Spatio-temporal modeling of urban extreme rainfall events at high resolution

Nice, February 10, 2026

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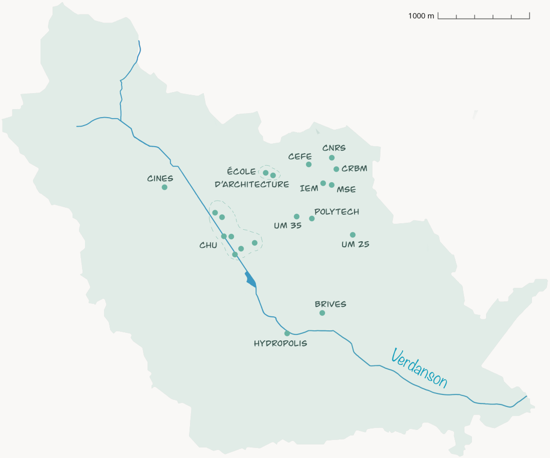
General context - Montpellier, France

Floods in Montpellier, August 2015 and December 2025 (*Midi Libre*)

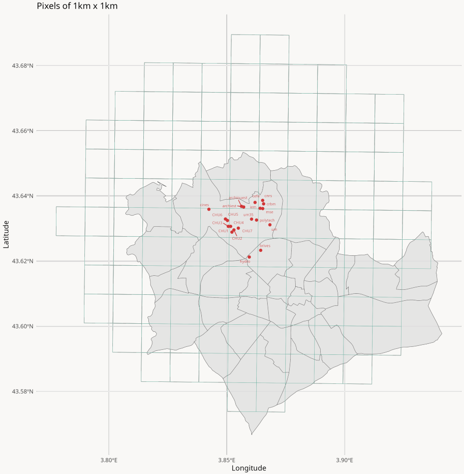
- Mediterranean events, localized rainfall
- Urban area, flood risks



- **Study area:** Verdanson water catchment
- **Source:** Urban observatory of HydroScience Montpellier (HSM)[2]
- **Time period:** [Sept.2019, Jan.2025[
- **Temporal resolution:** 5 minutes
- **Spatial resolution:** 77 m to 2259 m

$\mathcal{S} = \{$**20 rain gauges**$\} \subset \mathbb{R}^2$ and $\mathcal{T} \subset \mathbb{R}_+$

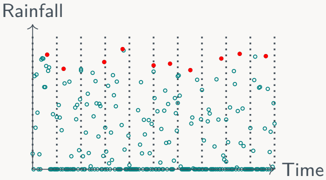
[1] Observ. Montpellierain et au Sud de l'Eau dans la Ville
[2] **data2023pluvio**



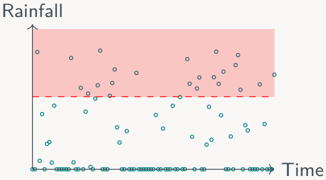
- **Source:** COMEPHORE, Météo France
- **Time period:** $[1997, 2023[$
- **Temporal resolution:** Every hour
- **Spatial resolution:** 1 km^2

Extreme precipitation

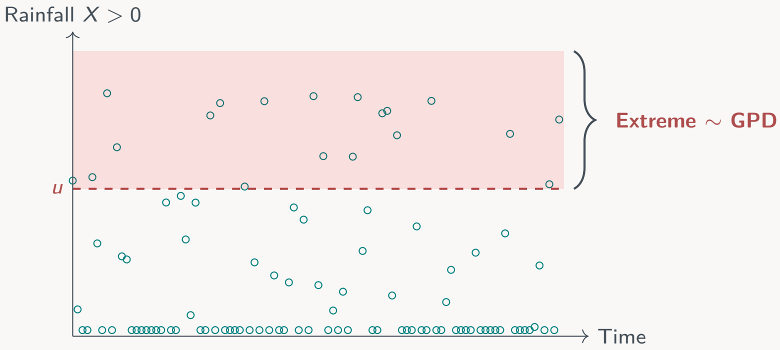
- Block-maxima
- Peaks-Over-Threshold



Generalized Extreme Value distribution (GEV)



Generalized Pareto Distribution (GPD)

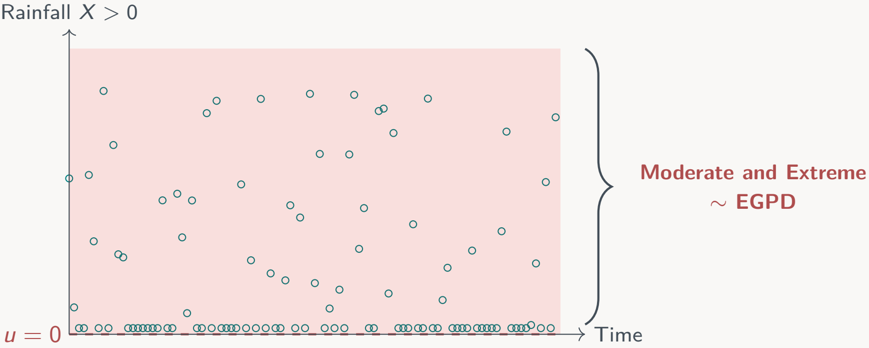


- **Generalized Pareto Distribution (GPD)**[1]

$$X \mid X > u \sim \underbrace{H_\xi}_{\text{GPD}(\xi,\sigma,u)} \text{ with } \xi \in \mathbb{R},\ \sigma > 0.$$

ξ: shape (tail behavior), σ: scale, u: threshold

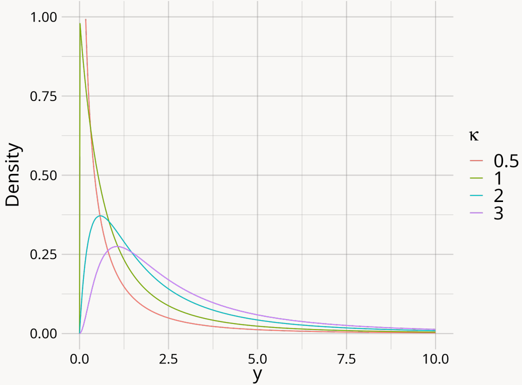
[1] **pickands1975statistical**



- **E**xtended **G**eneralized **P**areto **D**istribution (**EGPD**)[2]

$$X \sim \underbrace{G(H_\xi)}_{\text{EGPD}(\xi,\sigma,\kappa)} \text{ with } G(x) = x^\kappa,\ \kappa > 0$$

[2] **naveau_modeling_2016**



$\sigma = 1$, $\xi = 0.5$

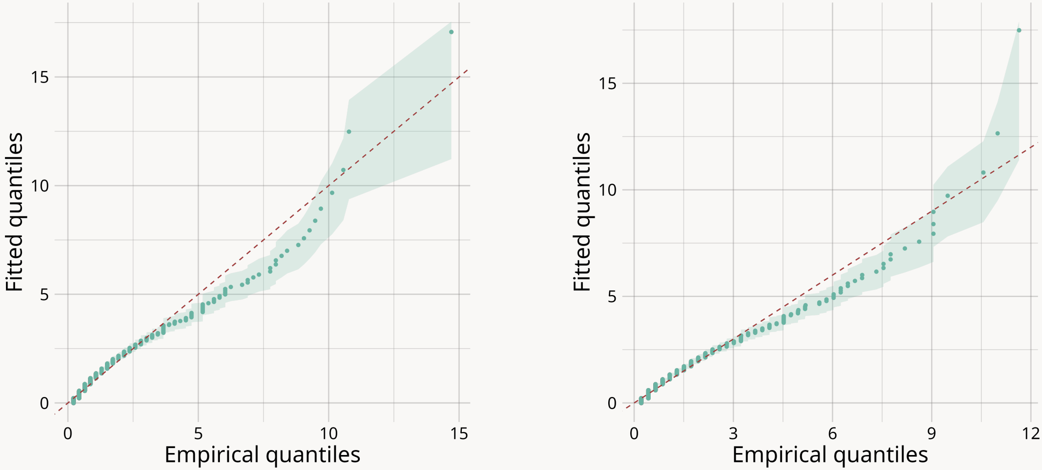
Extended Generalized Pareto Distribution

$$F(x) = G\left(H_\xi\left(\frac{x}{\sigma}\right)\right),$$

where $G(x) = x^\kappa$, $\kappa > 0$

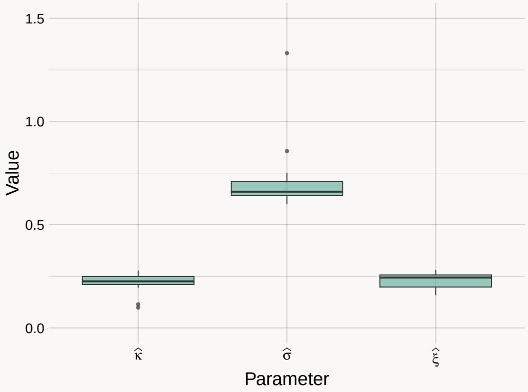
- κ: controls the bulk of the distribution
- Models **moderate and extreme** precipitation
- Avoids a threshold choice

EGPD fitting



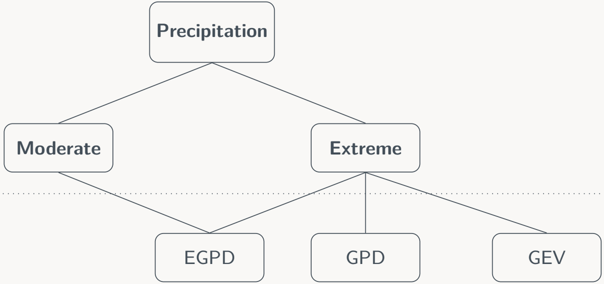
EGPD fitting for two rain gauges, CRBM (left) and UM (right) with left-censoring and 95% CI

EGPD estimated parameters



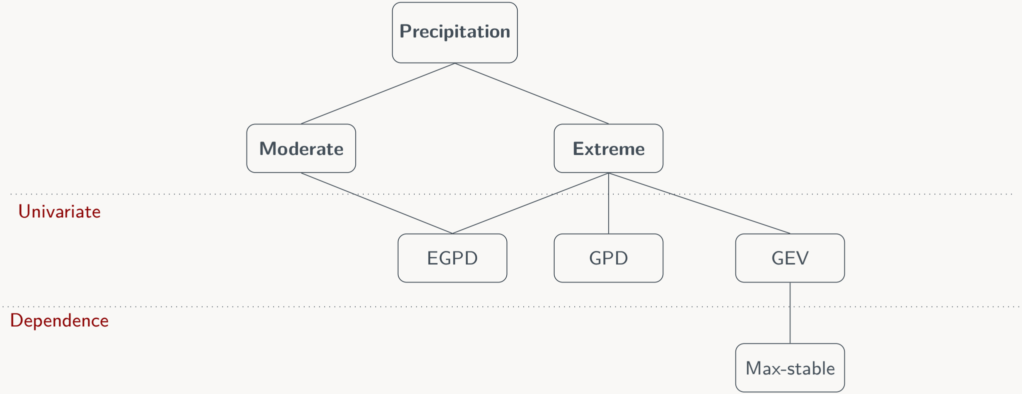
Estimated parameters across rain gauges

- $\widehat{\xi} \approx 0.25$: extreme rainfall tail
- $\widehat{\kappa} \approx 0.25$: convective rainfall
- $\widehat{\sigma} \approx 0.6$: short-duration scale

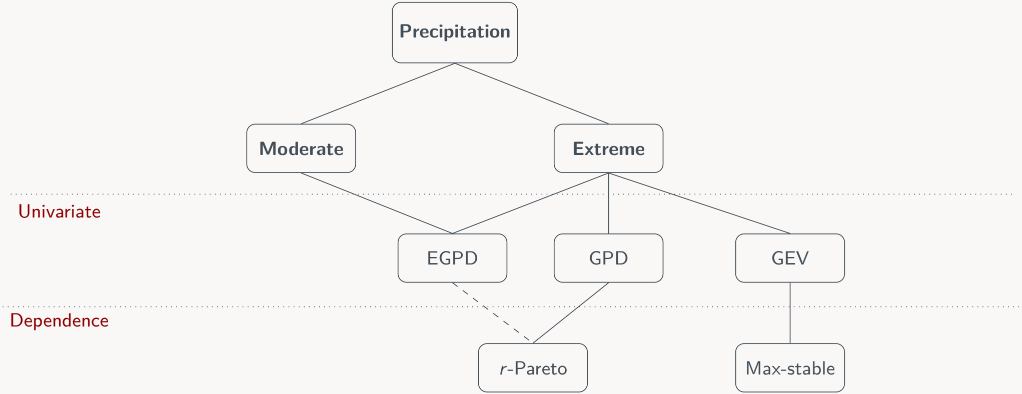


Univariate

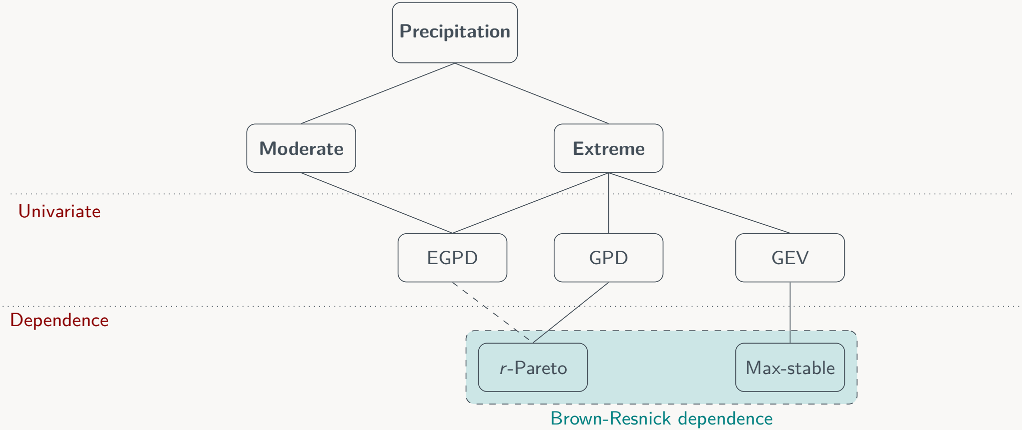
Dependence


Precipitation
Moderate
Extreme
Univariate
EGPD
GPD
GEV
Dependence
Max-stable

Spatio-temporal dependence modeling



Spatio-temporal dependence modeling



Rainfall random field: $\boldsymbol{X} = \{X_{\boldsymbol{s},t},\ (\boldsymbol{s}, t) \in \mathcal{S} \times \mathcal{T}\}$

Let $\Lambda_{\mathcal{S}} \subset \mathbb{R}_+^2$ and $\Lambda_{\mathcal{T}} \subset \mathbb{R}_+$ be sets of spatial and temporal lags respectively.

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Variogram (matheron1963principles)

$$\gamma(\boldsymbol{h}, \tau) = \frac{1}{2}\text{Var}(X_{\boldsymbol{s},t} - X_{\boldsymbol{s}+\boldsymbol{h},t+\tau})$$

- Quantifies variability
- Higher $\gamma(\boldsymbol{h}, \tau) \rightarrow$ weaker dependence

$\boldsymbol{h} \in \Lambda_\mathcal{S},\ \tau \in \Lambda_\mathcal{T}$

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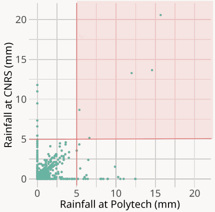
Extremogram (davis2009extremogram)

$$\chi(\boldsymbol{h}, \tau) = \lim_{q \to 1} \mathbb{P}(X^*_{\boldsymbol{s},t} > q \mid X^*_{\boldsymbol{s}+\boldsymbol{h},t+\tau} > q)$$

- Measures tail dependence
- Higher $\chi(\boldsymbol{h}, \tau) \rightarrow$ stronger dependence

$\boldsymbol{h} \in \Lambda_{\mathcal{S}}$, $\tau \in \Lambda_{\mathcal{T}}$, $X^*_{\boldsymbol{s},t}$ uniform margins.

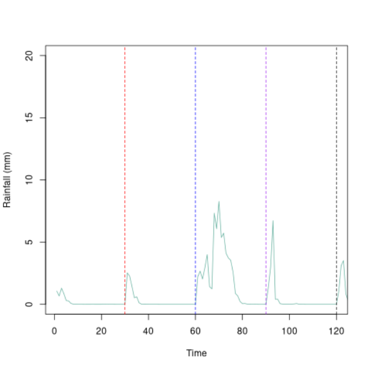


Definition (de_fondeville_high-dimensional_2018)

For all $\boldsymbol{s} \in \mathcal{S}$ and $t \in \mathcal{T}$, a risk function $r(\boldsymbol{X}) = X_{\boldsymbol{s}_0,t_0}$,

$$u^{-1}X_{\boldsymbol{s},t} \mid X_{\boldsymbol{s}_0,t_0} > u \xrightarrow{d} Y_{\boldsymbol{s},t} \quad \text{with} \quad Y_{\boldsymbol{s},t} = Re^{W_{\boldsymbol{s},t} - W_{\boldsymbol{s}_0,t_0} - \gamma(\boldsymbol{s}-\boldsymbol{s}_0, t-t_0)},$$

where $(\boldsymbol{s}_0, t_0)$ is a space-time location, u is a high threshold, $R \sim \text{Pareto}(1)$, $W_{\boldsymbol{s},t}$ is a Gaussian process.



- *r*-extremogram

$$\chi_r(\boldsymbol{h}, \tau) = \lim_{q \to 1} \mathbb{P}(X^*_{\boldsymbol{s}_0+\boldsymbol{h},t_0+\tau} > q | X^*_{\boldsymbol{s}_0,t_0} > q)$$

- Brown-Resnick dependence structure

$$\chi_r(\boldsymbol{h}, \tau) = 2\left(1 - \phi\left(\sqrt{\frac{1}{2}\gamma(\boldsymbol{h}, \tau)}\right)\right)$$

Spatio-temporal extremogram with a Brown-Resnick dependence

Let $\boldsymbol{h} \in \Lambda_{\mathcal{S}}$ and $\tau \in \Lambda_{\mathcal{T}}$. We have

$$\chi(\boldsymbol{h}, \tau) = 2\left(1 - \phi\left(\sqrt{\frac{1}{2}\gamma(\boldsymbol{h}, \tau)}\right)\right)$$

with ϕ the std normal c.d.f. and γ the variogram of $\boldsymbol{W}$.

Spatio-temporal extremogram with a Brown-Resnick dependence

Let $\boldsymbol{h} \in \Lambda_{\mathcal{S}}$ and $\tau \in \Lambda_{\mathcal{T}}$. We have

$$\chi(\boldsymbol{h}, \tau) = 2\left(1 - \phi\left(\sqrt{\frac{1}{2}\gamma(\boldsymbol{h}, \tau)}\right)\right)$$

with ϕ the std normal c.d.f. and γ the variogram of $\boldsymbol{W}$.

Separable model: Fractional Brownian motion with additive separability.

$$\frac{\gamma(\boldsymbol{h}, \tau)}{2} = \beta_1 ||\boldsymbol{h}||^{\alpha_1} + \beta_2 |\tau|^{\alpha_2}$$

with $0 < \alpha_1, \alpha_2 \leq 2$, $\beta_1, \beta_2 > 0$ (**buhl2019semiparametric**).

Case of additive separability: $\frac{\gamma(\boldsymbol{h},\tau)}{2} = \beta_1 \|\boldsymbol{h}\|^{\alpha_1} + \beta_2 |\tau|^{\alpha_2}$, $\; 0 < \alpha_1, \alpha_2 \leq 2\,,\; \beta_1, \beta_2 > 0$

Spatio-temporal

$$\chi(\boldsymbol{h}, \tau) = 2\left(1 - \phi\left(\sqrt{\tfrac{1}{2}\gamma(\boldsymbol{h}, \tau)}\right)\right)$$

Transformation:

$$\zeta(\chi) = 2\log\left(\phi^{-1}\left(1 - \tfrac{1}{2}\chi\right)\right)$$

Spatial

$$\zeta\left(\chi(\boldsymbol{h}, 0)\right) = \log \beta_1 + \alpha_1 \log\|\boldsymbol{h}\|\,,\;\; \boldsymbol{h} \in \Lambda_{\mathcal{S}}$$

Temporal

$$\zeta\left(\chi(0, \tau)\right) = \log \beta_2 + \alpha_2 \log \tau\,,\;\; \tau \in \Lambda_{\mathcal{T}}$$

Case of additive separability: $\frac{\gamma(\boldsymbol{h},\tau)}{2} = \beta_1 \|\boldsymbol{h}\|^{\alpha_1} + \beta_2 |\tau|^{\alpha_2}, \quad 0 < \alpha_1, \alpha_2 \leq 2\,, \; \beta_1, \beta_2 > 0$

Spatio-temporal

$$\chi(\boldsymbol{h}, \tau) = 2\left(1 - \phi\left(\sqrt{\tfrac{1}{2}\gamma(\boldsymbol{h}, \tau)}\right)\right)$$

Transformation:

$$\zeta(\chi) = 2 \log\left(\phi^{-1}\left(1 - \tfrac{1}{2}\chi\right)\right)$$

Spatial

$$\eta\left(\chi(\boldsymbol{h}, 0)\right) := c_1 + \alpha_1 x_h\,, \quad \boldsymbol{h} \in \Lambda_{\mathcal{S}}$$

Temporal

$$\eta\left(\chi(0, \tau)\right) := c_2 + \alpha_2 x_\tau\,, \quad \tau \in \Lambda_{\mathcal{T}}$$

Weighted Least Squares Estimation (WLSE)

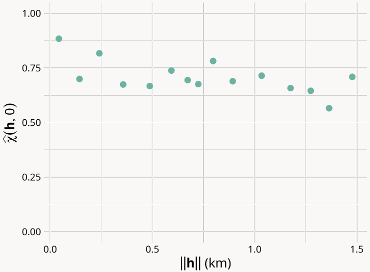
$$\begin{pmatrix} \widehat{c_i} \\ \widehat{\alpha_i} \end{pmatrix} = \text{argmin}_{c_i, \alpha_i} \sum_x w_x \left(\zeta\left(\hat{\chi}\right) - (c_i + \alpha_i x)\right)^2$$

Empirical spatial extremogram

For a fixed $t \in \mathcal{T}$ and q a high quantile,

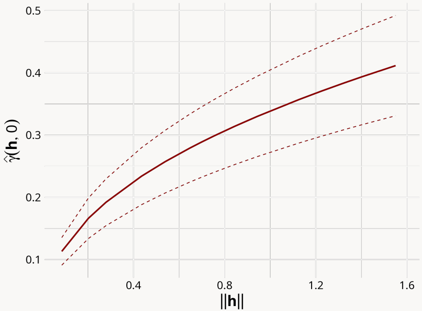
$$\widehat{\chi}_q^{(t)}(\boldsymbol{h}, 0) = \frac{\frac{1}{|N_{\boldsymbol{h}}|} \sum_{i,j \,|\, (\boldsymbol{s}_i, \boldsymbol{s}_j) \in N_{\boldsymbol{h}}} \mathbb{1}_{\{X^*_{\boldsymbol{s}_i,t} > q,\, X^*_{\boldsymbol{s}_j,t} > q\}}}{\frac{1}{|\mathcal{S}|} \sum_{i=1}^{|\mathcal{S}|} \mathbb{1}_{\{X^*_{\boldsymbol{s}_i,t} > q\}}},$$

where $C_{\boldsymbol{h}}$ are equifrequent distance classes and
$N_{\boldsymbol{h}} = \left\{ (\boldsymbol{s}_i, \boldsymbol{s}_j) \in \mathcal{S}^2 \;\middle|\; \|\boldsymbol{s}_i - \boldsymbol{s}_j\| \in C_{\boldsymbol{h}} \right\}$.



Transformation and WLSE

$\Longrightarrow$

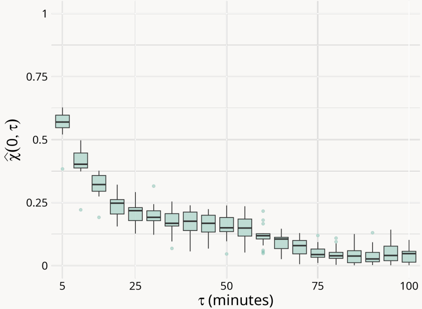


Spatial variogram $\widehat{\gamma}(\boldsymbol{h}, 0) = 2\widehat{\beta}_1 \|\boldsymbol{h}\|^{\widehat{\alpha}_1}$

Empirical temporal extremogram

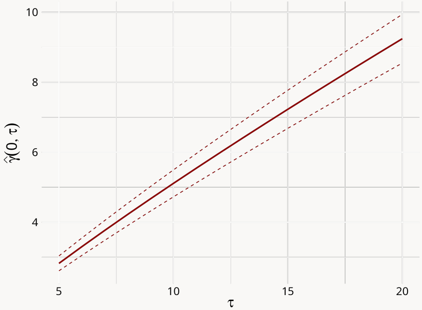
For a location $\boldsymbol{s} \in \mathcal{S}$, a high quantile q and $t_k \in \{t_1, \ldots, t_T\}$,

$$\widehat{\chi}_q^{(\boldsymbol{s})}(\mathbf{0}, \tau) = \frac{\frac{1}{T-\tau} \sum_{k=1}^{T-\tau} \mathbb{1}_{\{X^*_{\boldsymbol{s},t_k} > q \,, X^*_{\boldsymbol{s},t_k+\tau} > q\}}}{\frac{1}{T} \sum_{k=1}^{T} \mathbb{1}_{\{X^*_{\boldsymbol{s},t_k} > q\}}}$$



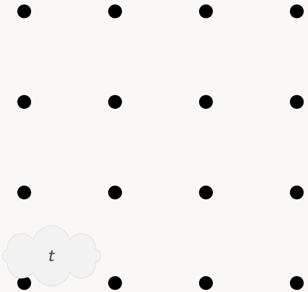
Transformation and WLSE

$\Longrightarrow$

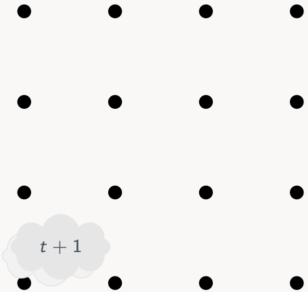


Temporal variogram $\widehat{\gamma}(\mathbf{0}, \tau) = 2\widehat{\beta}_2 |\tau|^{\widehat{\alpha}_2}$

Separable model



Separable model



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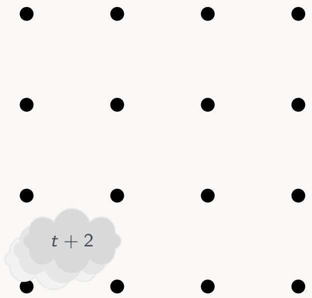

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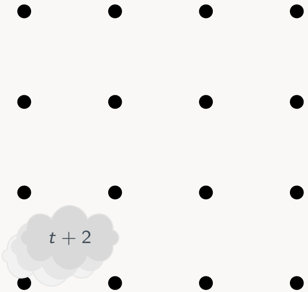
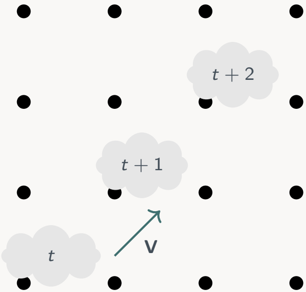


Non-separable model



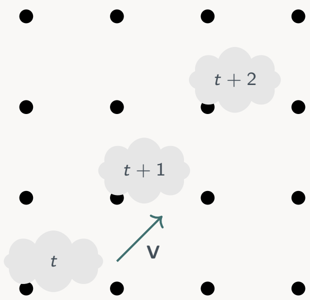
Towards more realistic modeling: introduce advection $\boldsymbol{V}$ to relax separability

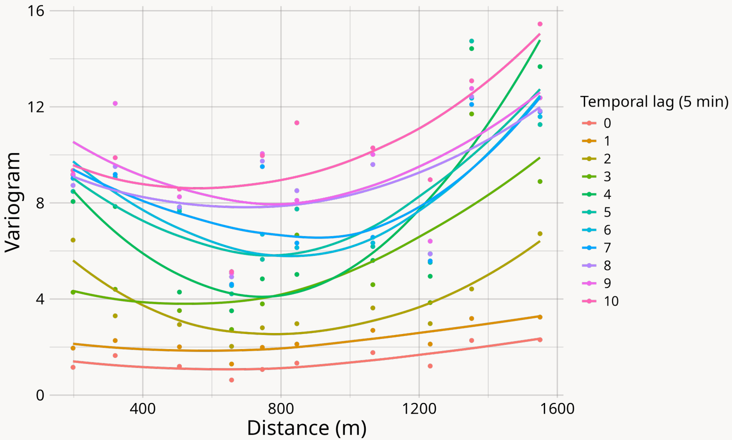
$$\gamma_L(\boldsymbol{h}, \tau) = \gamma(\boldsymbol{h} - \tau \boldsymbol{V}, \tau)$$

$$\Rightarrow \quad \frac{1}{2}\gamma_L(\boldsymbol{h}, \tau) = \beta_1 \|\boldsymbol{h} - \tau \boldsymbol{V}\|^{\alpha_1} + \beta_2 |\tau|^{\alpha_2}$$

- Parameters: $\boldsymbol{\Theta} = (\beta_1, \beta_2, \alpha_1, \alpha_2, \boldsymbol{V})$

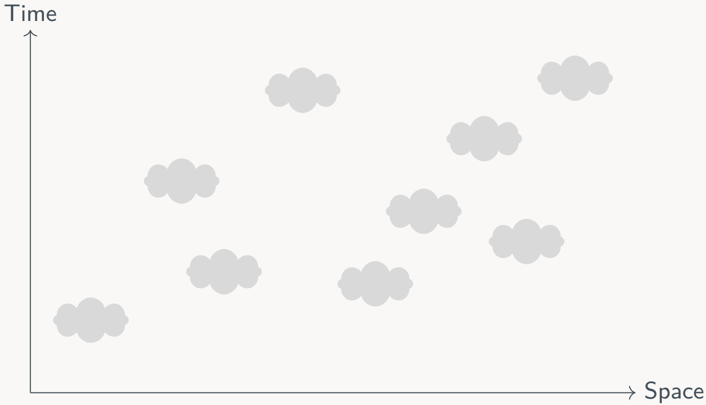
Non-separable model



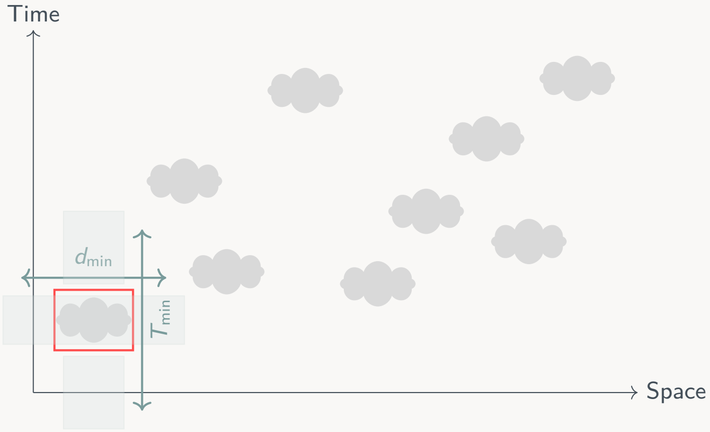


Empirical spatio-temporal variogram $\gamma(\boldsymbol{h}, \tau)$ on OMSEV data

All rainfall events



Extreme episodes:
Each episode is characterized by $(\mathbf{s}_0, t_0)$ for which $X_{\mathbf{s}_0, t_0} > u$



Episode selection:

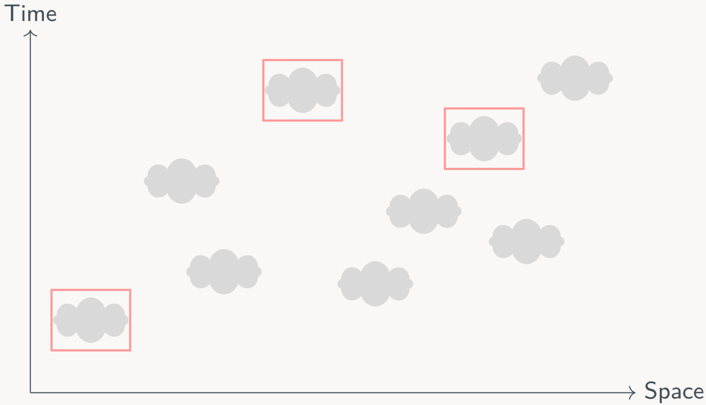
Only episodes separated by

- spatial distance $\geq d_{\text{min}}$

OR

- temporal gap $\geq T_{\text{min}}$

$\Rightarrow$ reduces dependence between selected episodes $\in \mathcal{E}$.



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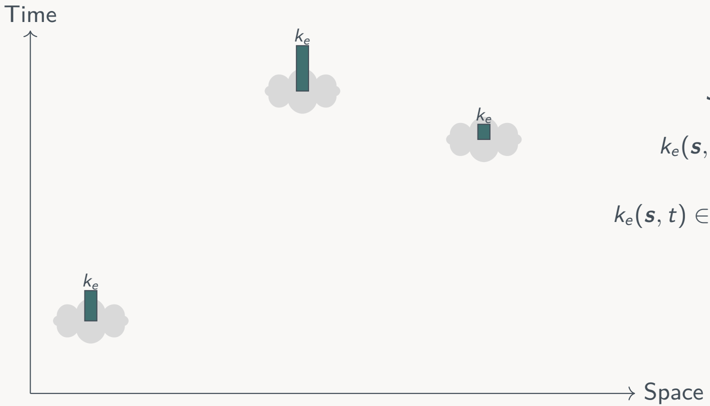
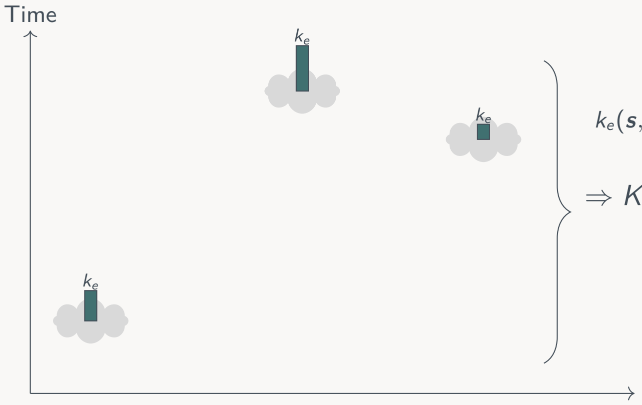


Joint exceedances

$$k_e(\boldsymbol{s}, t) = \mathbb{1}_{\{X_{\boldsymbol{s}_0, t_0} > u,\ X_{\boldsymbol{s}, t} > u\}},$$
with $(\boldsymbol{s}, t) \in \mathcal{N}(\boldsymbol{h}, \tau)$

$$k_e(\boldsymbol{s}, t) \in [0, 1] \sim \text{Bernoulli}(\chi_\Theta(h, \tau))$$

with $\mathcal{N}(\boldsymbol{h}, \tau) = \{(\boldsymbol{s}, t) \in \mathcal{S} \times \mathcal{T} \mid \boldsymbol{s} - \boldsymbol{s}_0 = \boldsymbol{h},\ t - t_0 = \tau\}$



Total joint exceedances:

$$k_e(\boldsymbol{s}, t) \in [0, 1] \sim \text{Bernoulli}(\chi_\Theta(h, \tau))$$

$$\Rightarrow K_{\boldsymbol{h},\tau} = \sum_{e \in \mathcal{E}} \sum_{(\boldsymbol{s},t) \in \mathcal{N}(\boldsymbol{h},\tau)} k_e(\boldsymbol{s}, t)$$

Bernoulli contributions

with $\mathcal{N}(\boldsymbol{h}, \tau) = \{(\boldsymbol{s}, t) \in \mathcal{S} \times \mathcal{T} \mid \boldsymbol{s} - \boldsymbol{s}_0 = \boldsymbol{h},\ t - t_0 = \tau\}$

Bernoulli contributions (large u):

$$k_e(\boldsymbol{s}, t) = \mathbf{1}_{\{X_{\boldsymbol{s}_0, t_0} > u,\, X_{\boldsymbol{s}, t} > u\}}, \qquad (\boldsymbol{s}, t) \in \mathcal{N}(\boldsymbol{h}, \tau),$$

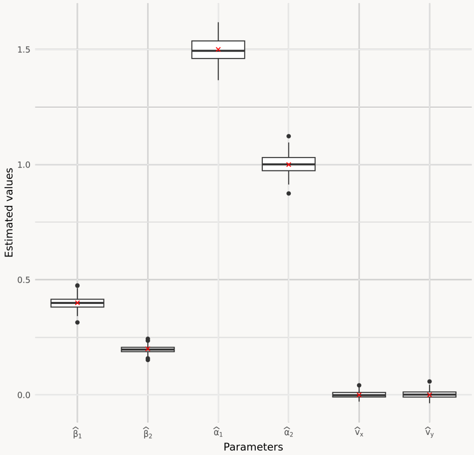
each treated as

$$k_e(\boldsymbol{s}, t) \sim \mathrm{Bernoulli}\big(\chi_\Theta(\boldsymbol{h}, \tau)\big).$$

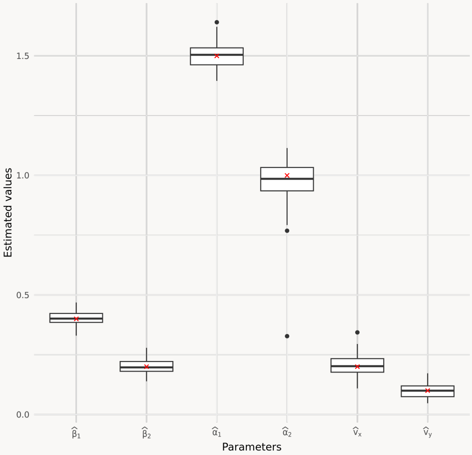
Composite log-likelihood

$$\ell_C(\Theta) \propto \sum_{e \in \mathcal{E}} \sum_{(\boldsymbol{h}, \tau) \in \Lambda_{\mathcal{S}} \times \Lambda_{\mathcal{T}}} \sum_{(\boldsymbol{s}, t) \in \mathcal{N}(\boldsymbol{h}, \tau)} k_e(\boldsymbol{s}, t) \log \chi_\Theta(\boldsymbol{h}, \tau) + (1 - k_e(\boldsymbol{s}, t)) \log(1 - \chi_\Theta(\boldsymbol{h}, \tau)).$$

- Optimization via maximization of $\ell_C(\Theta)$
- Initial parameters: from WLSE of the separable model (i.e., $\boldsymbol{V} = \mathbf{0}$)



Without advection



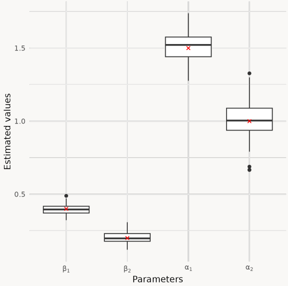
With advection

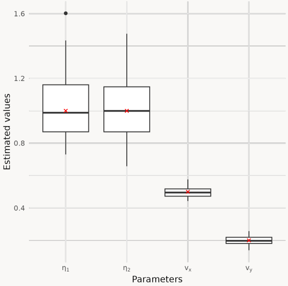
50 simulations, 500 replicates, 25 sites, 30 time steps

Episode-wise advection to global model

$$\mathbf{V}^{\text{emp}} = \begin{bmatrix} \mathbf{V}^{(1)} \\ \mathbf{V}^{(2)} \\ \vdots \\ \mathbf{V}^{(N)} \end{bmatrix} \in \mathbb{R}^{N\times 2} \xrightarrow{\text{global model}} \underbrace{\mathbf{V}^{\text{final}} = \eta_1 \left\|\mathbf{V}^{\text{emp}}\right\|^{\eta_2} \frac{\mathbf{V}^{\text{emp}}}{\left\|\mathbf{V}^{\text{emp}}\right\|},\ \eta_1 > 0, \eta_2 > 0}_{\text{unified transformation} \Rightarrow \eta \text{ to estimate}}$$

one component $=$ one episode





50 simulations, 500 replicates, 25 sites, 30 time steps

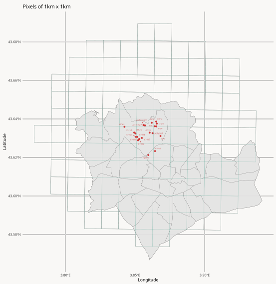
$$\mathbf{V}^{\mathrm{emp}} = \begin{bmatrix} \mathbf{V}^{(1)} \\ \mathbf{V}^{(2)} \\ \vdots \\ \mathbf{V}^{(N)} \end{bmatrix} \in \mathbb{R}^{N\times 2} \xrightarrow{\text{global model}} \underbrace{\mathbf{V}^{\mathrm{final}} = \eta_1 \|\mathbf{V}^{\mathrm{emp}}\|^{\eta_2} \frac{\mathbf{V}^{\mathrm{emp}}}{\|\mathbf{V}^{\mathrm{emp}}\|},\ \eta_1 > 0, \eta_2 > 0}_{\text{unified transformation} \Rightarrow \eta \text{ to estimate}}$$

one component = one episode

Parameters: $\mathbf{\Theta} = (\beta_1, \beta_2, \alpha_1, \alpha_2, \eta_1, \eta_2)$

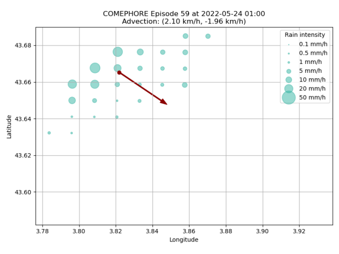
Challenge:
OMSEV data $\Rightarrow$ limited information for advection

Approach:
Fusion COMEPHORE–OMSEV $\rightarrow$ more reliable advection

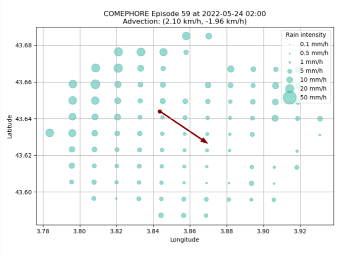


COMEPHORE pixels
Météo France

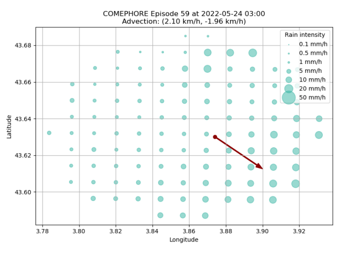
For one episode (COMEPHORE):



$t_0 - 1$



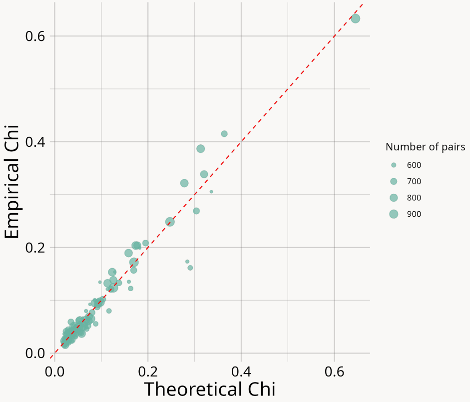
t_0



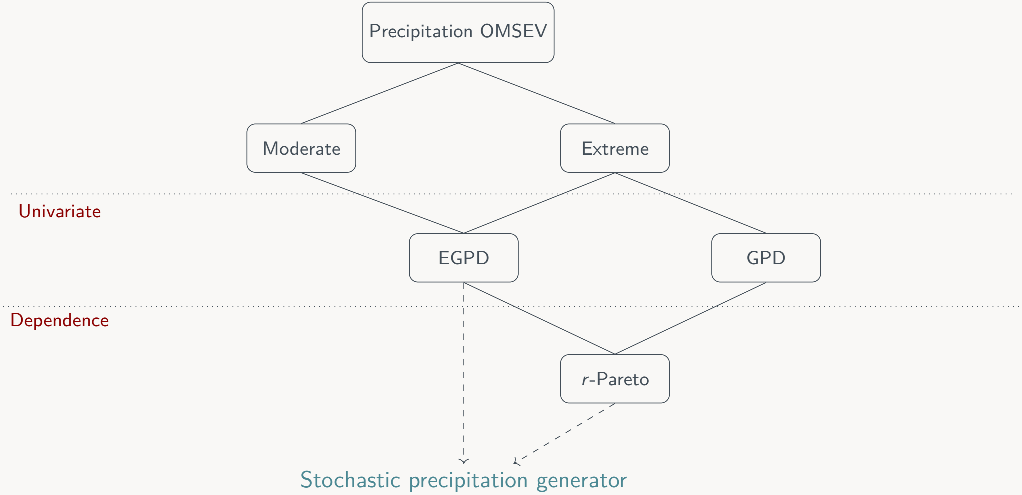
$t_0 + 1$

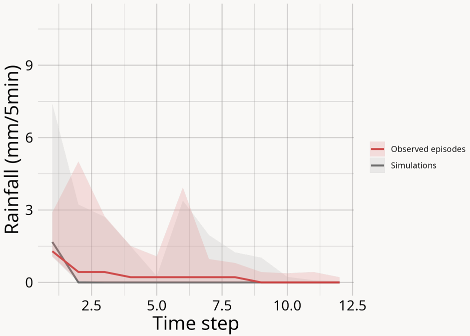
$\boldsymbol{V}^{\mathrm{emp}}$ is estimated from **rain storm barycenter displacement** within a time window.

Parameter estimates over $|\mathcal{E}| = 384$ episodes
$\widehat{\eta}_1 = 1.621$ and $\widehat{\eta}_2 = 5.219$ fixed (COMEPHORE)

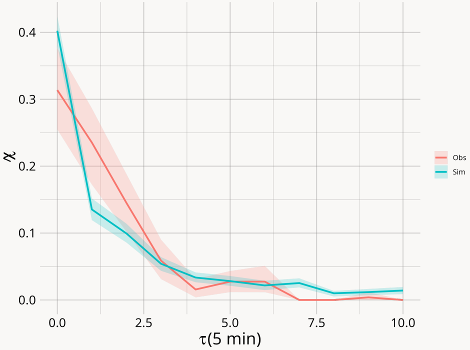


	km/h	m/5 min
$\widehat{\beta}_1$	1.090	0.230
$\widehat{\beta}_2$	4.628	0.786
$\widehat{\alpha}_1$	0.225	0.225
$\widehat{\alpha}_2$	0.713	0.713


Precipitation OMSEV
Moderate
Extreme
Univariate
EGPD
GPD
Dependence
r-Pareto
Stochastic precipitation generator

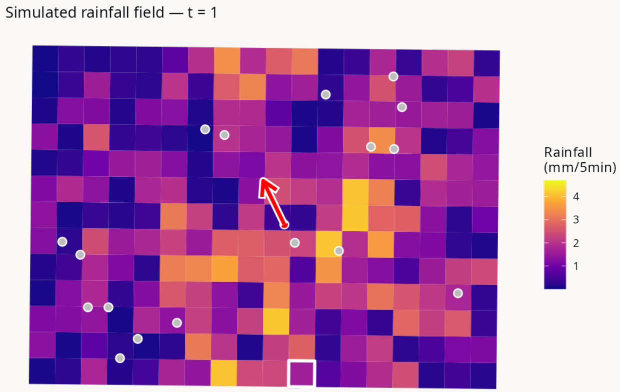


Simulations vs observations at all sites s_0



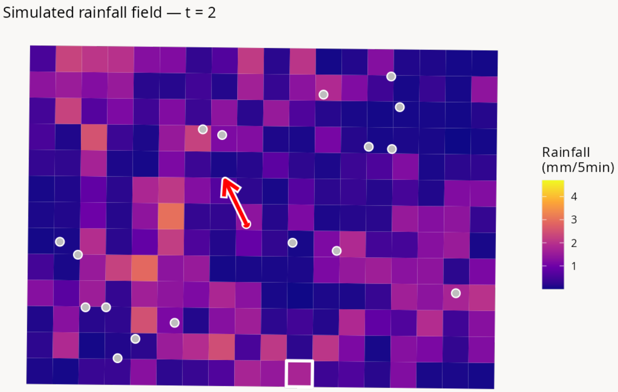
Temporal r-extremogram for fixed sites

100 simulations with significant advection speed > 1 km/h and South direction



Over the OMSEV network area

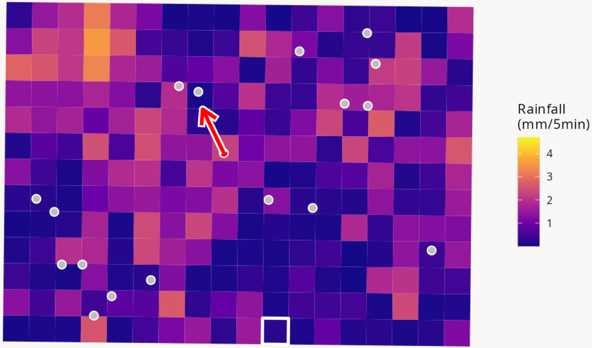
- Spatial resolution: 100 m × 100 m
- Temporal resolution: 5 min
- Stochastic rainfall simulation



Over the OMSEV network area

- Spatial resolution: 100 m $\times$ 100 m
- Temporal resolution: 5 min
- Stochastic rainfall simulation

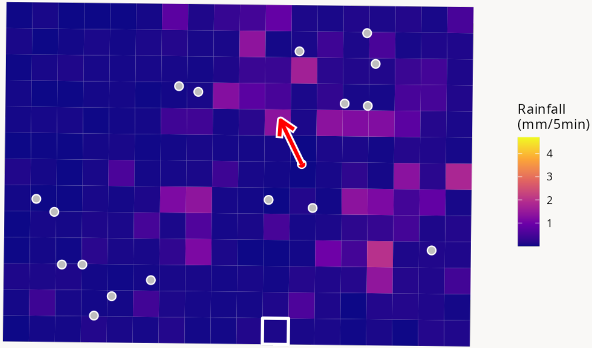
Simulated rainfall field — t = 3



Over the OMSEV network area

- Spatial resolution: 100 m $\times$ 100 m
- Temporal resolution: 5 min
- Stochastic rainfall simulation

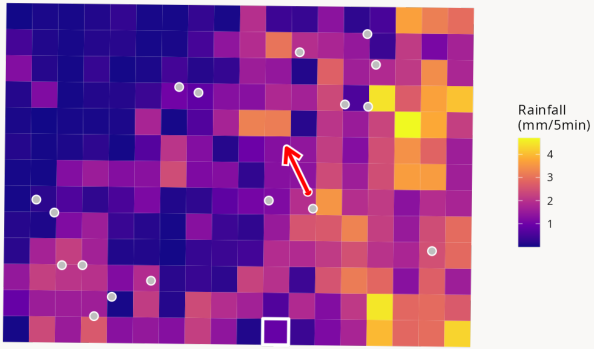
Simulated rainfall field — t = 4



Over the OMSEV network area

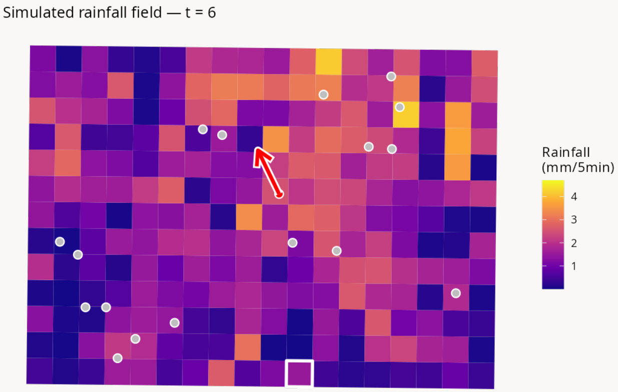
- Spatial resolution: 100 m × 100 m
- Temporal resolution: 5 min
- Stochastic rainfall simulation

Simulated rainfall field — t = 5



Over the OMSEV network area

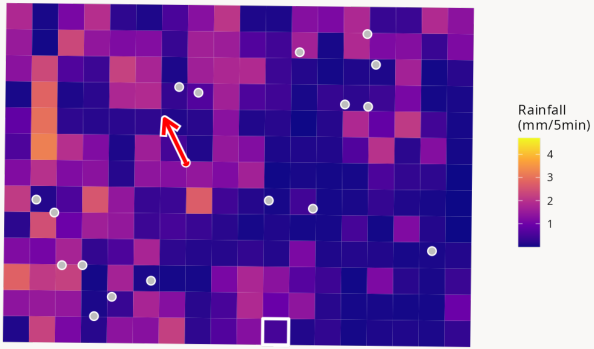
- Spatial resolution: 100 m $\times$ 100 m
- Temporal resolution: 5 min
- Stochastic rainfall simulation



Over the OMSEV network area

- Spatial resolution: 100 m × 100 m
- Temporal resolution: 5 min
- Stochastic rainfall simulation

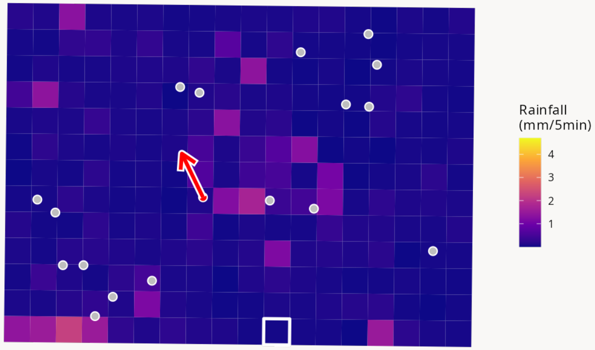
Simulated rainfall field — t = 7



Over the OMSEV network area

- Spatial resolution: 100 m $\times$ 100 m
- Temporal resolution: 5 min
- Stochastic rainfall simulation

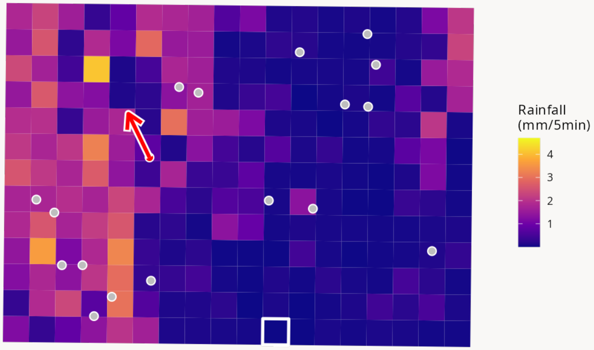
Simulated rainfall field — t = 8



Over the OMSEV network area

- Spatial resolution: 100 m $\times$ 100 m
- Temporal resolution: 5 min
- Stochastic rainfall simulation

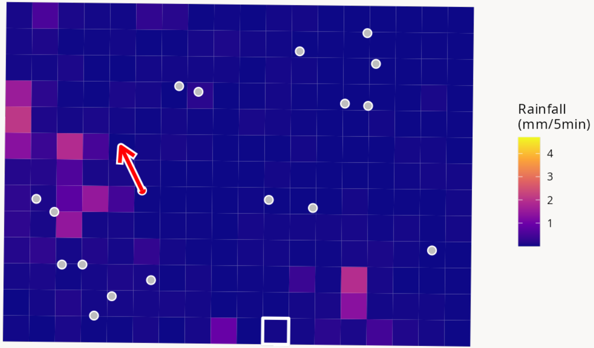
Simulated rainfall field — t = 9



Over the OMSEV network area

- Spatial resolution: 100 m $\times$ 100 m
- Temporal resolution: 5 min
- Stochastic rainfall simulation

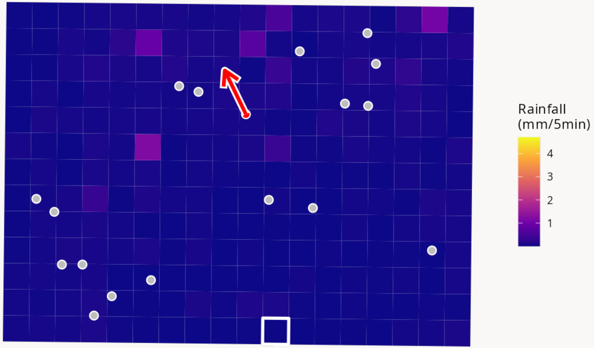
Simulated rainfall field — t = 10



Over the OMSEV network area

- Spatial resolution: 100 m $\times$ 100 m
- Temporal resolution: 5 min
- Stochastic rainfall simulation

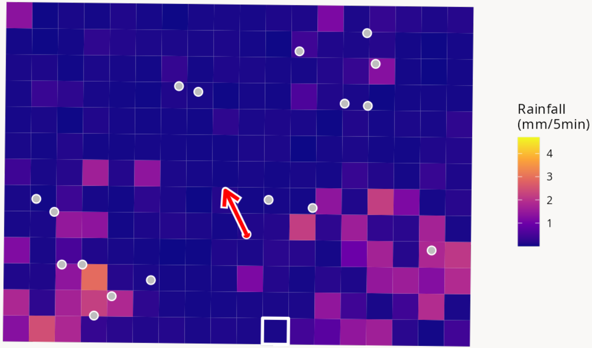
Simulated rainfall field — t = 11



Over the OMSEV network area

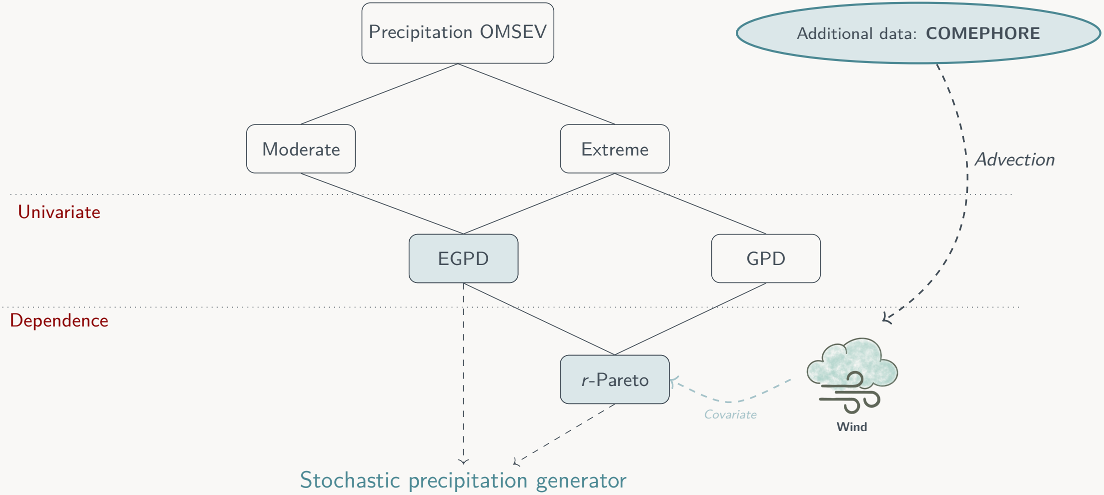
- Spatial resolution: 100 m $\times$ 100 m
- Temporal resolution: 5 min
- Stochastic rainfall simulation

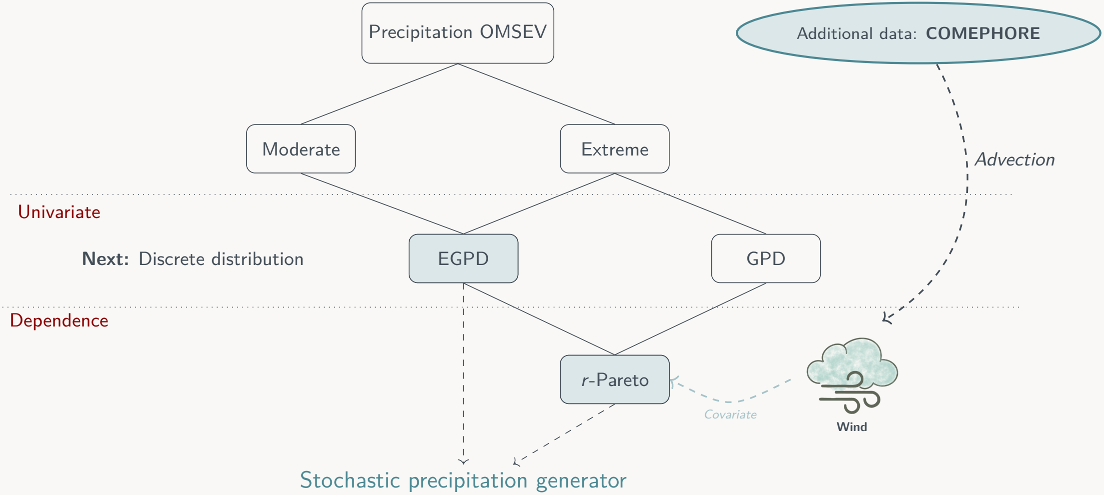
Simulated rainfall field — t = 12

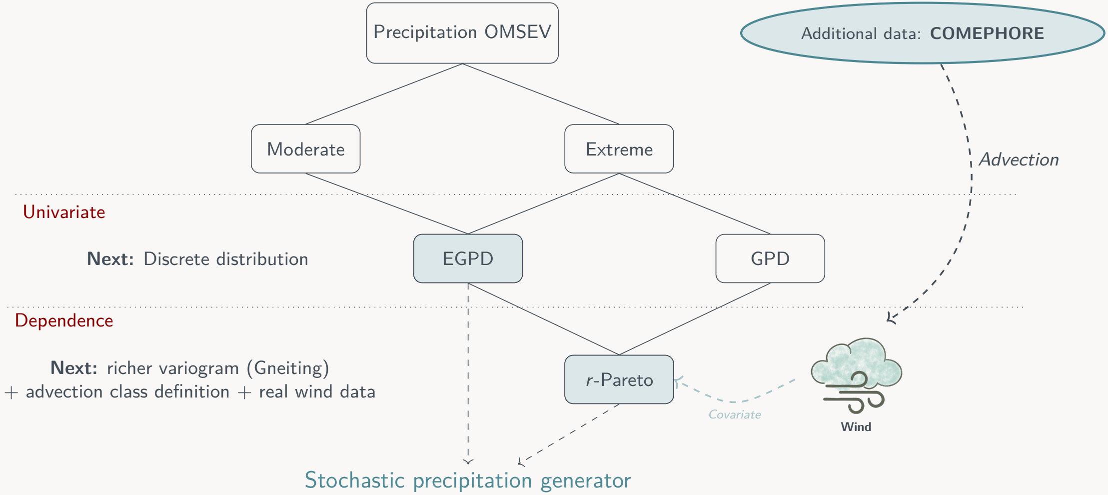


Over the OMSEV network area

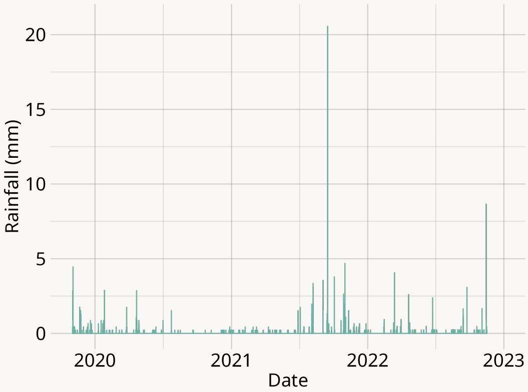
- Spatial resolution: 100 m × 100 m
- Temporal resolution: 5 min
- Stochastic rainfall simulation

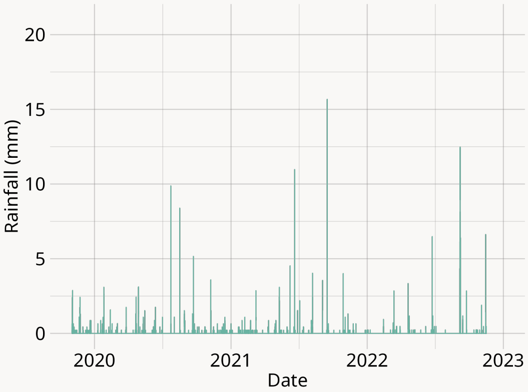

Precipitation OMSEV
Additional data: COMEPHORE
Moderate
Extreme
Advection
Univariate
EGPD
GPD
Dependence
r-Pareto
Covariate
Wind
Stochastic precipitation generator


Precipitation OMSEV
Additional data: COMEPHORE
Moderate
Extreme
Advection
Univariate
Next: Discrete distribution
EGPD
GPD
Dependence
r-Pareto
Covariate
Wind
Stochastic precipitation generator


Precipitation OMSEV
Additional data: **COMEPHORE**
Moderate
Extreme
Advection
Univariate
Next: Discrete distribution
EGPD
GPD
Dependence
Next: richer variogram (Gneiting)
+ advection class definition + real wind data
r-Pareto
Covariate
Wind
Stochastic precipitation generator

References





Rainfall amounts on CNRS and Polytech rain gauges

Generalized Pareto Distribution ⟶ **Extended GPD**[1]

$$\overline{H}_\xi\left(\frac{x-u}{\sigma}\right) = \begin{cases} \left(1+\xi\frac{x-u}{\sigma}\right)_+^{-1/\xi} & \text{if } \xi \neq 0\,, \\ e^{-\frac{x-u}{\sigma}} & \text{if } \xi = 0\,, \end{cases}$$

where $a_+ = \max(a, 0)$, $\sigma > 0$, $x - u > 0$

- Models extreme precipitation
- Depends on a threshold choice

$$F(x) = G\left(H_\xi\left(\frac{x}{\sigma}\right)\right),$$

where $G(x) = x^\kappa$, $\kappa > 0$

- Models **moderate and extreme** precipitation
- Avoids a threshold choice

[1] **naveau_modeling_2016**