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Original
The role of elevation in the spatial distribution of sub-daily rainfall extremes / Mazzoglio, Paola; Butera, Ilaria; Claps, Pierluigi. - ELETTRONICO. - (2025), pp. 243-245. (Geomorphometry 2025 Perugia (Ita) 9-13 June 2025) [10.5281/zenodo.15212750].

Publisher:
CNR Edizioni

Published
DOI:10.5281/zenodo.15212750

The role of elevation in the spatial distribution of sub-daily rainfall extremes

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Cite as: Mazzolgio, P., Butera, P., Claps, P. (2025). The role of elevation in the spatial distribution of sub-daily rainfall extremes. In: Proceedings of Geomorphometry 2025, 9-13 June, Perugia, Italy. M. Alvioli, L. Melelli, I. Marchesini eds. CNR Edizioni, Rome. ISBN 978-88-8080-765-0. DOI: 10.5281/zenodo.15212750

Abstract—**In regions with significant elevation variability like Italy, interpolation methods applied to rainfall depths should explicitly account for the elevation effect. This study examines the spatial variability of sub-daily rainfall extremes across Italy, focusing on assessing the role of elevation. Utilizing the Improved Italian - Rainfall Extreme Dataset (I^2-RED), we analyzed average annual maxima from approximately 3,800 time series spanning at least 10 years between 1916 and 2020. To assess orographic influences, a local geo-regression approach was employed, aggregating stations located within a certain search radius centered in each 1km size cell used to segment the territory. Various constraints were applied to address challenges posed by low data density in certain regions and elevation-related extrapolation issues, and different criteria for selecting local samples were evaluated. Our findings corroborate previous studies with enhanced detail, revealing a general increase of the 24-hour average annual maxima with elevation (orographic effect), with the exception of few hilly/mountainous areas. Conversely, for 1-hour maxima, negative gradients (reverse orographic effect) were observed in extensive mountainous regions, suggesting decreased short-duration rainfall extremes at higher elevations. These insights contribute to a deeper understanding of rainfall patterns in Italy and can inform the development of improved hydrological models and infrastructure planning.**

I. INTRODUCTION

Large-scale rainfall datasets with high spatial and temporal coverage are often created through spatial interpolation of irregularly spaced rain gauge data onto regular grids. In flat areas, standard interpolation methods like inverse distance weighting and ordinary kriging can provide reliable estimates. In contrast, regions with complex terrain require the application of models that explicitly account for elevation effects, such as regression models, geographically weighted regressions or kriging with an external drift, which incorporate elevation as a predictor.

While the application of a single linear regression model on a wide area is statistically stable with respect to small errors in the observations, it often produces clustered residuals in complex terrains, making localized applications more effective. Geographically weighted regression models like PRISM [1] and Daymet [2] were thus suggested with the aim of improving accuracy by dynamically adjusting station influence based on terrain features and station density. However, their application over new areas remain difficult due to the need of defining a wide set of predictors and related weighting functions. Moreover, most of these models were applied only to ordinary rainfall (daily, monthly or annual totals), while none of them was applied to annual maximum rainfall depths.

In this work, we present a geo-regression approach that optimizes station density and a series of constraints that can be applied to address challenges posed by low data density in certain regions and elevation-related extrapolation issues. This study addresses this gap by using a comprehensive sub-daily rainfall dataset with nationwide coverage. It also allows to analyze elevation impact on rainfall extremes.

II. DATASET

Short-duration (1 to 24h) annual maximum rainfall depths come from the Improved Italian-Rainfall Extreme Dataset (I^2-RED) [3]. In this work, we computed average annual maxima from approximately 3,800 time series spanning at least 10 years between 1916 and 2020.

The elevation of the rain gauges and of the surrounding terrain was derived from the Shuttle Radar Topography Mission (STRM) Digital Elevation Model (DEM) at 30 m resolution resampled at 1-km resolution using a cubic interpolation, following the approach suggested in PRISM [1] and adopted also in Daymet [2]. Lower-resolution elevation information was used here since the relationship between precipitation and elevation is more representative if the elevation of the surrounding area is used in place of the actual elevation of the point.

III. METHODOLOGY

A linear geo-regression model was implemented to assess the local relationship between rainfall extremes and elevation in each pixel with coordinates (x, y), by using the equation

$$h_d(x, y) = a(x, y) + b(x, y) \cdot z(x, y) + \varepsilon(x, y)$$

where h_d is the average annual maximum of an assigned duration d (with $d = 1$, 3, 6, 12 and 24 h), a is the intercept, b is the slope (that represents the rainfall gradient), z is the elevation and ε is the residual of the regression. Unlike other models [1], negative rainfall gradients with elevation were considered valid, reflecting previous findings in Italy [4, 5, 6].

To estimate local regression parameters, a circular area around each grid cell was used to select n nearby rain gauges. Two strategies were tested, by using: i) a fixed radius r_{fix} or ii) a variable radius adjusted based on data density to ensure statistical significance. In the first approach we evaluated the regression parameters by using the data of n rain gauges that are located inside a circular area with fixed radius, whatever the statistical significance of the regression model. This approach is in line with the one used in the PRISM and in Daymet models. In the second approach, instead, the search radius increases from r_{min} to r_{max} in each cell, until a statistically-significant regression model (at a 5% level) is found (thus, the “optimal” radius can vary cell by cell). The r_{max} was set to avoid regression models that gather data from areas that are too large, thus leading to the possible presence of high residuals.

To mitigate artifacts from inconsistent rainfall gradients or excessive extrapolation, the study introduced several constraints, such as requiring a minimum elevation range Δz in the local samples of at least 100 m and limiting extrapolation beyond data-supported elevations. Three strategies were explored for handling extrapolation:

i) disallowing it entirely (in grid cells with an elevation z that is higher/lower than those of all the data of the local sample, the regression model is not applied and the predicted value is set as the value obtained by the model in correspondence of the elevation of the highest/lowest rain gauge used);

ii) restricting it within a defined range, while elsewhere the regression limit value is used (in grid cells with an elevation z that is higher/lower than those of the data of the local sample by an amount e_{max}, the model is not applied and the predicted value is set as the value obtained by the model at an elevation that is e_{max} higher/lower than those of the highest/lowest rain gauge of the sample);

iii) restricting it within a defined range, while elsewhere the mean value is used (in grid cells with an elevation z that is e_{max} higher/lower than those of the data of the local sample, the model is not evaluated and the predicted value is computed using the 5 nearest stations).

For a more detailed description of the geo-regression model, the reader can refer to [7].

IV. RESULTS

The geo-regression approach presented in this work, even if simple, involves the selection of different parameters: the number n of rain gauges that forms the local sample, the elevation difference among the rain gauges of the local sample Δz, the search radius (r_{fix}, r_{min}, r_{max}) and the maximum extrapolation allowed e_{max}. Meaningful combinations of the different parameters were applied and several techniques (cross-validation, evaluation of error metrics, comparison of observed vs reconstructed values through boxplots, quantification of the entity of model residual, visual inspection of residual to assess the possible presence of clusters of residuals oh high entity and same sign) were jointly used to select the most accurate model.

The optimal configuration for the Italian case study resulted to be the one that considers a local sample of at least $n = 5$ rain gauges with a minimum difference in elevation Δz of 100 m obtained by pooling data by using a variable search radius that ranges from 1 up to 15 km with no extrapolation allowed. In grid cells with an elevation that is higher/lower than those of all the data of the local sample, the regression model is not applied and the predicted value is set as the value obtained by the model in correspondence of the elevation of the highest/lowest rain gauge used.

For this model configuration it can be worth examining the spatial variability of the slope coefficients emerged by the regression models, that quantify the influence of elevation on the spatial variability of rainfall extremes (Fig. 1).

Across most parts of the Alps, the Liguria region, and sections of the Apennines, there is a noticeable decrease in the 1-hour average annual maxima as elevation increases (Fig. 1a). This observation supports the presence of the "reverse orographic effect," previously identified by [4, 5, 6]. In contrast, in most of the hilly, pre-alpine, and flat regions, the average annual maxima tend to rise with elevation. Fig. 1b, instead, confirms that the 24-hour average annual maxima generally increase with elevation across Italy, with the exception of certain hilly and mountainous areas where this trend does not hold.

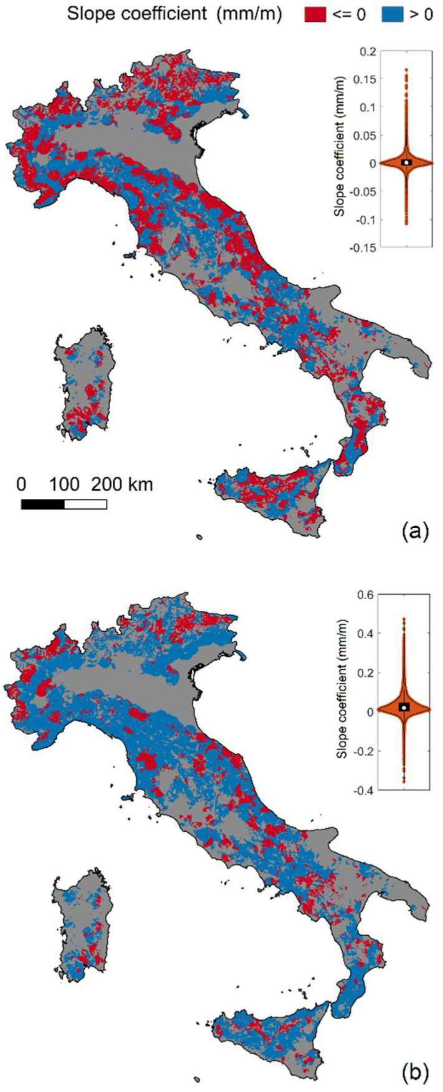

Figure 1. Slope coefficients of the selected regression models for the 1 h (a) and 24 h (b) duration. The grey color is used for the areas where the regression model cannot be applied due to low data density or extrapolation constraints. Source: [7].

V. CONCLUSIONS

This study introduces an enhanced local regression method to analyze the spatial variability of average annual maximum rainfall depths for short durations (1, 3, 6, 12, and 24 hours) across Italy with respect to the elevation. The approach improves interpolation by selecting small, localized samples that leverage areas with high rain gauge density. Special attention was given to mitigating artifacts caused by inconsistent rainfall gradients and extrapolation issues. Unlike other approaches, which treat negative rainfall gradients as errors, this study allows negative values but controls them through constraints on the elevation range of the data.

Results indicate that using a local regression within a 15 km radius best preserves local variability, accommodating the uneven distribution of rain gauges across the country.

This method identifies several regions in Italy with negative orographic gradients, where rainfall decreases with elevation, especially for the 1 h duration. The classical orographic effect instead prevails for longer durations.

VI. ACKNOWLEGMENTS

This research has been supported by the RETURN Extended Partnership and received funding from the European Union NextGenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005 – Spoke TS2).

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