Integrating physics into stochastic weather generators for extreme rainfall assessment

Nadav Peleg

Hydrometeorology and Surface Processes

University of Lausanne

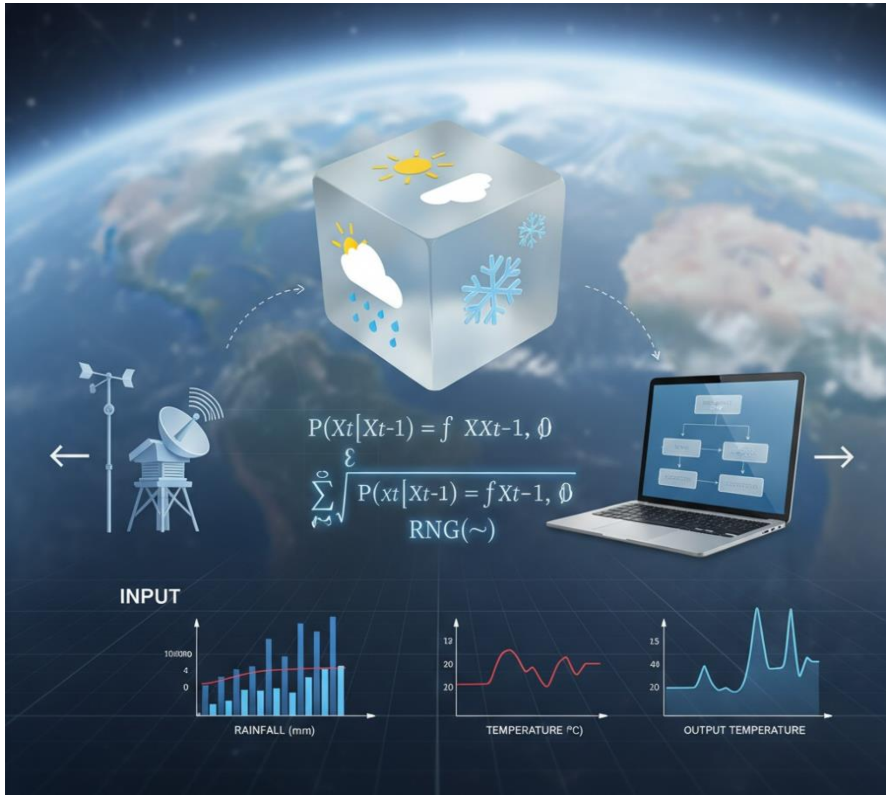
SWGEN 2025, Grenoble

December 2nd, 2025

Unil.

Weather generators

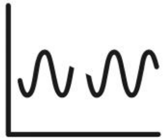
- A statistical model that stochastically produces synthetic time series of meteorological variables (precipitation, temperature, …)
- **Temporal resolution:** minutes to decades
- **Dimension:** point scale (1D) → multiple sites → gridded fields (2D)
- **Spatial resolution:** meters to hundreds of kilometers



Weather generators

Extending short climate records

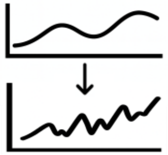
Exploring rare, unprecedented, and compound climatic events

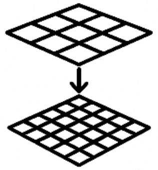


Stochastic gap filling of climatic variables

Climate change impact studies

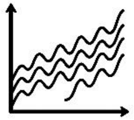
Temporal disaggregation of time series





Statistical downscaling

Uncertainty and internal variability analysis



Weather generators

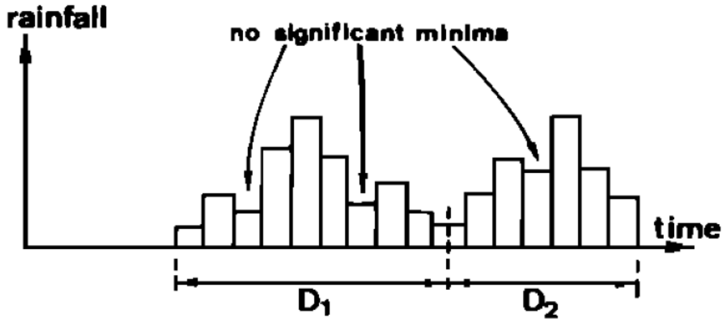
Historical perspective

WATER RESOURCES RESEARCH, VOL. 22, NO. 4, PAGES 475–482, APRIL 1986

A Point Rainfall Generator With Internal Storm Structure

J. L. MARIEN AND G. L. VANDEWIELE

Center for Statistics and Operations Research and Laboratory of Hydrology, Free University of Brussels, Belgium



Weather generators

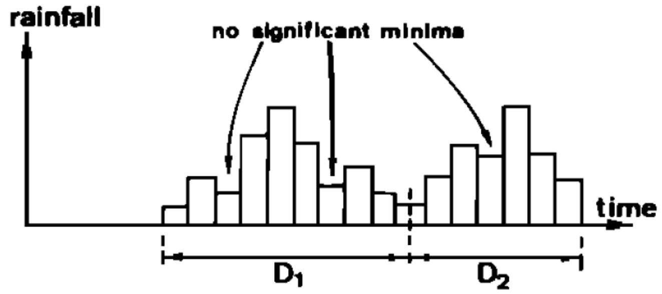
Historical perspective

WATER RESOURCES RESEARCH, VOL. 22, NO. 4, PAGES 475–482, APRIL 1986

A Point Rainfall Generator With Internal Storm Structure

J. L. Marien and G. L. Vandewiele

Center for Statistics and Operations Research and Laboratory of Hydrology, Free University of Brussels, Belgium



PROCEEDINGS SYMPOSIUM ON STATISTICAL HYDROLOGY

Held at Tucson, Arizona
August 31–September 2, 1971

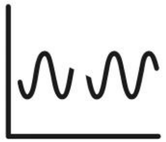
A Precipitation Data Simulator Using a Second Order Autoregressive Scheme, by E. H. Wiser..................................
Cross Spectra of Short-Duration Rainfall, by D. M. Hershfield and B. Levy..............
Hourly Rainfall Generation for a Network, by D. D. Franz..................................
Stochastic Generation of the Occurrence, Pattern, and Location of Maximum Amount of Daily Rainfall, by A. D. Nicks ...
Comments on the Statistical Distribution of Rainfall per Period Under Various Transformations, by P. Skees and L. R. Shenton..
Stochastic Models of Spatial and Temporal Distribution of Thunderstorm Rainfall, by H. B. Osborn, L. J. Lane, and R. S. Kagan...
Stochastic Model of Daily Rainfall, by P. Todorovic and D. A. Woolhiser..............
An Event-Based Stochastic Model of Areal Rainfall and Runoff, by M. M. Fogel, L. Duckstein and J. L. Sanders ....

Weather generators

Extending short climate records

Exploring rare, unprecedented, and compound ~~climatic~~ events

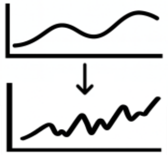
rainfall

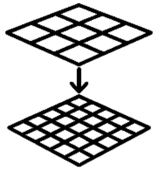


Stochastic gap filling of climatic variables

Climate change impact studies

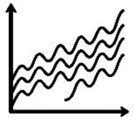
Temporal disaggregation of time series





Statistical downscaling

Uncertainty and internal variability analysis

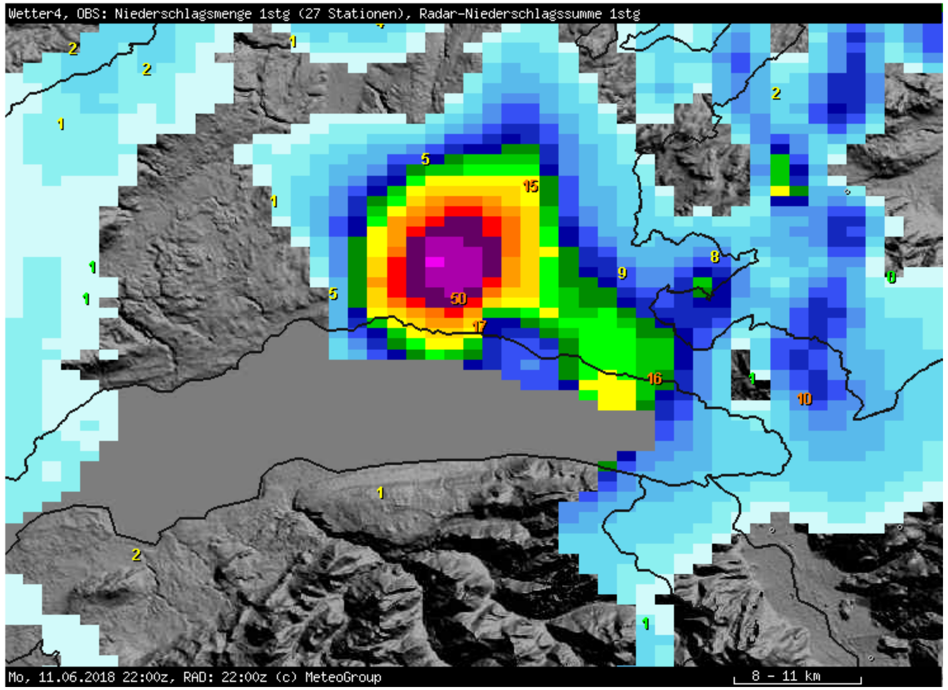



Intense short-duration (convective) rainfall

Impacts of short-duration extreme rainfall

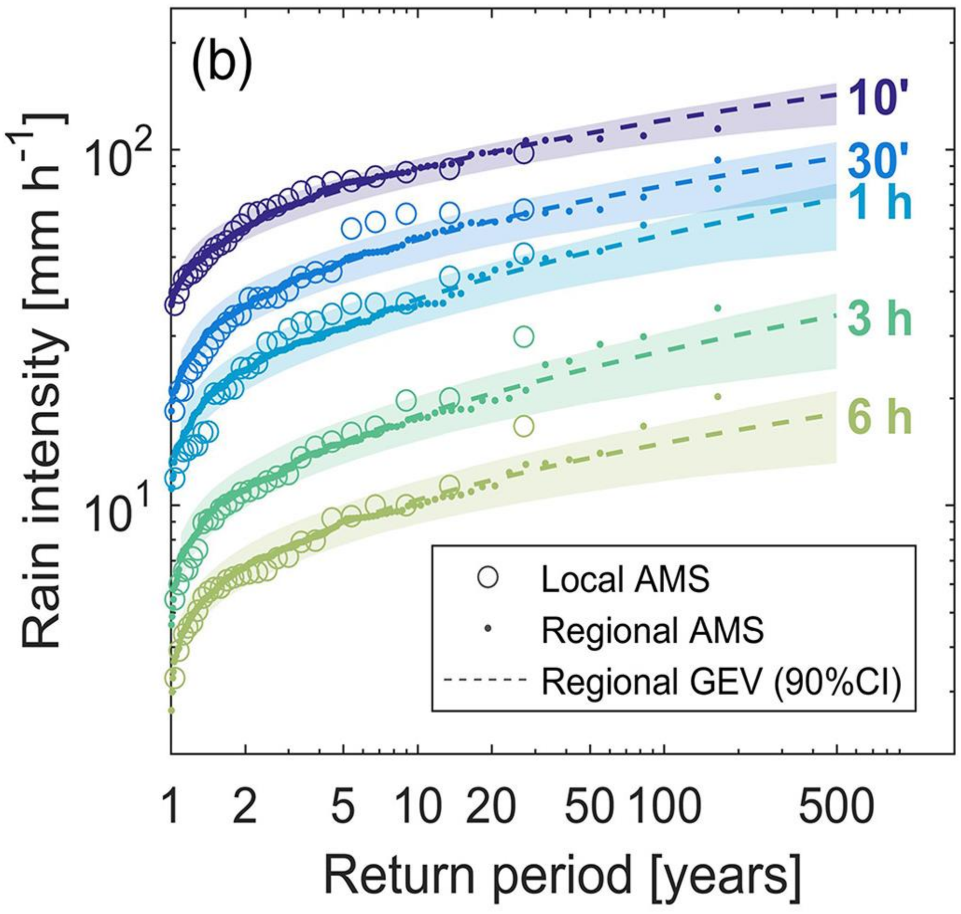
The heavy storm of 11th June 2018 at Lausanne

(Swiss record high of 41 mm per 10 min rainfall)



Rainfall extremes

- Planning urban drainage systems commonly relies on **intensity–duration–frequency (IDF) curves**
- These curves are computed from annual rainfall maxima and require long records (>30 years)
- Are WG can be used to create reliable IDF curves?

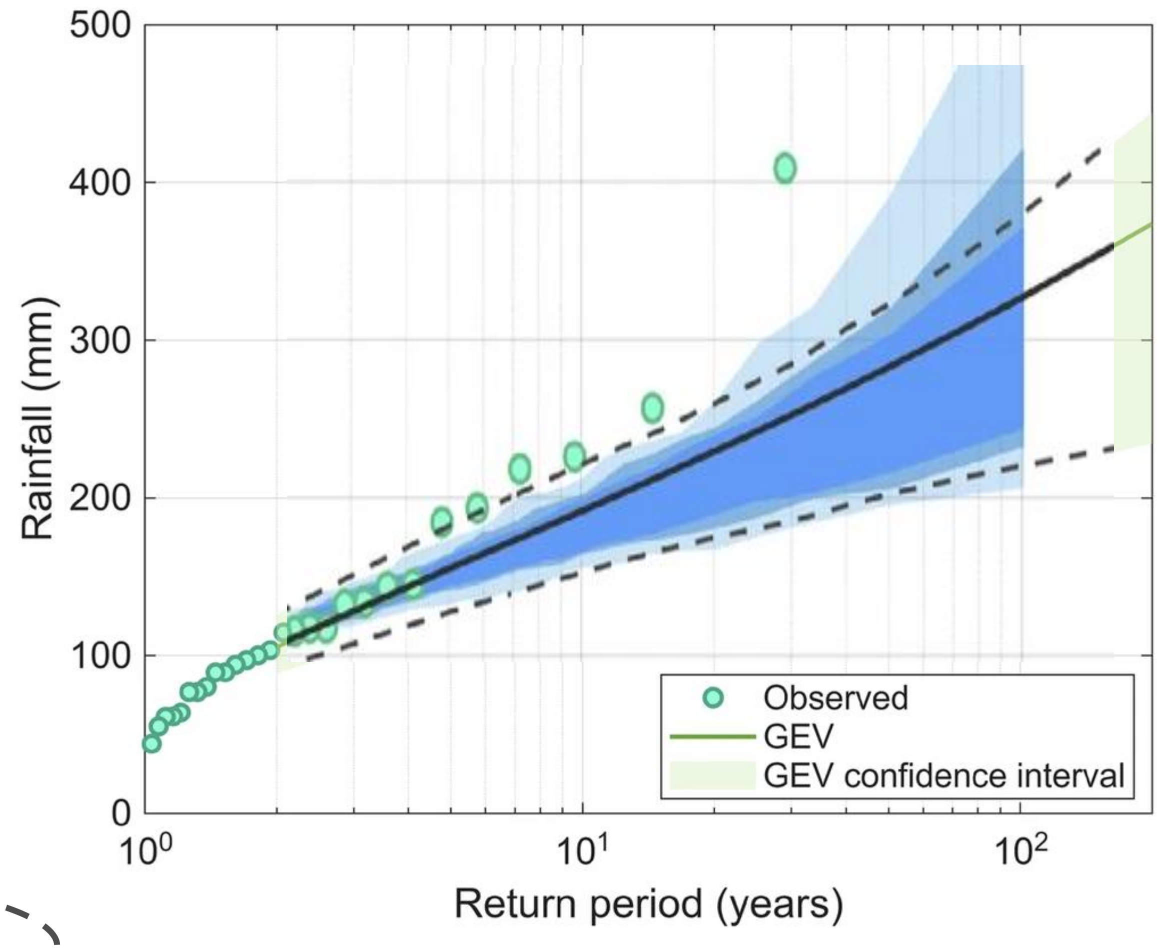


Marra et al. *GRL* **2020**

Rainfall extremes

… Yes!

And even, if properly representing the natural (internal) climate variability, reliably capture yet unseen rainfall extremes

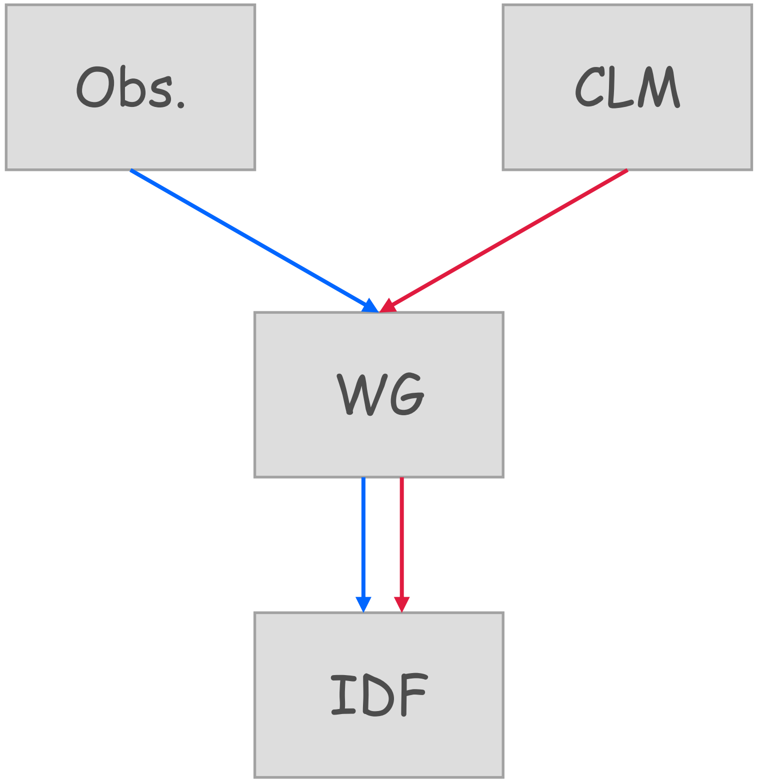


Record-breaking rainfall: a stochastic approach for its prediction

Chen et al. *npj Natural Hazards* **2025**

Rainfall extremes

- Future IDFs are typically derived from climate model outputs
- But climate models* do not solve deep convection



*Besides convection-permitting models

Rainfall physics 101

Rainfall depends on:

- **Vertical velocity** – Dynamics

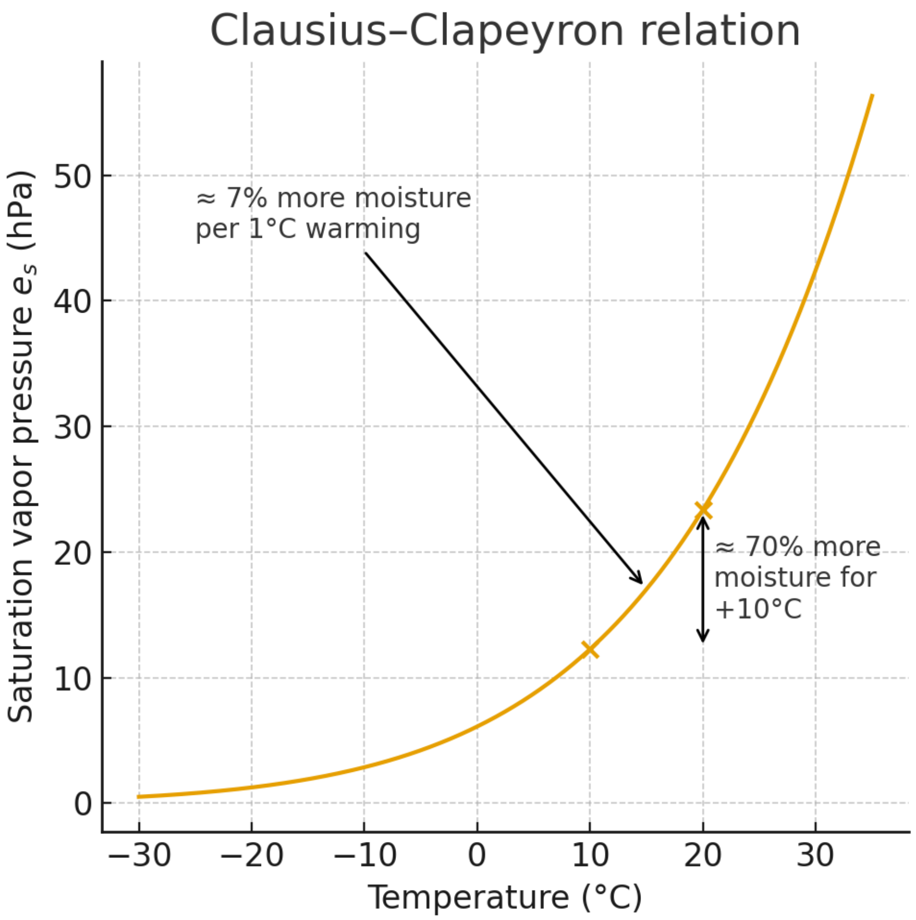
  how much water is condensed

- **Efficiency** – Microphysics

  how much condensation precipitates

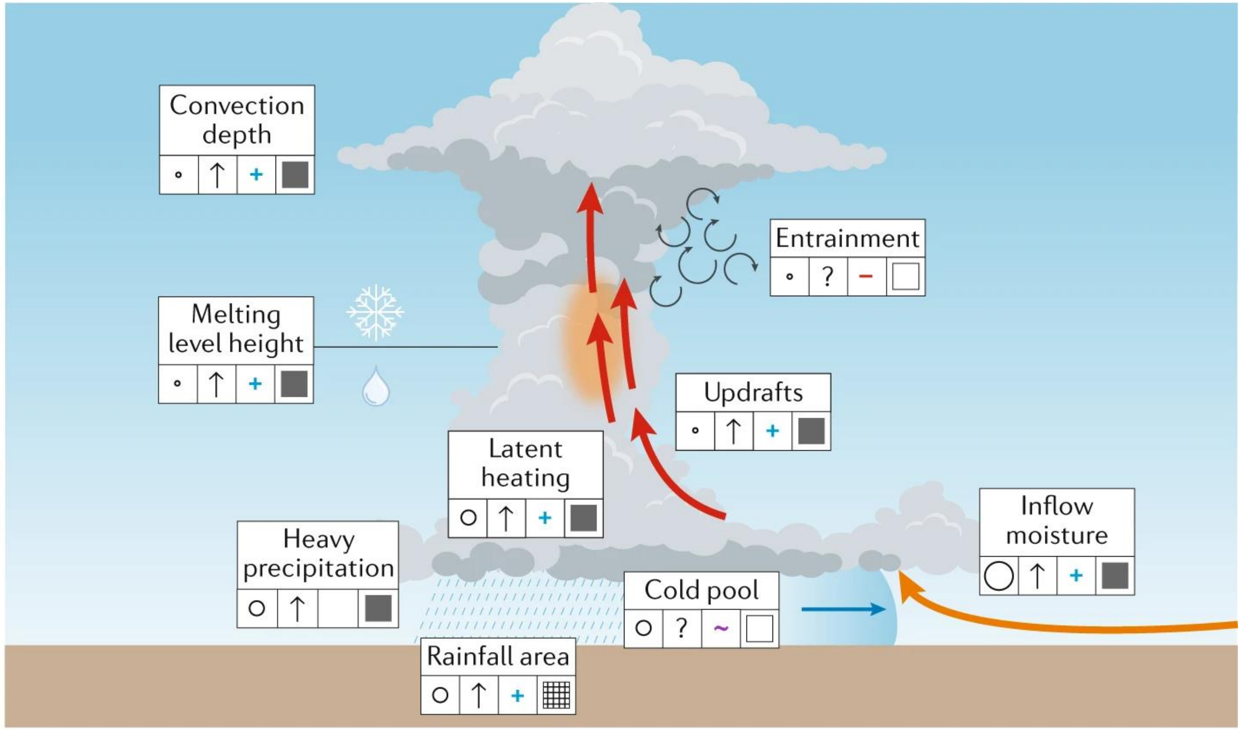
- **Moisture content** – Thermodynamics

  how much water is available

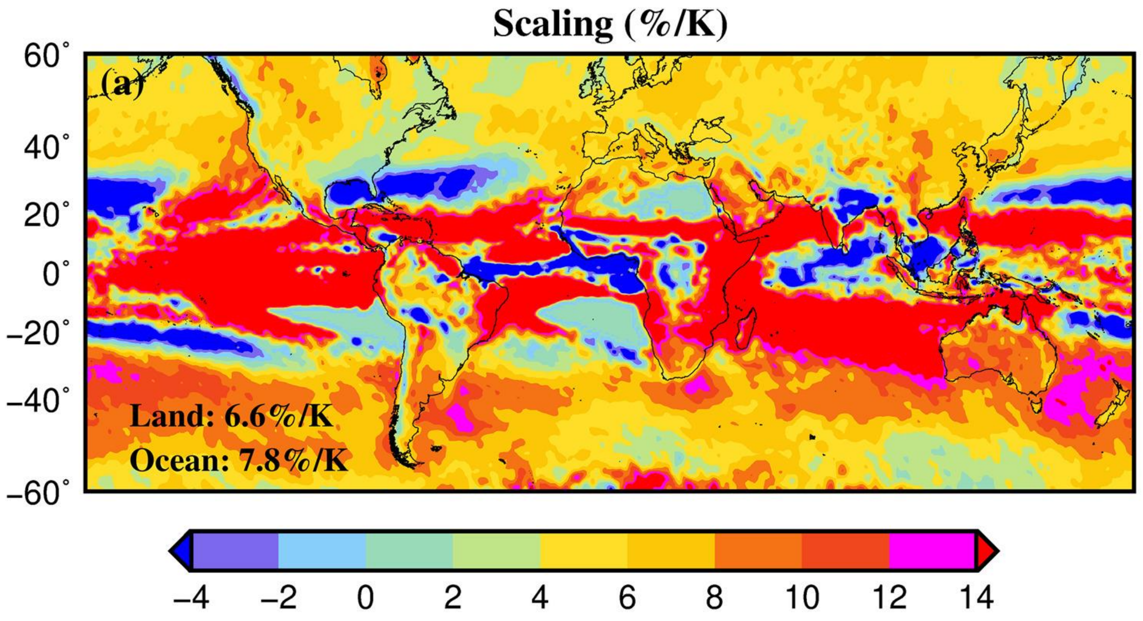


Thermodynamic processes driving extreme rainfall intensification

On a global scale, extreme sub-daily rainfall intensity is expected to rise by about **7% per degree of warming**, following the Clausius–Clapeyron relation



Fowler et al., *Nature Rev.* 2021



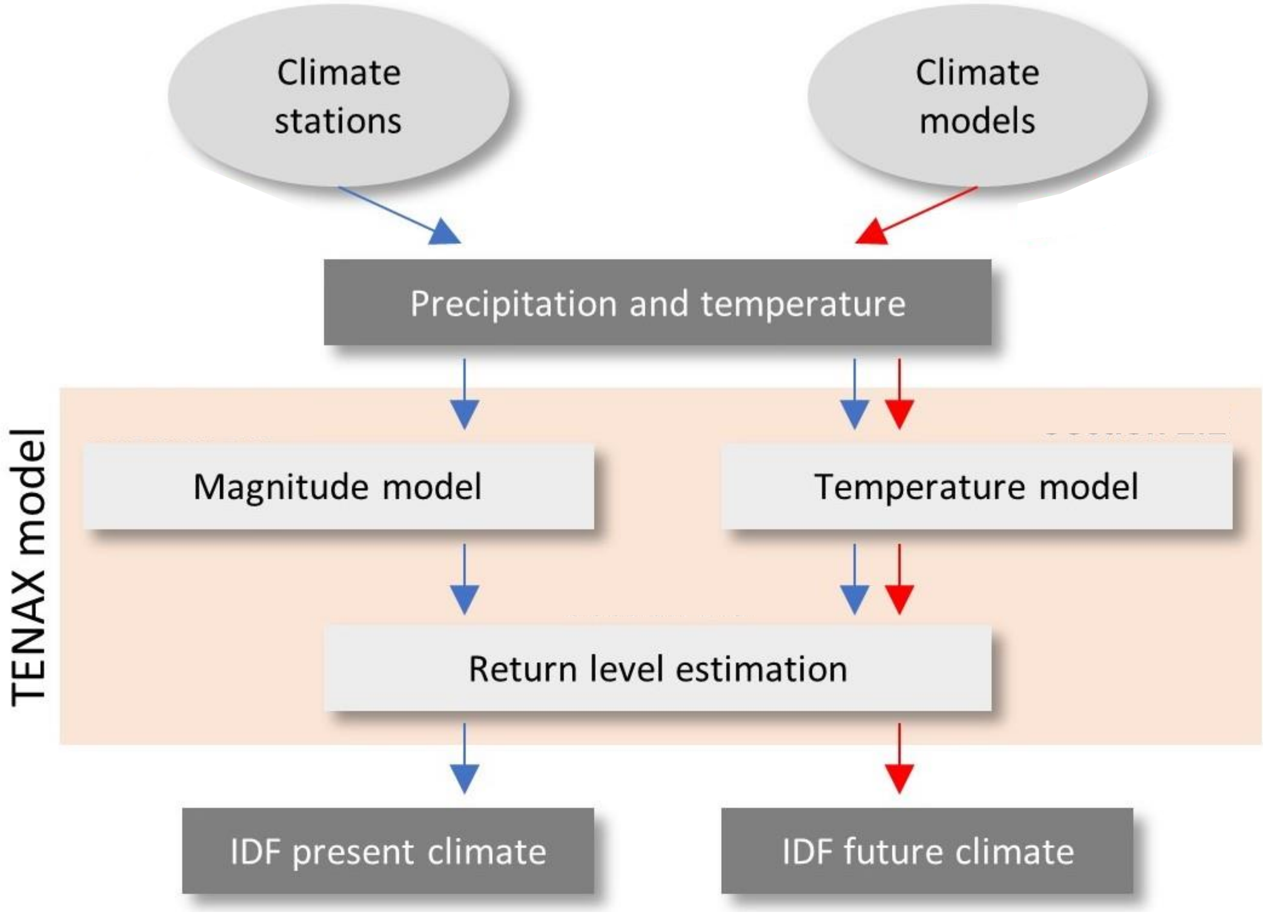
Ali et al. *GRL* 2021

Can we use temperature as a covariate in weather generator models to better constrain and predict rainfall extremes?

The TENAX model

The TENAX model

- We developed the **TE**mperature-dependent **N**on-**A**symptotic statistical model for e**X**treme return levels (**TENAX**)
- A **parsimonious** non-stationary and non-asymptotic theoretical framework that incorporates **temperature as a covariate** in a physically consistent manner



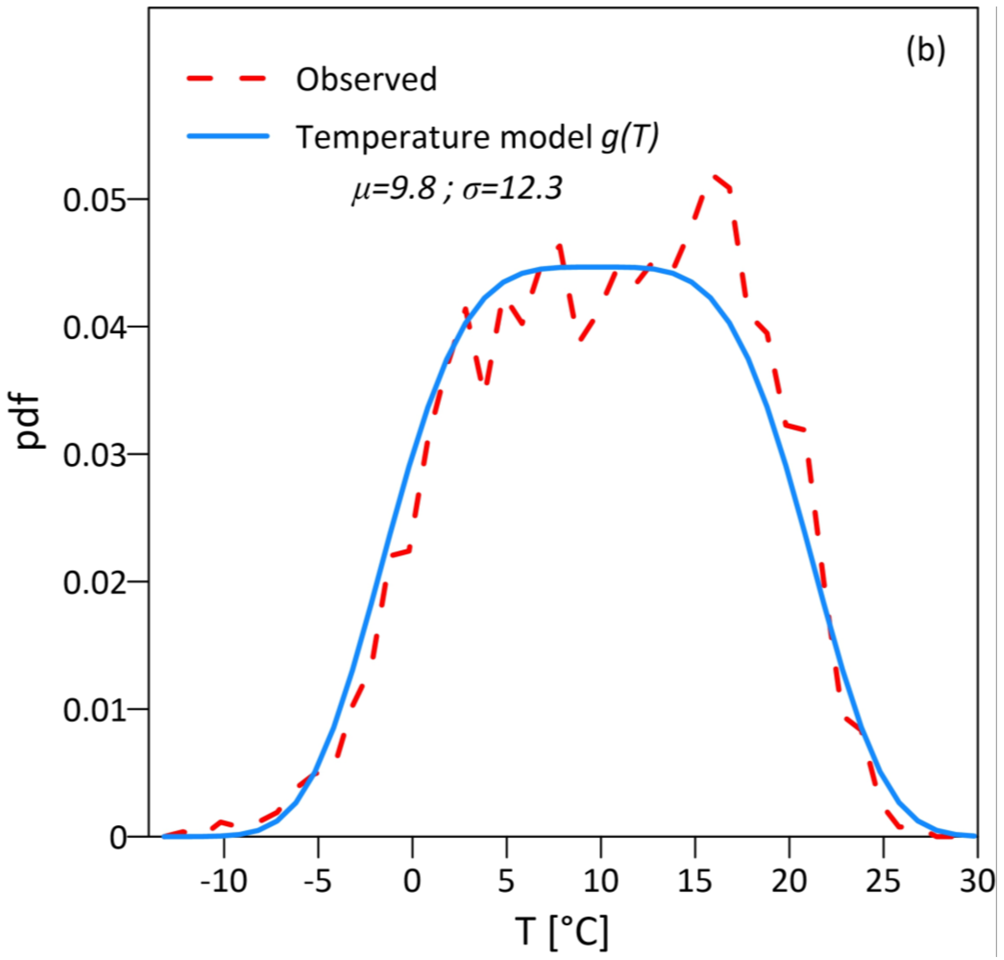
Marra et al. *HESS* 2024

TENAX: Temperature model

- The average temperatures observed during 24 hours preceding the peak intensities are described by a Generalized Gaussian distribution

$$g(T) = \frac{2}{\sigma\Gamma\left(\frac{1}{\beta}\right)} \exp\left[-\left(\frac{T-\mu}{\sigma}\right)^{\beta}\right]$$

μ – location, σ – scale , β – shape



Marra et al. *HESS* **2024**

TENAX: Precipitation event magnitude model

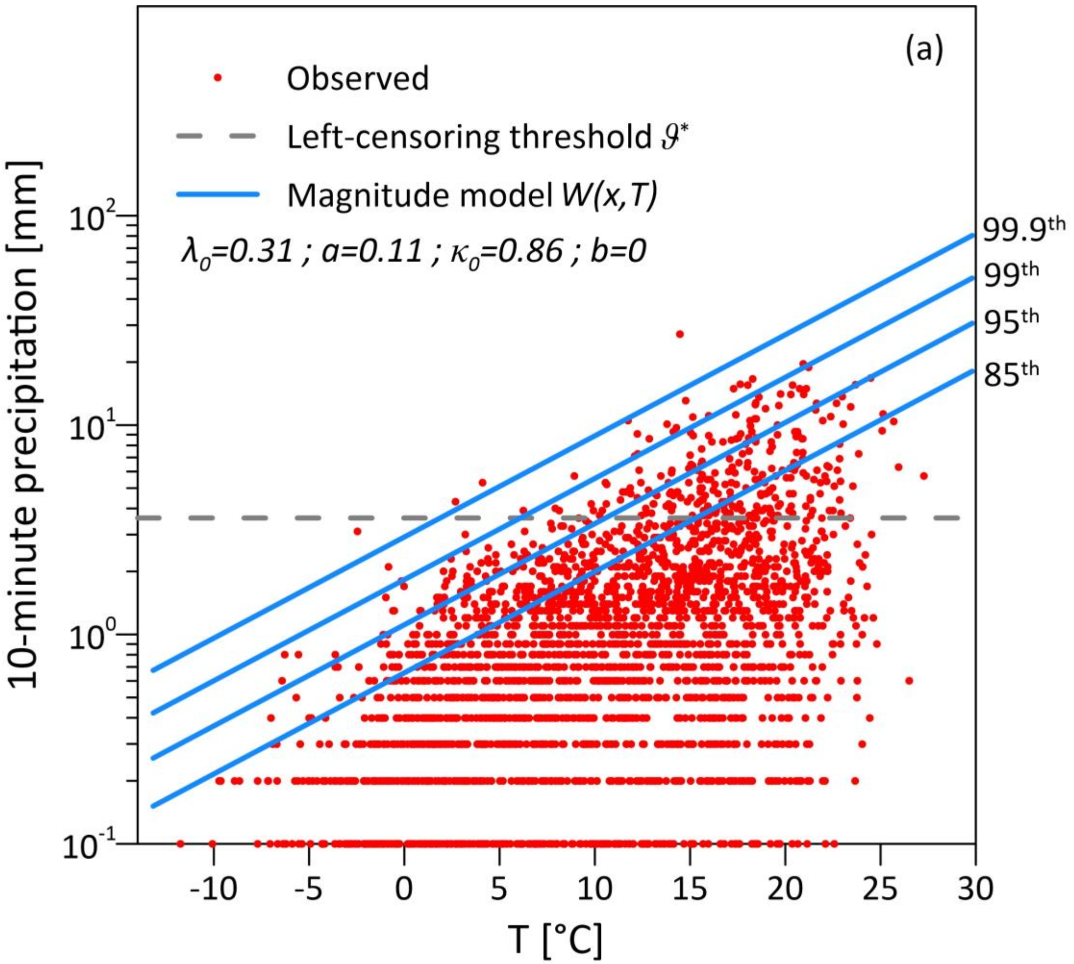
- We use the Weibull distribution, explicitly dependent on **temperature as covariate**, to model the magnitudes of sub-hourly ordinary precipitation events

$$W(x;T) = 1 - \exp\left(-\left[\frac{x}{\lambda(T)}\right]^{\kappa(T)}\right)$$

λ(T) – scale , κ(T) – shape

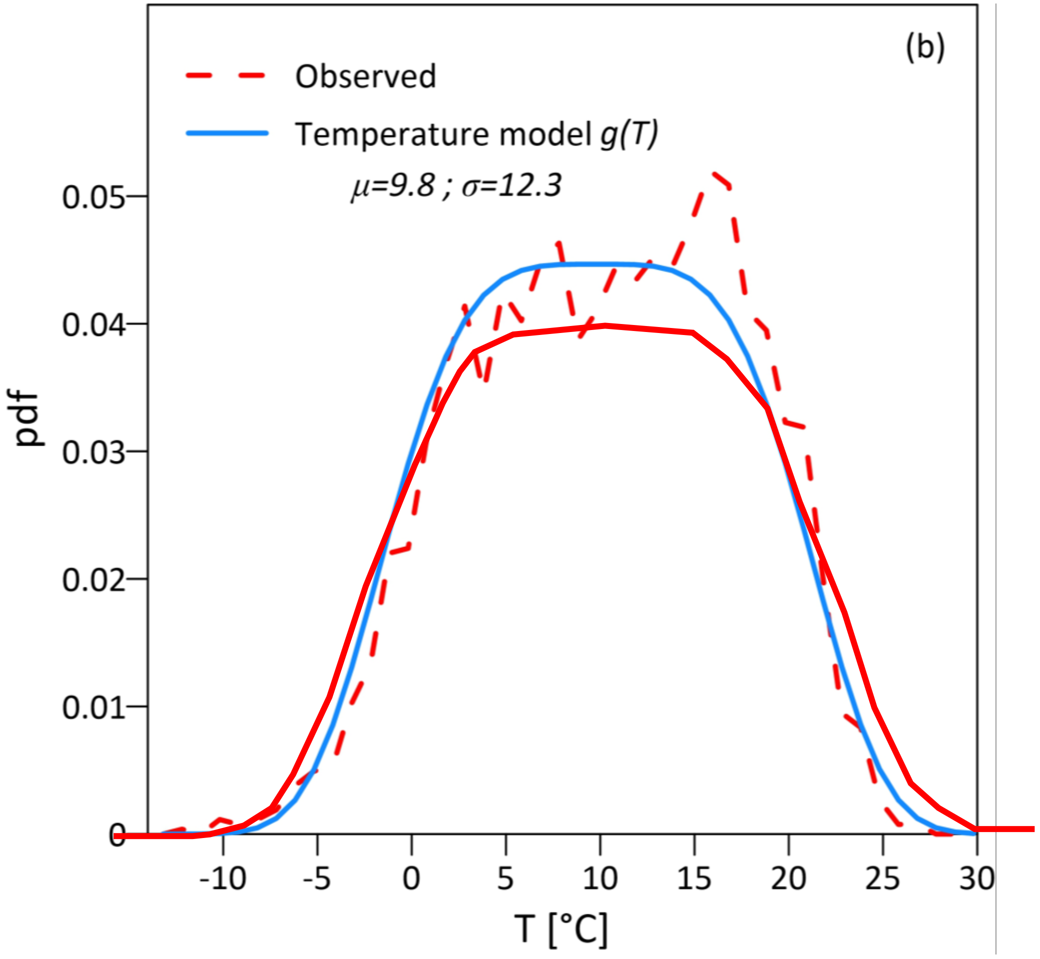
$$\lambda(T) = \lambda_0 e^{aT}$$

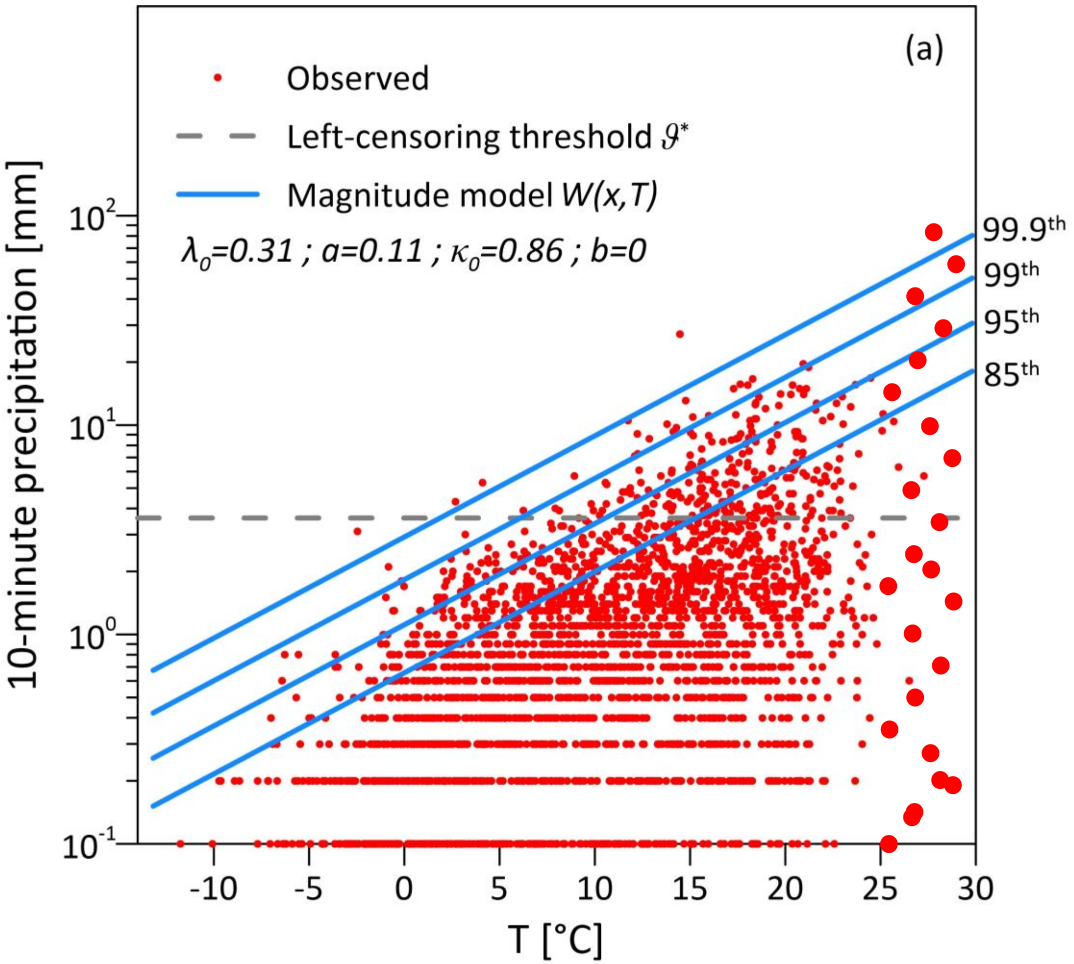
$$\kappa(T) = \kappa_0 + bT$$



Marra et al. *HESS* **2024**

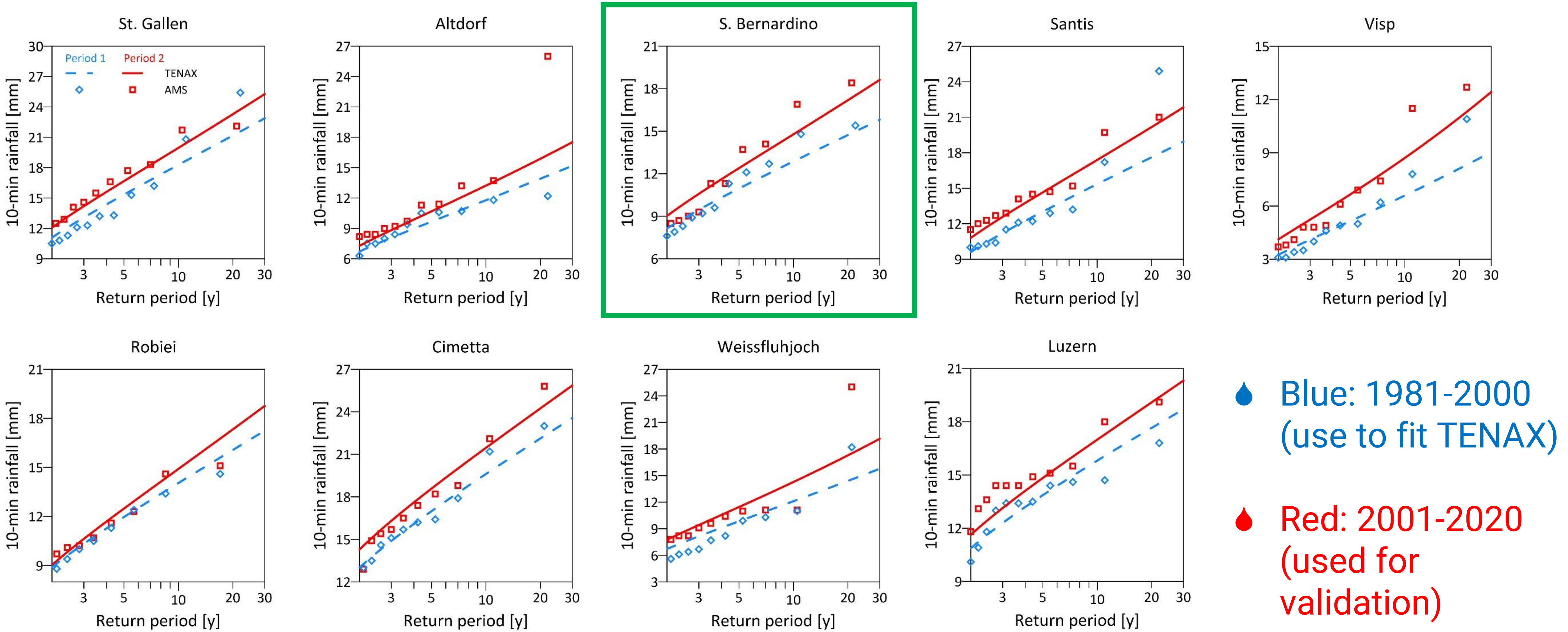
TENAX: Projections





Marra et al. *HESS* **2024**

TENAX: evaluation (hindcast, 10-min)

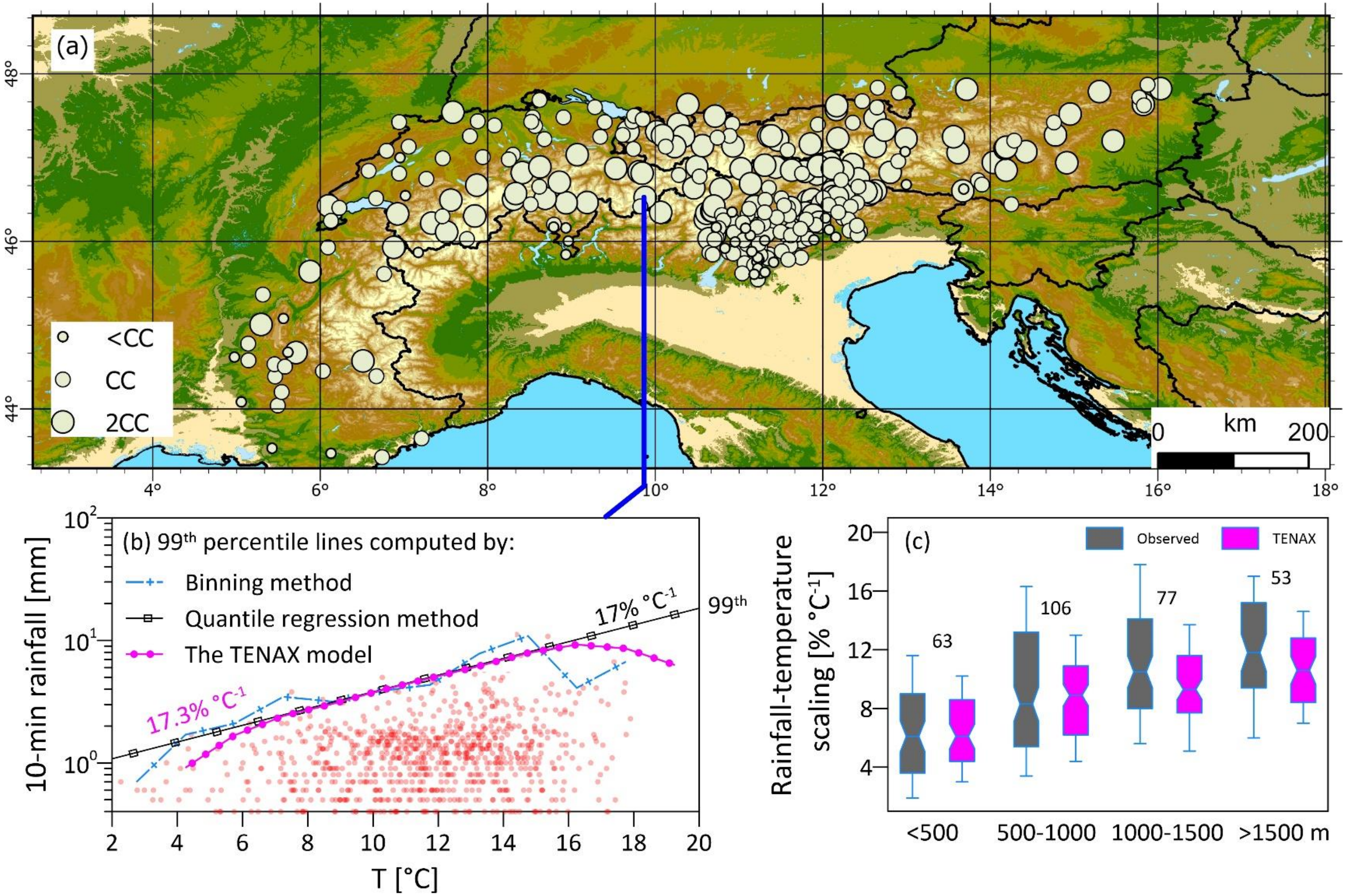


- Blue: 1981-2000 (use to fit TENAX)
- Red: 2001-2020 (used for validation)

Peleg et al. *npj Clim. Atmos. Sci.* **2025**

Rainfall intensification over the Alpine region

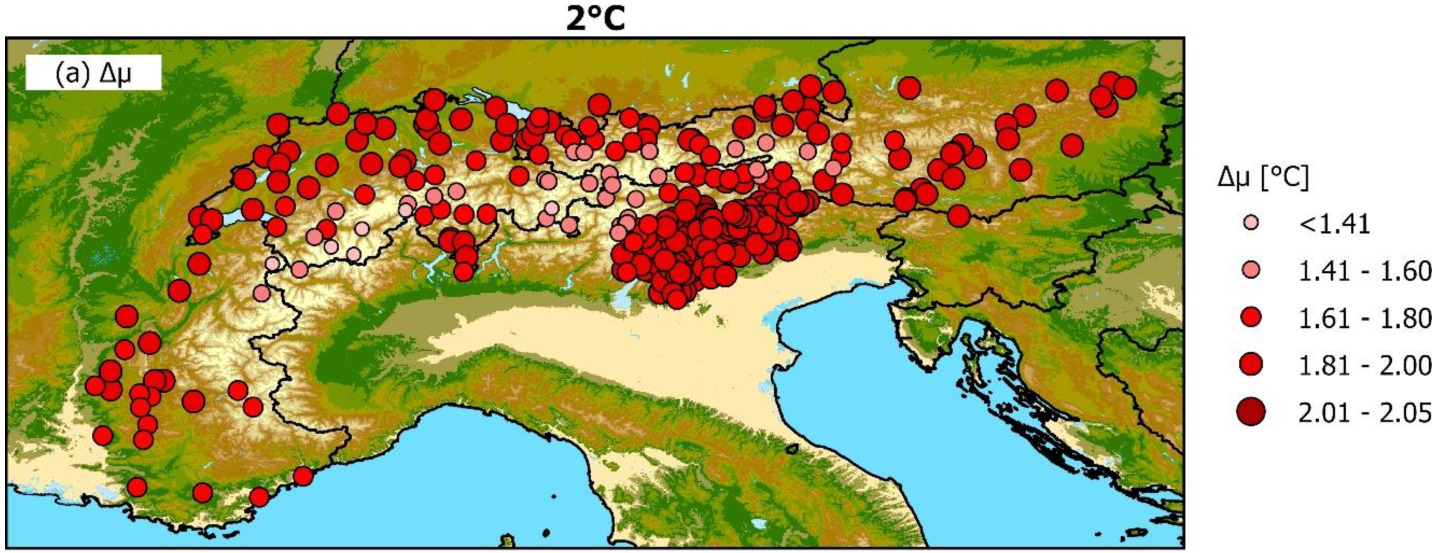
- 299 climate stations from France, Switzerland, Italy, Germany, and Austria
- Summer convective rainfall
- Rainfall–temperature scaling increases with elevation



Peleg et al. *npj Clim. Atmos. Sci.* **2025**

Rainfall intensification over the Alpine region

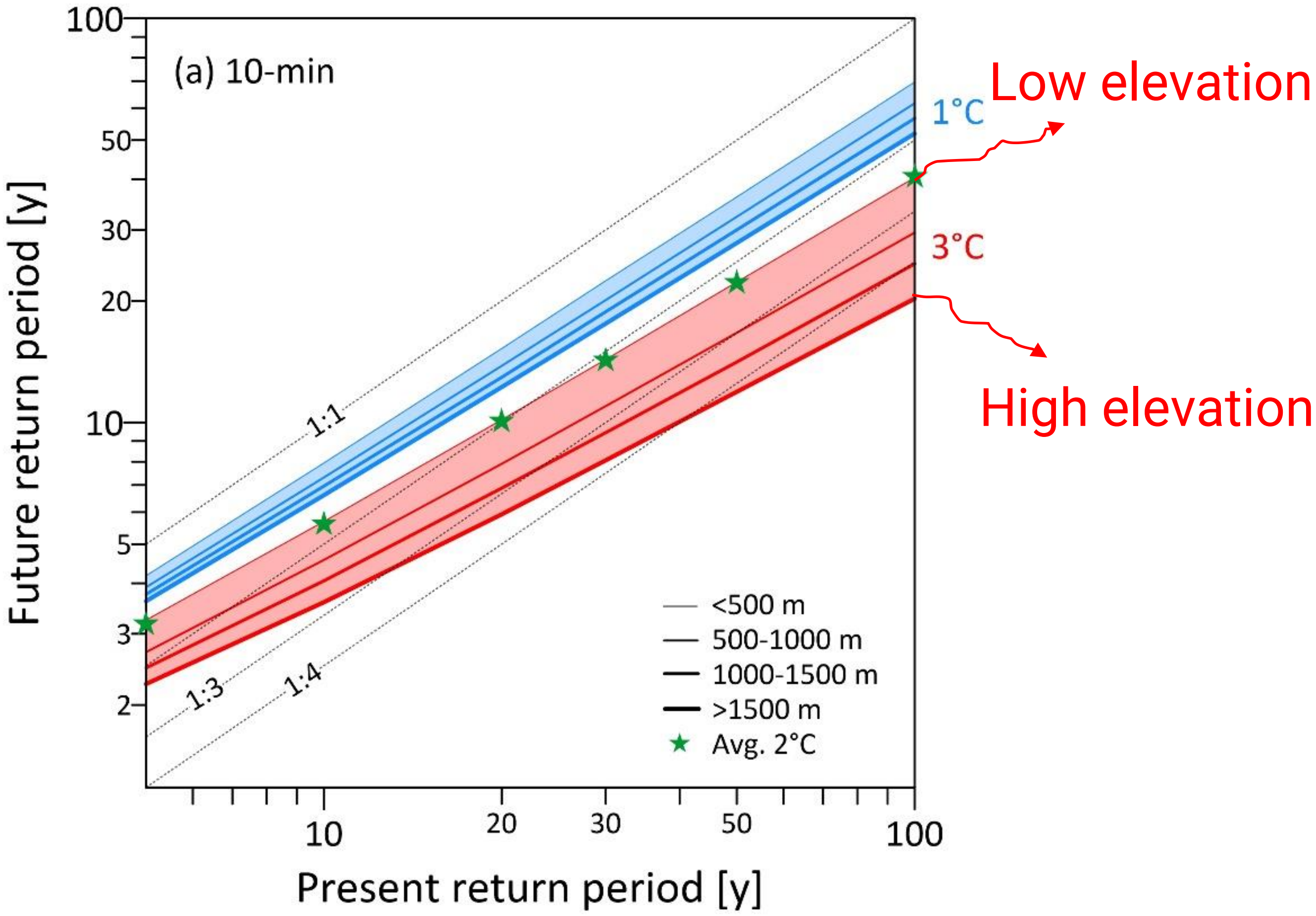
- Regional Warming Levels of 1°C, 2°C, and 3°C warming over the Alps were derived
- Outputs from 17 regional climate models of the EURO-CORDEX project were used for this purpose



Peleg et al. *npj Clim. Atmos. Sci.* **2025**

Rainfall intensification over the Alpine region

- Sub-daily rainfall in the Alpine region is projected to intensify with rising regional temperatures
- The intensification is more pronounced at higher elevations

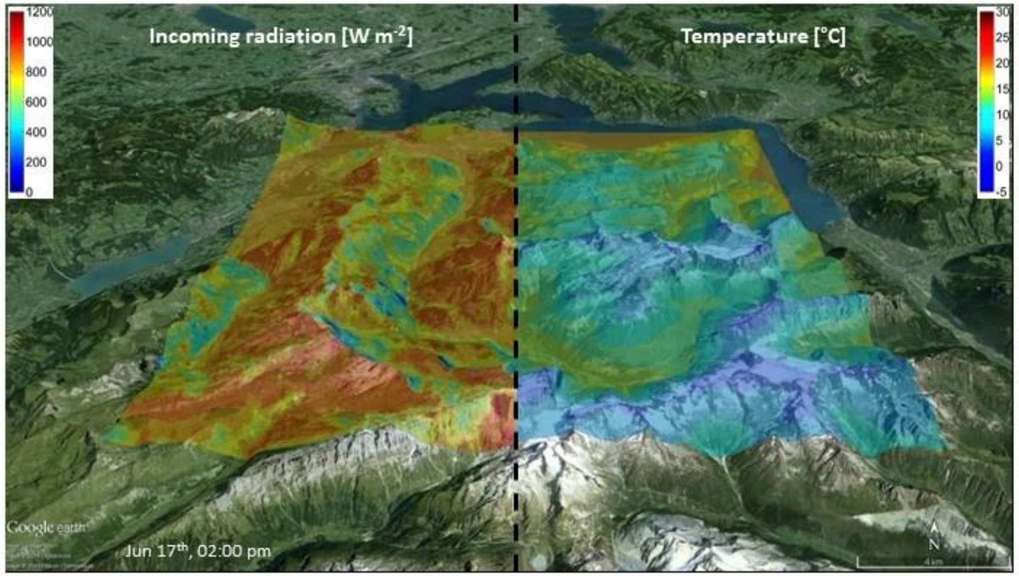


Peleg et al. *npj Clim. Atmos. Sci.* **2025**

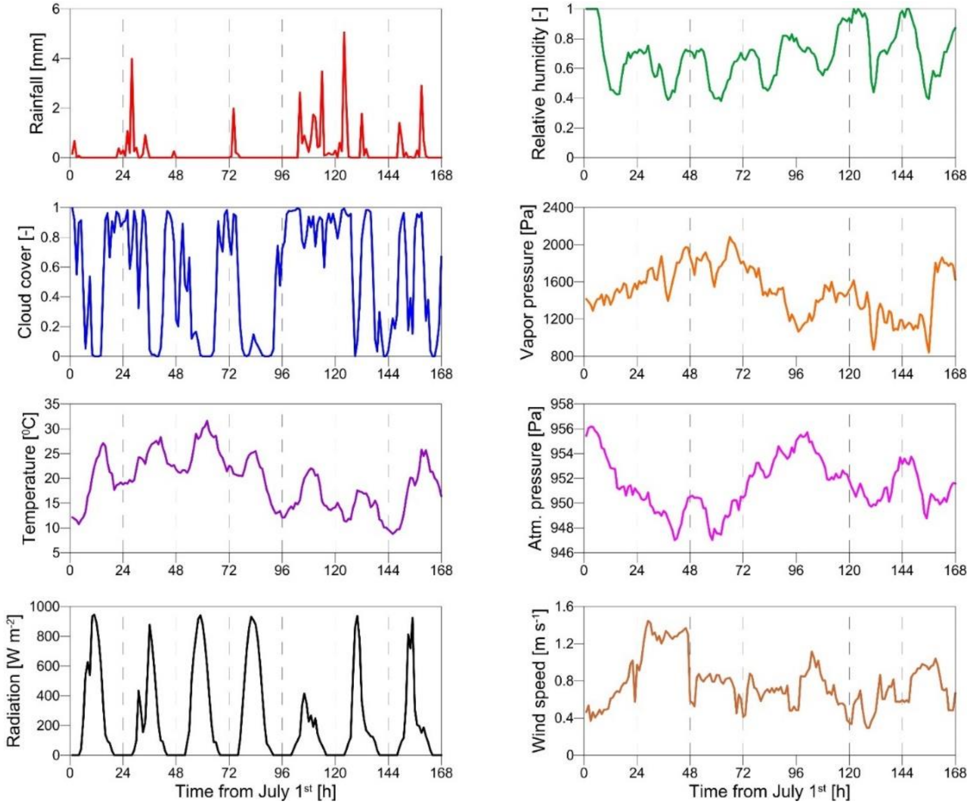
The AWE-GEN-2d-CC model

AWE-GEN-2d in a nutshell

AWE-GEN-2d follows the philosophy of combining **physical and stochastic approaches** to generate gridded climate variables in a high spatial and temporal resolution



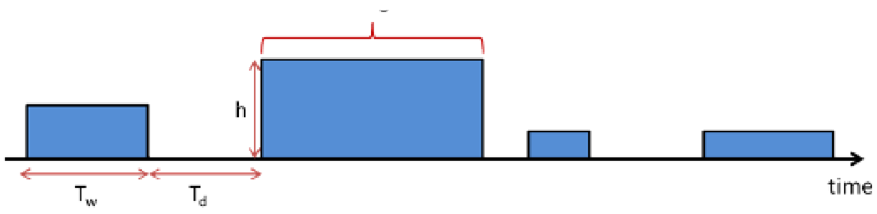
The AWE-GEN-2d (**A**dvanced **WE**ather **GEN**erator for **2-D**imensional grid) model



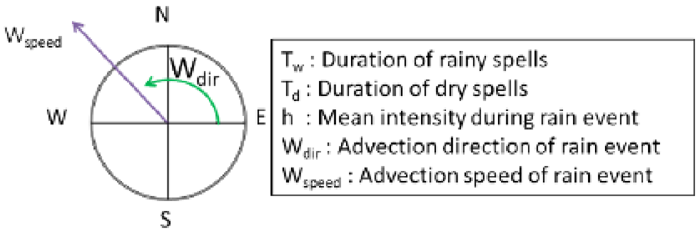
Peleg et al., *JAMES* **2017**

AWE-GEN-2d in a nutshell

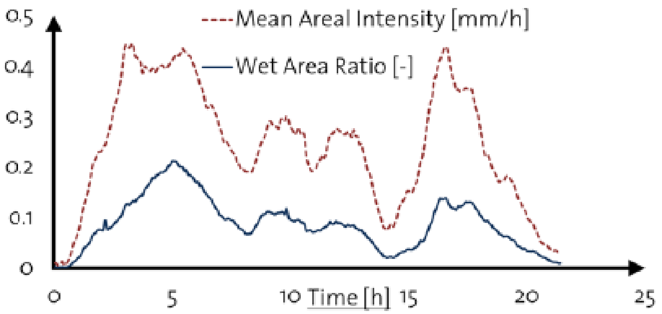
(1) Storm arrival process



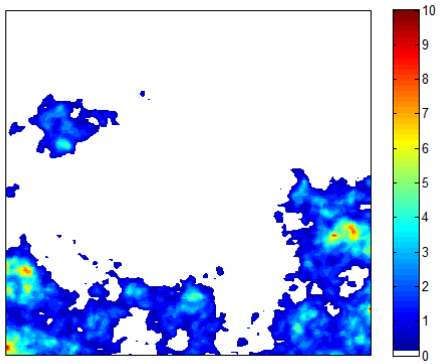
(2) Advection

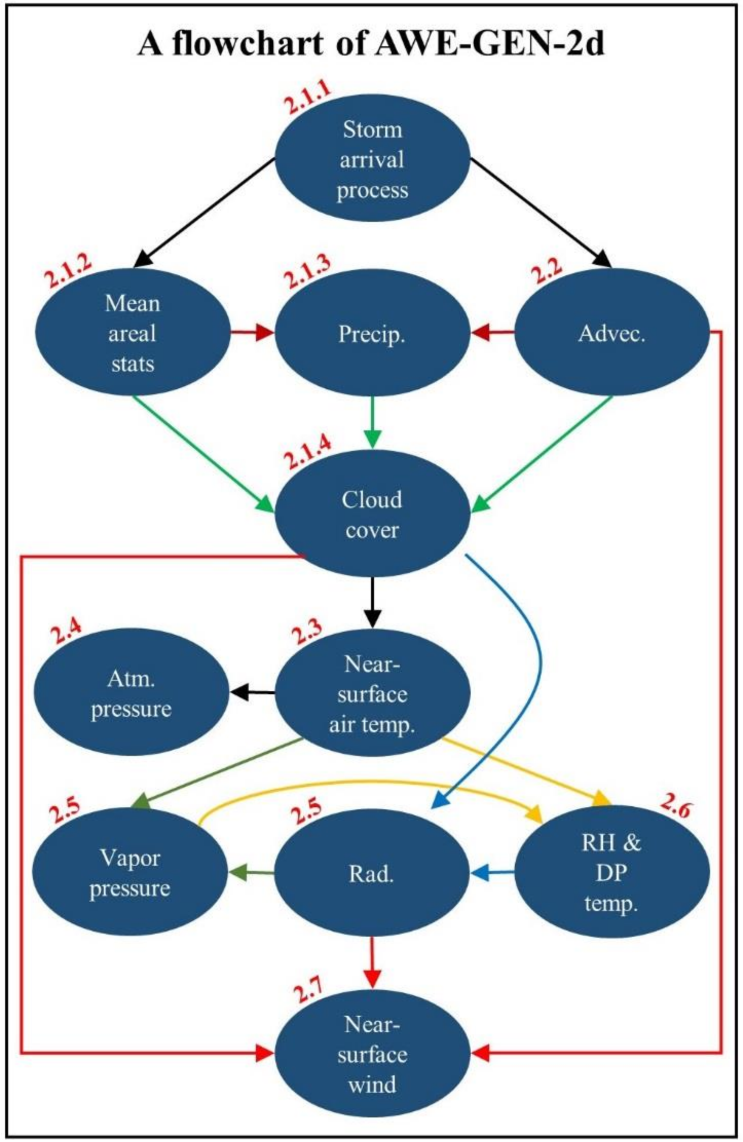


(3) Temporal evolution of areal statistics



(4) Space-time evolution of precipitation/cloud fields

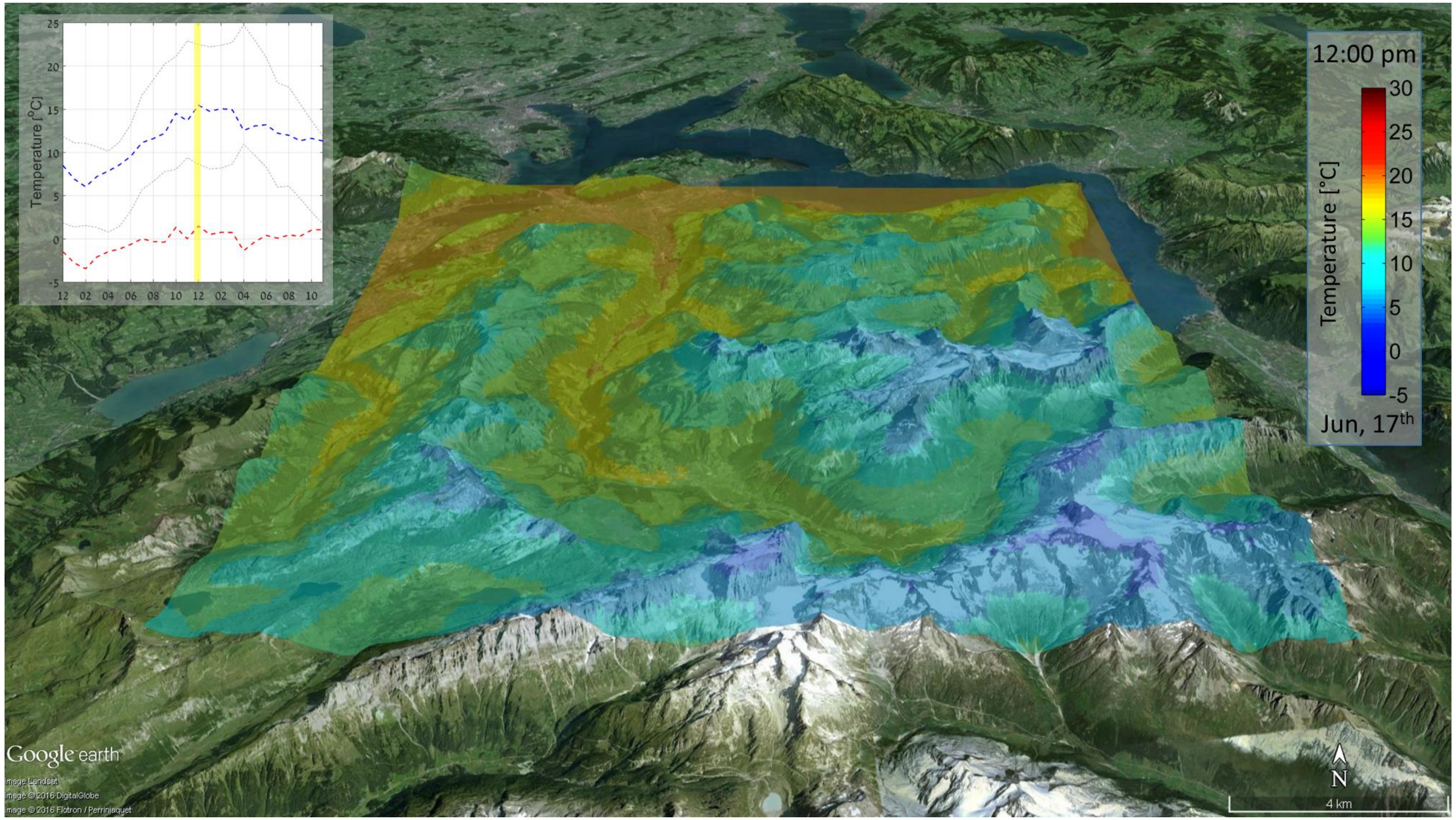


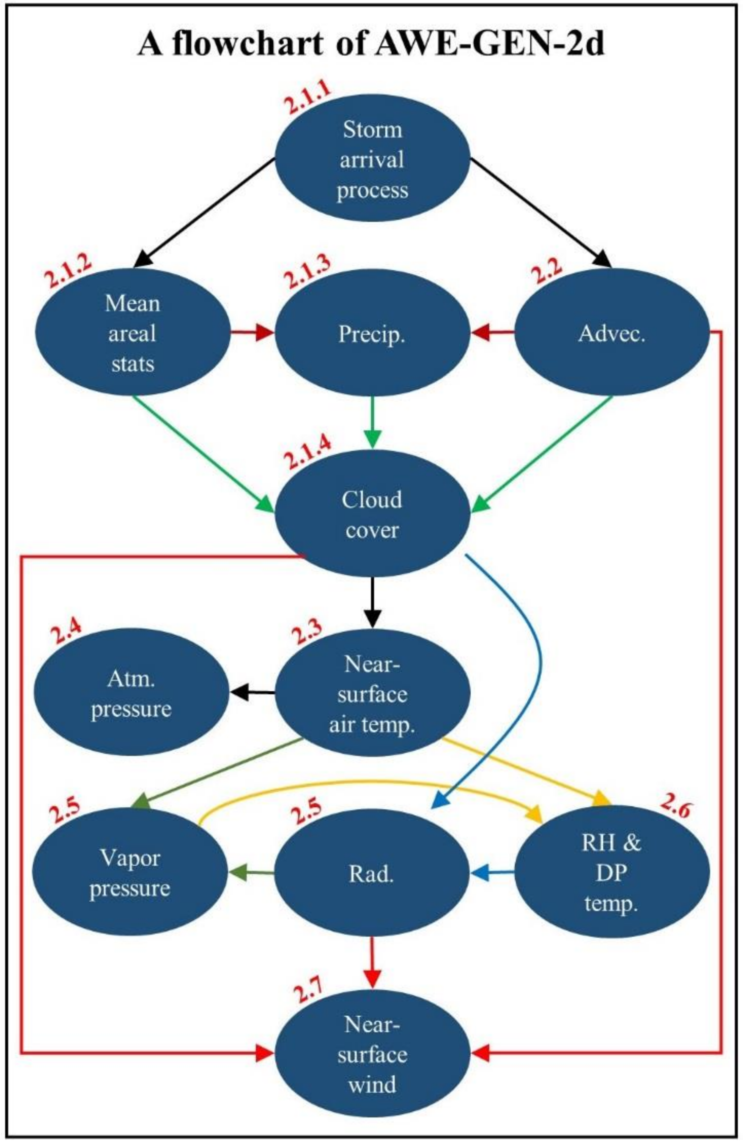


Peleg et al., *JAMES* **2017**

AWE-GEN-2d in a nutshell

(5) Near-surface air temperature



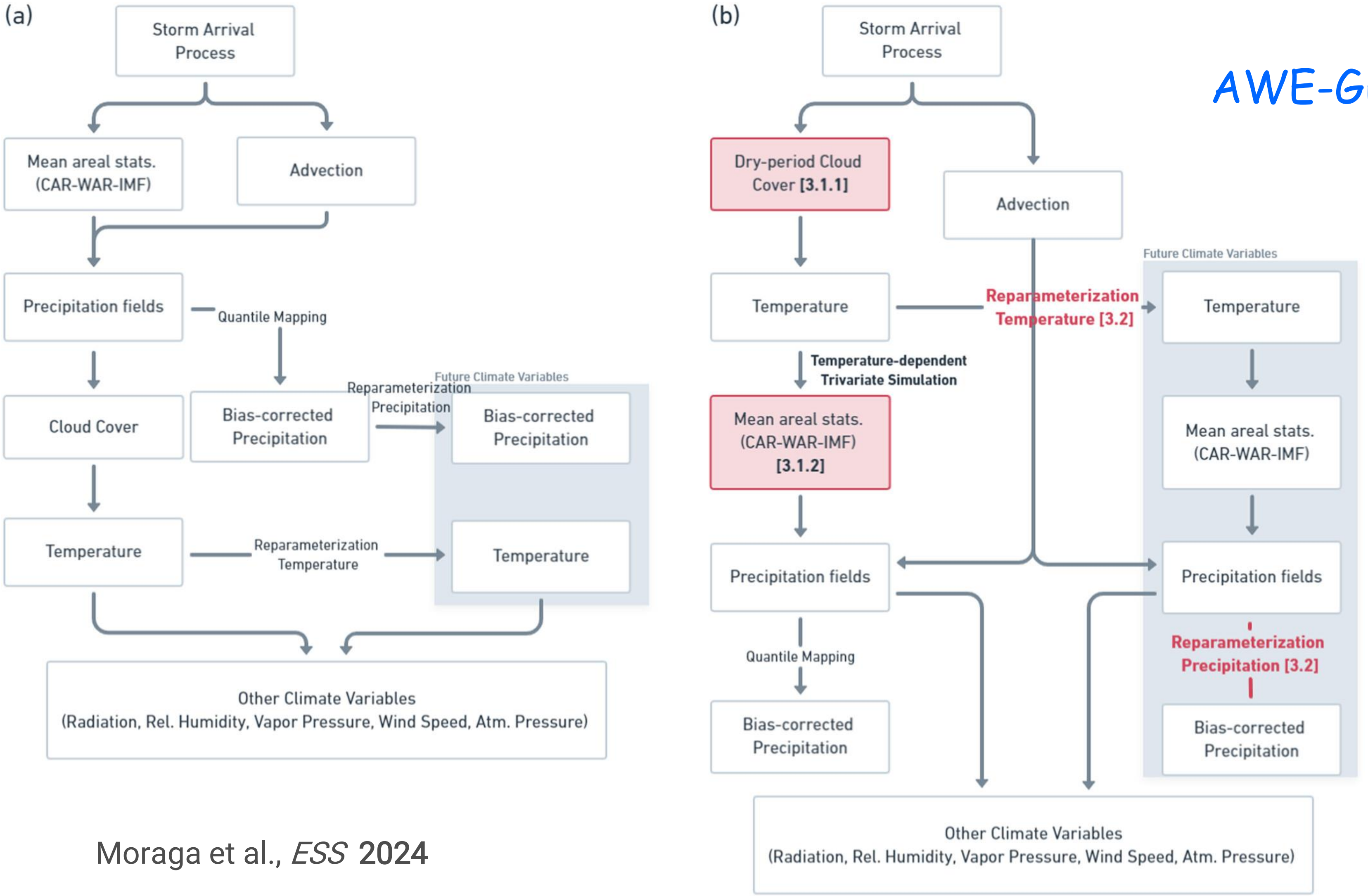


Peleg et al., *JAMES* **2017**

From AWE-GEN-2d to AWE-GEN-2d-CC

AWE-GEN-2d

AWE-GEN-2d-CC

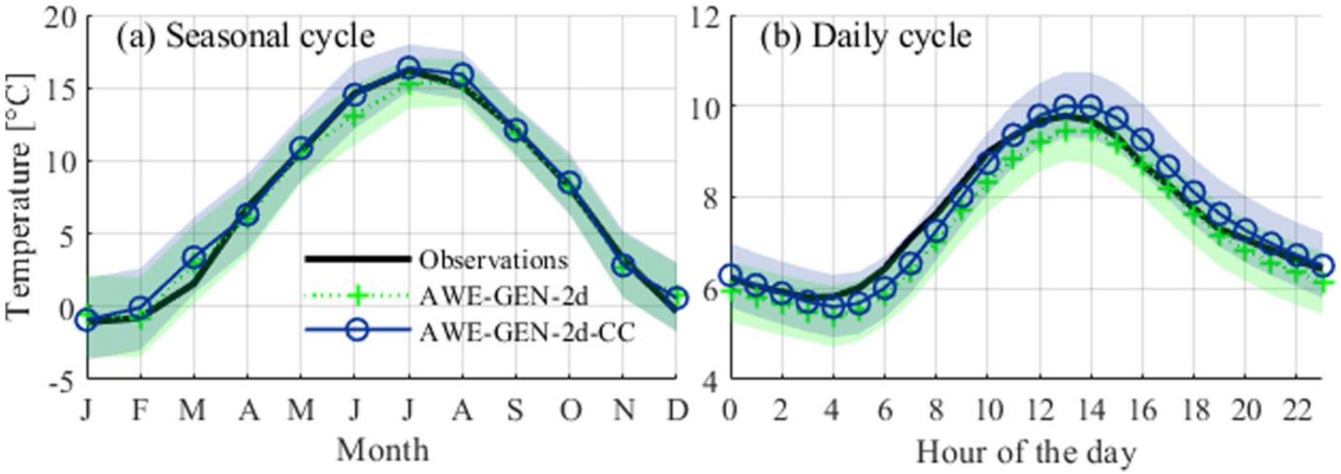


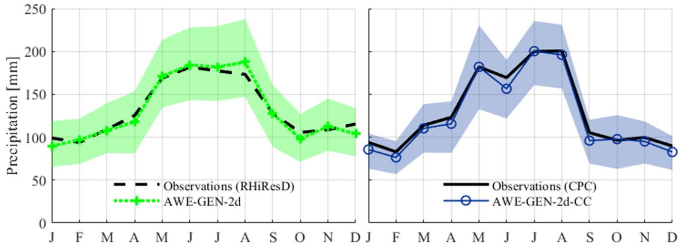
Moraga et al., *ESS* **2024**

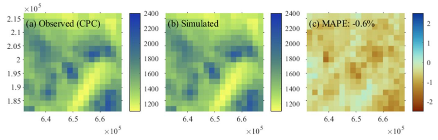
From AWE-GEN-2d to AWE-GEN-2d-CC

Validation

Temperature



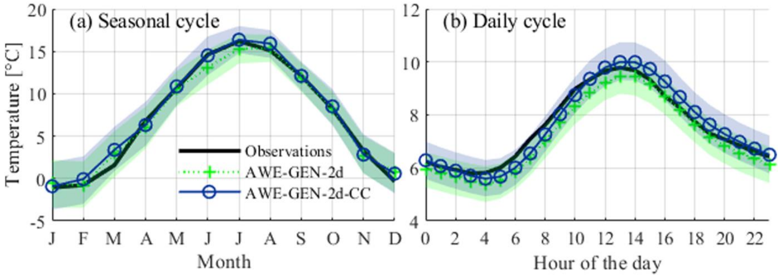




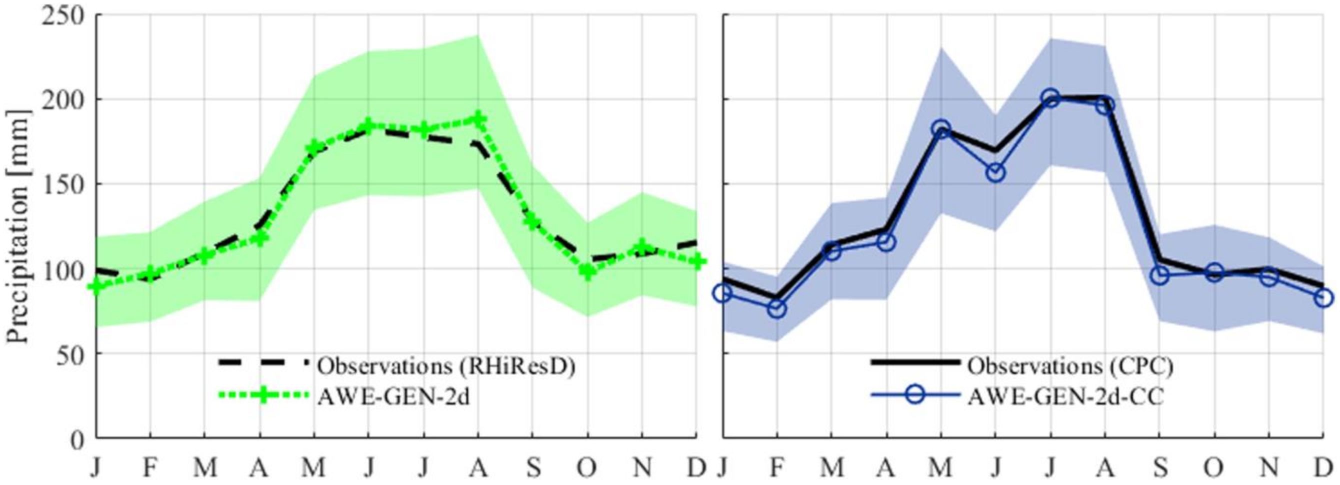
Moraga et al., *ESS* **2024**

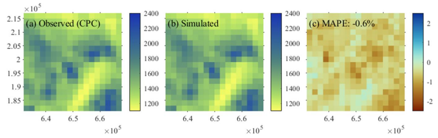
From AWE-GEN-2d to AWE-GEN-2d-CC

Validation



Precipitation

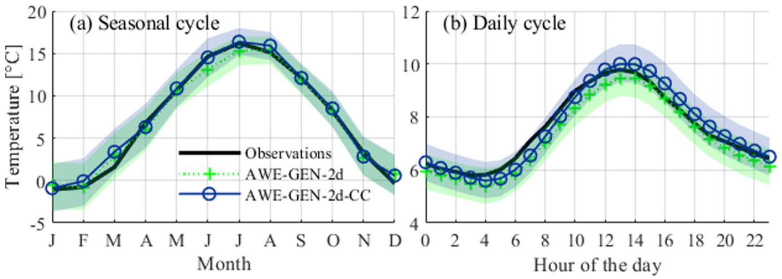


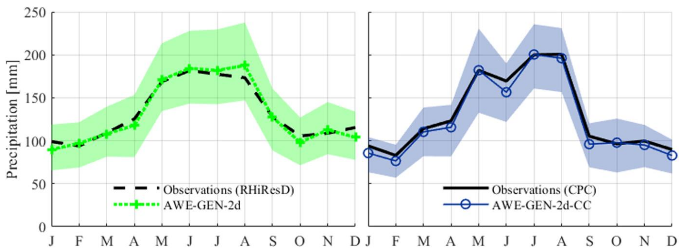


Moraga et al., *ESS* **2024**

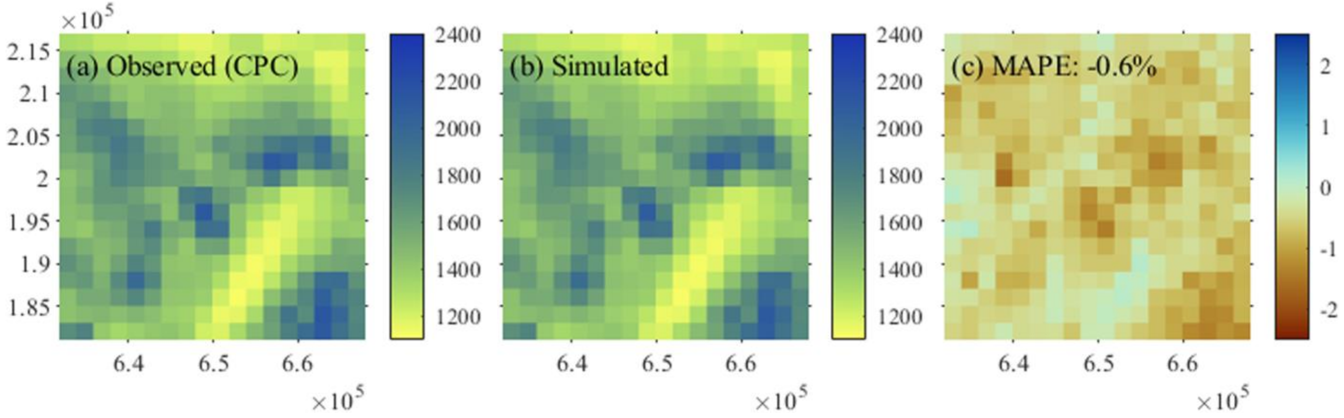
From AWE-GEN-2d to AWE-GEN-2d-CC

Validation





Distributed precipitation

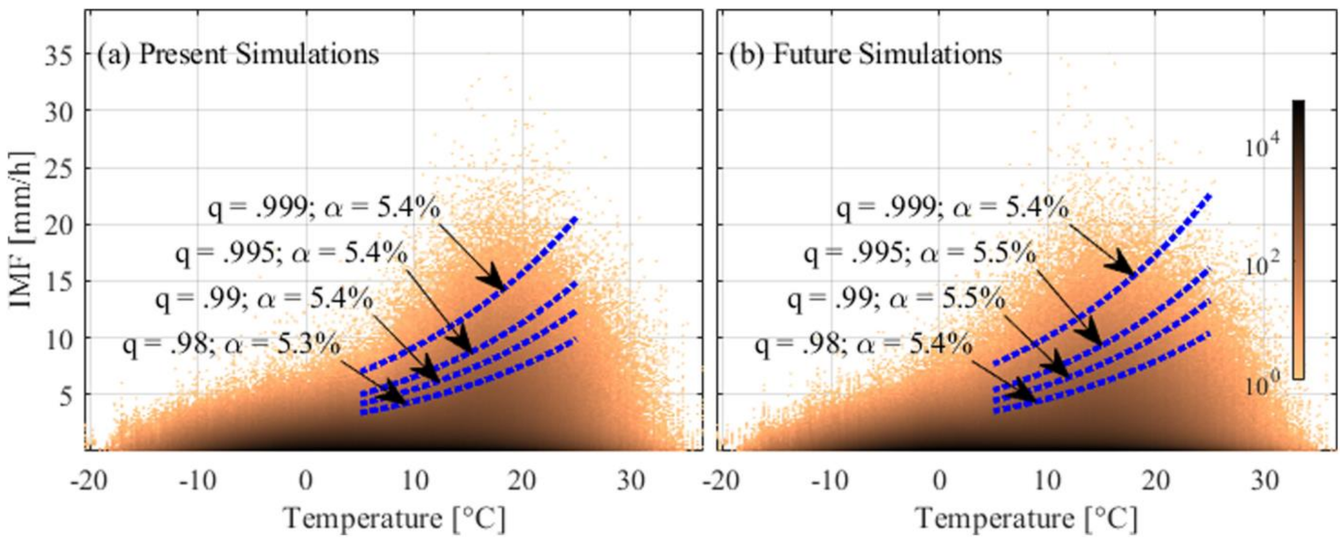


Moraga et al., *ESS* **2024**

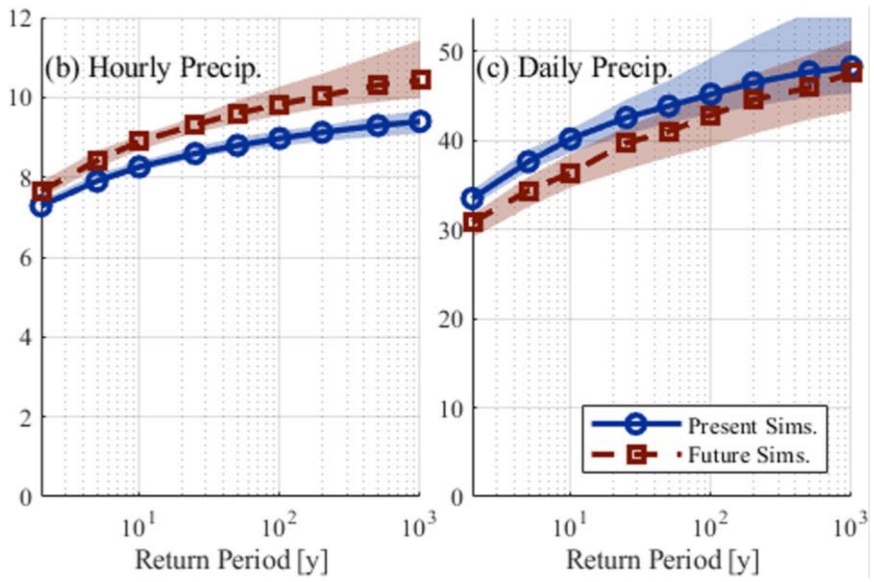
From AWE-GEN-2d to AWE-GEN-2d-CC

Temperature-conditioned rainfall intensification

Precipitation-temperature relationship



Precipitation return period

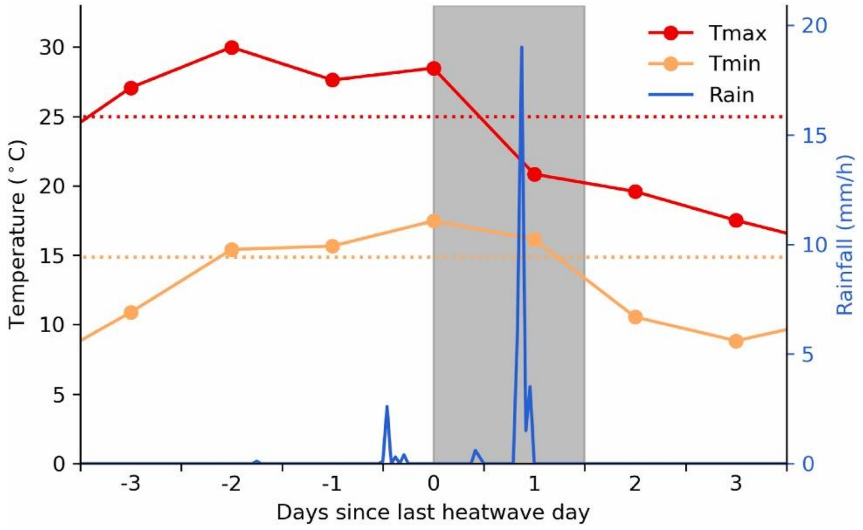


Moraga et al., *ESS* **2024**

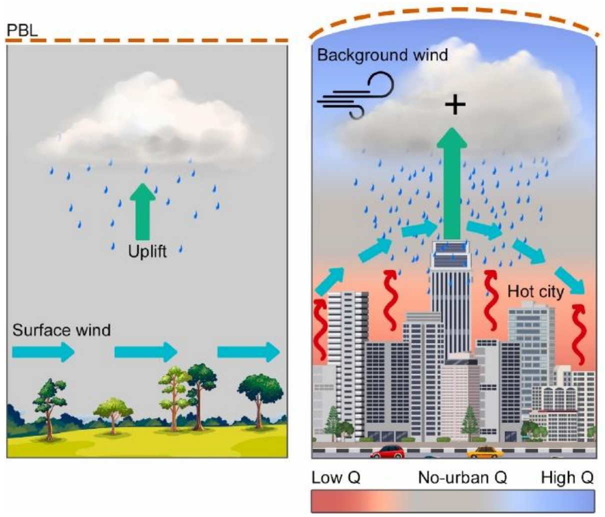
Challenges and future developments

- Can stochastic WG provide reliable simulations of present and future (temperature-related) compound climatic events?
- How can WG incorporate evolving land-use feedbacks on local weather statistics?

Sauter et al., *WCE* 2024



Torelló-Sentelles et al., *Urban Climate* 2025



Summary

- Weather generators may benefit from the explicit representation of weather-related physical process
- For example, by adequately representing the relationship between precipitation and temperature
- However, this integration should be implemented carefully, since these physical processes are scale dependent in space and time and shaped by the local climate

Thank You!

Unil.

nadav.peleg@unil.ch