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Original research article

Leveraging observations and model reanalyses to support regional climate change adaptation activities: An integrated assessment for the Marche Region (Central Italy)

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HIGHLIGHTS

- Large-scale reanalyses and observation products still represent a useful complement for regional-scale climate assessments.
- The Italian case of Marche Region showed that the inter-comparison and integration of multiple products for different analyses can improve the accuracy and interpretation of the regional climate assessment.
- Decision-making processes benefit from tailored climate products at national and regional levels, while a centralized access point is key to ease and harmonize sub-national initiatives towards climate risk management and adaptation planning.

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ABSTRACT

Acknowledging the increasing urgency of climate change, many local administrations, in Italy as well as abroad, are currently elaborating their own adaptation strategy. A key step of this process is understanding the current climate, past variability and ongoing trends. Combined with the analysis of vulnerable and exposed elements, it supports the identification of key climatic impacts and risks for the territory and the elaboration of future scenarios. Several climatic datasets are available for this purpose, ranging from station observations to interpolated products and to model reanalyses, each with its own features. The study aimed to shed light on these differences and thus help practitioners make better, more informed decisions. Three gridded datasets, offering global, European and national coverage, were compared to derive a local characterization of mean climatic features, recent trends and climate extremes for the Marche Region (Central Italy). The assessment was based on temperature and precipitation variables from the global reanalysis ERA5-Land, the European observation dataset E-OBS, and the high-resolution reanalysis dynamically downscaled for Italy VHR-REA_IT. The analysis showed that large-scale products such as E-OBS and ERA5-Land can still represent a robust complement for adaptation planning. However, important limitations in describing spatial and temporal patterns need to be properly accounted for in the decision-making process. Only an integrative approach based on a multi-source data evaluation would properly address the multi-faceted aspects of climate variability on a regional scale, derive a more comprehensive analysis of past and current conditions and better manage the underlying uncertainty.

Practical implications

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To mitigate the consequences of the unavoidable impacts of climate change, accurate adaptation strategies and plans are needed, hinged on the understanding of past, present and future climate in the area of interest. These analyses can be based on many different climate datasets available at national, European and global level. For instance, the assessment of past and current climatic conditions, trends and extreme characteristics is crucial to identify the main risks and their potential evolution under climate change (Adger et al., 2018; Tonmoy et al., 2019). However, in-depth knowledge of the potential and limitations of each climate product is paramount to avoid getting erroneous conclusions about, e.g., ongoing climatic changes in a region, or under/overestimating specific climatic conditions. This is particularly important if a reference dataset tailored to the region of interest is not available and local studies have to rely on alternative sources, e.g., reanalyses and large-scale observational grids (Mavromatis and Voulanas, 2021; Rianna et al., 2023).

To demonstrate and discuss the importance of dataset evaluation and selection for the past and current climate assessment in support of decision-making, we apply three well-known climatic datasets available from national, European and global sources to analyze mean climate, past trends and extremes over Marche Region (Central Italy). The assessment focuses on temperature and precipitation and includes the European gridded observation dataset E-OBS, the global reanalysis ERA5-Land and the national reanalysis VHR-REA_IT. In contrast, weather station observations are considered for the local evaluation of results.

The findings highlight key features of each dataset. They can provide decision makers in regional contexts with a critical view of the applicability of different products in supporting analyses for local climate change adaptation planning. Regarding climatic spatial patterns, the observation-based product E-OBS offers a reliable representation of climatological conditions over the Marche Region. In contrast, the global reanalysis ERA5-Land, despite the same spatial resolution, is significantly more smoothed, thus leading to substantial underestimations of regional climatic features and spatial gradients. A high-resolution dynamically downscaled reanalysis as VHR-REA_IT offers the most realistic representation of small-scale climatic gradients even though local overestimations in both temperature and precipitation values should be expected, as also reported in other intercomparison analyses (e.g., Adinolfi et al., 2023; Cavalleri et al., 2024). The advantage of using a high-resolution dataset in space and time becomes particularly evident in the description of extreme values and the detection of past intense events.

The dataset choice is particularly crucial for the assessment of the long-term temporal variability: observation-based products, such as E-OBS, are directly affected by single station inhomogeneities and by changes in the data availability over time, which can alter the real climate signal and introduce spurious spatial heterogeneities. On the contrary, ERA5-Land reanalysis, even if still affected by potential inhomogeneities over time, reports a more consistent spatial distribution of climatic trends, but may underestimate the magnitude of changes. A combined analysis could thus enable a more robust understanding of long-term trends.

The study shows evidence that a multi-source evaluation can be key to derive a more reliable and comprehensive assessment of past and current climatic conditions in a certain area of interest.

Introduction

Climate change is increasingly affecting natural and social systems worldwide, producing profound modifications in human activities, threatening security, and impacting a variety of sectors across multiple scales (Aguiar et al., 2018; IPCC, 2023). While mitigation actions are crucial to contain global warming and its impacts in the long term, especially through a progressive abatement of greenhouse gas emissions, there is an urgent need of adopting adaptation measures, both as individuals and as societies, in the short- and mid-term to the unavoidable effects of ongoing climate change (Ledda et al., 2020). In recent years the elaboration of adaptation strategies, and related plans, ideally in synergy with greenhouse gas emission mitigation policies, has become a multi-level governance priority (Pasimeni et al., 2019; Setzer et al., 2020). In the European context, the new EU Adaptation Strategy has been published in 2021 and national and sub-national authorities are asked to effectively adopt and implement consistent adaptation strategies and plans (Rayner et al., 2023; Serra et al., 2022). In Italy, the National Climate Change Adaptation Plan (PNACC) has been officially approved only in 2023 (Ministero dell'Ambiente e della Sicurezza Energetica, 2023), but, acknowledging the urgency of the matter, several regional administrations have already approved or started elaborating their own regional climate change adaptation strategy with the involvement of interdisciplinary working groups and domain experts (Pietrapertosa et al., 2021).

One of the primary steps of this process consists in understanding current regional climates, their variability over the recent past, and the ongoing trends. Combined with the analysis of vulnerable and exposed elements, this task is crucial to identify the key climatic impacts and risks for the territory and to derive their plausible evolution under future scenarios (Mysiak et al., 2018; Zebisch et al., 2022). The past and current climate assessments must be based on adequate datasets, consistently with the spatial and temporal scales required for the analysis. Historical meteorological observations and regional gridded datasets derived from local weather stations represent the most truthful sources of information for regional and local studies. However, station data often suffer from temporal discontinuities and uneven spatial coverage. Hence, substantial efforts are often required not only to collect data, but also to improve their quality and to develop regional products, e.g., high-resolution gridded datasets of key climatic variables (Crespi et al., 2021).

This is particularly evident in Italy, where a national climate service is still under development, and the collection and management of climate data is operated by different national, regional, or sub-regional offices. Gridded observational products have been developed for several Italian regions, although in some cases including only one climatic variable, or not systematically updated (e.g., Antolini et al., 2016; Crespi et al., 2021; Pavan et al., 2019). On a national level, the SCIA platform developed by the Italian Institute for Environmental Protection and Research (ISPRA) offers unified access to meteorological time series from several regional and national weather station networks, pre-computed climate indicators, and, more recently, it includes a national gridded dataset of daily temperature and precipitation based on collected observations (Desiato et al., 2011). The dataset has been already applied in several studies and intercomparison analyses (e.g., Padulano et al., 2021; Rossi et al., 2022; Raffa et al., 2023) and is intended to become an official reference product for Italy, although additional efforts are required to address data heterogeneity in space and time and publish a thorough description and evaluation of data and interpolation. High-resolution climate reanalyses for Italy have been recently derived from regional climate simulations and made freely available, e.g., by the Euro-Mediterranean Centre for Climate Change (CMCC, Raffa et al., 2021) and by the Italian company Ricerca sul Sistema Energetico (RSE S.p.A., Bonanno et al., 2019). Other notable experiments for producing high-resolution reanalyses for Italy by applying limited-area models have been recently presented by Giordani et al. (2023) and Capecchi et al. (2023). State-of-the-art reanalyses and observation-based products with global and European coverage are also easily accessible from open repositories, such as the Climate Data Store of the Copernicus Climate Change Service (C3S, Buontempo et al., 2022) and the CHELSA initiative, providing high-resolution climate data for the Earth's land surface areas (Karger et al., 2023). All these datasets can be considered accessible alternatives to provide baseline climate information at the local scale, or to complement available local data (Ledesma and Futter, 2017; Torres-Vázquez et al., 2023).

However, each type of dataset is characterised by advantages and limitations, resulting in a heterogeneous accuracy in representing regional climatic features, especially in view of the complex Italian orography (Adinolfi et al., 2023; Padulano et al., 2021). Due to the variety of climate products and their features, a targeted evaluation becomes essential in the context of regional studies on climate risks to select the most suitable datasets for the description of climate phenomena and their evolution in the recent past. This also improves the interpretation of results through a better understanding of underlying data uncertainties (My et al., 2022).

These aspects emerged and were elaborated in the framework of the definition of the Climate Adaptation Plan for the Marche Region (Central Italy), for which a risk-oriented regional climate assessment was required (Regione Marche, 2022). While previous studies focused on specific climatic features, such as trends in temperatures and precipitation extremes across the region based on local station observations (e.g., Gentilucci et al., 2019; Gentilucci et al., 2020a; b), an interpolated dataset of local observations for the Marche Region was not available and no earlier regional assessments were conducted to evaluate the performance of alternative gridded products. A few studies were carried out for other Italian regions (e.g., My et al., 2022; Vanella et al., 2022), but focusing only on one product at a time (reanalysis or observation based) and for specific purposes, e.g., historical trend assessment or mean climate description.

Here, we evaluated the applicability of three gridded datasets, one derived from observations and two from reanalyses, with a global, European and national coverage for the description of mean climate, historical trends and climate extremes in the Marche Region based on temperature and precipitation variables. Specifically, the observation-based European product E-OBS, the global reanalysis ERA5-Land, and the high-resolution reanalysis for Italy VHR-REA_IT were considered. The climate extreme assessment was based on daily values since they are the primary and the most common source of information employed for conducting a first climate assessment. Moreover, they are still reliable proxies for identifying risks related to weather extremes typically occurring on sub-daily scales (Mysiak et al., 2018; Pesce et al., 2022). Starting from the test area of Marche Region, the work aims to showcase how the dataset choice depends on the type of analysis and influences the results, and to foster a more standardised approach for data selection in the context of regional climate assessments supporting adaptation planning. The study also highlights the relevance of high-quality climate observational time series and the key role of a national harmonization and coordination of the multi-level efforts supporting climate change adaptation in Italy.

Material and methods

Study area

Marche is a region in Central Italy between the Apennines Mountains

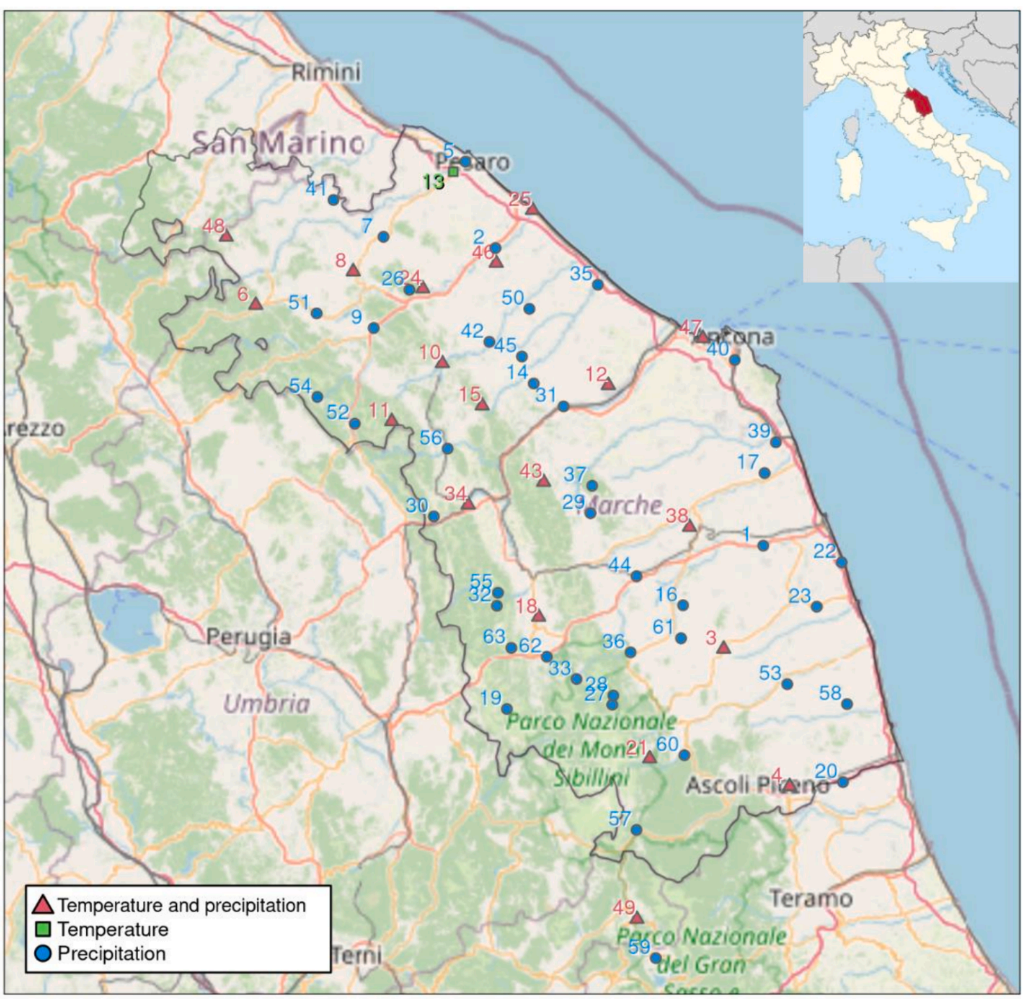

Fig. 1. Map of Marche Region and distribution of weather stations considered in this study. Temperature and precipitation stations are represented by red triangles, precipitation-only by blue dots and temperature-only by green squared. All sites are numbered as in Table S1. The inset shows the location of the Marche Region in Italy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and the Adriatic Sea with a surface of 9′694 km^2. A very heterogeneous orography characterizes the territory. The western part of the region is dominated by mountains, with peaks exceeding 2′000 m above sea level (a.s.l.) only in the south where the Sibillini Mountains are located. Most of the territory is characterized by hills, with plains at sea level limited to a narrow strip along the coast, which extends for about 170 km (Fig. 1).

Data

To investigate the different features of observation-based products and model reanalyses when applied to regional climate studies, daily temperature and precipitation fields from the European-wide E-OBS observation dataset, the global improved-resolution reanalysis ERA5-Land, and the Italian high-resolution reanalysis VHR-REA_IT were considered. Each dataset is described in detail below, along with the archive of local observations from the regional weather station network included in the intercomparison.

E-OBS

E-OBS is a pan-European observational dataset providing daily fields for several climate variables through the interpolation of weather station records from national and sub-national networks (Cornes et al., 2018; Haylock et al., 2008; Hofstra et al., 2009). E-OBS starts in 1950 for all variables except wind speed (since 1980) and is regularly updated. It became a reference product for validating model outputs and for monitoring the European climate (Bandhauer et al., 2022). Moreover, E-OBS was also adopted by the Italian PNACC to describe the mean climate conditions for Italy over the reference period 1981–2010. Even though the number of observation sites included in the database underlying E-OBS is continuously increasing, the station coverage remains nonuniform over Europe, depending on the data released by national and regional providers. It is important to note that changes in data density over time, as well as inhomogeneities in the observation records, might influence the long-term climate variability reproduced by the gridded fields, especially on a local level. In this study, daily fields of maximum and minimum temperature and total precipitation at 0.1° x 0.1° resolution from 1950 to 2021 for the Marche Region were derived from the 26.0e E-OBS version. The station coverage underlying E-OBS (26.0e) is rather heterogeneous over Italy. However, Marche is one of the Italian regions with the highest number of weather stations included in the interpolation, with 21 stations for temperature and 74 for precipitation, rather uniformly distributed over the area (Figure S1). Daily precipitation is the equivalent total liquid amount of rain, snow, and hail as measured by weather stations. Due to the heterogeneous definitions adopted by data providers, precipitation totals do not always refer to the same 24-hour cumulative period (e.g., from 06 UTC to 06 UTC). While this discrepancy might become relevant when specific daily fields over large domains are considered, it is not expected to influence the regional assessment of long-term temporal variability or the climatological characterization.

The homogenized version E-OBS v19.0HOM (hereafter E-OBS HOM) was also considered. It contains daily temperature fields on a 0.1°x0.1° grid based on homogenized station series (Squintu et al., 2019). Since E-OBS HOM ends in November 2018, it was here adopted only for discussing the influence of potential inhomogeneities in the long-term temperature trend analysis. E-OBS and related information are available from https://www.ecad.eu/.

ERA5-Land

ERA5-Land replicates the land component of the ERA5 climate reanalysis at a higher spatial resolution (9 km). It provides hourly data for land variables with global coverage from 1950 to present (Muñoz-Sabater et al., 2021). ERA5-Land does not assimilate observations, but rather uses ERA5 atmospheric fields interpolated to the finer grid as input to control land model simulations. In addition, a lapse-rate correction is applied to the forcing fields to account for the elevation difference between ERA5 and the 9-km grid. Because of its spatial and temporal resolution and of its temporal extent, it is used for supporting impact-oriented applications and for assessing the state of the climate (e.g., Bain et al., 2023; Barbosa and Scotto, 2022). Among all available reanalyses, ERA5-Land was preferred since its nominal spatial resolution and temporal coverage are directly comparable with those of E-OBS and enable long-term climate assessments. Daily temperature and precipitation records date from 1950 to 2021 for the study domain covering the Marche Region. Daily maximum and minimum temperatures were computed as the maximum and minimum hourly temperatures over 24 hours (from 00 to 23 UTC). Precipitation in ERA5-Land is the average over the grid cell of the total water, in both liquid and solid form, falling to the surface over a certain period. Since it is stored as a cumulated variable with hourly steps from 00:01 to 24:00 UTC, the daily precipitation was extracted from the last hourly simulation of each day, which, for the adopted convention, corresponds to 00 UTC. ERA5-Land and related documentation is available from C3S CDS: https://cds.climate.copernicus.eu/.

VHR-REA_IT

VHR-REA_IT (Very High Resolution REAnalysis for ITaly, Raffa et al.; 2021) is a dynamical downscaling of ERA5 reanalysis at a convection-permitting scale (~2.2 km) over Italy without data assimilation. In its first release, the dataset covers 1989–2020 and provides surface variables and soil water content at hourly resolution. In the present work, 1989–2020 temperature and precipitation fields for the Marche Region were considered and aggregated daily to assess the performance of the high-resolution product in describing the regional climate. Even though the latest version extends back to 1981, the period 1989–2020 was chosen to ensure comparability with other existing studies using this product, all considering data from 1989. Daily maximum and minimum temperatures were computed as the maximum and minimum of hourly temperatures on the same day (from 00 to 23 UTC), while daily precipitation is the cumulative total water (liquid and solid) falling to the surface from 23:01 UTC of the previous day to 23:00 UTC. VHR-REA_IT was developed by CMCC and hourly model outputs are freely available through the CMCC Data Delivery System (https://dds.cmcc.it/#/dataset/era5-downscaled-over-italy).

Local weather stations

Daily temperature (maximum and minimum) and precipitation observations collected by weather stations in the Marche Region were provided by the regional Multiple-Risk Functional Centre of the Civil Protection managing the regional network. All records are freely accessible from the online platform (Sistema Informativo Regionale Meteo-Idro-Pluviometrico, SIRMIP, https://app.protezionecivile.marche.it/sol/indexjs.sol?lang=it). The SIRMIP archive is the result of the integration of the mechanical station records managed by the former National Hydrographic Service (ex-SIMN) and the measurements of the new automatic network, which replaced the mechanical one during the 2000s. Here only the historical meteorological series starting before 2000 and covering continuously the last decades were considered. All data were checked for outliers and unreliable values (e.g., negative precipitation), while no specific homogeneity tests were applied to the longest records. The historical database contains 20 temperature series and 62 precipitation series including two sites from the adjacent regions of Lazio and Abruzzo (as shown in Fig. 1). Besides short periods of missing values, the data availability for both the temperature and precipitation historical series remained almost stable over the decades from the starting year, 1957 for temperature and 1951 for precipitation, to 2021 (figure not shown). Data availability for precipitation shows a noticeable reduction in the year 1990, when the transition to the automatic network started and the annals of ex-SIMN reported the measurements only for about half of the rain-gauge network. However, this temporary lack of precipitation data is not expected to have a significant impact on the results.

Methods

The multi-step intercomparison of E-OBS, ERA5-Land and VHR-REA_IT over the Marche Region included the evaluation of mean climate description for temperature and precipitation, the trend assessment on an annual and seasonal basis, and the description and detection of temperature and precipitation extremes.

Mean temperature was computed as the average of minimum and maximum values and monthly time series of temperature and precipitation were derived. The 1991–2020 climatologies, i.e., the 30-year averages, were then computed for annual, seasonal (December to February for winter – DJF, March to May for spring – MAM, June to August for summer – JJA, September to November for autumn – SON) and monthly aggregated values. ERA5-Land and VHR-REA_IT data were bilinearly resampled onto E-OBS grid and the climatologies were computed at each point of the study domain. The 1991–2020 climatologies were also computed for the station time series and included in the comparison. Station daily series were first aggregated into monthly values, only for months with no missing records, then monthly climatologies were computed by considering more than 20 years of available data in the 1991–2020 period. This resulted in 19 sites for temperature and 52 sites for precipitation available for the climatological analysis. The reference 1991–2020 period was chosen since it represents the most recent climatological period (WMO, 2017) and it excludes the year 1990, when a temporary reduction of precipitation records occurred. Station climatologies were compared with those derived from the gridded datasets by interpolating the values of the four nearest grid cells and mean error (bias) was computed.

The temporal variability was assessed on both regional and grid-point scale. The 1950–2021 regional series of annual and seasonal mean temperature and precipitation were derived for E-OBS, ERA5-Land only by averaging over all grid cells included, also partially, in the Marche Region. The historical series were analysed both as absolute values and as anomalies, i.e., the differences (relative differences for precipitation) with respect to the 1991–2020 climatologies. The non-parametric Theil-Sen method (Sen, 1968) was used to derive the long-term trends over the 72-year period and their statistical significance at 5 % was evaluated through the Mann-Kendall test (Kendall, 1975). The long-term signal from gridded products was also compared with the one reported by station observations. To maximize the temporal coverage of station series, monthly aggregates were computed requiring at least 85 % of available daily records in each month, then yearly and seasonal aggregates were derived only if all monthly values were available. Trends for yearly and seasonal aggregated values were then evaluated from the year of first observation (1957 for temperature and 1951 for precipitation) to 2021. Only stations with at least 90 % of yearly values available in the analysed period were used. Stations were not intended as a benchmark, rather they were used to assess how the local observations, including potential inhomogeneities, are reflected in the grid-based results. An additional evaluation of data inhomogeneity was added for temperature only, by including in the comparison of trends the results based on E-OBS-HOM for the available period.

The analysis of extremes was performed over the period 1989–2020 for daily precipitation and daily maximum and minimum temperatures. To investigate the distribution of daily values over Marche Region, the Probability Density Function (PDF) was calculated over all the daily series and grid points within the region based on E-OBS and resampled reanalyses. Daily fields of ERA5-Land and VHR-REA_IT were interpolated using the first-order conservative remapping method over the E-OBS grid over the entire study period to preserve spatial integrals of the data between the source and target grids (Jones, 1999). In addition, the spatial distribution of extremes was evaluated by computing upper or lower percentiles for each grid point, based on the daily records over 1989–2020. In particular, the 95th percentile was considered for daily precipitation (on wet days only, i.e., with precipitation above 1 mm) and daily maximum temperature, while the 5th percentile was computed for daily minimum temperature.

Moreover, in view of further investigating the representation of extreme precipitation events by the coarser products and the convection-permitting resolution of VHR-REA_IT, the top 10 % most intense daily precipitation events in the Marche Region over the period 1989–2020 were identified for each dataset. To this aim, the 3-day total precipitation series were computed for each dataset and for each cell of the native grid and converted into standardized anomalies. Standardized anomalies were derived by computing the daily departures from the climatological mean μ for the corresponding calendar day and dividing by the standard deviation σ. A 21-day moving average was applied to μ and σ series to smooth out the noise in the climatological values. The 3-day estimates would limit the possible 1-day mismatches among the three datasets arising from using different conventions to define daily records. Following the method described by Ramos et al. (2014), for each day from 1989 to 2020 and each dataset, the fraction of the grid with anomalies above two σ was computed, and their mean value was calculated. All dates were finally sorted by magnitude, i.e., the product of the area fraction and spatial mean of anomalies exceeding the threshold.

Results

The 1991–2020 climatologies

The three gridded datasets exhibit a comparable spatial distribution of mean temperature climatologies (Fig. 2) in each season, with values gradually decreasing from the coast to the mountainous areas along the inner regional boundary. In all products the lowest temperatures are located over the highest reliefs of Sibillini Mountains in the south-west. However, the spatial patterns represented in ERA5-Land are smoother compared to E-OBS and VHR-REA_IT, with temperature values systematically lower, as regional average, especially in spring and summer. On the contrary, warmer conditions are represented in VHR-REA_IT for all seasons except winter. As for regional averages, summer climatology from VHR-REA_IT is 1.7 °C and 2.7 °C warmer than for E-OBS and ERA5-Land, respectively, with the highest temperatures over mid- and low-elevation areas. The comparison with the 19 selected stations shows an overall agreement of E-OBS and local observations confirming the mean regional discrepancies in temperature climatologies among the gridded datasets (Table 1). Besides systematic differences, all products and stations exhibit a similar seasonal pattern (Fig. 4a).

As for the precipitation, all products represent the main orographic gradients from the coast to the inner mountain area (Fig. 3). However, the spatial gradients are much smoother in ERA5-Land fields. On the contrary, precipitation amounts are emphasized by VHR-REA_IT over the highest mountain area in the south with values locally exceeding 400 mm in spring and winter. On a regional level, except for summer, differences in the seasonal regimes can be noted (Fig. 4b). Autumn is the wettest season in the observation-based product, while both reanalyses place the annual precipitation peak in spring. The comparison at the 52 station sites selected for the climatological evaluation also confirms these seasonal discrepancies. The mean relative bias is the most negative in autumn for both reanalyses, especially for VHR-REA_IT whose underestimation of observed values is close to 20 %. E-OBS shows the largest agreement with station values with a more pronounced relative bias of about −7 % in summer (Table 1). Moreover, the variability for monthly precipitation in autumn is larger for E-OBS and station observations than reanalyses (Fig. 4b).

These findings highlight the direct influence of local observations in constructing E-OBS and suggest a more limited ability of reanalyses,

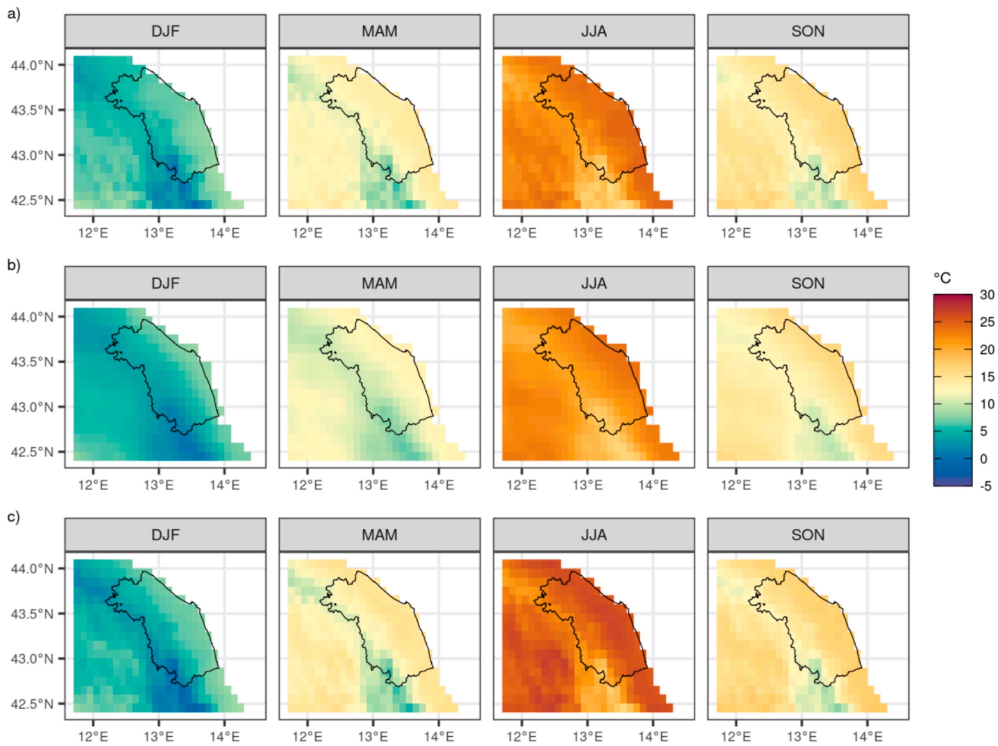

Fig. 2. 1991–2020 climatologies of mean temperature in winter (DJF, from December to February), spring (MAM, March to May), summer (JJA, June to August) and autumn (SON, September to November) computed for a) E-OBS, b) ERA5-Land and c) VHR-REA_IT on a 0.1°x0.1° grid.

Table 1
Mean error (bias) of seasonal temperature and precipitation 1991–2020 climatologies for the gridded products with respect to station observations (19 for temperature and 52 for precipitation).

	Temperature (°C)					Precipitation (%)			
	DJF	MAM	JJA	SON	Year	MAM	JJA	SON	Year
E-OBS	+0.1	−0.1	−0.2	−0.1	−0.1	−2.6	−7.4	−1.1	−2.2
ERA5-Land	−0.9	−1.4	−1.3	−0.8	−1.1	+5.5	+6.1	−14.3	−3.3
VHR-REA_IT	−0.7	+0.5	+1.7	+0.5	+0.5	+4.3	−1.0	−19.4	−5.3

especially ERA5-Land, in reproducing local observations and spatial patterns. Biases in VHR-REA_IT might be partly due to the absence of a station data assimilation in the downscaling procedure (Raffa et al., 2021), while ERA5-Land fields, besides the finer spatial grid, remain mostly driven by the atmospheric forcing of the native ERA5 reanalysis (~31 km).

Long-term climate signal

The temporal variability of mean temperature and precipitation (1950–2021) from E-OBS and ERA5-Land was analysed over the Marche Region on both yearly and seasonal basis. The regional temperature series remark the colder conditions reproduced by ERA5-Land with respect to E-OBS with about 1 °C of mean discrepancy (Fig. 5a). Besides the early decades, the annual series from the two products are highly correlated (correlation = 0.91), as clearly pointed out by the annual anomalies (Figure S2). However, due to the different behaviour in the early period, a more pronounced warming trend for E-OBS than for ERA5-Land emerges. While the increase of mean annual temperature is statistically significant in both cases, the 1950–2021 Theil-Sen trend is +0.30 [0.24 – 0.36, 95 % confidence interval] °C/decade for E-OBS and +0.22 [0.16 – 0.29] °C/decade for ERA5-Land. By excluding the first decade, annual trends converge around +0.3 °C/decade for both datasets. Similar discrepancies are also found in seasonal temperature series (figure not shown), with the largest warming occurring in summer temperatures and the most limited increase in autumn. Precipitation analysis underlines the major differences in the first decades between the two datasets, which influence the slightly more negative trend of E-OBS compared to ERA5-Land (Fig. 5b). However, precipitation trends are not statistically significant for both datasets.

To investigate the potential influence of inhomogeneity and changes in observation series underlying E-OBS, the trend assessment was extended to the temperature fields of E-OBS HOM. In this case, the regional annual time series were compared over the shorter period 1950–2017 spanned by E-OBS HOM (Figure S3). Temperatures from the homogenized E-OBS dataset are slightly higher over the first decades and lower over the central decades than original E-OBS estimates. The regional long-term trend is slightly reduced for E-OBS HOM (+0.28 [0.18 – 0.36] °C/decade) with respect to the original E-OBS (+0.31 [0.24 – 0.37] °C/decade) but still different from ERA5-Land signal (+0.20 [0.12 – 0.26] °C/decade).

On a grid level, all products report positive and significant trends throughout the region with greater warming along the coast and the northern part of the domain (Fig. 6a). However, the spatial distribution of trend values is more heterogeneous for E-OBS with respect to E-OBS HOM and ERA5-Land. A more pronounced warming can be observed in some localized areas in the central southern part of the region, with hotspots in the north and over the Sibillini Mountains along the southern boundary. In addition, it is worth noting that E-OBS shows a few inner areas outside the Marche Region where temperature trends are locally

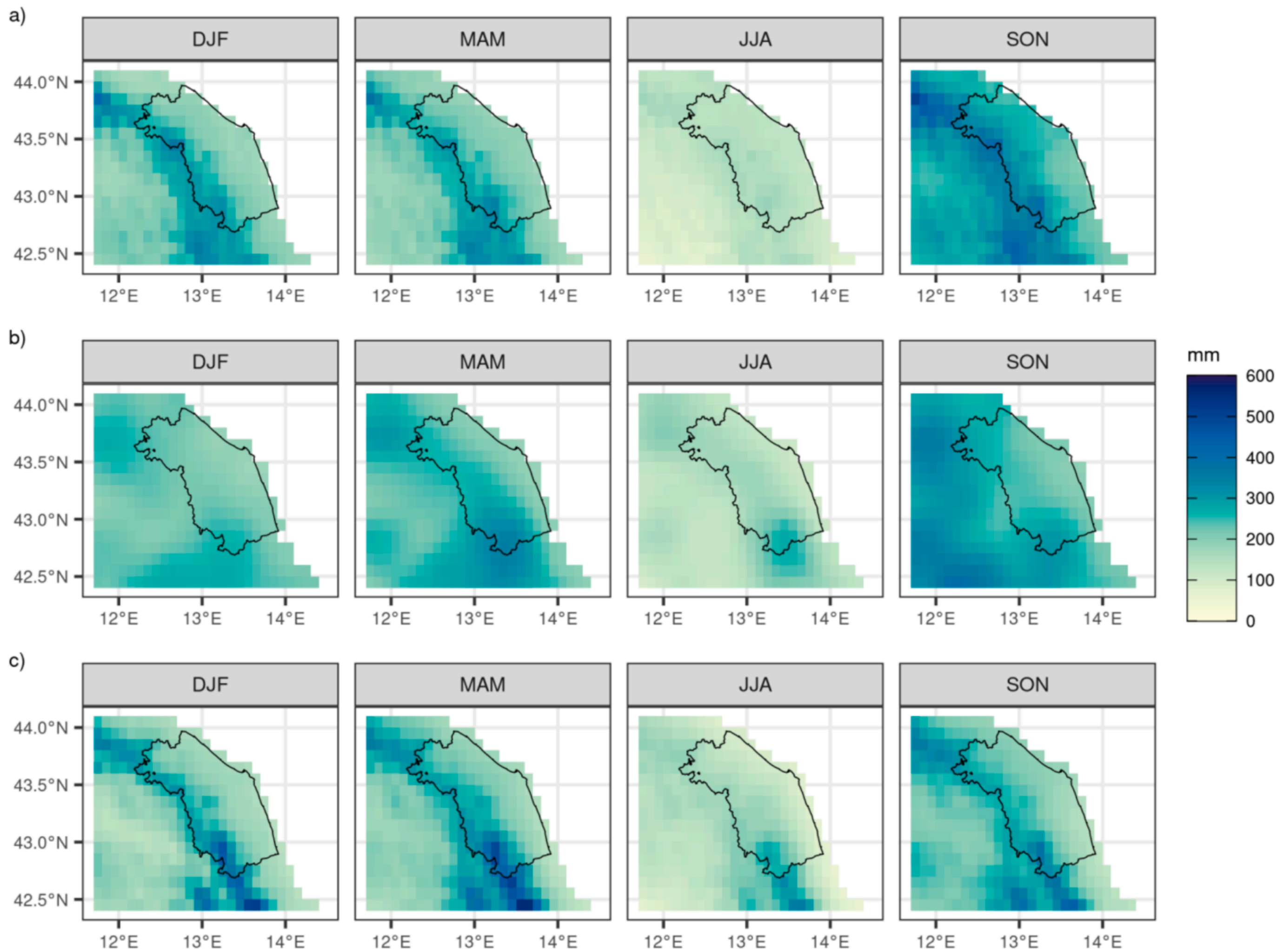

Fig. 3. 1991–2020 climatologies of total precipitation in winter (DJF, from December to February), spring (MAM, March to May), summer (JJA, June to August) and autumn (SON, September to November) computed for a) E-OBS, b) ERA5-Land and c) VHR-REA_IT on a 0.1° x 0.1° grid.

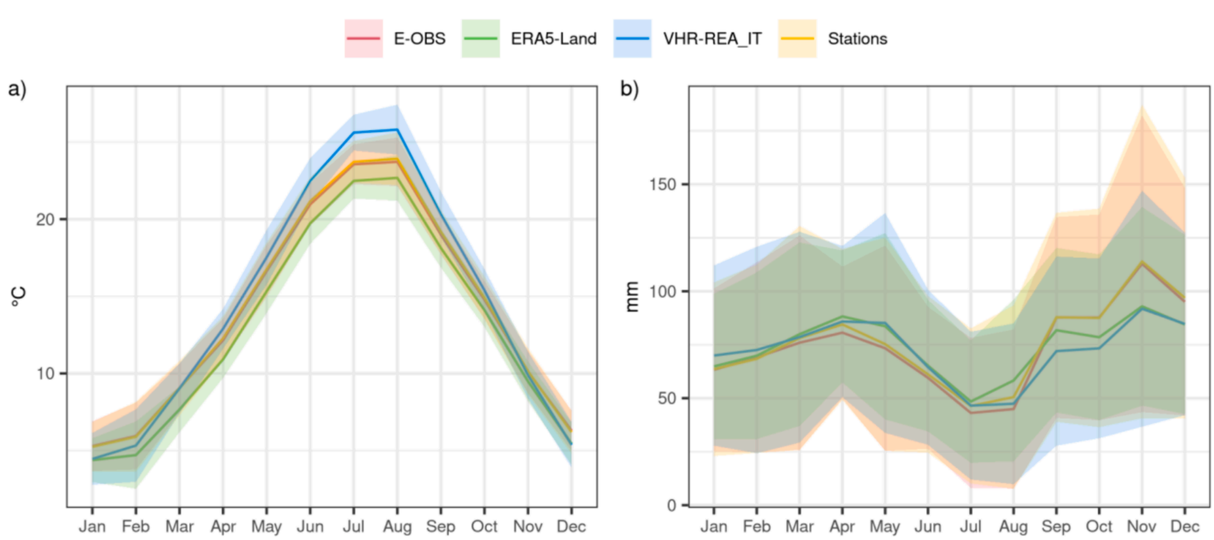

Fig. 4. Annual cycle of a) mean temperature and b) precipitation for 1991–2020 computed for E-OBS, ERA5-Land, VHR-REA_IT and station observations as averaged over station sites (19 for temperature and 52 for precipitation). Shaded areas represent the variability based on the standard deviation.

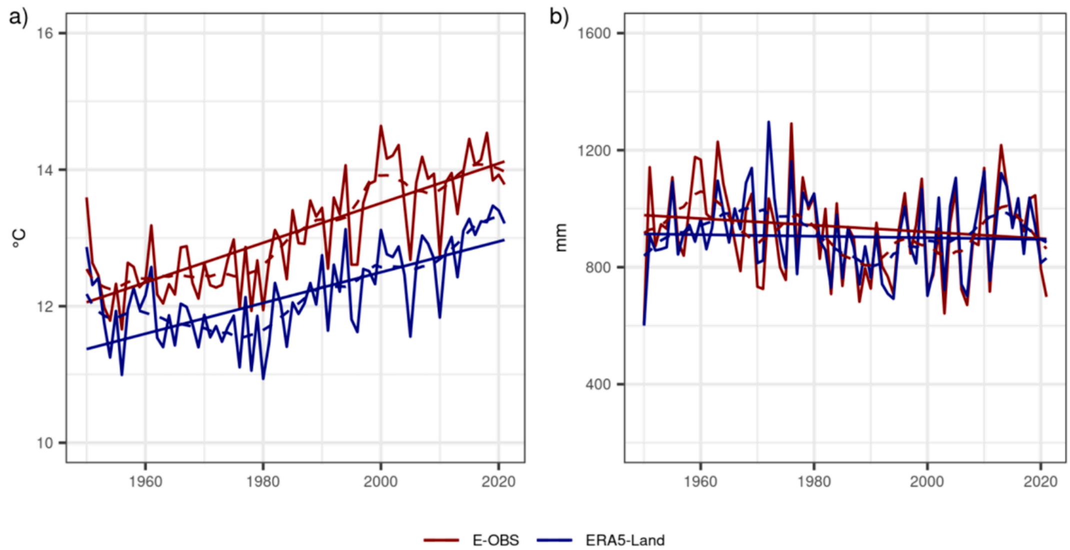

Fig. 5. Time series of a) annual mean temperature and b) annual total precipitation over 1950–2021 calculated as areal average over the Marche Region from E-OBS and ERA5-Land. Solid straight lines are the linear Theil-Sen fit, while dashed lines represent a 11-year Gaussian filter.

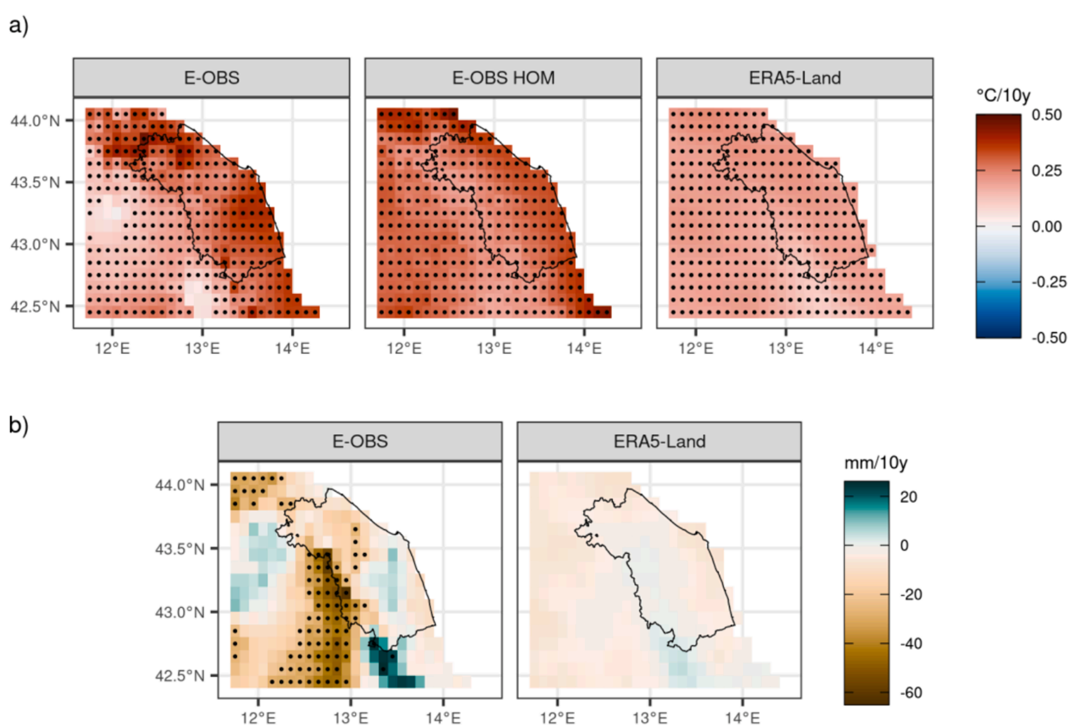

Fig. 6. Spatial distribution of trends (Theil-Sen) in annual mean temperature (upper panel) and precipitation (lower panel) expressed per decade. Temperature trends are relative to the 1950–2017 period in common among E-OBS, homogenized E-OBS version and ERA5-Land. Precipitation trends refer to the 1950–2021 period, no homogenized E-OBS version exists for precipitation. Dots indicate significant trends (Mann-Kendall p-value < 0.05).

almost null. These patterns are removed in E-OBS HOM.

The spatial heterogeneity of trends and the presence of potential local inconsistencies are also highlighted if the warming rate is compared to grid-cell elevation, based on the orography of E-OBS grid. ERA5-Land and E-OBS HOM report a gradual increase of trend values with increasing elevation, while the elevation-trend relationship is more dispersed in E-OBS with an unrealistic warming enhancement above 1′000 m (Figure S4).

The calculation of trends from station records requires long and continuous observation series to derive a robust estimation. Only 6 temperature stations have less than 10 % of missing yearly records over the common period 1957–2017 and are thus included in the trend comparison. All station trends in annual mean temperature are significant and range between +0.11 and +0.37 °C/decade. It is important to remark that since data inhomogeneity was not investigated and corrected in this study, station records are not intended as a benchmark, but only as an additional data source for evaluating trend variability and uncertainty. As expected, station trends are locally closer to the ones derived from E-OBS. It is noteworthy that the station series showing the weakest warming report the largest discrepancies with the homogenized dataset, likely due to the homogenization procedure which led to a local enhancement of the warming rate (Figure S5). When trends are computed over a shorter period, i.e., 1991–2020, to include also VHR-REA_IT in the comparison, the spatial distribution of annual trends in E-OBS is even more heterogeneous, with decreasing temperatures in the north and warming in the south-east near the coast. The other products do not reproduce this pattern: in E-OBS HOM the warming is even enhanced throughout the region, while ERA5-Land and VHR-REA_IT trends are all positive but weaker and with smoother spatial variations (figure not shown). The signal in E-OBS is driven by local observations whose temporal variability must be further investigated to evaluate the robustness and reliability of this trend heterogeneity which is not present in the other datasets.

Similar findings are obtained for precipitation trends. The regional series of annual and seasonal precipitation totals from E-OBS and ERA5-Land are highly correlated (correlation = 0.82 for annual series) with the greatest discrepancies over the early decades (Fig. 5b). E-OBS reports higher annual precipitation values during this period, which results into a more negative trend than ERA5-Land in the long term. However, for both products regional trends are almost null, and no one is statistically significant at both annual and seasonal level (seasonal series not shown). However, the spatial distribution of annual trends over the domain is rather different between the two products (Fig. 6b) and the absolute value of the trends differs by an order of magnitude between E-OBS and ERA5-Land: ERA5-Land trends are within ±10 mm/decade and E-OBS trends range from −65 to +25 mm/decade. ERA5-Land shows negative values over most of the region, especially over the coastal areas, and increases along the inner mountain areas, especially in the south. However, no statistically significant trend is obtained. E-OBS trends are more pronounced and heterogeneous, with statistically significant trends along the inner border with decreases in annual precipitation values, in contrast to ERA5-Land. Only over the Sibillini Mountains in the southernmost portion of the region the negative trend sign agrees with the reanalysis.

Station trends are closer to the ones of E-OBS, both in sign and in magnitude, especially in the northern part of the region, confirming the direct contribution of in-situ observations in defining the E-OBS long-term signal (Figure S6).

Temperature and precipitation extremes

The PDF of daily maximum temperature of VHR-REA_IT over the Marche Region shows longer tails of the distribution compared to E-OBS and ERA5-Land (Fig. 7a): this means that maximum temperatures of VHR-REA_IT in summer over the coast are higher compared to E-OBS and ERA5-Land, while mountain areas are characterised by lower maximum temperatures in winter. The spatial distribution of the 95th percentile of daily maximum temperature (Fig. 8a) shows a similar spatial pattern for all datasets, with lower values on mountains and higher values along the coast and in the inner portion of Central Italy, west of the Marche Region. The PDF for minimum temperature (Fig. 7b) reports overestimations by VHR-REA_IT in summer, in line with findings from Adinolfi et al. (2023) for Central Italy, while ERA5-Land shows colder extremes. The spatial distribution of the 5th percentile of daily minimum temperatures (Fig. 8b) is characterised by colder values on mountain areas for all datasets but with smoother spatial gradients for E-OBS and ERA5-Land.

The PDF of daily precipitation over the Marche Region shows that, while ERA5-Land can represent daily intensities up to about 100 mm, E-OBS and, especially, VHR-REA_IT reproduce higher daily precipitation values (Fig. 7c). The spatial distribution of the 95th percentile of precipitation reveals that VHR-REA_IT, probably due to the improved ability of representing local-scale dynamics, can reproduce higher percentile values over some localized areas, especially over the highest reliefs in the south (Fig. 8c). In E-OBS and, especially ERA5-Land, these local-scale patterns are not present. Although ERA5-Land is

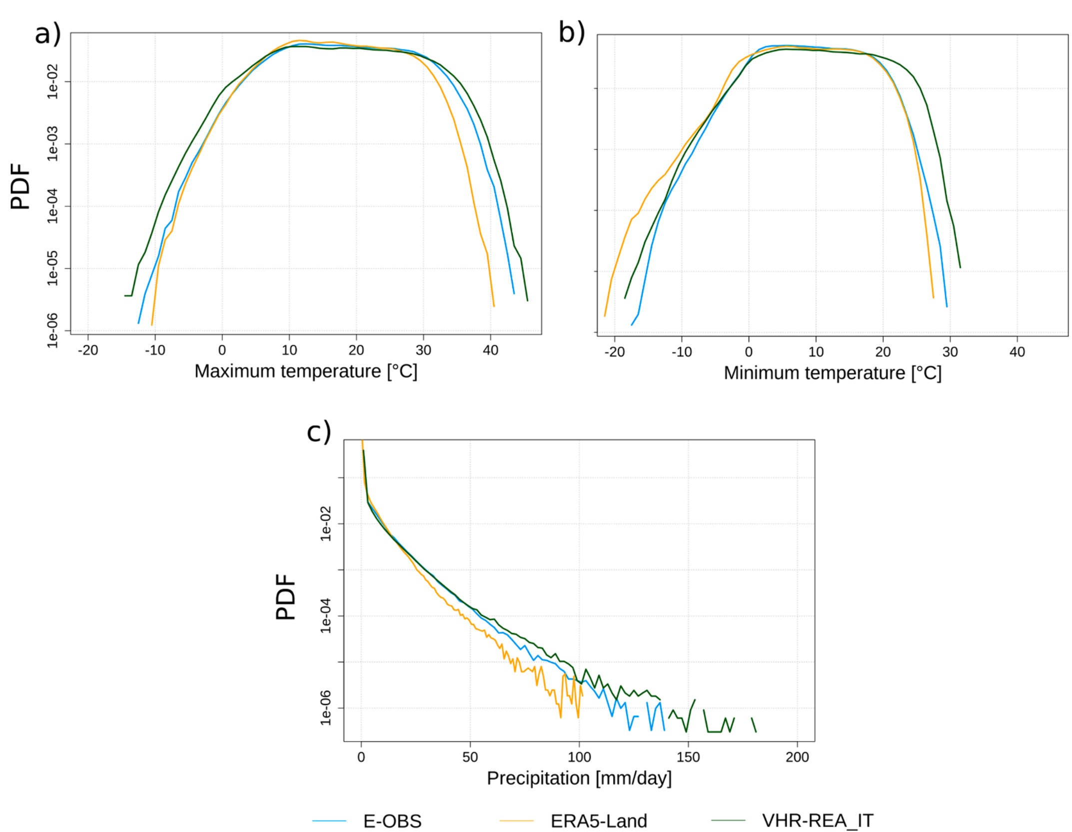

Fig. 7. Probability density function of a) daily maximum temperatures, b) daily minimum temperatures, c) daily precipitation over Marche Region over 1989–2020 for E-OBS, ERA5-Land and VHR-REA_IT. All datasets are resampled to the same 0.1° x 0.1° grid.

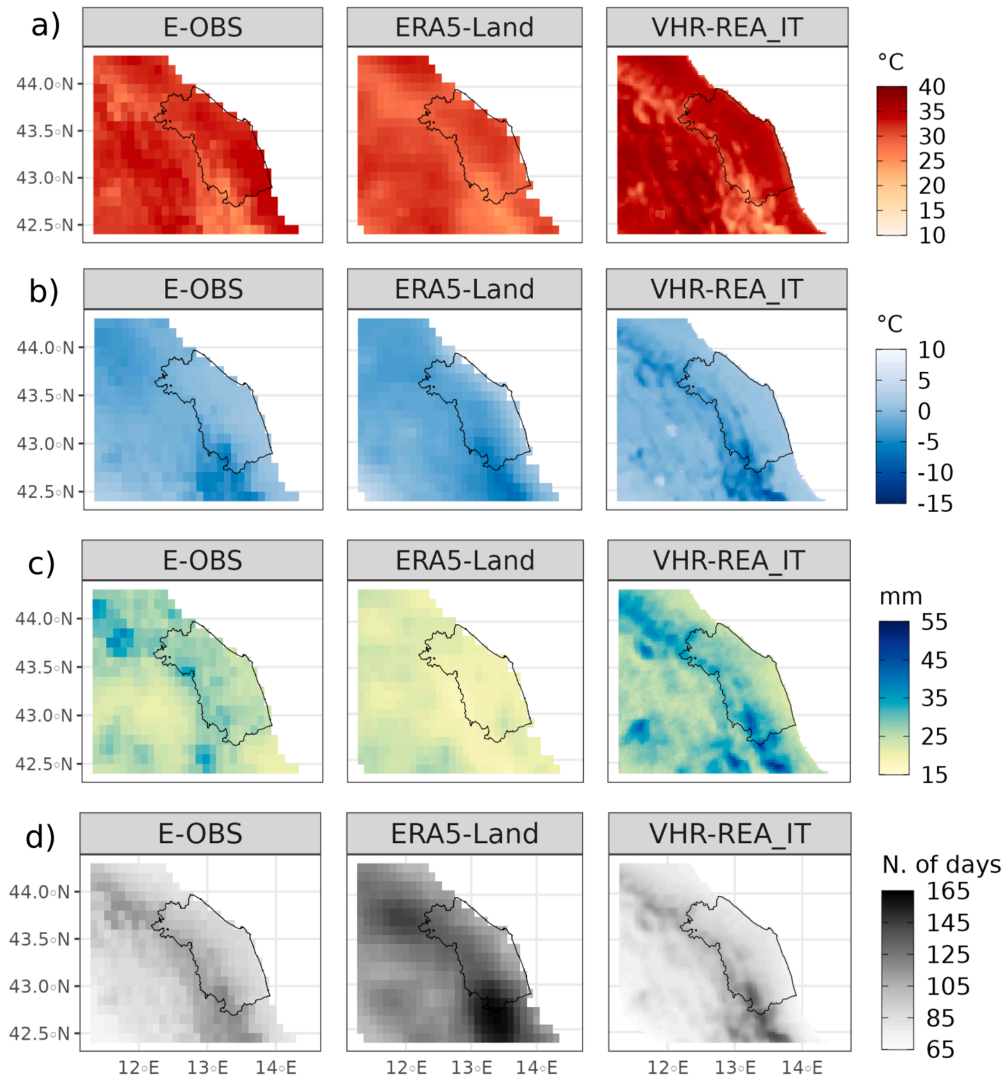

Fig. 8. Spatial distribution of a) 95th percentile of daily maximum temperature, b) 5th percentile of daily minimum temperature, c) 95th percentile of daily precipitation (on wet days only, i.e., daily precipitation >1 mm) and d) mean annual number of wet days. The analyses are computed over the period 1989–2020 and are based on native grids.

characterised by lower extreme precipitation values, the number of wet days per year is the largest among the datasets considered (Fig. 8d). It is worth noting that the same result is obtained also if higher thresholds are used to define a wet day. Frequent drizzle is a persistent problem in climate modelling, reflecting the tendency of large-scale climate models to overlook smaller-scale atmospheric factors that cause less or more precipitation than average. VHR-REA_IT, characterised by convection explicitly resolved, corrects the drizzle effect (Fig. 8d).

Besides the differences in the spatial representation of precipitation extremes, the calculation and ranking of magnitude (i.e., the product of mean intensity and fraction of area registering the event) of 3-day precipitation records provided further insight into the ability of the datasets to detect and characterize extreme events. The top-10 % greatest 3-day precipitation events (~1100 events) identified in the three datasets over the period 1989–2020 reveal differences in seasonal distribution (Fig. 9a). VHR-REA_IT reports the highest frequency of events in summer (~28 %) and, secondary, in spring (~24 %), while most of events selected from E-OBS and ERA5-Land occurred in autumn (26 % and 27 %, respectively). However, around 67 % and 74 % of detected events in E-OBS are in common with VHR-REA_IT and ERA5-Land, respectively, even though a different rank is assigned. It is interesting to compare the average annual distribution of the magnitude obtained by averaging over all top-10 % events in each calendar month (Fig. 9b). The monthly distribution is found to be mainly determined by the mean fraction of the regional area affected by the event (i.e., the number of grid cells with standardized anomalies $> 2\sigma$). The greater values of mean event magnitude of ERA5-Land, especially in spring and summer, are determined by the event extent and suggest the tendency of this product to exceedingly reproduce anomalies over a wider portion of the region. The differences in mean intensity among the datasets play a minor role in differentiating the seasonal patterns of magnitude, even though VHR-REA_IT and ERA5-Land report in all months the highest and lowest intensities, respectively.

Discussion

The comparison of E-OBS, ERA5-Land, VHR-REA_IT and local observations in representing climate features and long-term variability of precipitation and temperatures over the Marche Region revealed strengths and limitations of each product in supporting regional climate analyses. Each dataset showed a different ability in describing climatological values, trends and extremes, especially in terms of spatial patterns. It suggests that no unique optimal choice exists, but it depends on the scope of the analysis and that the integration of different products

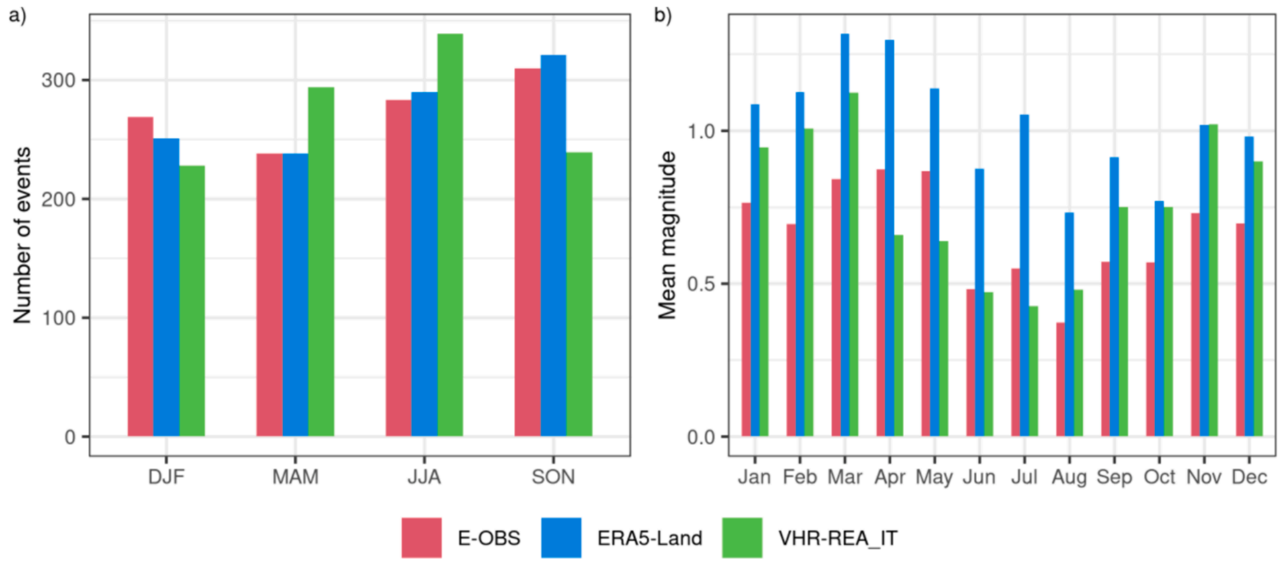

Fig. 9. Seasonal distribution (a) and mean monthly magnitude (b, dimensionless) of the top-10 % most intense 3-day precipitation events over 1989–2020 detected by each gridded product.

could be useful to improve the accuracy of the overall regional assessment.

Based on the spatial comparison with local observations, E-OBS represents still a proper baseline for climatological assessments on a regional level. Similar conclusions were also reported by Mavromatis and Voulanas (2021) by assessing E-OBS for the description of precipitation and drought for Greece and by Rianna et al. (2023) by evaluating the dataset for deriving thermal maps for Italy. Nevertheless, the robustness and the representativeness of E-OBS fields highly depends on the actual coverage of E-OBS input stations for the study area as also shown by Bandhauer et al. (2022) for several European regions and Kyselý and Plavcová (2010) over different regions of the Czech Republic. For practical applications, a preliminary evaluation of available input data density in space and time for E-OBS is necessary. In the case of Marche Region, since all historical station series are located below 1′000 m a.s.l., E-OBS estimates for higher elevations are extrapolated, hence the resulting values need to be considered cautiously. ERA5-Land climatologies is characterised by smoothed gradients, especially for precipitation, and a systematic underestimation of mean temperature values on a regional scale, particularly pronounced in spring and summer. It is probably associated with the smoother orography considered in ERA5-Land and the applied vertical correction, which does not consider the small-scale variability (Zhao and He, 2022). The smoothing effect is also combined with an overestimation of rainy day frequency, as already shown in other global and regional studies (e.g., Gomis-Cebolla et al., 2023; Xie et al., 2022). VHR-REA_IT offers an enhanced description of local gradients, but may overestimate certain climatic features, as also reported by Adinolfi et al. (2023). For instance, precipitation gradients can be emphasized especially in some mountain areas where the convection-permitting model simulates a substantial portion of precipitation as snowfall (Adinolfi et al., 2023; Pieri et al., 2015).

The dataset comparison reported greater differences for the long-term temporal variability. Long-term trends of mean temperature derived from E-OBS, E-OBS HOM and historical station observations were much more pronounced and varied more over the region than those computed from ERA5-Land. Since the main differences in E-OBS and ERA5-Land signals were reported for the early decades when data density is expected to be lower, the variability in station coverage over time as well as potential inhomogeneities or discontinuities in historical time series could have influenced the long-term signal of E-OBS or produced local artifacts. The presence of possible inaccuracies is suggested by the fact that E-OBS HOM slightly reduced the regional warming with main adjustments in the early period and showed a greater spatial consistency of temperature trends over the region. This was particularly evident over the Sibillini Mountains where the very low data density makes interpolated records more sensitive to the integration or relocation of stations over the years. It is also worth noting that due the low data coverage, inhomogeneities in single station records can have a relevant impact on a relatively wide portion of the E-OBS gridded fields. In a similar study focusing on trend evaluation for Apulia Region in Southern Italy, My et al. (2022) also concluded that gridded observation datasets, e.g., E-OBS, can only provide a general indication of the temporal evolution of the climate for a region while local deviations are expected. Similar considerations hold for precipitation trends: values are more pronounced and heterogeneous in E-OBS than in ERA5-Land, which, on the contrary, showed more spatially consistent trends but probably underrepresented. It is important to consider that also reanalyses, despite not solely relying on in-situ observations, can be affected by inconsistencies in the long-term signal due to e.g., changes in the data assimilation scheme, model settings and input data (Mayer et al., 2021). Only an integrated evaluation, supported by the product documentation, can unravel the specific limitations of each dataset, and provide a more balanced understanding of the regional climate trends. Moreover, when information for specific locations is needed, it would be desirable not to consider one single grid point, but rather to extend the long-term analysis over a broader area, to verify the overall coherence of the local signal.

As regards extreme description, the results of this study confirmed the superior performance of a high-resolution dynamically downscaled reanalysis such as VHR-REA_IT. For instance, only VHR-REA_IT reproduced the peak of precipitation intensities in the southern and inner part of the region, which was described by local observations and other previous regional studies (e.g., Gentilucci et al., 2019). The improved reliability of VHR-REA_IT was also discussed by Reder et al. (2022) in an urban-scale study where the authors highlighted the capability of the dataset to support the Disaster Risk Reduction community by improving the representation of local extremes, the estimation of occurrence probability of hazardous phenomena and thus the design of hazard maps. If ERA5-Land or E-OBS are used, a clear underestimation of potential impacts is expected, and this might be particularly important for applications requiring sub-daily information. However, the enhanced spatial representation does not prevent possible misrepresentations: local precipitation intensities in VHR-REA_IT can be overestimated, especially in mountain areas, while warm biases in extreme temperatures especially in flat terrains were reported also in other intercomparison analyses on a national level (Raffa et al., 2021; Adinolfi et al., 2023, Cavalleri et al., 2024).

In terms of event detection ability, VHR-REA_IT included a higher number of intense precipitation events in spring and summer than E-OBS and ERA5-Land, partly due to the improved ability to resolve convective phenomena. The coarse-resolution products were found to include and assign a high ranking mainly to large-scale precipitation events in the list of the most relevant ones. It is also noteworthy that the high-resolution reanalysis can improve the detection of impactful winter and late-winter snow events in the region at high elevations, which E-OBS and ERA5-Land do not capture. An example is represented by the event occurred in January 2017 (Fig. 10), when intense precipitation and snowfall led to severe damages on the southern portion of the Marche Region (Centro Funzionale Regionale, 2017). While it was reported as the third most anomalous 3-day precipitation event over 1989–2020 by VHR-REA_IT, E-OBS and ERA5-Land completely missed it. This mismatch can be explained, especially for E-OBS, by the underestimation of precipitation recorded at station sites, where the heated rain gauges may not operate under exceptional snowy conditions, especially in association with high wind speed. High-resolution reanalyses can thus represent relevant surrogates of observations, which, in combination with expert knowledge, metadata and additional data sources, potentially provide more insights into significant past events, support the detection of exceptional meteorological conditions, and link them to recorded impacts.

Conclusions

In this study, the applicability of three different gridded climate datasets (namely E-OBS, ERA5-Land and VHR-REA_IT) was investigated for the description of mean climatic features, historical trends and extreme values in support of climate risk assessment and adaptation planning for the Marche Region (Central Italy). Even though only three datasets were considered and analysed based on temperature and precipitation fields, the study revealed the importance of checking and comparing products before applying them for regional studies. The specific features of each dataset can lead to significant differences in resulting past trends and climatic variability. Global and European products, despite potential limitations in representing the spatial scales required by for local risk management processes, can still provide a useful integration to local observations for regional adaptation planning. Observation-based datasets such E-OBS provide a reliable estimate of regional climatologies. Still, they can be more prone to inconsistencies in the long-term analysis due to inhomogeneous historical records and data gaps. ERA5-Land, despite a finer nominal resolution with respect to ERA5, tends to smooth out local climatic features and gradients, while trends are more spatially consistent but probably underrepresent the magnitude of changes. High-resolution dynamically downscaled reanalyses, like VHR-REA_IT, while covering shorter time periods, are preferable to capture local extremes and fine-scale patterns. However, the high spatial resolution does not always guarantee reliability and lower uncertainty. A thorough understanding of data limitations and features becomes thus essential to truly assess past and current climate conditions and especially relevant when past data are used as input to impact models or as reference to calibrate future climate scenarios.

Further studies in the Italian national context are expected to support the approved Italian PNACC which has the main objective to provide a national framework for the implementation of actions minimising the future risks from climate change and guidelines for the definition of regional and local actions. A more comprehensive overview and understanding of the use and applicability of available climate datasets could be a valuable complement to the national recommendations for the development of sub-national climate risk assessments and climate change adaptation actions. Moreover, this would foster the harmonization of local frameworks adopted by different administrations of the national territory, also considering the continuously increasing number of released global, European and national products. For instance, recent downscaled reanalyses, such as the new European reanalysis CERRA providing 5-km sub-daily fields from 1984 (Ridal et al., 2024), and high-resolution observation-based products, such as the European Meteorological Observations dataset (EMO) including multiple daily and sub-daily variables at 1.5-km resolution from 1990 (Thiemig et al., 2022), can represent other valuable sources for the assessment of climate-related hazards and risks on a regional level. Based on the experience of the Marche Region, the choice of reference datasets may also depend on the adaptation measures that need to be set and on the temporal and spatial coverage required for their evaluation and implementation. A proper trade-off between available data and the local scales effectively resolved is necessary. To evaluate measures for mitigating the risk from climate extremes, using datasets at high spatio-temporal resolution, such as VHR-REA_IT, is crucial, provided that the time series would be long enough to enable a robust statistical analysis. In this context, further inter-comparison studies extended on sub-daily variables, especially precipitation, would represent a key complement to this work to analyze weather events that can cause significant impacts on society and

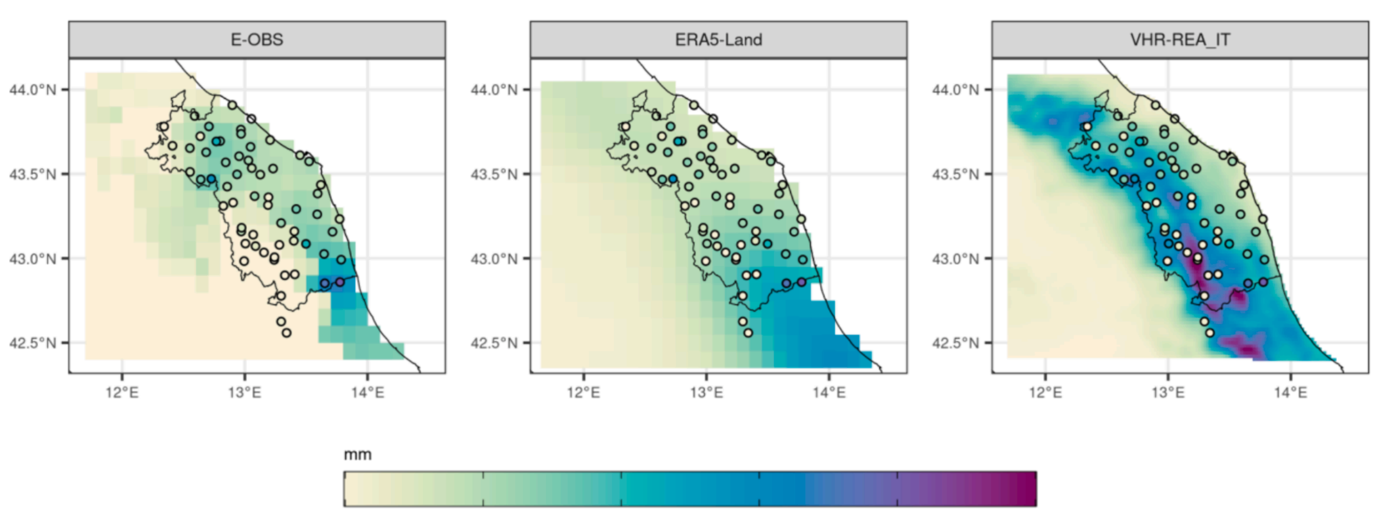

Fig. 10. 3-day precipitation on 16th-18th January 2017 reported by E-OBS, ERA5-Land and VHR-REA_IT on their native grid. Station observations are superimposed to the gridded fields.

the environment. Finally, decision makers need to be aware of the uncertainty associated with the datasets when interpreting the results. For instance, long-term changes from large-scale products should not be considered punctually but as an overall indication of ongoing climate tendencies and potential evolution over future decades in the area of interest.

Fostering coordinated actions to collect national climate observations and generate established and easily accessible high-resolution gridded observation products would be a key step towards the strengthening of the climate change adaptation capabilities at both national and regional scale. Common climate references, together with a comprehensive evaluation of other existing products, will increase the consistency of single local initiatives and studies, supporting the definition of national climate change scenarios calibrated on observations. Deriving and evaluating local climate change model simulations and underlying uncertainties are in fact the final steps of a scientifically consistent regional climate change assessment.

CRediT authorship contribution statement

Alice Crespi: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Anna Napoli:** Writing – original draft, Visualization, Formal analysis, Data curation. **Gaia Galassi:** Writing – review & editing, Resources. **Marco Lazzeri:** Resources. **Antonio Parodi:** Writing – review & editing. **Dino Zardi:** Writing – review & editing. **Massimiliano Pittore:** Writing – review & editing, Supervision.

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.

Data availability

All datasets used in this work are freely available through online repositories. In particular, ERA5-Land is accessible from the Climate Data Store of the Copernicus Climate Change Service (https://cds.climate.copernicus.eu/#!/home), E-OBS versions and underlying station information from the website of the European Climate Assessment & Dataset project (https://www.ecad.eu/), VHR-REA_IT from the Data Delivery System of CMCC (https://dds.cmcc.it/) and station records of Marche Region can be retrieved from the Regional Meteorological-Hydrological Information System (https://app.protezionecivile.marche.it/sol/indexjs.sol?lang=en).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2024.100512.

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