Multi-hazard Scenarios for Analysis of Compound Extreme Events

Amir AghaKouchak,
University of California, Irvine

Moji Sadegh, Hamed Moftakhari, Laurie Huning, Elisa Ragno, Felicia Chiang, Charlotte Love, Linyin Cheng, Omid Mazdiyasni, Gianfausto Salvadori, Brett Sanders, Richard Matthew, Jo Schubert

Email: amir.a@uci.edu
Instagram: @AghaKouchak
Twitter: @AmirAghaKouchak
Coastal Flooding
Compound Coastal Flooding
Motivation

Compound Ocean-Fluvial Flooding

Compound Ocean-Fluvial (terrestrial)-Pluvial (local rain) Flooding
Compound Events

Two or more extreme events occurring simultaneously or successively

Combinations of extreme events with underlying conditions that amplify the impact of the events

Combinations of events that are not themselves extremes but lead to an extreme event or impact when combined.

Consecutive inter-dependent events that do not occur at the same time, but they have compounding impacts.
Multivariate Copula Analysis Toolbox (MvCAT)  
Multi-hazard Scenario Analysis Toolbox (MhAST)

Sadegh et al., 2017, Water Resources Research

http://amir.eng.uci.edu/software.php
Multi-hazard Scenario Analysis Toolbox (MhAST)

1. Estimates the most likely scenario on any critical layer (isoline): highest density on any critical layer.

2. Includes different Hazard Scenarios (e.g., AND, OR, Kendall).

3. Uncertainty analysis and posterior distribution of the parameter using a Bayesian MCMC approach.

http://amir.eng.uci.edu/software.php

Sadegh et al., 2018, Geophysical Research Letters
Compound Coastal Flooding
Hazard Scenarios for Compound Coastal Flooding

\[ \alpha_X^V = P(X \in S_X^V) = 1 - C_X(F_1(x_1), F_2(x_2)) \]

For a given design life time of $T$ the failure probability ($\tilde{P}_T$) is calculated as

Univariate

$$\tilde{P}_T = 1 - (1 - p)^T$$

Multivariate

$$\tilde{P}_T = 1 - P\left(X_1 \in S_1^C, \ldots, X_T \in S_T^C\right) = 1 - \left(C_X\left(F_1(\bar{x}_1), F_2(\bar{x}_2)\right)\right)^T$$
Failure Probability: Compound Coastal Flooding

Washington, DC

Link: http://www.pnas.org/content/early/2017/08/22/1620325114
Estimated failure probability for a temporal horizon of 30 years. The solid black and red curves show, respectively, the estimated failure probability computed based on the univariate and bivariate OR hazard scenarios, according to the presently observed climate conditions. The solid and dashed purple curves show the estimated probability of failure using a bivariate OR approach and an associated 95% confidence band considering the projected SLR for 2030 under RCP 4.5.
Difference in water surface elevations a) given by the proposed composite profile method compared to the FEMA method.
Compound Extreme Events

Moftakhari, et al., 2019, AWR
Alaska, USA

California, USA
Drought and Heatwaves
Compound Drought and Heatwaves

Amplified Warming of Droughts in Southern United States in Observations and Model Simulations

Chiang et al., 2018, Science Advances
Amplified Warming of Droughts in Southern United States in Observations and Model Simulations

Chiang et al., 2018, Science Advances
2014 California Drought: How Bad is It?

California November-April Mean Precipitation

- 5th on record since 1896
- $T \approx 24$ yr

California November-April Mean Temperature

- Warmest on record since 1896
- $T \approx 120$ yr
2014 California Drought: How Bad is It?

Assuming two variables $X$ (precipitation) and $Y$ (temperature) with cumulative distribution functions $F_X(x) = \Pr(X \leq x)$ and $F_Y(y) = \Pr(Y \leq y)$, the copula $(C)$ can be used to obtain their joint distribution function:

$$F(x, y) = C(F_X(x), F_Y(y)),$$

where $F(x, y)$ is the joint distribution function of $X$ and $Y$:

$$F(x, y) = \Pr(X \leq x, Y \leq y)$$

The joint survival distribution $\bar{F}(x, y) = \Pr(X > x, Y > y)$ can be obtained using the concept of survival copula:

$$\bar{F}(x, y) = \hat{C}(\bar{F}_X(x), \bar{F}_Y(y))$$

$\bar{F}_X$ and $\bar{F}_Y$ (i.e., $\bar{F}_X = 1 - F_X$, $\bar{F}_Y = 1 - F_Y$) are the marginal survival functions of $X$ and $Y$, and $\hat{C}$ is the survival copula.

Survival critical layer (or isoline) is then defined as:

$$\mathcal{L}_t^n = \{x, y \in R^d : \bar{F}(x, y) = t\}$$

where $\mathcal{L}_t^n$ is the survival critical layer associated with the probability $t$.

The survival return period of $X$ and $Y$ is defined as: $\tilde{\kappa}_{XY} = \frac{\mu}{1 - \bar{K}(t)}$ where $\tilde{\kappa}_{XY}$ is called the survival Kendall’s return period; $\mu > 0$ is the average interarrival time of $X$ and $Y$ ($\mu = 1$ indicates the average interarrival time between subsequent values in the time series is one year); and $\bar{K}$ is the Kendall’s survival function associated with $\bar{F}$ defined as:

$$\bar{K}(t) = \Pr(\bar{F}(X, Y) \geq t) = \Pr(\hat{C}(\bar{F}_X(x), \bar{F}_Y(y)) \geq t)$$

For any return period $T$, the corresponding survival critical layer $\mathcal{L}_t^{\bar{F}}$ can be estimated by inverting the Kendall’s survival function $\bar{K}(t)$ at the probability level $p = 1 - \frac{\mu}{T}$:

$$\bar{q} = \bar{q}(p) = \bar{K}^{-1}(p),$$
Compound Drought and Warm Spells
Time series of major rain-fed crop yields in Australia (top) and drought information based on precipitation (SPI, blue bars) and soil moisture (SSI, purple bars) over the same period (bottom). The grey vertical shading across the panels indicates the driest years (Madadgar et al., 2017, GRL).
Mountain Snowpack Response to Different Levels of Warming

Huning & AghaKouchak, 2018 PNAS
MORE FIRES, MORE SNOWMELT

Natural blazes in the western United States are (1) scorching larger areas and (2) spreading to higher altitudes than they did in the 1980s.

Area equivalent to the size of Florida

1

<table>
<thead>
<tr>
<th>Year Range</th>
<th>Number of hectares burned (per decade)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986–1995</td>
<td>5,909,602 hectares</td>
</tr>
<tr>
<td>1996–2005</td>
<td>11,248,393 hectares</td>
</tr>
<tr>
<td>2006–2015</td>
<td>16,050,851 hectares</td>
</tr>
</tbody>
</table>

After fires, water supplies can be affected if soot and fewer trees alter where snow builds up and when it melts.

4

AghaKouchak, 2018 Nature
Compound Hazards

Ensemble Mean, Historic

Ensemble Mean, RCP4.5

Ensemble Mean, RCP8.5

HadGEM2-ES Historic

HadGEM2-ES RCP8.5
Rain over Burned Areas: Cascading Hazards
Multivariate Copula Analysis Toolbox (MvCAT)
Multi-hazard Scenario Analysis Toolbox (MhAST)

Sadegh et al., 2017, *Water Resources Research*

http://amir.eng.uci.edu/software.php
Multi-hazard Scenario Analysis Toolbox (MhAST)

1. Estimates the most likely scenario on any critical layer (isoline): highest density on any critical layer.

2. Includes different Hazard Scenarios (e.g., AND, OR, Kendall).

3. Uncertainty analysis and posterior distribution of the parameter using a Bayesian MCMC approach.

Sadegh et al., 2018, *Geophysical Research Letters*

http://amir.eng.uci.edu/software.php
• Ignoring compounding effects of fluvial and ocean flooding leads to underestimation of coastal flood risk

• Droughts have warmed faster than the average climate in the southern and northeastern U.S.

• MvCAT and MhAST can be used for modeling the relationship between different hazards (analysis of compound hazards).

• Ignoring compounding effects of hazard drivers can lead to underestimation of the risk.
Questions?

Amir AghaKouchak

Email: amir.a@uci.edu

Instagram: @AghaKouchak

Twitter: @AmirAghaKouchak