On updating climate extremes related engineering design values in a warming climate

M.A. Ben Alaya[1], F. Zwiers[1] and X. Zhang[2]

[1]Pacific Climate Impacts Consortium, University of Victoria,

PO Box 1700 Stn CSC, Victoria, BC V8W2Y2, Canada

[2] Climate Research Division, Environment and Climate Change Canada, Toronto,

ON M3H 5T4, Canada

OUTLINES

1- Probable maximum precipitation

2- The uniform risk approach

3- Statistics of extremes: a distinct problem formulation

OUTLINES

1- Probable maximum precipitation

2- The uniform risk approach

3- Statistics of extremes: a distinct problem formulation

Probable maximum precipitation (PMP)

- Rational engineering solution, to provide a possible **magnitude of extreme precipitation** values that can be used by engineers as **a practical upper limit** where scientific knowledge does not provide the desired guidance.

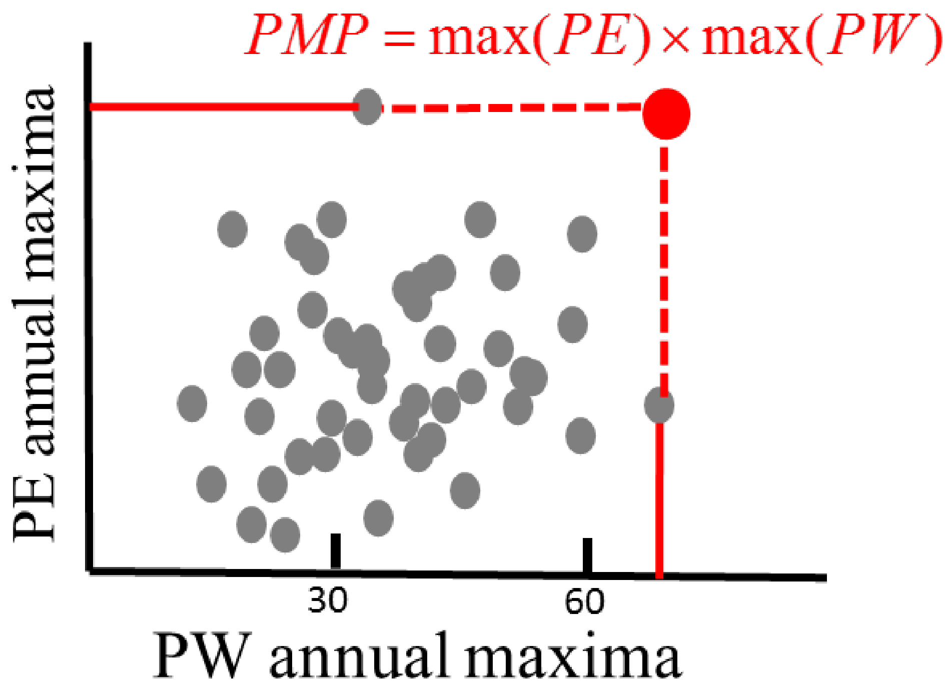
- A key parameter to calculate the **probable maximum flood (PMF)** that is often used for dam safety and civil engineering purposes.

Probable maximum precipitation (PMP)

- Precipitable water: the depth of water that would be produced at a given location if all the water in the atmospheric column above that location was precipitated as rain.

- Precipitation efficiency: is defined as the ratio of actual precipitation amount to the actual PW.

Moisture maximization method

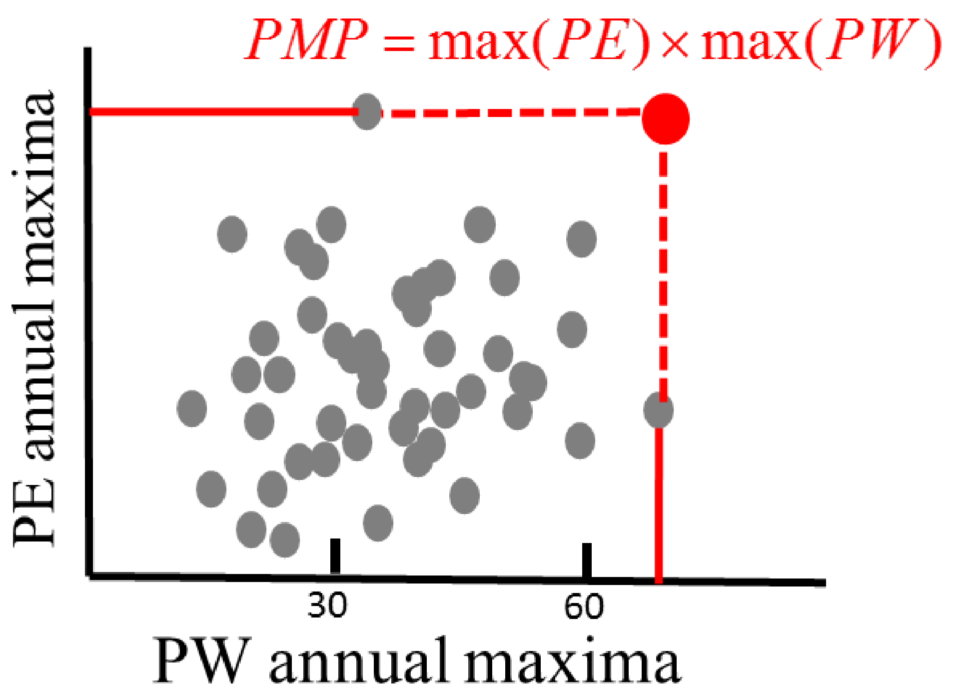


Context: Climate change

- The atmosphere's water holding capacity is expected to increase at the Clausius-Clapeyron (C-C) rate by about 7% per 1 °C warming.

- Such an increase **may** lead to more intense extreme precipitation events and thus **directly affect the probable maximum precipitation (PMP)**.

Moisture maximization method



Objective

The use of two Canadian RCMs, CanRCM4 and CRCM5 to study how the probable maximum precipitation will change in a warming Climate.

Concerns

1. The deterministic nature of moisture maximization approach.
(Inability to evaluate the uncertainty in PMP estimates)

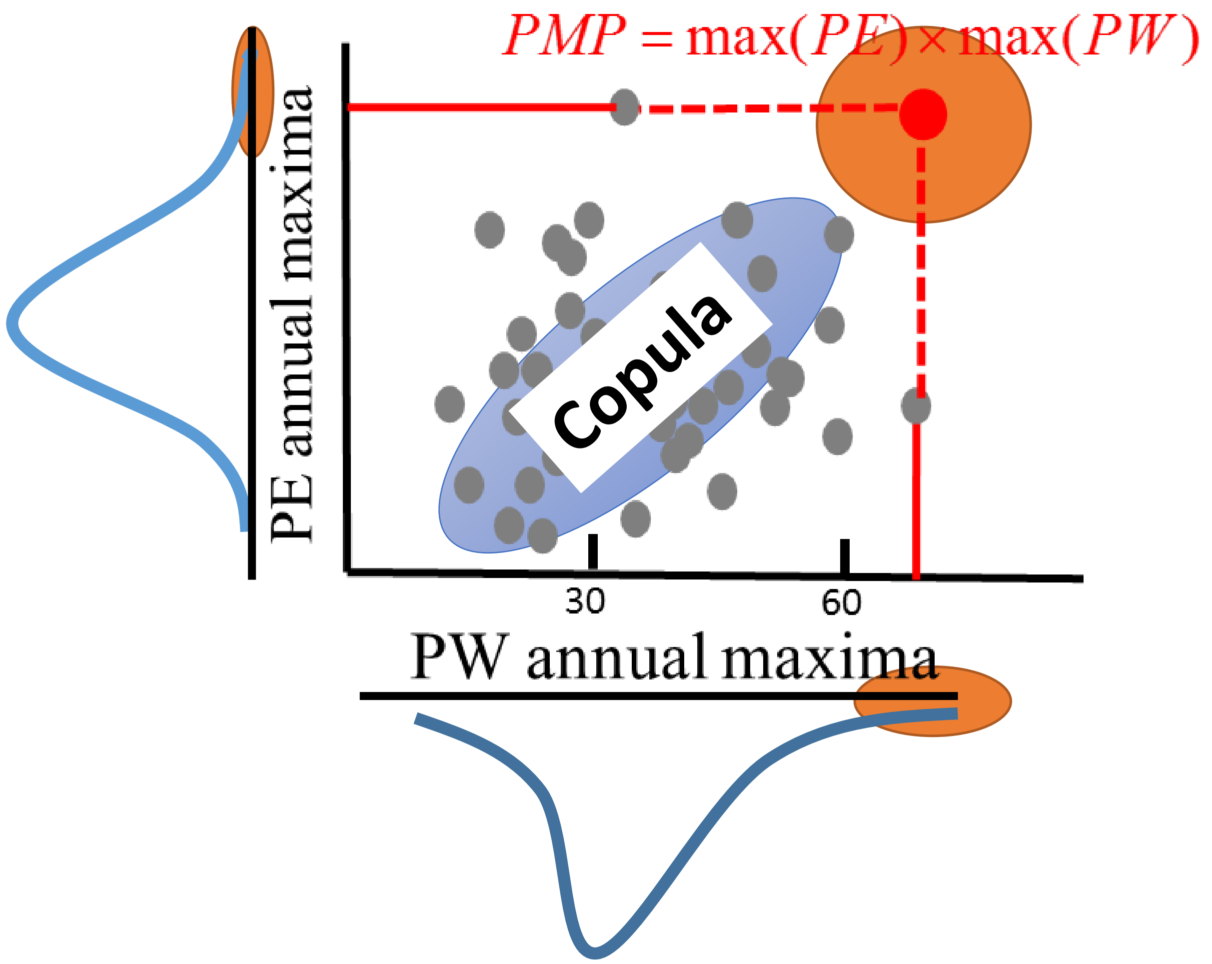
2. The ability of RCMs to produce reliable PMP estimates needs to be assessed.

3. Moisture maximization needs to be adapted for non-stationary conditions

Concern 1: Inability to evaluate the uncertainty in PMP estimates.

Method

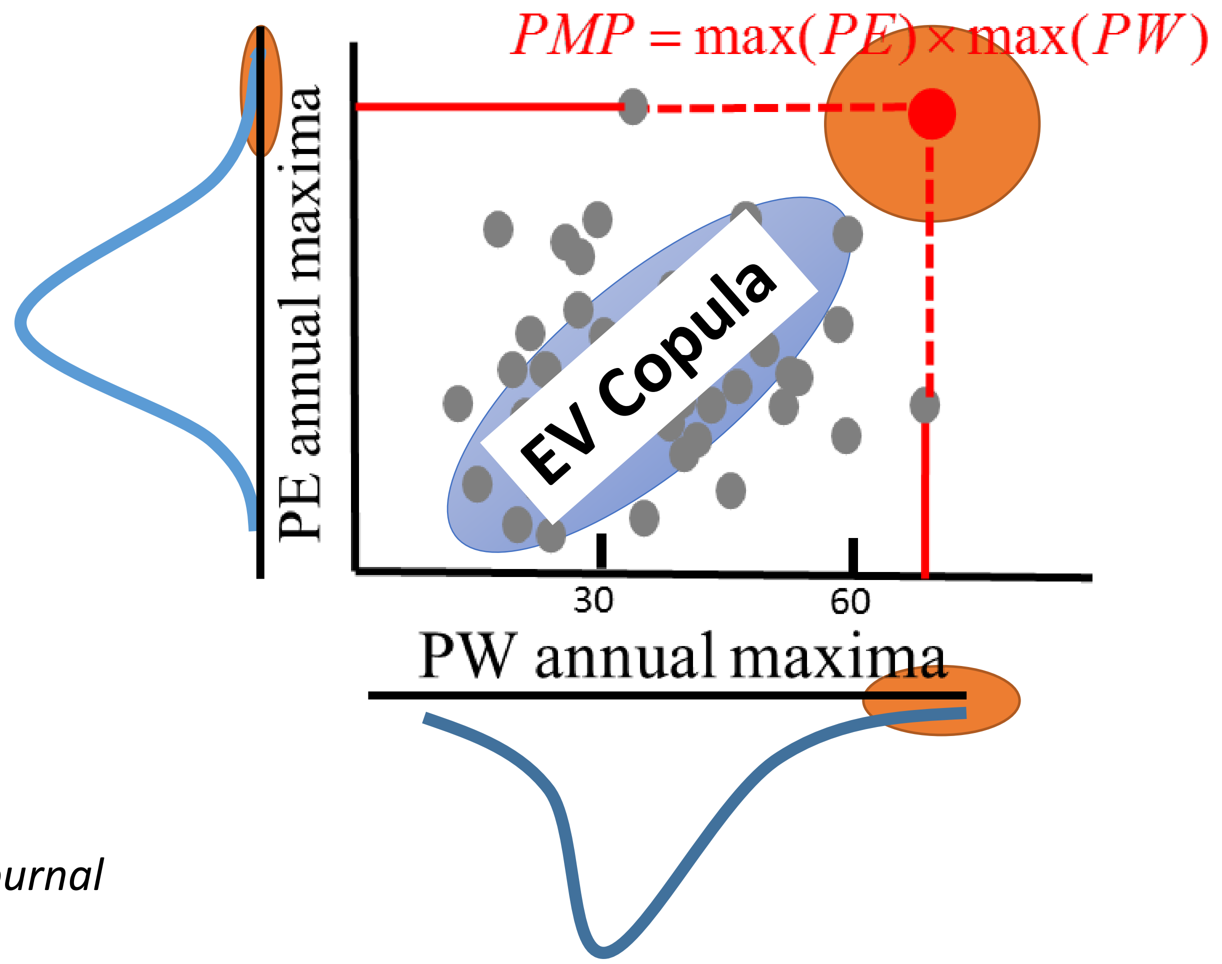
A probabilistic framework based on a bivariate extreme value distribution to aid in the interpretation and the uncertainty evaluation of PMP estimates



Concern 1: Inability to evaluate the uncertainty in PMP estimates.

Method

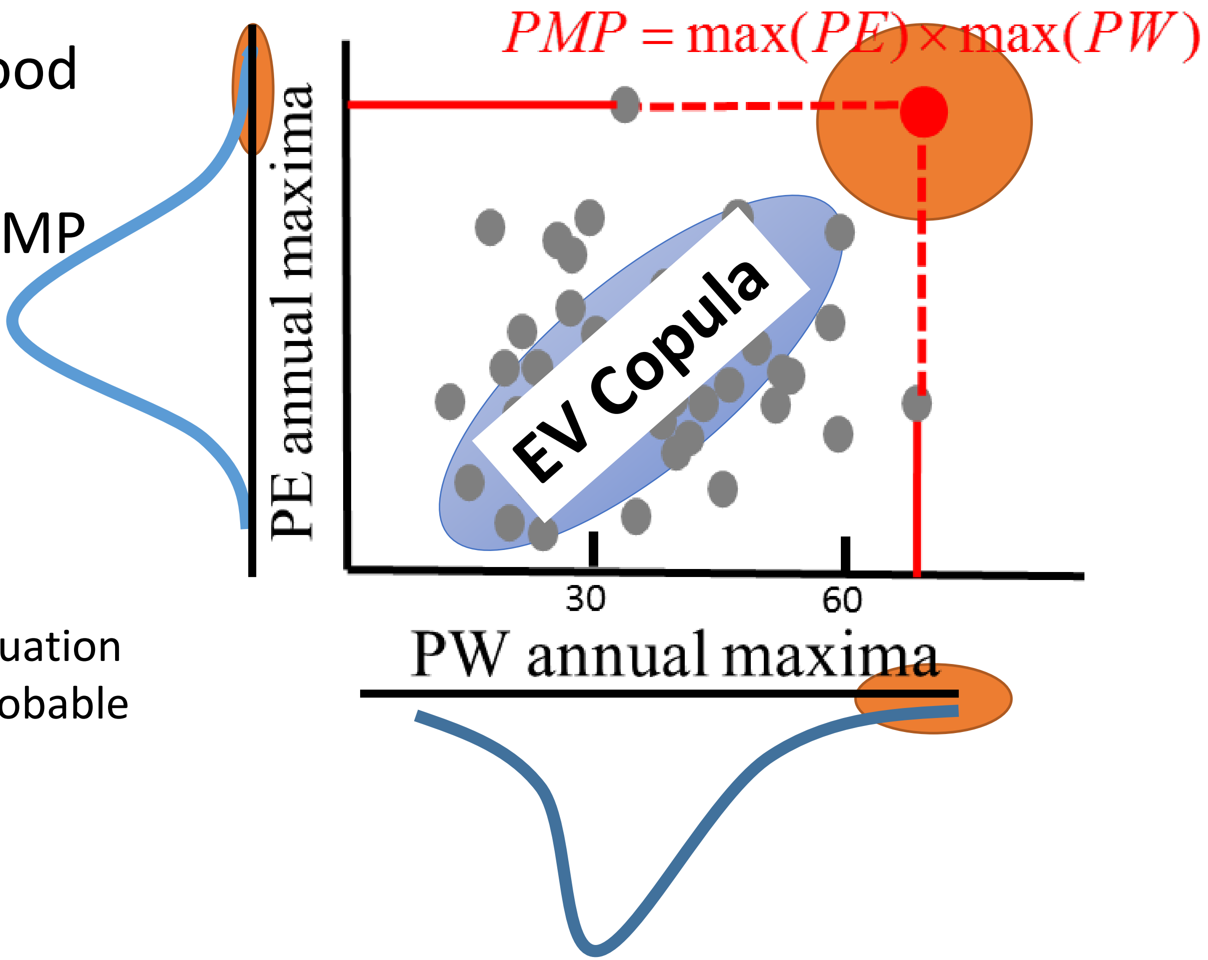
A probabilistic framework based on a bivariate extreme value distribution to aid in the interpretation and the uncertainty evaluation of PMP estimates



Ben Alaya, M., F. Zwiers, and X. Zhang, 2018a: Probable Maximum Precipitation: Its Estimation and Uncertainty Quantification Using Bivariate Extreme Value Analysis. *Journal of Hydrometeorology*, **19,** 679-694

Concern 2 The ability of RCMs to produce reliable PMP estimates needs to be assessed

This approach allowed us to confirm the good performance of the two Canadian RCMs, CanRCM4 and CRCM5 to provide reliable PMP values (Ben Alaya et al. 2019).



Ben Alaya, M. A., F. W. Zwiers, and X. Zhang, 2019b: Evaluation and comparison of CanRCM4 and CRCM5 to estimate probable maximum precipitation over North America. *Journal of Hydrometeorology*, **20,** 2069–2089.

Concern 3: Moisture maximization needs to be adapted for non-stationary conditions

Method

We have adapted our probabilistic framework for non-stationary conditions by **including temperature as a covariate** (Ben Alaya et al. 2020).

Ben Alaya, M., F. Zwiers, and X. Zhang, 2019a: Probable maximum precipitation in a warming climate over North America in CanRCM4 and CRCM5. *Climatic Change*, 1-19.

Probable maximum precipitation in a warming Climate

Data

- Output from the CanRCM4 and CRCM5 regional climate model (driven by CanESM2 global model) at 0.44° spatial horizontal resolution
- Period 1951-2100: combining historical and RCP 8.5 future simulation
- Domain: North America
- Total precipitation and precipitable water (vertically integrated water vapor through the atmospheric column), both at a 6-hourly temporal resolution.

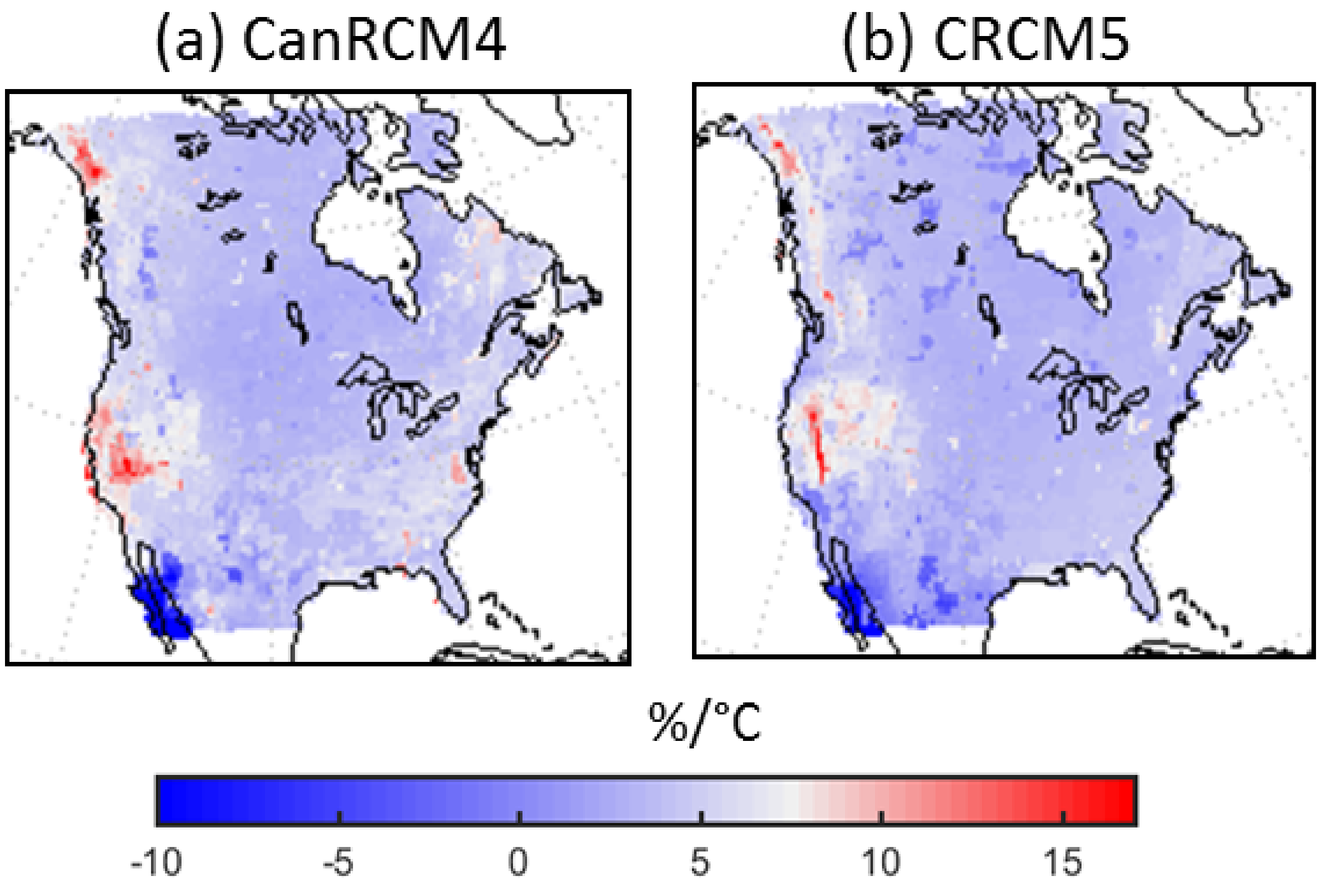
Probable maximum precipitation in a warming Climate

Application: non-stationary PMP

- Covariate: anomalies of annual mean near surface air temperature from CanESM2.
- Covariate on either only the location parameter, or on both the location and scale parameters separately for annual maxima of PE and PW.
- A stationary dependence structure between the two GEV distributions.
- The likelihood-ratio test (LRT) is used to test whether the introduction of the covariate significantly improves the fit

Results: Probable maximum precipitation in a warming Climate

Rate of change of mean PMP for 6-hour accumulations in % per 1°C near surface warming in (a) CanRCM4 and (b) CRCM5. White shading corresponds to the Clausius-Clapeyron rate (approximately 7%/°C).



OUTLINES

1- Probable maximum precipitation

2- The uniform risk approach

3- Statistics of extremes: a distinct problem formulation

Context: Statistical Frequency Analysis

- The need for accurate estimation of the occurrence of hydrometeorological extremes
- The occurrence of extremes are often expressed in terms of return level (RL) value
- Uniform risk approach: estimates of **extreme precipitation or wind loads** with very low annual probabilities of exceedance, corresponding to **return periods of up to 2000-years are required**
- The common approach in hydrology and climatology involves the use of **statistical inferences**

The typical procedure

1-Try out many parametric families of **distributions** or **probability models**

2- Estimate the parameters using some statistical methods

3- Choose the one that **best fits** the data (**AIC**, **BIC, ME** and **RMSE, ….)**

4- Use the tail of the fitted model to **estimate quantiles** with very low exceedance probabilities

Can the typical procedure go wrong ?

(1)Simulate a sample of **n=100 independent** values from a known **lognormal(1,2)**.

(2) **Guessing** which one from 2 possible suspects is responsible for generating the data:

Suspect 1:The true lognormal model

Suspect 2: A Gumbel model fitted to the data using the MLE method.

(3) We use 4 clues: AIC, BIC, RMSE and MAE by taking the empirical quantile 0.9 as reference

(4) Repeat steps (1) ,(2) and (3) 1000 times

Percentage of wrong choices

- AIC: 100%
- BIC: 100%
- RMSE : 78%
- MAE: 55%

In a great mystery story, the most obvious clues often lead to the wrong suspect

Issues with the Typical procedure

- Chance to *overfit* the data
- No efforts to quantify and reduce model selection bias
- Confusion between characterizing observed variability and quantifying uncertainty
- Optimism Principle (Picard and Cook (1984)): inferences from the final model tend to be biased, with uncertainties underestimated, and statistical significance overestimated
- The evaluation using empirical quantiles is not enough

We need exploratory research

Tong, C., 2019: Statistical inference enables bad science; **statistical thinking** enables good science. The American Statistician, 73, 246-261.

- A deep statistical thinking is required to enable good science
- The first step (which is the most important one) is a hard detective Job
- Find the first right clues that are specific to solve problem at hand

We need exploratory research

1- We look for an approximate answer to the right question

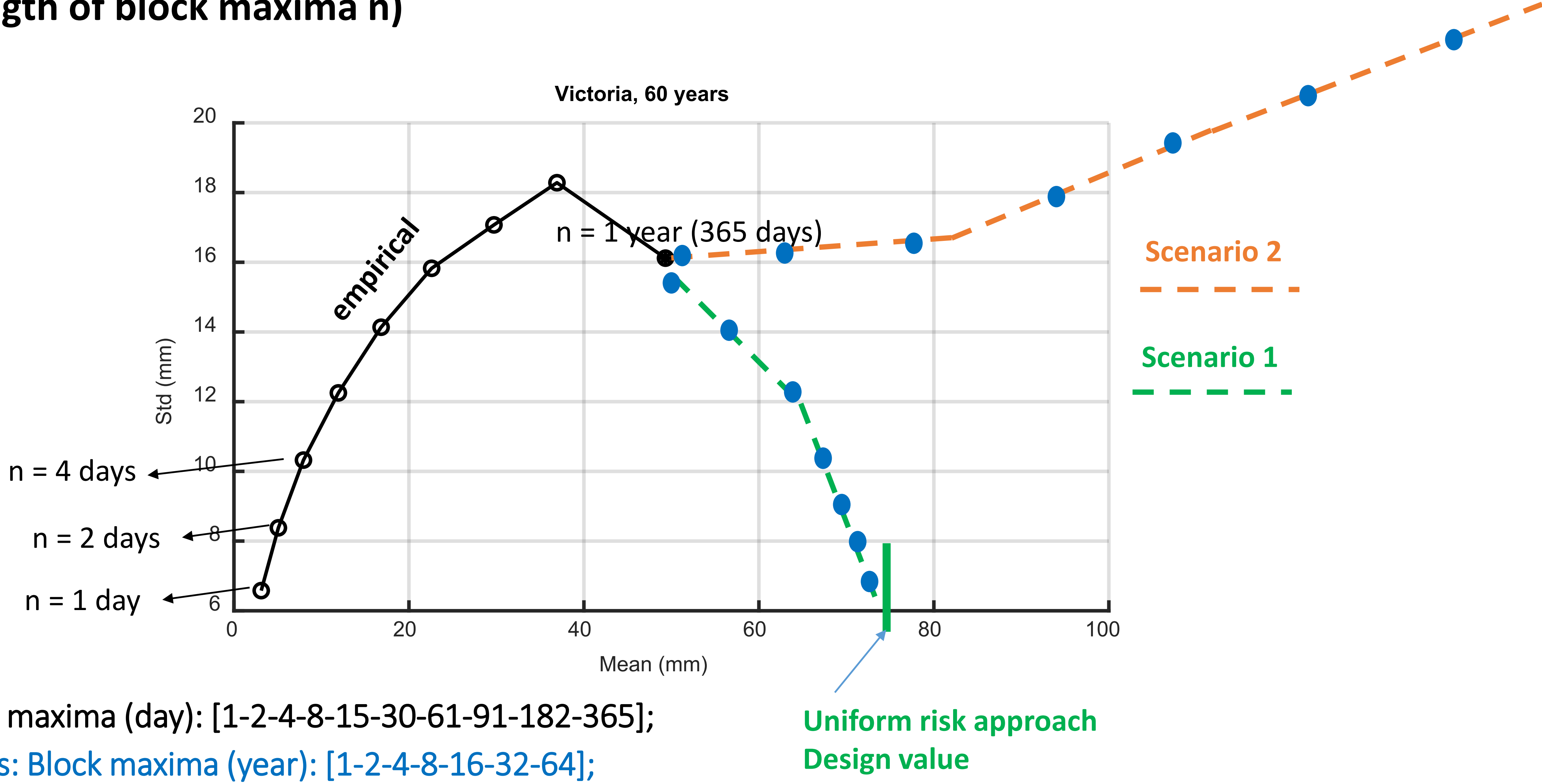
How do largest values get larger?

2- A precise definition of the distribution of largest values is required

Block maxima setting (Example: the distribution of maxima of 10 values is larger than the distribution of maxima of 5 values)

3- Think closely about how the distributions of block maxima behave for increasing block length n

❖ Precipitation: Relation (variances, mean, length of block maxima n)

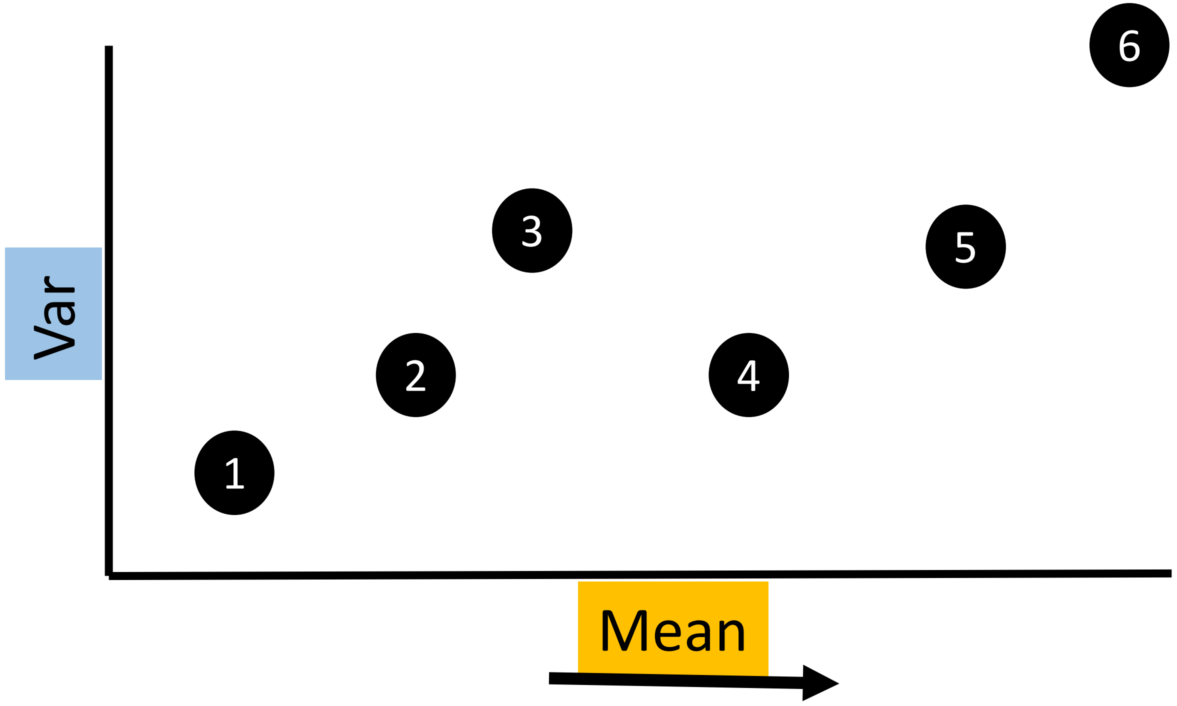


O Block maxima (day): [1-2-4-8-15-30-61-91-182-365];

● Guess: Block maxima (year): [1-2-4-8-16-32-64];

How the distributions of block maxima behave with increasing block length

- Relation (variances, mean, length of block maxima n)
- The mean increases with n
- The variance affects the speed at which the mean increases

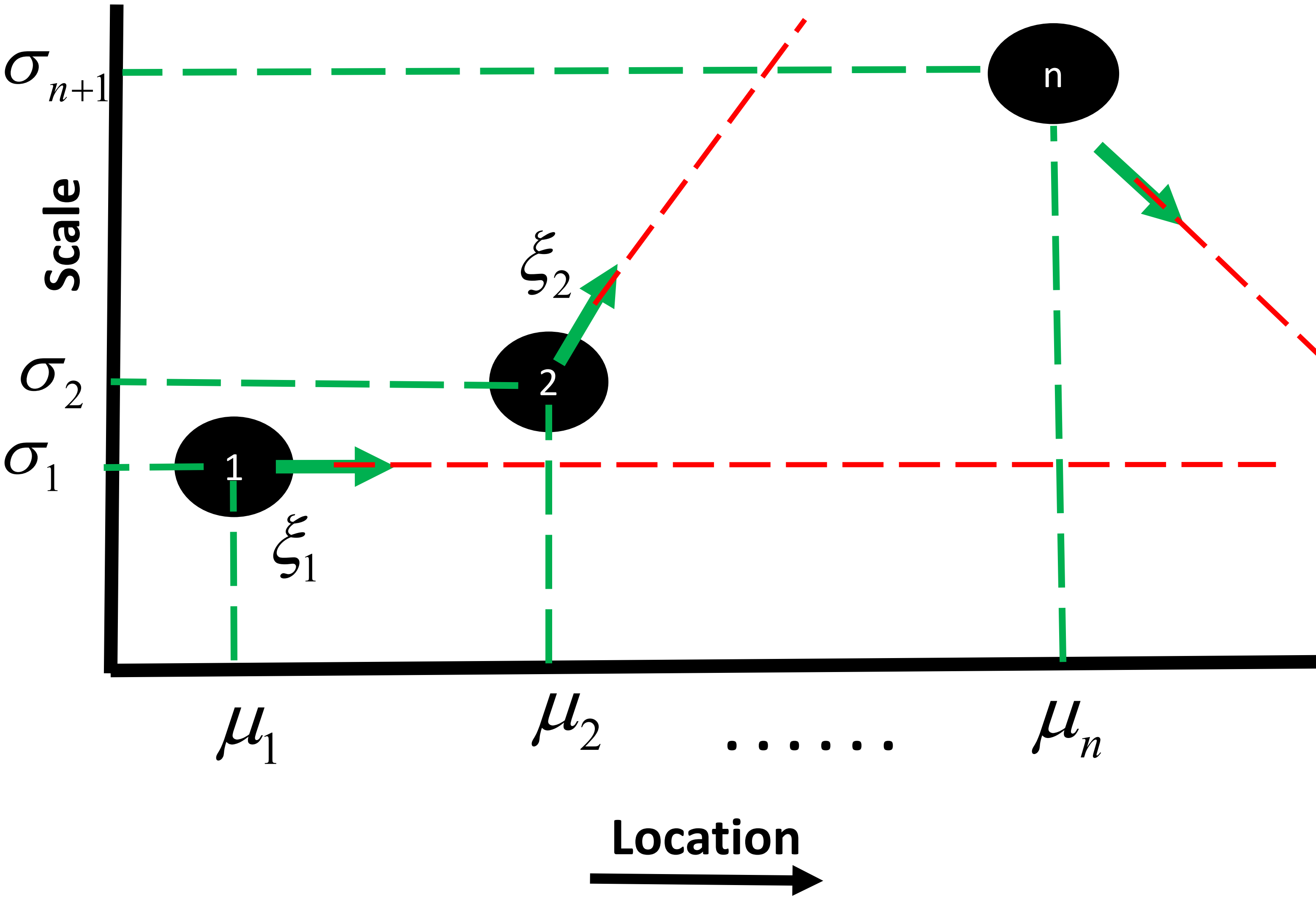


We don’t know how the variance changes with increasing block length n

We need an instrument

- ❖ **A key trick: Globally curved, locally linear**
- ❖ **Basic concept (the fundamental idea): the variance changes linearly at a stable rate for all n**

Concept of max-stability (Fisher and Tippett 1928)



$$GEV(\mu, \sigma, \xi)$$

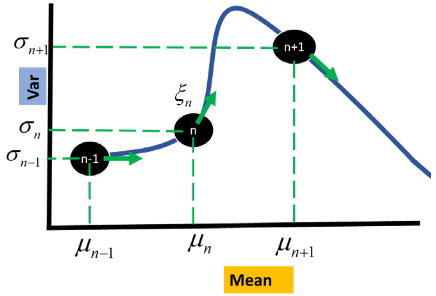
The concept of max-stability

An instrument for scientific investigations (Fisher and Tippett 1928)

To reduce the complexity and draw a picture about the only essential feature of how largest values get larger

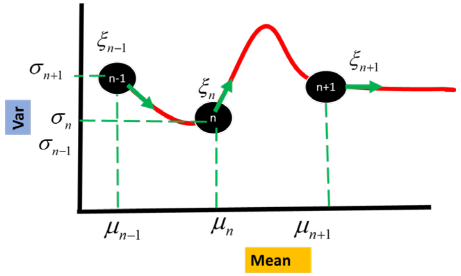
Picture of the real feature (fundamental knowledge)

Complicated observations



Compare

Model/theory



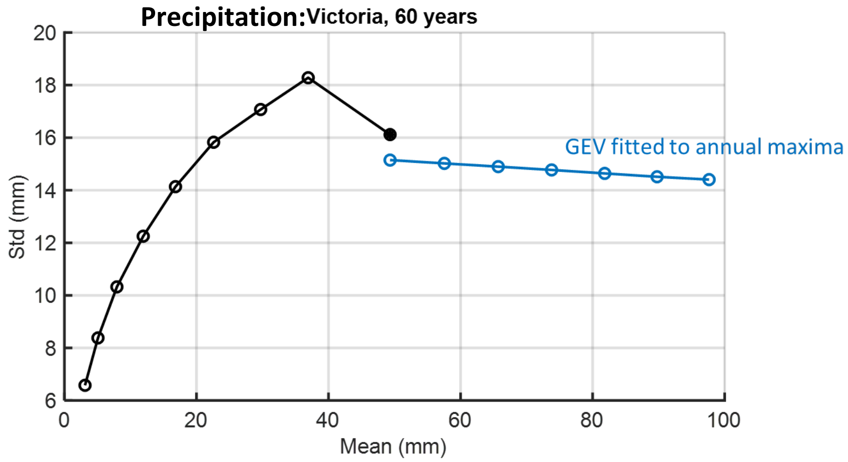
Picture of Model/theory feature

helps

- avoiding statistical pitfalls
- reducing model selection bias

A theory for extrapolation (Gumbel 1958): The GEV distribution

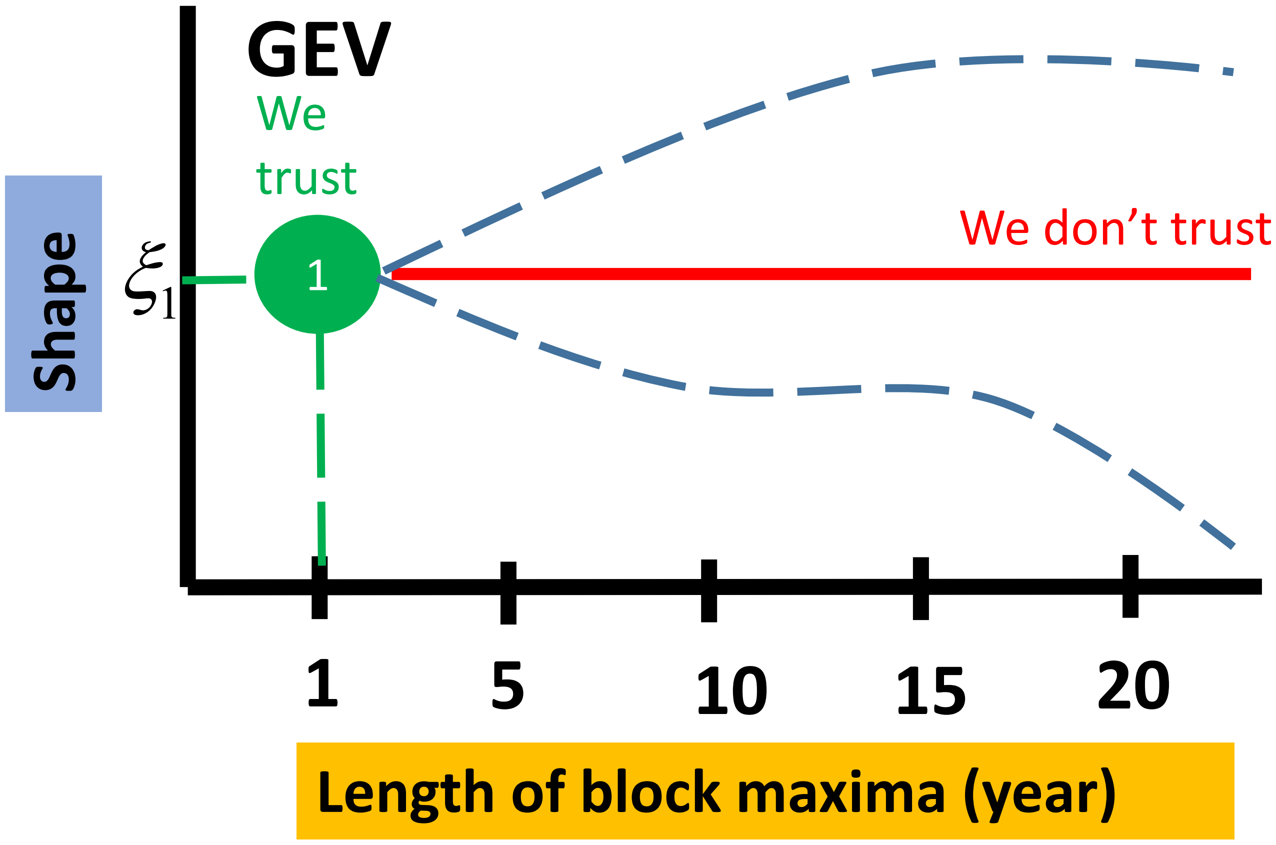
- A creative initial solution
- The extremal type theorem
- A success story in estimating precipitation and wind speed return levels



Block maxima (day): [1-2-4-8-15-30-61-91-182-365];

Extended Block maxima (year): [1-2-4-8-16-32-64];

Objective/Approach



We use max-stability as an instrument

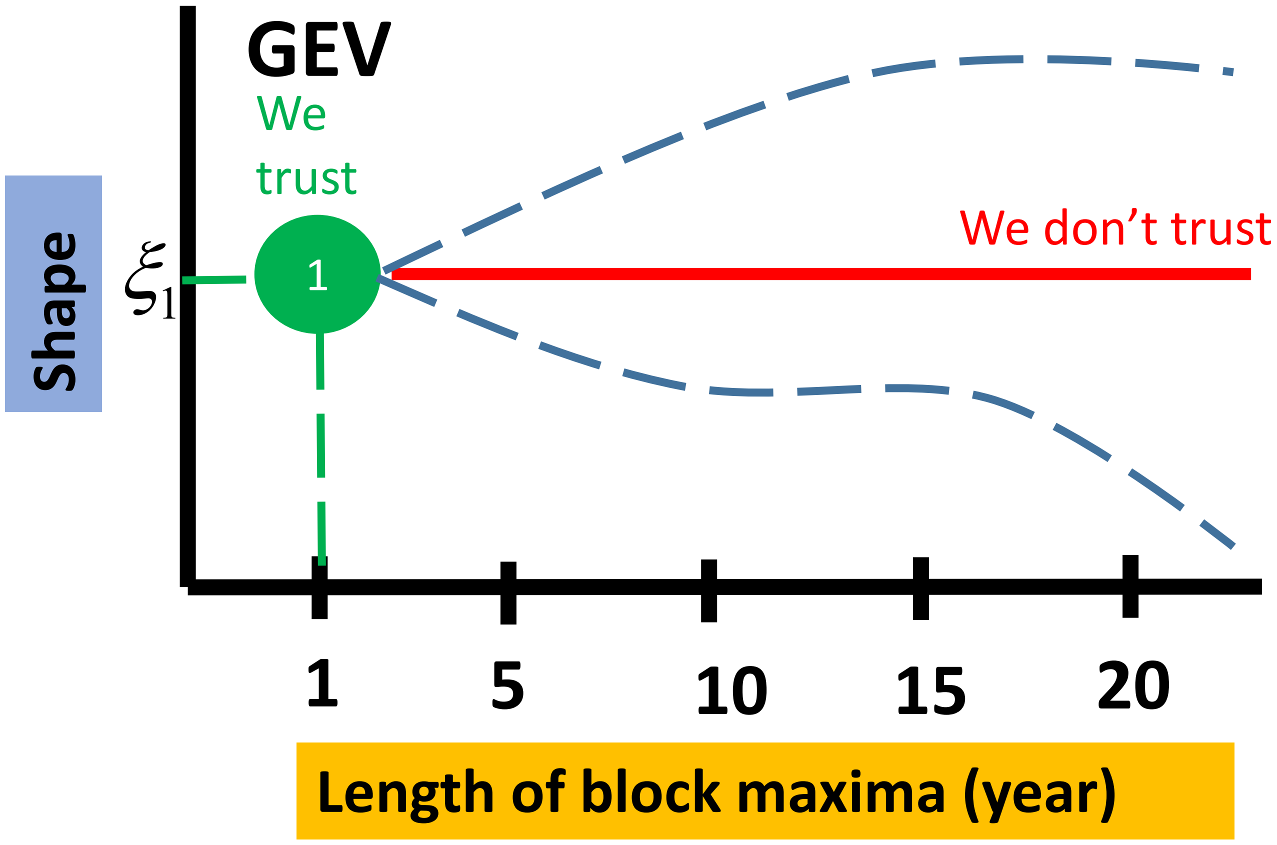
To assess the GEV fitted to hourly precipitation annual maxima for estimating long period return levels (1000-year events)

Data:

- Hourly precipitation
- large ensemble canRCM4, 0.44° spatial horizontal resolution (~50 km), over North America
- 35 simulations for the historical period 1951-2000.

1750 annual maxima of hourly precipitation

Objective/Approach



We use **max-stability as an instrument**

To assess the GEV fitted to wind speed annual maxima for estimating long period return levels (1000- and 2000-year events)

Data:

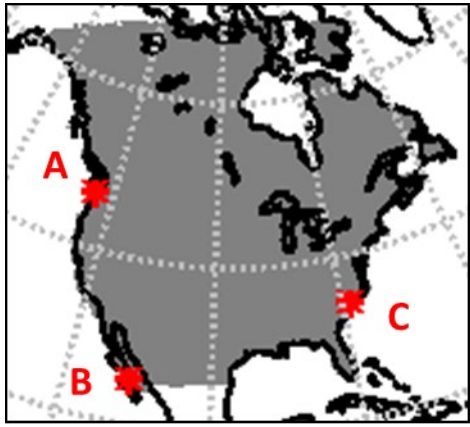
- daily maximum of "instantaneous" near surface (10 m anemometer height) wind speed
- large ensemble canRCM4, 0.44° spatial horizontal resolution (~50 km), over North America
- 50 simulations for the historical period 1951-2000.

2500 wind speed annual maxima

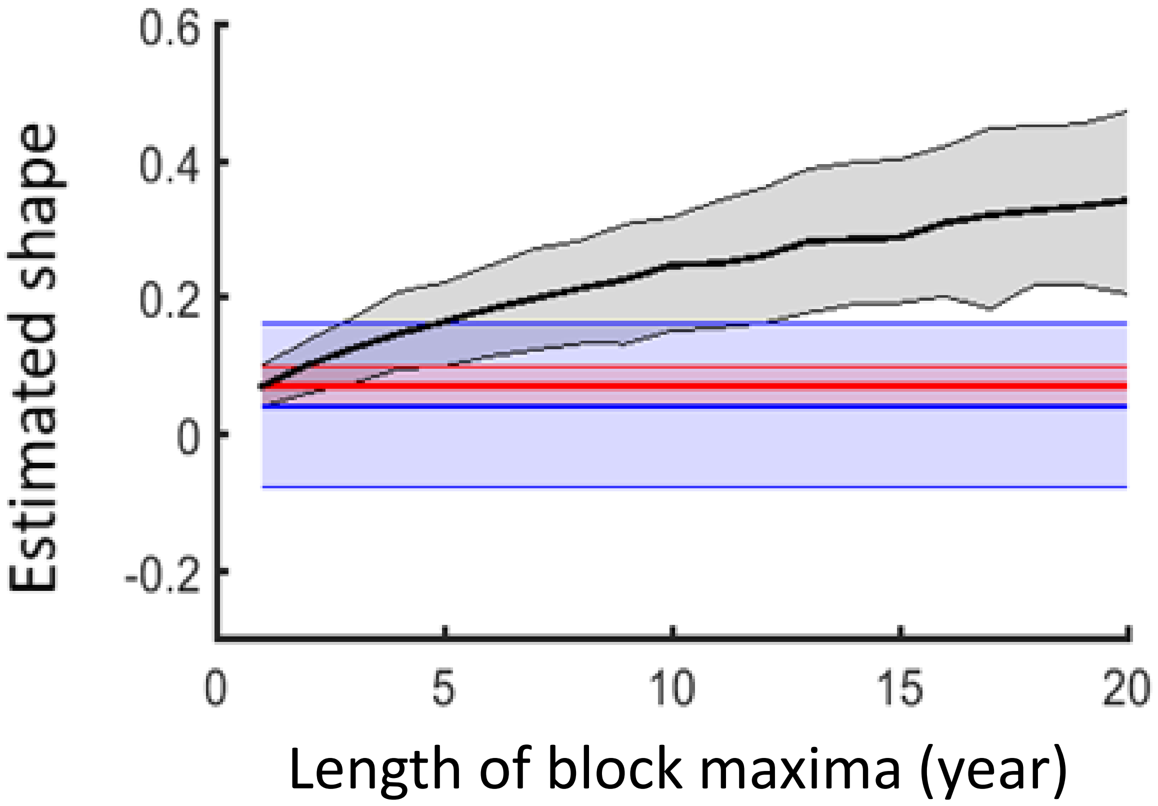
Results: precipitation

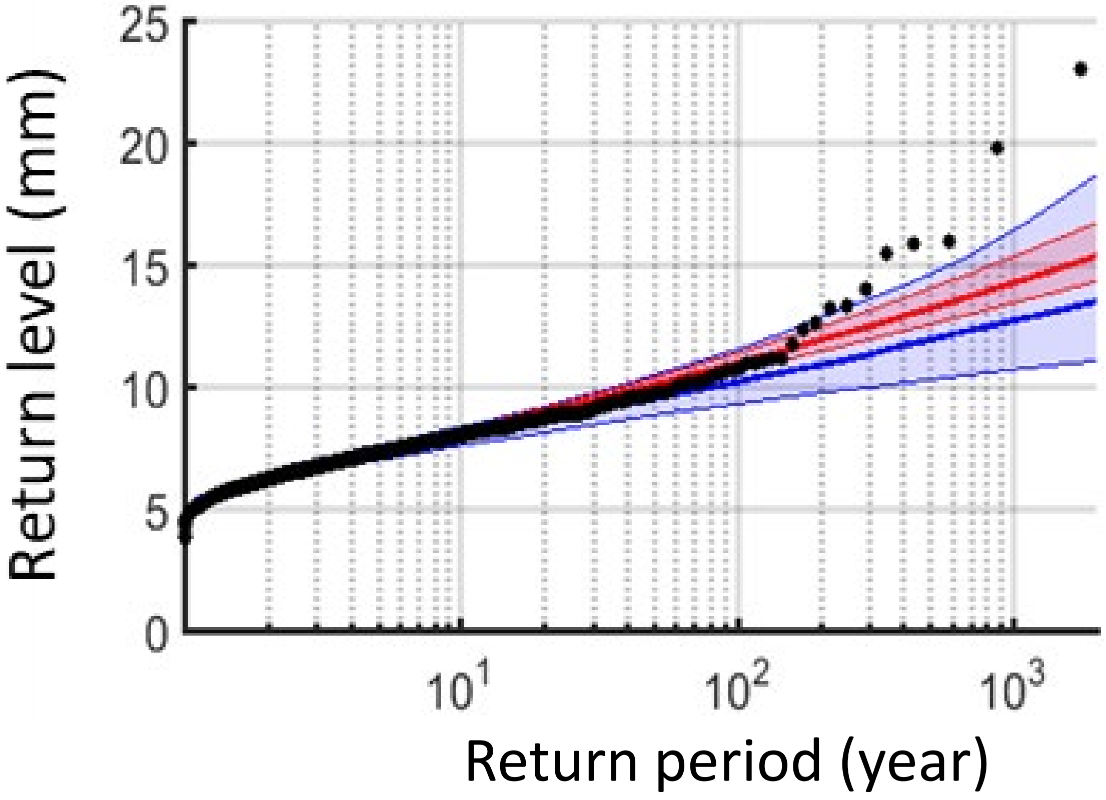
Ben Alaya, M. A., F. W. Zwiers, and X. Zhang, 2020: An Evaluation of Block-Maximum-Based Estimation of Very Long Return Period Precipitation Extremes with a Large Ensemble Climate Simulation. *Journal of Climate*, **33,** 6957-6970.

Results

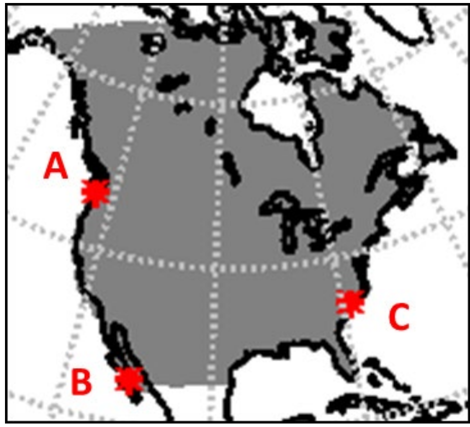


Location A





Results



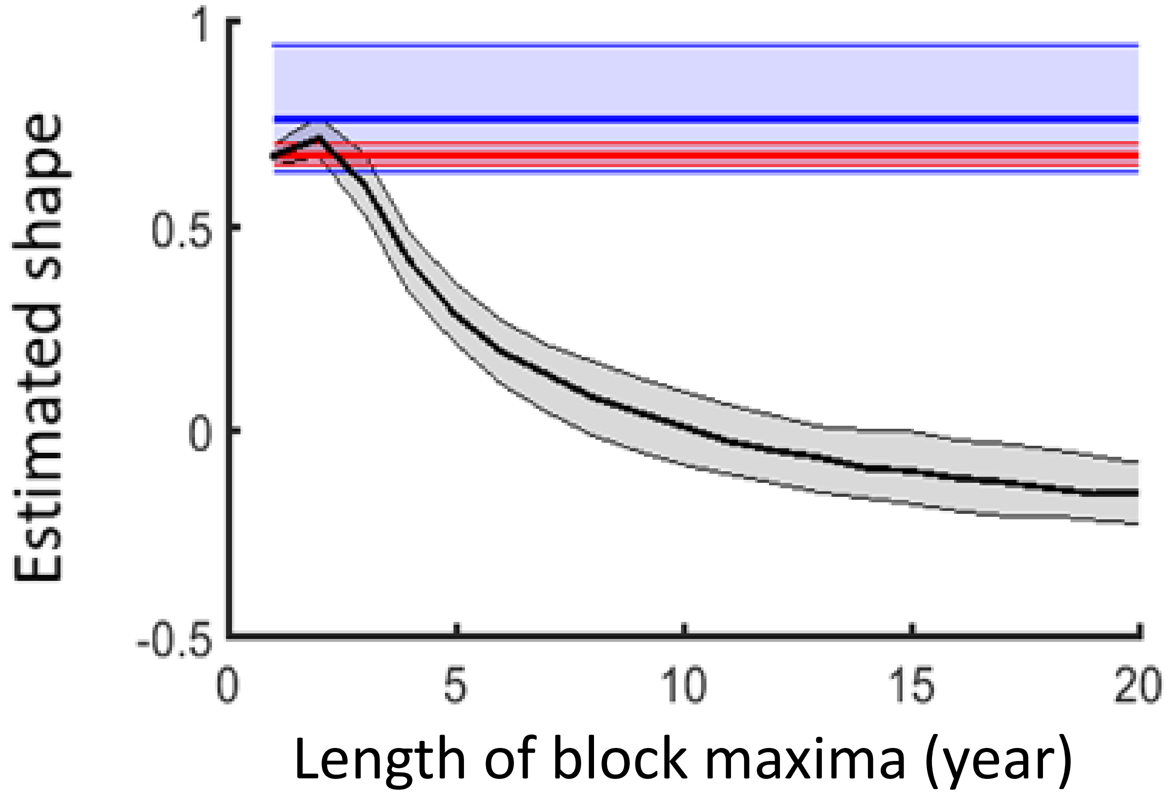
Shape parameter

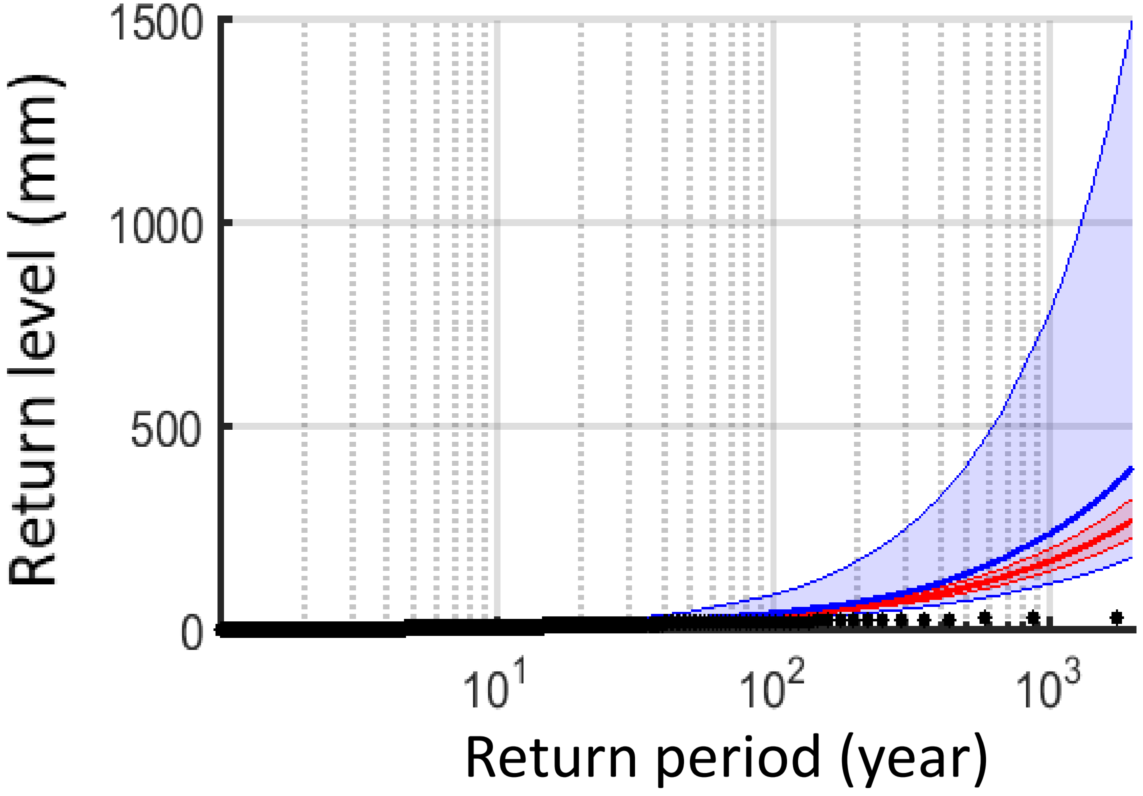
GEV fitted to 1750 annual maxima

Empirical quantile estimates

GEV fitted to 50 annual maxima

Location B





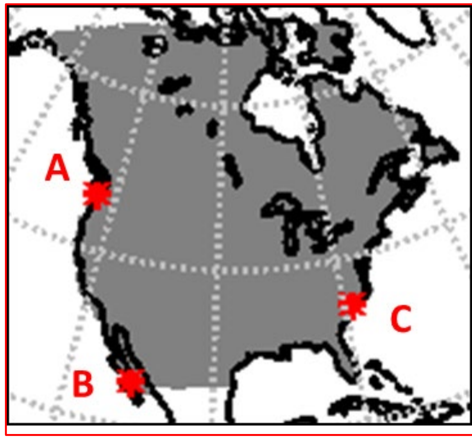
Results

Shape parameter

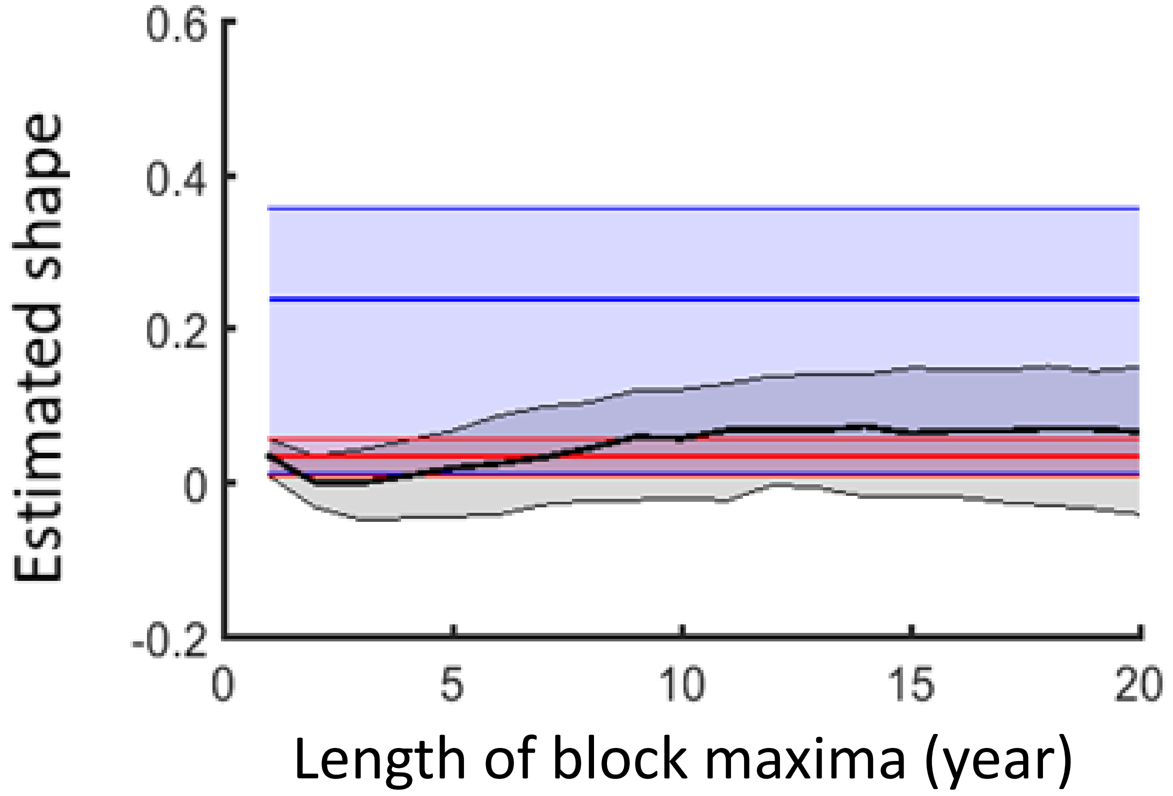
GEV fitted to 1750 annual maxima

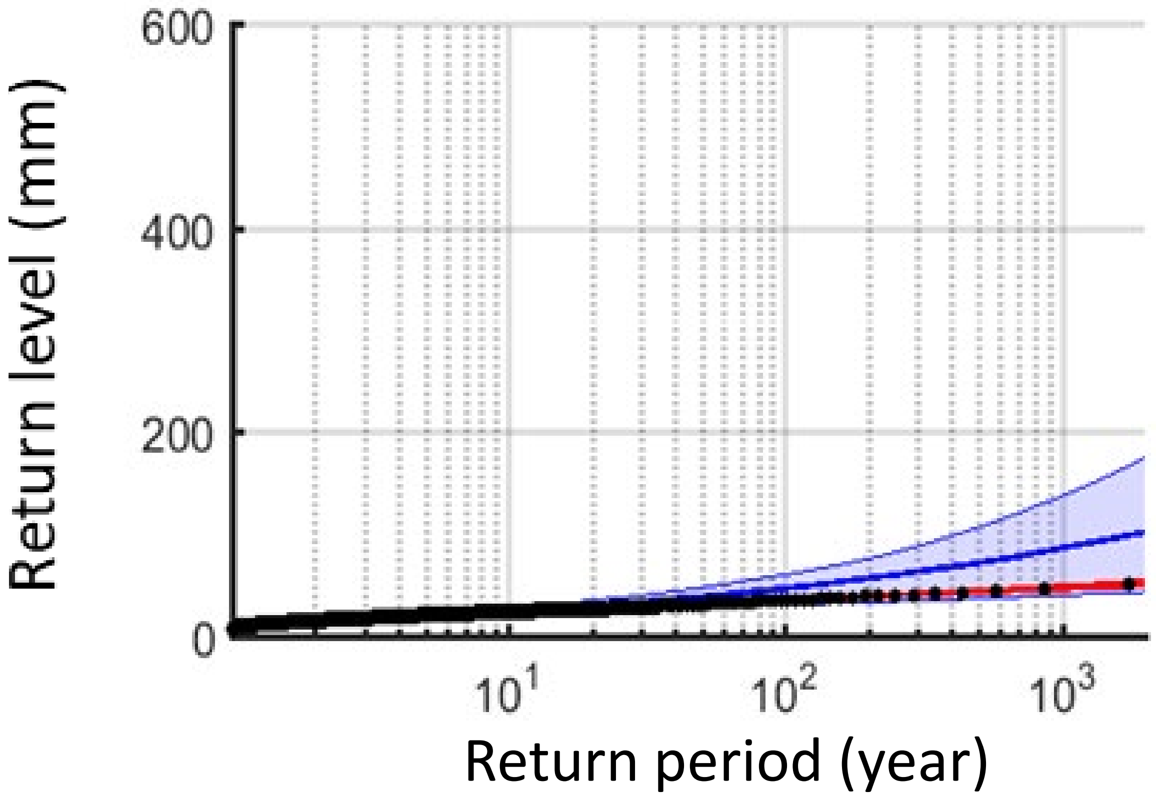
Empirical quantile estimates

GEV fitted to 1750 annual maxima



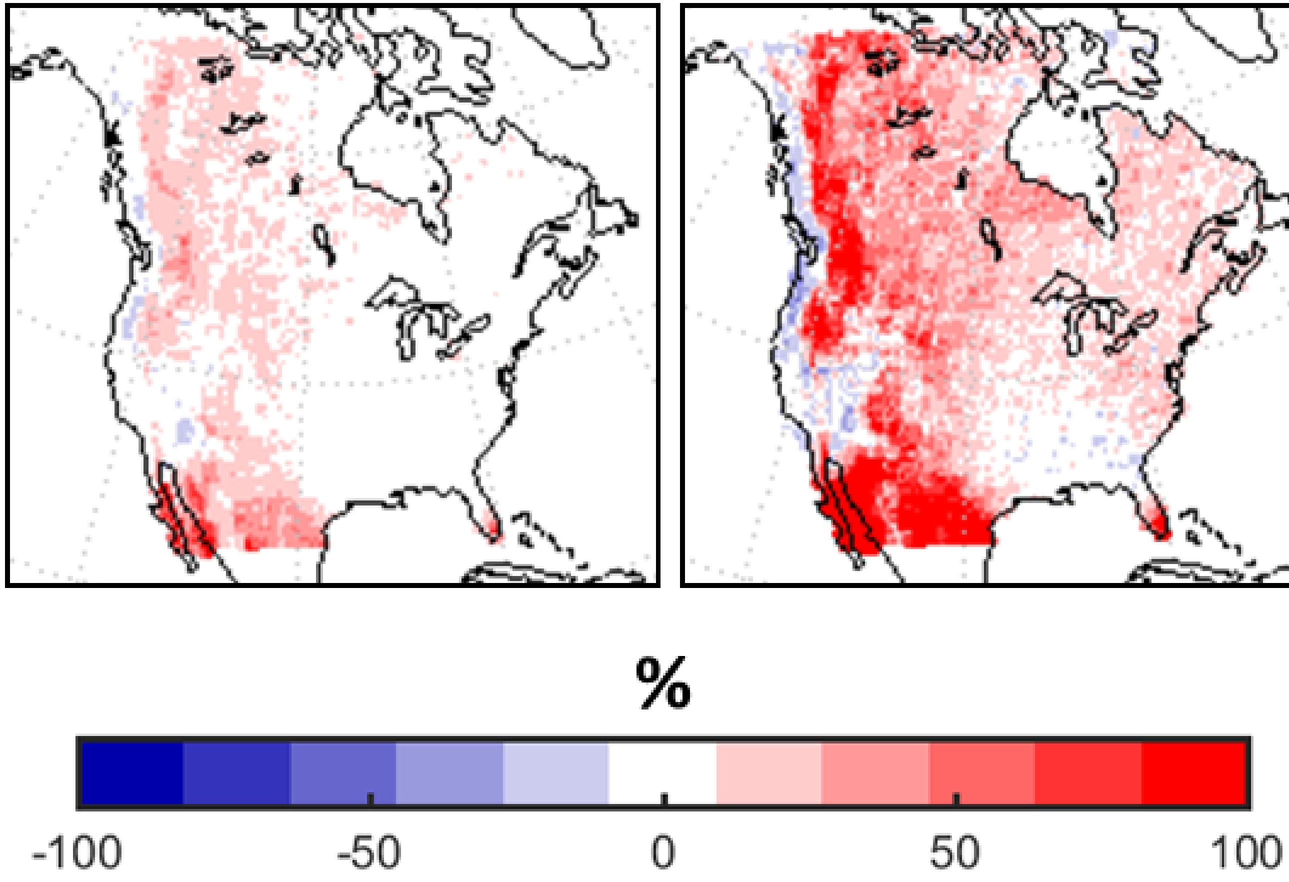
Location C



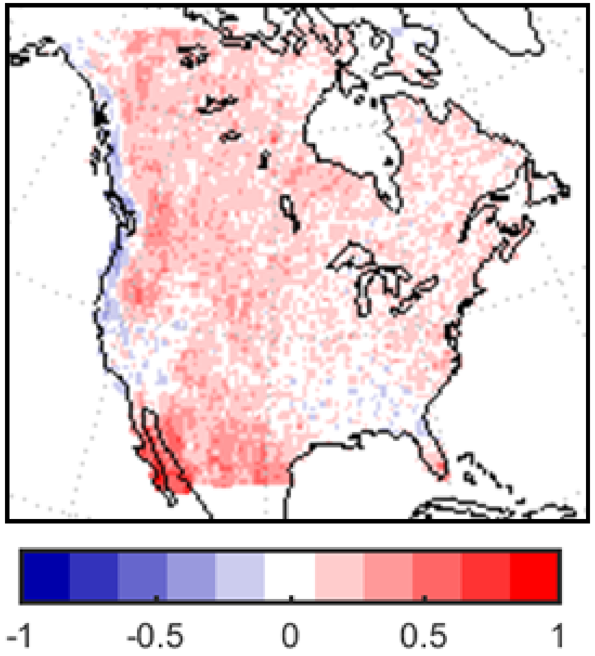


Results

100-year RL **1000-year RL**



$$D = \xi_{1\,year} - \xi_{10\,year}$$



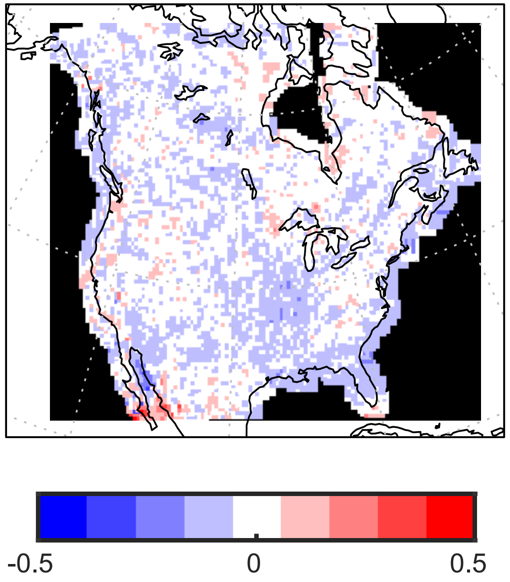
Relative difference between GEV-based (fitted to 1750 annual maxima) and empirical return level estimates for 100-year and 1000-year events

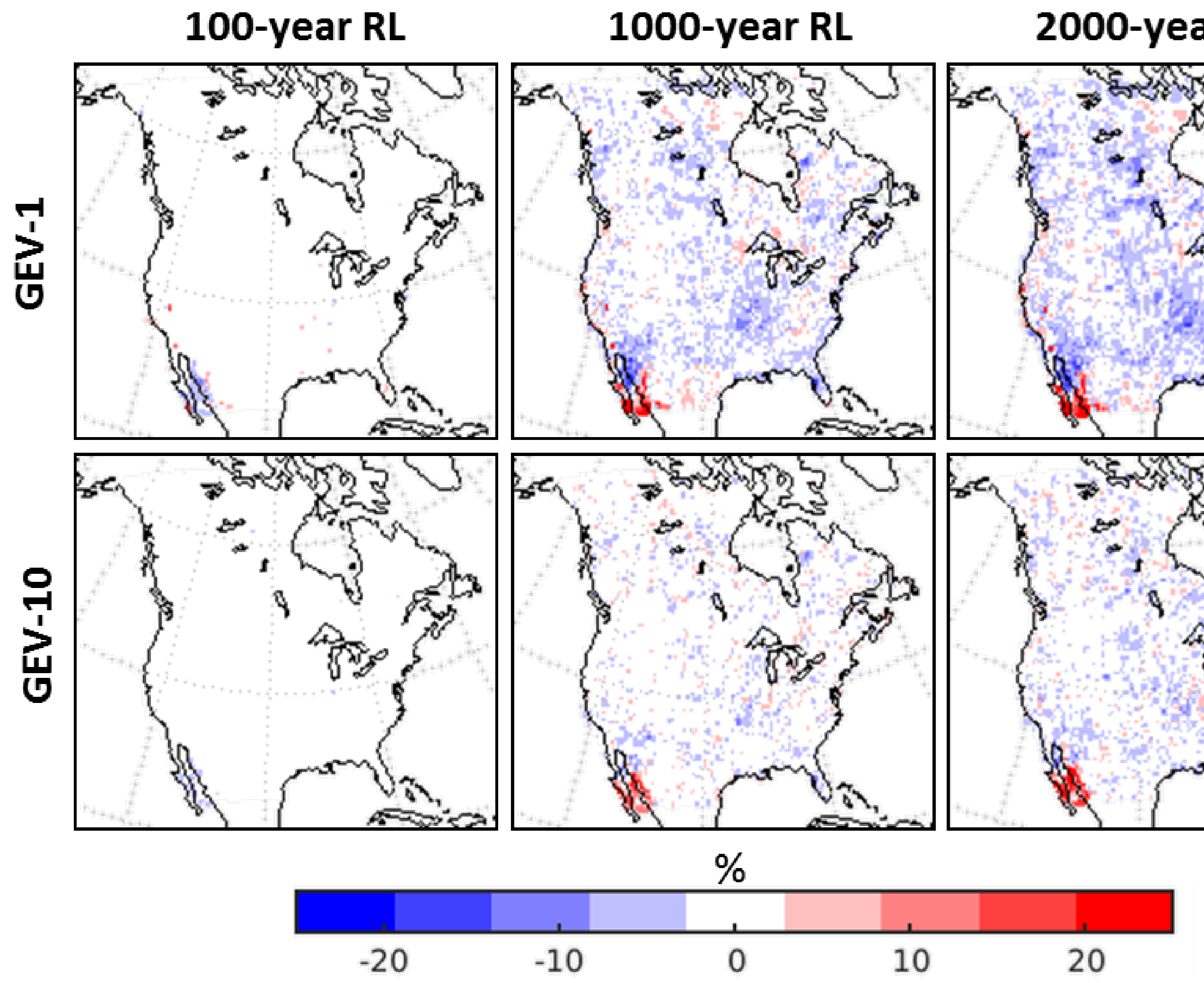
Results: wind speed

Ben Alaya, M. A., F. W. Zwiers, and X. Zhang, 2021: On estimating long period wind speed return levels from annual maxima. Weather and Climate Extremes, 34, 100388.

Results

$$D = \xi_{1\,year} - \xi_{10\,year}$$





<u>Maps of the bias</u> in return levels estimated using GEV-1 distributions (GEV fitted to annual maximum wind speed) and GEV-10 distributions (GEV fitted to 10-year maxima of wind speed) using the 50 CanRCM4 historical simulations of the period 1951-2000.

Results (summary):

We used max-stability as "an instrument" to assess max-stability as a "the theory"

Precipitation

- The rate at which largest values get larger decreases beyond annual maxima
- The GEV fitted to annual maxima underestimates long period return levels

Wind speed

- The rate at which largest values get larger increases beyond annual maxima
- The GEV fitted to annual maxima underestimates long period return levels

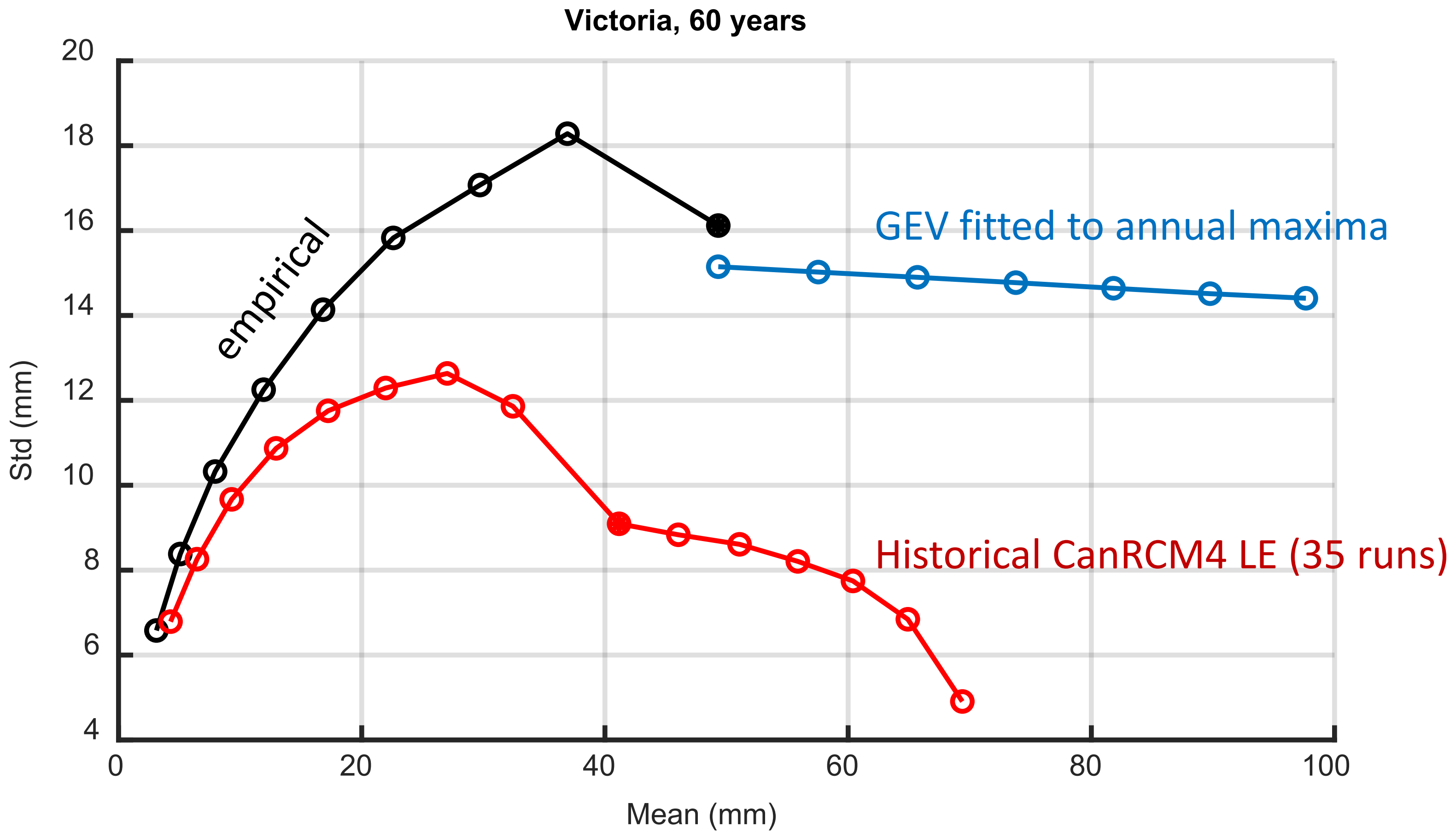
OUTLINES

1- Probable maximum precipitation

2- Uniform risk approach

3- Statistics of extremes: a distinct problem formulation

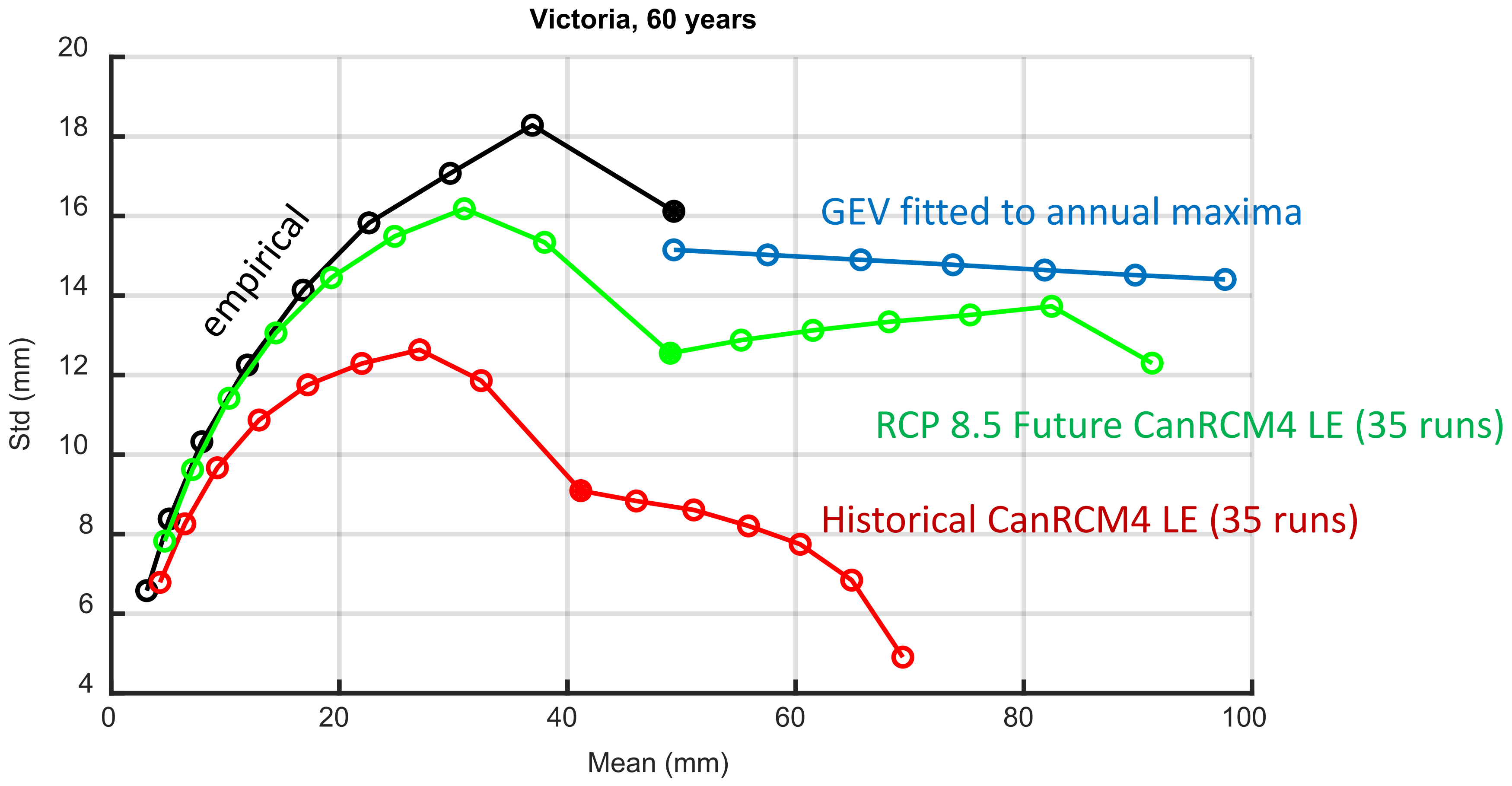
❖ Precipitation: Relation (variances, mean, length of block maxima n)



O Block maxima (day): [1-2-4-8-15-30-61-91-182-365];

Extended Block maxima (year): [1-2-4-8-16-32-64];

❖ Precipitation: Relation (variances, mean, length of block maxima n)



O Block maxima (day): [1-2-4-8-15-30-61-91-182-365];

Extended Block maxima (year): [1-2-4-8-16-32-64];

Conclusions

- The cutting edge on the topic of climate extremes in a warming climate needs exploratory research

- A fundamental primitive concept is max-stability:

  (1) an initial clue to **formulate the problem**
  (2) a creative **solution,** a theory, to be improved gradually

- How the mean and the standard deviations changes for increasing length of block maxima is the picture that engineers need.

- Extending this picture when block lengths increase without limit is interdisciplinary task.

A Poem

The information you have is not the information you want
The information you want is not the information you need
The information you need is not the information you can obtain
The information you can obtain costs more than you want to pay

Thanks ….!