UFZ HELMHOLTZ Centre for Environmental Research

TECHNISCHE UNIVERSITÄT DRESDEN

The benefits of compound event research for climate risk assessments




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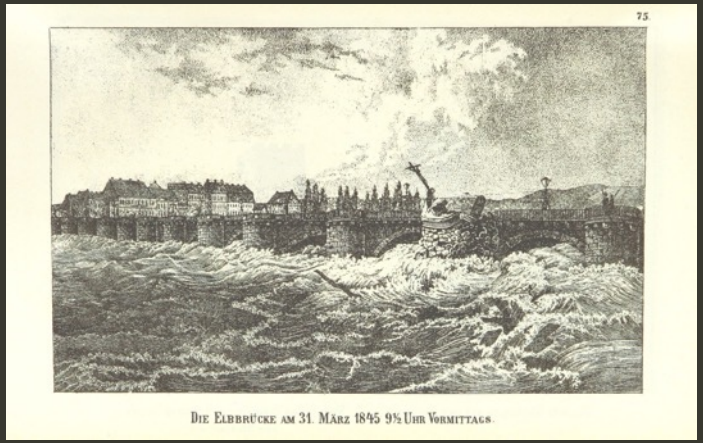
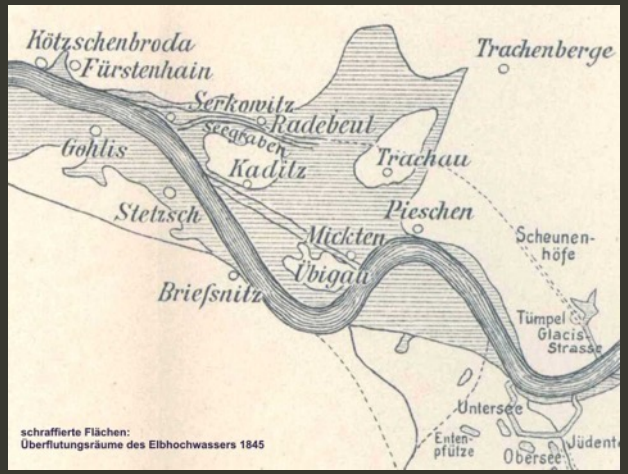
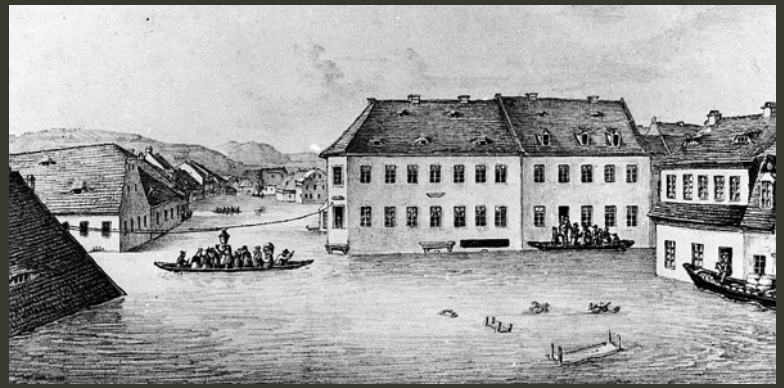
Elbe flood 1845



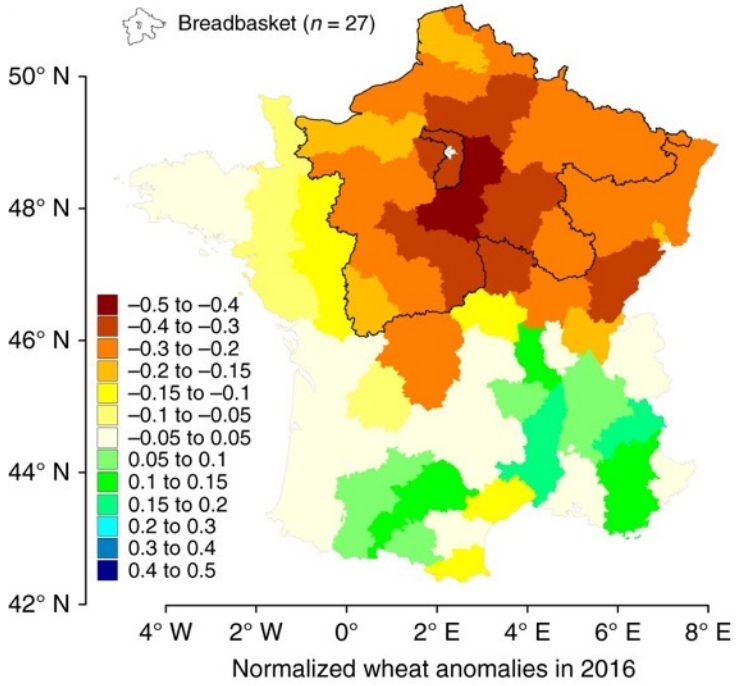


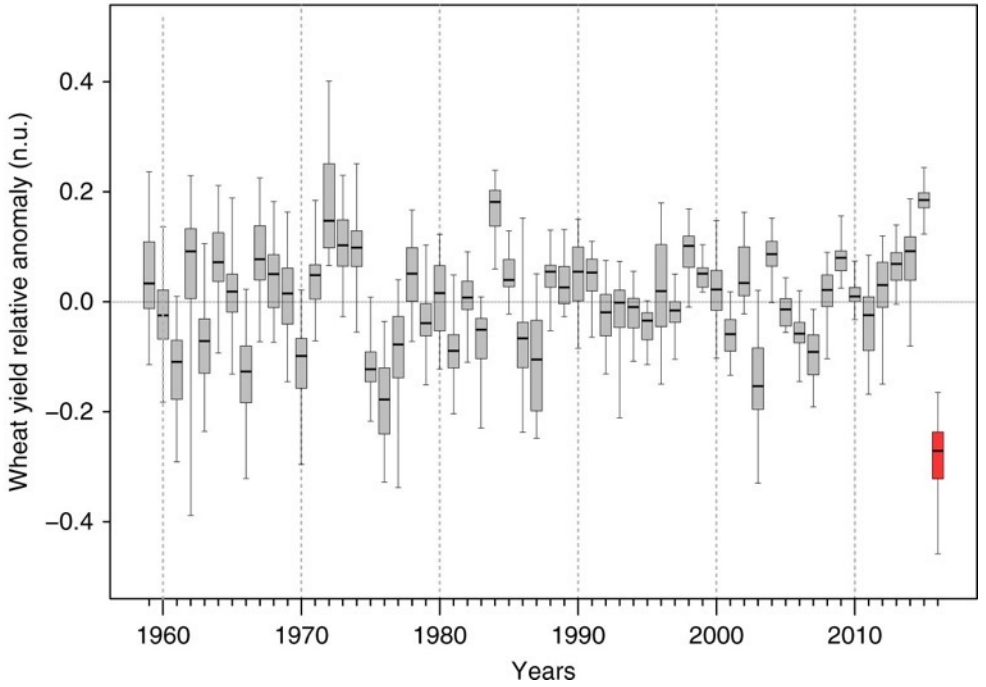


Aftermath of hurricane Ida

- Caused a blackout in many regions
- Air conditioning was not available during the following heatwave

2016 crop failure in France

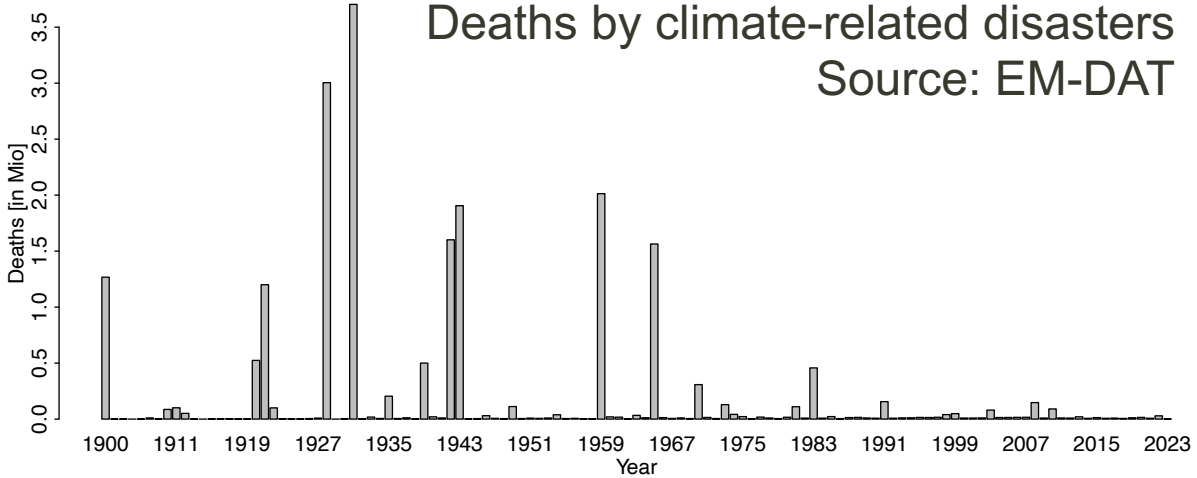




Ben-Ari et al. (2018) *Nature Communications*

Extreme weather events and their impacts

- Droughts
- Floods
- Heatwaves
- Wildfires
- Storms/Hurricanes
- …



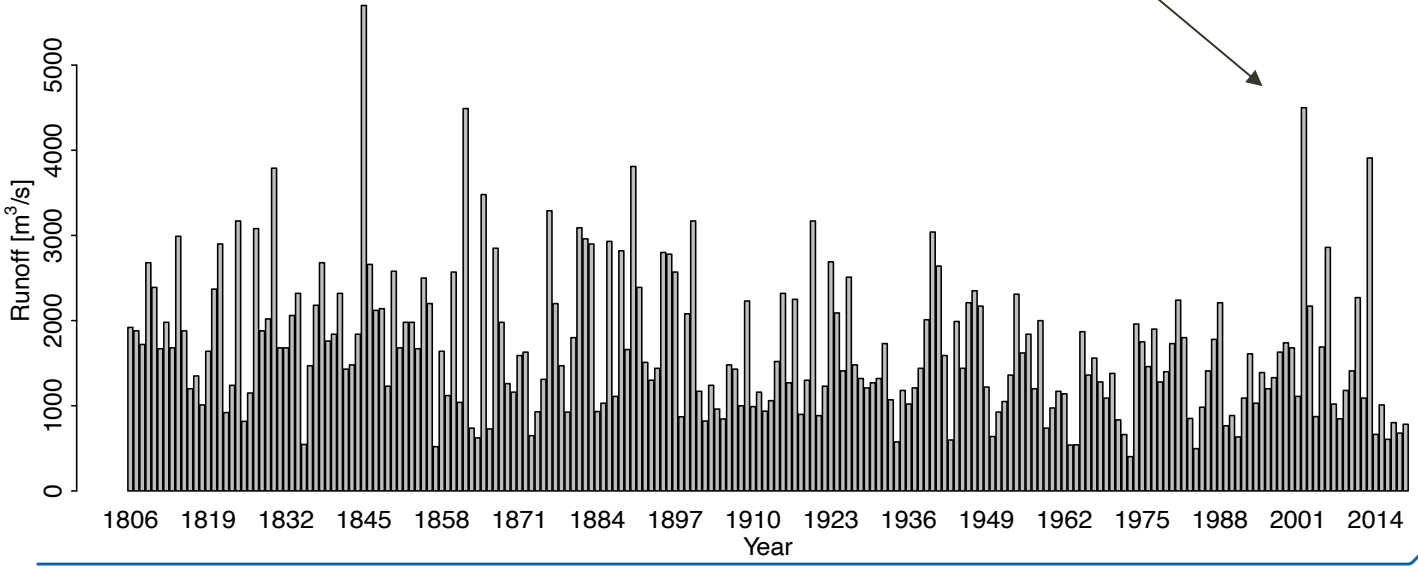
Annual maximum streamflow in Dresden

1845

2002

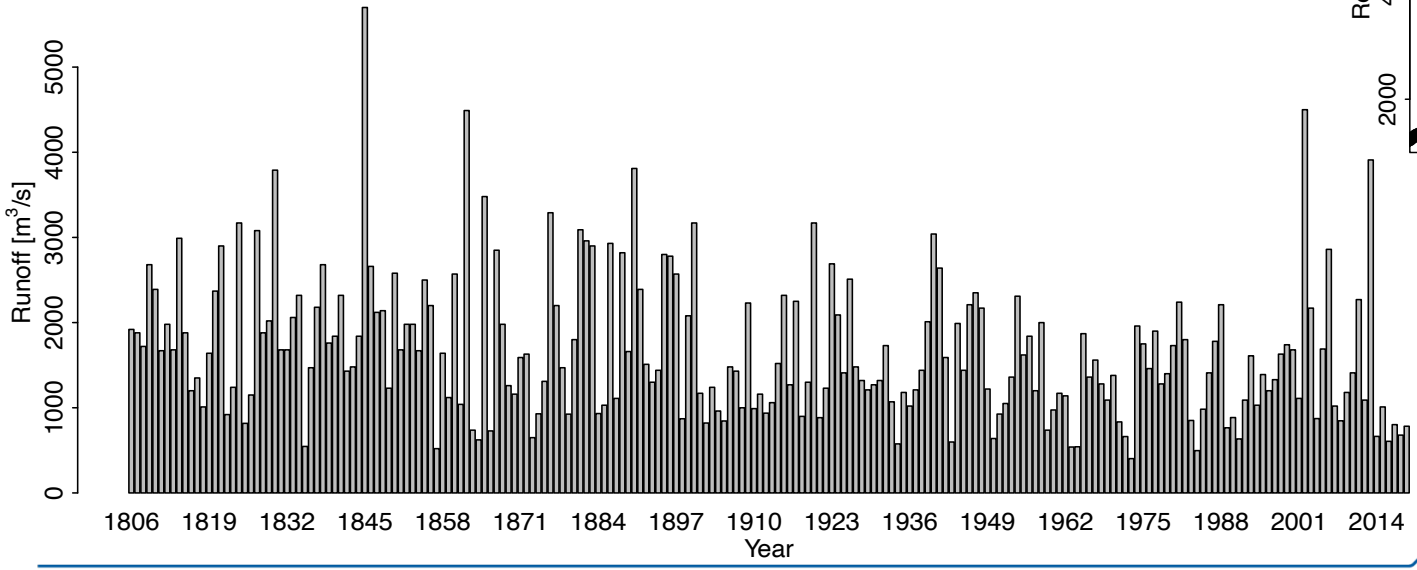
Pirna

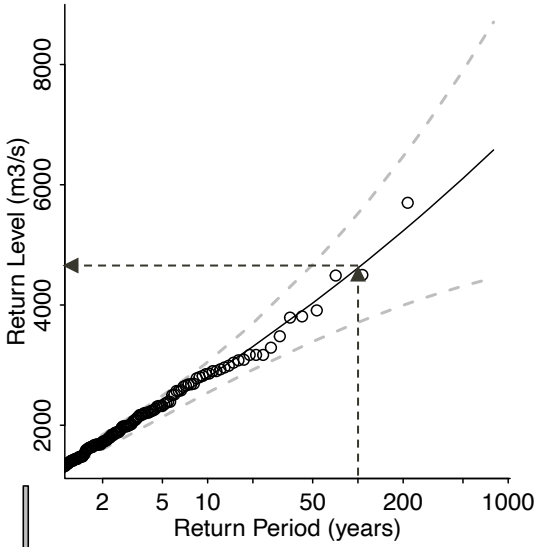
Pillnitz



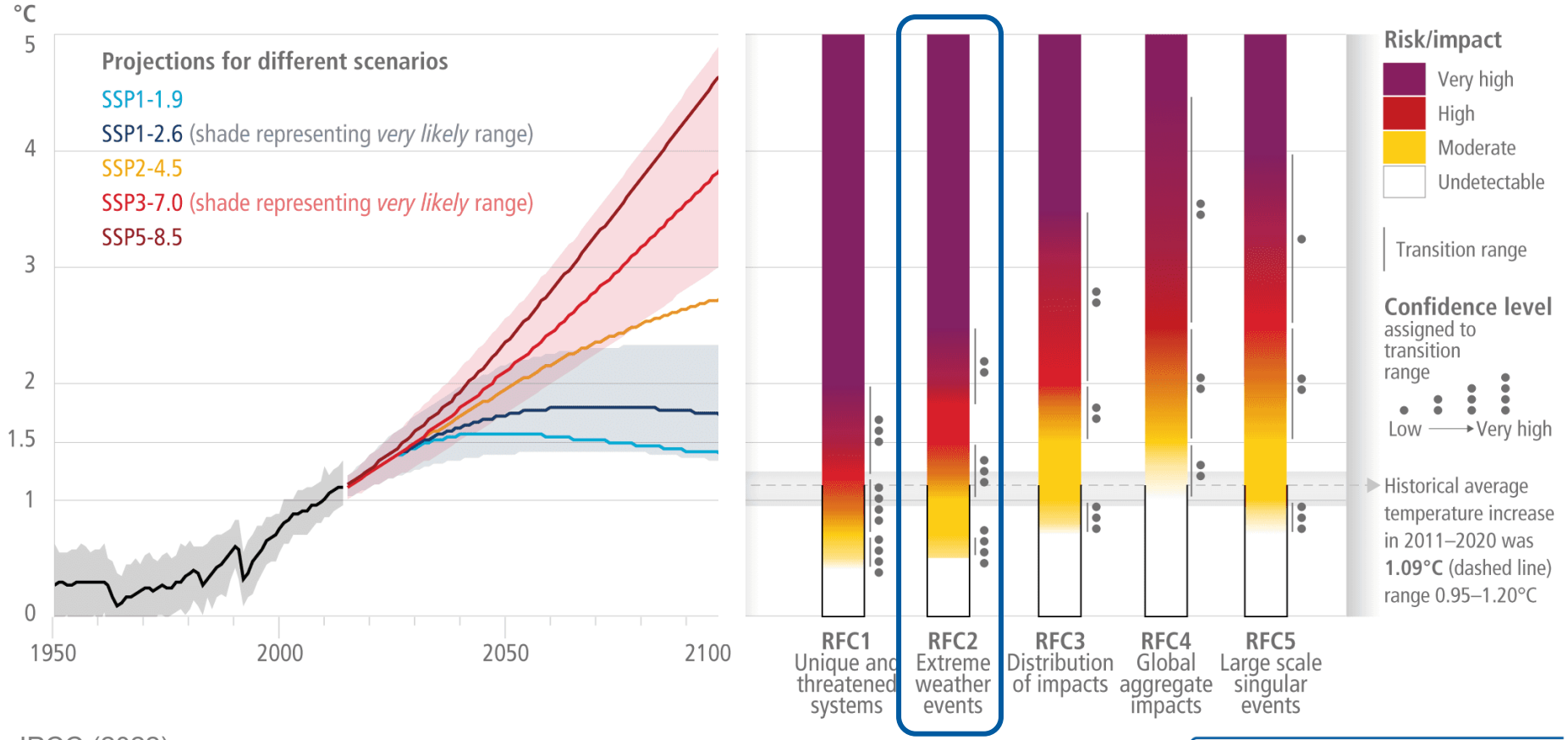
Flood frequency analysis

- Used to estimate return levels of 100-year floods (floods that occur on average every 100 years)
- Helpful for designing flood barriers





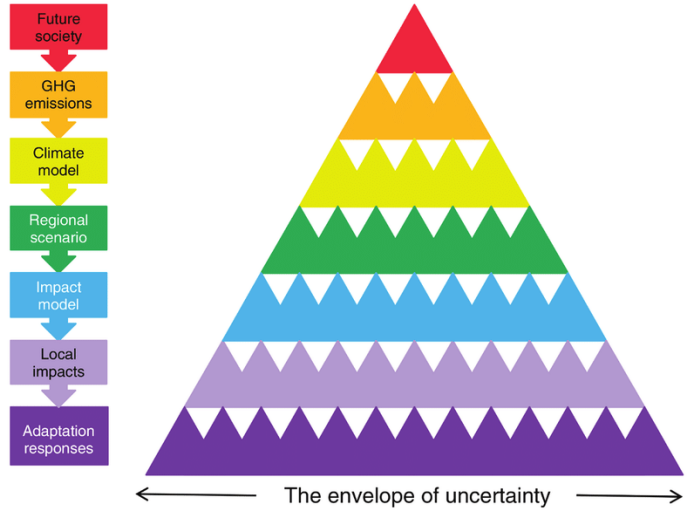
Climate change projections



IPCC (2022)

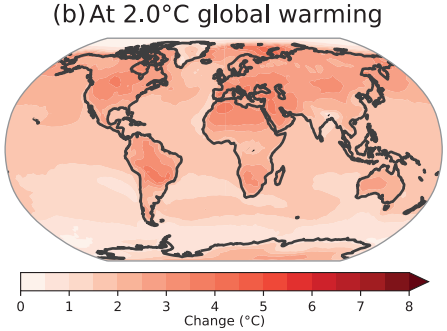
Traditional approaches to climate risk

- Warmest day of the year (TXx)
- Maximum daily precipitation (RX1day)
- Maximum length of dry spell
- Frequency of heat waves
- Intensity of droughts
- …

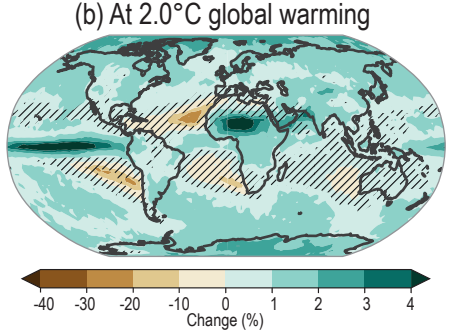


Top-down modelling chain

TXx



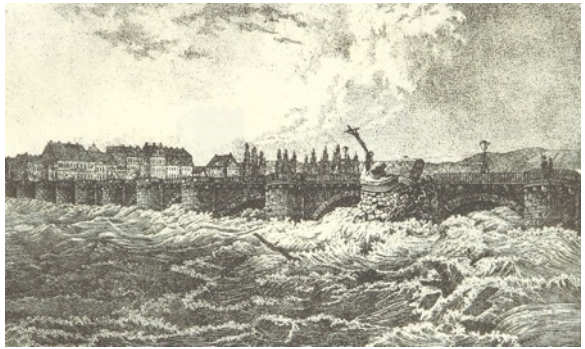
RX1day

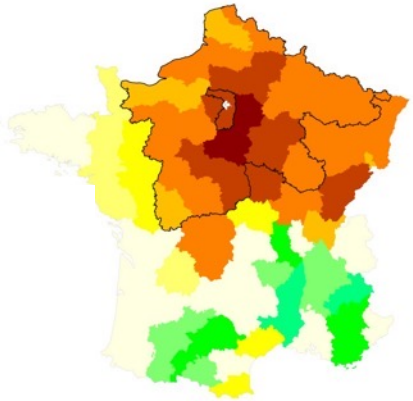


IPCC (2021); Wilby and Dessai (2010) *Weather*

Climate risk assessment for the three case studies

- 1845 Dresden flood:
  cold winter + lots of snow followed by increasing temperatures + rain
- 2021 Hurricane Ida:
  power outage followed by heatwave, people can't use air conditioning
- 2016 crop failure in French breadbasket:
  what are the drivers?





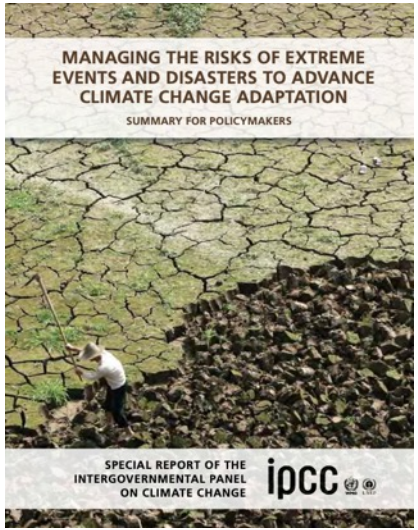
Limitations of traditional climate risk assessments

- Impacts are rarely driven by a single climate extreme
- Currently limited knowledge on
  1) Which **weather conditions** lead to impacts?
  2) What is the **dependence** between climate impact drivers?
  3) Do climate models simulate **climate impact drivers** well?
  4) Do impact models simulate **climate-impact relationships** well?




Compound events

"(1) two or more extreme events occurring simultaneously or successively,
(2) combinations of extreme events with underlying conditions that amplify the impact of the events, or
(3) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined."



Criticism
Ambiguities include:

- the role of the **underlying conditions** (amplifying? part of the event?),
- the **scale** implied by the terms 'successive' (temporal) or 'simultaneous' (spatial);
- whether the **combination of events** leading to an impact is restricted to **non-extremes**;
- whether a single event can be a compound event of **multiple variables** or the event is made up of **two or more distinct events**.

IPCC SREX (2012); Leonard et al. (2014)

New proposal (2014)

"A compound event is an **extreme impact** that depends on multiple **statistically dependent** variables or events."

➢ Shift of focus from climate extremes to extreme impacts!

Criticism
How do we know whether the drivers are statistically dependent?

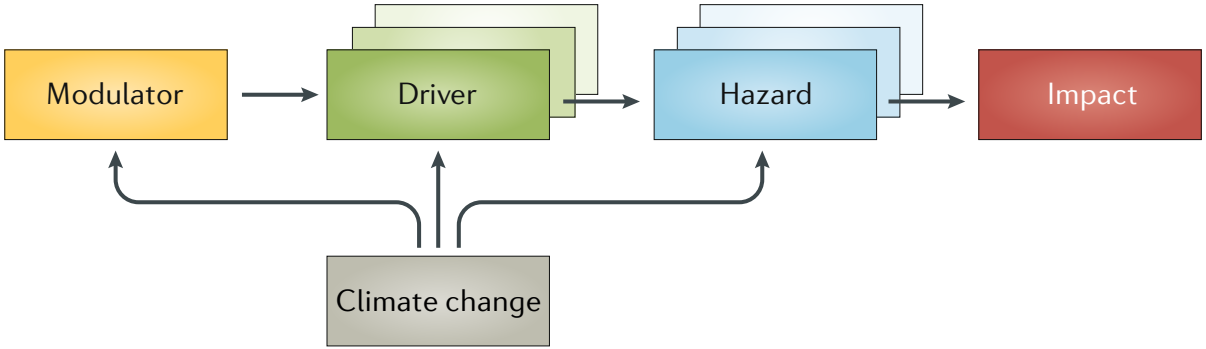



Leonard et al. (2014) *WIREs Climate Change*

“Reconciliation” workshop in Zurich (Spring 2017)

- IPCC SREX authors
- Leonard et al authors
- Experts from different domains
- Early career scientists

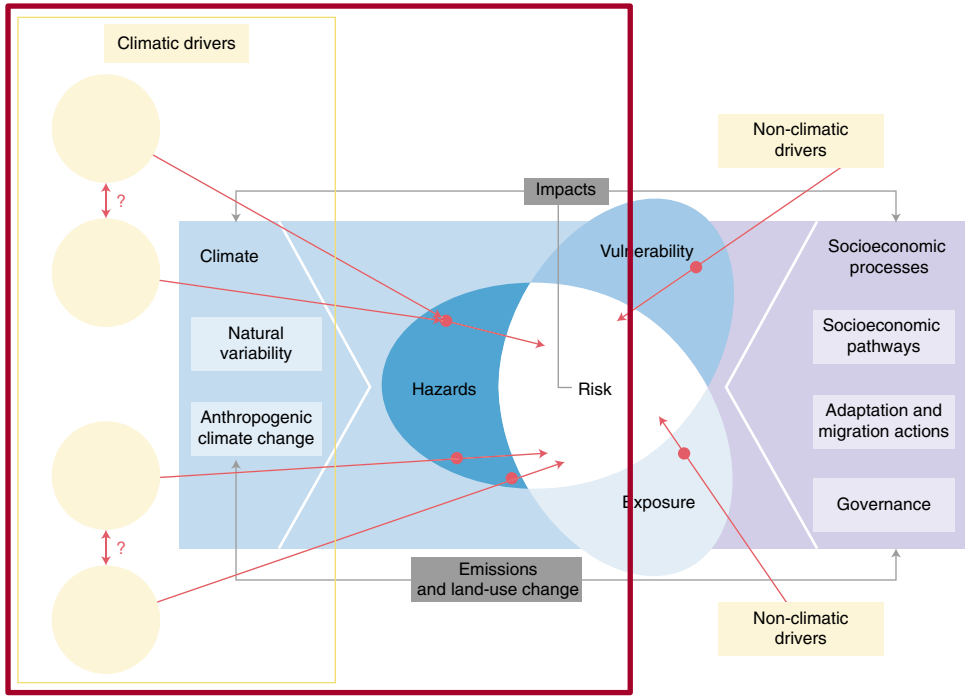
“Compound weather and climate events refer to the **combination of multiple drivers and/or hazards** that contributes to societal or environmental **risk**.”



Zscheischler et al. (2018) *Nature Climate Change*

Embedding in the IPCC risk framework

"Compound weather and climate events refer to the **combination of multiple drivers and/or hazards** that contributes to societal or environmental **risk**."



Zscheischler et al. (2018) *Nature Climate Change*

What is not a compound event?

- Definition is very broad
- Encapsulates many different events at many different spatial and temporal scales
- How can we meaningfully structure such events to aid analysis?




A typology of compound events

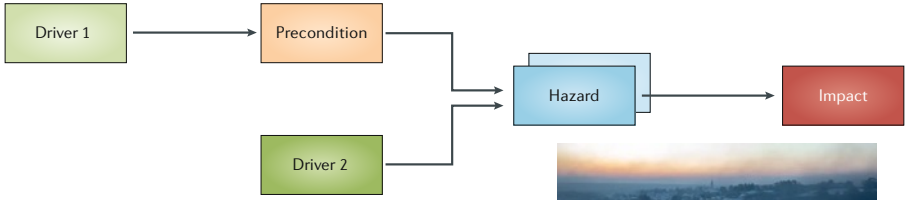
- Can help structure our thinking on high-impact events
- Can help select/develop appropriate analysis tools for a given event type
- Can trigger synergies between different impact communities for which similar event types are relevant




Zscheischler et al. (2020) *Nature Reviews Earth & Environment*

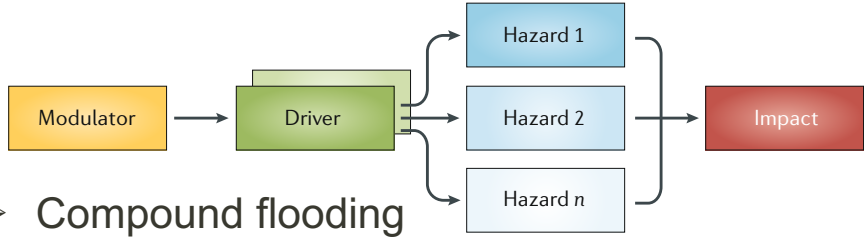
A typology of compound events

Preconditioned events



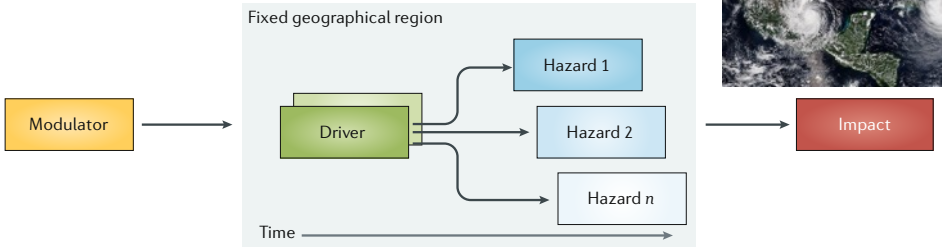
- False spring
- Rain-on-snow flood

Multivariate events



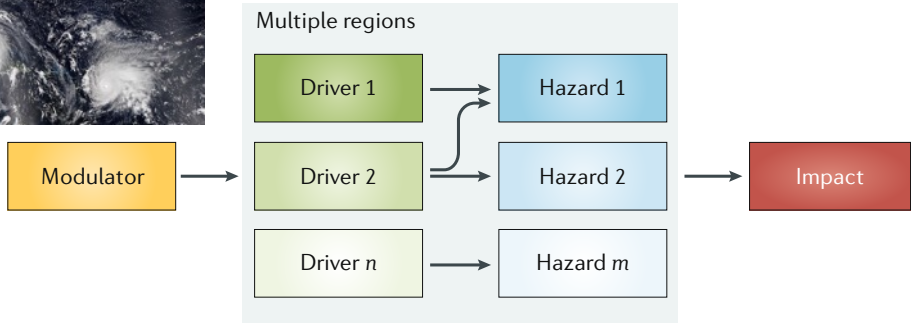
- Compound flooding
- Concurrent drought & heat
- Concurrent wind & precipitation extremes

Temporally compounding events



- Sequence of storms/heavy precip. events
- Cyclone followed by a heatwave

Spatially compounding events



- Global crop failure

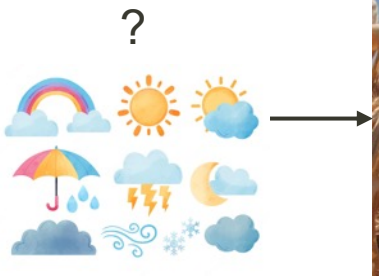
Spatially compounding: 2002 Floods in Central Europe

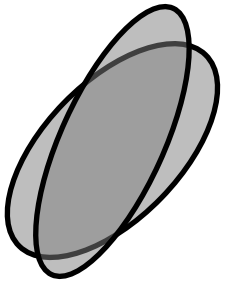
Led to the creation of the European Union Solidarity Fund

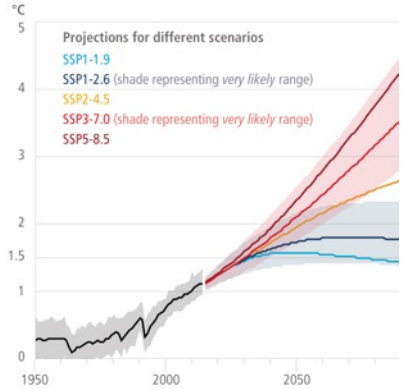
Dresden, August 2002

Challenges in compound event research

1. Identifying meteorological drivers of extreme impacts.
2. Evaluating climate and impact models with respect to compound events.
3. Creating robust projections of high-impact events.

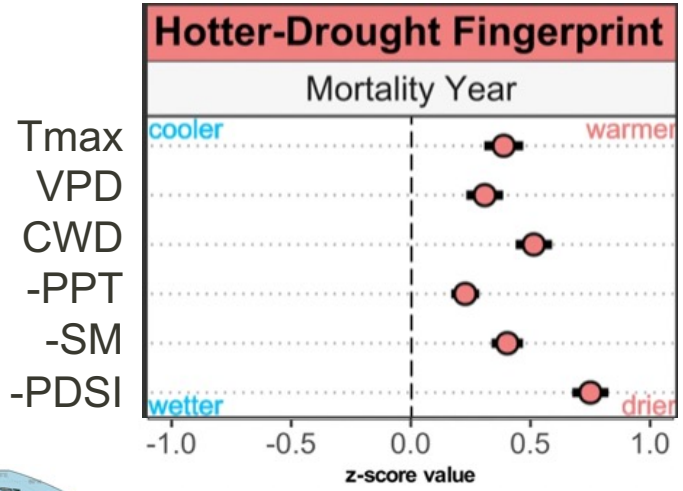


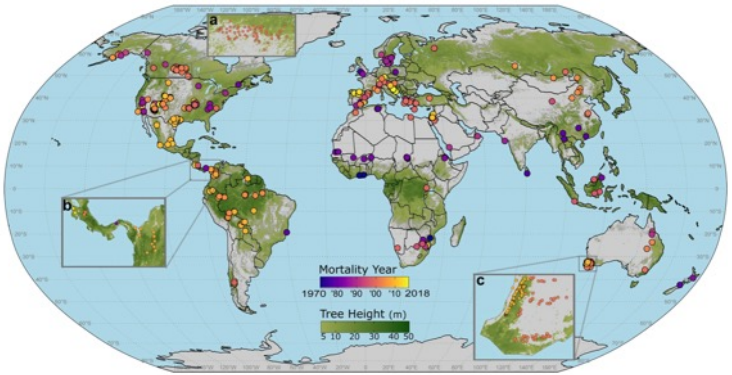




Drivers of tree mortality

Credit: Emily Solly

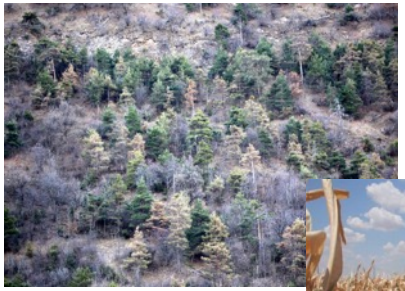




Hammond et al. (2022) *Nature Communications*

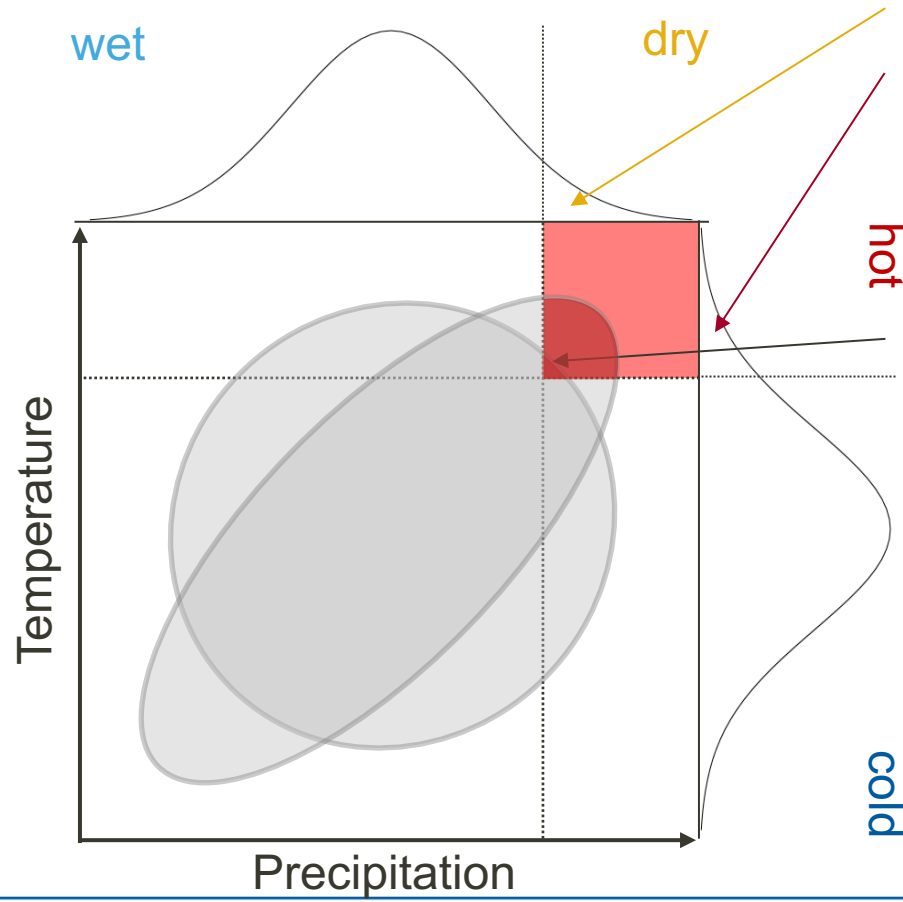
Impacts of concurrent drought-heat events

- Forest mortality
- Crop failure
- Mega-wildfires
- Fish die-off
- Reduced energy production
- …





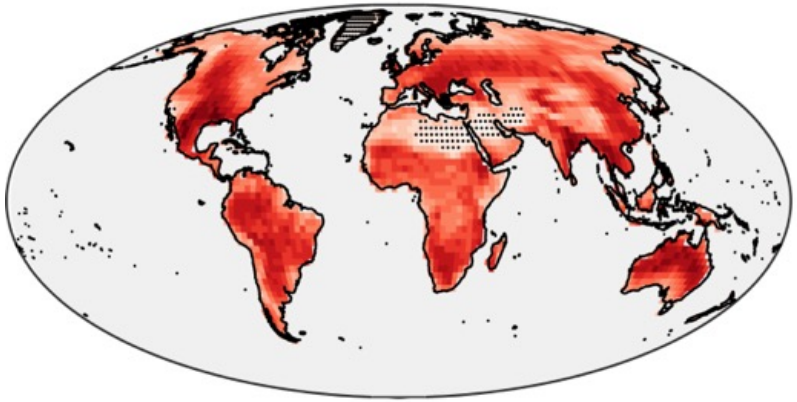
Dependence of drivers affects occurrence probability



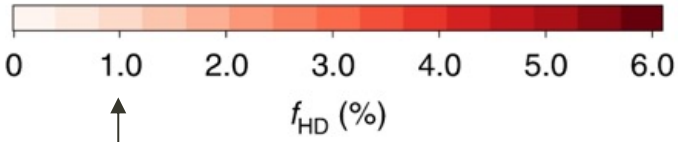
Compound drought-heatwave events

$P = 1/10 \times 1/10 = 1/100$

Hot and dry summers often co-occur, but spatially variable



Less frequent hot & dry summers



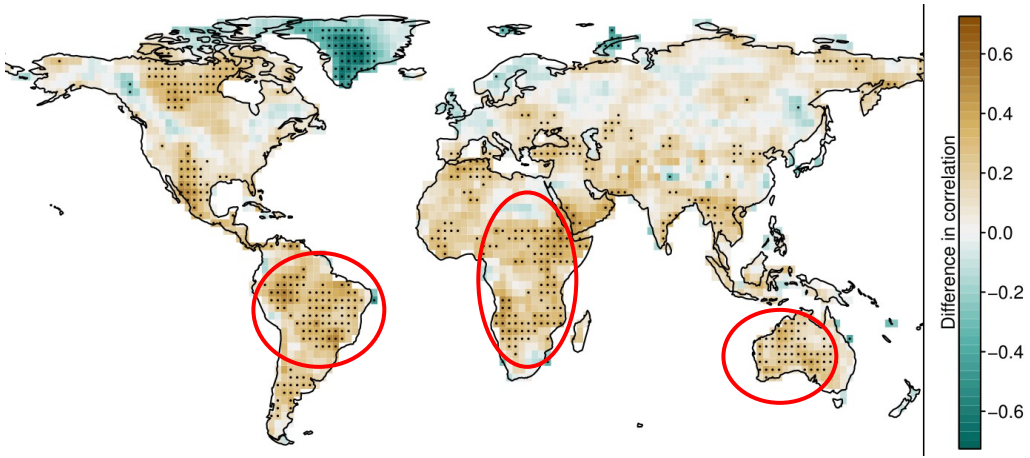
More frequent hot & dry summers

When temperature and precipitation are independent

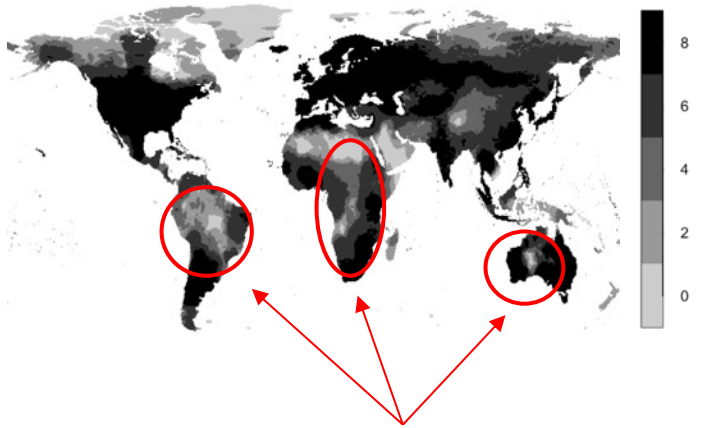
Bevacqua et al. (2022) *Nature Climate Change*

Comparison: Observations vs climate models

Brown areas: models show stronger negative correlations compared to observations



Average number of stations for precipitation



Models show stronger dependence in some regions.

- Overestimation of models?
- Missing observational constraint?

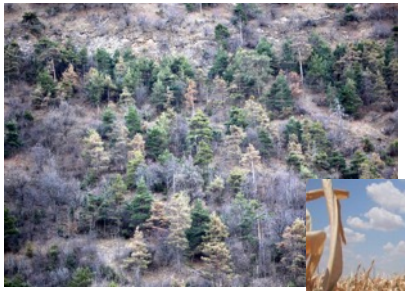
No observations!

Zscheischler & Seneviratne (2017) *Science Advances*

Impacts of concurrent drought-heat events

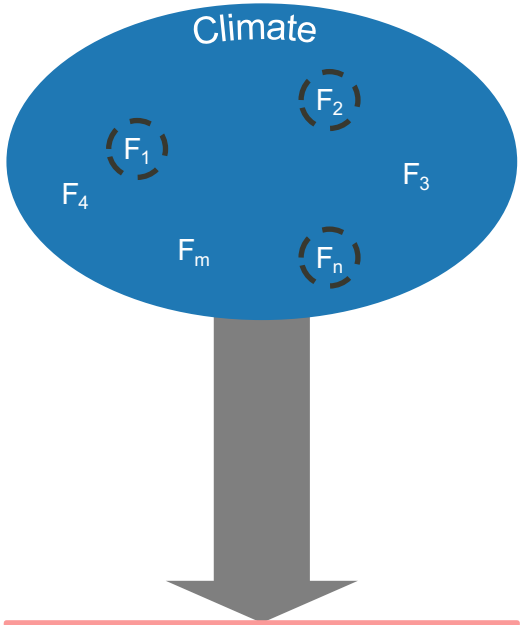
- Forest mortality
- Decreased carbon uptake
- Crop failure
- Reduced energy production
- Fish die-off
- …

- What about other high-impact events for which drivers are not well known?



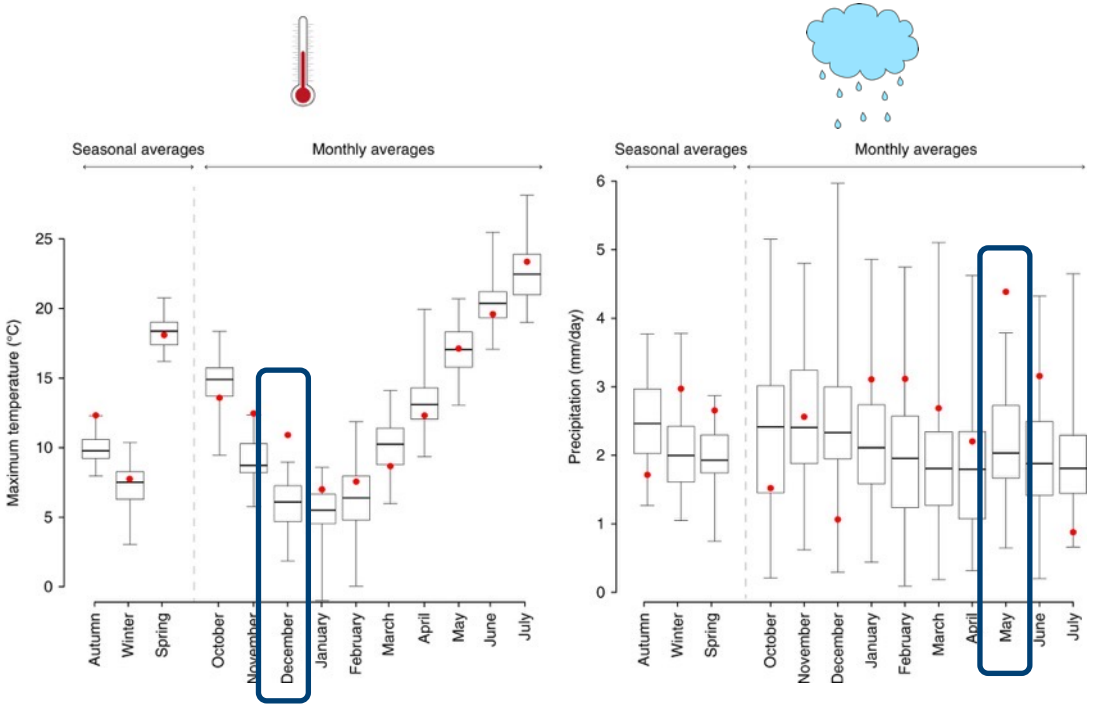


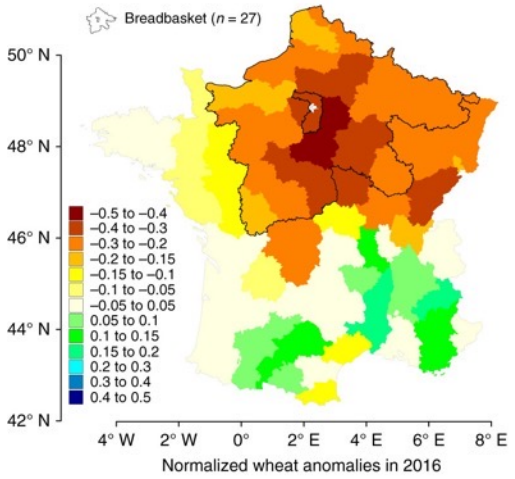
More sophisticated approaches for driver identification



- Create large set of potential predictors
- Select those that best predict impact

2016 crop failure in France

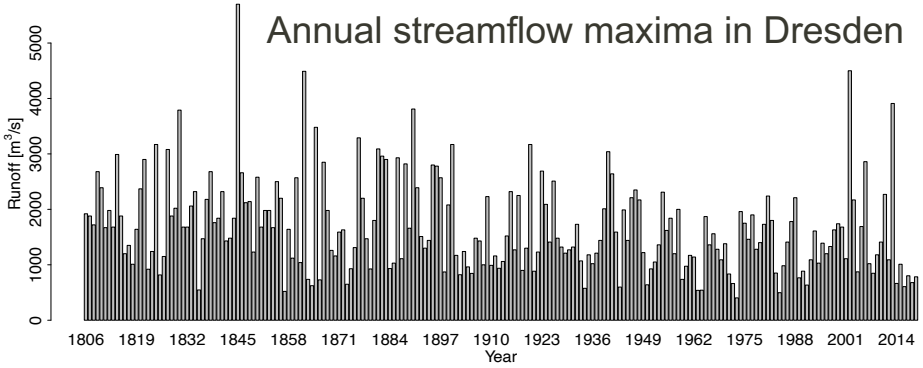


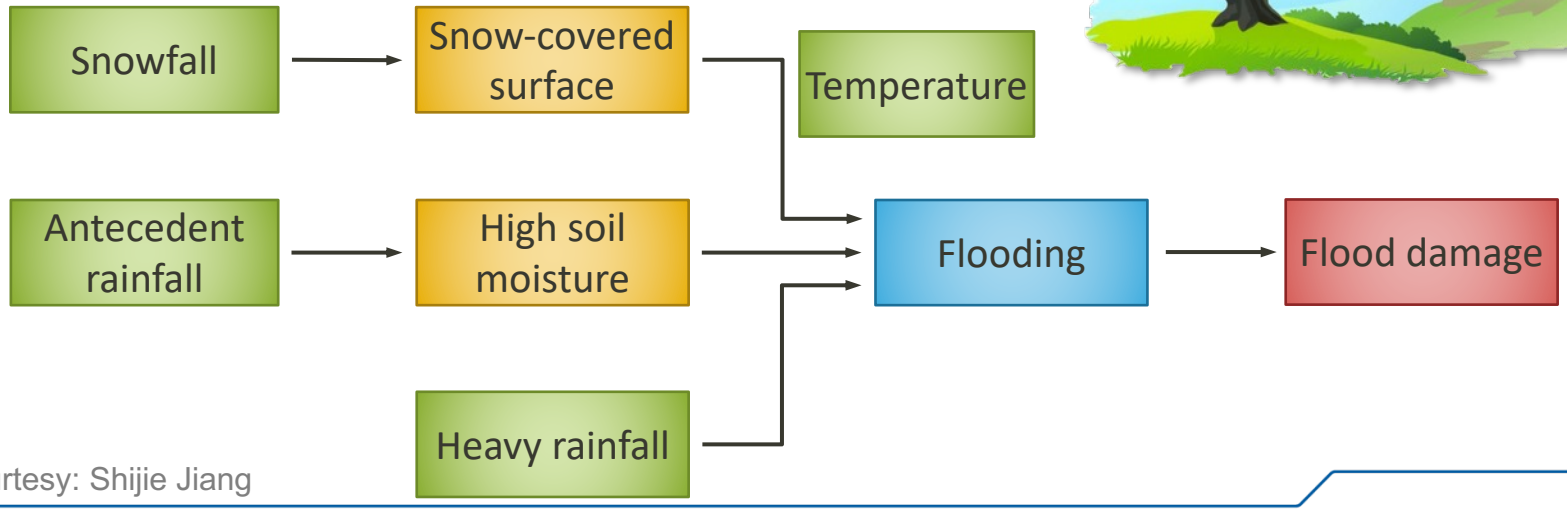


- “Non-standard event”

Ben-Ari et al. (2018) *Nature Communications*

Using machine learning to identify impact drivers

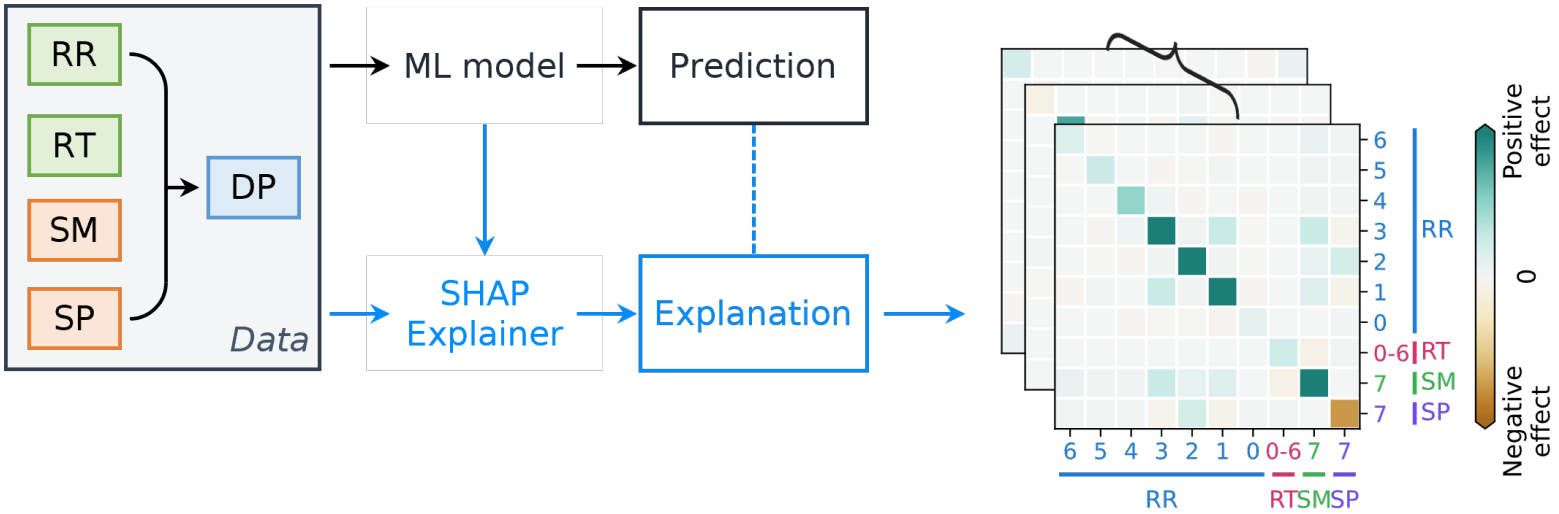




Courtesy: Shijie Jiang

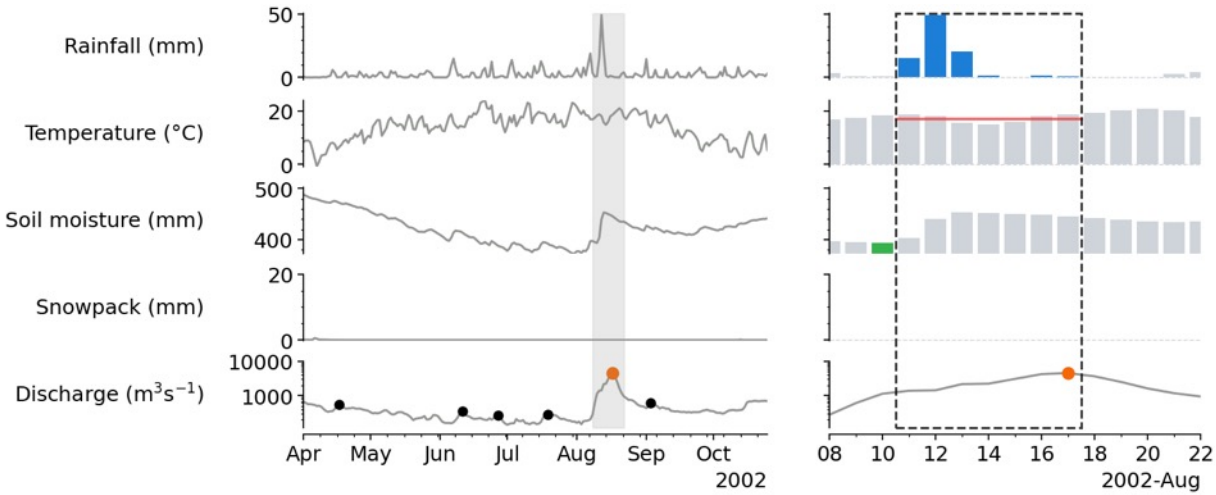
Quantifying (compounding) drivers with machine learning

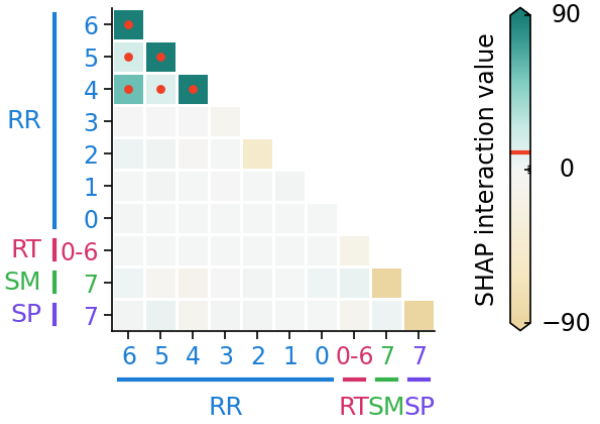
RR: recent rainfall
RT: recent temperature
SM: soil moisture
SP: snow pack
DP: discharge peak



Jiang et al. (in prep)

2002 Elbe flood, Dresden

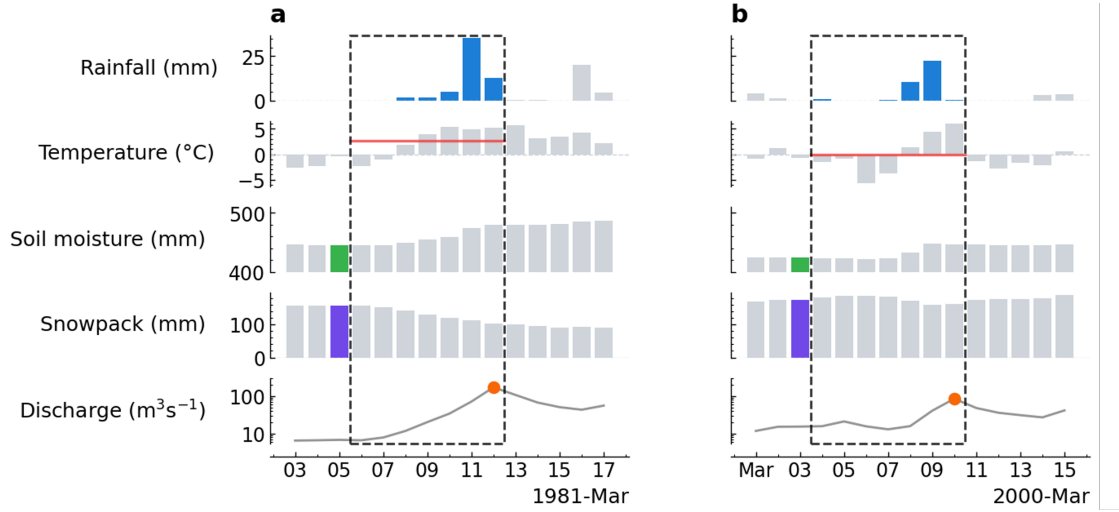




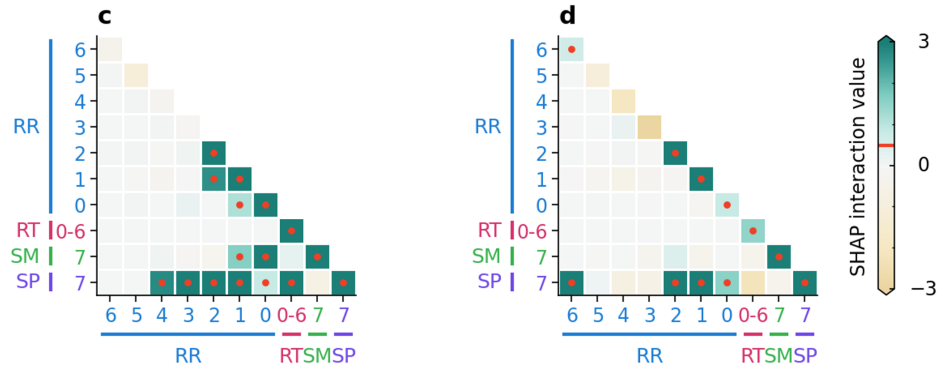
Interaction richness
6/48=12.5%

Jiang et al. (in prep)

New metric: Richness in interactions



Interaction richness
16/48=33.3%

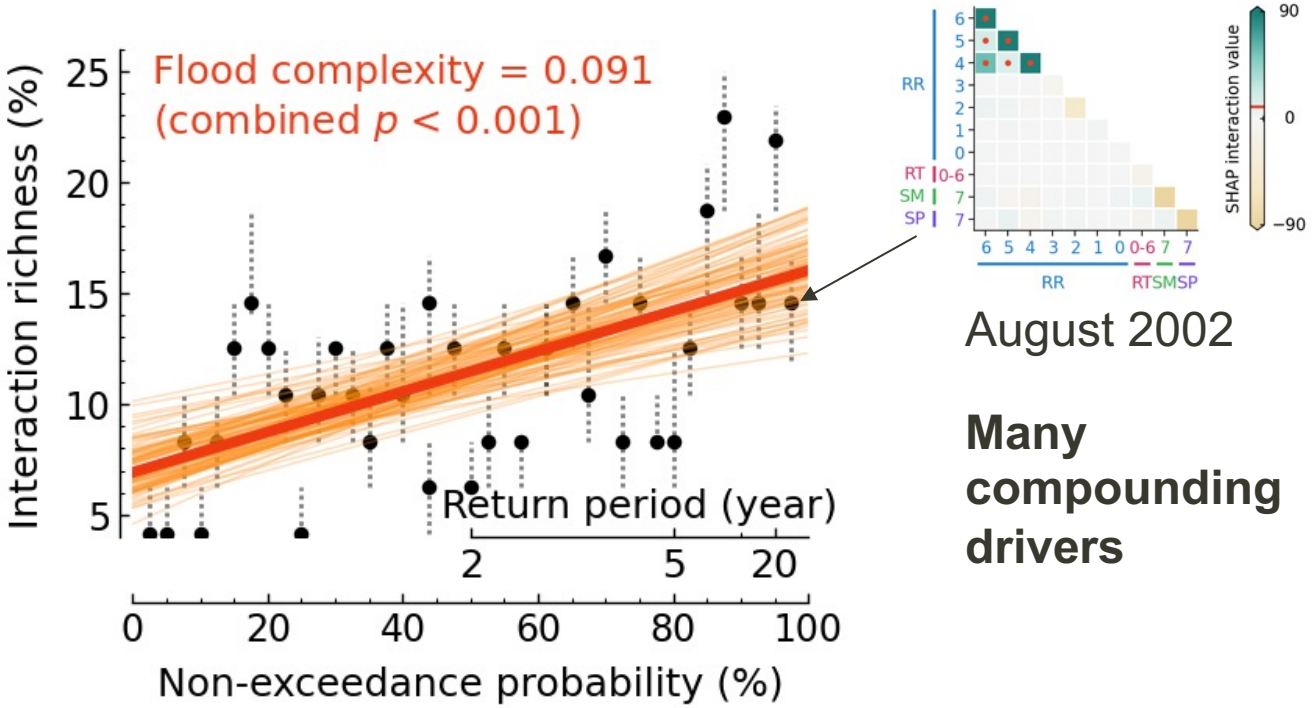


Interaction richness
11/48=23%

Jiang et al. (in prep)

New metric: Flood complexity

Elbe (Dresden)



August 2002

Many compounding drivers

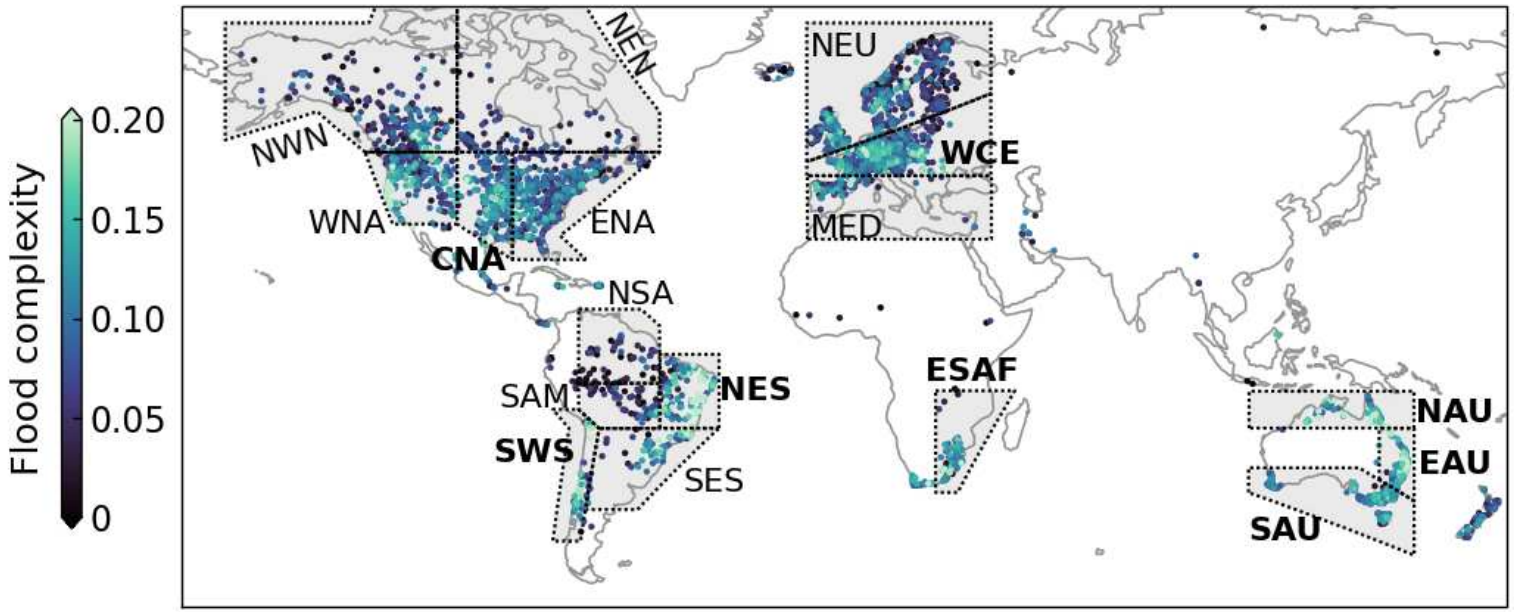
Few compounding drivers

Flood magnitude increases →

Jiang et al. (in prep)

Flood complexity

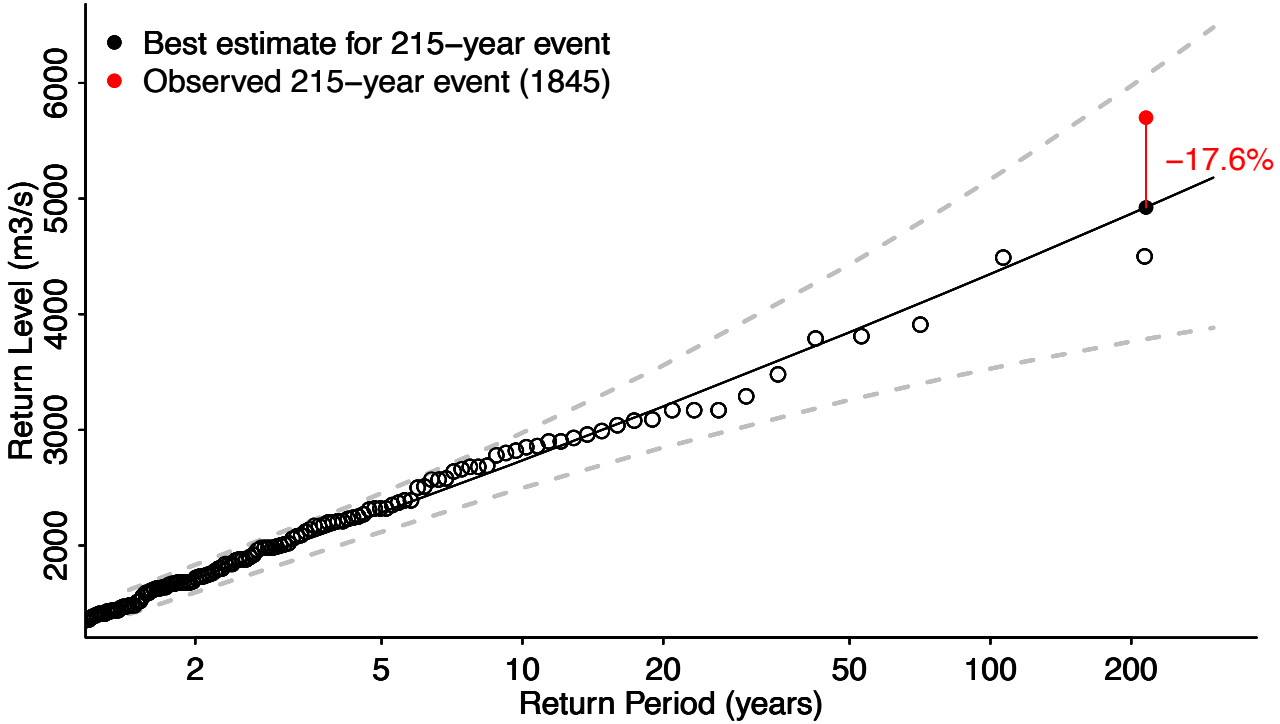
Application to 3527 catchments

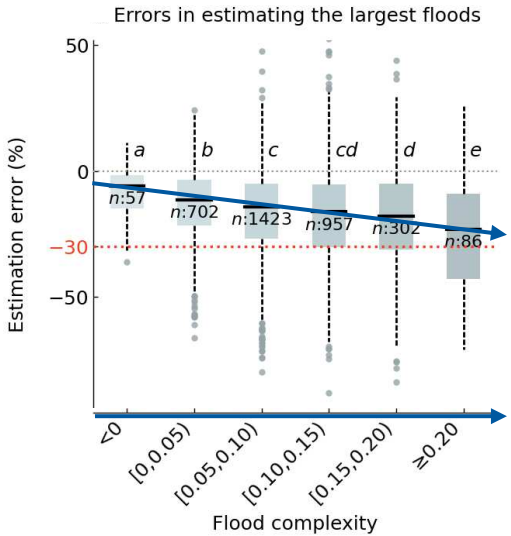


Jiang et al. (in prep)

Large floods underestimated when flood complexity is high

Dresden: Flood frequency analysis without largest event (1845)



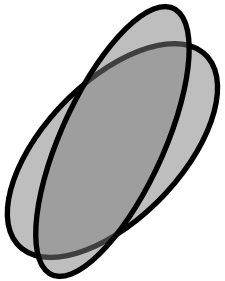


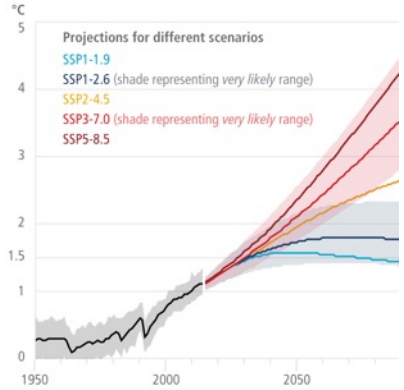
Heterogeneity in flood generating processes

Jiang et al. (in prep)

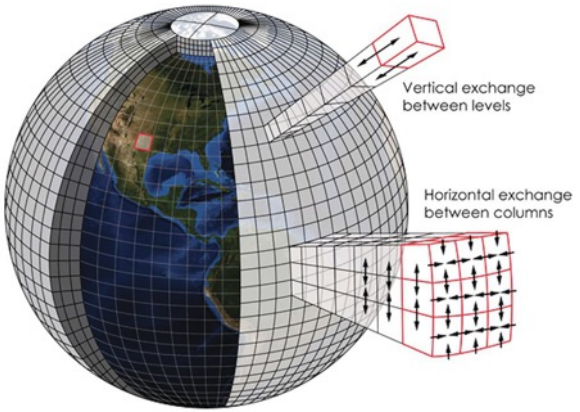
Challenges in compound event research

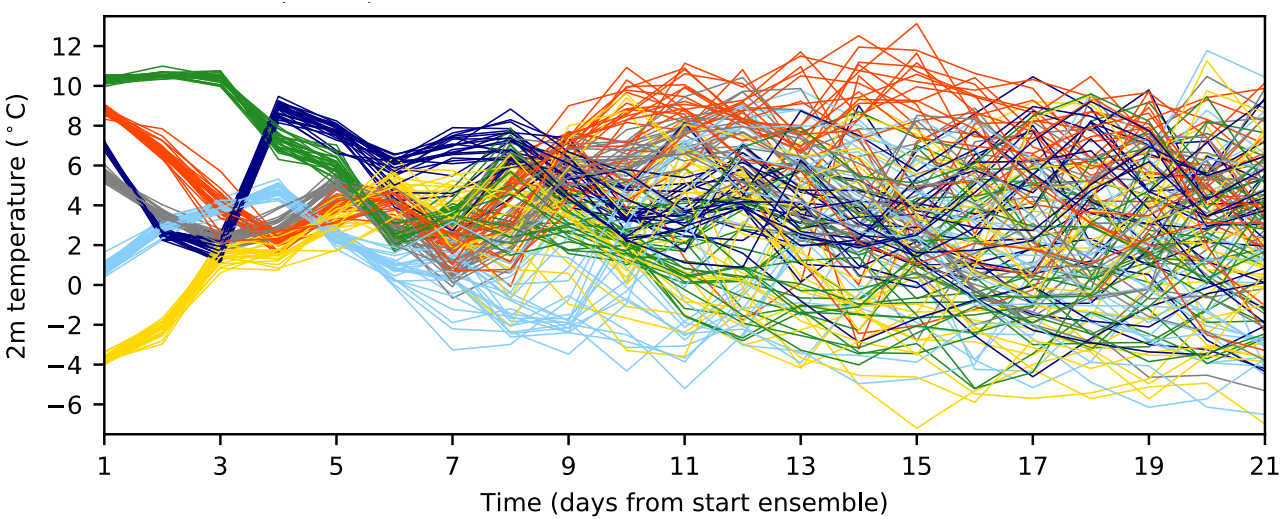
1. Identifying meteorological drivers of extreme impacts.
2. Evaluating climate and impact models with respect to compound events.
3. **Creating robust projections of high-impact events.**





The value of large ensemble simulations

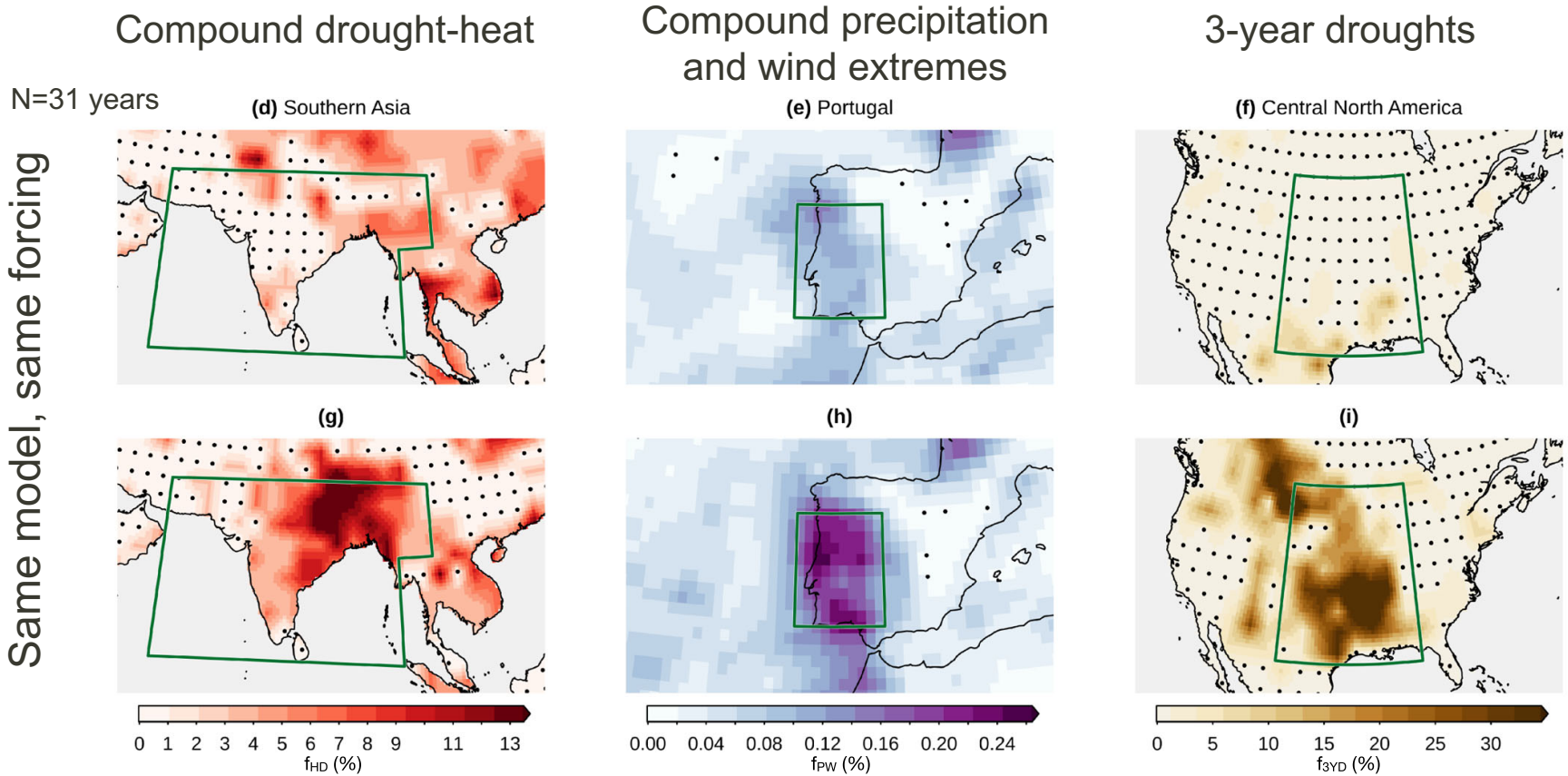




- Separation of climate change trends from internal climate variability
- Identification of worst case scenarios
- Robust projections of complex events

Courtesy: Karin van der Wiel (KNMI)

Uncertainty in risk estimates

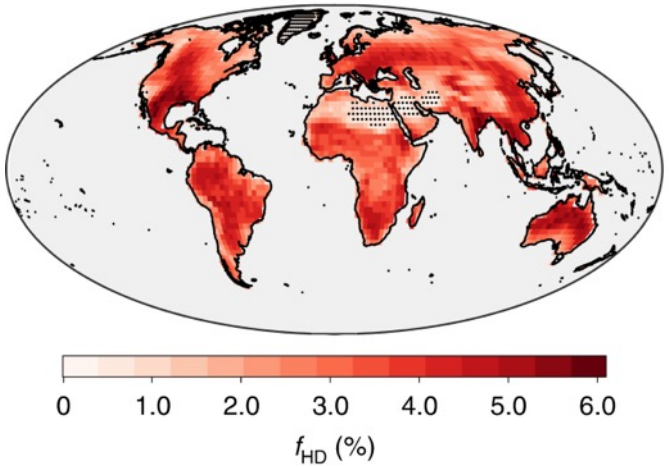


Bevacqua et al. (2023) *Nature Communications*

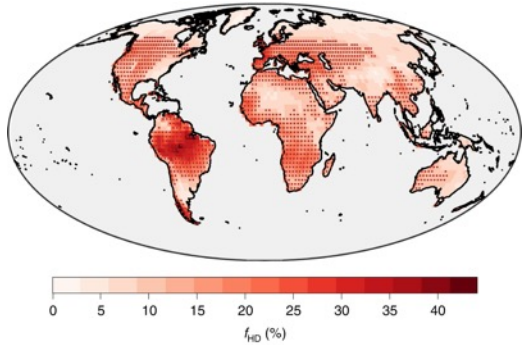
Projections of compound hot-dry summers

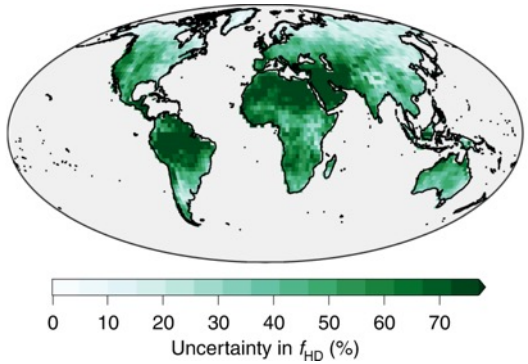
1950-1980

f_{HD} = Probability of concurrent hot & dry summer



2° C warmer world
(rel. to preindustrial)



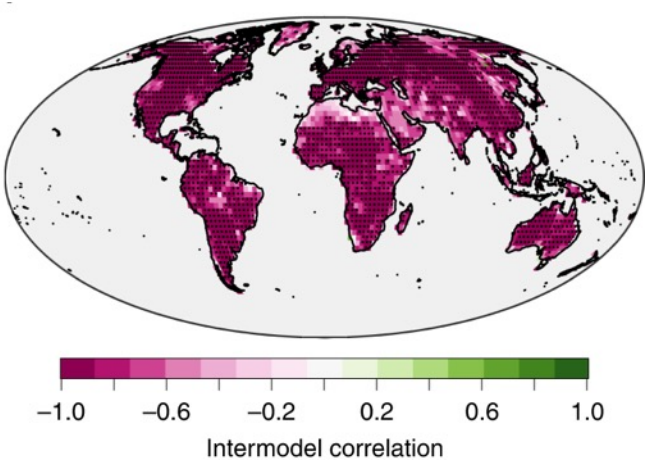


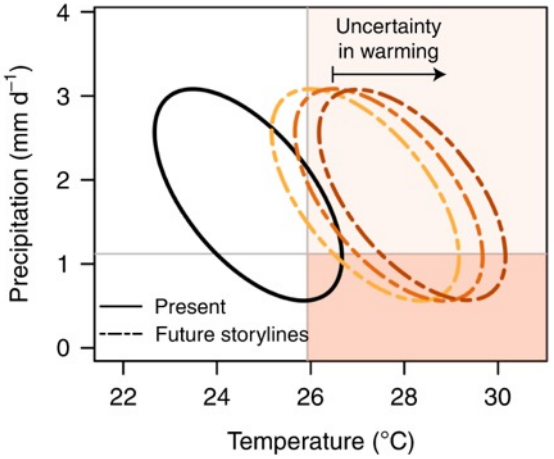
Uncertainty large in the future

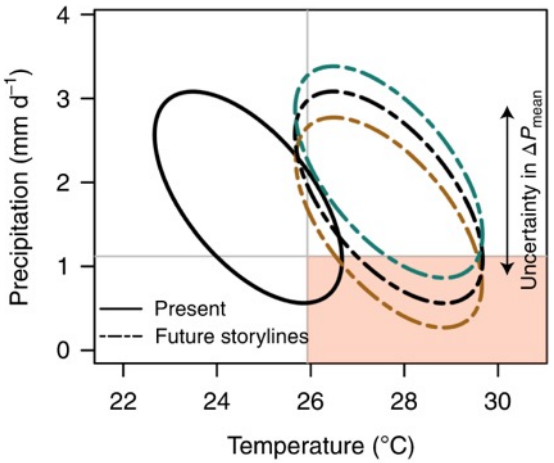
Bevacqua et al. (2022) *Nature Climate Change*

Precipitation trends drive future occurrence of hot-dry events

Correlation
between f_{HD} and ΔP_{mean}

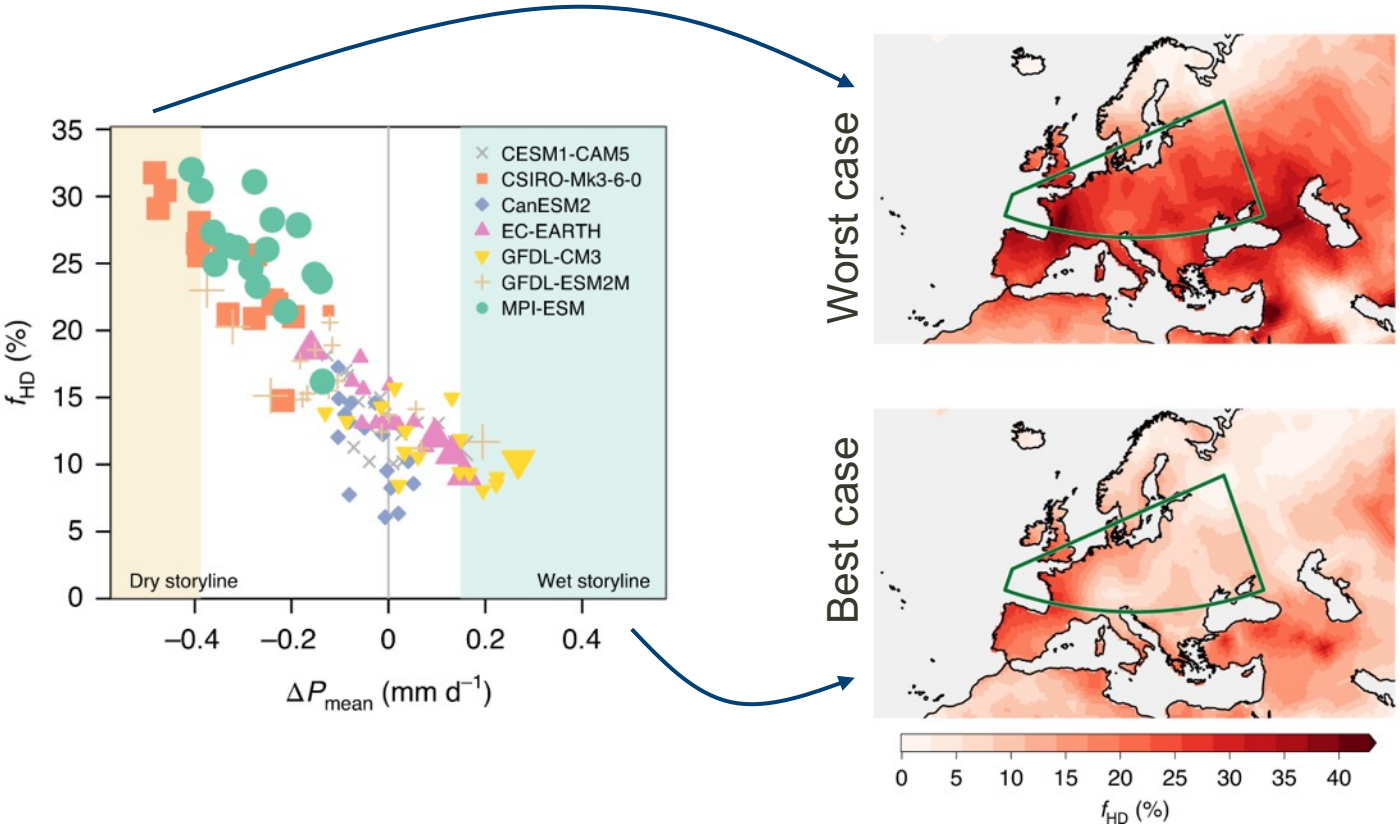






However: uncertainties in precipitation projections are often irreducible.

Climate storylines for central Europe



Hot-dry summer every ~4 years

Hot-dry summer every ~10 years

Bevacqua et al. (2022) *Nature Climate Change*

Conclusions

- Viewing climate climate impacts through a “compound event” lens offers new perspectives on climate risk assessment
- Compound event research aims to develop new paradigms to better understand and project climate risks
- Ignoring compounding drivers can lead to misspecification of climate risks