Compound and Cascading Hazards and their impacts on critical infrastructure systems

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Moji Sadegh, Laurie Huning, Hamed Moftakhari, Elisa Ragno, Felicia Chiang, Charlotte Love, Omid Mazdiyasni, Gianfausto Salvadori, Brett Sanders, Richard Matthew, Jo Schubert, F Vahedifard, and many more…

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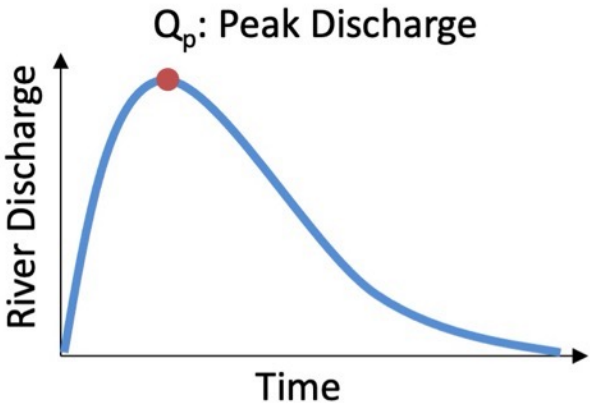
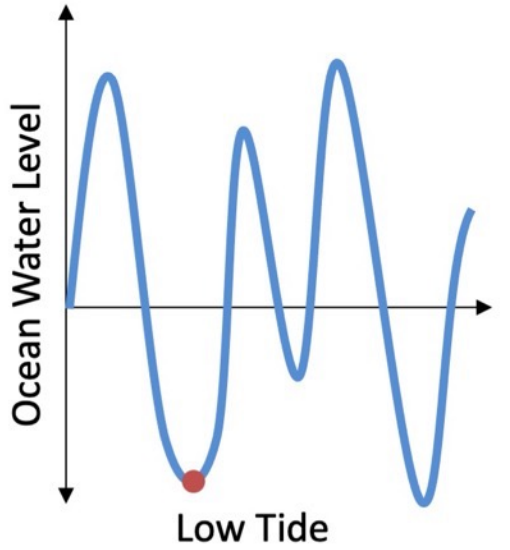
: @AmirAghaKouchak

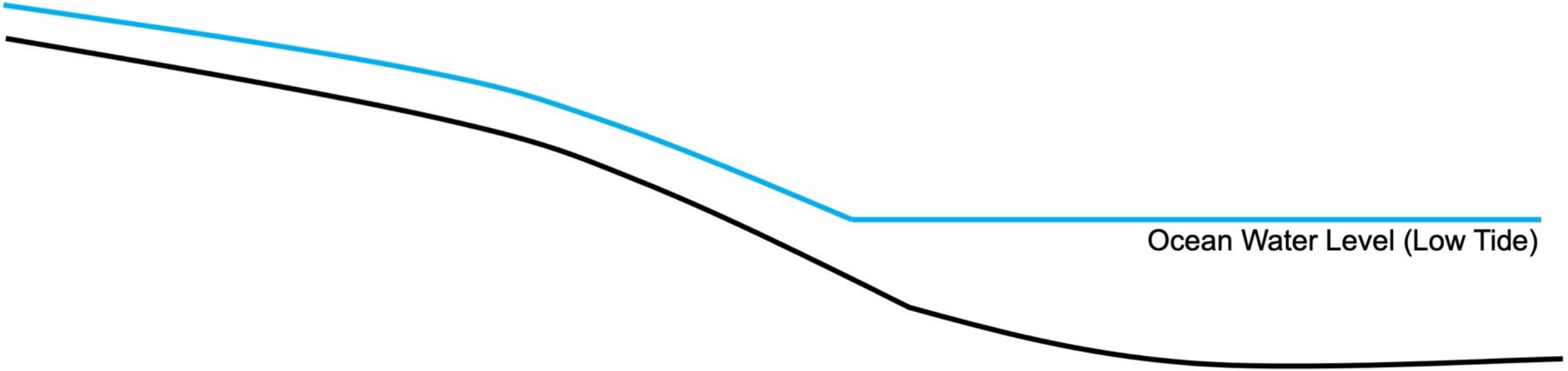
Coastal Flooding

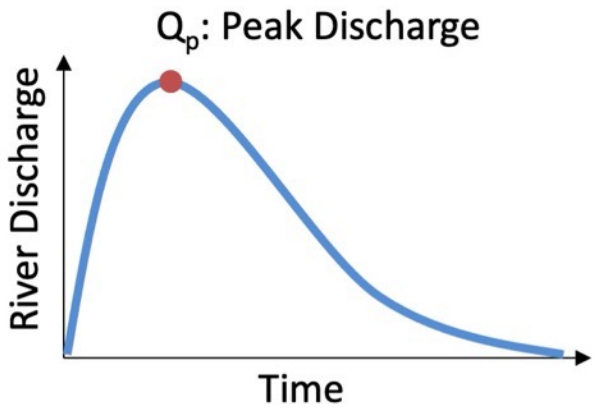
Compound Ocean-Fluvial Flooding

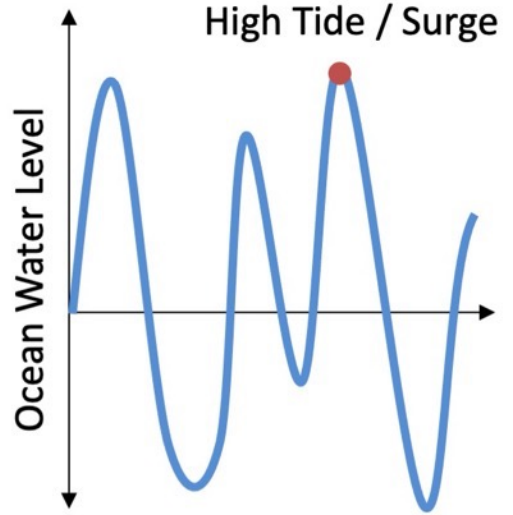
Compound Ocean-Fluvial (terrestrial)-Pluvial (local rain) Flooding

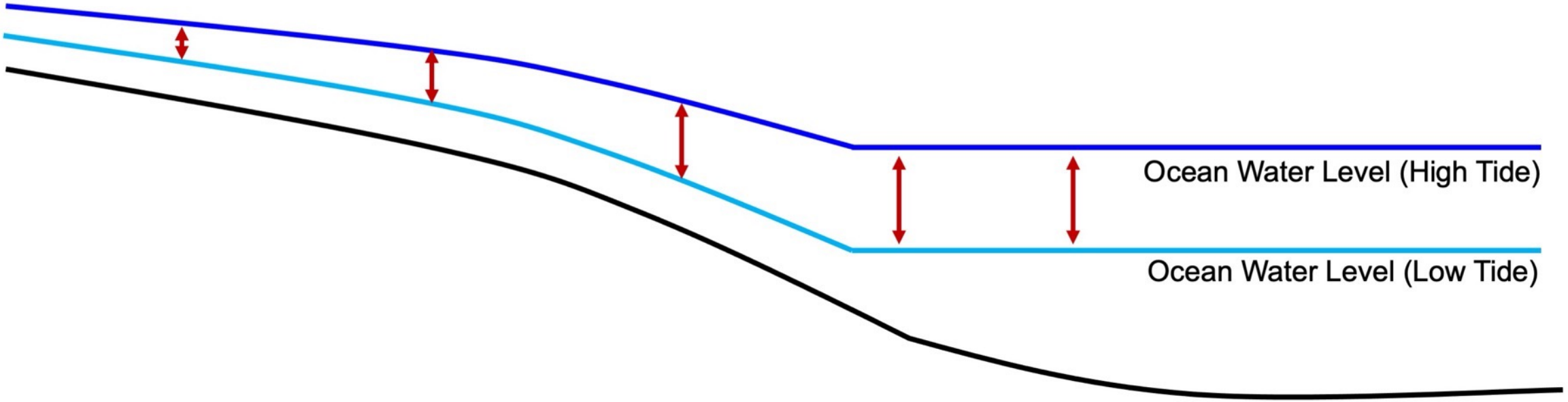

Q_p: Peak Discharge
River Discharge
Time

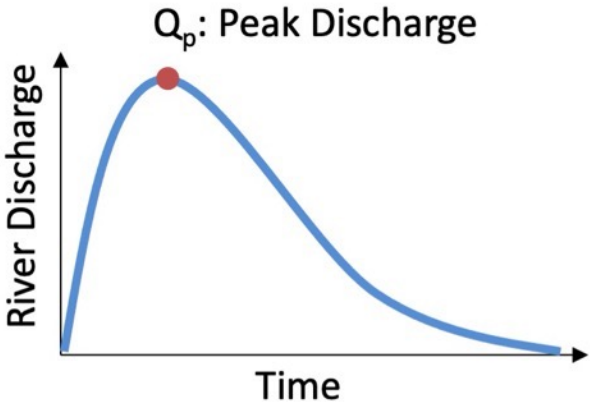

Ocean Water Level
Low Tide


Ocean Water Level (Low Tide)


Q_p: Peak Discharge
River Discharge
Time


High Tide / Surge
Ocean Water Level

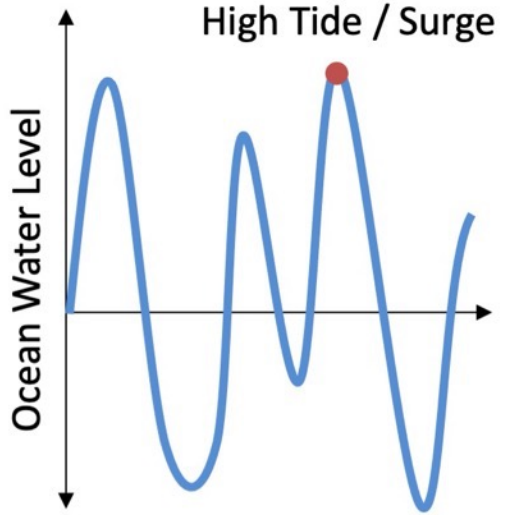

Ocean Water Level (High Tide)
Ocean Water Level (Low Tide)

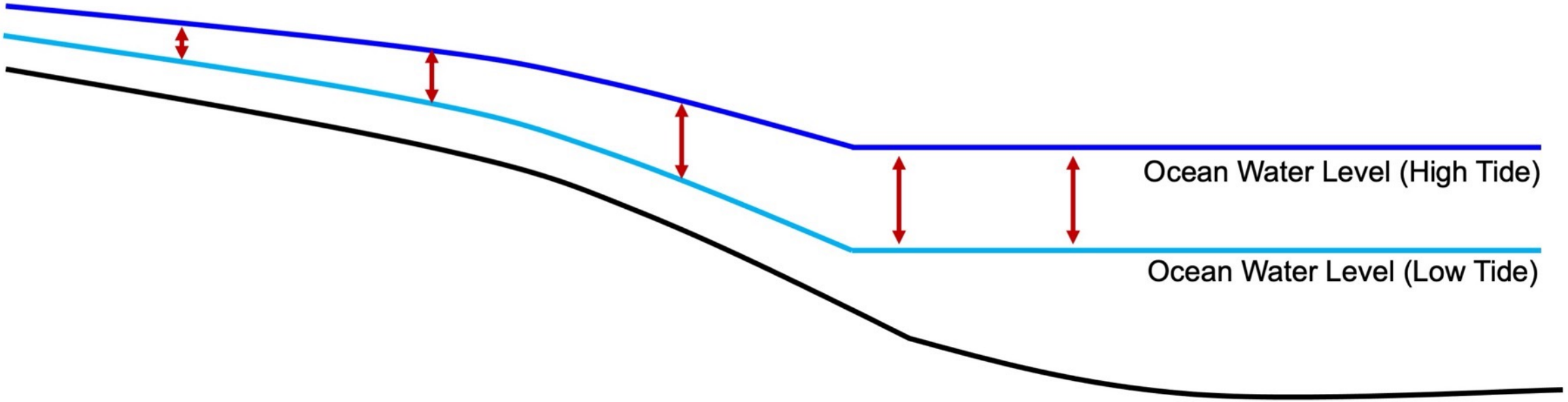


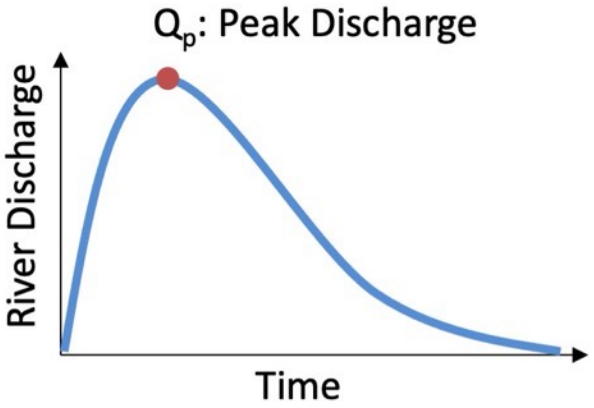
Univariate

$$p_F = 1 - (1 - p)^T$$

T: lifetime (years)
p: exceedance probability







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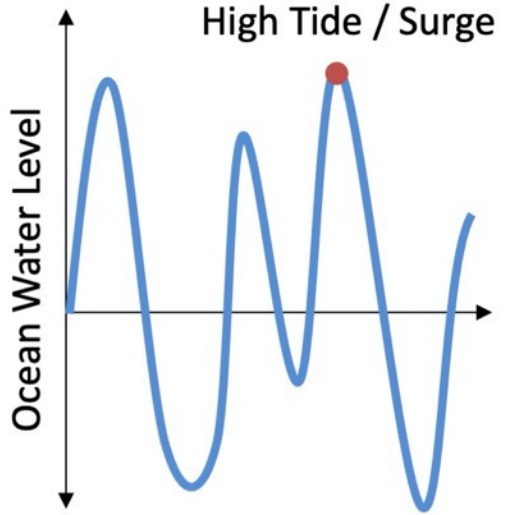
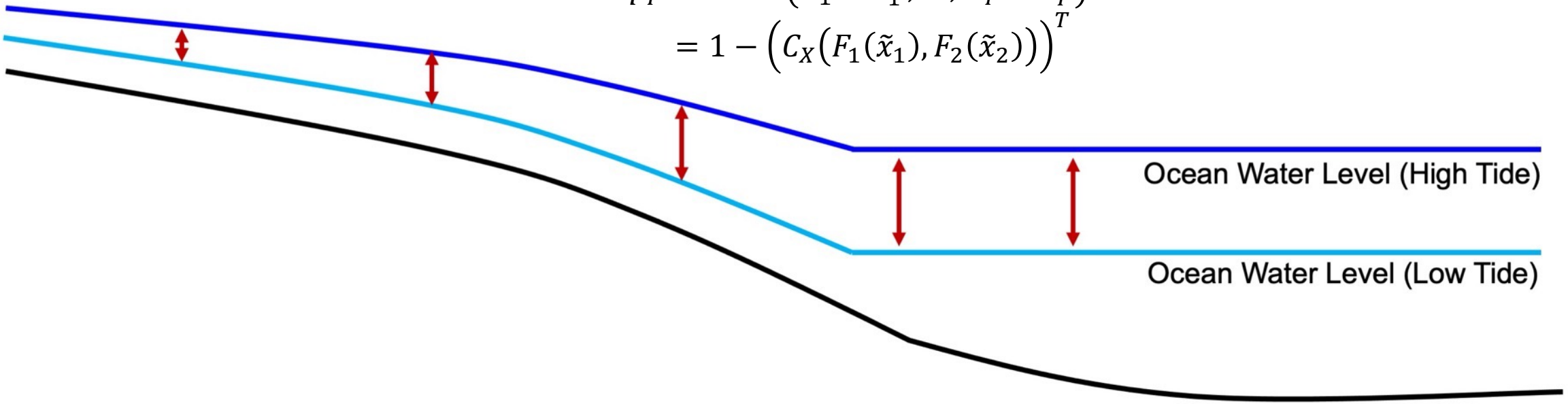
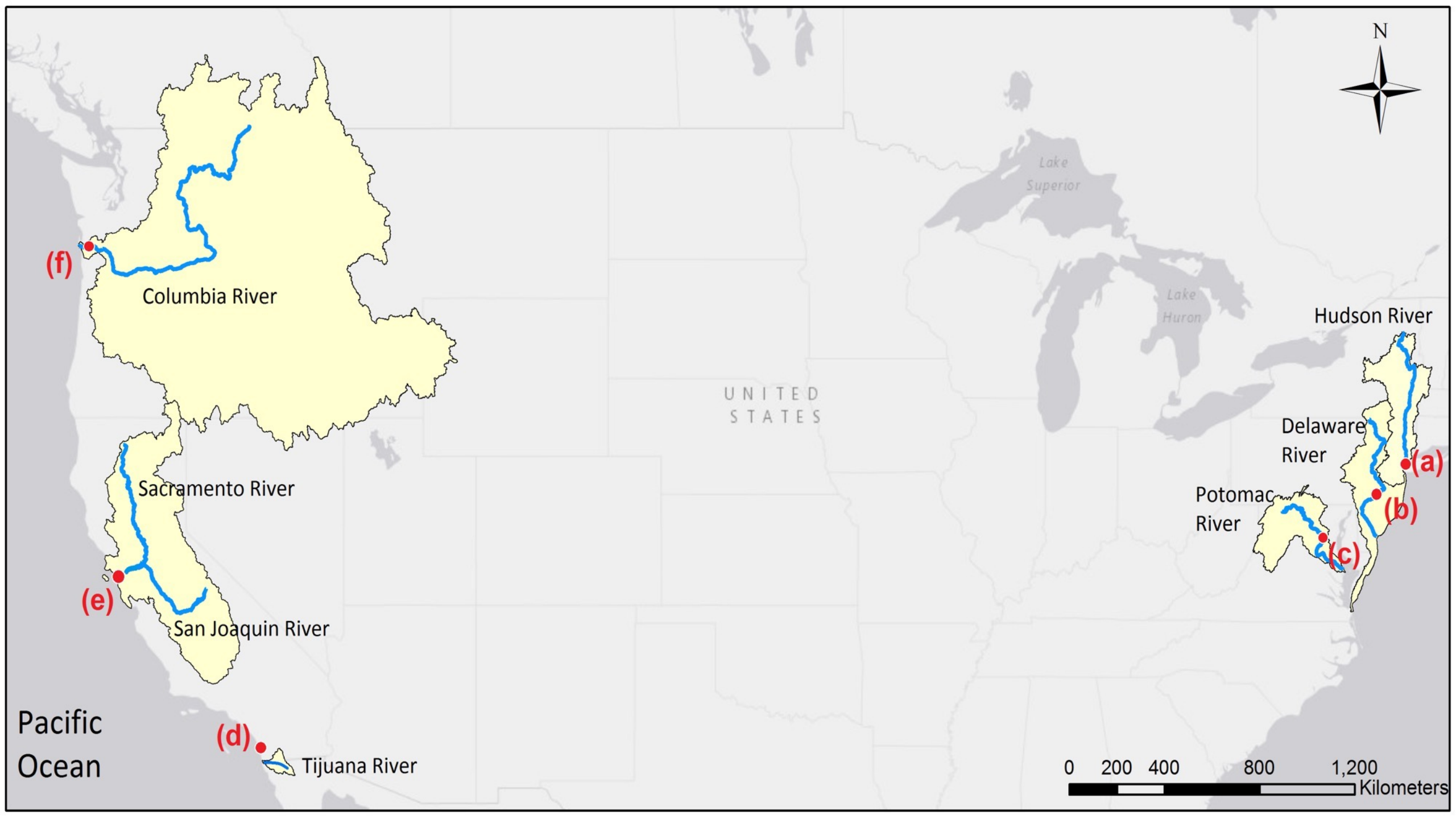


Multivariate

(Moftakhari, et al., 2017, *PNAS*)

$$p_F = 1 - P\left(X_1 \in S_1^C, \ldots, X_T \in S_T^C\right)$$
$$= 1 - \left(C_X\left(F_1(\tilde{x}_1), F_2(\tilde{x}_2)\right)\right)^T$$




N
Lake Superior
Lake Huron
UNITED STATES
Hudson River
Delaware River
Potomac River
(a)
(b)
(c)
(d)
(e)
(f)
Columbia River
Sacramento River
San Joaquin River
Tijuana River
Pacific Ocean
0 200 400 800 1,200
Kilometers

For a given system/infrastructure design lifetime of T the failure probability ($\check{P}_T$) is calculated as:

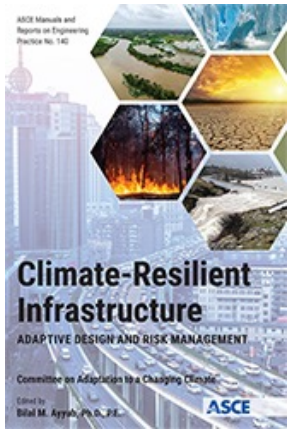
Univariate

$$p_F = 1 - (1 - p)^T$$

Multivariate

(Moftakhari, et al., 2017, *PNAS*)

$$p_F = 1 - P\left(X_1 \in S_1^C, \ldots, X_T \in S_T^C\right)$$
$$= 1 - \left(C_X\left(F_1(\tilde{x}_1), F_2(\tilde{x}_2)\right)\right)^T$$



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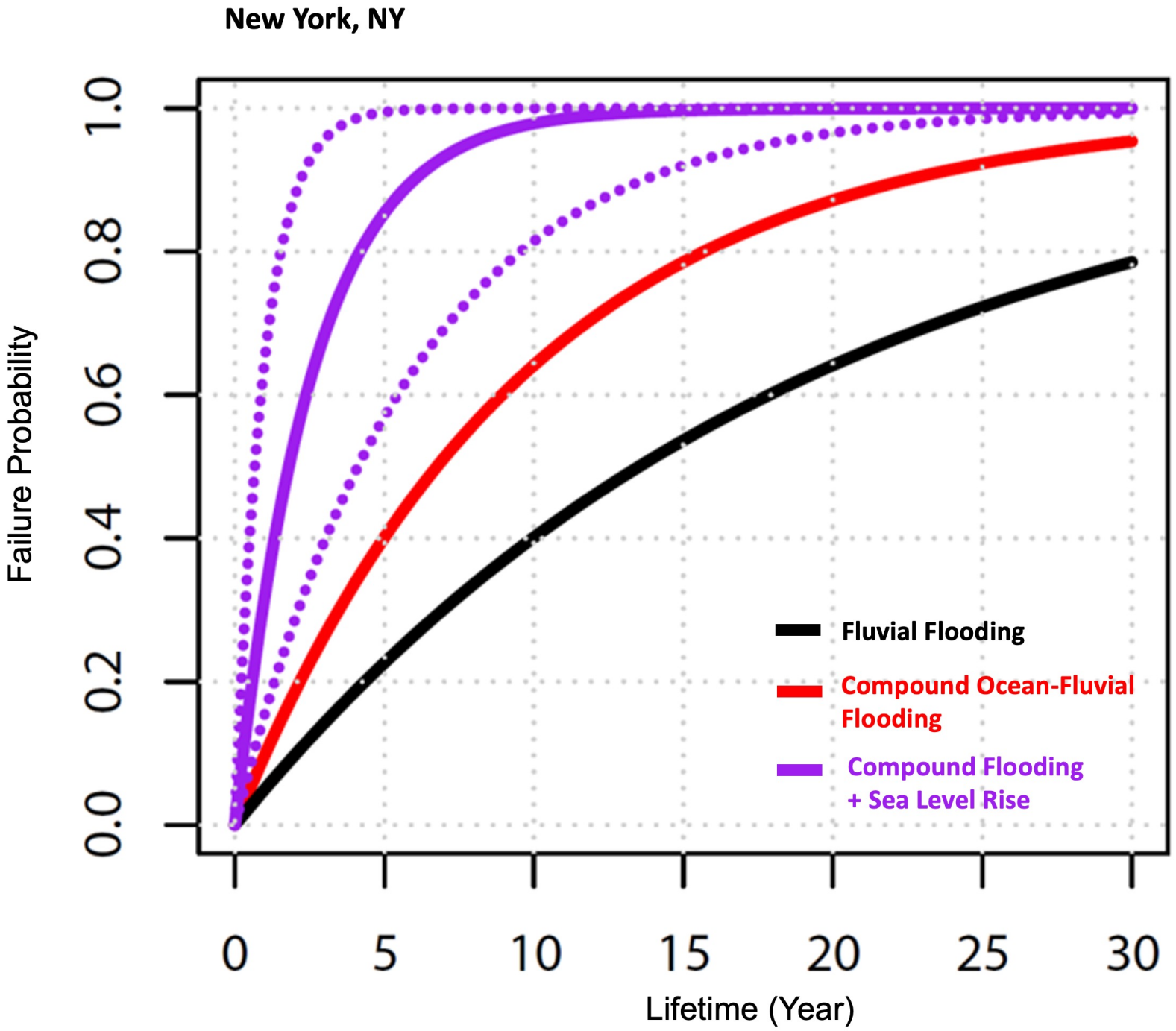
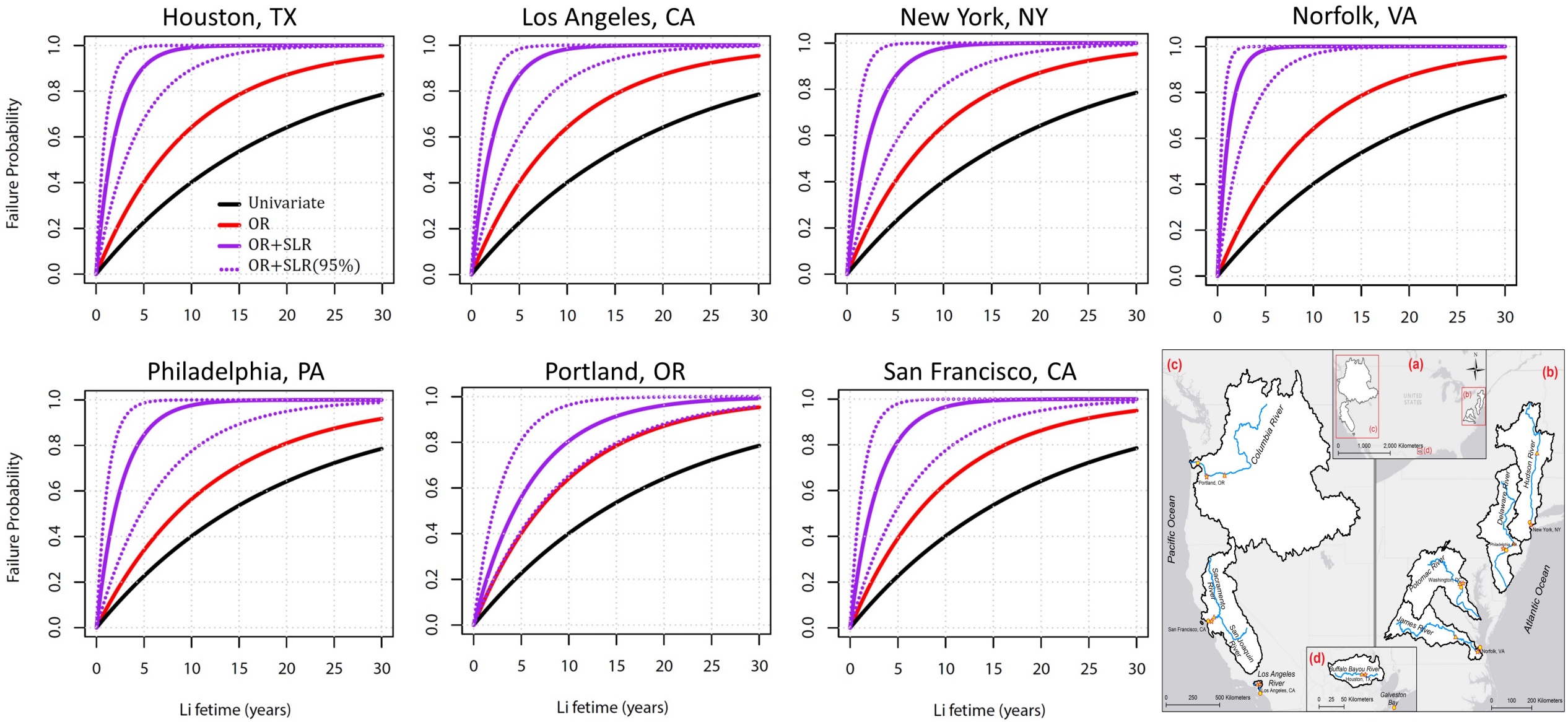


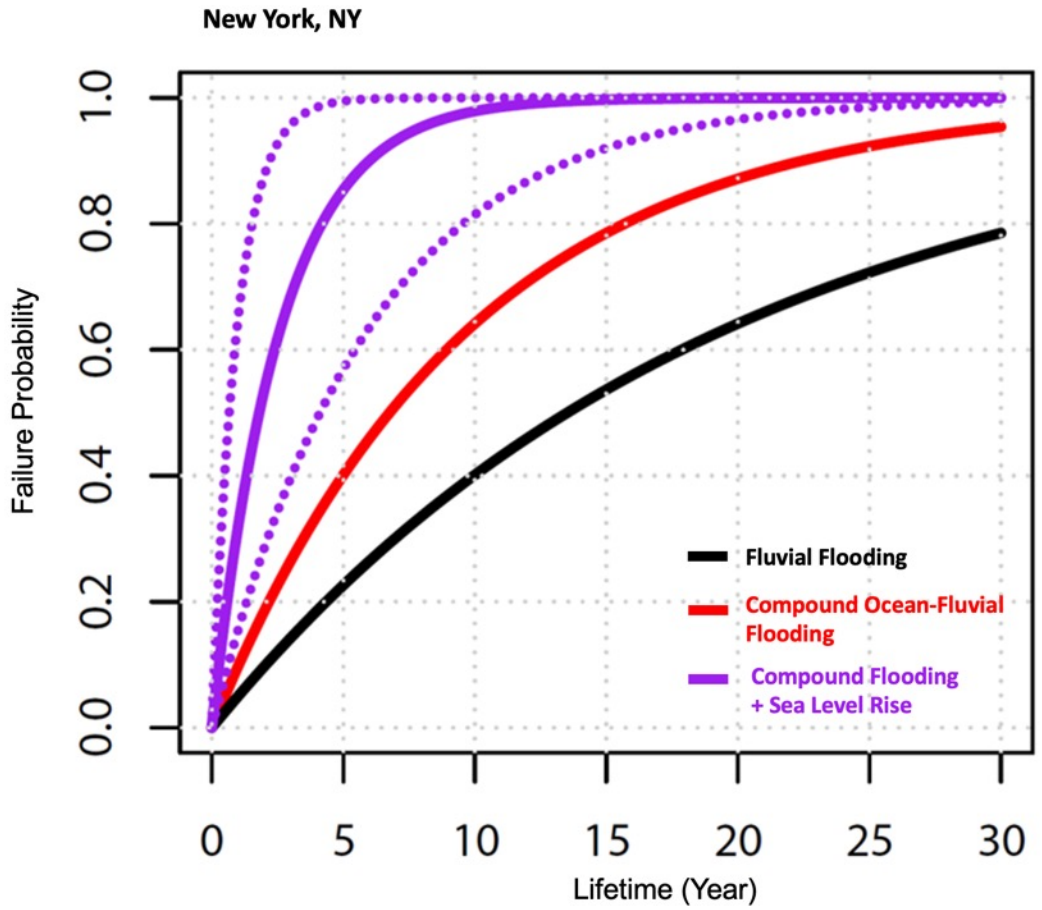
Compound Coastal Flooding

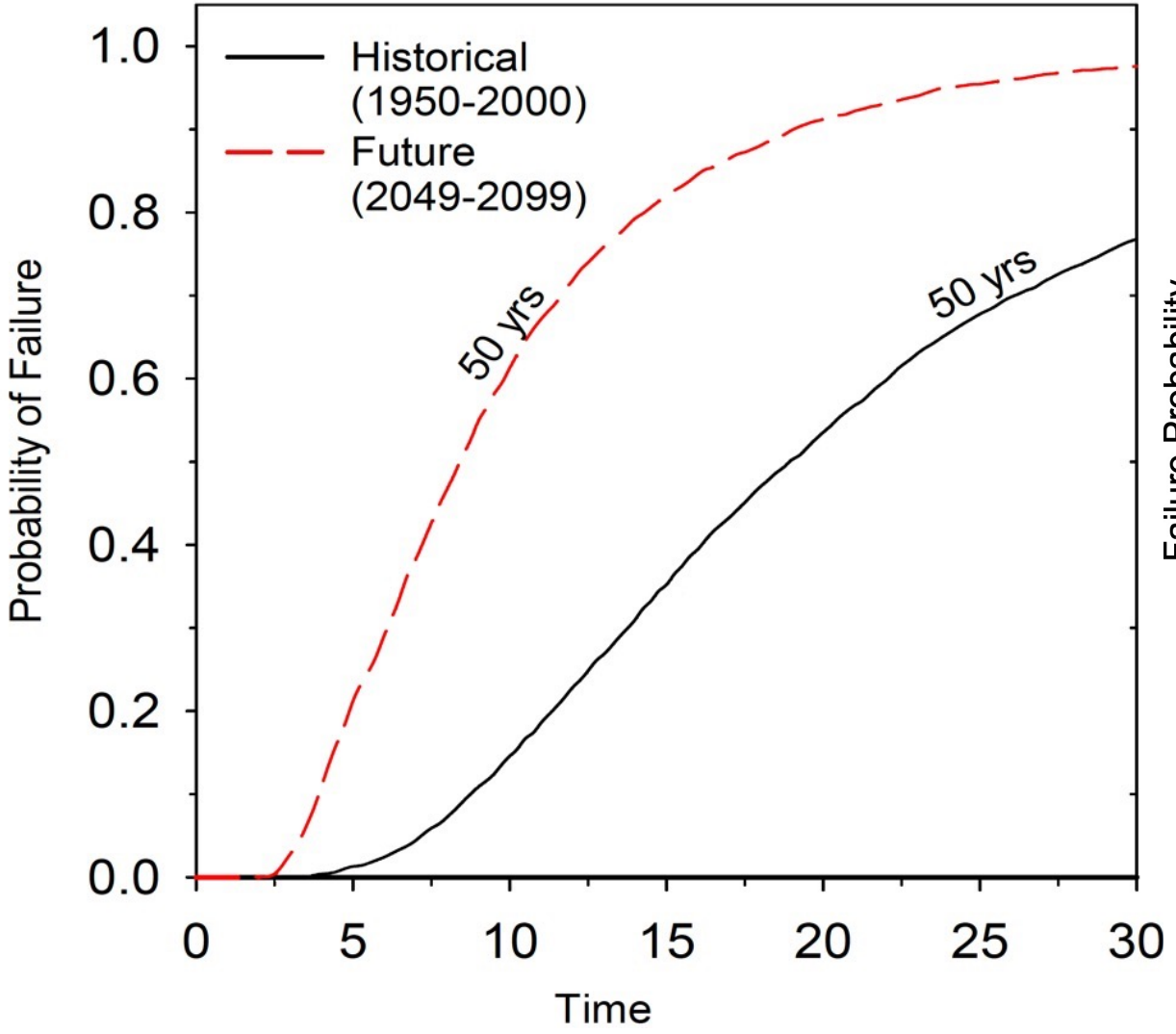


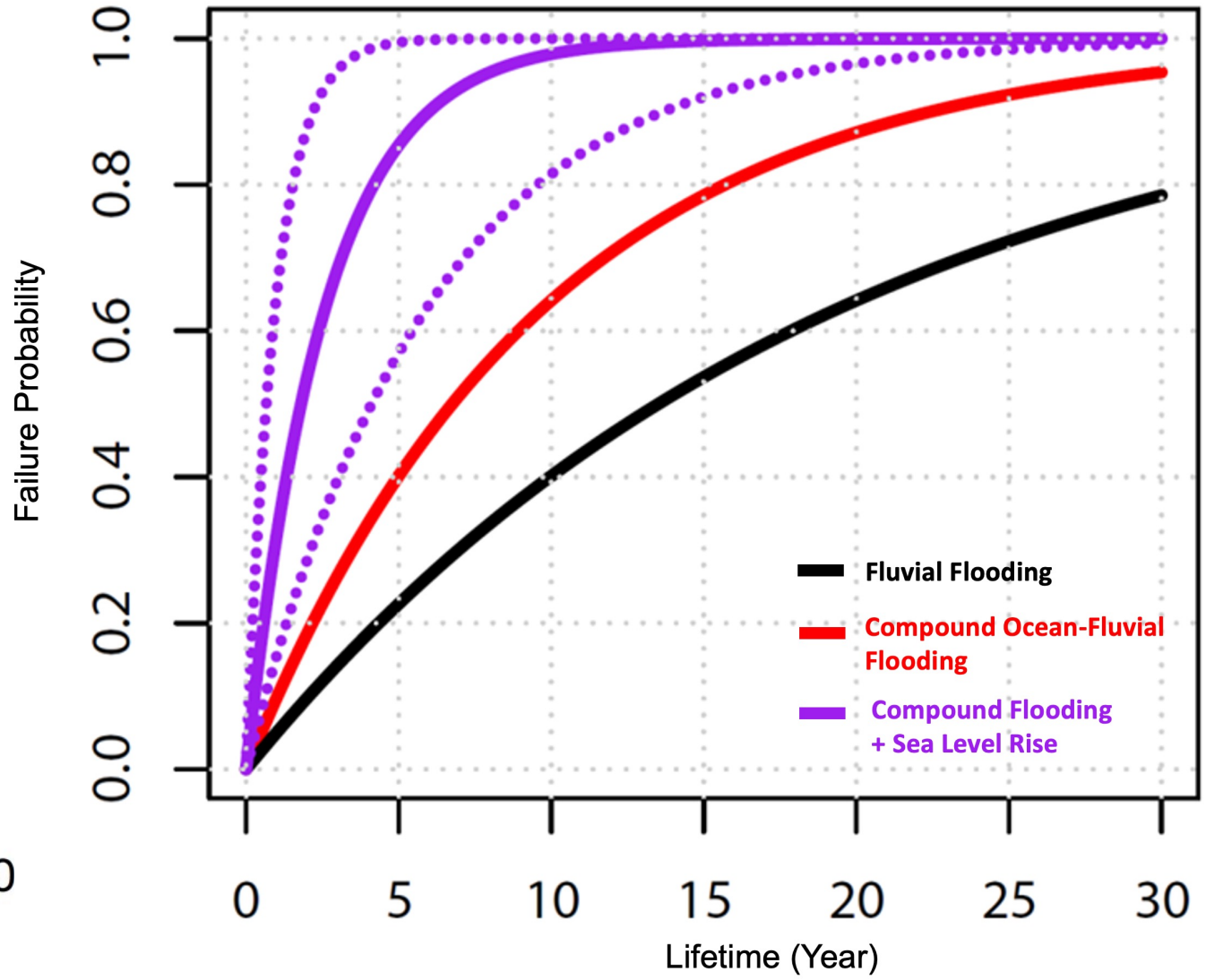
Moftakhari, et al., 2017, *PNAS*


California


Alaska


New York, NY
Failure Probability
0.0
0.2
0.4
0.6
0.8
1.0
0
5
10
15
20
25
30
Lifetime (Year)
Fluvial Flooding
Compound Ocean-Fluvial Flooding
Compound Flooding + Sea Level Rise

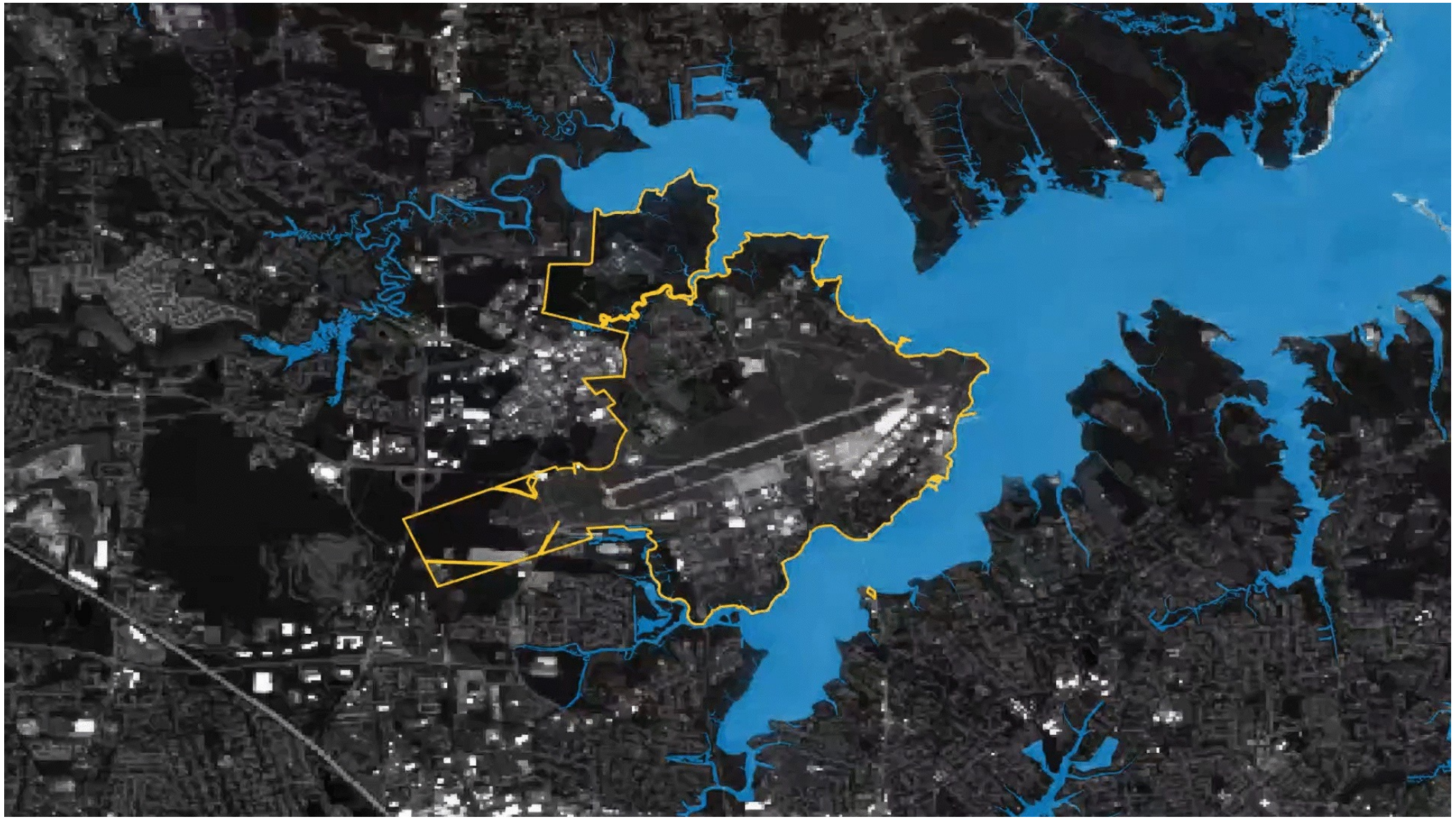




Linking **Statistical Failure** Probability to **Physical Failure**
(Bridging the Gap between Climate Science and Engineering)

Vahedifard, et al., 2020, *JGGE*

In the United States, there are at least **400 federal facilities** identified as being at risk from rising sea levels and compound coastal floods. The list includes thirteen executive agencies, including **Departments of Defense military bases**.



Source: Bloomberg Law

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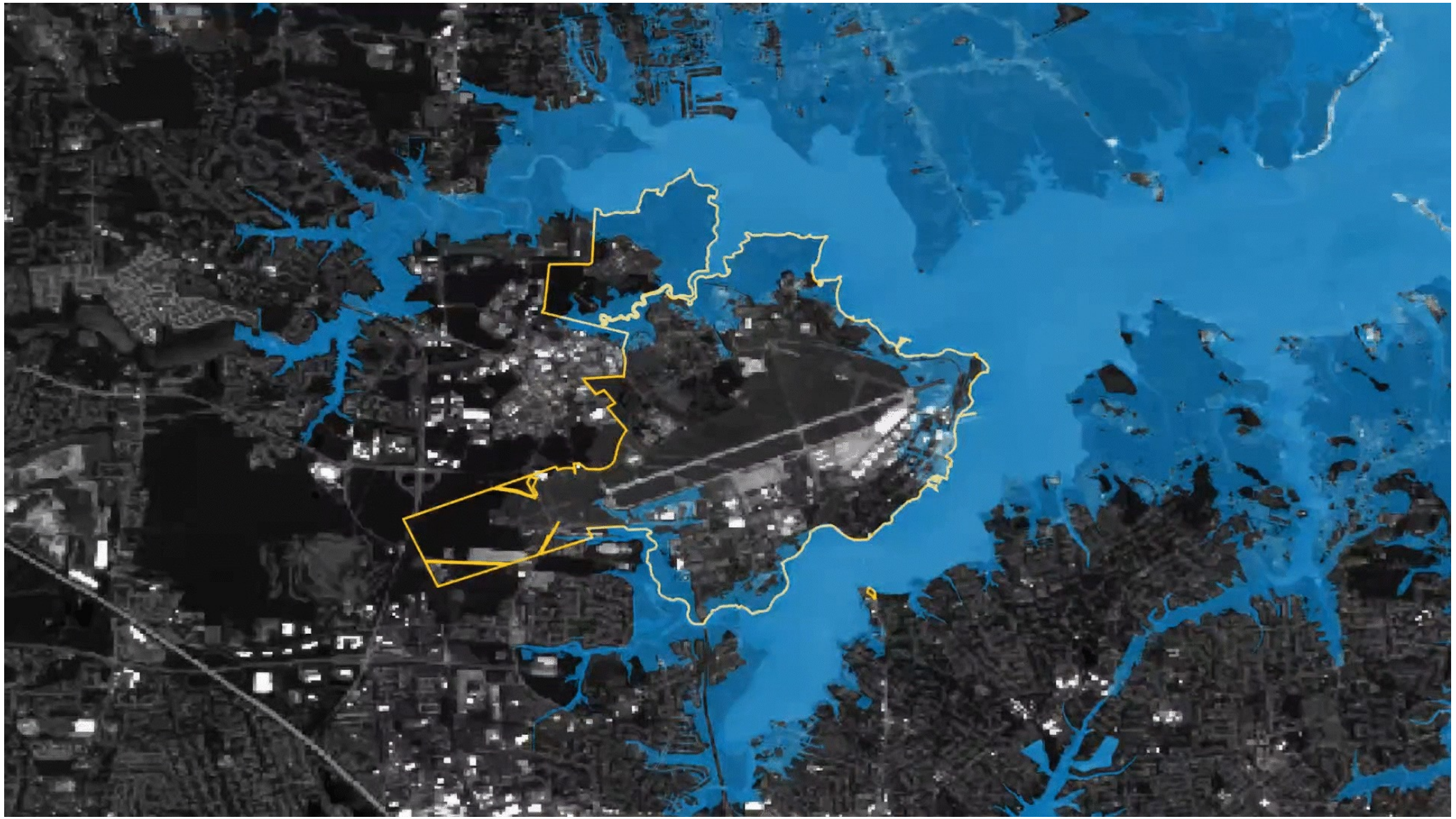

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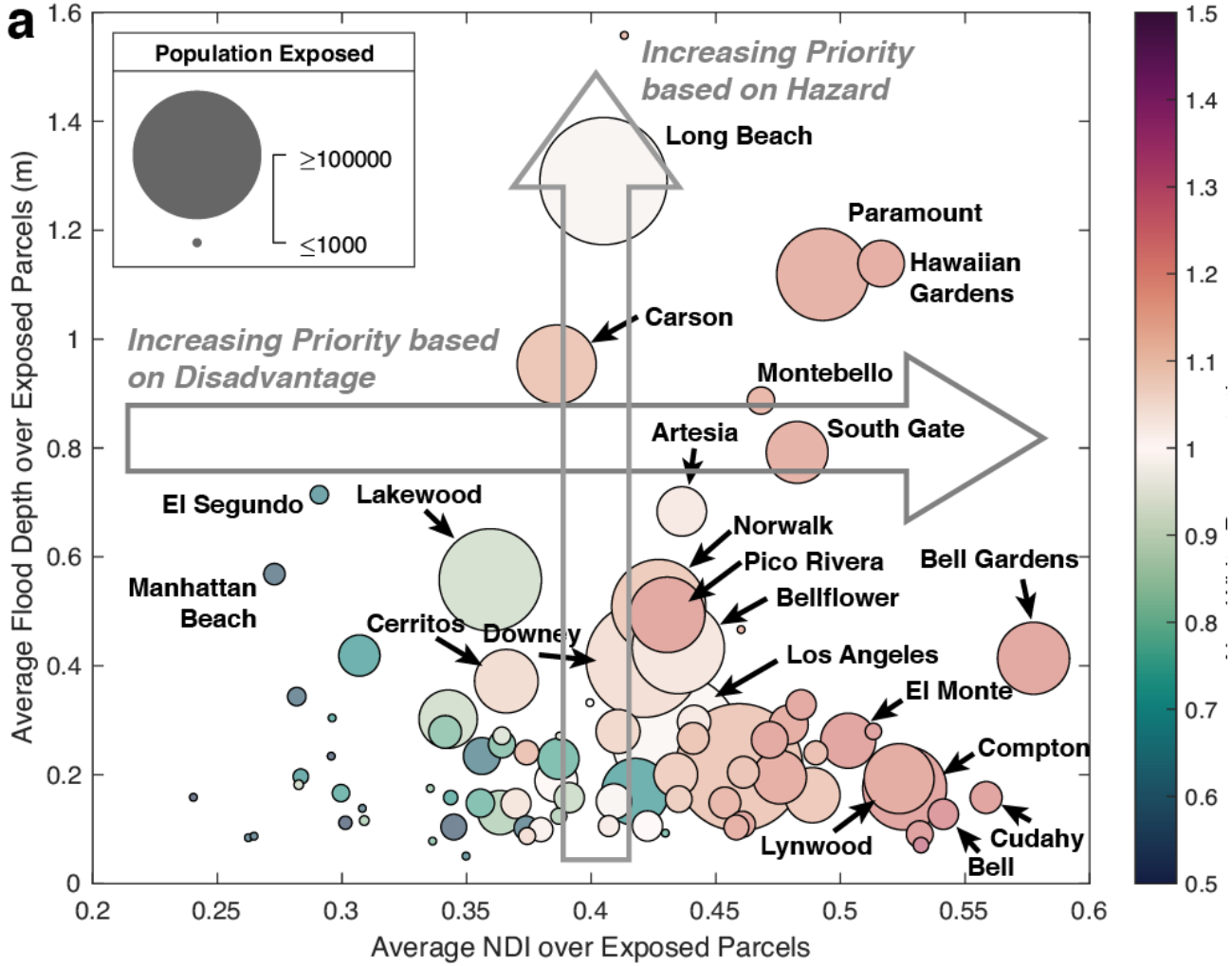
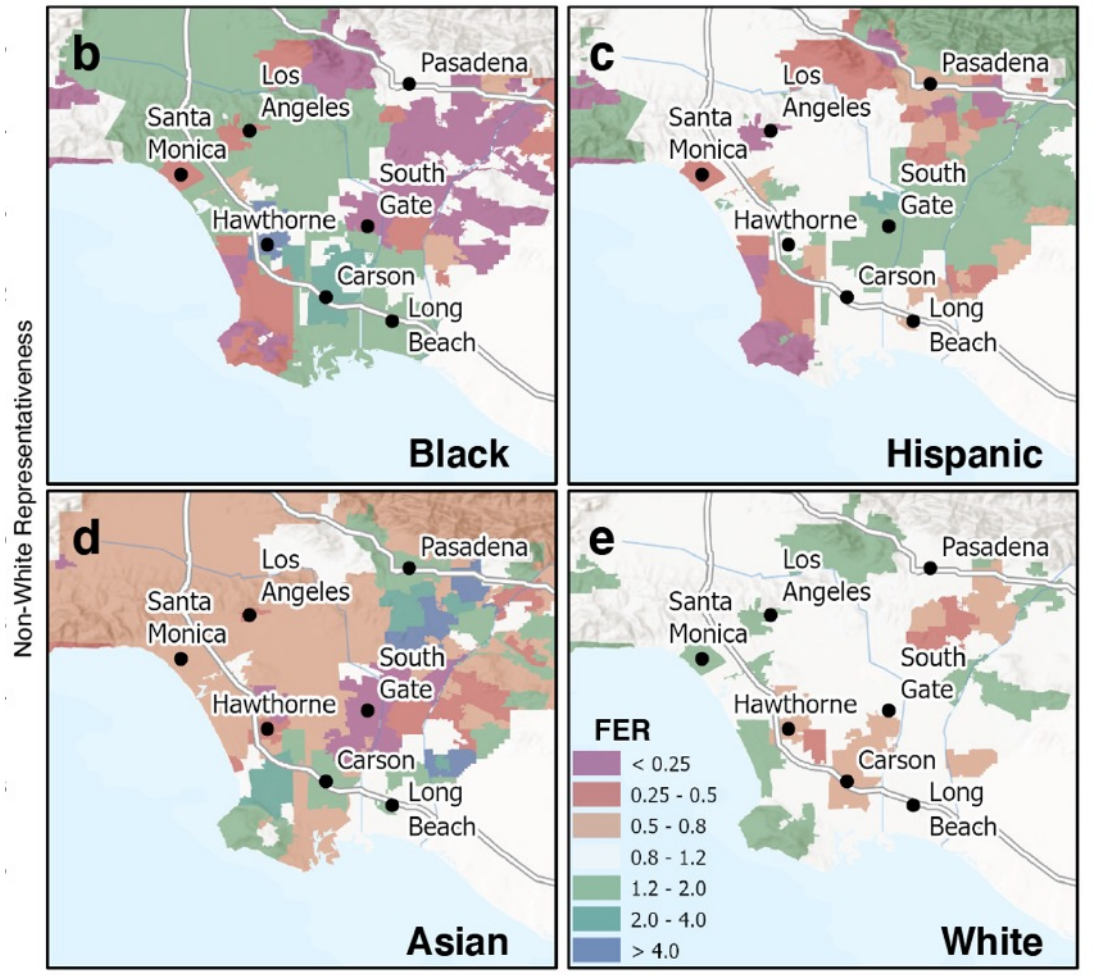




Neighborhood Disadvantage Index

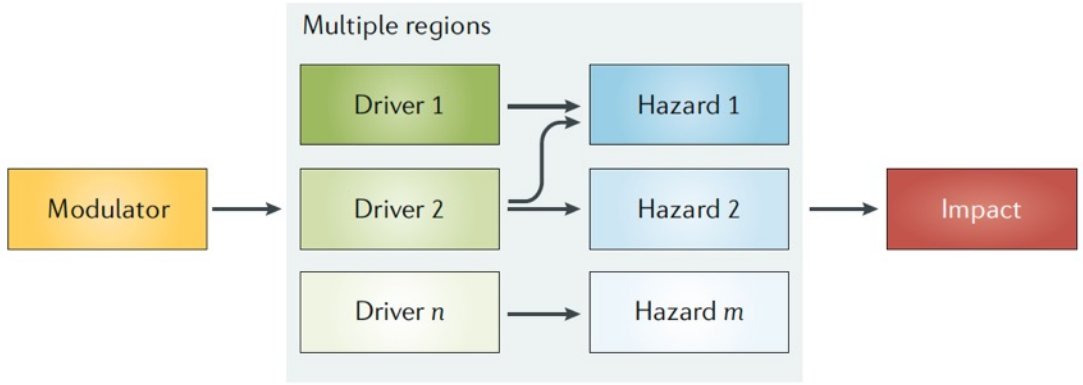
(**a**) Aggregation of parcel level data at municipal levels in Los Angeles considering exposed population (bubble size), flood hazard (y-axis), and neighborhood disadvantage index (x-axis). Flood Exposure Representativeness (FER), including communities with high (>1.2) FER for (**b**) Black, (**c**) Hispanic and (**d**) Asian populations.

High resolution modeling reveals severe flood risks that are disproportionately higher for Black, Hispanic and disadvantaged populations

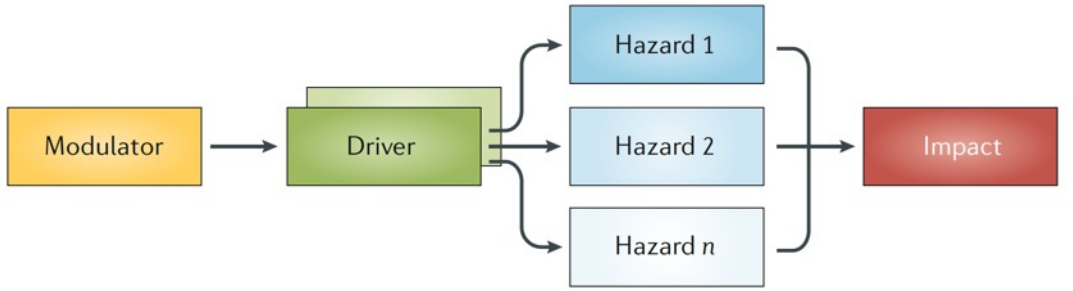
Sanders, et al., *Nature Sustainability*

Typology of Compound Events

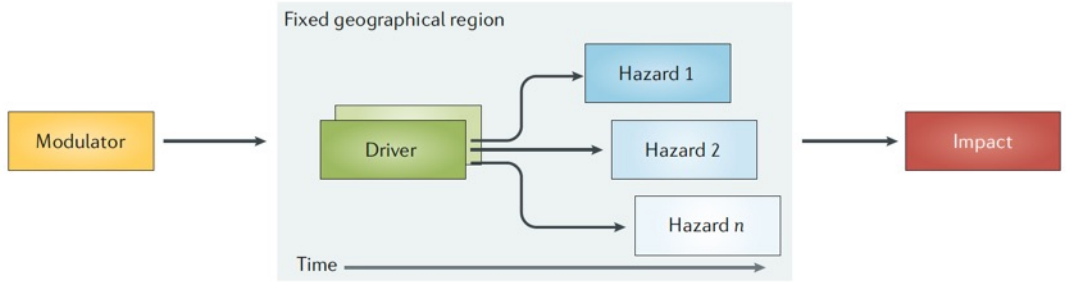
Multivariate Compound Events



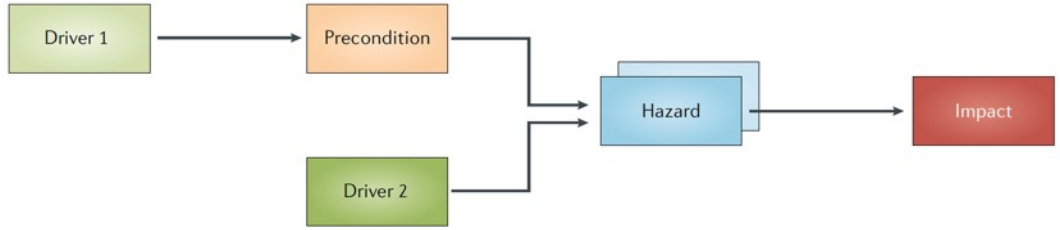
Spatially Compound Events



Temporally Compounding (Cascading) Events

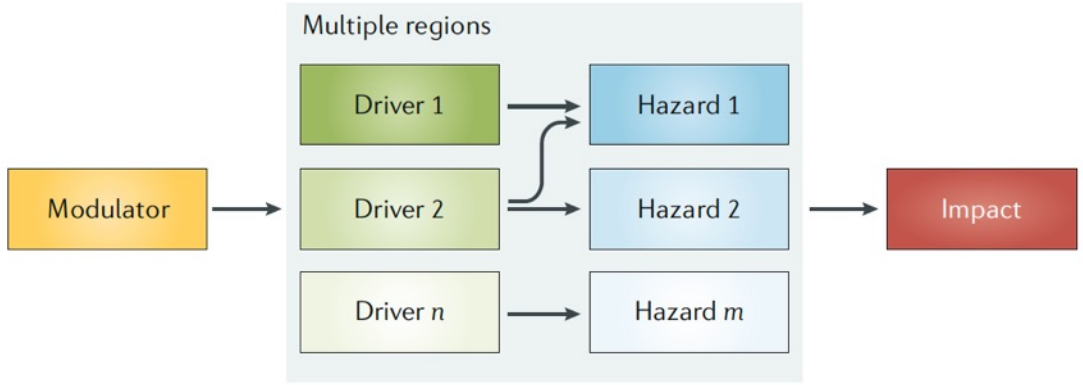


Preconditioned Compound Events



Zscheischler, et al. 2020, *Nature Reviews Earth & Environment*

Multivariate Compound Events



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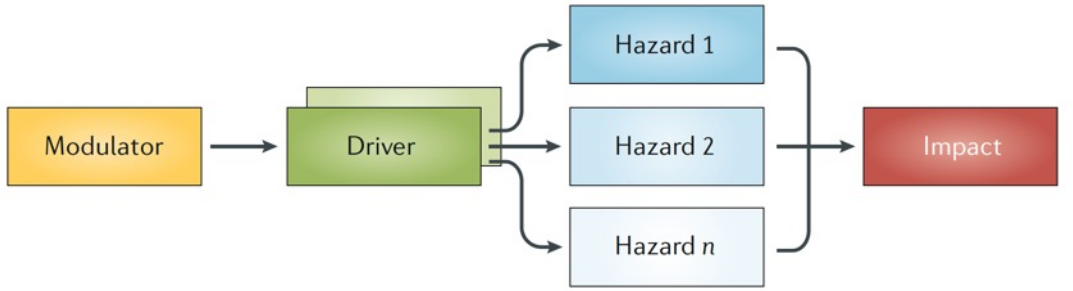
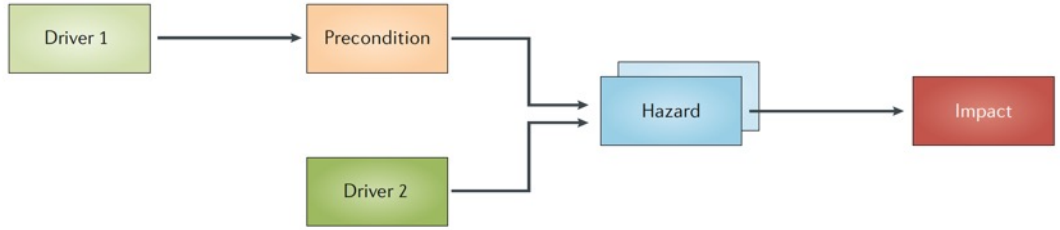


Temporally Compounding (Cascading) Events

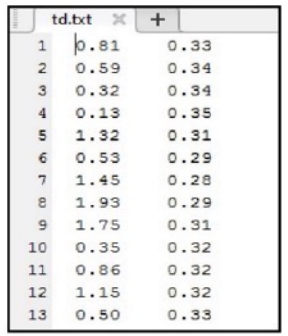
Preconditioned Compound Events

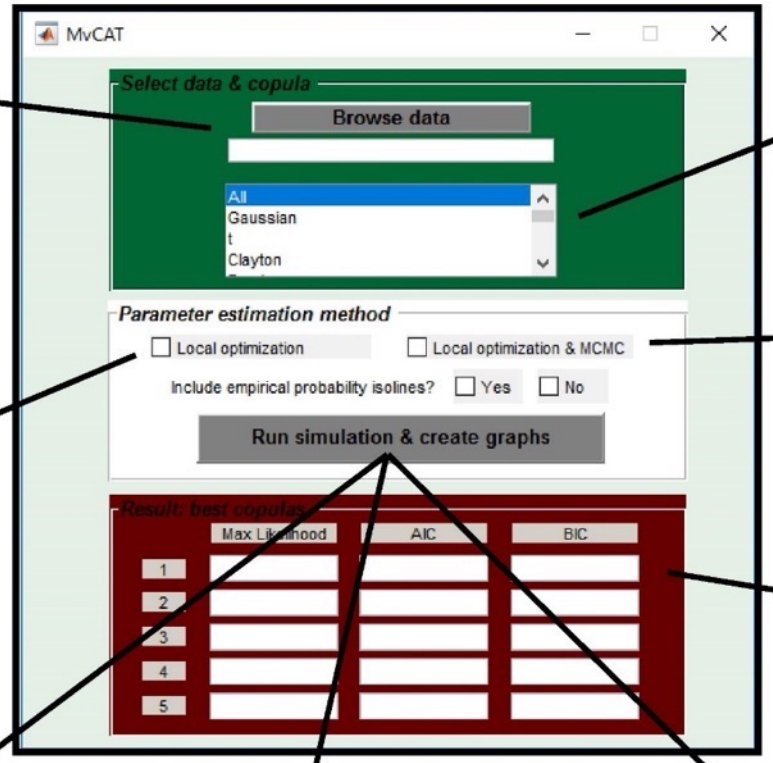


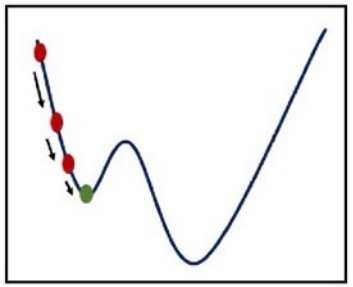
Zscheischler, et al. 2020, *Nature Reviews Earth & Environment*

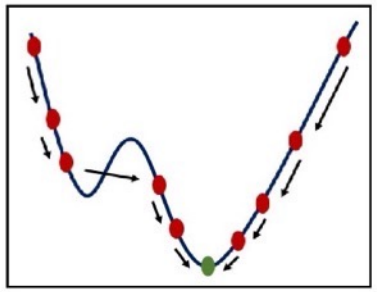
Multivariate Copula Analysis Toolbox (MvCAT)
Multi-hazard Scenario Analysis Toolbox (MhAST)

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



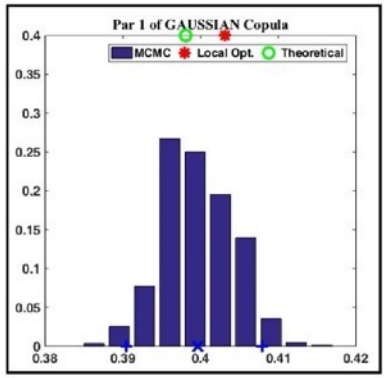


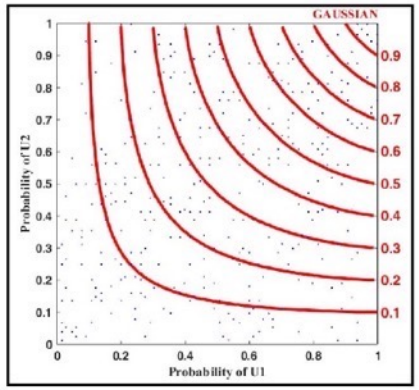


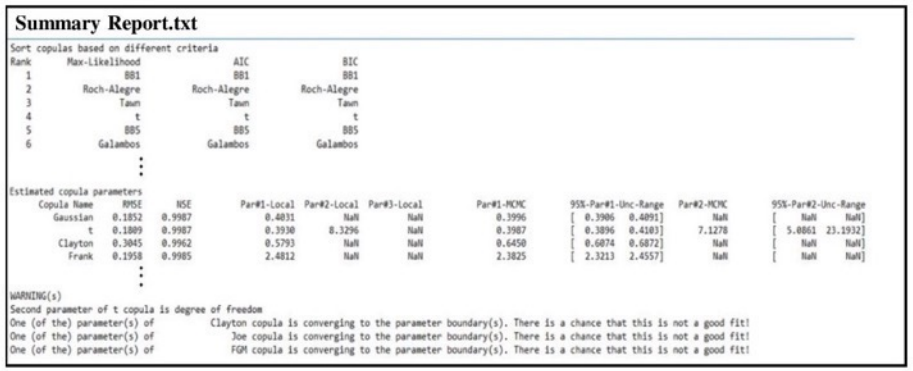


Sadegh et al., 2017,
Water Resources Research

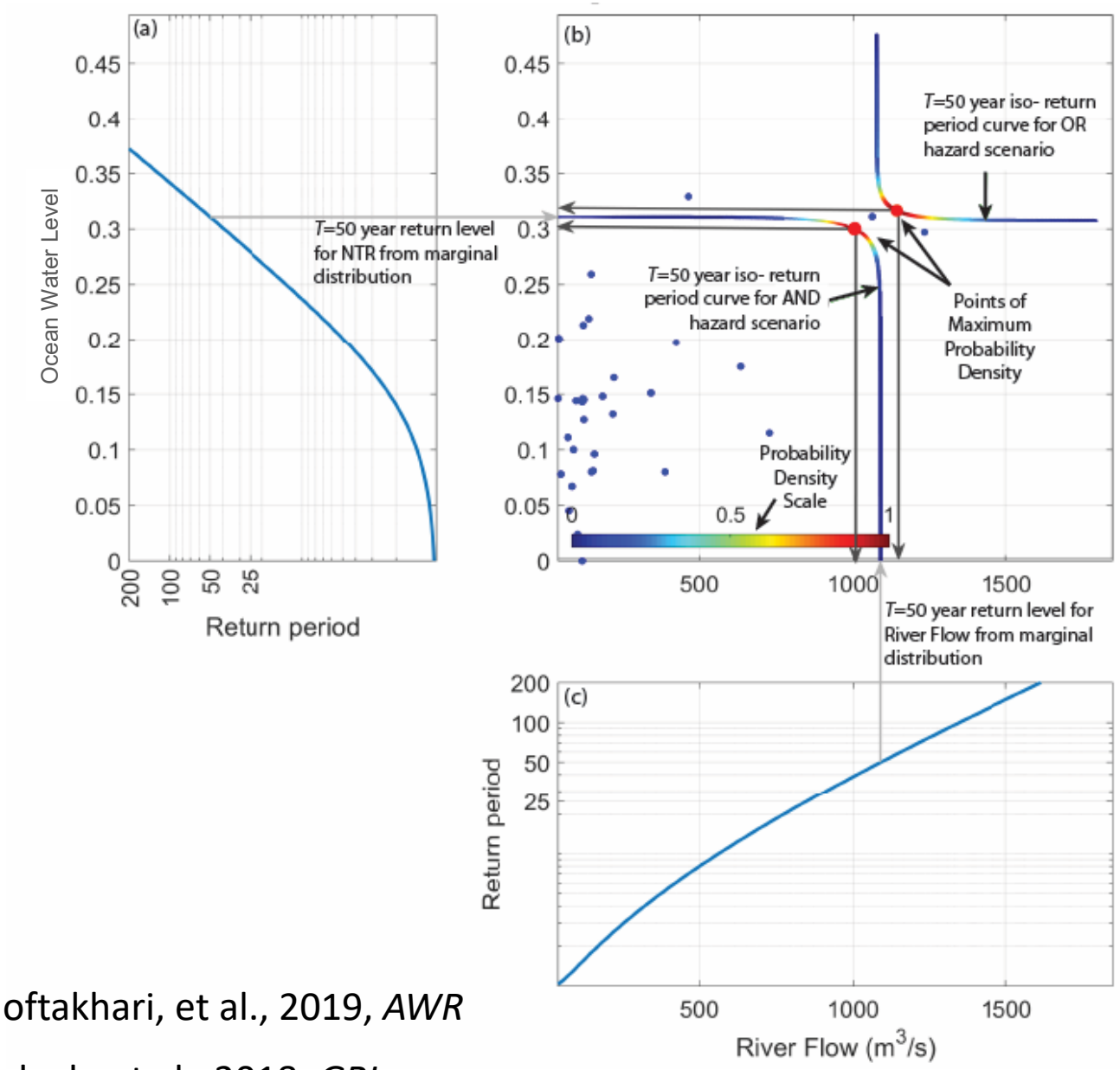
Sadegh et al., 2018,
Geophysical Research Letters







Generalized Multi-Hazard Scenarios for Compound Extremes



$$RP_q^1 = \frac{\mu}{\Pr\left(\boldsymbol{x} \in R_q^{>}\right)} = \frac{\mu}{1 - P_q^1},$$

Univariate Return Period

Parametric Model

$$C(\boldsymbol{u}) = H\left[F_1^{-1}(u_1), F_2^{-1}(u_2), \cdots, F_d^{-1}(u_d)\right],$$

Multiple Hazards

$$p(\theta|\tilde{\mathbf{D}}) = \frac{p(\theta)p(\tilde{\mathbf{D}}|\theta)}{p(\tilde{\mathbf{D}})} \propto p(\theta)p(\tilde{\mathbf{D}}|\theta)$$

$$p(\tilde{\mathbf{D}}|\theta) \cong \mathcal{L}(\theta|\tilde{\mathbf{D}}) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi\tilde{\sigma}^2}} \exp\left\{-\frac{1}{2}\tilde{\sigma}^{-2}\left[\tilde{d}_i - d_i(\theta)\right]^2\right\},$$

Bayesian Based Parameter Estimation

$$RP_q^{2+} = \frac{\mu}{\Pr\left(\boldsymbol{x} \in R_q^{>}\right)} = \frac{1}{1 - C(\boldsymbol{u}^q)}.$$

Multivariate Return Period

$$\boldsymbol{x}^{ex} = \left(\sum_{i=1}^{5} \frac{1}{RP_{q_i}^{2+}} \operatorname{argmax}\ h(\boldsymbol{x}), \quad \boldsymbol{x} \in L_{q_i}^{P}\right) / \left(\sum_{i=1}^{5} \frac{1}{RP_{q_i}^{2+}}\right),$$

$$RP_{\boldsymbol{q}}^{2+} = [2, 10, 25, 50, 100].$$

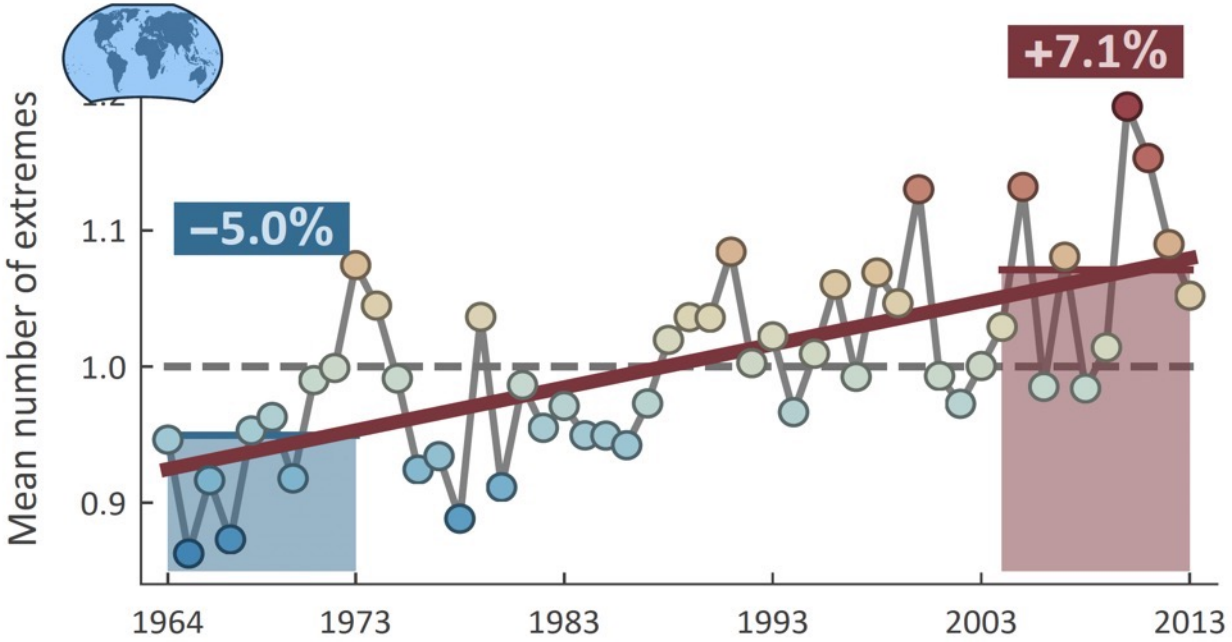
Expected Scenario

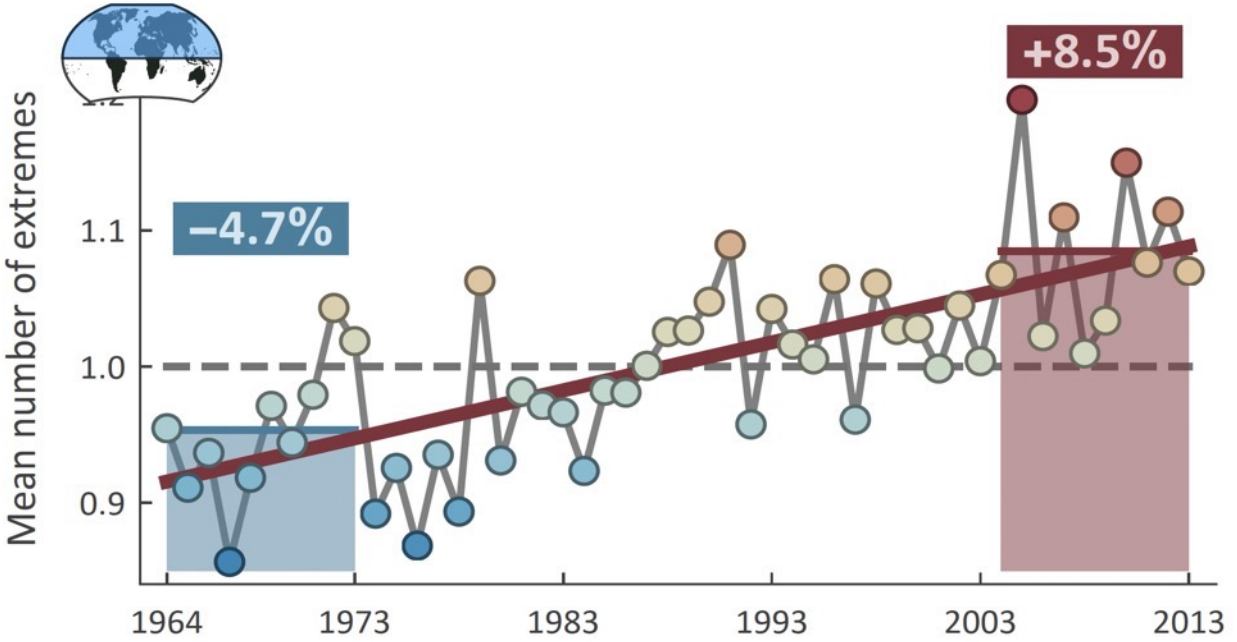
Moftakhari, et al., 2019, *AWR*

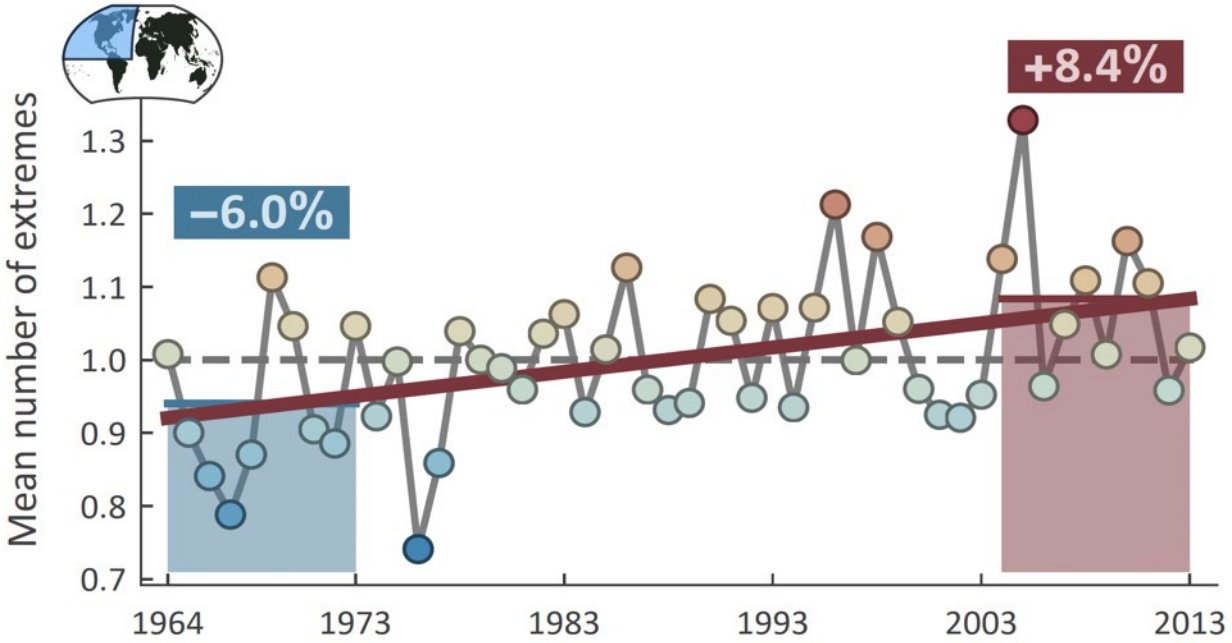
Sadegh, et al., 2018, *GRL*

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

Environmental Risk Assessment and Non-stationarity



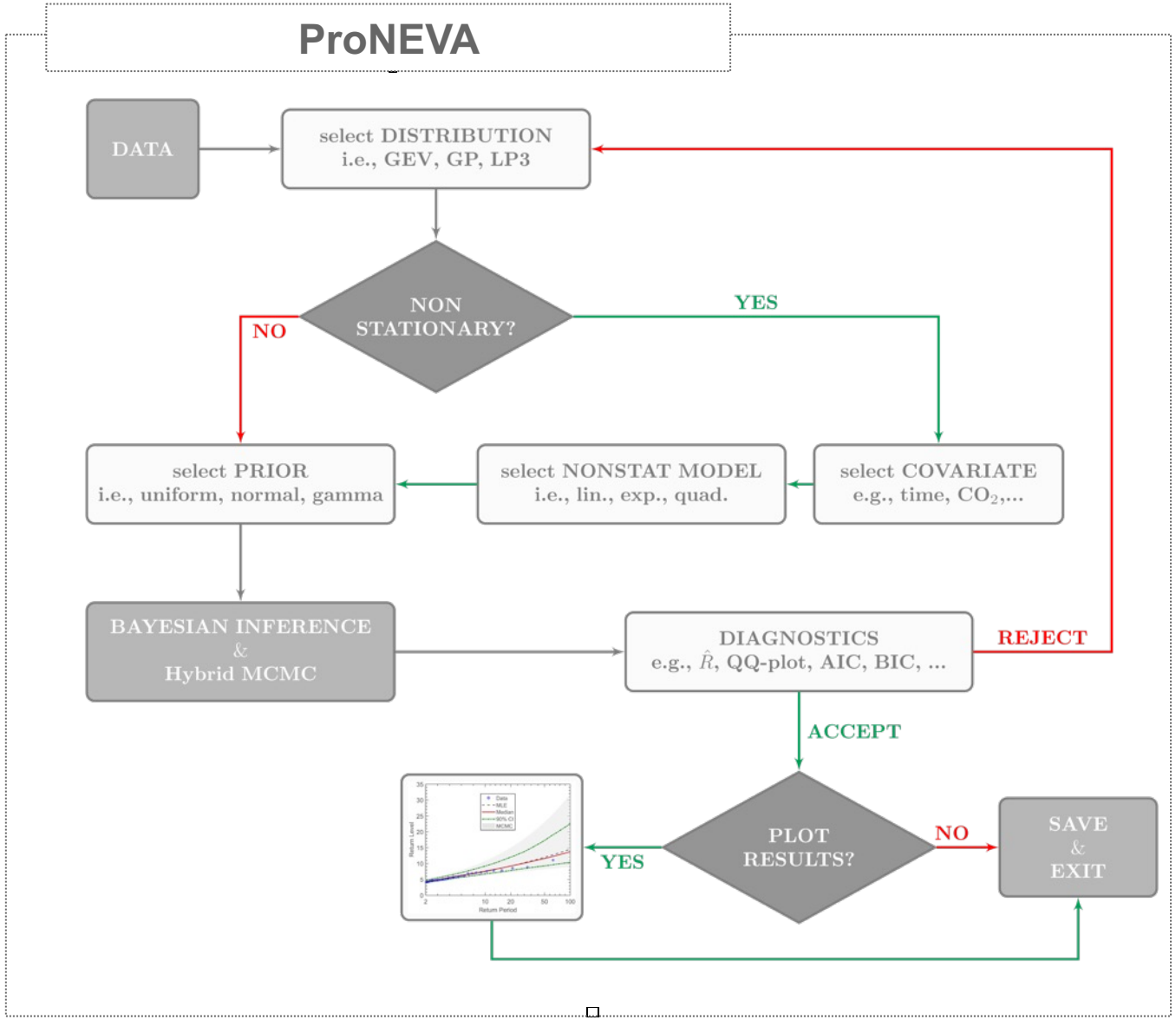




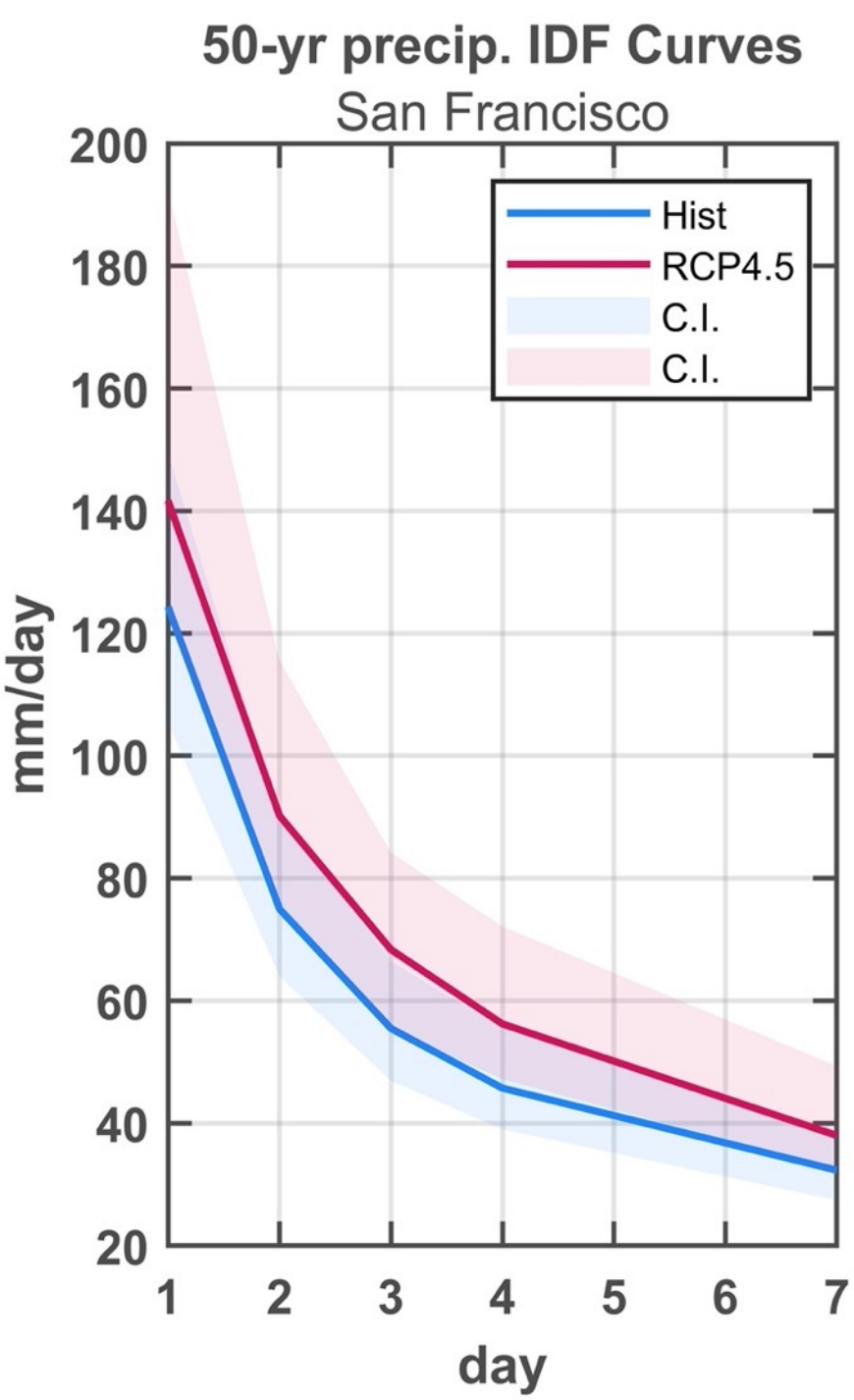
Considering the *N* largest precipitation extremes in an *N*-year record, under the assumption of stationarity, we expect no significant trend (i.e., on average one extreme per year). Analysis of 8,730 records shows evidence of change in the frequency of extreme precipitation around the world.

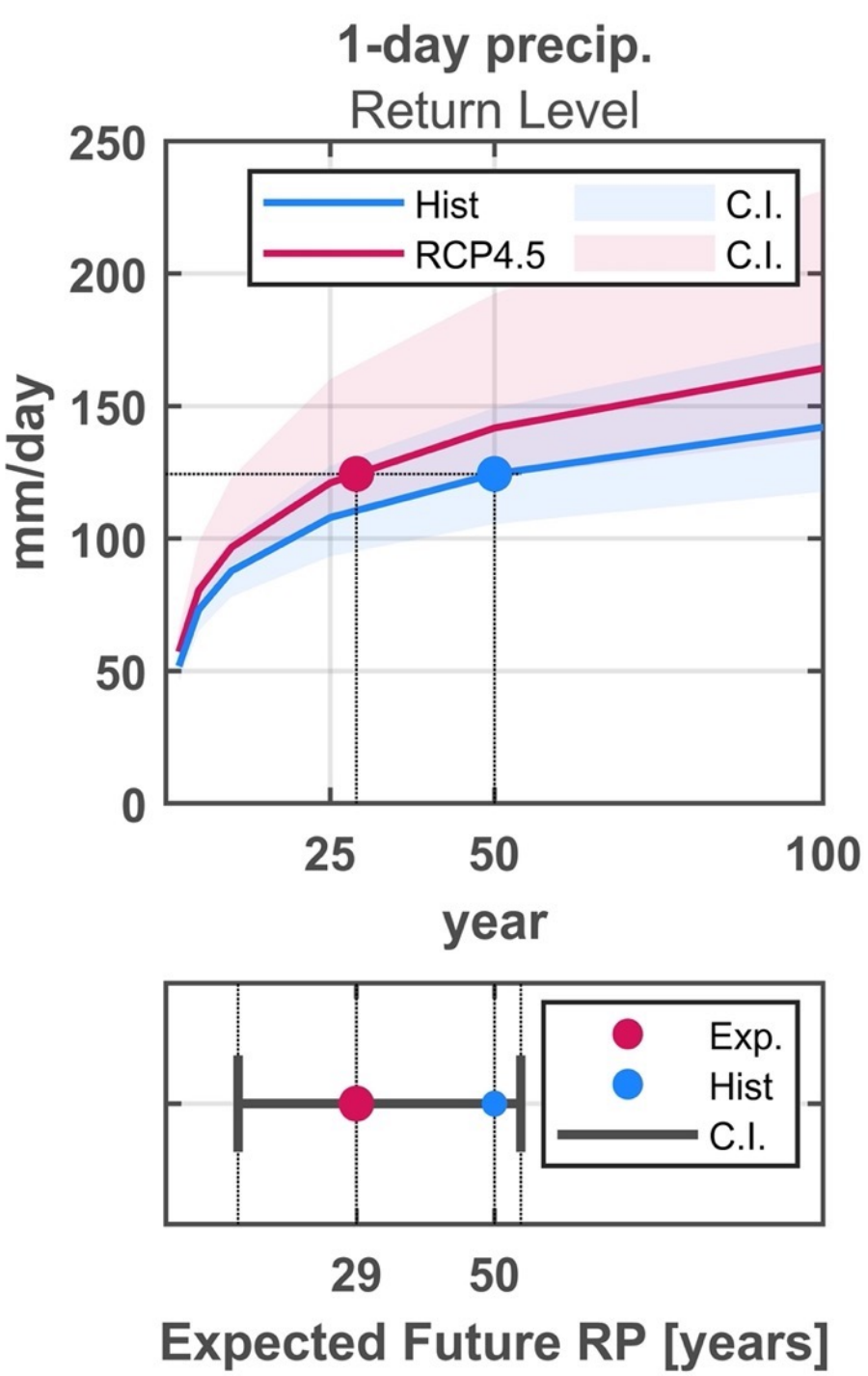
AghaKouchak et al., 2020, *Annu Rev Earth Planet Sci*

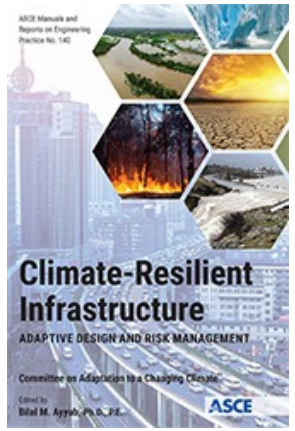
Process-informed Nonstationaty Extreme Value Analysis (ProNEVA)



Ragno et al., 2019, *Advances in Water Resources*
http://amir.eng.uci.edu/downloads/ProNEVA.zip

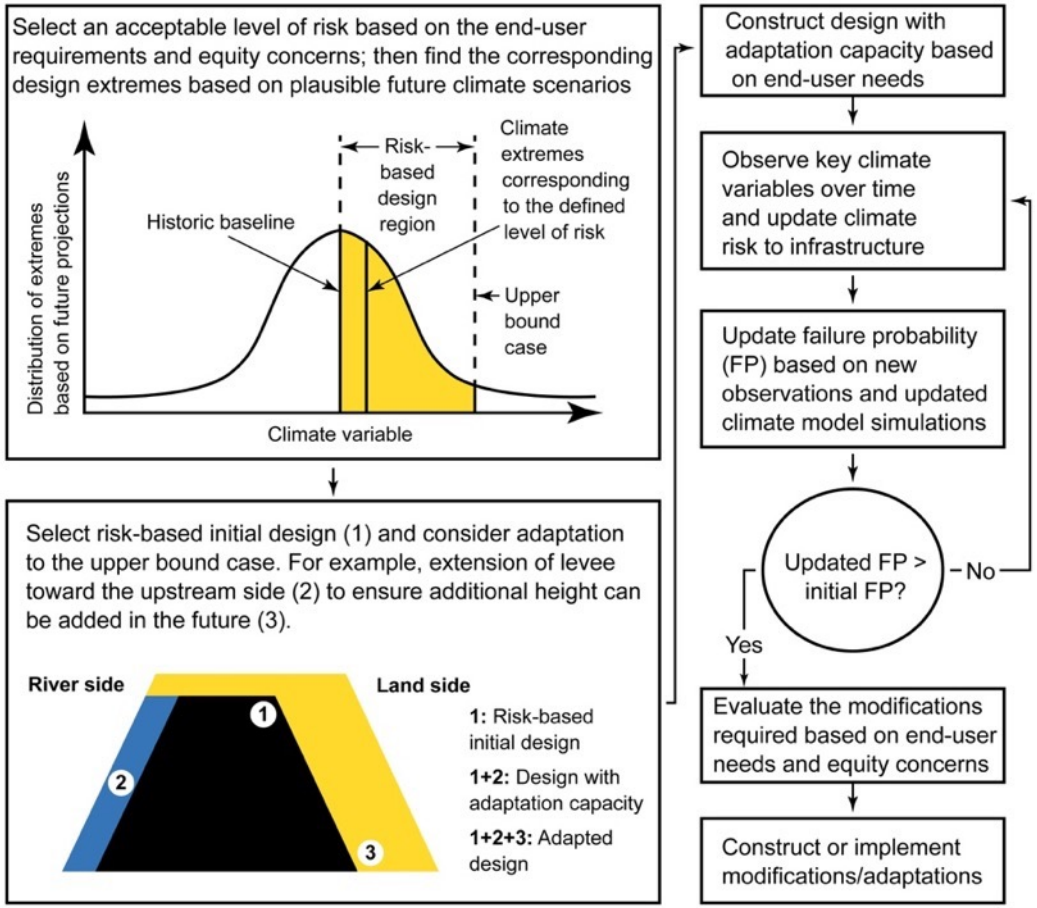


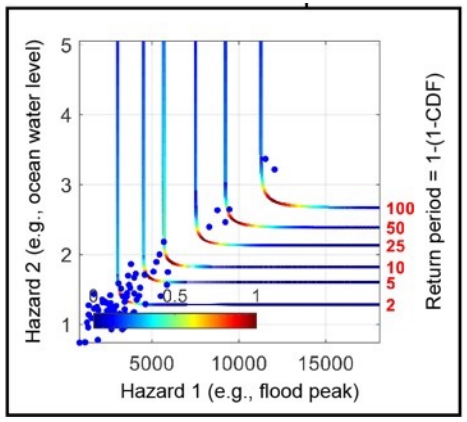


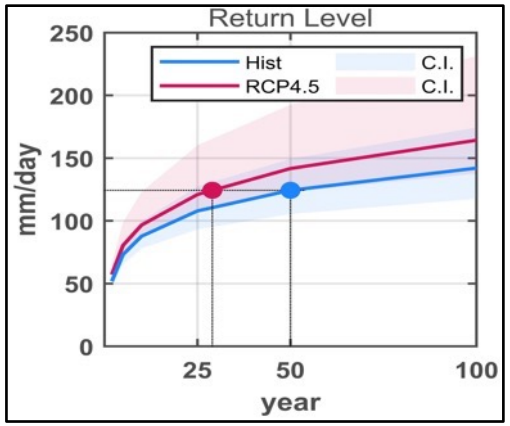


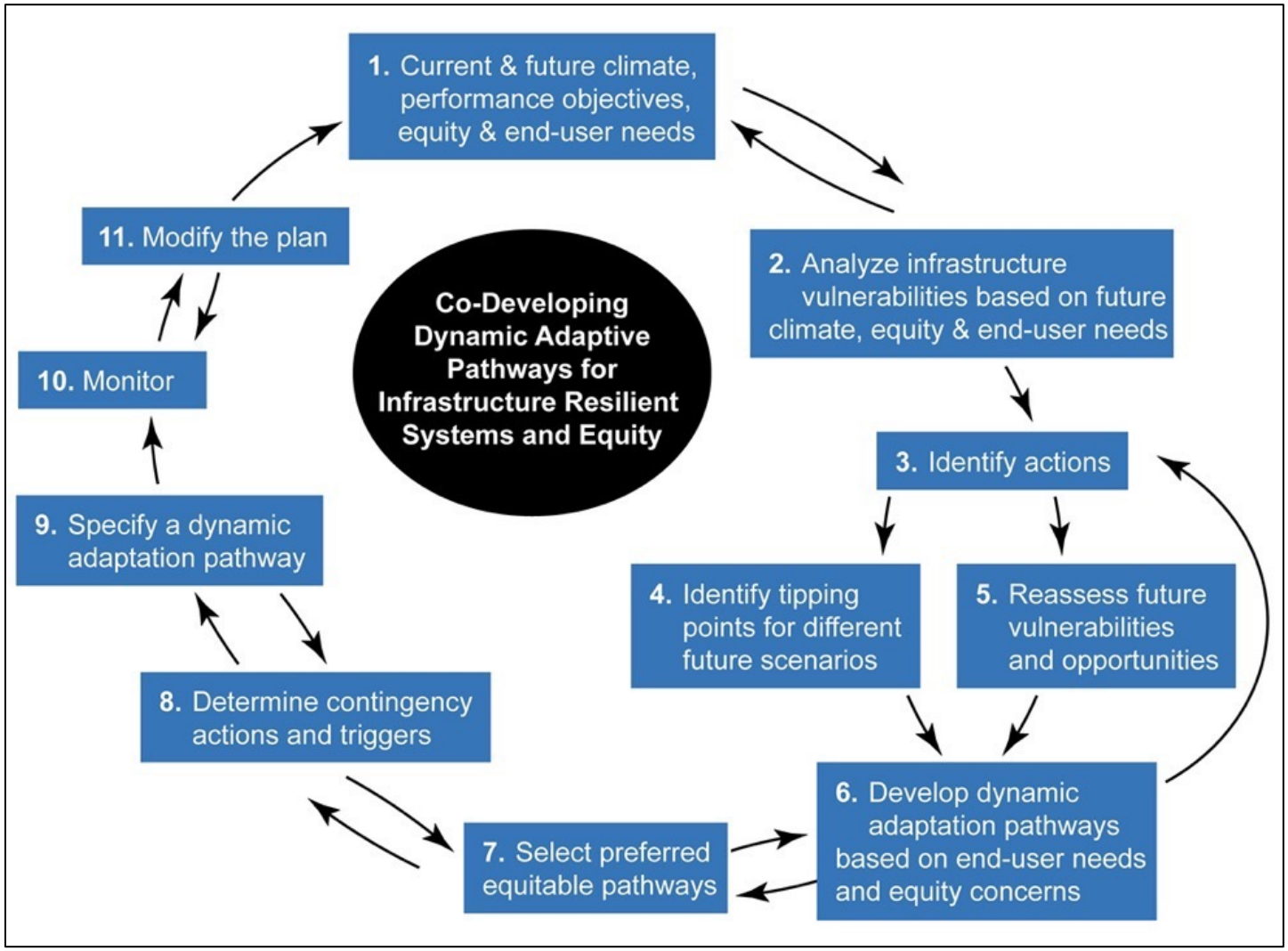
ASCE Manual of Practice 140: Methodology recommended to quantify changes in statistics of extreme rainfall for infrastructure design and risk assessment.

Adaptive Concepts for Infrastructure Design, Monitoring, and Risk Assessment







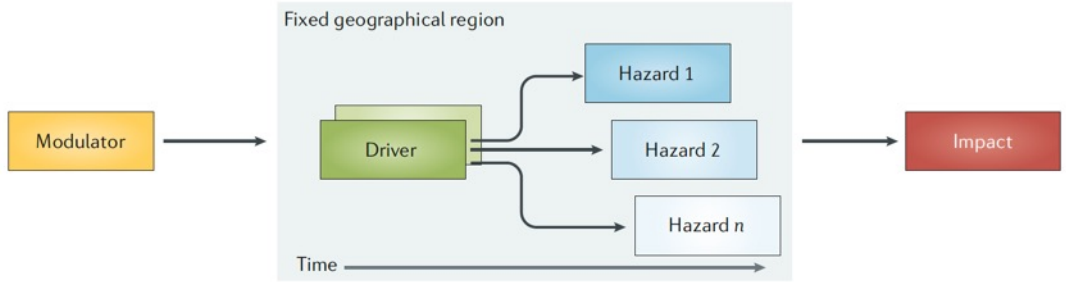


Cascading Hazards

Multivariate Compound Events

Spatially Compound Events

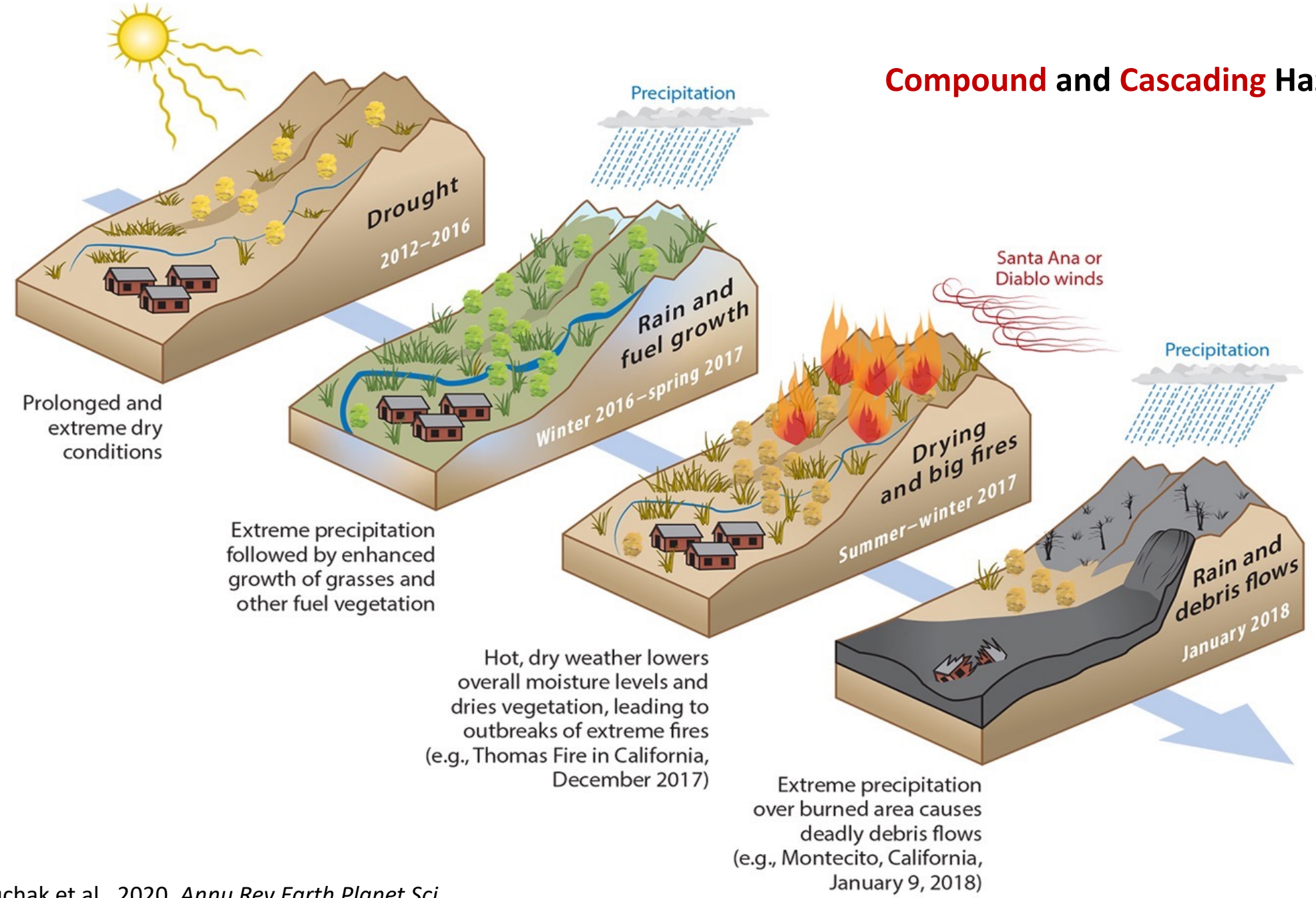
Temporally Compounding (Cascading) Events



Preconditioned Compound Events

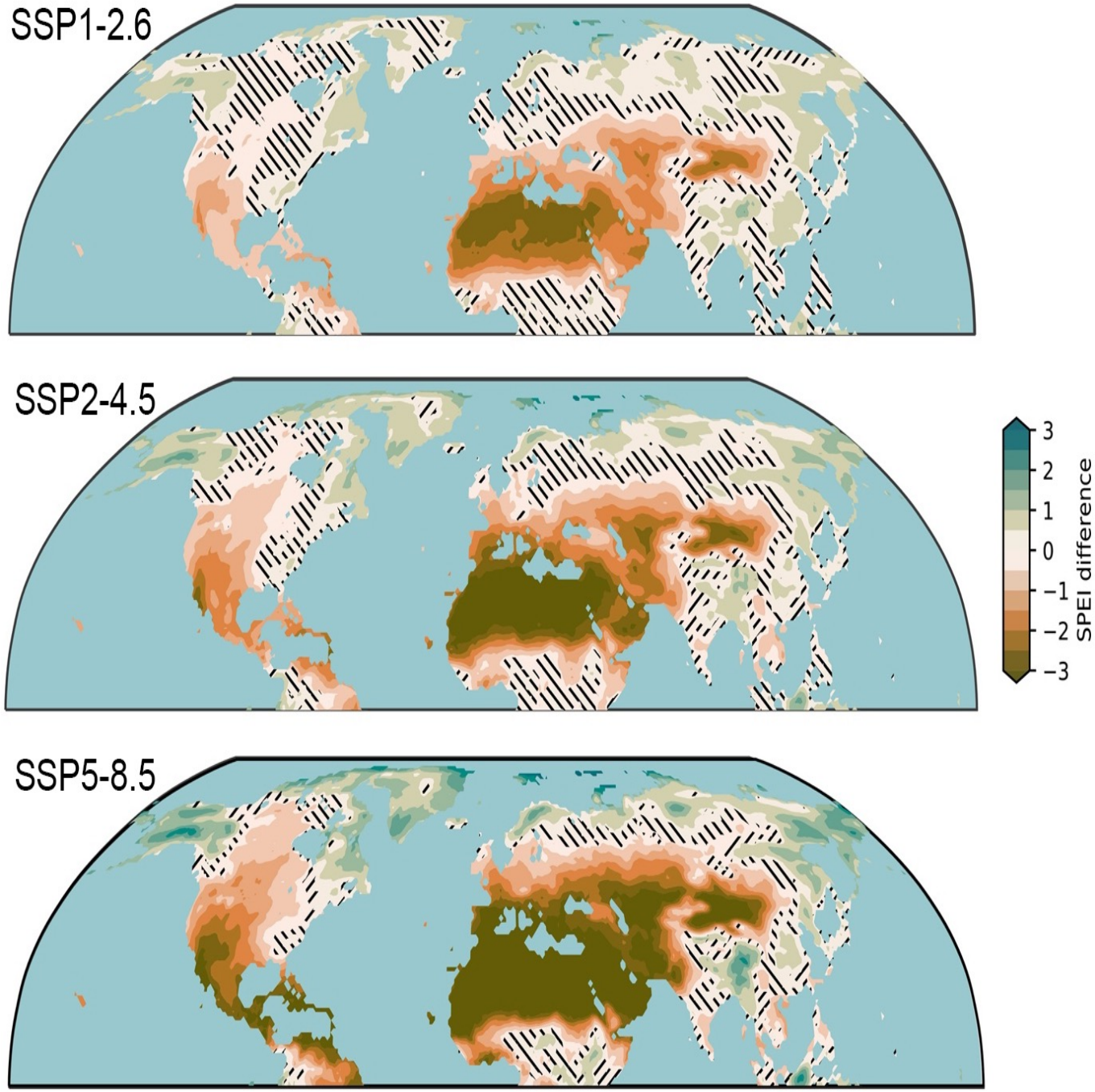
Zscheischler, et al. 2020, *Nature Reviews Earth & Environment*

Compound and Cascading Hazards

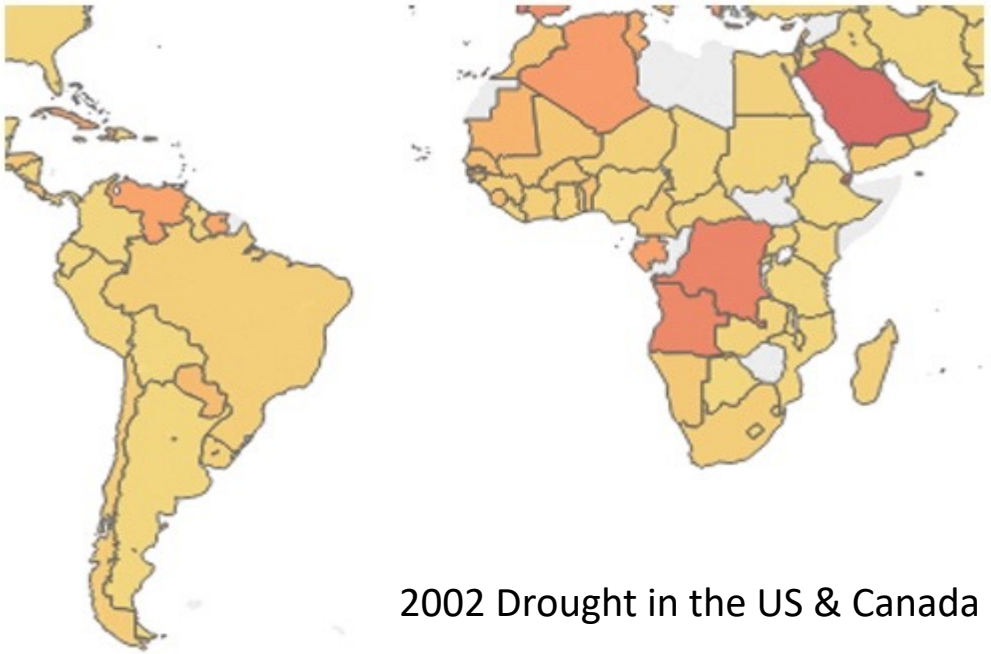


AghaKouchak et al., 2020, *Annu Rev Earth Planet Sci*

Martinez et al., 2021, PhD Dissertation

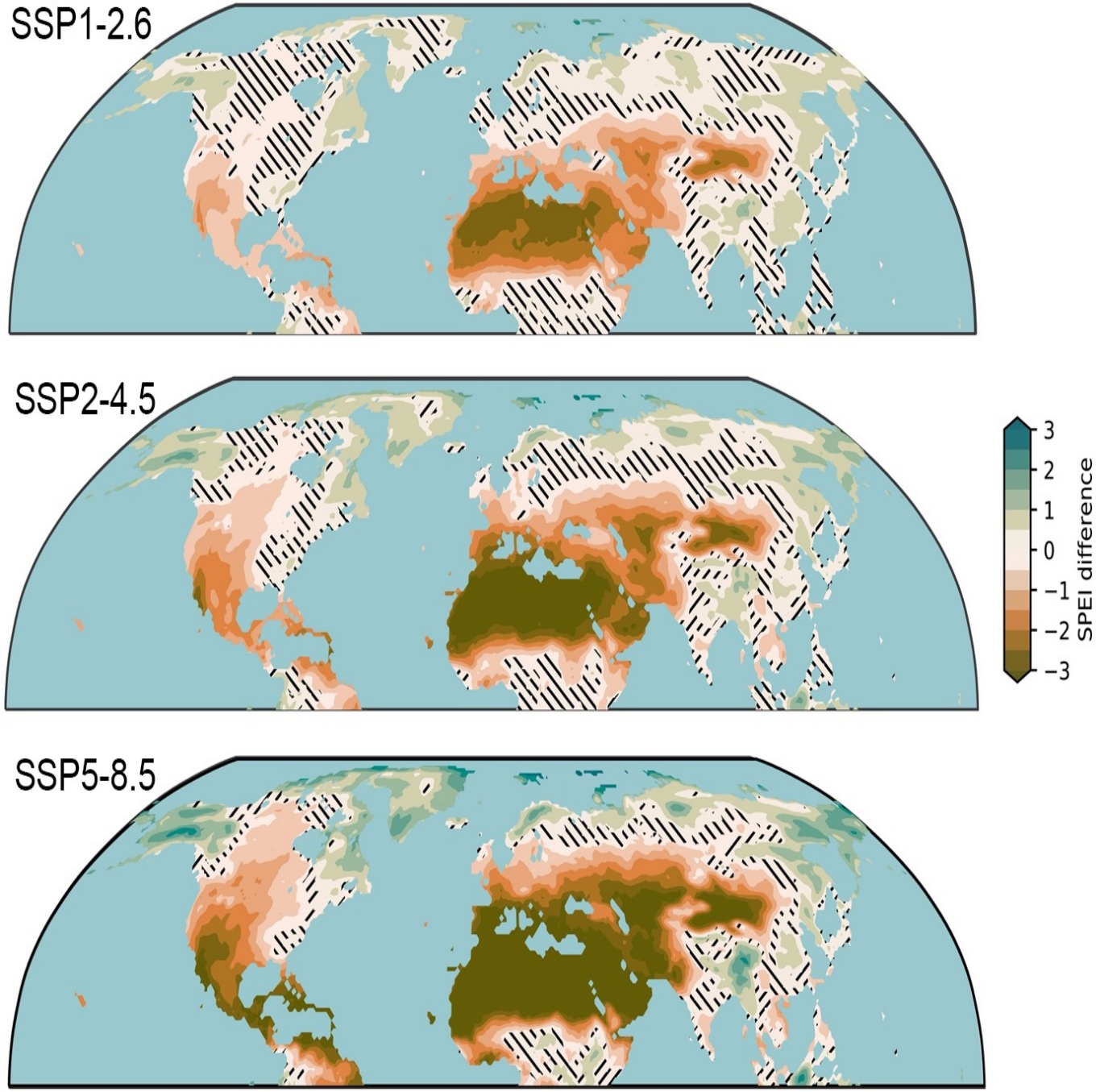


https://www.nature.com/articles/s41612-021-00218-2/figures/3



2002 Drought in the US & Canada

Martinez et al., 2021, PhD Dissertation



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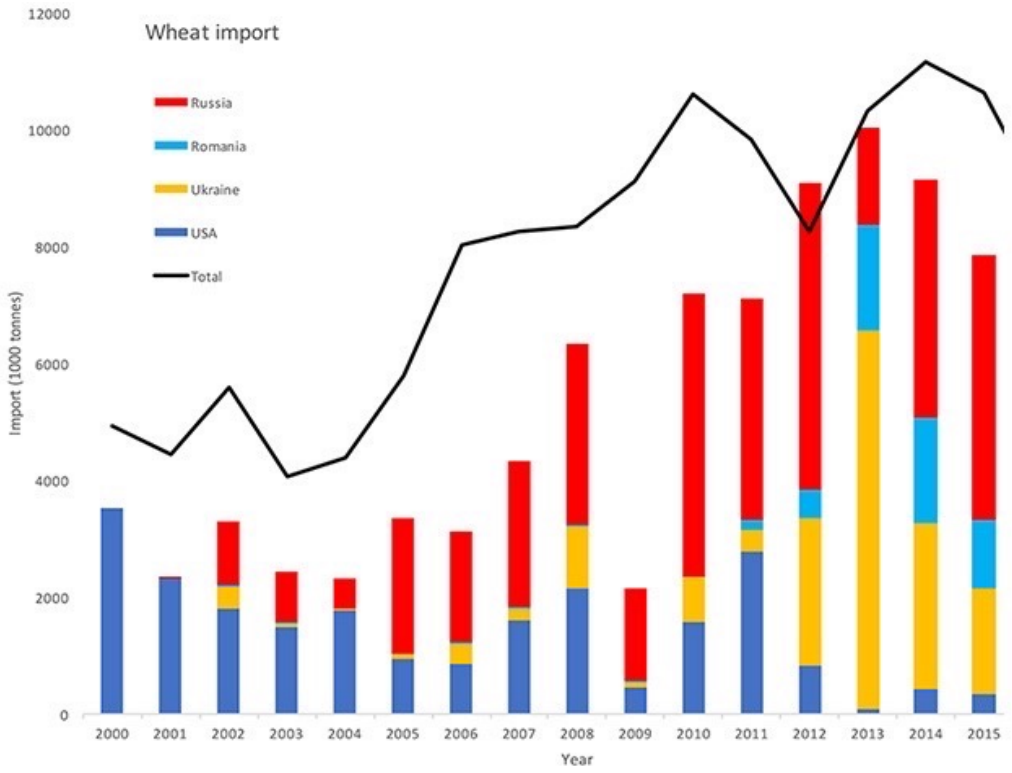
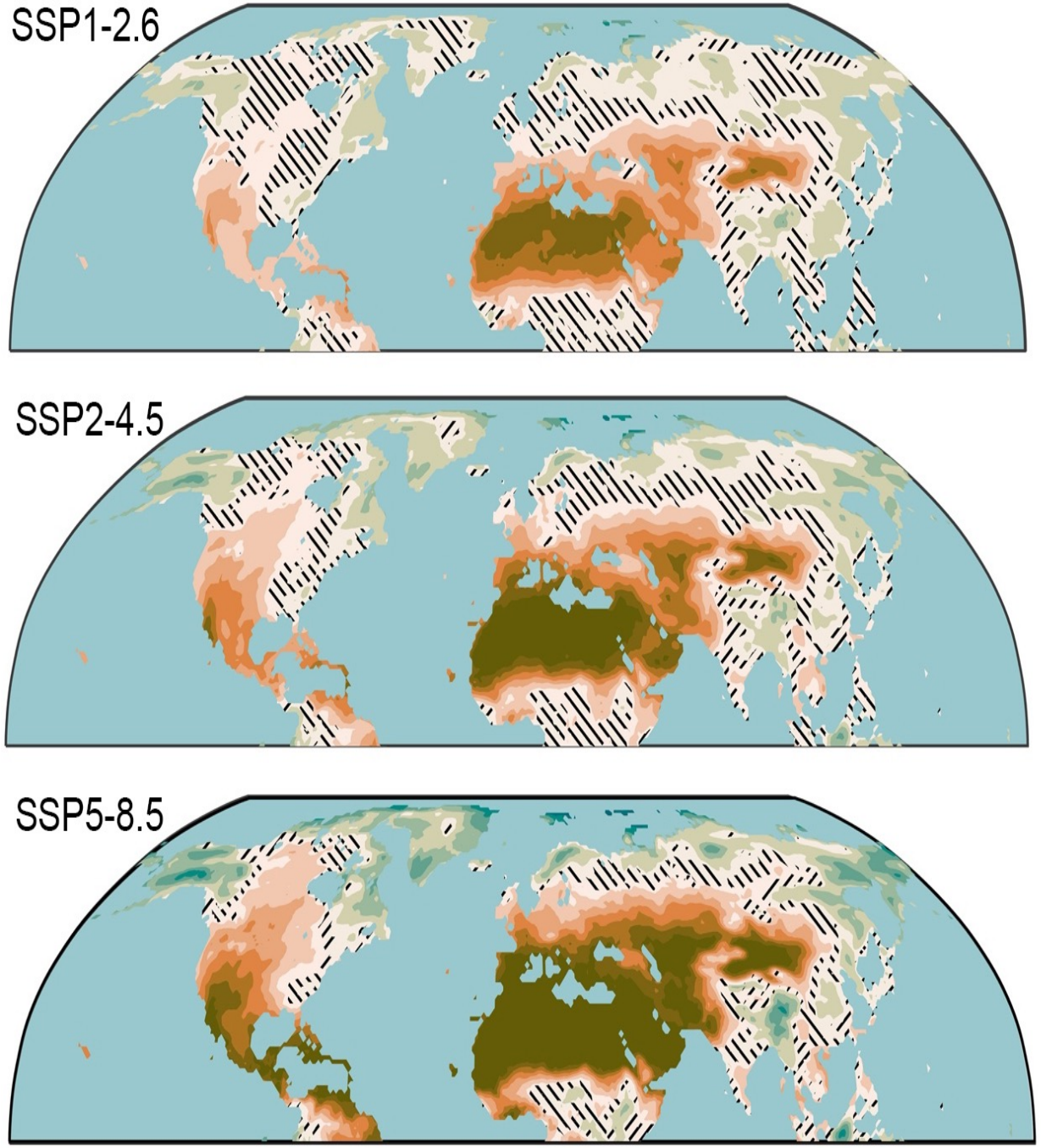


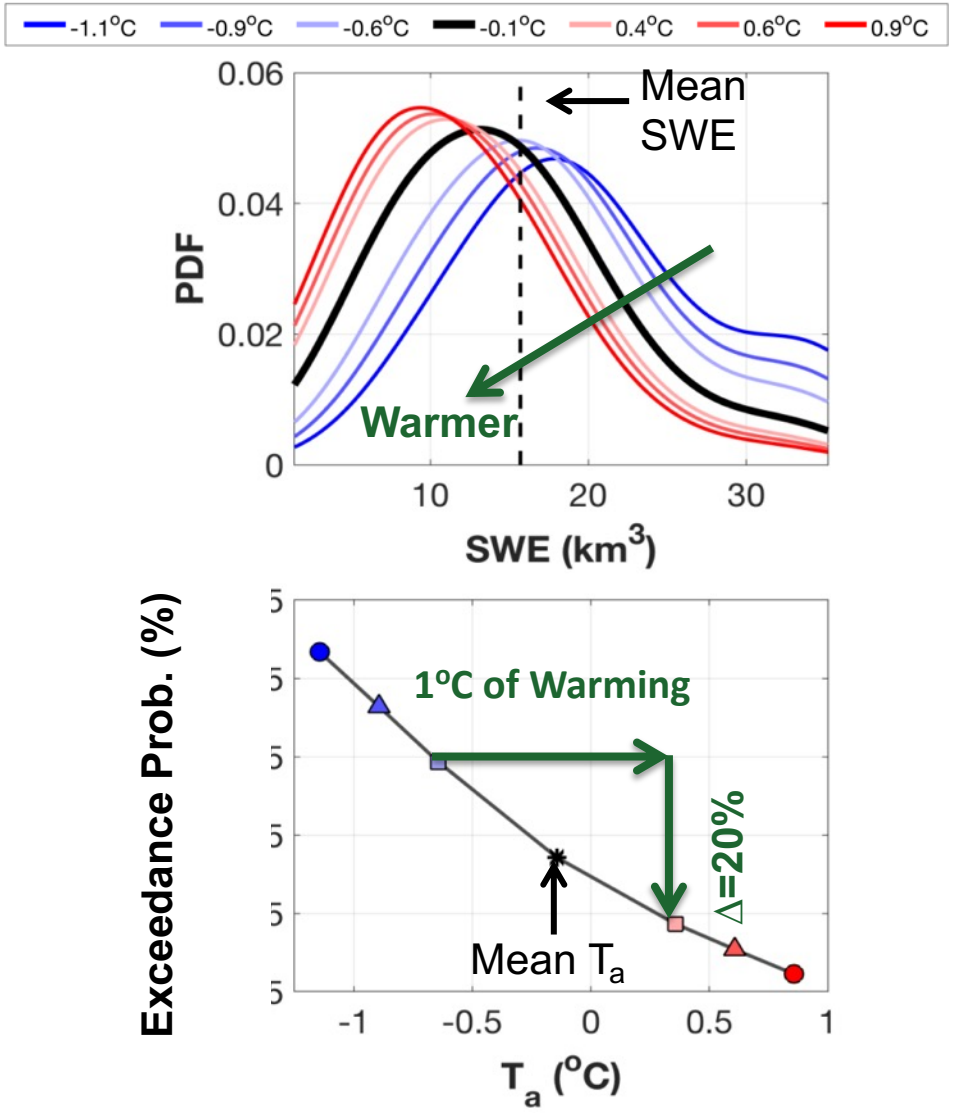
Martinez et al., 2021, PhD Dissertation



https://www.nature.com/articles/s41612-021-00218-2/figures/3

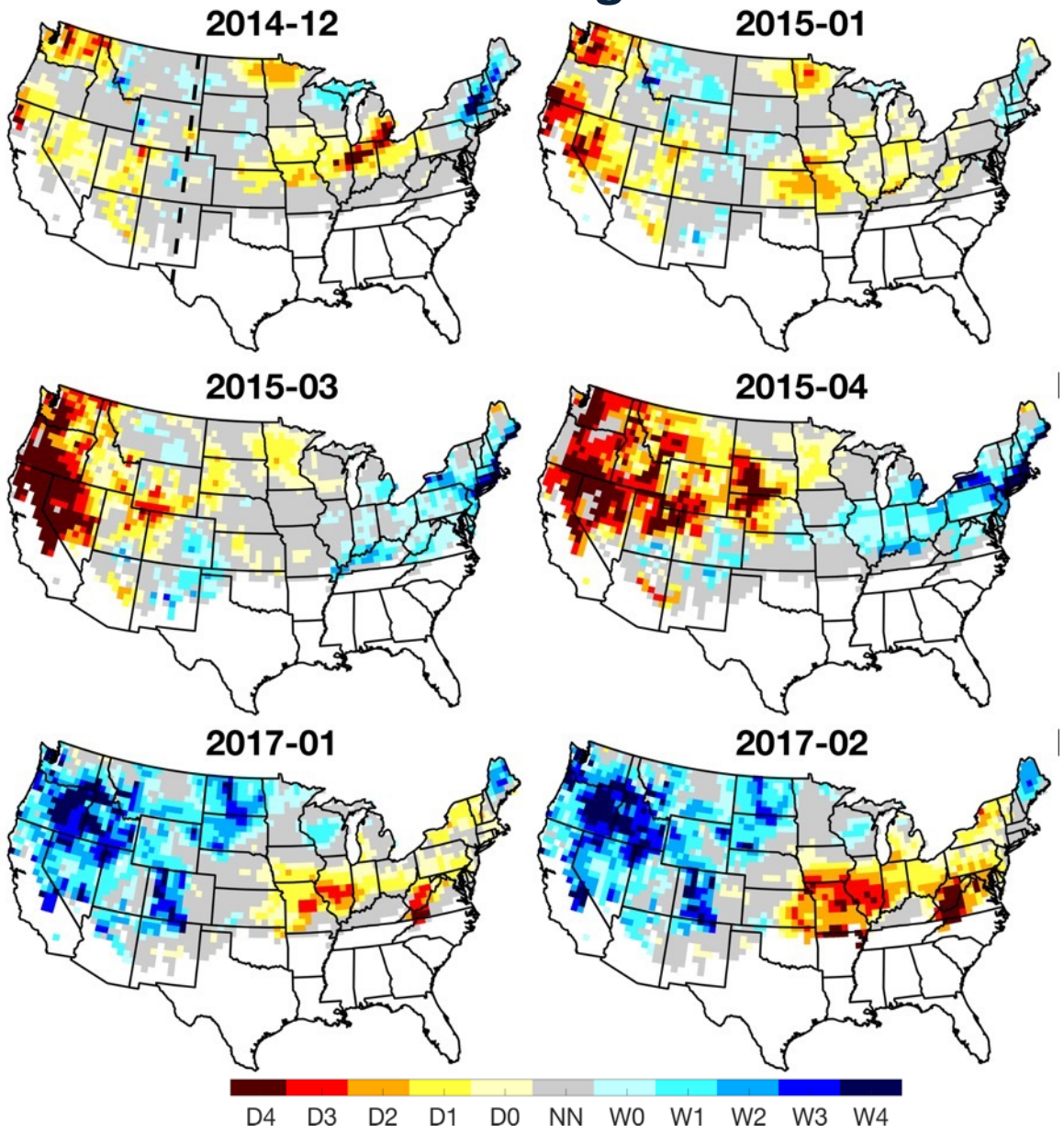
Snow-Temperature-Fire Dynamics

Mountain Snowpack Response to Different Levels of Warming



Huning & AghaKouchak, 2018, *PNAS*

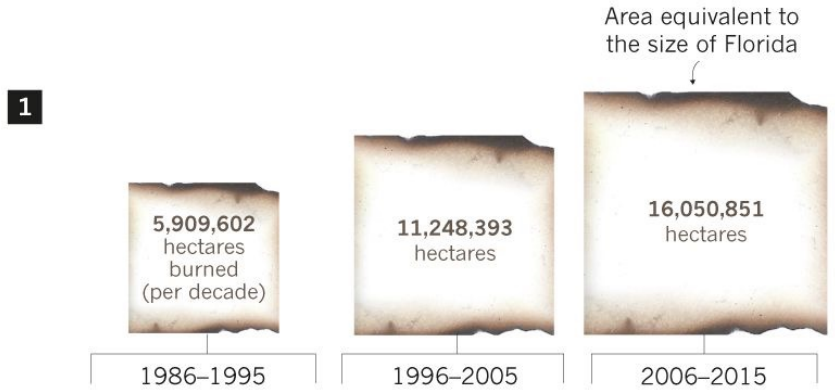
Snow Drought



Huning & AghaKouchak, 2020, *PNAS*

MORE FIRES, MORE SNOWMELT

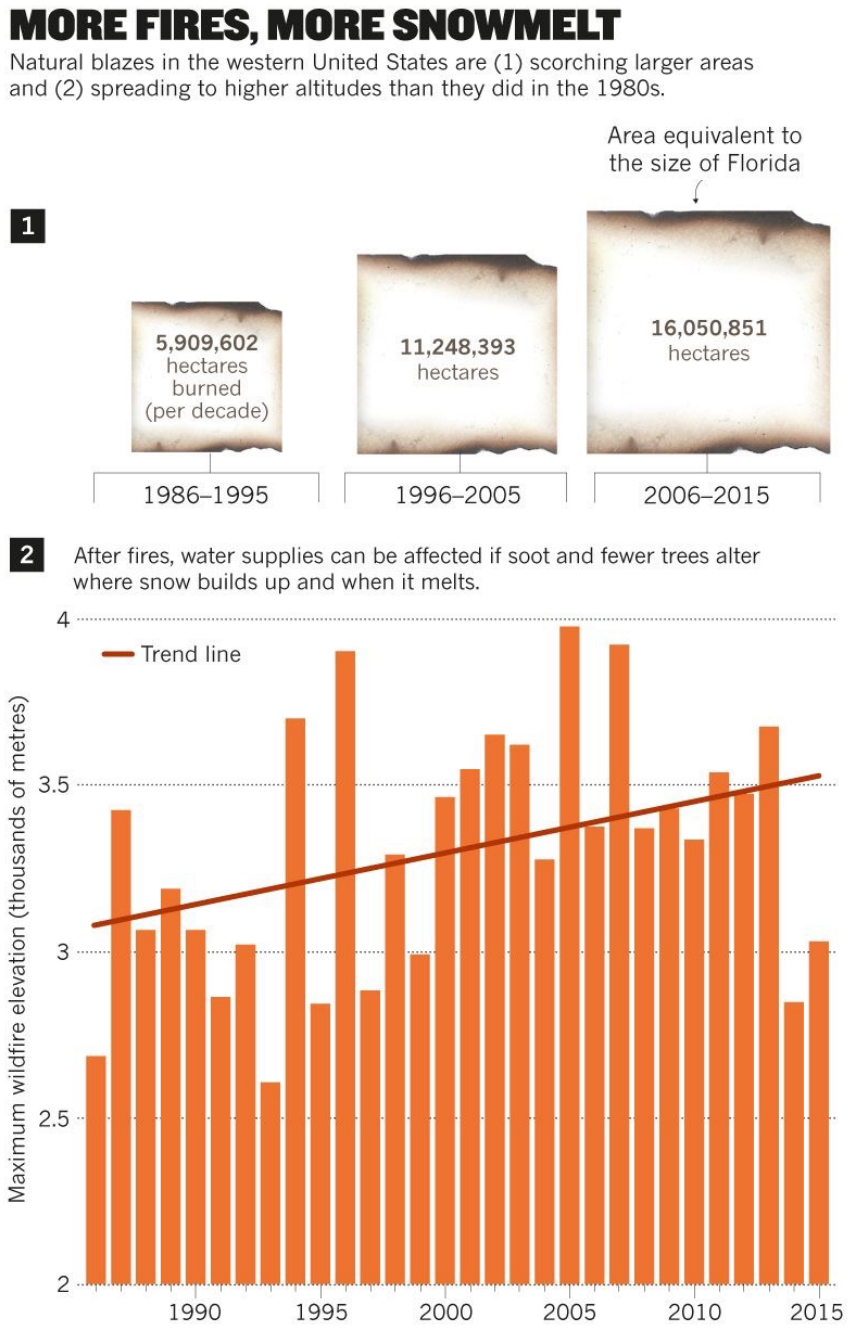
Natural blazes in the western United States are (1) scorching larger areas and (2) spreading to higher altitudes than they did in the 1980s.



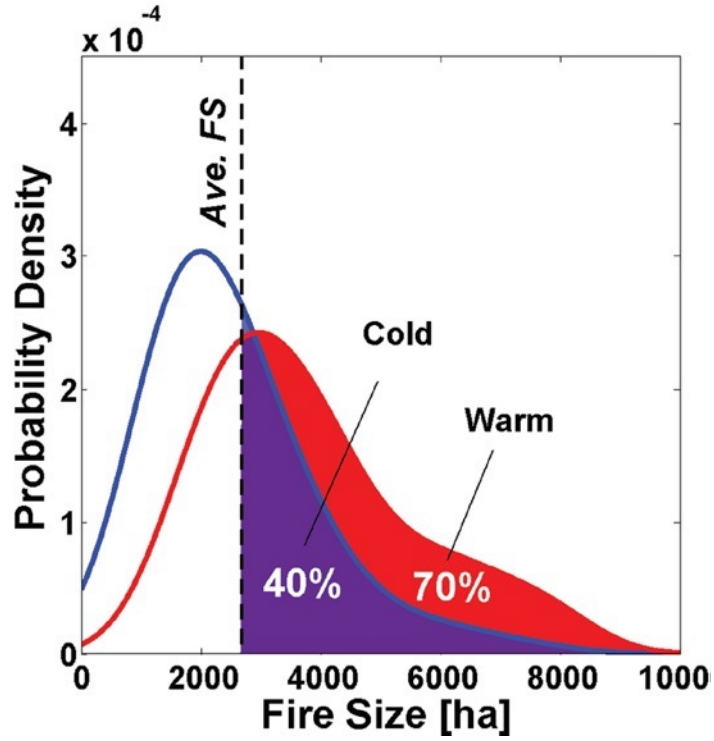
2 After fires, water supplies can be affected if soot and fewer trees alter where snow builds up and when it melts.

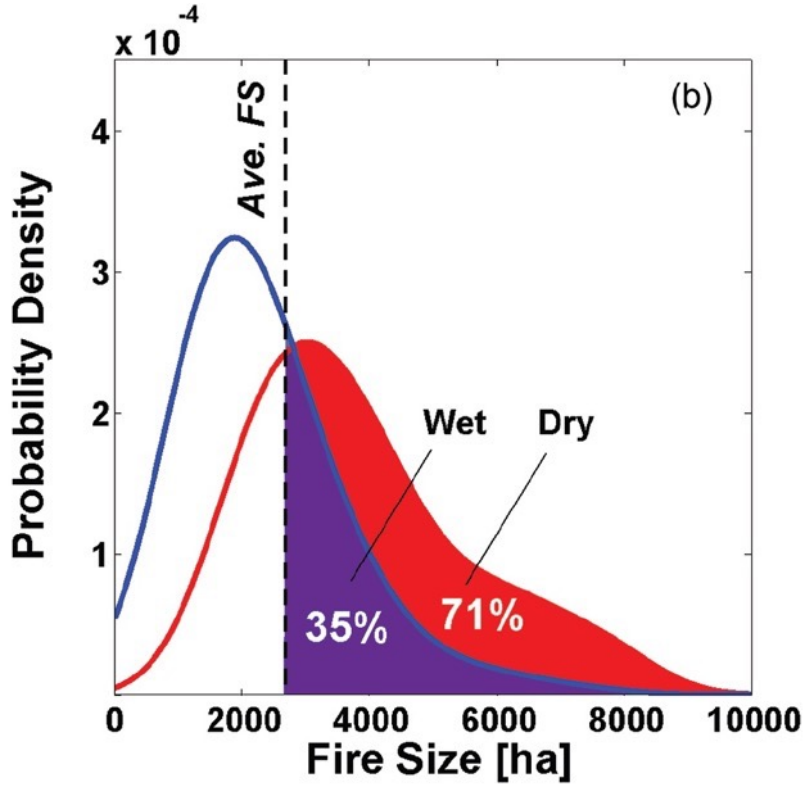
AghaKouchak et al., 2018, *Nature*

Climate Drivers of Wildfires

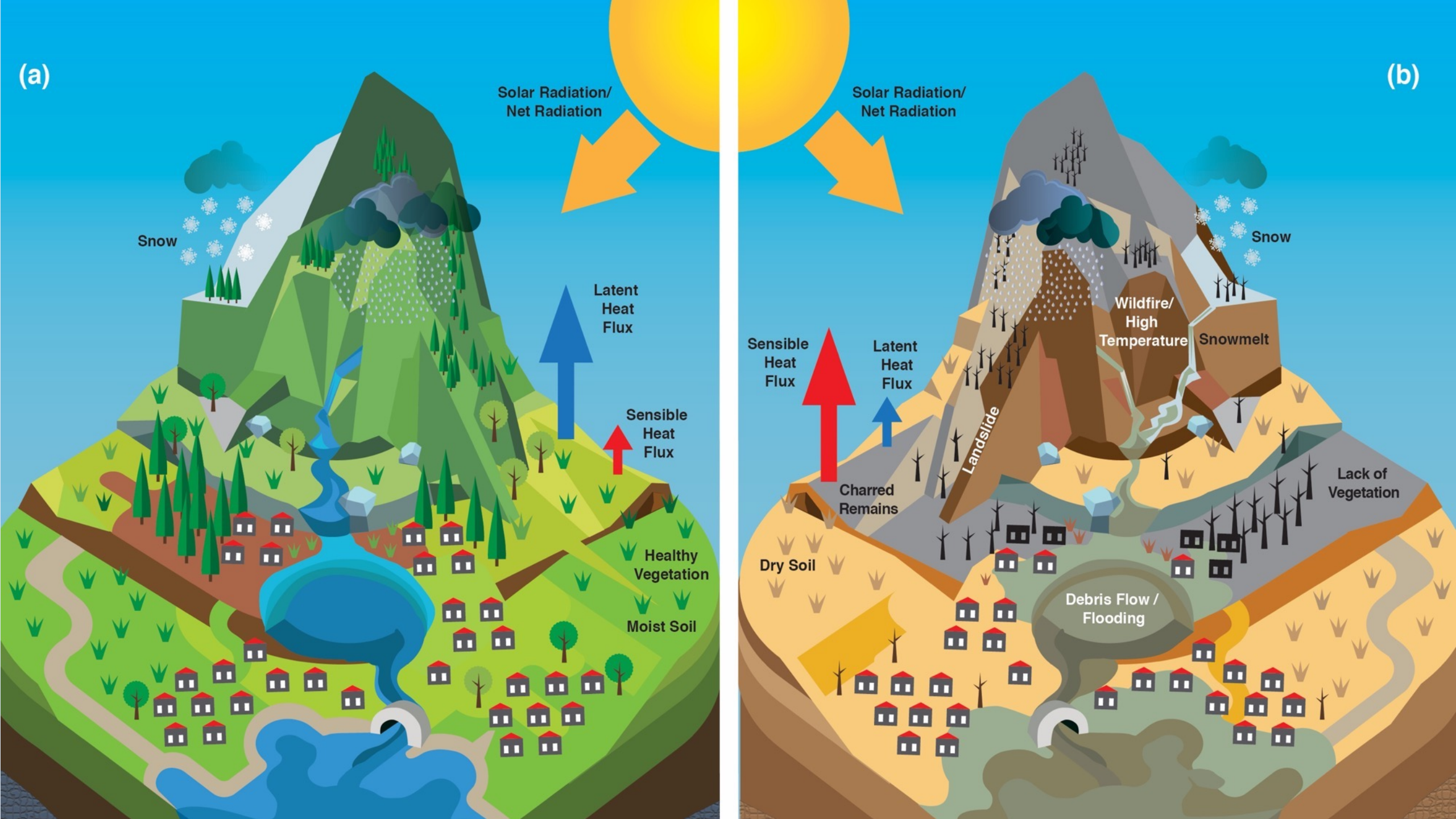


AghaKouchak et al., 2018, *Nature*





Madadgar et al., 2021, *SERRA*


(a)
Solar Radiation/
Net Radiation
Snow
Latent
Heat
Flux
Sensible
Heat
Flux
Healthy
Vegetation
Moist Soil
(b)
Solar Radiation/
Net Radiation
Snow
Wildfire/
High
Temperature
Snowmelt
Sensible
Heat
Flux
Latent
Heat
Flux
Landslide
Charred
Remains
Lack of
Vegetation
Dry Soil
Debris Flow /
Flooding

Final Remarks

- Ignoring the 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., affecting snow drought and wildfires.
- Current models developed for compound events, often fail when used for modeling cascading hazards.
- We are exploring bottom-up learning concepts for analysis of cascading hazards, and methods for evaluating infrastructure risk and performance in a warming climate.

Questions?

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