**Supplement n°1: fitting of the national-scale simple regression models**

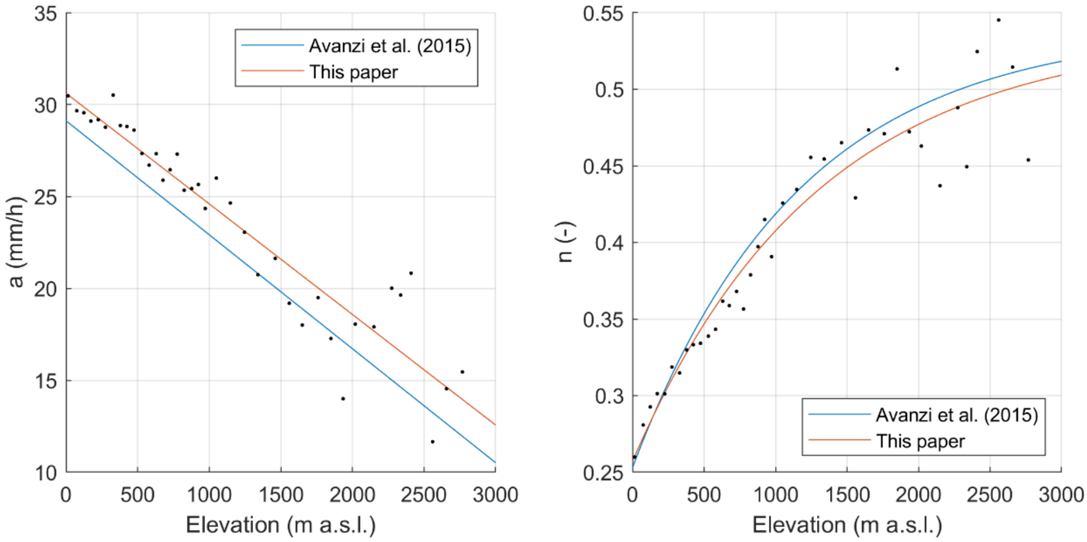


**Figure S1. Fitting of the national-scale simple regression models of Avanzi et al. (blue line) and the one proposed in this work (red line) on I²-RED data.**

**Supplement n°2: four-regions multiple linear regression models**

The best regression models built for the four-regions using up to four covariates are reported hereafter, together with the corresponding $R^2_{adj.}$

**Alps**

$h_1 = 12.5631 – 0.0053 \cdot z + 0.0145 \cdot MAR$ ($R^2_{adj} = 0.65$) (S1)

$h_1 = -28.0382 – 0.0051 \cdot z + 0.0139 \cdot MAR + 29.5758 \cdot OP$ ($R^2_{adj} = 0.73$) (S2)

$h_1 = 60.9365 – 1.6664 \cdot 10^{-5} \cdot LAT – 0.0046 \cdot z + 0.0148 \cdot MAR + 25.1825 \cdot OP$ ($R^2_{adj} = 0.75$) (S3)

$h_{24} = 751.4719 – 1.4892 \cdot 10^{-4} \cdot LAT + 0.0839 \cdot MAR$ ($R^2_{adj} = 0.74$) (S4)

$h_{24} = 63.0269 – 7.2339 \cdot 10^{-5} \cdot LONG – 0.2079 \cdot C + 0.0828 \cdot MAR$ ($R^2_{adj} = 0.76$) (S5)

$h_{24} = 59.0632 – 7.2955 \cdot 10^{-5} \cdot LONG – 0.2223 \cdot C + 0.4306 \cdot OBS + 0.0822 \cdot MAR$ ($R^2_{adj} = 0.76$) (S6)

**Apennines**

$h_1 = 19.5774 – 0.0083 \cdot z + 0.0128 \cdot MAR$ ($R^2_{adj} = 0.36$) (S7)

$h_1 = 21.5180 – 0.0075 \cdot z – 0.0387 \cdot C + 0.0122 \cdot MAR$ ($R^2_{adj} = 0.40$) (S8)

$h_1 = -12.0037 – 0.0072 \cdot z – 0.0399 \cdot C + 0.0139 \cdot MAR + 20.8086 \cdot OP$ ($R^2_{adj} = 0.41$) (S9)

$h_{24} = 22.8286 - 0.1775 \cdot C + 0.0645 \cdot MAR$ ($R^2_{adj} = 0.66$) (S10)

$h_{24} = 35.6610 – 1.2603 \cdot 10^{-5} \cdot LONG - 0.2097 \cdot C + 0.0629 \cdot MAR$ ($R^2_{adj} = 0.67$) (S11)

$h_{24} = 179.2636 – 3.3612 \cdot 10^{-5} \cdot LONG – 2.6594 \cdot 10^{-5} \cdot LAT - 0.1979 \cdot C + 0.0623 \cdot MAR$ ($R^2_{adj} = 0.68$) (S12)

**Sicily**

$h_1 = 11.2186 – 1.9845 \cdot 10^{-5} \cdot LONG – 0.0036 \cdot z$ ($R^2_{adj} = 0.12$) (S13)

$h_1 = 252.6852 – 5.5699 \cdot 10^{-5} \cdot LAT – 0.0061 \cdot z + 0.0163 \cdot MAR$ ($R^2_{adj} = 0.25$) (S14)

$h_1 = 187.8533 – 5.4790 \cdot 10^{-5} \cdot LAT – 0.0069 \cdot z + 0.0220 \cdot MAR + 37.6608 \cdot OP$ ($R^2_{adj} = 0.34$) (S15)

$h_{24} = 975.8822 – 0.0002 \cdot LAT + 0.1077 \cdot MAR$ ($R^2_{adj} = 0.53$) (S16)

$h_{24} = 704.6903 + 8.9786 \cdot 10^{-5} \cdot LONG – 0.0002 \cdot LAT + 0.0916 \cdot MAR$ ($R^2_{adj} = 0.61$) (S17)

$h_{24} = 816.4861 + 8.5718 \cdot 10^{-5} \cdot LONG – 0.0002 \cdot LAT - 0.0140 \cdot z + 0.1064 \cdot MAR$ ($R^2_{adj} = 0.65$) (S18)

**Sardinia**

$h_1 = 42.1910 + 3.8767 \cdot 10^{-5} \cdot LONG – 25.3164 \cdot OP$ ($R^2_{adj} = 0.18$) (S19)

$h_1 = 42.3615 + 4.3842 \cdot 10^{-5} \cdot LONG - 0.0693 \cdot C – 26.2139 \cdot OP$ ($R^2_{adj} = 0.23$) (S20)

$h_1 = 54.8897 + 4.1827 \cdot 10^{-5} \cdot LONG – 1.3045 \cdot 10^{-5} \cdot LAT - 0.0890 \cdot C + 0.0091 \cdot MAR$ ($R^2_{adj} = 0.29$) (S21)

$h_{24} = -171.0751 + 0.0003 \cdot LONG + 0.0964 \cdot MAR$ ($R^2_{adj} = 0.54$) (S22)

$h_{24} = -186.5050 + 0.0004 \cdot LONG – 0.7802 \cdot C + 0.1167 \cdot MAR$ ($R^2_{adj} = 0.68$) (S23)

$h_{24} = -169.9531 + 0.0004 \cdot LONG – 0.7002 \cdot C + 0.8954 \cdot MSA + 0.0965 \cdot MAR$ ($R^2_{adj} = 0.71$) (S24)

**Supplement n°3: maps of the residuals of the multiple regression models**

Residuals of both the national-scale and the four-region multiple regression models have been spatially interpolated using ordinary kriging. The spatial interpolations are reported hereafter for comparison purposes.

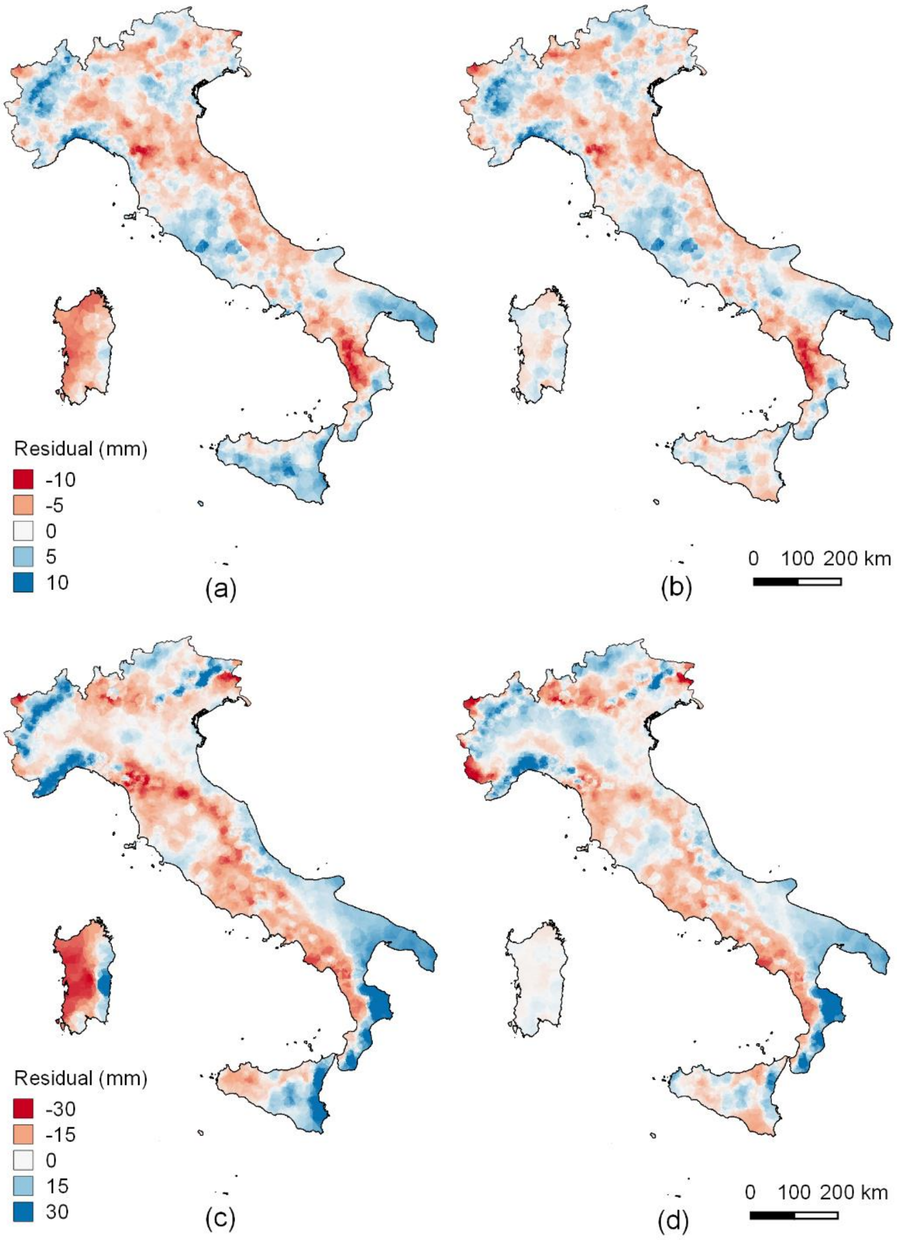


**Figure S2. Maps of the residual for the 1-hour national-scale multiple linear regression model (a), 1-hour four-region multiple linear regression model (b), 24-hour national-scale multiple linear regression model (c) and 24-hour four-region multiple linear regression model. Marked improvements can now be achieved in some areas adopting a regional approach, especially for Sardinia. However, these models are not able to reduce the clustering effect in the peninsular region.**

## Supplement n°4: 24-hour GC simple regression models

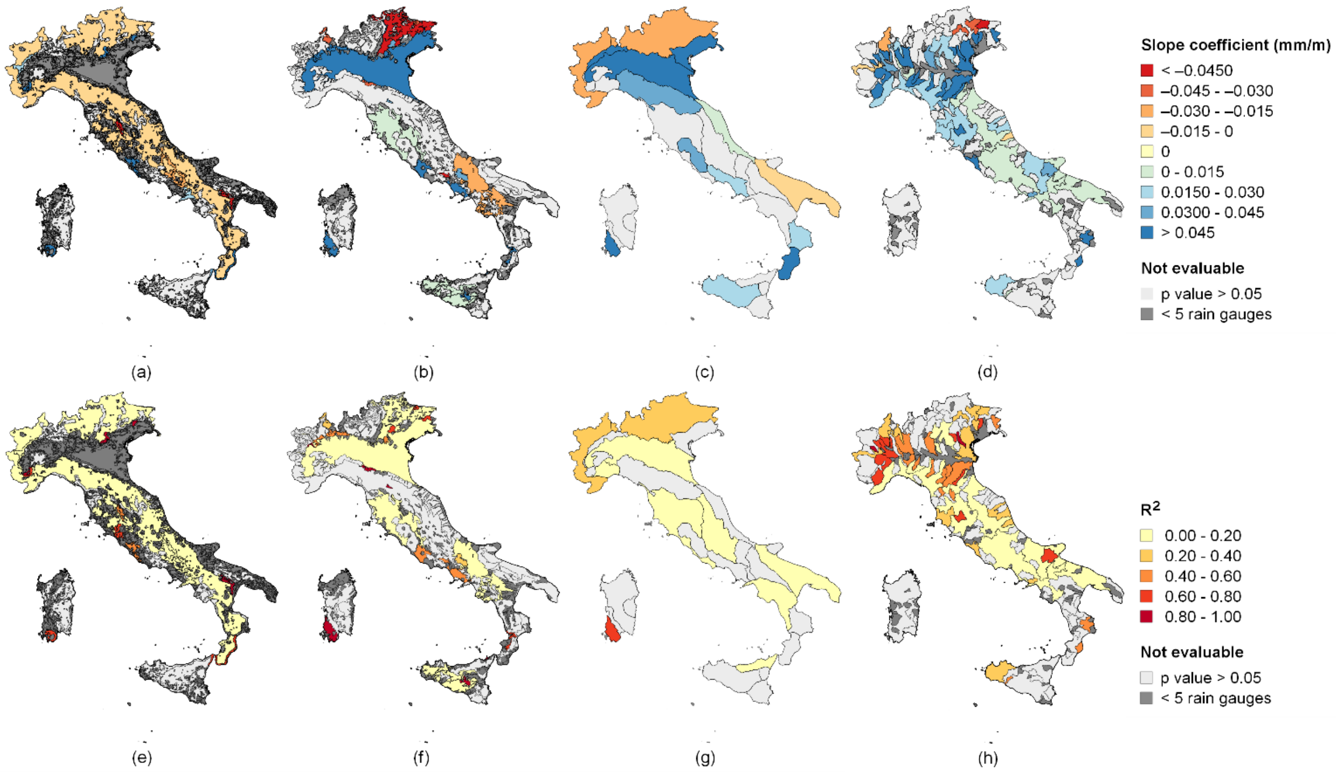


**Figure S3. Slope coefficients of the regression between the mean 24-hour rainfall depth and elevation for GC1 (a), GC2 (b), GC3 (c) and GC4 (d); $R^2$ of the regression between the mean 24-hour rainfall depth and elevation for GC1 (e), GC2 (f), GC3 (g) and GC4 (h). Note that GC1 covers a very large Apennine area, ranging from Friuli Venezia Giulia (North West Italy) to Calabria (South of Italy). The low value of $R^2$ (0.17) shown in Figure S3e indicates a low significance of the linear regression found in GC1. We tested the difference obtained after splitting this huge zone into two areas, using the end of the Alpine region as a border: the analysis (not shown here, for the sake of brevity) produced results that were in agreement with the other classifications, with a negative slope emerging in the Alps and a positive slope for the peninsular Apennines. Geomorphological data source: Iwahashi and Pike (2007), Amadei et al. (2003), Guzzetti and Reichenbach (1994) and Alvioli et al. (2020).**

**Supplement n°5: comparison of the error statistics for the 1- and 24-hour durations**

The spatial distributions of the error statistics in the rainfall depth estimation when using the national-scale simple regression model, the national-scale multiple linear regression model, the four-region multiple regression model and the GC4 simple regression model are reported in Figure S4 (1-hour) and in Figure S5 (24-hours). The maps in the fourth columns (Figures S4d-i-n-s and S5d-i-n-s) contain fewer areas because the relationship is not statistically significant for some areas, as highlighted in Sect. 4. The high error statistics values that emerge for the national-scale simple regression (Figures S4a-f-k and S5a-f-k) are reduced when the other approaches are used. Figures S4b-c and Figures S5b-c clearly point out that, even though the multiple linear regression model reduces the average bias at the national scale (Table 2), some areas still present significant bias, and this may hamper the reliability of the model at a local level. In other words, it can be noted, in the first to the third columns in Figures S4 and S5 that the residuals of the regressions that do not consider morphological classifications present high absolute values when applied within each of the morphological regions, thus suggesting a bias clustering due to an unaccounted local relationship between the morphology and rainfall distribution.

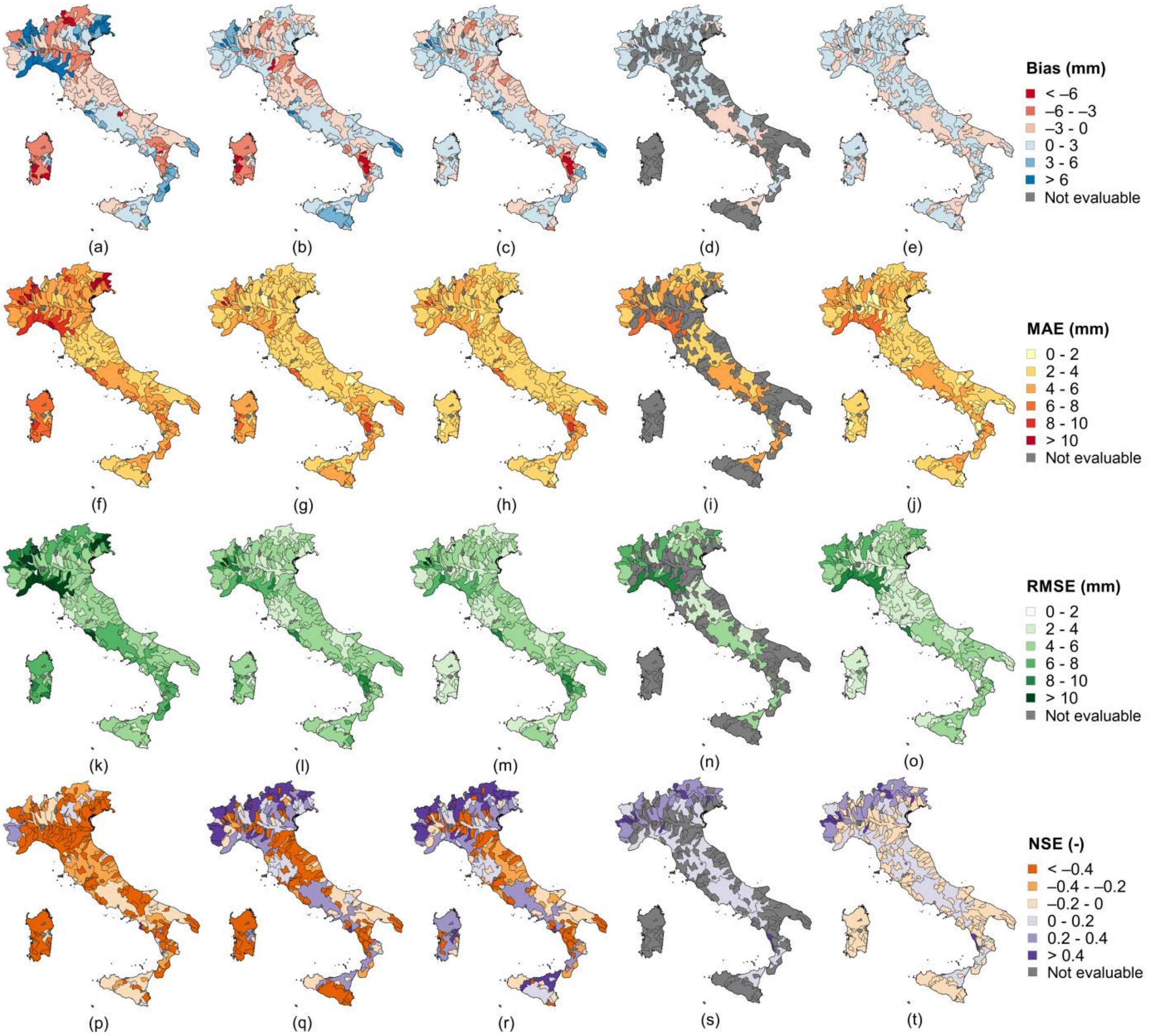


**Figure S4. Error statistics for the 1-hour duration in the case of the national-scale regression model (a, f, k, p), the national-scale multiple linear regression model (b, g, l, q), the four-region multiple regression model (c, h, m, r) and GC4 simple linear regression model over statistically significant areas (d, i, n, s) and over the entire nation (e, j, o, t). Geomorphological data source: Alvioli et al. (2020).**

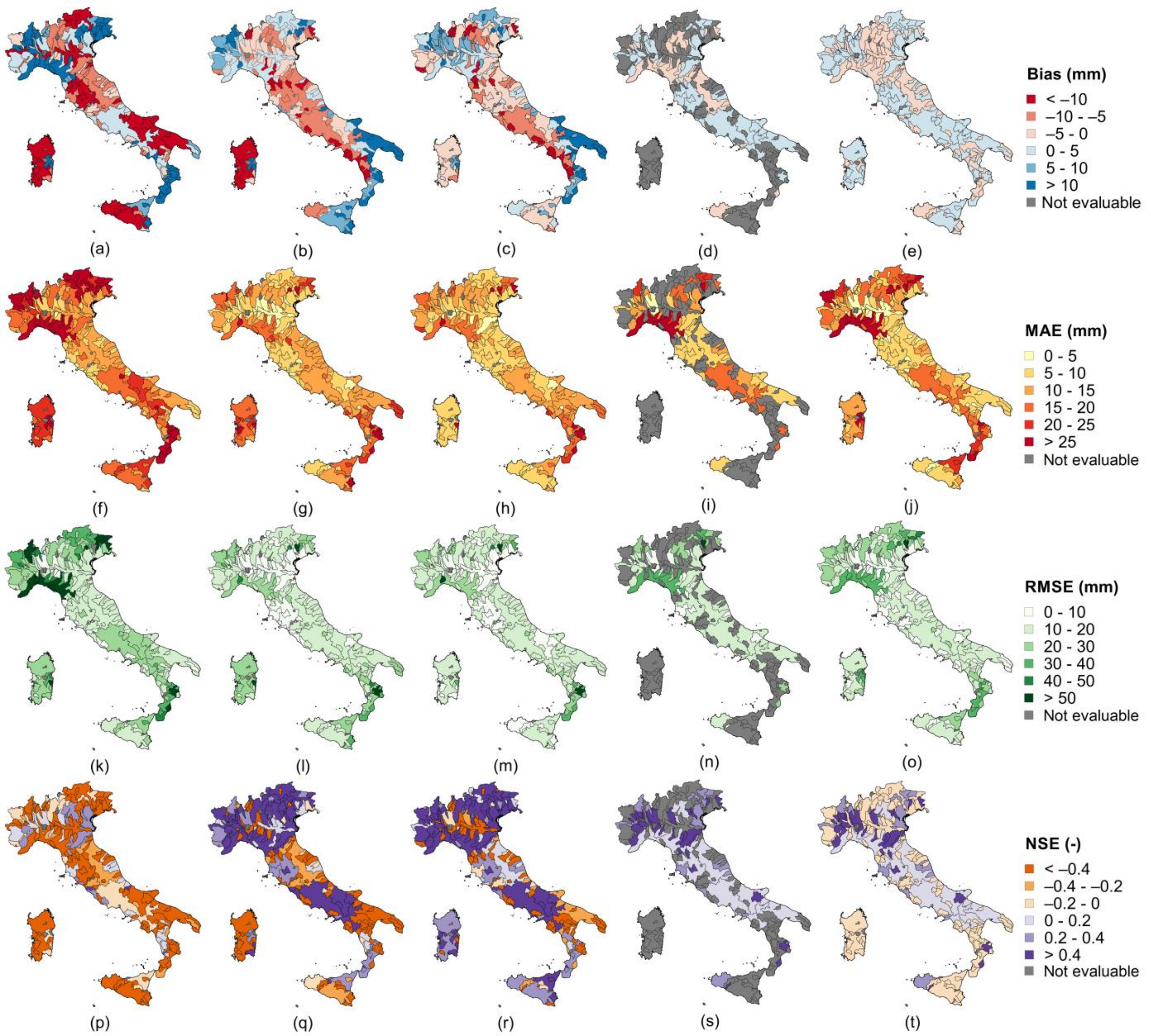


**Figure S5. Error statistics for the 24-hour duration in the case of the national-scale regression model (a, f, k, p), the national-scale multiple linear regression model (b, g, l, q), the four-region multiple regression model (c, h, m, r) and GC4 simple linear regression model over statistically significant areas (d, i, n, s) and over the entire nation (e, j, o, t). Geomorphological data source: Alvioli et al. (2020).**