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Orographic and land-sea contrast effects in convection-permitting simulations of extreme sub-daily precipitation

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ABSTRACT

Convection-permitting climate models (CPMs) represent a significant advancement compared to regional climate models, enabling more accurate simulations of extreme precipitation at fine spatial and temporal scales. Assessing the reliability of CPM projections for extreme short-duration precipitation requires understanding how well CPMs reproduce observed extremes—especially in Mediterranean regions, where such evaluations are rare. In this study, we assess the accuracy of simulations from a high-resolution CPM covering the entire Italy (VHR-PRO_IT), in reproducing sub-daily precipitation extremes. For this, we exploit observations from I^2-RED, a comprehensive dataset of more than 5 000 quality-checked annual maximum time series from rain gauge observations. The comparison is performed by considering the median values of the annual maxima at 1, 3, 6, 12 and 24-h as a first step and rainfall quantiles up to 200-year return period as a second step. Our results show that model performance is influenced by both the distance from the coastline and elevation, highlighting an important role of orography and land-sea contrast in explaining CPM biases. Moreover, we find better performances when longer duration extremes are considered, while shorter durations are affected by strong underestimations, especially in coastal and low-elevation areas. These results hold significant implications for stakeholders and policymakers dealing with climate adaptation and flood risk management.

1. Introduction

Extreme sub-daily precipitation events are projected to increase in a warmer climate, possibly enhancing water-related hazards, such as flash floods, urban flooding and debris flows (Fowler et al., 2021; IPCC, 2022). Although the impact of climate change have been considered in flood risk assessments for several decades (Prudhomme et al., 2010; Wilby and Keenan, 2012; Merz et al., 2014; Wasko et al., 2024), these assessments have generally used coarse resolution projections downscaled from Global Circulation Models (GCMs) and Regional Climate Models (RCMs), which use parametrizations to simulate deep convection and are unable to explicitly resolve atmospheric moist deep convection and other dynamical processes responsible for flooding (Orr et al., 2021). During the last two decades, these limitations have been a

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strong driver in pursuing more advanced, higher resolution climate models, such as Convection Permitting Models (CPMs) (Prein et al., 2015; Clark et al., 2016; Kendon et al., 2017). With grid sizes of 2–4 km, which may explicitly resolve convective processes, CPMs provide an opportunity to describe convection and atmospheric processes that previously were represented by parametrizations with large uncertainties (Fosser et al., 2020a, 2020b). This capability is crucial for capturing detailed structures of convective storms and precipitation patterns (Thomassen et al., 2021) which are often missed or poorly represented in coarser models. Also, fine space-time information helps to improve climate simulations along sharp environmental boundaries, such as coastal lines and lagoons, and over rough orography, which are all relevant in a Mediterranean context, as shown in Dallan et al. (2024b), Fosser et al. (2024) and Cortes-Hernandez et al. (2024). Thus, the enhanced resolution of CPMs has the potential to provide a better understanding of the impacts of global warming on sub-daily extreme precipitation, which is key for societal adaptation.

Recent studies showed that CPMs substantially improve the representation of sub-daily precipitation over convection-parameterized models and better capture the details of convective organization (Leutwyler et al., 2016; Fosser et al., 2024). Nonetheless, certain biases persist, primarily attributable to specific model formulations — for instance, the overestimation of heavy rainfall resulting from inadequately resolved cloud processes such as entrainment (e.g., Prein et al., 2021). Also, CPMs are not able to capture the small-scale details of storms, with rainfall cells tending to be too large with too heavy rainfall (Hanley et al., 2015). Assessing the accuracy of CPMs in reproducing observed precipitation extreme events is therefore crucial to increase the reliability of future flood risk assessment analyses (Dale, 2021; Soriano et al., 2023; Lompi et al., 2023; Poncet et al., 2024). This evaluation is often assessed by looking at precipitation percentiles computed considering all the wet time intervals (e.g., Kendon et al., 2012; Berthou et al., 2019; Armon et al., 2020). However, only a few studies to date have evaluated the capability of CPMs to simulate sub-daily extreme precipitation with return periods typically used in hydrological and engineering applications (Ban et al., 2020; Dallan et al., 2023, 2024a; Chan et al., 2023; Meredith et al., 2020; Correa-Sanchez et al., 2025). Specifically, Ban et al. (2020) compared an ensemble of CPMs with an ensemble of RCMs over the Alps, by considering rainfall quantiles for 2- up to 100-year return periods, for 1-h, 1-day and 5-day rainfall durations. Overall, they found that the CPMs improvements are more evident in summer, when convection plays a major role. Over just northeastern Italy, Correa-Sanchez et al. (2025) considered sub-daily durations and return periods up to 100 years for an ensemble of CPM, and highlighted that the ensemble tends to overestimate hourly extremes at higher elevations, and to underestimate them at lower elevations. This implies that the model could not fully capture the reverse orographic effect, that is the decrease of rainfall depths with increasing elevations, reported by several previous studies (Allamano et al., 2009; Avanzi et al., 2015; Formetta et al., 2022, 2024; Marra et al., 2022; Mazzoglio et al., 2022, 2023). As a result, Dallan et al. (2023) conclude that CPM bias-correction approaches should also account for orography. However, an overall good agreement between CPMs and observed extremes is reported for daily durations. In an application conducted over Catalonia (Spain), Meredith et al. (2020) performed an analysis at sub-hourly durations and pointed out that, at these scales, CPMs simulate precipitation extremes with an accuracy comparable to the one that characterizes the hourly duration. Similar results were also obtained by Vergara-Temprado et al. (2021).

To the best of authors knowledge, a comprehensive assessment of high-quantile precipitation using CPM over a large area and across the full range of sub-daily durations is notably lacking for the Mediterranean region. This gap is particularly significant given that the Mediterranean region is recognized as a climate change hotspot (Giorgi, 2006), facing an increasing frequency of extreme precipitation events (Armon et al., 2020; Hochman et al., 2022; IPCC et al., 2022; Mazzoglio et al., 2025) as well as decreasing annual precipitation amounts (Caporali et al., 2021). Moreover, the region is characterized by complex topography and land-sea contrasts, which are expected to impact extreme sub-daily precipitation quantiles (Marra et al., 2022; Cortes-Hernandez et al., 2024). Quantifying the ability of CPM simulations to capture the interactions among these forcing factors is thus central for the representation of regional extreme precipitation in this area.

In this study, we present the first assessment of the accuracy of sub-daily precipitation extremes from a CPM in the Mediterranean context, using the entire Italy as a representative case study. We examine a recently developed CPM, VHR-PRO_IT (Very High-Resolution PROjections for Italy; Raffa et al., 2023), which provides coverage for the entire country. Our evaluation is based on a unique quality-controlled dataset comprising more than 5 000 time series of sub-daily annual maximum rainfall depths at the national scale. The focus is on extreme events with a medium-to-low probability of occurrence obtained with a regionalization approach, offering valuable insights into the behavior of rare precipitation patterns.

2. Study area and data

This study focuses on Italy, a peninsula that extends southward from central Europe into the central Mediterranean Sea (Fig. 1a). The country is characterized by major mountain ranges, including the Alps in the North and the Apennines, which run along the peninsula. A detailed overview of Italy's sub-daily extreme precipitation is reported in Avanzi et al. (2015) and in Mazzoglio et al. (2020). According to Avanzi et al. (2015), the 50-year return period rainfall quantiles vary between 17 and 220 mm for the 1-h duration, and between 40 and 1 025 mm for the 24-h duration. High 1-h extremes occur along much of Italy's coastline, especially in Liguria, Friuli–Venezia Giulia, the central western coasts, eastern Sicily, Calabria, and Sardinia. Inland areas like the Po Valley and the Apennines also show high values, particularly near mountains. As the duration increases to 24 h, extreme precipitation becomes more localized, concentrating in the northwestern and northwestern Alps, Liguria, the western coasts, eastern Sardinia, southern Calabria, eastern Sicily, and Friuli–Venezia Giulia, reflecting a shift from convective storms (short duration) to stratiform precipitation (long duration).

VHR-PRO_IT (Very High-Resolution PROjections for Italy; Raffa et al., 2023) is an open access hourly climate projection with a $\simeq$2.2 km resolution that covers Italy and adjacent regions for the period 1981–2070, including a comprehensive set of near-surface and atmospheric variables, such as 2-m temperature, precipitation, 10-m wind speed and direction, surface pressure, specific humidity, as well as radiation fluxes and soil moisture at various depths. VHR-PRO_IT is produced by dynamically downscaling the Italy8km-CM climate projection (spatial resolution $\simeq$8 km; output frequency = 6 h; driven CMIP5 GCM = CMCC-CM, Scoccimarro et al., 2011), driven by the CMCC-CM global climate model under the CMIP5 RCP4.5 and RCP8.5 scenarios, with the Regional Climate Model COSMO-CLM (Rockel et al., 2008). In this configuration, where the CPM is indirectly forced by the CMCC-CM global model, the biases in large-scale atmospheric circulation, humidity, temperature, and sea surface temperatures (SSTs) may propagate into the high-resolution simulation. SST fields, inherited from the GCM without coupling to an interactive ocean model, may particularly affect coastal circulations and precipitation processes during summer, due to a potential misrepresentation of land-sea thermal contrasts. It is important to distinguish that, unlike an evaluation run driven by reanalysis (e.g., VHR-REA_IT, Raffa et al., 2021, which uses ERA5), the historical climate projection analyzed here cannot fully isolate model-intrinsic biases from errors in the boundary conditions. Therefore, part of the deviations from observations, especially for extreme precipitation, may reflect inherited GCM biases rather than only CPM deficiencies. By examining the GCM-RCM-driven historical CPM model, we quantify the biases we should expect also in the future period simulations, which are GCM-RCM-driven.

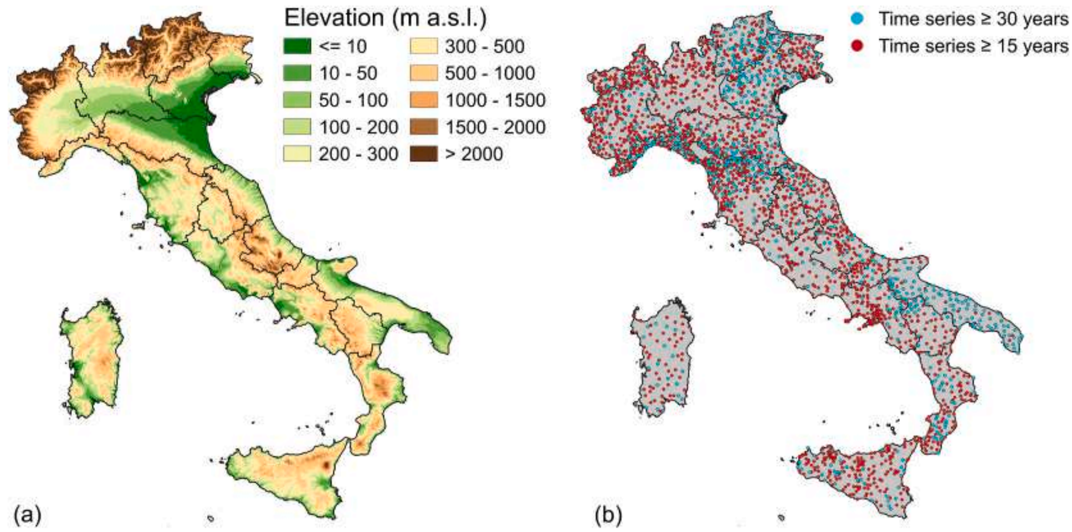

Fig. 1. Digital Elevation Model of Italy (a). Location of the rain gauges with at least 30 (light blue) and 15 (red) years of data in the 1980–2022 period (b).

The capability of VHR-PRO_IT in reproducing observed annual maxima and medium-to-low probability of occurrence events is evaluated using I^2-RED (Improved Italian – Rainfall Extreme Dataset; Mazzoglio et al., 2020) as a reference. I^2-RED is a collection of sub-daily (1, 3, 6, 12 and 24 h) annual maximum rainfall depths measured by more than 5 000 rain gauges from 1916 up to 2022. The dataset is obtained by merging the historical data collected by the Servizio Idrografico e Mareografico Nazionale (SIMN) with the most recent data provided by the 21 regional hydrological agencies, now in charge of managing the Italian rain gauge network.

In this work, each series extracted at a given rain gauge location from I^2-RED is compared with the time series of sub-daily annual maxima of the co-located grid point of VHR-PRO_IT.

Given the purpose of the comparison, the reference period for the analysis is selected to maximize the overlap between the two datasets and, for I^2-RED, to maximize the availability of information in terms of spatial density and time series length, taking into account its fragmentation. The length of the periods is selected after careful examination as a time window sufficiently short to guarantee that the non-stationary effects related to climate change would only marginally affect moments and probability distribution parameters, but sufficiently long to allow for a reliable estimation of the precipitation quantiles. Thus, the 30-year period 1981–2010 is selected for VHR-PRO_IT. The period includes the historical simulation period (1981–2005) and 5 years from the RCP8.5 scenario (2006–2010) of the CPM simulation. From I^2-RED, a slightly longer reference period (1980–2022) is selected to cope with missing data issues. Around the late 1980s, the SIMN was dismantled, and 21 regional hydrological agencies were created. These agencies began operating at different times and with different priorities, leading to issues such as the repositioning of rain gauges due to modernization efforts and gaps in the historical series caused by reduced maintenance of the monitoring network. To maximize the availability and continuity of observed data, it is therefore necessary to extend the observation period by approximately a decade with respect to the CPM. Since CPM historical simulations do not cover periods prior to 1980, we chose to extend the evaluation period forward by including the first few years of the RCP8.5 scenario.

Regarding the observation data, we consider two subsets of rain gauges. The first one comprises 2 605 stations with at least 15 years of annual maxima within the reference period (in red in Fig. 1b), allowing a good spatial coverage of Italy. The second subset consists of 742 rain gauges with a time series of at least 30 years in the reference period (in blue in Fig. 1b), used to compute high return period rainfall quantiles. This subset covers all the Italian regions, although some of them are sparsely sampled due to the fragmentation of the Italian monitoring network.

3. Methodology

Annual maxima from I^2-RED are used to evaluate the accuracy of the VHR-PRO_IT convection-permitting model in reproducing precipitation statistics over Italy for the five durations available in the observations: 1, 3, 6, 12 and 24 h. The assessment is carried out in two steps.

The first step aims to evaluate how a set of geographical features such as latitude, elevation and distance from the coastline may impact VHR-PRO_IT accuracy in representing extreme rainfall statistics. The median of the annual maxima, corresponding to an empirical return period of 2 years, is used for this purpose in order to maximize the availability of stations with use of records of at least 15 years. The median values of annual precipitation extremes derived from the two datasets are then compared using both scatter plots and in relative terms. Specifically, the relative difference Δh between observed and simulated values is calculated at each station as follows

$$\Delta h = \frac{h_{VHR-PRO\_IT} - h_{I^2-RED}}{h_{I^2-RED}} \cdot 100 \quad (1)$$

where $h_{VHR\text{-}PRO\_IT}$ and h_{I^2-RED} are the medians extracted from VHR-PRO_IT and I^2-RED, respectively. In this phase, we investigate potential relationships between the median values of the two series and key geographical features – namely latitude, elevation and distance from the coastline of the gauging stations – using the Pearson correlation coefficient (ρ). The model's ability (or lack thereof) to capture dependencies on these features is expected to reflect its accuracy in representing relevant atmospheric processes, such as convection, moisture transport, and mesoscale dynamics. To help disentangle the effects of elevation and distance from the coastline, the analysis also includes an evaluation across four latitudinal/longitudinal transects (two reported in Section 4.3, two in the Supplementary Material, section "Additional transects").

In a second step, we assess the accuracy of VHR-PRO_IT in estimating medium-to-high return period rainfall quantiles — potentially corresponding to yet unobserved extreme events. For this purpose, we use 30-year-long time series from the I^2-RED dataset. Specifically, we compare rainfall quantiles from the two datasets for selected durations d and return periods T = 20, 50, 100 and 200 years, using a Generalized Extreme Value (GEV) model (Von Mises, 1936; Gumbel, 1954). In the GEV model used in this work, a positive shape parameter indicates a bounded (thin) upper tail characteristic of the Weibull type, whereas a negative shape parameter denotes a heavy tail, typical of the Fréchet type. Details of the methodology are provided in the Supplementary Material, section "Computation of rainfall quantiles (GEV distribution)". To reduce the effects of sampling uncertainties, we adopt a region-of-influence approach, in which the GEV parameters at each station are estimated using data from the station itself and its two nearest neighbors. To ensure a fair and consistent comparison, the same pooling geometry is applied to the VHR-PRO_IT dataset. The GEV distribution parameters are thus estimated using the regionalization method of the L-moments (Hosking and Wallis, 1993, 1997). The pooled L-moment ratios used for estimating the GEV parameters at each station is derived from the at-site sample L-moment ratios, calculated as weighted regional averages. The regionalization approach is verified using the Hosking and Wallis homogeneity test, based on the computation of the H test statistic (Hosking and Wallis, 1993). Time series found to be heterogeneous ($|H| > 2$) are excluded from the analysis. For comparison, we also evaluate rainfall quantiles obtained using two alternative configurations: i) data from the single station only, and ii) a two-station region consisting of the target station and its nearest neighbor. The results from these configurations are reported in the Supplementary Material (Section "Rainfall quantiles") and will not be discussed in the next section for the sake of brevity.

The comparison between both the median values and the rainfall quantiles from VHR-PRO_IT and the corresponding I^2-RED reference values is quantified using the Pearson correlation coefficient (ρ) and the percent bias (*PBIAS*), defined as

$$PBIAS = \frac{\sum_{i=1}^{n}\left(h_{VHR-PRO\_IT_i} - h_{I^2-RED_i}\right)}{\sum_{i=1}^{n}\left(h_{I^2-RED_i}\right)} \cdot 100 \quad (2)$$

where h represents either the median value or the rainfall quantile, depending on the analysis, and n is the total number of stations.

4. Results

4.1. Medians of annual maxima: correlation with geographical features

The correlation between the median values of the two datasets (evaluated at all gauging locations where at least 15 years of data are available) and a series of geographical features (latitude, elevation and distance from the coastline) is reported in Table 1. In the Supplementary Material, we provide the scatter plots between the geographical feature and the median values (Figs. S1–S3).

The median values of the 1-h annual maxima from the I^2-RED dataset exhibit negative correlations with both elevation and distance from the coastline, while showing almost no correlation with latitude. In contrast, for the same duration, the VHR-PRO_IT dataset displays positive correlations with elevation, distance from the coastline, and latitude. For the 24-h annual maxima, the I^2-RED dataset shows positive correlations with latitude and elevation, but no significant correlation with distance from the coastline. VHR-PRO_IT shows similar, though slightly stronger, correlations with latitude and elevation, and also shows a positive correlation with distance from the coastline.

Table 1
Pearson correlation coefficient (ρ) between the median values of the two datasets and three geographical features (latitude, elevation and distance from the coastline). In boldface we report the statistically significant relationships (significance level = 0.05).

	Latitude	Elevation	Distance from the coastline
1 h median I^2-RED	−0.01	**−0.32**	**−0.30**
1 h median VHR-PRO_IT	**0.47**	**0.25**	**0.39**
24 h median I^2-RED	**0.23**	**0.23**	0.02
24 h median VHR-PRO_IT	**0.33**	**0.57**	**0.30**

4.2. Medians of annual maxima: comparison with I^2-RED

The comparison is initially illustrated through scatter plots, one for each considered duration, where points corresponding to each gauge are colored according to their elevation (Fig. 2a) or their distance from the coastline (Fig. 2b). The Pearson correlation coefficient (ρ) and the percent bias (*PBIAS*) are reported in Fig. 2a.

As illustrated in Fig. 2, the correlation between the medians of simulated and observed annual maxima increases with event duration, with correlation coefficient ρ exceeding 0.75 for durations of 12 and 24 h (0.78 and 0.81, respectively). A clear duration-dependent pattern is also evident for the bias: the VHR-PRO_IT climate model better represents longer duration extremes (e.g., $PBIAS = -9.6$ % for 24-h extremes), while it significantly underestimates shorter-duration extremes on average (e.g., $PBIAS = -37.9$ % for 1-h extremes). The median values of annual maxima for 1-h duration in VHR-PRO_IT seem to be upper bounded: Fig. 2 shows that VHR-PRO_IT is not able to provide annual maxima higher than about 30 mm, while observations also contain several values in the range 50–60 mm. The scatter plots in Fig. 2 also reveal a clear relationship between accuracy and both elevation and distance from the coastline. Specifically, VHR-PRO_IT tends to produce values more consistent with observations at stations located at higher elevations and farther inland, particularly for short durations.

To further explore spatial patterns, we compare the median values in terms of relative differences for the 1-h and 24-h durations (Fig. 3). A systematic underestimation of the median 1-h extremes estimated using VHR-PRO_IT is evident across most of Italy, with the exception of certain mountainous areas in the Alpine region of Northern Italy (Fig. 3a). Pronounced distortions are observed close to the coastline. The underestimation of the median values also prevails for the 24-h duration, even if in this case the relative differences are smaller than those obtained for shorter durations (Fig. 3b). For the 24-h duration, positive anomalies are present close to the reliefs, both over the Alps and along the Apennines.

4.3. Medians of annual maxima: assessment across latitudinal and longitudinal transects

Given the existing strong correlation between orography and distance from the coastline, with elevation increasing with the distance from coastline, we investigate here the relative differences in their impact along transects with fixed latitude or longitude. To better understand how model errors are associated with these geographical features, two of the selected transects are located over Northern Italy, an area with higher station density. However, the results obtained in this area are comparable with analogous transects in Central and Southern Italy (reported in the Supplementary Material, section "Additional transects", Figs. S4 and S5). For each transect, we created a buffer of 10 km for each side (20 km in total) to pool all the stations together and we computed the mean elevation of the transect by using the SRTM DEM (Farr et al., 2007) resampled at 1 km resolution with a bicubic interpolation. After having defined the buffer, all the rain gauges located within it are considered to represent how the relative difference varies with respect to the geographic position.

Two transects placed in Northern Italy with constant longitude (Fig. 4) and latitude (Fig. 5) are presented here. Both figures are organized into several panels (a-h), each providing insights into the relationships between the relative differences and geomorphological features.

Fig. 4d and e and Fig. 5d and e show moderate correlation between the relative difference of the median values of the 1-h extremes and the elevation (>0.37 in both cases). This is well represented in panels c, showing general underestimation below about 2000 m a.s.l., and increasing overestimation at higher elevation. The correlation with the distance from the coastline is slightly lower (0.24 in the first case, 0.36 in the second one). For shorter durations, thus, both elevation and distance from the coastline seem to have an influence on model performances

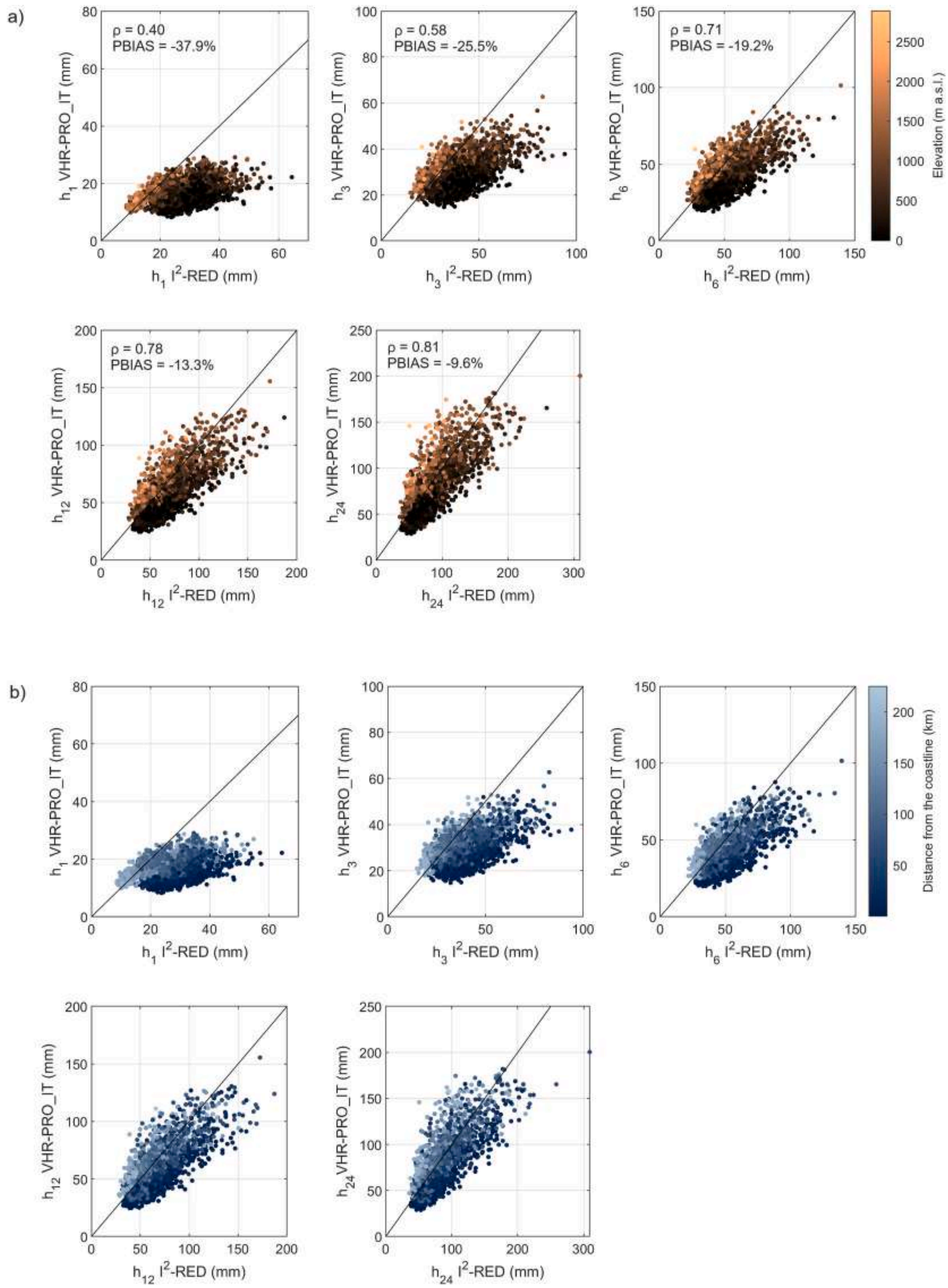

Fig. 2. Scatter plots of the median values of the sub-daily (1, 3, 6, 12 and 24 h) annual maxima from the CPM against those from the stations. The color of the dots represents the elevation of the rain gauge in panel a and the distance of the rain gauge from the coastline in panel b. In panel a we report the Pearson correlation coefficient (ρ) and percent bias (*PBIAS*) between simulated and observed median values of the annual maxima. The same values are true also for panel b.

(this feature emerges also when comparing Fig. 3a with Fig. 1a). Figs. 4g and 5g show high values of correlation between the relative difference of the median values of the 24-h extremes and the elevation (while the correlation with the distance from the coastline is smaller). Figs. 4f and 5f offer a clear representation of the bias along the transect, with negative bias mostly located below 1 000 m a.s.l., irrespective of the distance from the coastline, while above 1 000 m a.s.l. higher positive bias with higher elevation is found. This feature also emerges when comparing Fig. 3b with Italian orography in Fig. 1a: larger overestimations are usually present in regions with complex orography and high elevation, while underestimations are usually present in lowlands.

4.4. *Assessment of medium-to-high return period rainfall quantiles*

Here we focus on the assessment of medium-to-high return period rainfall quantiles estimated using the GEV distribution. In this analysis, 49 time series are excluded due to heterogeneity: 45 are identified using

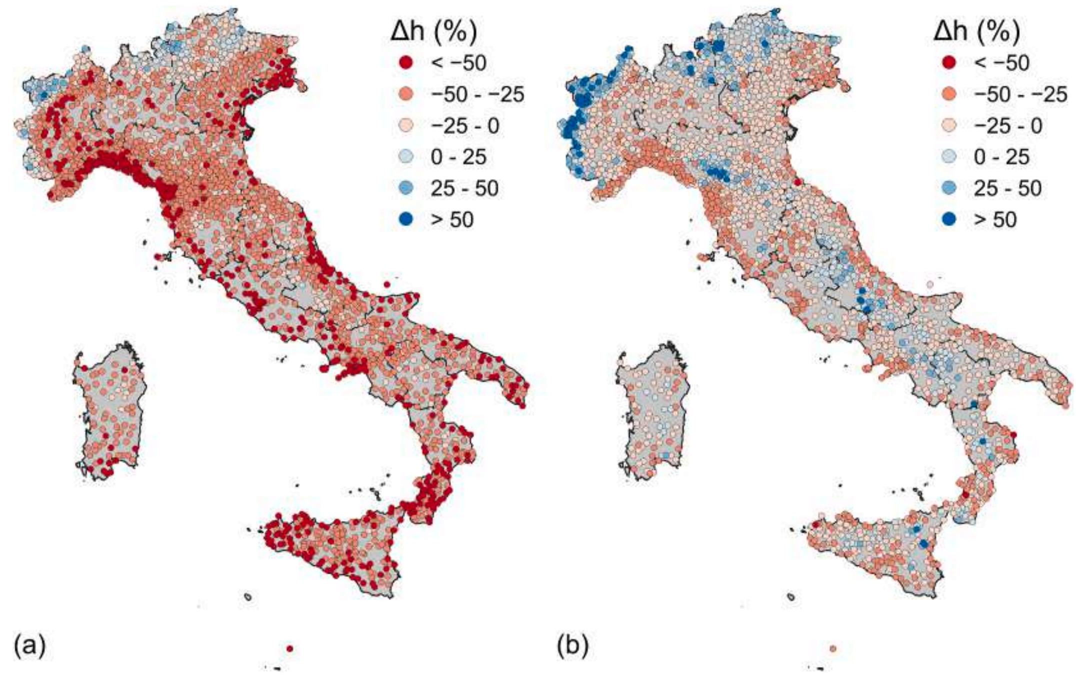

Fig. 3. Relative differences between the median values of the two datasets (VHR-PRO_IT and I^2-RED) for the 1 (a) and 24 (b) hour durations. Negative values (in red) indicate locations where the CPM underestimates the median annual maxima, while positive values (in blue) indicate overestimation.

the Hosking and Wallis homogeneity test applied to the rain gauge data, and 4 based on the same test applied to the CPM data (see Fig. S6 in the Supplementary Material for station locations). As shown in Fig. S6, the removed stations are characterized by the largest inter-station distances (30–56 km). Thus, we interpret the detected heterogeneity as physically meaningful, even though the percentage of stations that we removed (about 6 %) is close to the selected significance level, making it statistically comparable to what might be expected in a fully homogeneous dataset. The spatial distribution of the GEV shape parameter for both datasets and for two durations (1 and 24 h) is presented in the Supplementary Material (Figs. S7 and S8), while the L-moments ratio diagrams are reported in Figs. S9 and S10.

Fig. 6 shows the comparison between rainfall quantiles with 20 and 200 years return period and 1, 3, 6, 12, and 24 h durations computed by using the regionalization approach based on merging to each time series the data of the two closest ones. In these plots, each point represents a gauged location and provides insight into how elevation may influence the computation of rainfall quantiles. For all the return periods here considered, the analysis showed that the rainfall quantiles computed using VHR-PRO_IT tend to align more closely with the values computed by using observed data at higher elevations, confirming previous findings that emerged when investigating the median values and matching the findings by Dallan et al. (2023) obtained using another CPM.

In Fig. 7 and Fig. S11, the evaluation metrics (Pearson correlation coefficient and *PBIAS*) are presented for the 4 return periods and the 5 durations. As detailed in the Methodology Section, the results shown in Fig. 7 correspond to estimates derived by using data from the considered station, as well as from the two closest stations. Fig. S11, on the other hand, displays results for rainfall quantiles obtained using data from a single station only as well from a two-station region (the station itself and its nearest neighbor). These results confirm that the correlation coefficients between the rainfall quantiles computed with the two datasets increase with increasing durations, confirming the higher accuracy of VHR-PRO_IT in reproducing longer extreme events. As expected, for all the durations, extreme precipitation events with high return periods are less correlated with the observations than those with lower return periods. Also in this case, long durations are represented in a better way, as the correlation increases with the duration of the rainfall extreme for all the considered quantiles. Interestingly, *PBIAS* is systematically negative, confirming a problem of underestimation of VHR-PRO_IT in reproducing extreme precipitation for all considered durations and return periods. The bias is less affected by return periods than by the rainfall duration, and becomes smaller for longer durations (6–24 h).

A discussion on the influence of the distribution choice on the estimated rainfall quantiles is provided in the Supplementary Material (Section Rainfall quantiles, Table S2). In particular, the same statistics reported in Fig. 7 were also computed by using a Gumbel distribution in cases where the GEV shape parameter is positive.

5. Discussion

The biases of heavy rainfall in CPM reported in this work were also found in previous studies and, depending on the comparison setting, linked to a number of processes. Ban et al. (2020) reported CPM overestimation over highlands and suggested that errors in the observations (gauge undercatch) can partly explain this type of error. A major possible source of gauge undercatch is indeed related to the presence of strong wind. Depending on the wind speed, rain gauge shape, and precipitation type, the presence of strong wind could lead to losses of up to 40 % for rain and up to 80 % for snow at high wind speed (8–10 ms^{-1}; Cauteruccio et al., 2021). Our study reveals that CPM overestimation in highlands is stronger for extreme short-duration rainfall, which is mostly related to convection and is thus less subject to measurement underestimation of snowfall, as also discussed in Dallan et al. (2023). However, longer duration extreme events can be comparatively more affected by this type of observation error, particularly at high elevations. Part of the CPM overestimation found at high elevations at 12- and 24- hour could thus be due to this kind of undercatch.

The tendency of high-resolution climate models to overestimate heavy rainfall at short temporal aggregation has been reported in previous studies (Dallan et al., 2023) and is often attributed to the incomplete resolution of convective processes, even at convection-permitting scales (Kendon et al., 2012; Ban et al., 2020; Panosetti et al., 2020). Although our simulation uses a grid spacing of 2.2 km, its effective resolution is actually coarser (see also Reder et al., 2022). Based on

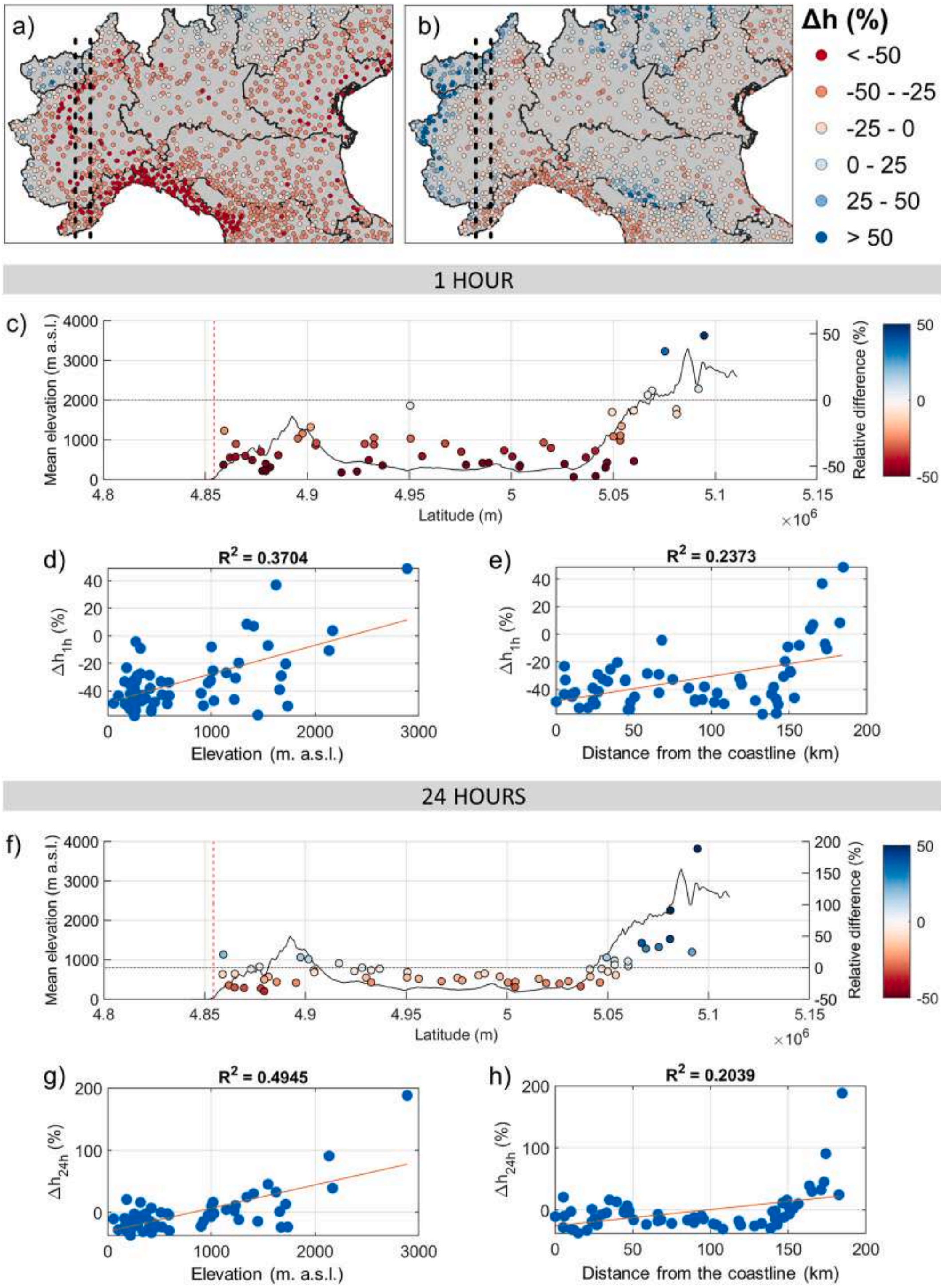

Fig. 4. Relative differences between the median values of the two datasets (VHR-PRO_IT and I^2-RED) for the 1 (a) and 24 (b) hour durations over the North of Italy, with an indication of the position of the transect with constant longitude of North-West Italy, depicted with a dashed black line. The color gradient of the points in panels a, b, c, and f indicates the magnitude of the differences, with red representing underestimation and blue representing overestimation by the CPM (as depicted in the color scale on the right). The transect considered is visible in (c) and (f): the black line indicates the mean elevation of the transect, referred to the left y-axis, the red dashed line represents the coastline while the dots represent the relative difference between the median values of the two datasets for the 1 (c) and 24 (f) hour durations. Scatter plots of the relative differences for 1 (d, e) and 24 (g, h) durations with respect to elevation (d, g) and distance from the coastline (e, h). For each scatter plot, the coefficient of determination R^2 is reported.

kinetic energy spectra, Skamarock (2004) estimated that the effective horizontal resolution of the Weather Research and Forecasting (WRF) model — whose dynamical core is similar to that of COSMO — resolves only wavelengths that are approximately 5–7 times the grid spacing. A later study comparing the COSMO and ECMWF-IFS models reported similar findings (Zeman et al., 2021). Therefore, in our case, wavelengths smaller than about 10–15 km are only partially resolved. Furthermore, climate models compute area-averaged values over grid cells, whereas rain gauges provide point-specific measurements, which results in greater variability (Schroeder et al., 2018). This discrepancy is

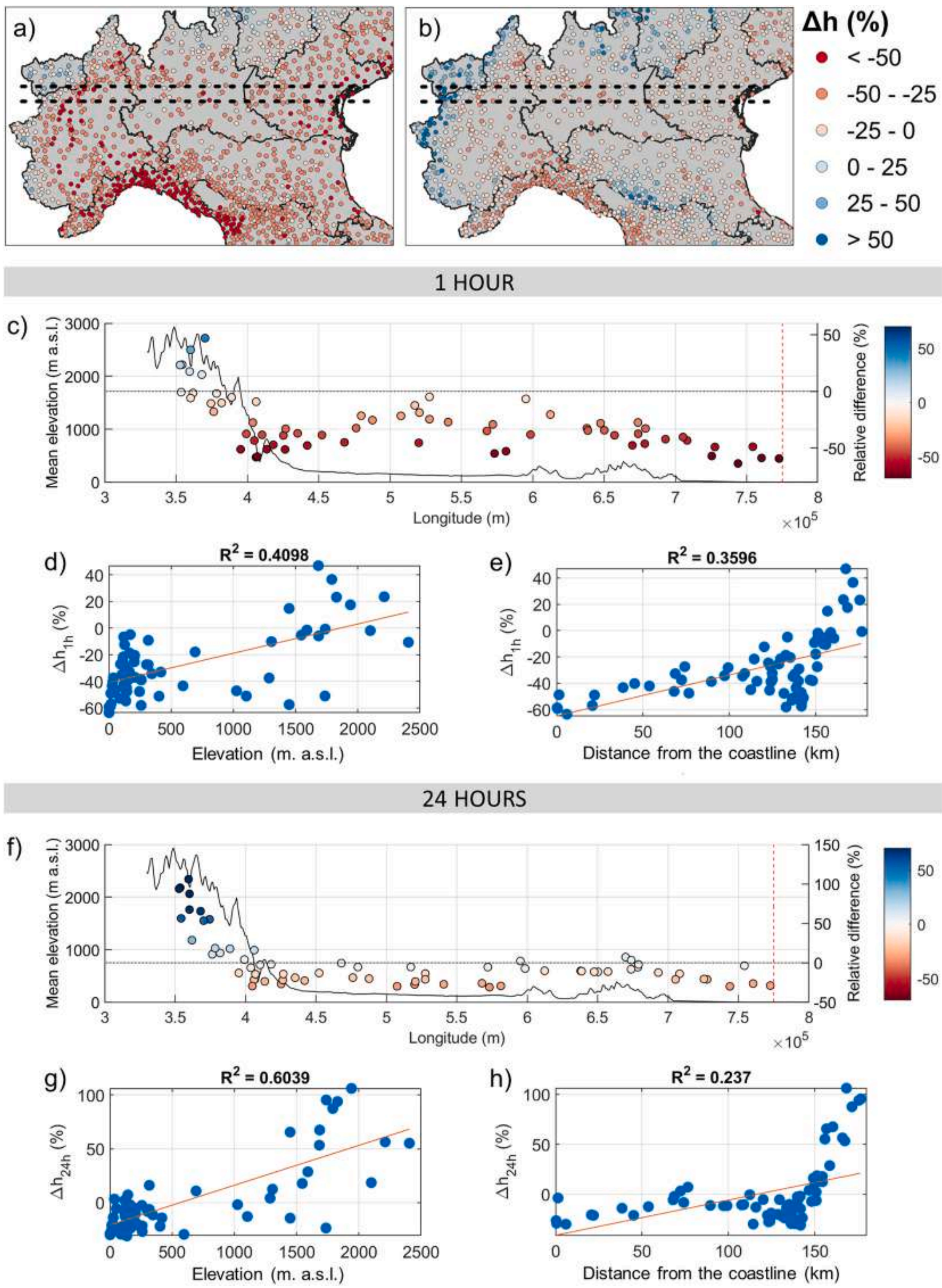

Fig. 5. The same as in Fig. 4 for the latitudinal transects.

particularly pronounced during extreme events, as highlighted by Peleg et al. (2018). Moreover, the alternation of hills and narrow valleys, responsible for the development of local winds and turbulence crucial for triggering convection, may not be well represented by the 2.2 km CPM spatial resolution. Our findings also indicate that the model is not able to capture the reverse orographic effect, which is typically associated with short-duration events. For these shorter durations, rainfall tends to be reduced as the elevation increases, while longer durations often see orographic enhancement due to prolonged uplift of moist air over mountainous regions. The model exhibits an overestimation of rainfall across mountainous areas at all durations, with the largest discrepancies observed for 24-h events (as illustrated in Figs. 3, 4c and 4f, 5c, 5f). All the above-mentioned issues could limit the ability of the CPM to fully represent the interaction of convective cells with orography, thus leading to a bias in the estimation of short-duration extremes over this orographically complex region.

The findings of this study highlight a significant underestimation of extreme precipitation in lowland areas, where elevation is not a major influencing factor, as previously noted by Raffa et al. (2023). Similar outcomes were reported by Dallan et al. (2023) over northeastern Italy using a different CPM. In the present case, additional factors may be at play, such as proximity to the coastline (Marra et al., 2022). Indeed,

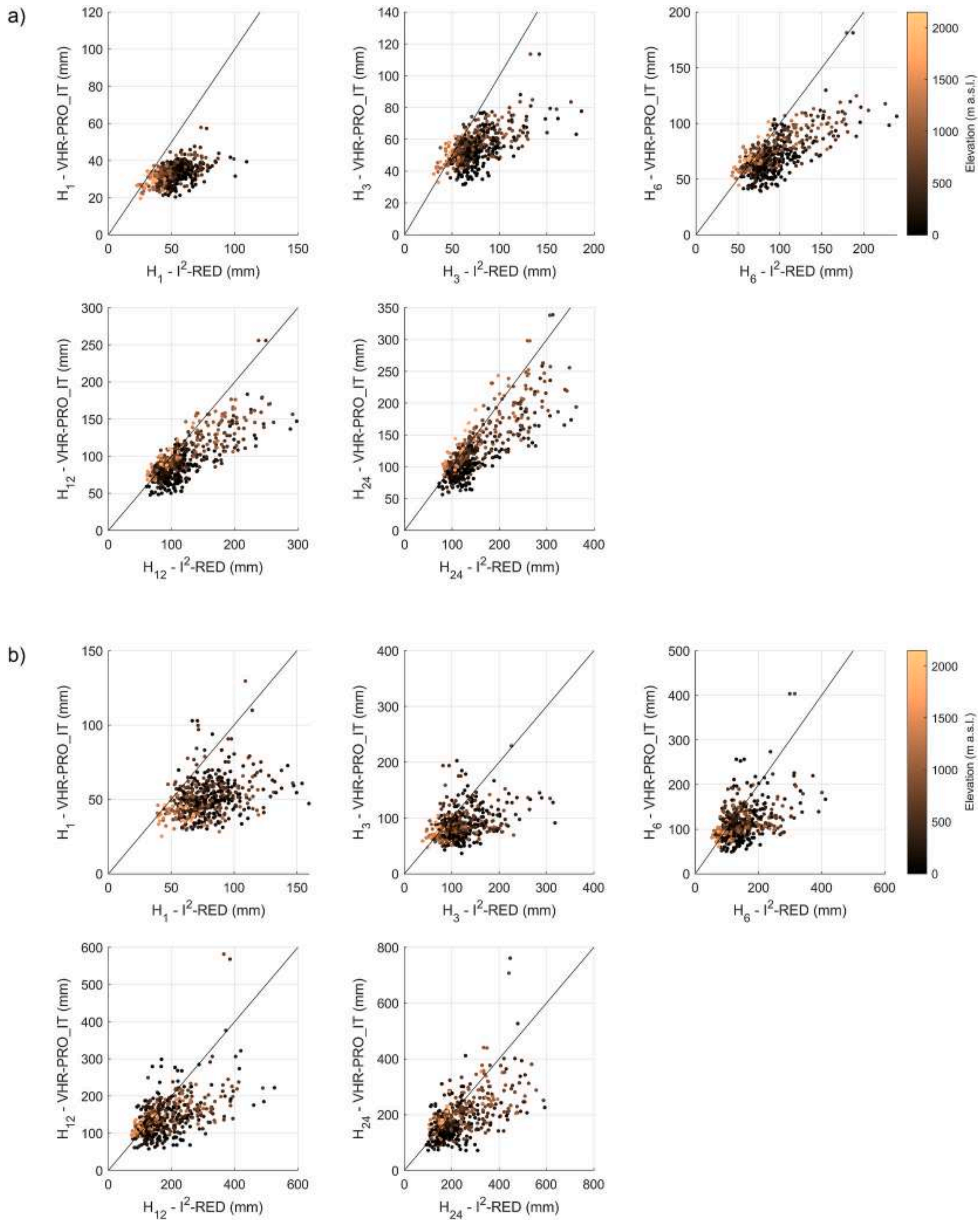

Fig. 6. Scatter plots of the 20-year (a) and 200-year (b) rainfall quantiles for durations of 1, 3, 6, 12 and 24 h. The color of the dots represents the mean elevation of the three rain gauges used to evaluate the rainfall quantile.

accurately modeling convection in coastal regions is particularly challenging due to the contrasting thermodynamic and surface roughness characteristics between land and sea. This may be related to the fact that the current generation of CPM have no representation of sea-atmosphere feedback, due to the fact that the CPM is not a coupled atmosphere-ocean model with an iterative ocean model. This result in decreased accuracy for sea-to-land moisture transport and convective events approaching the land from the sea (Cortés-Hernández et al., 2024; on RCMs, Ho-Hagemann et al., 2017).

The results suggest that the examined CPM faces challenges in accurately capturing sub-daily rainfall quantiles, especially at the land-sea interface and in both high and low elevations (Dallan et al., 2023; Correa Sanchez et al., 2025). At the same time, similar issues were reported for other CPMs, suggesting these challenges are not specific to this particular model but may be particularly relevant for the Mediterranean region. Biases related to elevation are generally positive and tend to increase with longer rainfall durations (Figs. 3 and 6). In contrast, the land–sea interface exhibits a pronounced negative bias, especially at shorter durations. Notably, the bias associated with the land-sea contrast—which diminishes with increasing latitude—accounts for much of the variation in the Pearson correlation coefficient between I^2-RED and VHR-PRO_IT and latitude, shown in Table 1. This highlights the challenges of accurately representing rainfall extremes in the Mediterranean region, where complex topography and strong land–sea contrasts play a critical role.

The use of the GEV distribution, particularly in cases where the shape parameter suggests a light tail, also warrants further discussion. As shown in Tables S2 and S3, applying the Gumbel distribution in

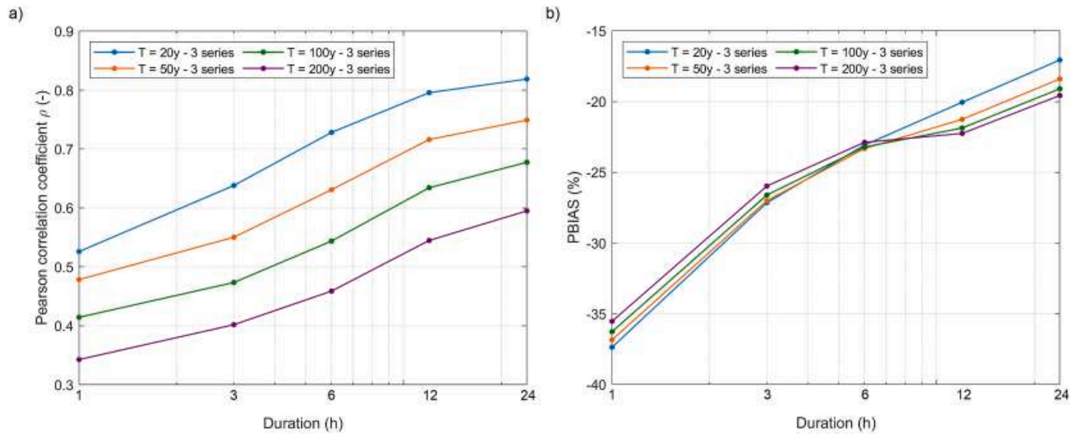

Fig. 7. Comparison between the rainfall quantiles computed for the 5 selected durations (1, 3, 6, 12, and 24 h) and the 4 return periods (20, 50, 100, and 200 years) for the regionalization model based on three stations in terms of Pearson correlation coefficient ρ (a) and percent bias *PBIAS* (b).

instances where the shape parameter is positive leads to improved correlation in some cases. However, the PBIAS remains largely unaffected, indicating that the overall tendency toward underestimation persists regardless of the distribution used.

6. Conclusions

According to Prein et al. (2015), a limiting factor for the detection of the added value of CPM climate simulations is the availability of suitable observational datasets. Thanks to a relatively dense network of rain gauges available in Italy through I^2-RED, in this work we were able to assess the accuracy of VHR-PRO_IT in the representation of sub-daily precipitation extremes, evaluating and quantifying local biases related to specific characteristics which are relevant for the Mediterranean environment. The comparison between simulations and observations is here performed considering in a first step the medians of the distribution of annual maxima, in an effort to explain the control of certain geographical features on CPM biases. In a second step, the comparison has been extended to medium-to-high return period rainfall quantiles, which are particularly relevant for hydrological design.

Both the comparisons highlighted that VHR-PRO_IT provides satisfactory results when considering longer duration events, while shorter durations (e.g., 1 and 3 h) are affected by strong underestimations especially in coastal and low-elevation areas. On the contrary, VHR-PRO_IT provides satisfactory results especially at medium-to-high elevations, that are usually poorly gauged (thus leading to a poor understanding of precipitation patterns), and over inland areas. Our results also show that model performance is influenced by both the distance from the coastline and elevation. Mountain reliefs play a different role depending on the location. High values of discrepancies between the model and the observations emerge over mountainous regions far from the coastline. In these cases, we can observe positive differences, meaning that the model overestimates the extremes for all the durations. The opposite occurs when the relief is close to the coastline: in this case, an underestimation of the extremes is observed, particularly at shorter durations. The presence of the coastline affects the model's reliability especially for short-duration extremes, while longer intervals seem to be less affected. This detailed exploration of topographic impacts in a Mediterranean region stands out as a significant finding in the context of CPMs, in view also of supporting the hydrological design of climate change adaptation measures.

It is worth highlighting that, in this study, all the results are obtained by using only one convection permitting model (that, to the author's knowledge, is the only CPM-GCM Driven with nationwide coverage). This is a limitation and further works should be conducted by using ensembles of CPMs instead of a single one as soon as new CPMs will be made available.

The results presented in this work hold significant implications for stakeholders and policymakers tasked with climate adaptation and water management, with a specific focus on the Mediterranean environments. With its complex topography and strong land-sea contrasts, this environment places specific challenges to the CPM correct representation of sub-daily rainfall extremes. This shows the need for specific research efforts in the Mediterranean region to better understand the sources of model weaknesses and guide further CPM-focused research.

CRediT authorship contribution statement

Paola Mazzoglio: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Lompi:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesco Marra:** Writing – review & editing, Methodology, Conceptualization. **Eleonora Dallan:** Writing – review & editing, Methodology, Conceptualization. **Roberto Deidda:** Writing – review & editing, Conceptualization. **Pierluigi Claps:** Writing – review & editing, Conceptualization. **Salvatore Manfreda:** Writing – review & editing, Conceptualization. **Leonardo Valerio Noto:** Writing – review & editing, Conceptualization. **Alberto Viglione:** Writing – review & editing, Conceptualization. **Mario Raffa:** Writing – review & editing. **Paola Mercogliano:** Writing – review & editing. **Marco Marani:** Writing – original draft, Conceptualization. **Enrica Caporali:** Writing – review & editing, Methodology, Conceptualization. **Marco Borga:** Writing – review & editing, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wace.2025.100798.

Data availability

The agreements we signed with the regional hydrological agencies involved in the management of the rain gauge network, aimed at monitoring the correct use of the data, restricted their use to the aims of the authors' project and did not allow the publishing of the complete dataset on repositories with open access. A complete description of how to access the raw data that the authors used in this work is reported in Mazzoglio et al. (2020): by downloading and merging all the data sources listed in this paper, the complete dataset can be reconstructed.

VHR-PRO_IT climate projection dataset is available with an open access policy at https://doi.org/10.25424/CMCC-J90A-5P12.

Both the datasets were processed and analyzed with MATLAB and QGIS3. The MATLAB scripts and functions used in the analysis to process the data, compute the L-moments, fit GEV parameters and computing rainfall quantiles, together with a synthetic, non-licensed version of the input data, are available at https://doi.org/10.5281/zenodo.15776898.

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