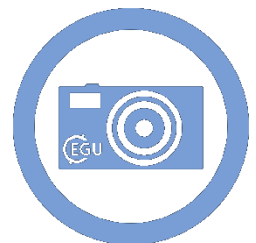

A physics-based approach for simulating future extreme design storms to assess flood risks

Nadav Peleg¹ and Francesco Marra^{2,3}

¹Institute of Earth Surface Dynamics, University of Lausanne, Lausanne, Switzerland

²Department of Geosciences, University of Padova, Padua, Italy

³Institute of Atmospheric Sciences and Climate, National Research Council, Bologna, Italy



Sharing is
encouraged

EGU General Assembly
April 16rd, 2024

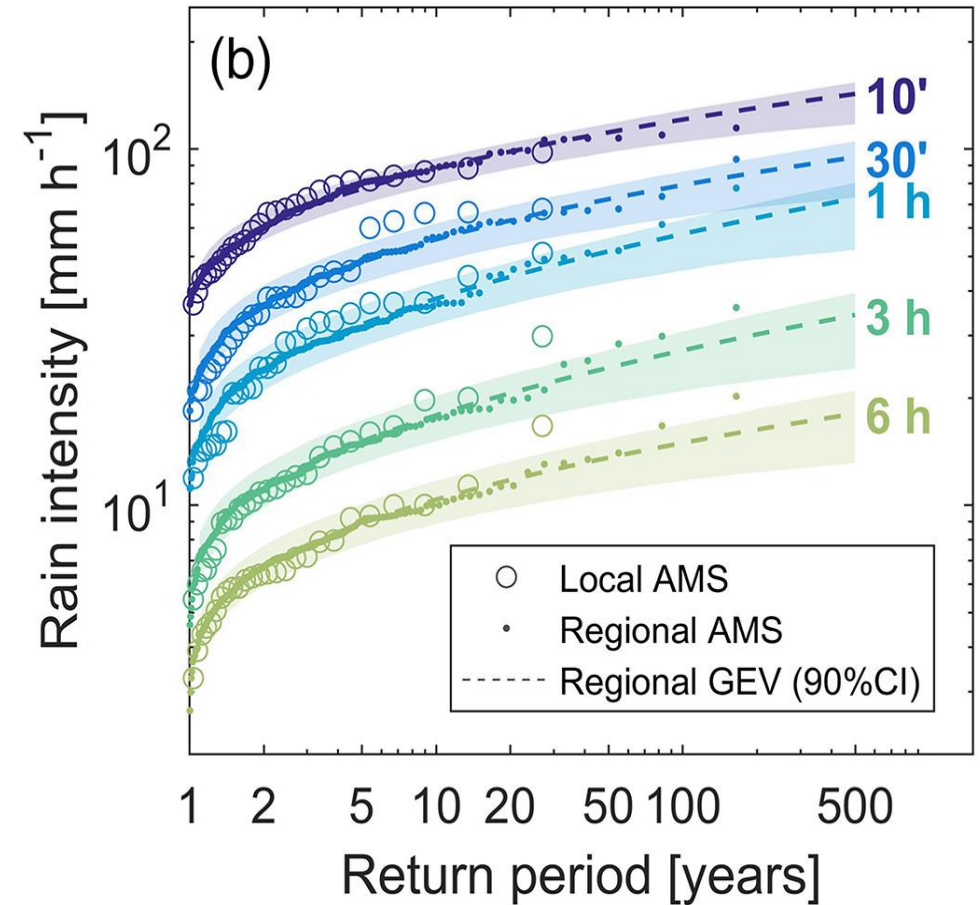
Motivation

- 🔹 **Extreme sub-hourly precipitation** can lead to natural disasters such as flash floods, urban pluvial floods, and debris flows
- 🔹 Quantification of the change in their statistics is essential in the context of climate change
- 🔹 In hydrology – most applications are considered using **Intensity-Duration-Frequency (IDF) curves**



Motivation

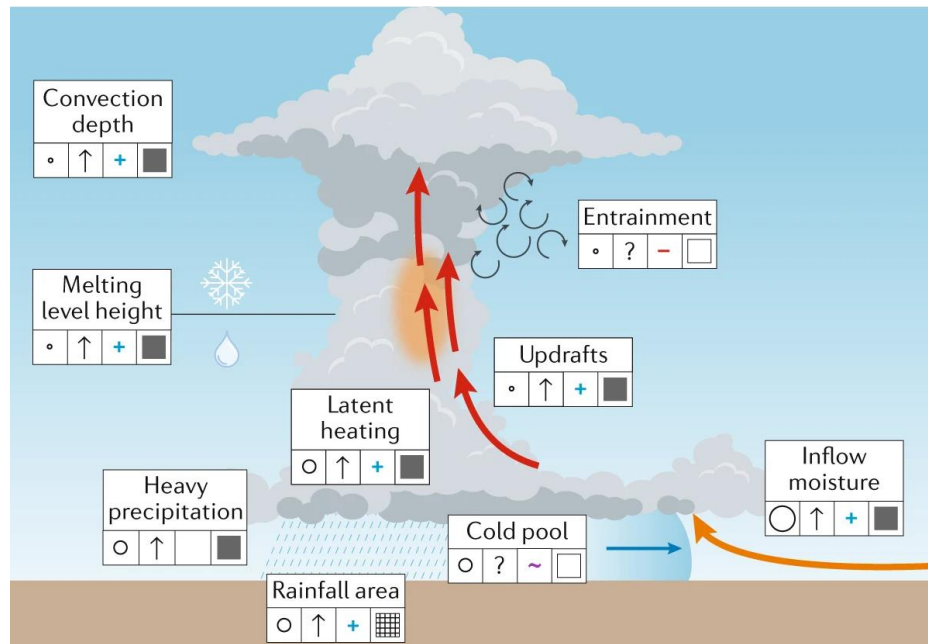
- Often, future IDF curves are derived from climate model data
- Statistical limitations: the bias-correction and downscaling procedures introduce uncertainties
- Physical limitations: climate models do not explicitly simulate convective precipitation, the most common sub-daily extreme rainfall event



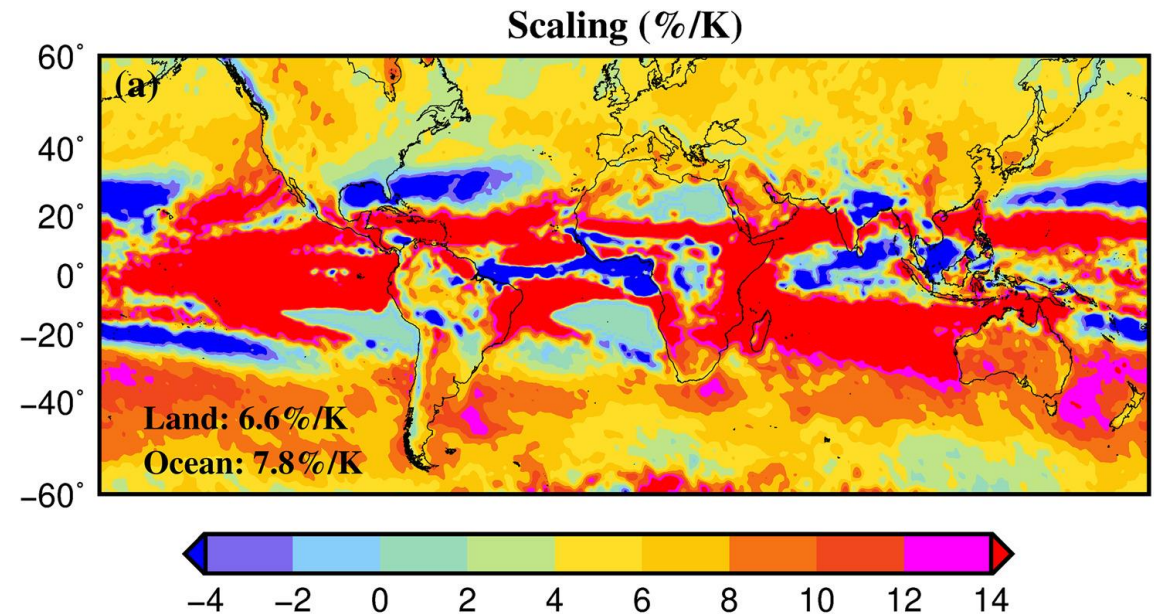
Marra et al. *GRL* 2020

Extreme rainfall intensification

- ☛ We do know that extreme sub-daily rainfall intensity should follow intensification at the rate of $7\% \text{ } ^\circ\text{C}^{-1}$ on a global average (following the Clausius–Clapeyron relation)



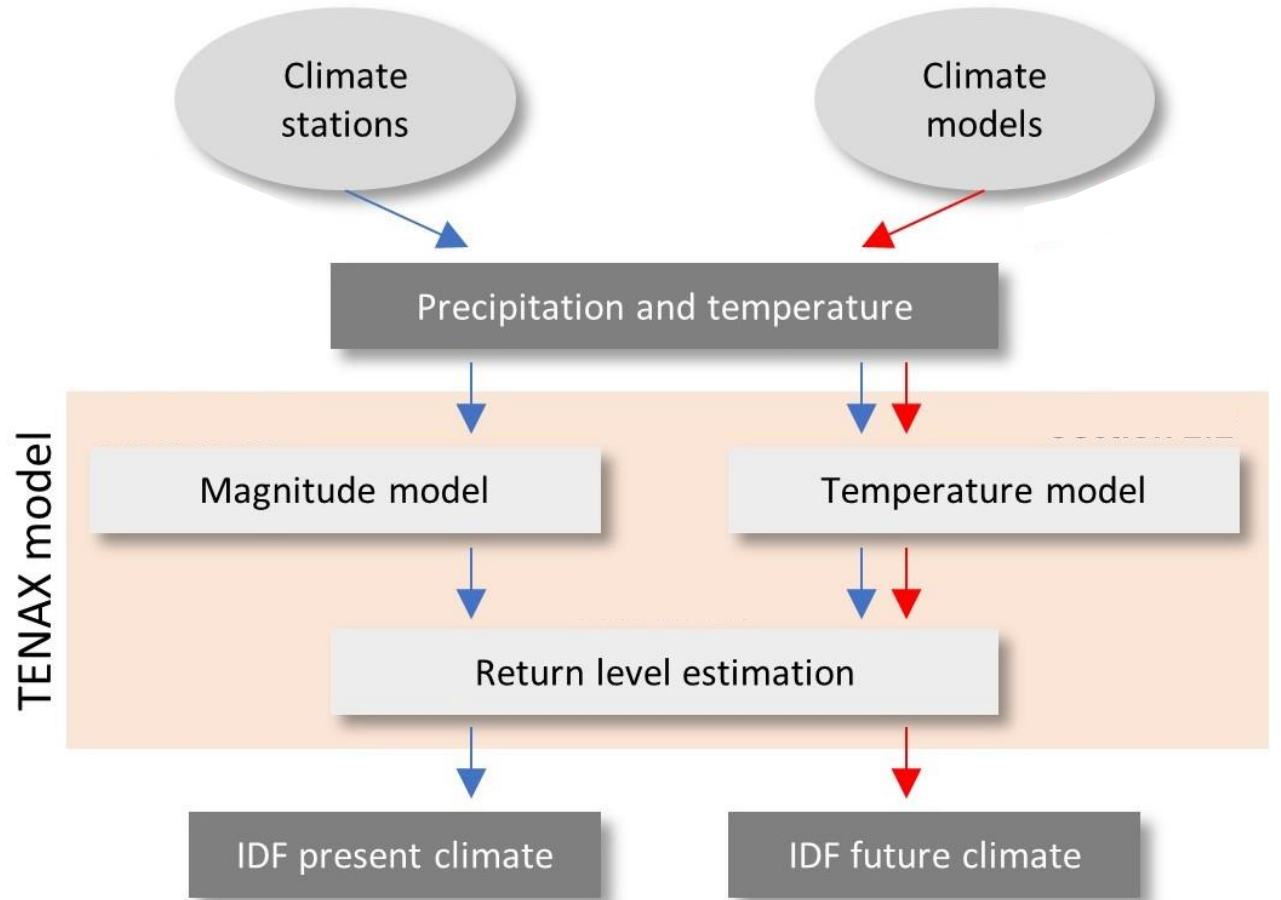
Fowler et al., *Nature Rev.* 2021



Ali et al. *GRL* 2021

The TENAX model

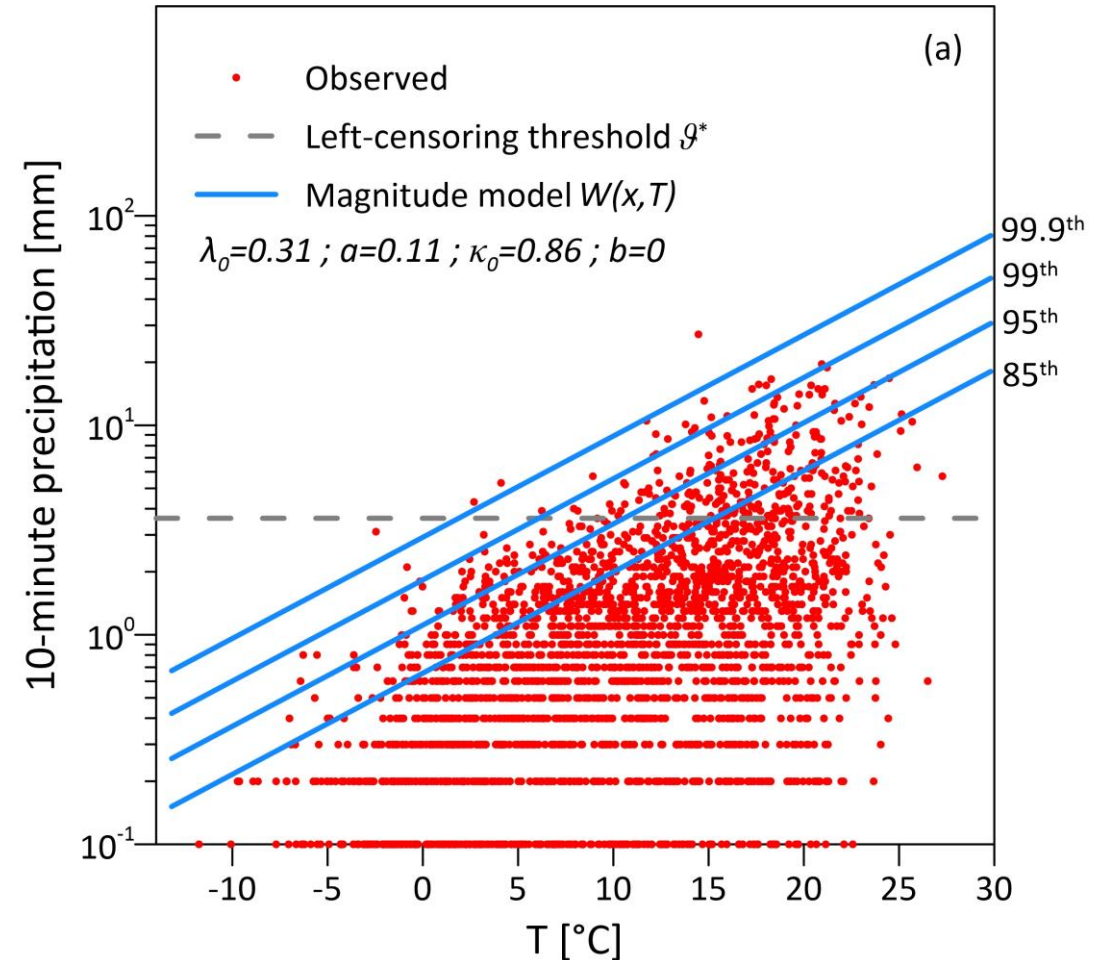
- We developed the **TE**mperture-dependent **Non-Asymptotic** statistical model for **eXtreme** return levels (**TENAX**)
- A **parsimonious** non-stationary and non-asymptotic theoretical framework that incorporates **temperature as a covariate** in a physically consistent manner



Marra et al. *HESS* 2024

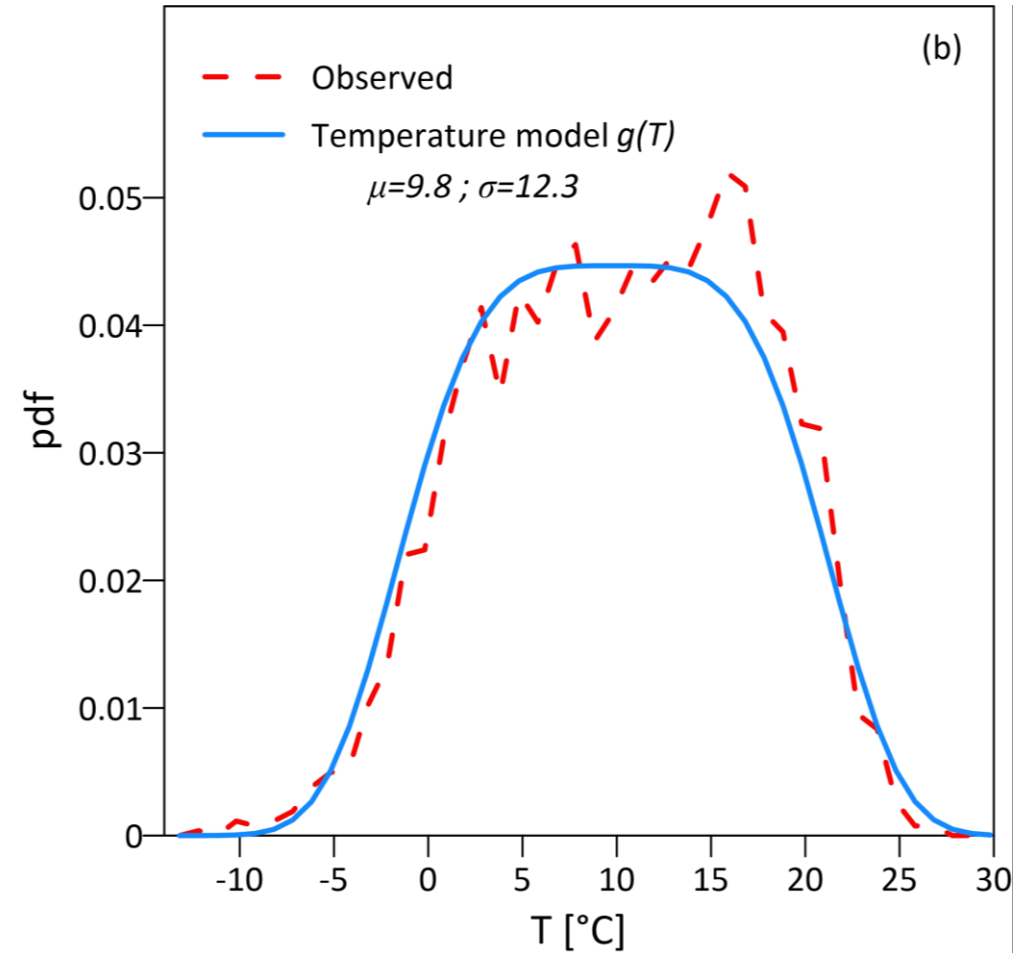
TENAX: Precipitation event magnitude model

- We use the Weibull distribution to model the magnitudes of sub-hourly ordinary precipitation events
- **The Weibull parameters are explicitly dependent on near-surface air temperature as covariate**
- An exponential dependence of the scale parameter on temperature is introduced following the Clausius–Clapeyron relation



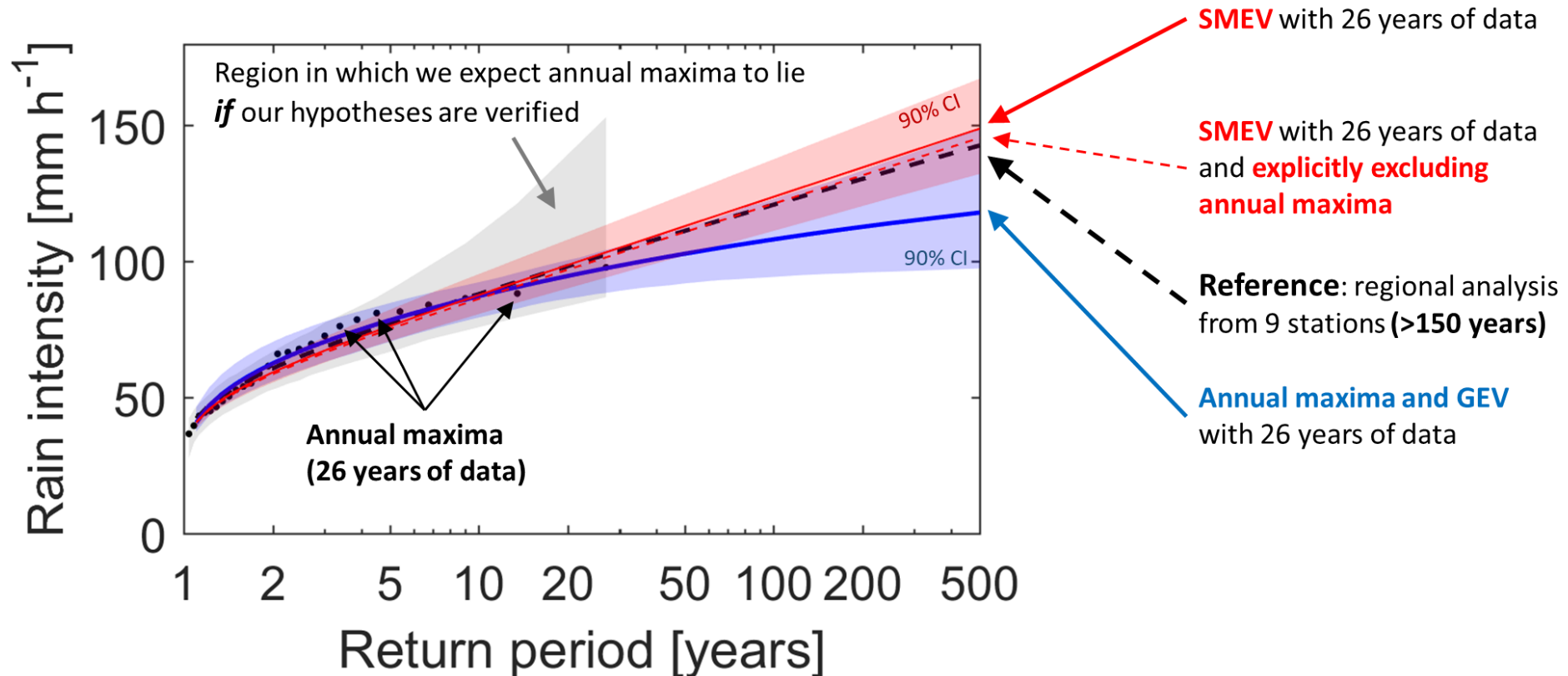
TENAX: Temperature model

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

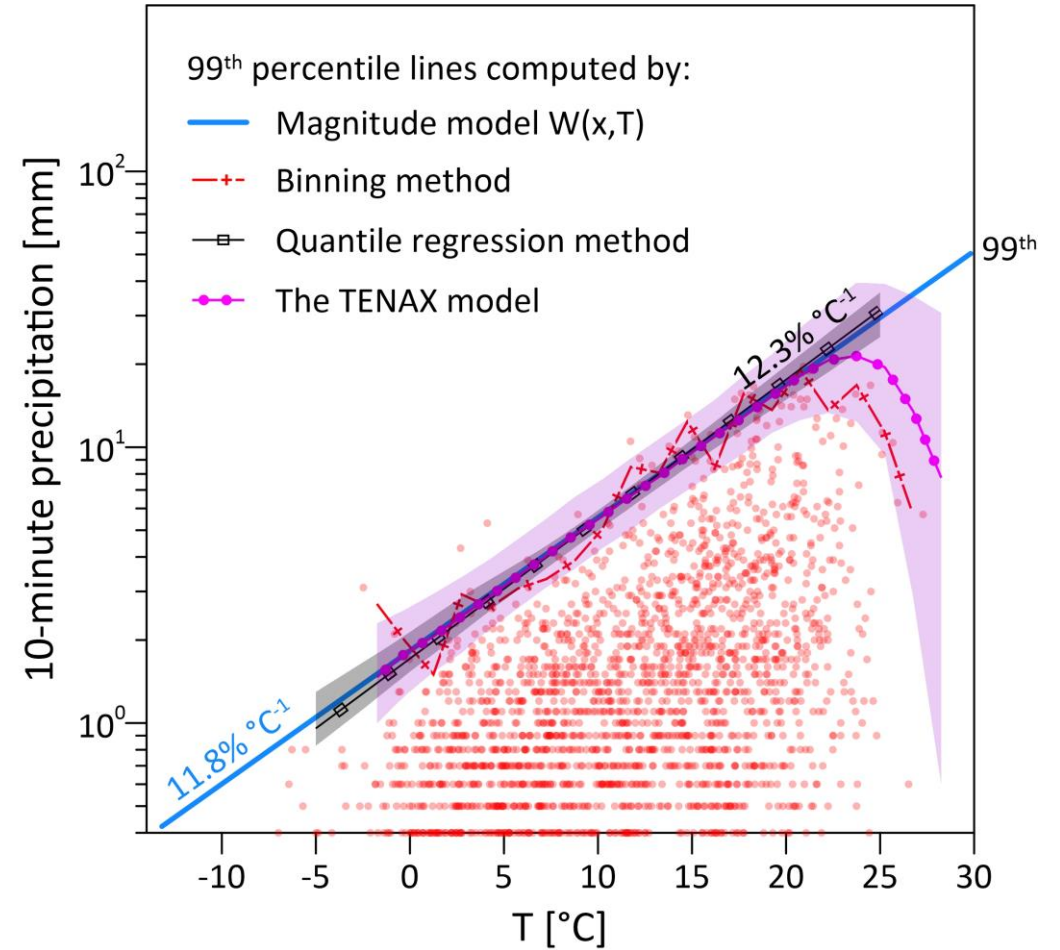
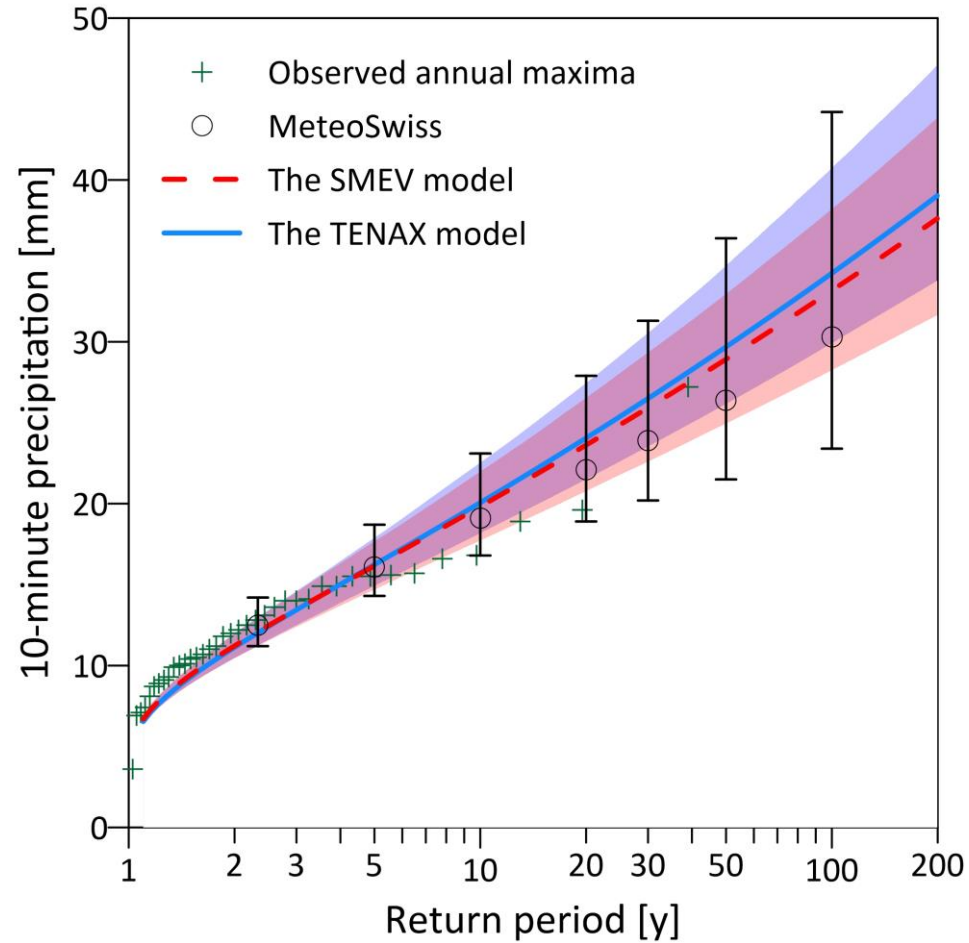


TENAX: Return level estimation

- ◆ The distribution of annual maxima is obtained with the Simplified Metastatistical Extreme Value (SMEV) formulation (Marra et al., *GRL 2020*)



TENAX: evaluation (Aadorf station, 10-min)



The TENAX model



A physics-based statistical model to predict sub-hourly extreme precipitation intensification based on temperature shifts

Francesco Marra^{1,2}, Marika Koukoulou³, Antonio Canale⁴, and Nadav Peleg³

Background and objectives

For climate change adaptation and resilience, we critically need information on future sub-hourly precipitation return levels

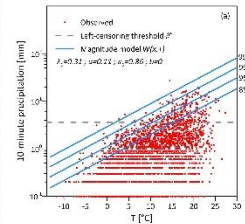
Current approaches are insufficient:

- limited availability of convection permitting model simulations (capable of simulating sub-hourly precipitation adequately)
- frequency analysis methods are merely data driven and do not consider the physics behind precipitation processes

We present TENAX: a new statistical model to predict future sub-hourly return levels

- Physically consistent
- Robust – based on variables well simulated by climate models
- Easy to use – also for practitioners and end users
- TENAX brings together thermodynamic theory and statistics
- TENAX reconciles extreme precipitation-temperature scaling rates with extreme precipitation frequency analysis

Temperature-dependent Non-Asymptotic model for extreme return levels (TENAX)



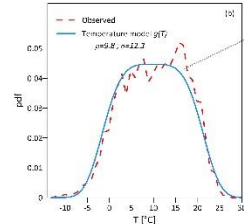
- Non stationary Weibull model for the exceedance probability of extreme intensities as a function of T
- Contains information on the physics of the processes at temperature T

$$W(x;T) = 1 - e^{-[\lambda(T)x^\alpha]^\beta}$$

$$\lambda(T) = \lambda_0 \cdot c^{\alpha T}$$

- Emerging statistics of extremes will depend on how temperature is sampled during events

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

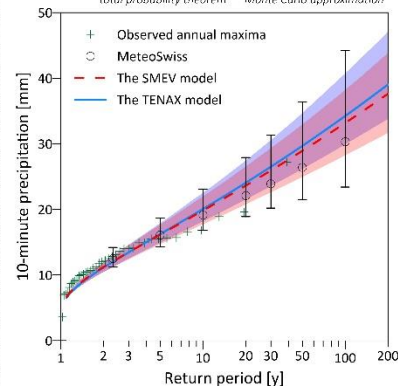


Return levels are estimated combining magnitude and temperature models:

$$\text{maxima from } n\text{-sized samples of } F(x): G(x) = F(x)^n$$

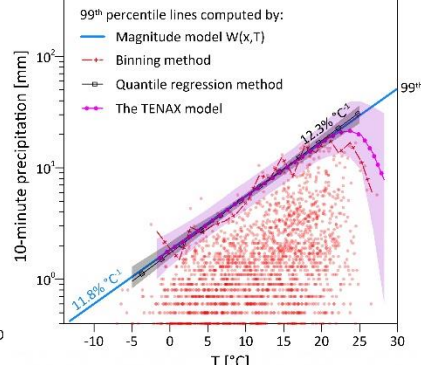
$$G_{\text{TENAX}}(x) = \left(\int_{-\infty}^{\infty} W(x;T) \cdot g(T) dT \right)^n \approx \left(\frac{1}{N} \sum_{i=1}^N W(x;T_i) \right)^n$$

total probability theorem *Monte Carlo approximation*

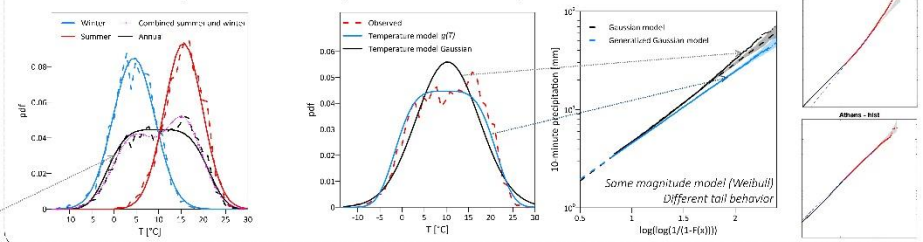


TENAX explains known properties of extreme precipitation

- Extreme precipitation-temperature scaling rate
- Breaking of the scaling relation at high temperatures (hook structure) is due to sharp decrease in probability of occurrence of precipitation events at high temperatures – right tail of the temperature model



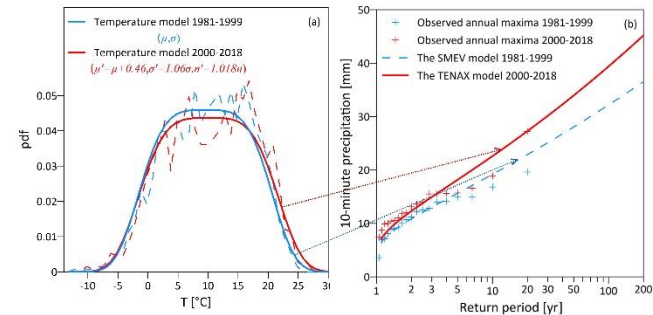
Physical basis and importance of the temperature model



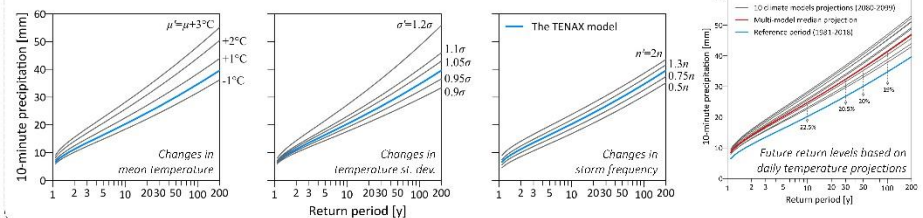
Predicting future return levels based on changes in daily temperature

hindcast validation:

- Split data into two time slices (equal length) (1981-1999, 2000-2018)
- Estimate W from 1981-1999 only (contains information on the physics)
- Estimate changes in mean and variance of g from 1981-1999 to 2000-2018
- Predict return levels for 2000-2018 using W estimated from 1981-1999 and projected changes in g



- Sensitivity to changes in mean, variance and storm occurrence frequency
- Future projections based on changes in temperature in an ensemble of 10 regional climate models



This study was funded by:
 • Department of Geosciences, University of Padua (FINAX project), as part of The Geosciences for Sustainable Development project (CUP 93C3/3002690001)
 • SNSF (grant no. 19649), Rainfall and Floods in Future Cities
 • CNRS-ERC (excellence Grant 7671), Resilience project

More info in the published paper:
<https://bes.sagepub.com/doi/10.1177/1474999120947484>
 Codes are free to replicate:
<https://github.com/10.1177/1474999120947484>



The TENAX model

- 🔹 Poster: “A physics-based statistical model to predict sub-hourly extreme precipitation intensification based on temperature shifts” presented by Francesco Marra
- 🔹 Wednesday, 10:45–12:30
- 🔹 Hall A | [A.42](#)

Paper



Codes



More info in the published paper:

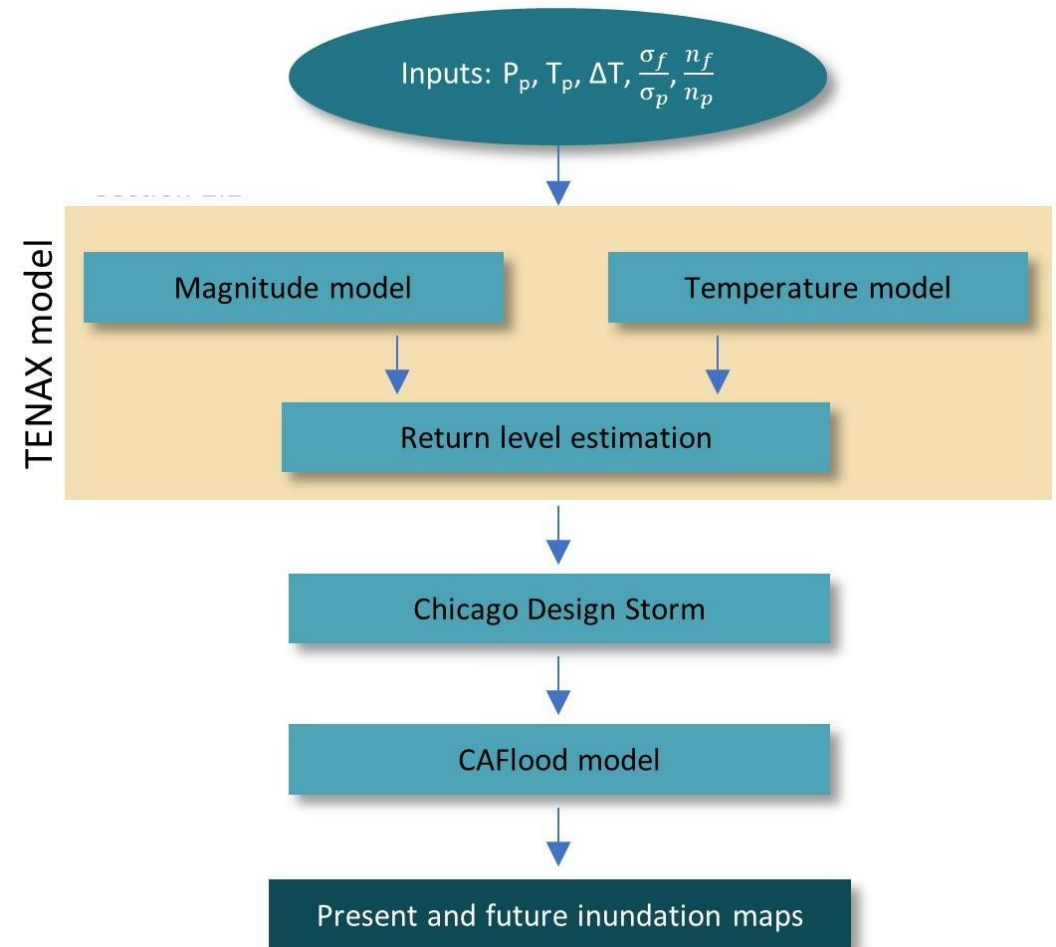
<https://hess.copernicus.org/articles/28/375/2024/>

Codes are freely available:

<https://doi.org/10.5281/zenodo.8345905>

The TENAX-CDS model

- We propose a framework for adjusting IDF curves and design storms to future climate conditions
- **Information from climate models at the daily scale can be used to construct design storms at the sub-hourly**
- Our approach is illustrated through a re-parameterization of the Chicago Design Storm (CDS)



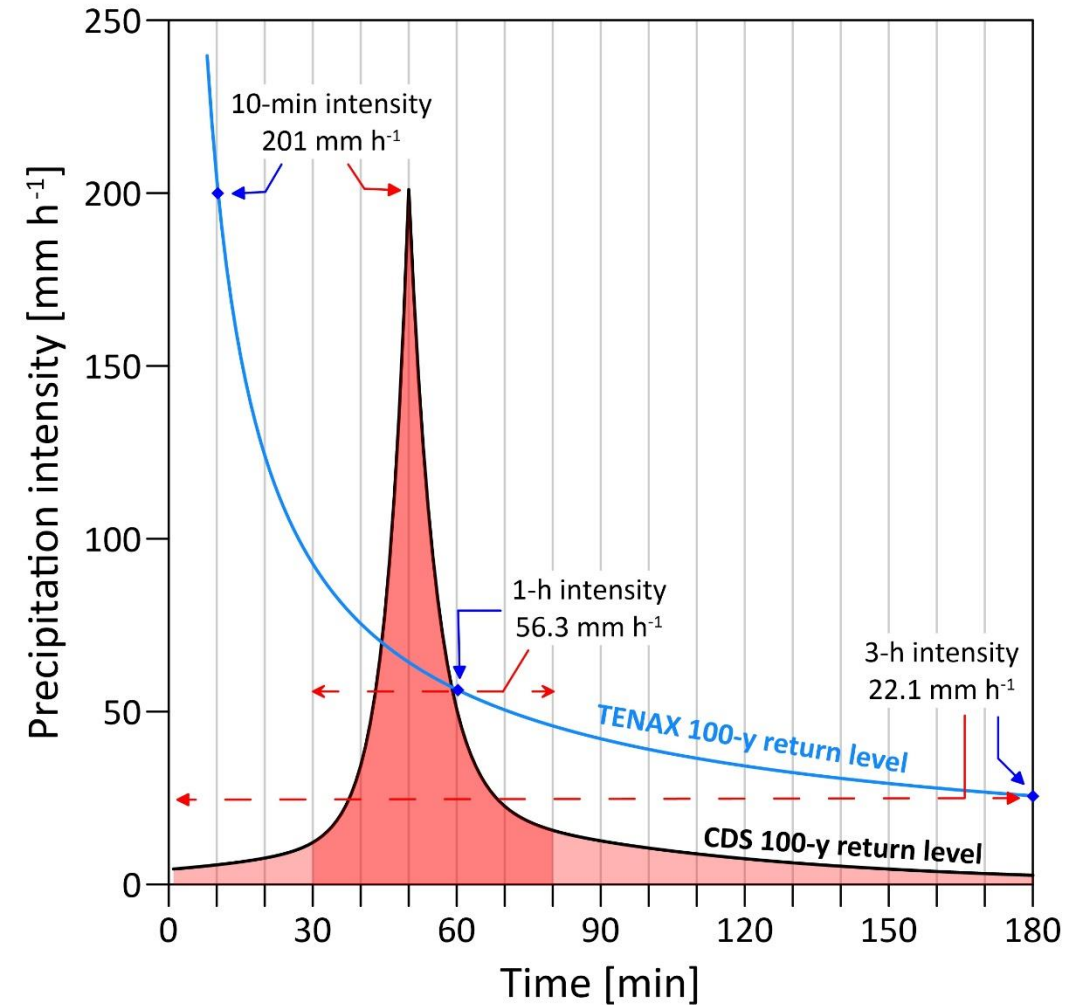
Peleg et al. *ADWR* under review

The Chicago Design Storm (CDS)

- ◆ The CDS approach enables a single synthetic storm to embed analytically a given precipitation return level for all durations of interest based on an intensity-duration curve

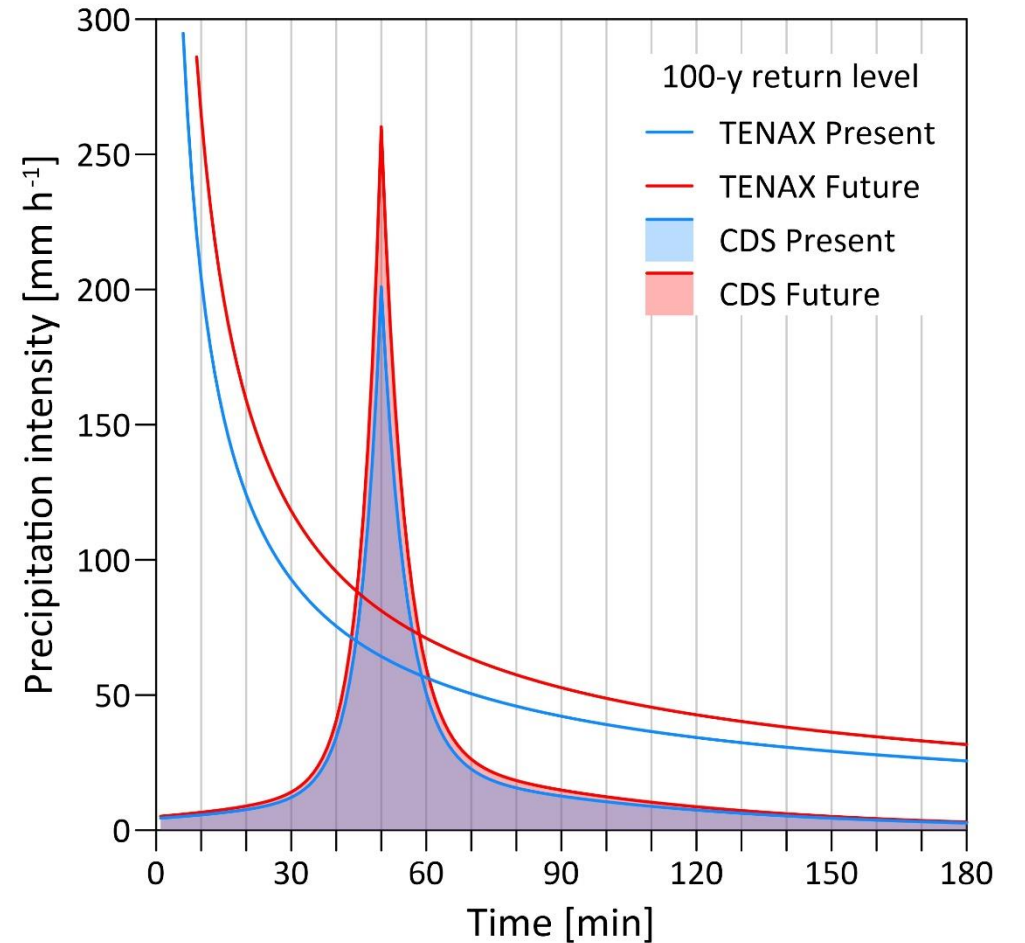
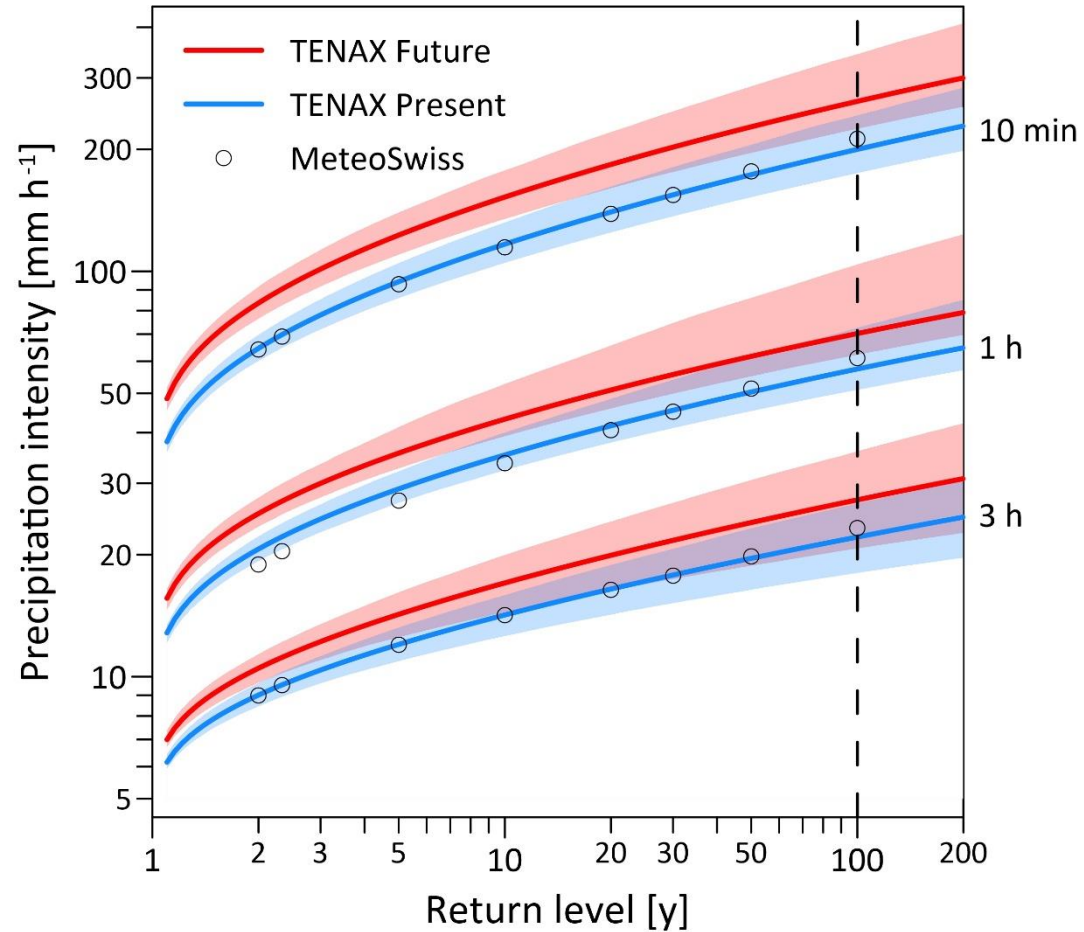
$$I(t_D; \mathcal{T}) = \frac{C_a}{(t_D + C_b)^{C_c}}$$

$$I(t_b; \mathcal{T}) = \frac{C_a \left((1 - C_c) \left(\frac{t_b}{r} \right) + C_b \right)}{\left(\frac{t_b}{r} + C_b \right)^{C_c + 1}} \quad I(t_a; \mathcal{T}) = \frac{C_a \left((1 - C_c) \left(\frac{t_a}{1-r} \right) + C_b \right)}{\left(\frac{t_a}{1-r} + C_b \right)^{C_c + 1}}$$

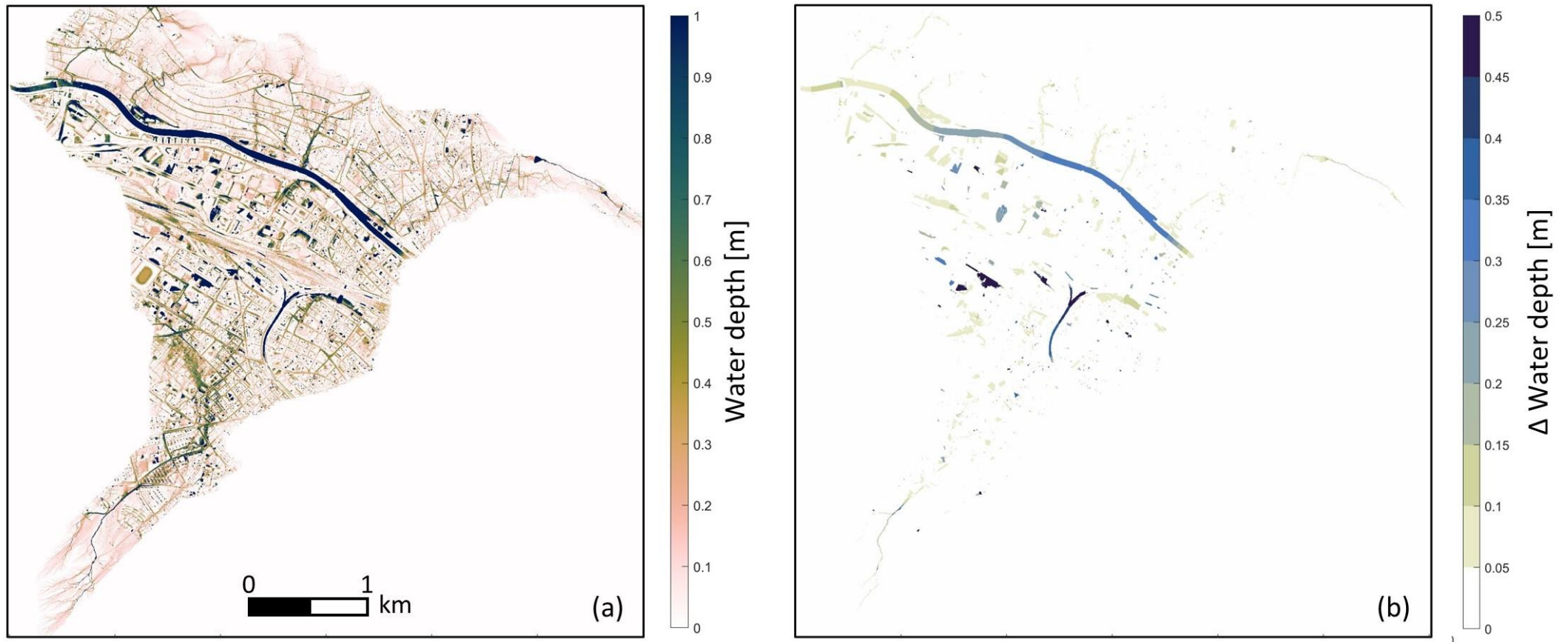


Peleg et al. *ADWR* under review

TENAX-CDS: example



TENAX-CDS: example



Thank You!

- 💧 We have presented a new method for computing short-duration IDF curves and design storms for flash flood assessments under increasing temperatures
- 💧 The physically-based TENAX-CDS model considers both thermodynamical and dynamical changes and is highly efficient in terms of its data requirements
- 💧 The TENAX-CDS code is freely available: <https://zenodo.org/records/10491542>



nadav.peleg@unil.ch

- Marra, F., Koukoula, M., Canale, A., and Peleg, N. (2024)
Predicting extreme sub-hourly precipitation intensification based on temperature shifts
Hydrology and Earth System Sciences
- Peleg, N., Wright, D.B., Fowler, H.J., Leitao, J.P., Sharma, A., and Marra., F. (under review)
A simple and robust approach for adapting design storms to assess climate-induced changes in flash flood hazard
Advances in Water Resources