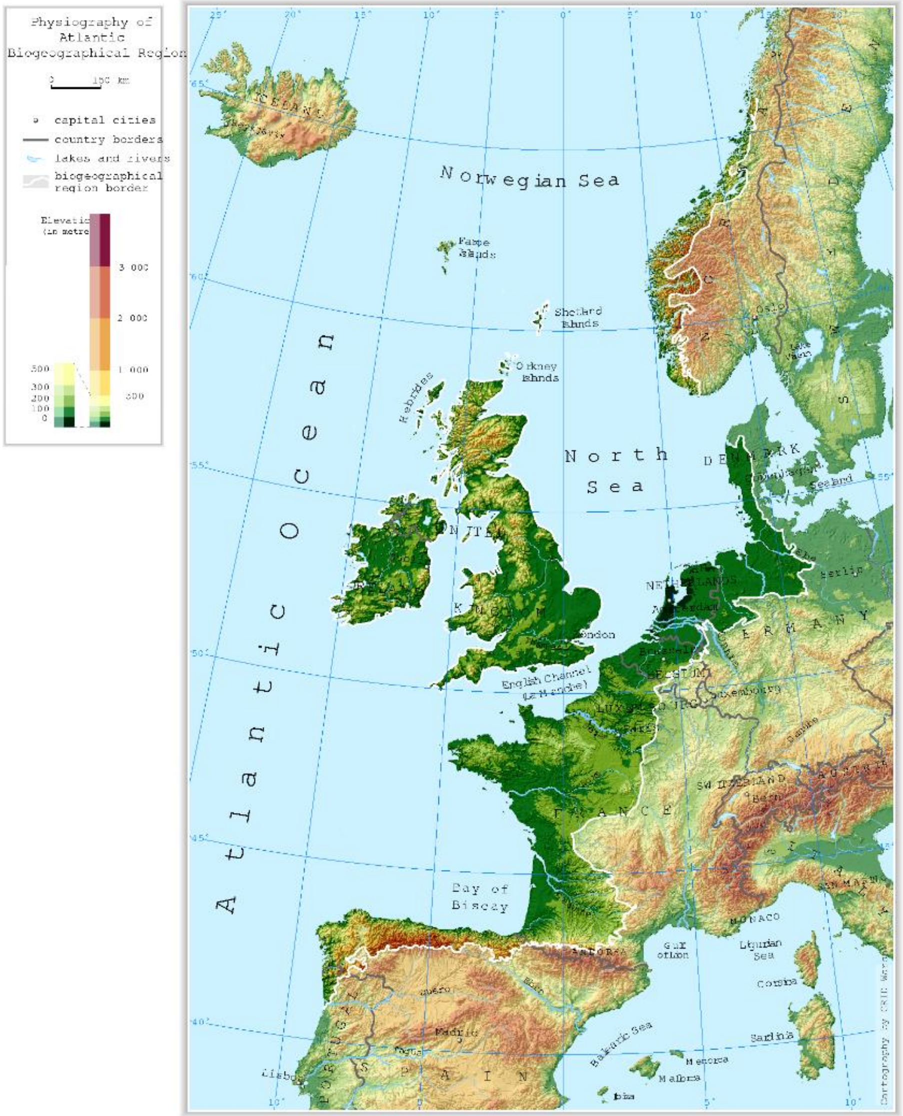


Map of Great Britain divided into 11 NUTS1 regions showing: (a) the number of events per region, (b) for each region, the hit rate

Drivers of multiple hazards in Western Europe

- Objective: Develop a **methodology** to identify **relevant hazards and hazard interrelations** for a given region.
- Region of interest: **European Atlantic biogeographic Region** (EAR)

- The identification of relevant natural hazards for the EAR is performed on three main criteria:
  i. frequency of occurrence,
  ii. spatial relevance,
  iii. potential to impact energy infrastructures



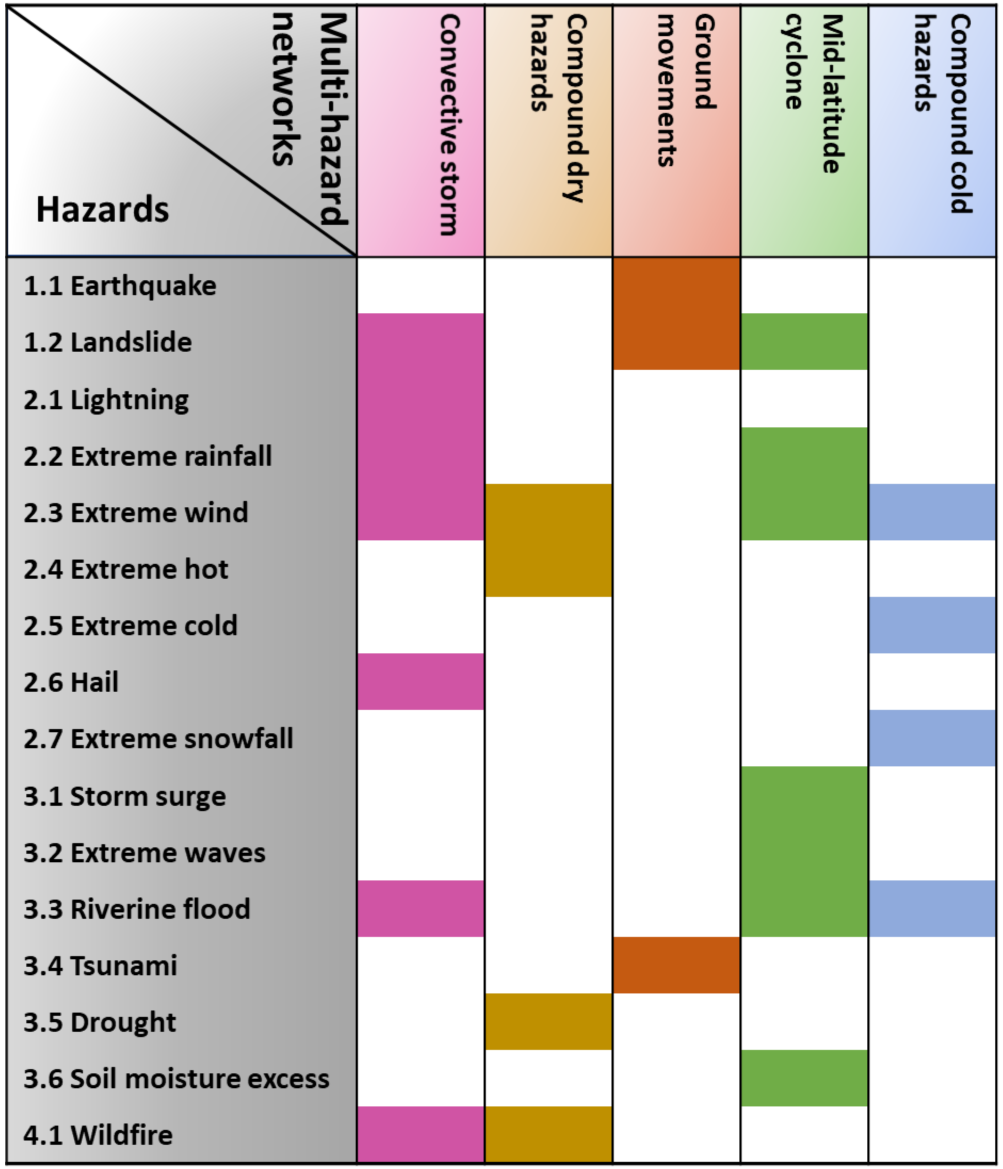
Physiographic map of Western Europe. The European Atlantic Biogeographical region is highlighted with a white. Figure from EEA (2003).

Multi-hazard networks

- 16 natural hazards selected from 4 hazard categories:

1 Geophysical hazards
2 Atmospheric hazards
3 Hydrological hazards
4 Biophysical hazards

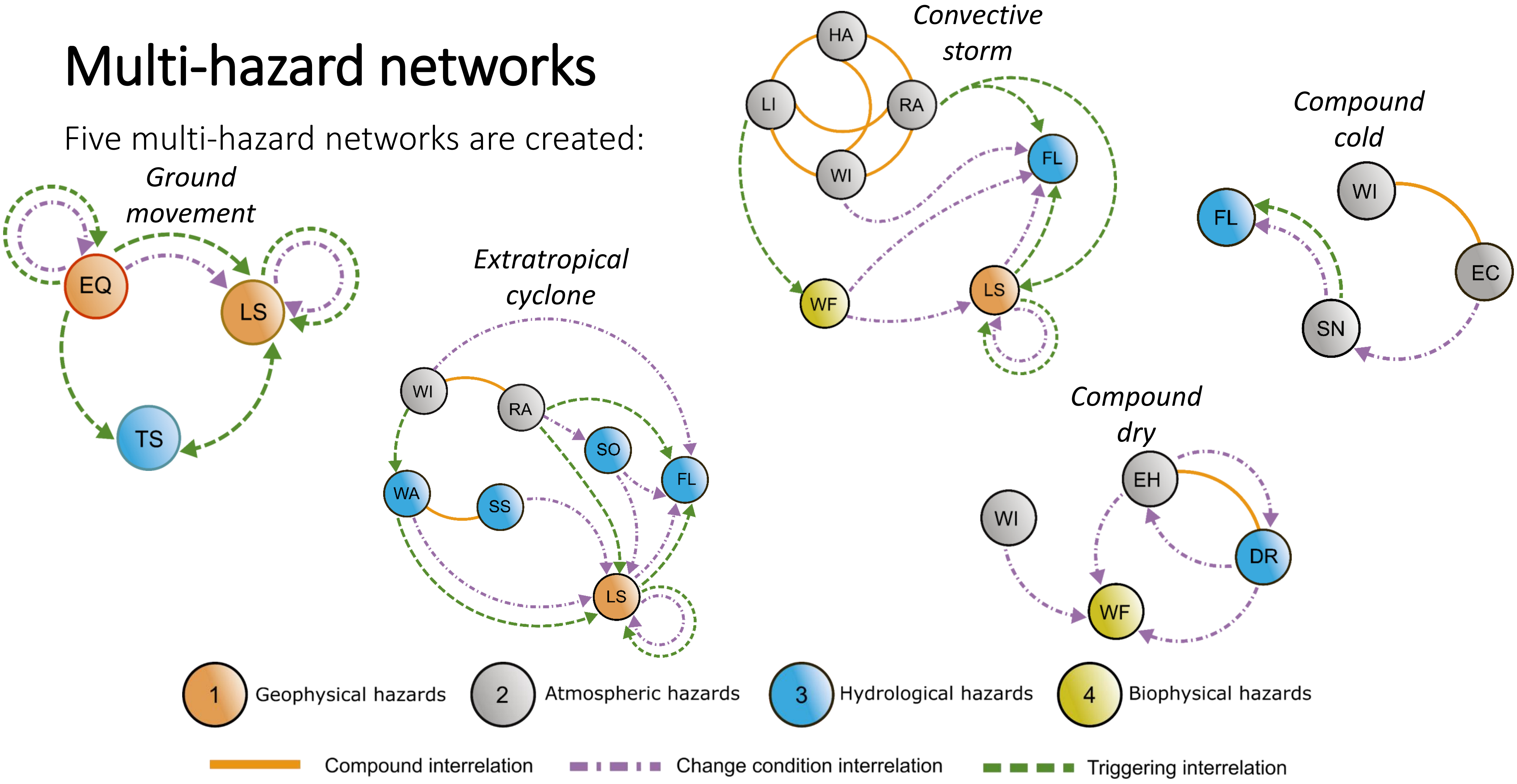
- *Multi-hazard network:* a set of interrelated hazards prone to be triggered by the same **underlying processes** and occurring in a **given space-time frame**.
- Multi-hazard networks construction is based on:
  - physical drivers (e.g., meteorological, geophysical),
  - prior knowledge on interrelations between hazards.



The five multi-hazard networks and their associated hazards From thesis Chapter 3

Multi-hazard networks

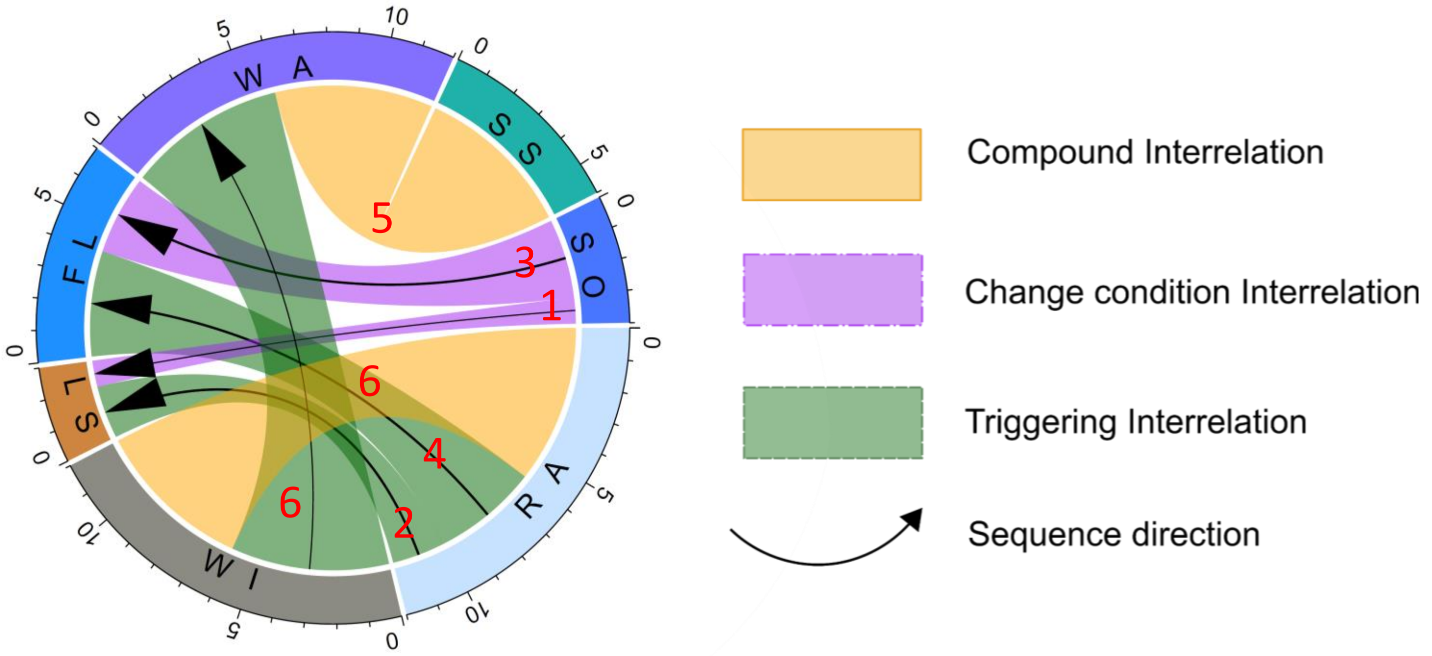
Five multi-hazard networks are created:



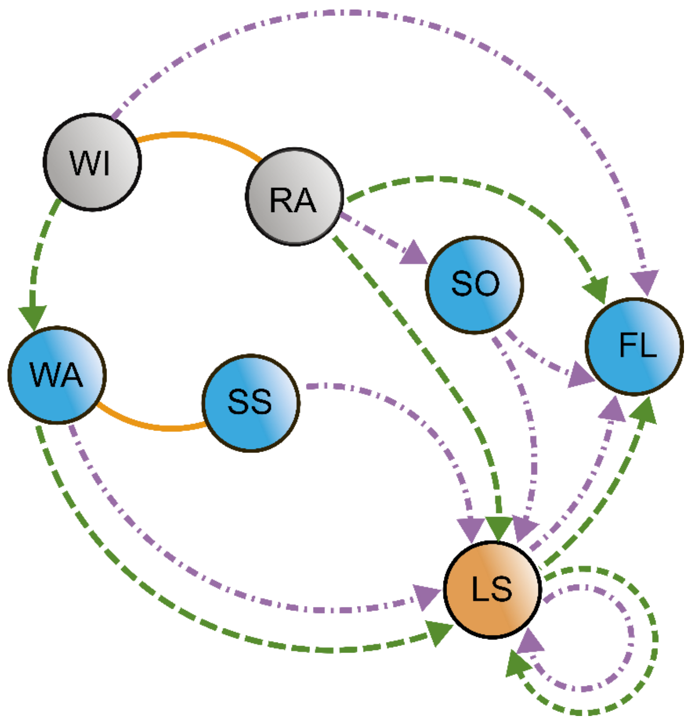
Dominant hazards & hazard interrelations

dominant hazard: most likely and most interconnected hazard within a multi-hazard network.

dominant hazard interrelation: most likely hazard interrelation within a multi-hazard network.



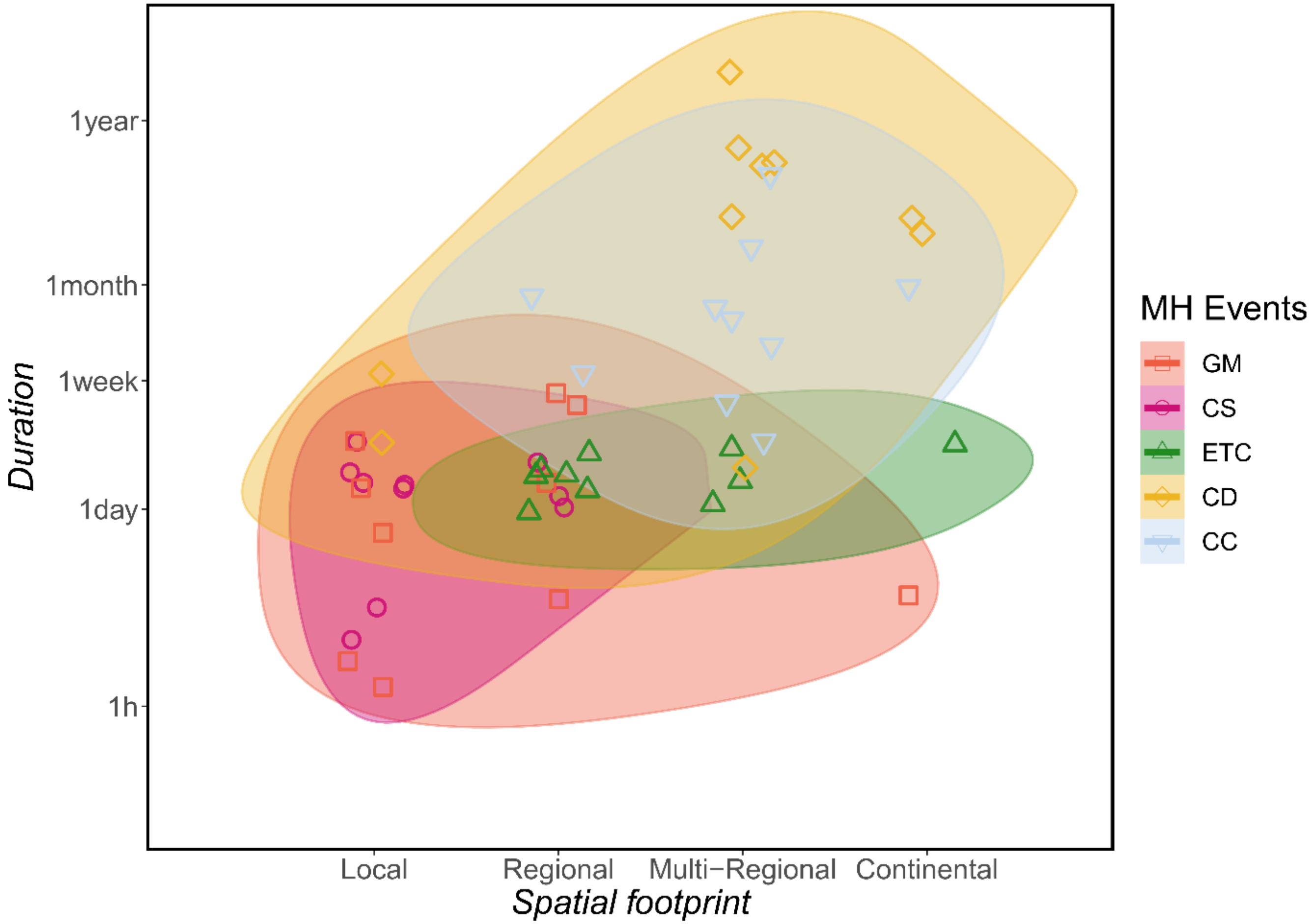
Chord diagram of hazard interrelations within an extratropical cyclone multi-hazard network using the multi-hazard events catalogue. From Thesis Chapter 3.



Network of natural hazards associated to an extratropical cyclone with their interrelation types. Storm surge (SS), extreme wind (WI), extreme precipitation (RA), extreme wave (WA), soil moisture excess (SO), river flooding (FL), landslide (LS). From Thesis Chapter 3.

Spatiotemporal scales of multi-hazard networks

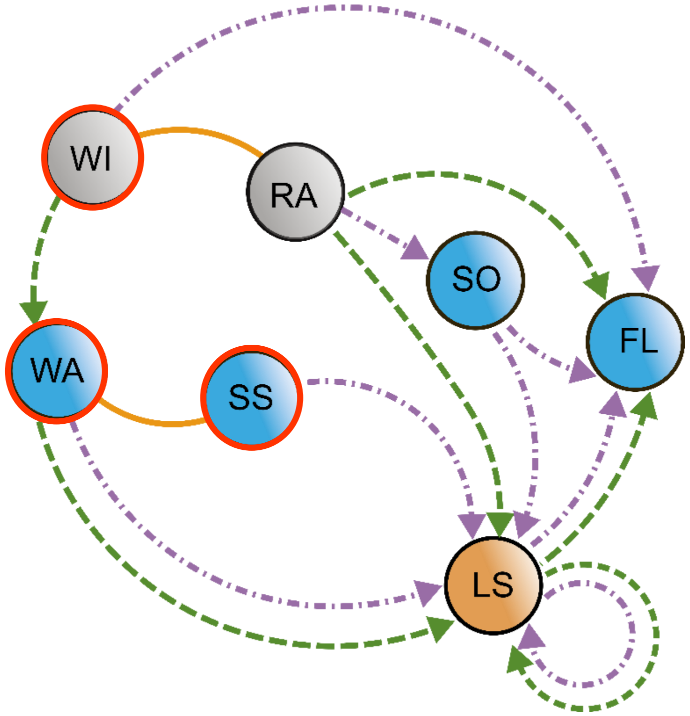
- Spatial footprint refers to the area that the hazard influences and temporal scale to the timescale that the single hazard acts upon the natural environment.
- Semi-quantitative assessment of the duration and spatial extent of the different multi-hazard networks
- Scatter plots of each MH network are encircled, highlighting the inter-group variability in both duration and extend.



Spatial and temporal scales of 50 multi-hazard events divided into five networks by colour: Ground Motion (GM), Convective Storm (CS), Extratropical Cyclone (ETC), Compound Dry (CD) and Compound Cold (CC). Shown on logarithmic axe.

Towards an historic multi-hazard events catalogue

- Catalogue of 50 multi-hazards events (10 per network)
- 32 sources used to build the catalogue:
  - single hazard catalogues (17);
  - catalogues of reported weather events (6);
  - peer review articles & books (5);
  - disaster databases (2);
  - multi-hazard catalogues (2)
- For each event: # of hazards, # of interrelations, spatial scale, temporal scale



Network of natural hazards associated to an extratropical cyclone with their interrelation types. Storm surge (SS), extreme wind (WI), extreme precipitation (RA), extreme wave (WA), soil moisture excess (SO), river flooding (FL), landslide (LS).

MH Event	Event	Start Date	End date	Hazards	Impacted place	N Haz	N inter	Spatial scale	D (days)	Source ID
	ETC07 Storm Xynthia 2010	28/02/2010	02/03/2010	Wind, Storm surge ,Waves	France, Spain, Portugal, United Kingdom	3	2	Multi-regional	3	13,25,26

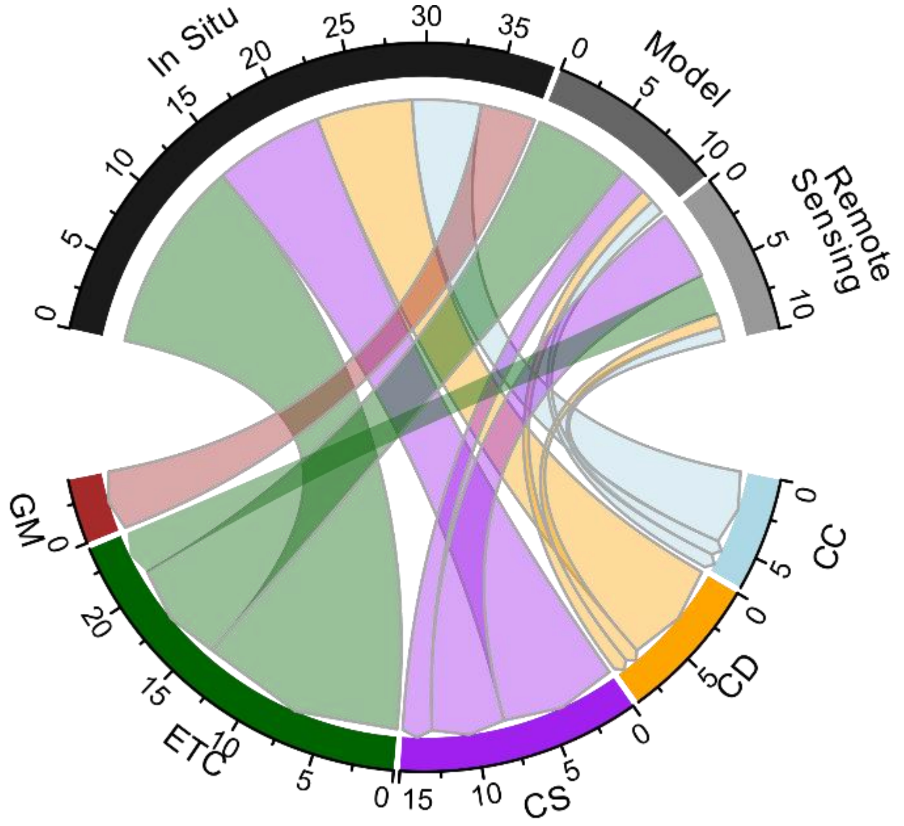
Data for multi-hazard analysis

Review of **35 freely available datasets** to model hazard interrelations between **16 natural hazards.**

Datasets \ Hazards	1.1 Earthquake	1.2 Landslide	2.1 Lightning activity	2.2 Extreme rainfall	2.3 Extreme wind	2.4 Extreme hot air temperature	2.5 Extreme cold air temperature	2.6 Hail	2.7 Extreme snowfall	3.1 Storm surge	3.2 Extreme waves	3.3 River flooding	3.4 Tsunami	3.5 Drought	3.6 Soil moisture excess	4.1 Wildfire
M1. ERA 5				×	×	×	×		×		×			×	×	
M2. UERRA				×	×	×	×									
M3. GTSR										×						
M4. Paired time series of daily discharge and storm surge										×						
M5. EFAS												×		×	×	
M6.POLCOMS-WAM											×					
M7. CMEMS Ocean waves hindcasts											×					
I1. Significan Eathquakes database	×												×			
I2. Earthquake catalogue	×															
I3. Tsunami database													×			
I4. EQIL Inventory	×	×														
I5. GLC		×														
I6. E-Obs				×		×	×									
I7. Hadley Centre observations datasets ISD				×	×	×	×		×							
I8. Integrated Surface Database (ISD)				×	×	×	×		×							
I9. GHNC - daily				×		×	×									
I10. MIDAS Open: UK Land Surface Stations Data				×	×	×	×									
I11. GRDC												×				
I12. National river flow archive												×				
I13. Base de donnée Hydrométrie												×				
I14. ISMN												×		×	×	
I15. GESLA										×						
I16. UK Tide Gauge Network										×						
I17. JASL										×						
I18. Wave data series											×					
I19. PRFD																×
I20. ESWD			×					×								
S1. ATDNet			×													
S2. MSWEP				×												
S3. NIMROD Database				×												
S4. PERSIANN CSS				×												
S5. GPM IMERG				×												
S6. CCI						×	×							×	×	×
S7. EUSTACE						×	×									

Data for multi hazard analysis

- Occurrences of natural hazards are measured differently
- Three main categories of numerical datasets:
  - In situ observations
  - Remote sensing
  - Modelled data

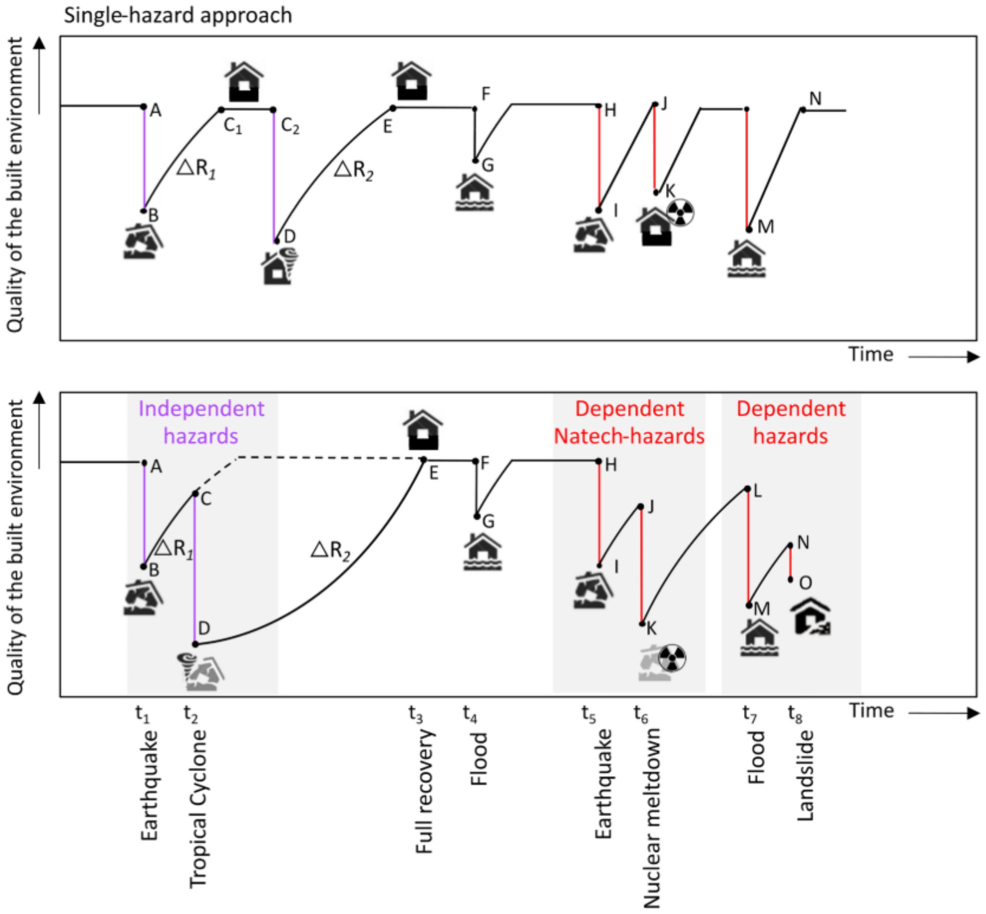


Availability of three types of data (in situ, model, remote sensing) for the five multi-hazard networks

Conclusions

Risk and vulnerability

- Development of multi-hazard disasters database
- Dynamic vulnerability
- Understanding the contribution of different risk drivers



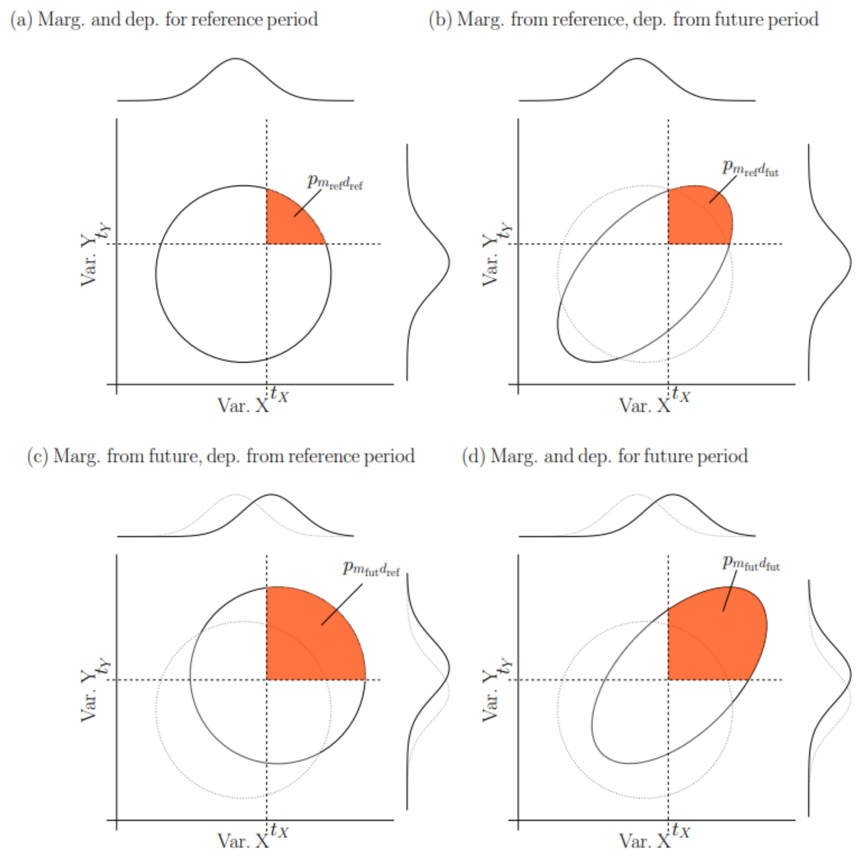
The difference between single risk (top panel) and consecutive risk assessments (bottom panel). Highlighting consecutive disasters and their different degrees of recovery at a given spatial scale. From de Ruiter et al. (2020)

de Ruiter, M. C., Couasnon, A., van den Homberg, M. J. C., Daniell, J. E., Gill, J. C. and Ward, P. J.: Why We Can No Longer Ignore Consecutive Disasters, Earth's Futur., 8(3), 2020.

Conclusions

Land and climate change impacts

- Shifts in natural hazards (extremes) distribution (e.g., temperature).
- Change in dependence structure
- Change in land cover (wildfire-flood sequence)
- Emergence of new hazard interrelations?



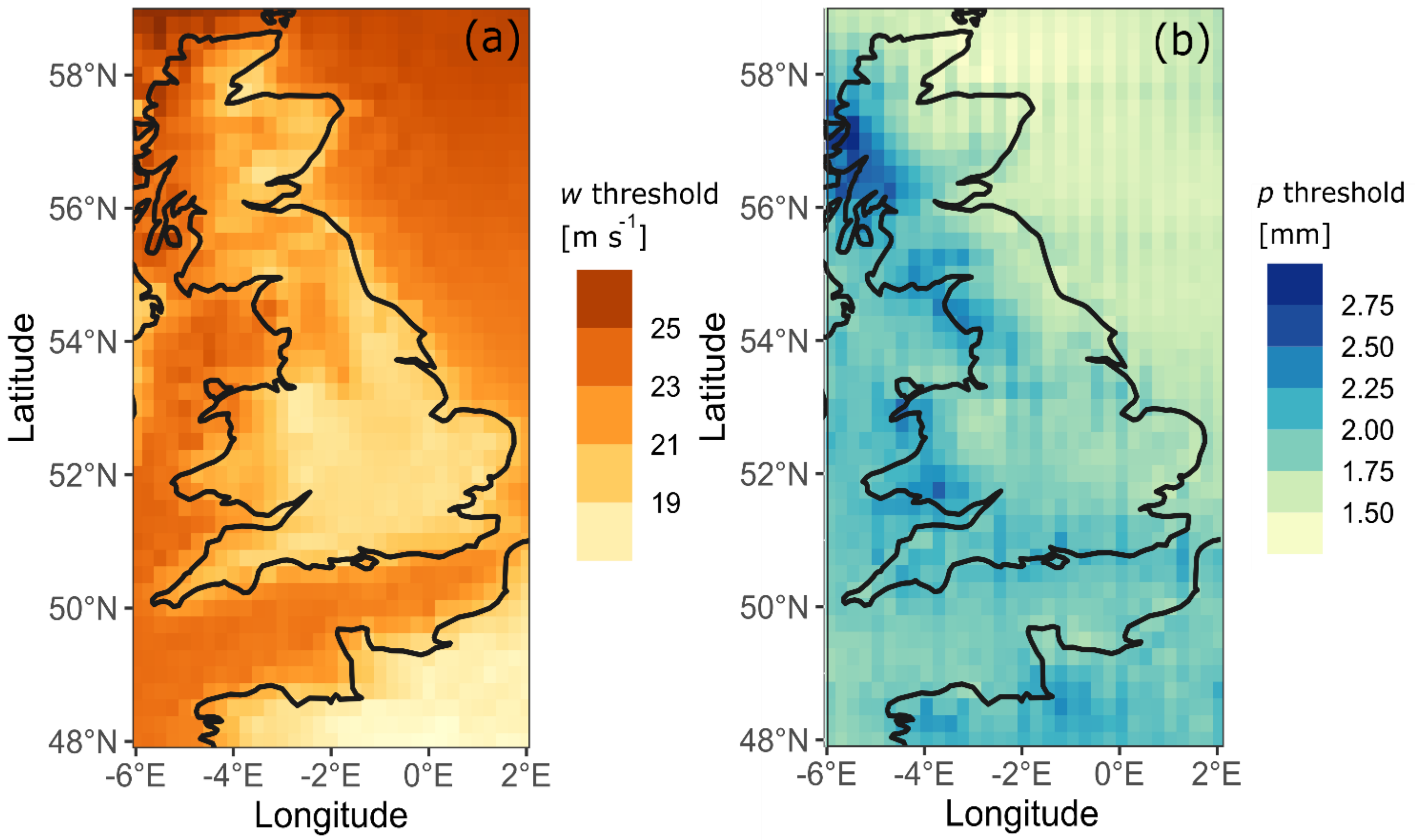
Possible changes in bivariate distributions of compound hazards induced by climate change. From Francois and Vrac (2022).

François, B. and Vrac, M.: Time of Emergence of compound events: contribution of univariate and dependence properties, Nat. Hazards Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/nhess-2022-127, in review, 2022.

Extra slides

Extremes sampling

- Hourly wind and precipitation data from ERA5 (1979–2019).
- We consider for each hour:
    - **Hourly maximum wind gusts** (average 3 s of wind)
    - **Precipitation** (total rainfall and snow).
- For each we take the **99th percentile** computed on each grid cell of the domain (1485 cells).
- **Compound hazard clusters**: **co-occurrences** of **extreme wind** and **extreme rainfall clusters.**

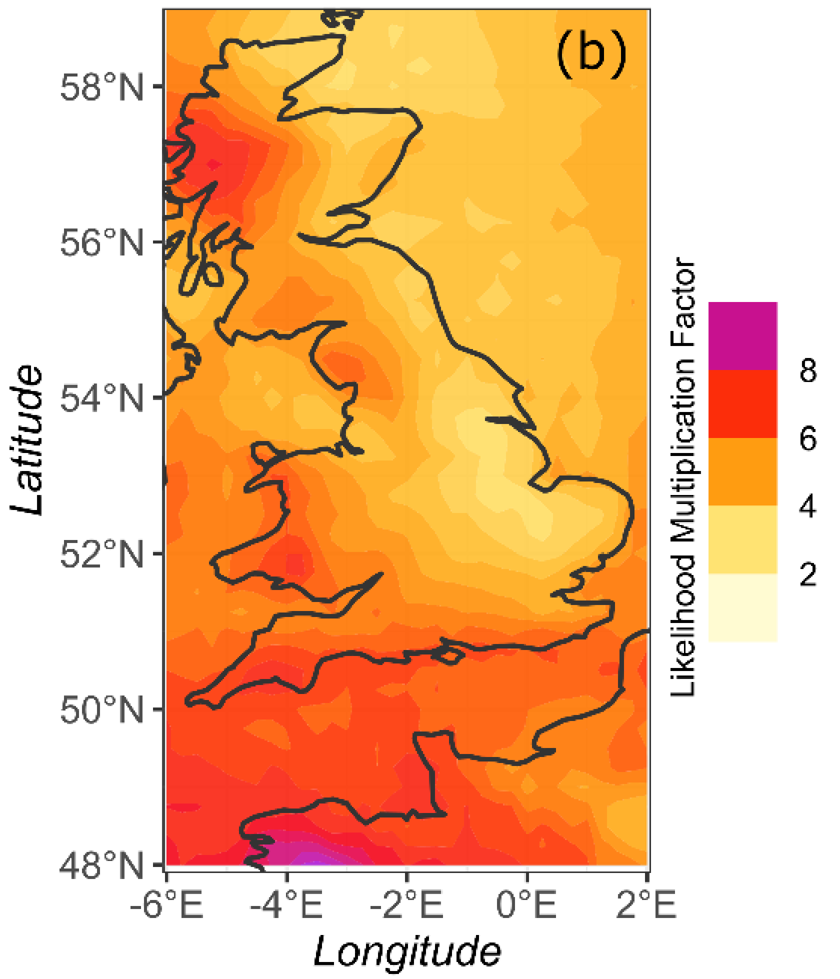


Threshold values corresponding to 99th percentile of each grid cell, 1979-2019, for hourly maximum wind gust (*w*) and hourly rainfall accumulation (*r*).

Hotspots for compound wind-precipitation

The likelihood multiplication factor (LMF) quantifies the influence of the dependence between wind events and rain events on the estimation of average number of hours in a CHE.

$$LMF = \frac{P\,(wind \cap rain)}{P(wind) * P(rain)} = \frac{T_{dep}}{T_{ind}}$$



Facteur de multiplication de probabilité
Entre le vent et la pluie extrême. Données ERA5 (Hersbach et al., 2020).
D'apres Tilloy et al. (2022) Earth Syst. Dyn.