

COMPOUND EVENTS

An aerial photograph of a residential neighborhood that has been completely inundated with floodwater. The water is a murky, brownish-grey color, covering the streets, yards, and surrounding areas. Numerous houses with various roof colors (brown, grey, red) are visible, partially submerged. Green trees are scattered throughout the landscape, some with their lower branches underwater. A central street runs vertically through the middle of the frame, with a few cars visible in the distance. To the right, a green golf course is partially visible, also surrounded by floodwater. The overall scene depicts a severe flooding event.

James Doss-Gollin

CEVE 543

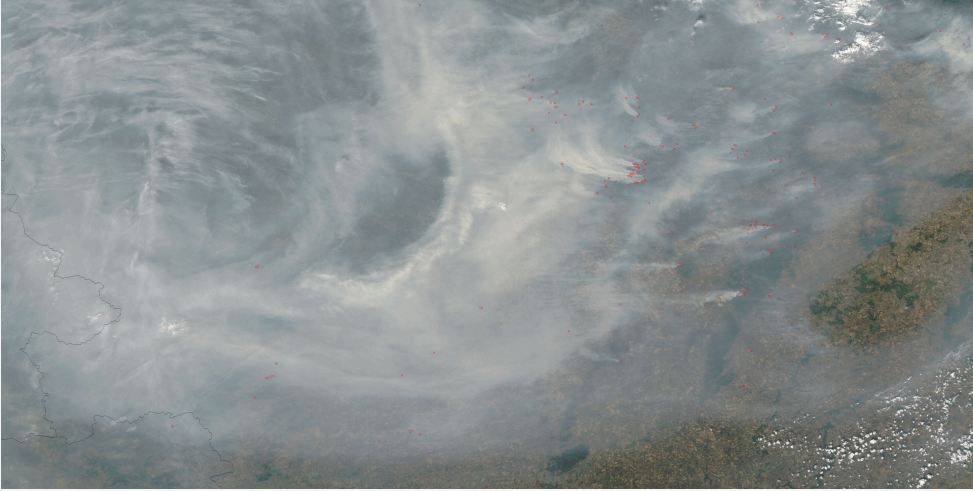
2026-10-19

Compound events

Multi-hazard fragility curves

Hazard models for compound extremes

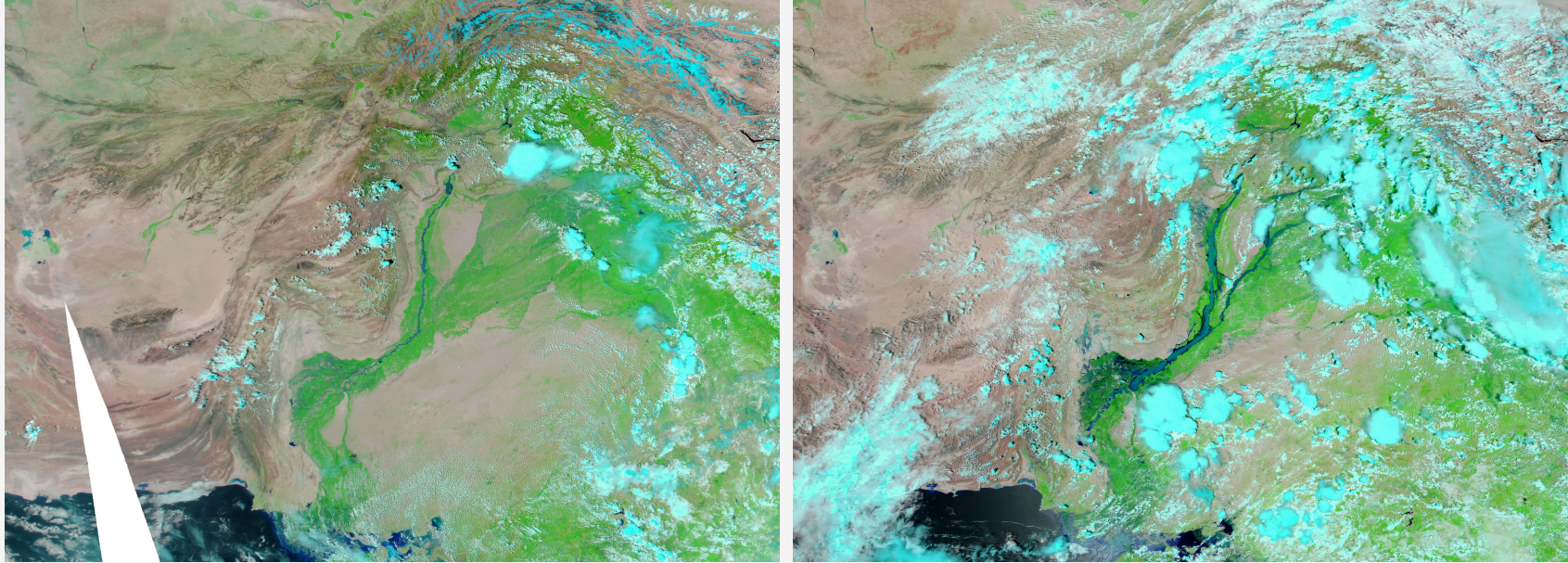
RUSSIA, SUMMER 2010



Wildfire smoke over Moscow, August 7, 2010. NASA.

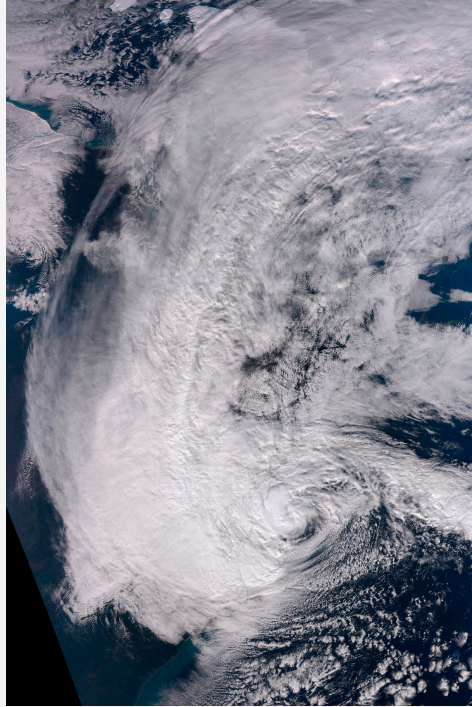
- A dry spring and summer drought exacerbated a heatwave.
- Wildfires followed.
- Global wheat prices rose.

SPATIALLY CO-OCCURRING CLIMATE EXTREMES



The Indus River on August 11, 2009 (left) and in flood on August 10, 2010 (right). NASA images from MODIS Rapid Response Team.

COMPOUND FLOODING



Hurricane Sandy, October 29, 2012. NASA Earth Observatory.

- A blocking high steered Hurricane Sandy (2012) into New York from the east.
- The highest storm surge in at least 300 years + spring tide + heavy rainfall + waves
- Damage passed US\$50 billion and 233 people died (Zscheischler et al., 2018)

SANDY RESHAPED THE COAST

i Note

Figure shown in class: New York coast before and after Sandy.

MOST HAZARDS HAVE MORE THAN ONE DRIVER

Hazard	Climate drivers
Heat stress	Temperature, humidity
Fire risk	Temperature, rain, humidity, wind, lightning
Coastal flood	River flow, rain, sea level, surge, wind
Drought and heat together	Temperature, rain, evaporation, humidity
Wind and rain together	Wind, rain, terrain, large-scale circulation
Heat and air pollution together	Temperature, sulfur dioxide, nitrogen oxides, particulates

Abridged from Table 1 of Zscheischler et al. (2018, p. 470), whose first recommendation is that most major weather and climate disasters are caused by several drivers acting together (Zscheischler et al., 2018, p. 474).

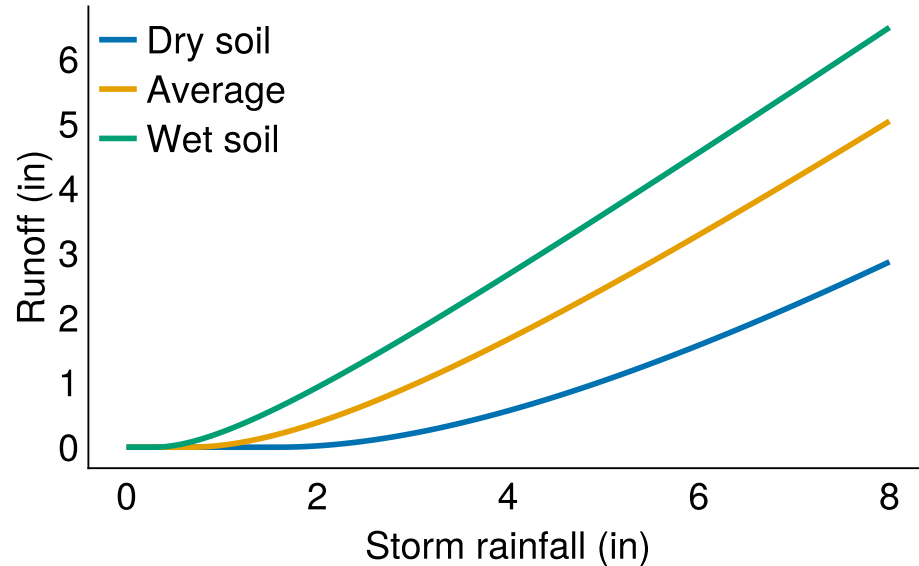
DEFINITIONS

“the combination of multiple drivers and/or hazards that contributes to societal or environmental risk” (Zscheischler et al., 2018)

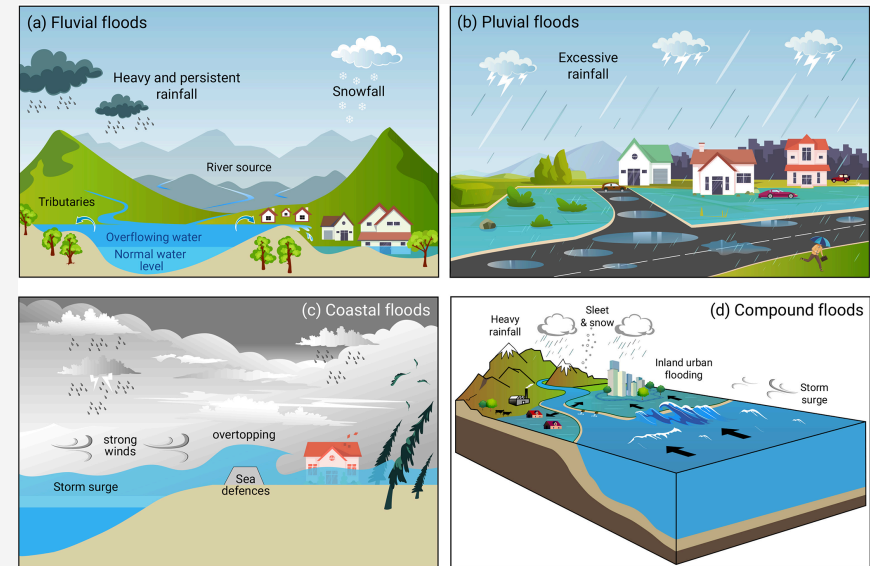
Earlier definitions, such as the IPCC special report on extremes (IPCC, 2012), required an extreme impact and dependent drivers.

FOUR TYPES OF COMPOUND EVENT

Preconditioned: an extreme event does more harm because of initial conditions



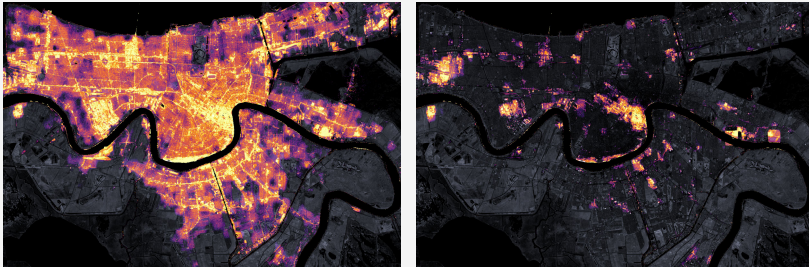
Multivariate: several drivers act at once.



Green et al. (2025), Fig. 1 (CC BY 4.0).

FOUR TYPES OF COMPOUND EVENT, CONTINUED

Temporally compounding: one hazard follows another. Hurricane Ida: wind + heat → 35 million customer-hours without power at a heat index above 100°F (Lin et al., 2024).



New Orleans at night before (left) and after (right) Ida, 2021. NASA.

Spatially compounding: many connected places at once.

i Note

Figure shown in class: Clustered extreme rainfall across 40 mining assets, after Bonnafous et al. (2017).

EXAMPLES: PRECONDITIONED AND MULTIVARIATE

Preconditioned

- Rain on saturated or snow-covered ground → flood
- Warm late winter, then frost → crop loss
- Dry year, then fire season → wildfire

Multivariate

- Rain + surge + river flow → coastal flood
- Heat + drought → crop failure, wildfire
- Heat + humidity → heat stress
- Wind + rain → storm damage

From Zscheischler et al. (2020)

EXAMPLES: TEMPORALLY AND SPATIALLY COMPOUNDING

Temporally compounding

- Storm after storm → flood and wind damage before repairs are done
- Heatwave after heatwave → health, energy demand, crops
- Flood or hurricane, then heatwave → heat exposure without power

Spatially compounding

- Floods across a region at once → regional trade, emergency response
- Heat or drought in several breadbaskets at once → global food system
- Extremes across many insured sites at once → (re)insurance

From Zscheischler et al. (2020)

Compound events

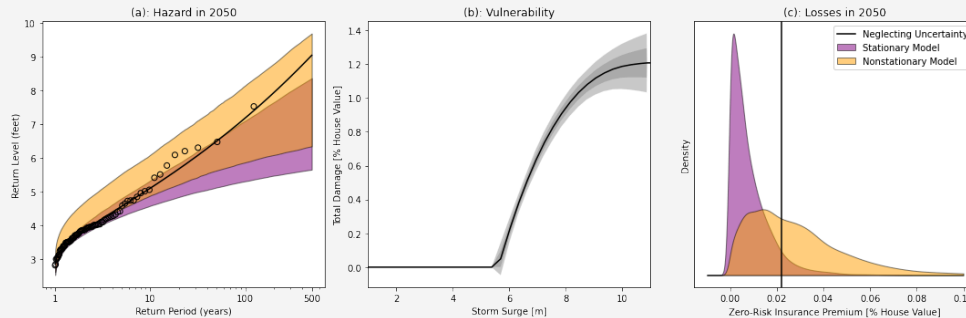
Multi-hazard fragility curves

Hazard models for compound extremes

DAMAGE AND FRAGILITY

A **damage function**, such as week 1's depth-damage curve, gives the expected loss as a fraction of value at each hazard intensity.

A **fragility function** gives the probability of reaching a damage state, such as a pole breaking, at each hazard intensity.



Damage results from hazard and vulnerability.

i Note

Figure shown in class: Each component of an infrastructure network may have a fragility function. From Rincon & Padgett (2024), Fig. 1a.

A HOUSE IN A FLOOD: DEPTH AND DURATION

More realistic damage assessments depend on more than one hazard, for example flood depth *and* duration (Nofal et al., 2020).

i Note

Figure shown in class: Total building loss as a surface over flood depth and flood duration, from Nofal et al. (2020), Fig. 16a.

A UTILITY POLE IN A HURRICANE

i Note

Figure shown in class: Wind, surge, and wave loads on a pole. Darestani et al. (2022), Fig. 1.

i Note

Figure shown in class: Probability of pole failure as wind, surge, and wave hazards increase. Darestani et al. (2022), Fig. 4.

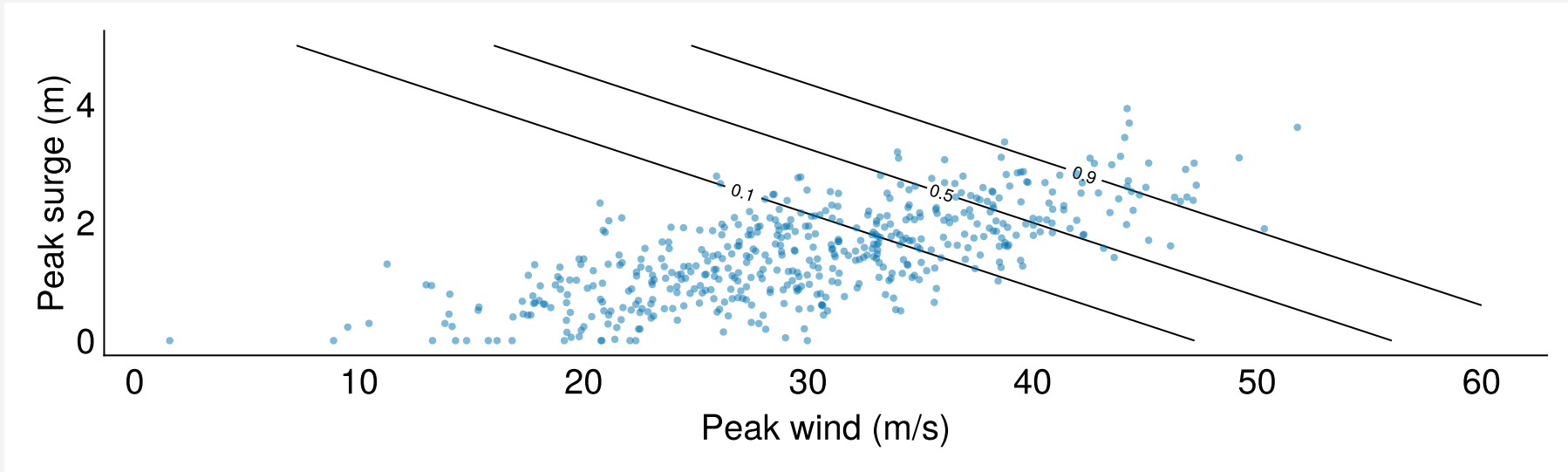
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WHAT A FRAGILITY SURFACE NEEDS FROM THE HAZARD MODEL

$$E[\text{failures}] = \sum_{\text{storms}} P(\text{fail} \mid \text{wind, surge})$$



Each point is a storm, and each contour a probability that a pole fails (simulated data).

THE SAME DRIVERS, DIFFERENT CLOUDS

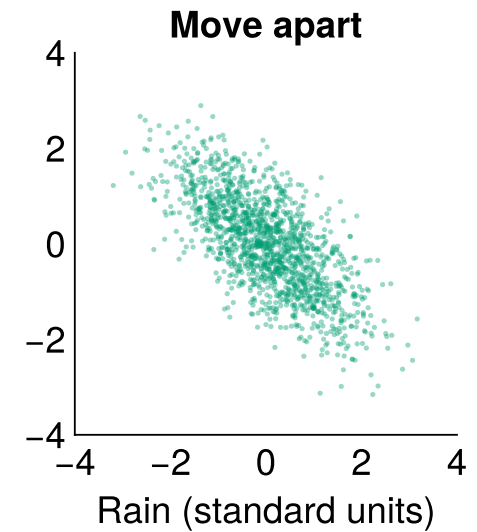
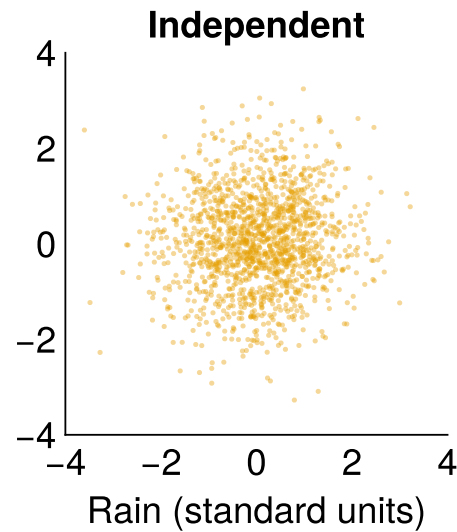
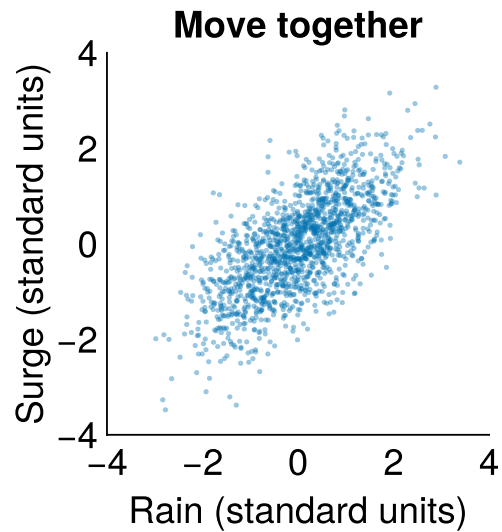
i Note

Figure shown in class: Driver distributions over two hazards. Zscheischler et al. (2018), Fig. 2.

Under the purple “Future 2” scenario, the distributions of driver 1 and driver 2 barely change, but hazard 1 becomes far greater (Zscheischler et al., 2018).

DEPENDENCE

We care about the *joint distribution* of drivers or hazards:



RAIN AND SURGE BOTH AT THEIR 100-YEAR LEVELS

Think

At a coastal site, you know the 100-year rainfall and the 100-year surge. How often do both happen in the same year: once in 100 years, once in 10,000, or something else?

EITHER OR BOTH

Let A be the event that rain passes its 100-year level in a given year, and B the same for surge. “ A or B ” means at least one happens; “ A and B ” means both happen in the same year.

...

At least one is never rarer than either alone, and both is never more common:

$$P(A \cup B) \geq \max\{P(A), P(B)\}, \quad P(A \cap B) \leq \min\{P(A), P(B)\}$$

so with return period $T = 1/P$,

$$T_{\text{OR}} \leq 100 \leq T_{\text{AND}}.$$

HOW RARE IS “BOTH”?

How far T_{AND} sits above 100 years depends on how rain and surge move together:

- If the two always come together, $T_{\text{AND}} = 100$.
- If they are independent, $P(A \cap B) = P(A)P(B)$, so $T_{\text{AND}} = 100 \times 100$ years, which is 10,000.
- If they move apart, “both” is rarer still, and T_{AND} exceeds 10,000.

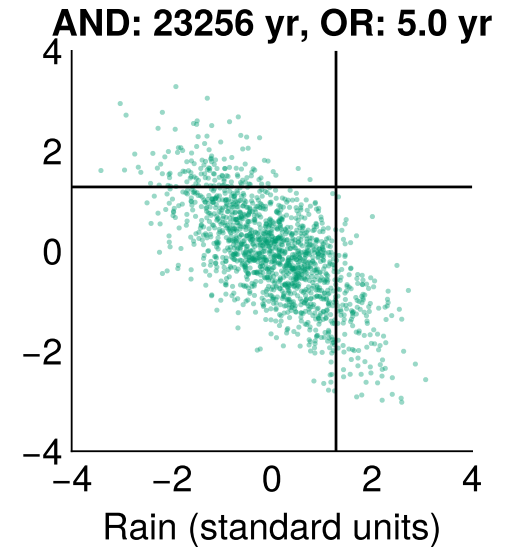
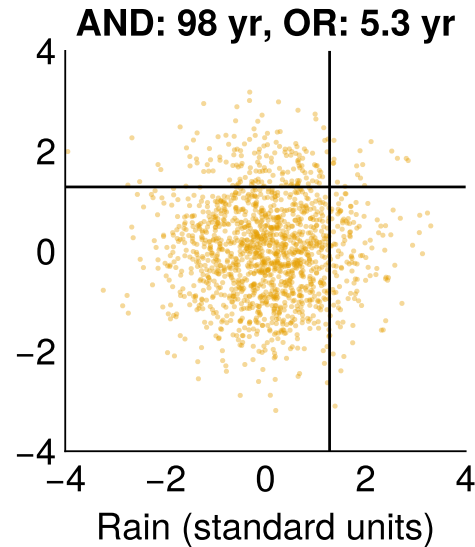
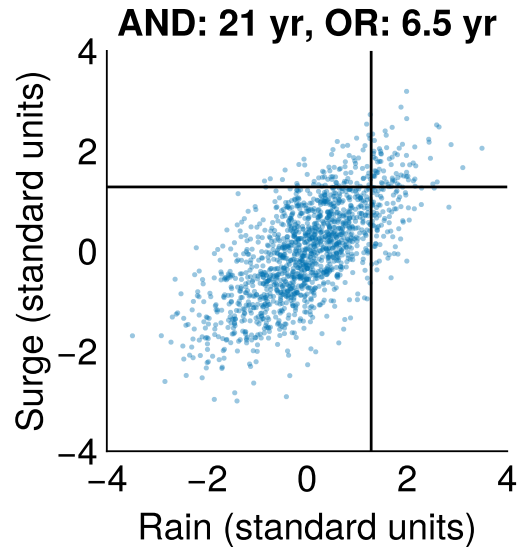
WHICH RETURN PERIOD AN ENGINEER NEEDS

The definitions answer different questions (Gräler et al., 2013, p. 1286; Salvadori et al., 2011, p. 3297).

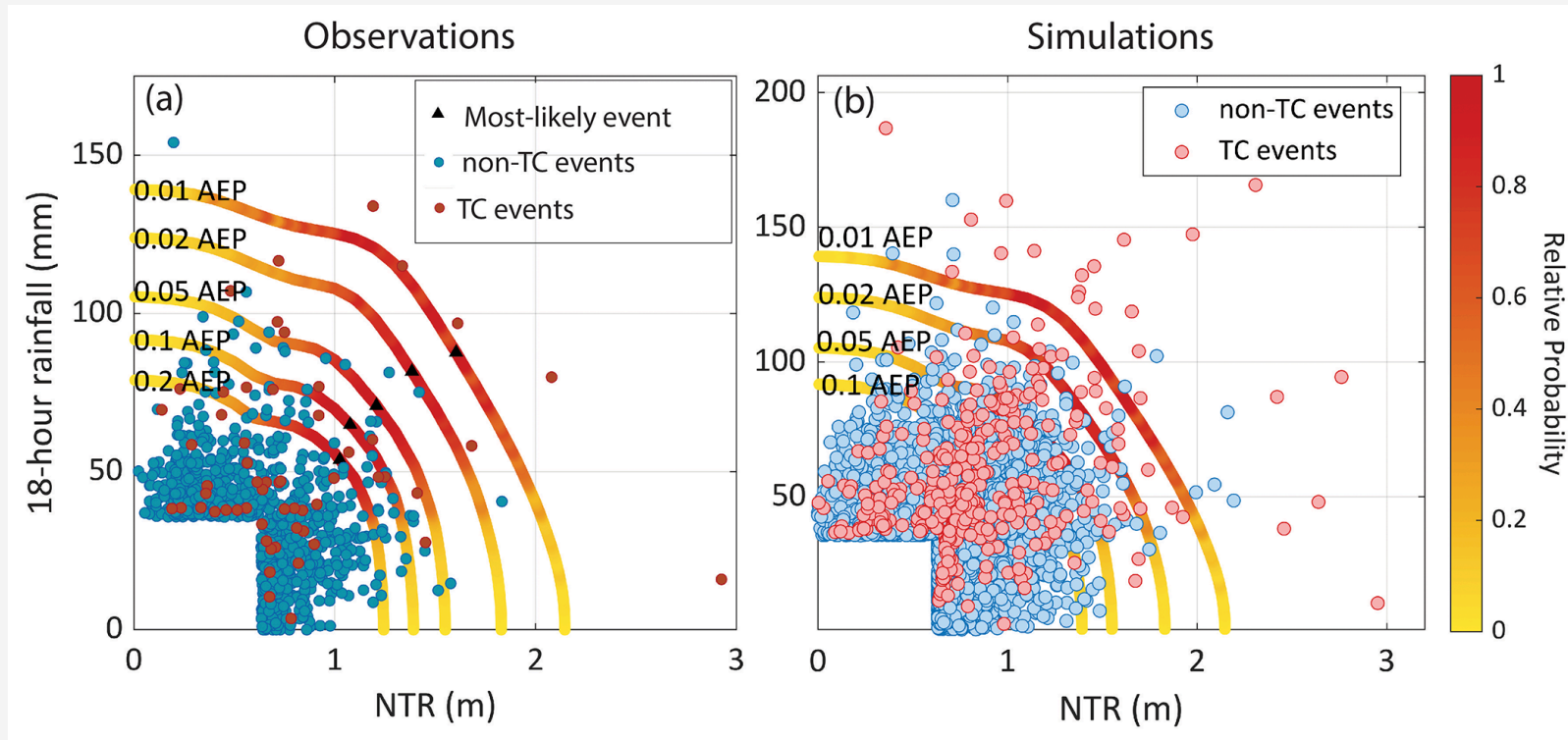
- A pole that fails when wind **or** surge is high needs T_{OR} .
- A drainage system that fails only when rain falls **and** the outlet is blocked by surge needs T_{AND} .
- The fragility surface says which combination fails the structure.

EITHER AND BOTH, BY SIMULATION

Each point is one simulated year, and the lines mark each driver's 10-year level. The 10-year level makes “both” common enough to count; under independence, $T_{\text{AND}} = 10 \times 10 = 100$ years.

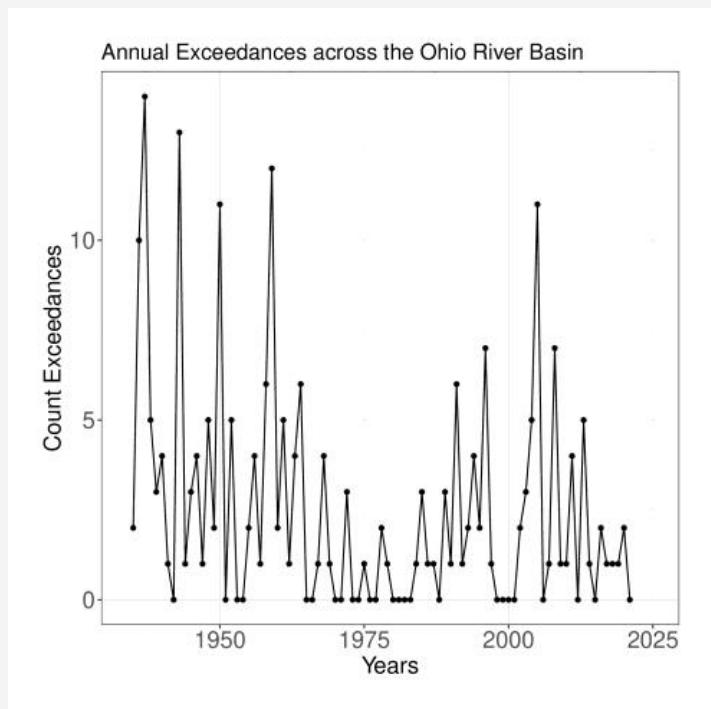


A 100-YEAR STORM, DIFFERENT FLOODS



Curves of equal AND joint return period for surge and rain: every point on a curve is exceeded in both drivers equally often. Maduwantha et al. (2026), Fig. 3 (CC BY 4.0).

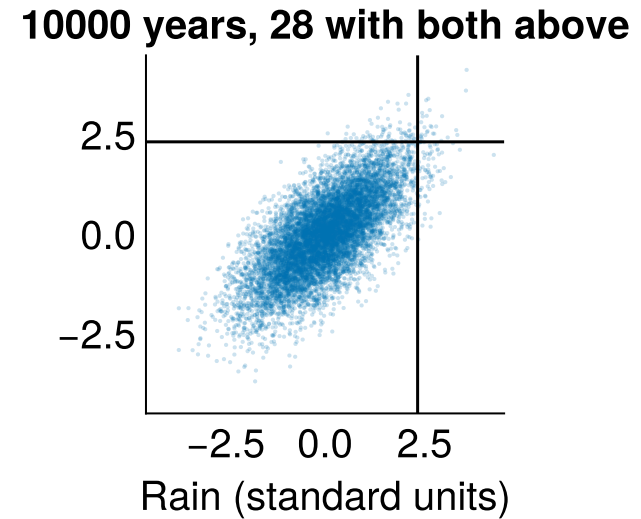
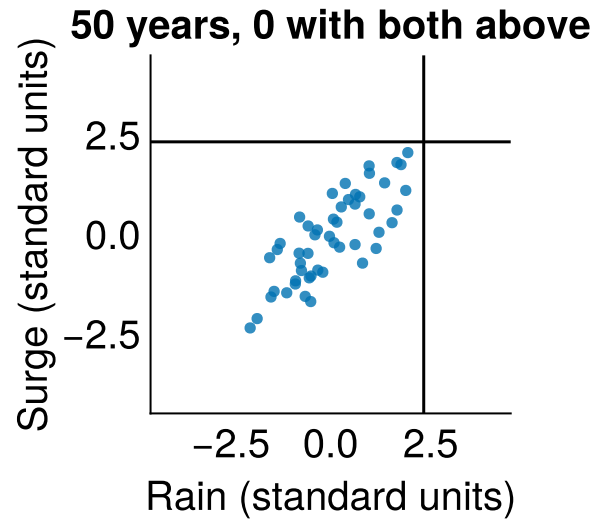
MANY SITES AT ONCE



Annual count of the 24 Ohio River Basin gauges whose annual maximum flow exceeded their own 10-year return level. From Amonkar et al. (2023), Fig. 2 (CC BY 4.0).

- At each gauge, $p = 0.1$
- If the 24 gauges were independent, the count would be $\text{Binomial}(24, 0.1)$, which implies $P(\text{count} \geq 10) \approx \frac{1}{20000}$
- Downstream floods depend on *all* the water coming from upstream

RARE COMBINATIONS AND SHORT RECORDS



A short record holds few years with both drivers extreme, so tail dependence is hard to estimate.