VALIDATION OF GRIDDED METEOROLOGICAL PRODUCTS THROUGH HYDROLOGICAL SIMULATION OVER EMILIA ROMAGNA, PIEDMONT, AND TUSCANY

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KEY POINTS

- *Evaluation of five gridded meteorological products for rainfall-runoff modeling in three regions in Northern Italy.*
- *Analysis of streamflow simulation performances as indirect validation of the meteorological forcing*
- *Gage-based datasets (the ISPRA-SCIA one in particular) are more reliable, but reanalysis products may be viable alternatives in areas with limited ground station coverage.*

1 BACKGROUND AND MOTIVATION

The accuracy of meteorological variables like precipitation and temperature directly influence rainfall-runoff modeling ability to simulate hydrological processes accurately, consequently affecting the reliability of streamflow predictions. The recent availability of a number of gridded meteorological products provides spatially-distributed meteorological forcings across national and international scales, facilitating hydrological modeling in various geographic areas and large-scale experiments. However, the accuracy of these products varies considerably in space and time.

The rigorous validation of gridded meteorological products is essential before their application in rainfall-runoff modeling. This validation process may entail direct comparisons with data from ground-based weather stations (e.g., Bandhauer et al., 2022) or indirect evaluations through their performance in hydrological models (e.g., Tarek et al., 2020). While numerous validation studies exist globally, a comprehensive assessment specifically focused on the Italian context remains limited. Notable efforts in this field are represented by the studies of Camici et al. (2018), Duan et al. (2016), Longo-Minnolo et al. (2022), Tuo et al. (2016), and Turco et al. (2013). However, the potential for further research remains substantial, including a broader assessment of available gridded meteorological products and expanding the geography of these analyses to cover diverse regions in Italy: since Italy faces significant challenges from water-related hazards and increasing water scarcity, robust hydrological modeling is particularly needed for proactive mitigation. Careful evaluation of available meteorological forcing products is crucial for selecting reliable inputs, enhancing model accuracy, and deepening our understanding of hydrological processes within Italian catchments.

This study evaluates the accuracy of five national and international gridded meteorological products for hydrological modeling within 155 catchments across Emilia-Romagna, Tuscany, and Piemonte. Our approach begins with a direct comparison of precipitation and temperature estimates within the study area. We then employ an indirect validation method, assessing the ability of each product to reproduce streamflow when used as input for a calibrated conceptual hydrological model. The ultimate goal is to identify the most suitable meteorological products for rainfall-runoff simulations, ultimately supporting improved flood forecasting, drought monitoring, and sustainable water allocation.

2 GRIDDED METEOROLOGICAL PRODUCTS

The meteorological products evaluated in this study include three sets derived from ground stations observations (SCIA, ARCIS, and E-OBS) and two reanalysis datasets (MERIDA, ERA5-Land). Table 1 summarizes the characteristics of each meteorological product.

The SCIA dataset (Desiato et al., 2007), set up by ISPRA, provides meteorological forcings over Italy, from a dense network of ground-based stations (Figure 1c, 1d). The ARCIS dataset (Pavan et al., 2019) provides daily gridded precipitation information only for Northern Italy (due to the lack of temperature data, we used SCIA temperature estimates with ARCIS precipitation data in the hydrological modelling). E-OBS (Cornes et al., 2018), developed in the ECA&D project, is a land-only sourced gridded daily observational dataset over

Europe. MERIDA (MEteorological Reanalysis Italian DAtaset) is developed by RSE-SpA (Bonanno et al., 2019): this study compares the higher-resolution version of the MERIDA dataset, MERIDA-HRES. ERA5-Land is a reanalysis global dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) through the Copernicus Climate Change Service (C3S) (Muñoz-Sabater et al., 2021).

Table 1. Characteristics and data availability of gridded products (for temperature and precipitation data).

Product Name	Time Period	Temporal Resolution	Spatial Coverage	Spatial Resolution	Methodology	Variables
SCIA	1961-2021 (P), 1981-2022 (T)	Daily	Italy	10 km (P), 5 km (T)	Gage-based: Inverse Distance Weighting (P), Gaussian Process Regression (T)	T_{min}, T_{max}, and P
ARCIS	1961-2023	Daily	Northern Italy	5 km	Gage-based: Shepard Algorithm with Topographic Adjustment	P
E-OBS	1950-2023	Daily	Europe	9 km	Gage-based: Kriging with external drift	T_{min}, T_{max}, T_{mean}, and P
MERIDA	1986-2021	Hourly	Italy	4 km	Reanalysis Dataset	T_{mean} and P
ERA5-Land	1950-2023	Hourly	Global	9 km	Reanalysis Dataset	T_{mean} and P

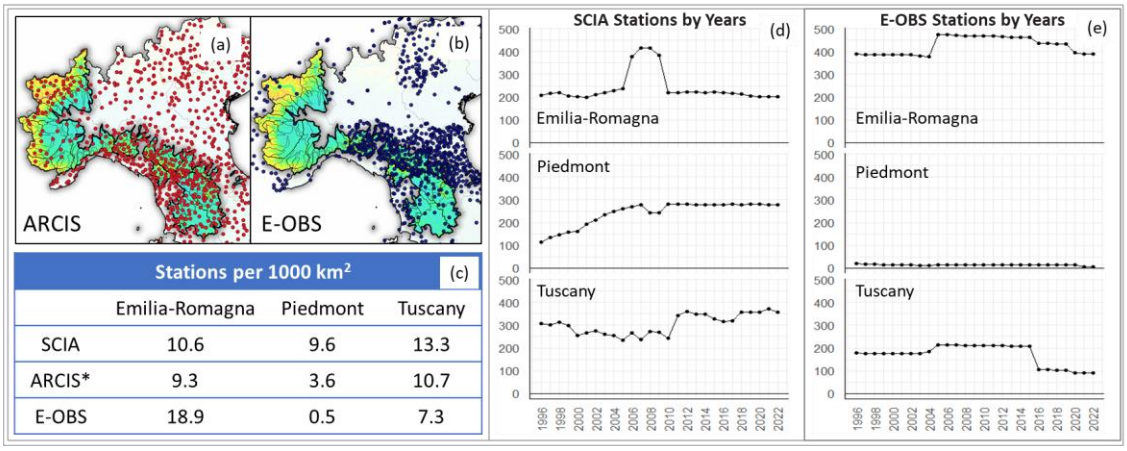

Figure 1. Catchment boundaries and spatial distribution of raingages used in ARCIS (a) and E-OBS (b). Mean density of the operational gages over the observation period for E-OBS, SCIA and ARCIS. *Note that ARCIS densities correspond to the total number of gages and not to those actually working (c). Number of stations used by SCIA and E-OBS along the observation years (d and e).

Availability of station data varies among the gage-based products. ARCIS website includes the list of all the stations coordinates, but without the actual working periods for each one. Meanwhile, ISPRA has elaborated for this study the counts of the working stations used in the SCIA gridded product (that are based also on some regional stations not included in the SCIA single stations dataset) by region, for each month. The SCIA network has the most uniform density of raingages across regions, with denser networks in Piedmont and Tuscany (Figures 1c and 1d). E-OBS raingages exhibit spatial and temporal inhomogeneity (Figures 1b, 1c, and 1e), particularly in Piedmont where station density is very low. While ARCIS shows better spatial homogeneity than E-OBS, its raingages in Piedmont remain sparse. Due to its density, temporal and spatial homogeneity, and nationwide coverage, the SCIA gridded dataset was identified as a suitable reference for evaluating the performance of other meteorological products in the next section. Temperature data was also analysed: the results are omitted here for brevity, but the mean areal temperature series over the catchments show moderate discrepancies among the different products.

3 COMPARISON OF THE PRECIPITATION PRODUCTS

Areal-averaged precipitation and temperature time-series were calculated for each catchment based on each gridded product data and catchment boundaries between the period 1986-2022. Scatterplots in Figure 2a present the comparison of catchment mean annual precipitation from the other four meteorological products against the reference SCIA estimates. Boxplots in Figure 2b detail the Pearson correlation and mean bias of monthly precipitation for each product compared to SCIA monthly precipitation estimates.

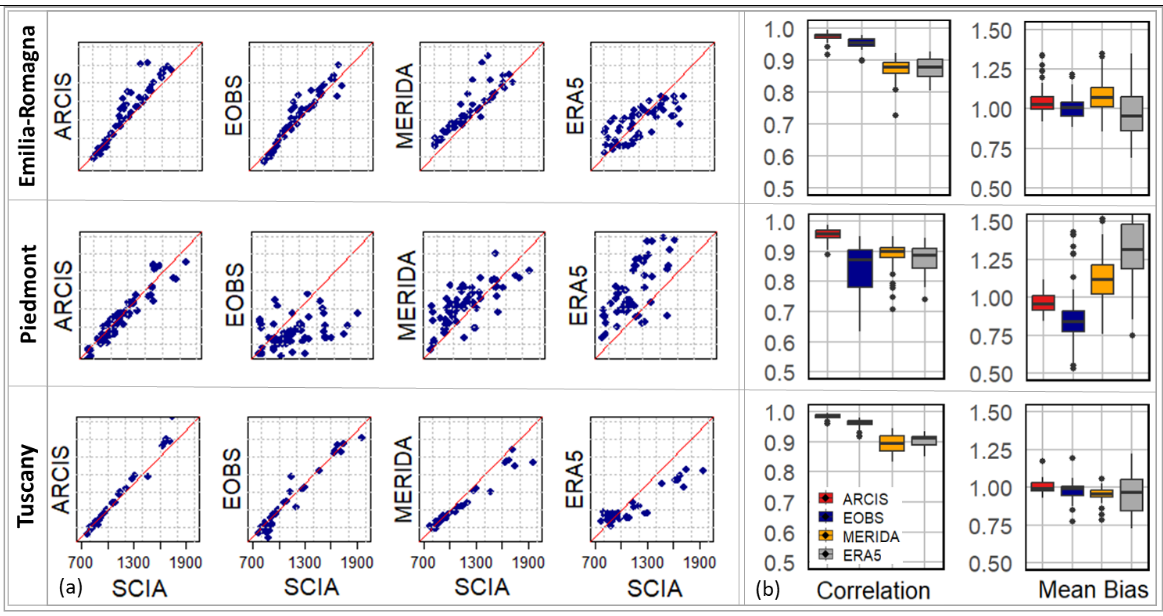

Figure 2. Comparison of annual mean and monthly precipitation estimates from ARCIS, EOBS, MERIDA and ERA5 with SCIA. (a) Scatters of annual mean precipitation estimates (b) Box plots of correlation and mean bias for monthly precipitation against SCIA. In each boxplot, the line refers to the median, the box to 1st and 3rd quartiles and whiskers to 1.5 times the interquartile ranges.

The scatterplots in Figure 2a reveal significant discrepancies between how the four gridded precipitation products estimate annual mean precipitation compared to the reference SCIA dataset, across the three regions. ARCIS consistently demonstrates the closest precipitation estimates to SCIA, further supported in boxplots for monthly estimates, with a narrow box and a median value close to 1. E-OBS precipitation estimates align well with SCIA in Emilia-Romagna and Tuscany, but perform poorly in Piedmont, where the stations from E-OBS appear sparse (Fig. 1b and c). Boxplots further highlight this underperformance, revealing low correlation and mean monthly bias indicative of underestimation in Piedmont. MERIDA tends to overestimate precipitation in both Emilia-Romagna and Piedmont, as seen in scatters and boxplots in Figure 2a and 2b. ERA5-Land exhibits the lowest accuracy across the three regions. In particular, it strongly overestimates the precipitation in Piedmont, as demonstrated by both the scatter plot and mean bias.

4 INDIRECT VALIDATION THROUGH RAINFALL-RUNOFF MODELLING

The rainfall-runoff model used for the indirect validation is the CemaNeige-GR6J (Coron et al., 2023), a daily lumped and continuously simulating model. Prior to calibration, the collected daily streamflow data from three different regional agencies managing hydroclimatic data were manually validated. The observation period of the streamflow varies from 1987 to 2022 with a minimum length of 6 years. For each catchment, the model is calibrated separately with each gridded product during the entire available streamflow observation period. The Kling-Gupta Efficiency (KGE; Gupta et al., 2009) served as the objective function, while the Dynamically Dimensioned Search algorithm (Tolson & Shoemaker, 2007) was used for the automatic optimization.

Figure 3 reports KGE model performances (better performance for values closer to 1) in the three regions for each product. Overall performance is good for all products, with median KGE scores ranging between 0.69 and 0.89. The model yields the best performance when using the SCIA dataset, achieving median KGE scores above 0.8 in all three regions. This is likely due to SCIA dense and uniform station distribution. The model forced with the ARCIS dataset, which showed similarity to SCIA in the direct comparison, also generally achieved high KGE scores. While the model run with E-OBS exhibits good performance in Emilia-Romagna and Tuscany (median KGE > 0.8), it performs significantly worse than other products in Piedmont (median KGE = 0.69). MERIDA consistently outperforms ERA5-Land. However, both reanalysis products (MERIDA and ERA5-Land) generally yield lower KGE scores compared to the gage-based datasets with the exception of E-OBS in Piedmont.

The findings of this study emphasize the importance of the accuracy of gridded precipitation products when selecting them for hydrological modeling. Meteorological products derived from dense station networks tend to produce more reliable streamflow simulations. However, in areas with low station density, reanalysis datasets may yield more accurate results, as demonstrated by the comparison of MERIDA with E-OBS forcing in Piedmont.

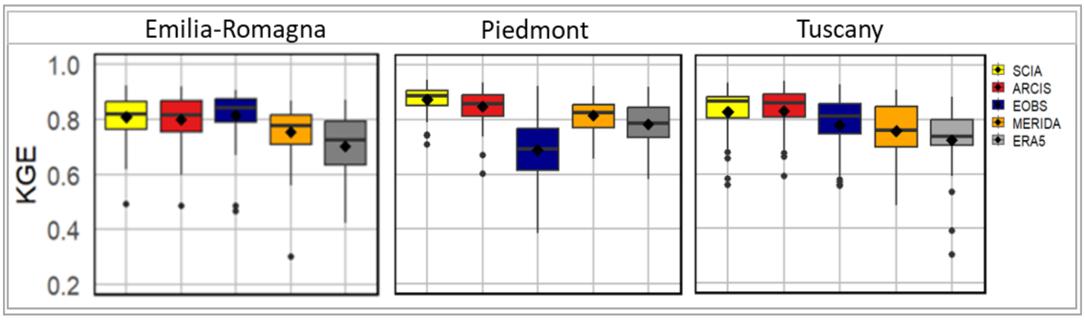

Figure 3. KGE boxplots for simulated streamflow when the model is fed by the different meteorological products

Catchment-specific factors such as elevation, slope, and anthropogenic influences can also affect the accuracy of the gridded products and model performance. Further analysis at the catchment level will provide more detailed insights into these factors. Investigating the impact of changes in station density over time or of the presence of seasonal patterns could also provide valuable insights for the optimal choice of precipitation inputs and improving streamflow simulations.

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