

Analysis of sub-regional climates in the European Alps based on the EEAR-Clim observational dataset

Giulio Bongiovanni^{1,2*}, Alice Crespi³, Michael Matiu²,
Anna Napoli^{2,4}, Bruno Majone², Dino Zardi²

¹University School for Advanced Studies Pavia (IUSS), Palazzo del Broletto, Piazza della Vittoria 15, Pavia, 27100, Italy.

^{2*}Department of Civil, Environmental and Mechanical Engineering (DICAM), University of Trento, Via Mesiano 77, Trento, 38123, Italy.

³Center for Climate Change and Transformation (CCT), Eurac Research, Viale Druso 1, Bozen, 39100, Italy.

⁴Center for Agriculture Food Environment (C3A), University of Trento, Via Edmund Mach 1, San Michele all'Adige, 38098, Italy.

*Corresponding author(s). E-mail(s): giulio.bongiovanni@unitn.it;

Abstract

The European Alps exhibit a complex geomorphology and undergo the influences of different climate regimes, resulting in high spatial variability of climatic variables and their changes. To provide a detailed analysis of climate regions and climatic changes occurring at a sub-regional scale during the 1961-2020 period, we exploited an updated regionalization of the European Alps that benefits from EEAR-Clim, a new observational daily dataset permitting a robust analysis of local-scale climate features.

The regionalization of the European Alps identifies five sub-regions exhibiting distinct climate features: North-West, North-East, South-West, Central-South, South & South-East (S&SE). The analysis of average climate conditions highlighted Central-South and S&SE as the sub-regions experiencing the warmest temperatures and the highest monthly precipitation totals, mostly in spring and

autumn, though characterized by a pronounced variability among stations. Conversely, colder temperatures and moderate yet frequent precipitations occurs in northern Alps.

Trends of air temperature and precipitation over these sub-regions highlights uneven warming in the Alpine region. North-East, South-West and S&SE were identified as the fastest warming sub-regions, with increases over 1961-2020 reaching +2.0°C for minimum temperature, +2.8°C (SW) and +2.4°C (NE and S&SE) for maximum temperature, respectively.

Despite the high spatial and temporal variability of precipitation over the European Alps, the S&SE sub-region exhibits drying conditions in spring and summer compared to the other regions. Trends in extreme precipitation are more statistically significant compared to changes in mean values, resulting in an increased frequency since 1961 of very extreme rainfall events, mostly in the southern Alps (+18 days).

The new regionalization of the European Alps presented here is expected to support a range of climate related applications including impact studies. Moreover, it demonstrates the importance of considering variations in both average climate conditions and ongoing trends across different parts of the Alps, helping to identify areas most vulnerable to the effects of climate change.

Keywords: in-situ stations, air temperature, precipitation, clustering, regionalization, climate zones, trends

1 Introduction

The European Alps are widely recognized as a climate change hotspot (Giorgi, 2006; Gulev et al., 2021) and are extremely vulnerable and sensitive to the ongoing climate change. Changes in Alpine climate such as rising temperatures, modifications in the seasonal water cycle, increasing frequency of climate extremes, snow cover reduction and glacier shrinking make the European Alpine region particularly prone to climate extreme events (Gobiet et al., 2014; Hock et al., 2019; Ménégoz et al., 2020). Extreme climate phenomena, such as floods, heat waves, cold breaks, droughts, landslides and snow avalanches deeply impact several socio-economic and environmental sectors, including tourism, agriculture, hydropower, human health, ecosystems, water resources, infrastructures, and the mountain cryosphere (Gobiet et al., 2014; Hock et al., 2019).

However, the complex geomorphology of the European Alpine Region, coupled with the influences of different climate regimes, lead to significant spatial variability

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in Alpine climate (Carvalho et al., 2016). Alpine-wide analyses require to take into account the high spatial variability of climate change across the Alpine region to avoid missing key sub-regional patterns in rising temperatures and changing precipitation regimes (Fischer and Knutti, 2016; Gulev et al., 2021). Thus, the definition of sub-regions sharing common climatic features and coherent temporal patterns is essential to improve our knowledge of the spatial and temporal variability of climatic variables in the Alps. This task is commonly achieved through a spatial classification approach called regionalization (Sarah Irwin and Burn, 2017).

The regionalization into coherent climatic areas finds an important application in identification of the drivers of climate variability across specific regions and seasons. It enhances understanding of how variability patterns differ among climate variables and provides an essential basis for regional applications and climate change studies (Iturbide et al., 2020). For instance, the regionalization is widely used in hydroclimatic forecasting applications (Beck et al., 2016), improving model parametrization, and enabling more accurate predictions of streamflow and runoff (Guo et al., 2021; Wang et al., 2021). Regionalization of hydroclimatic variables supports the definition of drought monitoring regions (Vicente-Serrano, 2006; Santos et al., 2010; Gocic and Trajkovic, 2014; Zhang et al., 2017), facilitates studies on climate-induced variations in crop yields (Araya et al., 2010; Garcia-Barreda et al., 2019), and enables accurate analyses of flood frequency (Du et al., 2014; Sarah Irwin and Burn, 2017; Wright et al., 2020). Moreover, the regionalization plays a critical role in the assessment of environmental responses to climate change, as well as, providing ecological classifications to study the ecological processes, the biodiversity, and the spatial distribution of biotopes, habitats and ecoregions, thus supporting conservation actions (Rogora et al., 2018; Tasser et al., 2024). The derivation of consistent sub-regional information is vital for assessing local impacts and risks of climate change on human activities. Thus, it plays

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a key role in disaster risk reduction, regional planning, and ecosystem management, including water resources (Viviroli and Weingartner, 2004; Kupzig et al., 2024).

Many efforts have been made to develop suitable approaches for climatic regionalization, including hierarchical clustering (Kaufman and Rousseeuw, 1990), quantile-based procedures (Gaetan et al., 2024), density-based algorithms (e.g. DBSCAN, Density-Based Spatial Clustering of Applications with Noise, Ester et al., 1996), or the combination of principal component analysis (PCA) with the cluster analysis (CA) (e.g. k-means algorithm, Hartigan and Wong, 1979). In the past decades, several studies have addressed the regionalization of the European Alpine region, but only few addressed the challenge of clustering large, transnational regions within the European Alps (Auer et al., 2007; Leuprecht and Gobiet, 2010; Lanfredi et al., 2020; Carvalho et al., 2016), while most of them focused on specific countries, such as Austria (Ehrendorfer, 1987), Germany (Uebachs et al., 2021; Crespi et al., 2023), Switzerland (Scherrer et al., 2016) or Italy (Di Giuseppe et al., 2013). Moreover, regionalization studies rely mostly on meteorological observations, and thus can potentially face limitations in complex terrain areas like the European Alps, due to uncertainties in measurements and low spatial density of the observational network (Haylock et al., 2008; Turco et al., 2013).

The first attempt to address the regionalization of the European Alpine region was made by the HISTALP project (Auer et al., 2007), that, even after two decades, still remains a key reference for Alpine climate studies. HISTALP applied a combination of PCA and K-means clustering to 1930-2000 monthly data, including air temperature, precipitation, air pressure, sunshine duration, relative humidity, vapor pressure, and cloudiness from in-situ weather stations. They identified four main sub-regions: North-West, North-East, South-West, and South-East of the Greater Alpine Region.

Among further studies focused on the regionalization of the European Alpine region, Leuprecht and Gobiet (2010) applied an agglomerative Ward's clustering (Jr.,

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1963) combined with the K-means algorithm to 1971-1999 daily precipitation data of the ETH dataset (Frei and Schär, 1998). This study identified six distinct sub-regions, showing marked differences in climate variability among the Southern, Northern and Western Alps. More recently, Lanfredi et al. (2020) proposed a regionalization of Central-Southern Europe, which includes much of the Alpine area. They applied the K-means method to 1981-2018 monthly precipitation data from the CHIRPS gridded product (Funk et al., 2015), which combines satellite and in-situ observations at a spatial resolution of 0.05° . This study identified seven clusters predominantly distributed along latitudinal zones.

The regionalization proposed by Leuprecht and Gobiet (2010) aligns with HISTALP for northernmost areas. However, significant differences emerge among HISTALP, Leuprecht and Gobiet (2010), and Lanfredi et al. (2020) in their regionalization of the southern areas. Moreover, the approaches of Leuprecht and Gobiet (2010) and Lanfredi et al. (2020) are limited to precipitation data. Multi-variable regionalization is essential to increase confidence in the results of climate studies and better understand the mutual interplay linking different climate variables (Huth and Pokorná, 2005; Brunetti et al., 2009).

These studies demonstrate that the methodology, temporal coverage, spatial density, temporal resolution, and the variables considered all have a strong impact on regionalization outcomes. Moreover, there is still high uncertainty and disagreement in previous studies for the southernmost areas of the European Alps.

In this study, we exploit the high-quality and spatially dense EEAR-Clim dataset (Bongiovanni et al., 2024a) to develop an updated regionalization of the European Alpine region. The new regionalization, based on daily air temperature and precipitation data, is discussed in comparison to the findings of previous regionalized-based studies to assess how it contributes to a more detailed understanding of climatic zones and climate changes in the European Alpine region. This work further extends the

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Alpine-wide trend analysis provided in Bongiovanni et al., 2024c to better assess the spatial distribution and spatial coherence of trends.

The paper is structured as follows: Section 2 introduces the study area and the observational data, outlines the methods including the details the regionalization procedure. Section 3 presents and discusses the key results. Finally, Section 4 summarizes the main findings of the study.

2 Data and Methods

2.1 Study Area and Data

The study domain, shown in fig. 1, is the Extended European Alpine Region (EEAR), bounded by 3°E to 18°E in longitude and 43°N to 49°N in latitude. The EEAR predominantly features a complex orography centered on the European Alps, while also encompassing lowlands and northern Mediterranean coastal areas.

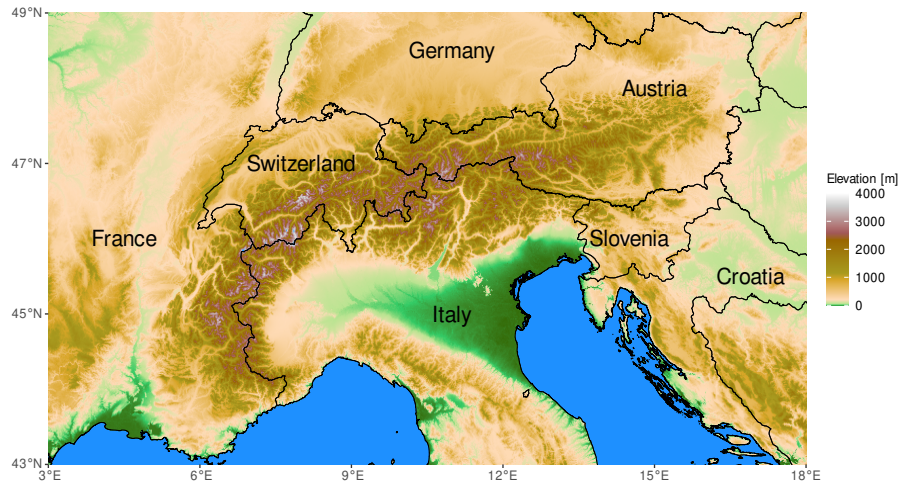


Figure 1 European Extended Alpine Region domain (EEAR) based on the Digital Elevation Model (DEM) of Shuttle Radar Topography Mission CGIAR-SRTM (90 m resolution) (<https://srtm.csi.cgiar.org/>). Country borders are retrieved from Global Administrative Areas (GADM) database (<https://gadm.org/>).

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The climate of the EEAR is shaped by the interplay of different regimes. Northern areas experience conditions typical of an oceanic climate, due to the influence far in land of the Atlantic Ocean. This regime transitions to humid subtropical in the southern lowlands and Mediterranean-influenced climate along the coastal areas. The main Alpine range exhibits colder conditions typical of a continental climate, with the more severe regime confined to the highest elevated areas (Koppen, 1936; Beck et al., 2018). Moreover, due to its complex orography, the barrier-effect of the Alps, and influence of several large-scale circulation patterns (Beniston, 2005), the EEAR experiences diverse local weather phenomena. This climate and meteorological diversity results in diverse spatial and elevational gradients (Auer et al., 2007; Isotta et al., 2014).

This study uses the daily observational data of precipitation (P) and mean (T), minimum (TMIN) and maximum (TMAX) air temperature from the EEAR-Clim dataset (Bongiovanni et al., 2024a), the densest and most comprehensive observational product available for the European Alpine region to date. In addition to daily air temperature and precipitation data, we consider a set of 16 climate indices designed to monitor, analyze, and detect changes in climate extremes at regional scales (Karl et al., 1999; Peterson et al., 2001; Tank and Können, 2003). Extreme indices used in this study (table S1) were computed as described in Bongiovanni et al., 2024c.

Two subsets of the EEAR-Clim dataset were used in this study. EEAR-Clim-30, extending over 1991-2020, is the subset specifically used for regionalization and EEAR-Clim-60, covering the 1961-2020 period, is used for trend analysis. Each subset consists of quality checked and homogenized data (Bongiovanni et al., 2024a), selecting only complete time series, following the requirements outlined by World Meteorological Organization (WMO, WMO (2017)). For more details, we refer to Bongiovanni et al., 2024c. In total, the selected subsets consist of 1219 mean temperature, 1125 minimum temperature, 1131 maximum temperature, and 2369 precipitation time series for

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EEAR-Clim-30 and respectively 301, 320, 318 and 989 time series for EEAR-Clim-60 (table S1 and fig. S1).

2.2 Methods

Studying the Alpine climate through spatial aggregation into a single average time series over the entire area, as in Bongiovanni et al., 2024c, destroys local to sub-regional features, which are fundamental especially for describing spatially variable parameters such as precipitation (Auer et al., 2007). However, the simultaneous clustering of multiple daily variables is challenging due to the different nature, distribution, and variability compared to data at monthly-to-annual resolutions (Uebachs et al., 2021). Therefore, alternative approaches are required (Auer et al., 2007).

In this study, we performed regionalization over 1991-2020 on daily values of air temperature and precipitation, separately, scaled to zero mean and unit variance. The scaling procedure ensures that each station contributes equally to the identification of spatial patterns, preventing the regionalization from being dominated by differences in absolute climatological values. Here, air temperature is defined as the average of minimum and maximum temperature. To maximize the reliability of the regionalization, which strongly depends on the spatial coverage of observations, we included all time series of EEAR-Clim-30 subset with at least 80% valid data.

First, for each variable, the common modes of spatial variability were determined using empirical orthogonal function (EOF) analysis, also known as principal component analysis (PCA). This widely used method in climate studies (Auer et al., 2007) was applied employing a modified EOF algorithm capable of handling time series with data gaps (Taylor et al., 2013). The number of PCs used were determined studying the scaled loadings and the percentage of variance explained by the respective PC. After computation of the EOF, we applied the k-means clustering algorithm (Carvalho et al., 2016) to the derived EOF matrices to identify sub-regions within the EEAR.

The optimal number of candidate clusters was determined by combining Elbow method (Schubert, 2023), Average Silhouette Score (ASS, Rousseeuw, 1987), and Davies-Bouldin Index (DBI, Davies and Bouldin, 1979) metrics to derive a more robust evaluation. We tested clustering metrics for two to ten clusters, and further validated the findings with a visual interpretation.

However, to compare air temperature and precipitation patterns, a unified regionalization for both variables is required. While this could in theory be achieved by clustering all variables simultaneously, the challenges posed by a unified regionalization, as mentioned above, and the lower number of available stations measuring both temperature and precipitation, made us to decide against it. Instead, common sub-regions (CSRs) were identified overlapping air temperature and precipitation clusters, providing a raw framework for the definition of the CSRs. For stations that did not belong to any CSRs, assignment was determined based on the Spearman's correlation coefficient. Specifically, correlations were computed between the air temperature and precipitation time series of each unassigned station and the cluster averages for each CSR contiguous to the station. The assigned cluster for the station was robustly identified whether air temperature and precipitation have the highest and statistically significant ($p < 0.05$) correlation with the same cluster and above minimum thresholds of 0.9 and 0.7 (Bongiovanni et al., 2024a), respectively. Station remained unassigned if this condition is not achieved or whether ambiguous results were obtained, i.e., similar correlation coefficients with multiple CSRs, or each variable correlating best with a different CSR. For the remaining unassigned stations, climatological and trend maps from previous studies (e.g. Bongiovanni et al., 2024c) were used to guide the finalization of the CSRs. In case of few or spatially sparse stations, they were assigned to the most suitable CSR, based on the spatial climate patterns observed.

The identified sub-regions were analyzed and compared both in terms of climatological features and trends. Air temperature and precipitation data from the

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EEAR-Clim-60 subset were used to provide an overview of average climate conditions in each sub-region during the period 1961-2020. Daily data were aggregated into monthly values and then averaged across all years to derive the annual cycles. Climatology within each sub-region was estimated as the average of annual cycles across all stations, with the 5th-95th percentiles range representing the uncertainty due to the spatial variability. The assessment of the spatial distribution of trends of air temperature, precipitation, and extreme indices across CSRs used the 1961-2020 trends as calculated in Bongiovanni et al., 2024c.

3 Results

3.1 Regionalization of Air Temperature and Precipitation

Scaled loadings and the percentage of variance explained by the respective PC (fig. S2 and S3), shown how much of the total variability is captured by each PC. Despite the first three PCs capture the main spatially coherent patterns at broad-scale, subsequent components, up to the 10th, still explain non-negligible fractions of variance, accounting for relevant spatial structures that would be lost by truncating the decomposition earlier. Thus, the first ten PCs had to be considered in the clustering procedure to fully account the high variability of data.

The optimal number of clusters for air temperature and precipitation ranged from four to seven, depending on the metric. These configurations capture different aspects of spatial variability, such as longitudinal, latitudinal, and elevation gradients. Among these candidate configurations, we selected the optimal number of clusters based on the combination of results from clustering metrics of elbow method (fig. S4 and S5), ASS (fig. S6 and S7), and DBI (fig. S8 and S9). Thus, the selected number of clusters for each variable is the best compromise between optimal clustering metrics and meaningful spatial patterns.

The clustering of the EEAR based on air temperature (fig. S10a) resulted in five sub-regions across the European Alps, with an unclear separation of central-northern Alps from nearby clusters, mainly due to the uneven spatial distribution of high-elevation areas in the EEAR. Air temperature clusters (fig. S10a) differ from the precipitation clusters (fig. S10b), in both the number of clusters and the spatial distribution. In particular, precipitation clustering includes a distinct cluster for northern-central area, while the temperature cluster covering high elevations was replaced by a larger area encompassing the Italian Alps and Prealps.

The overlay of single variable clusters (fig. S11) as described in section 2.2 directly assigned stations located in regions of overlap (21.9%) to the corresponding CSR. Among the unassigned stations (78.1%), some are related to the absence of a similar sub-region for air temperature (14.1%), especially those belonging to the North-Center precipitation cluster. Others were unassigned because of missing observations for both variables (53.1% for P and 10.9% for T), despite being apparently located within the same cluster.

These cases were solved in the next stage of the procedure with the evaluation of the correlation coefficient between unassigned stations and CSRs, as described in section 2.2, allowing to assign most of the stations (77.65%) to the proper cluster. Only a small subset of stations (0.45%) remained unassigned due to low correlations for one or both variables, and in such cases the climatological information was used to assess the most suitable cluster. Despite the high subjectivity of the last step, required for a very small portion of stations, the process remained largely objective.

The final regionalization of the EEAR in terms of both air temperature and precipitation is shown in fig. 2. The five sub-regions were renamed as North-West (NW), North-East (NE), South-West (SW), Central-South (CS), and South&South-East (S&SE). The amount of time series and the elevation range of each cluster are reported in fig. S12.

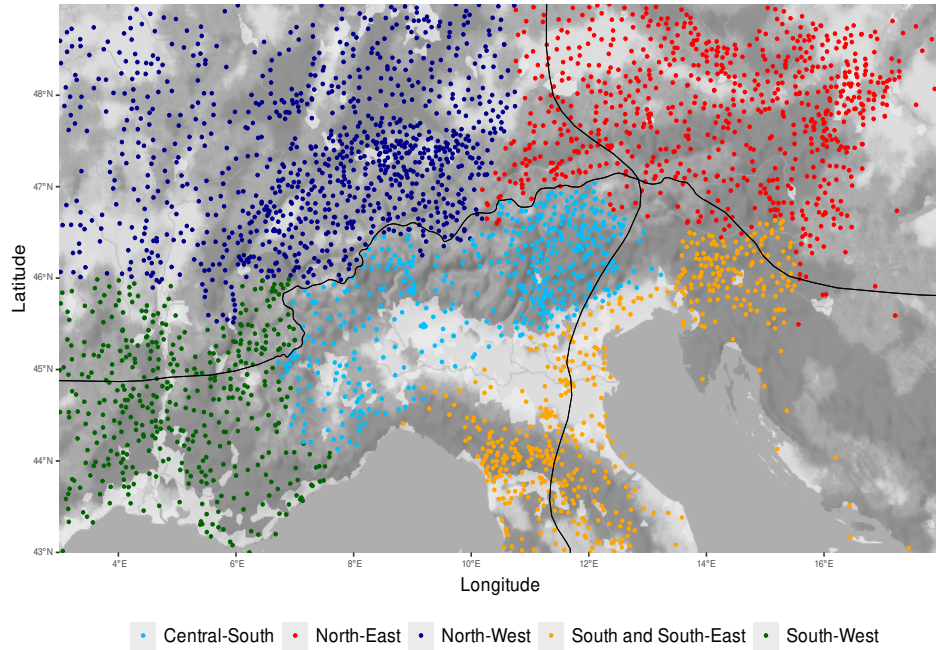


Figure 2 Map of identified common sub-regions (CSRs) after the regionalization procedure. Black lines show HISTALP regions (Auer et al., 2007)

North-West and North-East clusters in Northern Alps include extensive lowlands and the highest mountain peaks. This results in a wide elevation range (65-3571 m a.s.l.), but not adequately covered despite the high station density, being most of them located in 300-800 m band. The Central-South cluster covers the Italian Alps and Prealps as well as the northernmost Po Valley, with an elevation range similar to the Northern Alps. Here, the elevation distribution of stations is more homogeneous, with a 25th-75th percentile range of 200-1400 m. The South-West extends from the coastal areas of southern France to the French Alps, exhibiting a more complex orography given the presence of the sea and an elevation distribution similar to the Central-South (200-1000 m). A similar orography is shown by South&South-East, which covers the southeastern regions, the southern Po Valley, and the Apennines, though here the presence of the sea is more massive and mountains only reach elevations below 3000 m. The elevation gradient is well covered by the stations, with most of them located in

0-600 m band. Comparing the elevation distribution of stations in the EEAR-Clim-30 and EEAR-Clim-60 subsets (fig. S12), despite fewer stations in the latter, the elevation gradient in each cluster is similar, ensuring a well representation of the entire elevation range of each cluster in the subsequent 1961-2020 analyses.

3.2 1961-2020 Climatological Overview

The five CSRs exhibit specific climatic characteristics, as shown by both air temperature and precipitation climatologies over 1961-2020 (fig. 3).

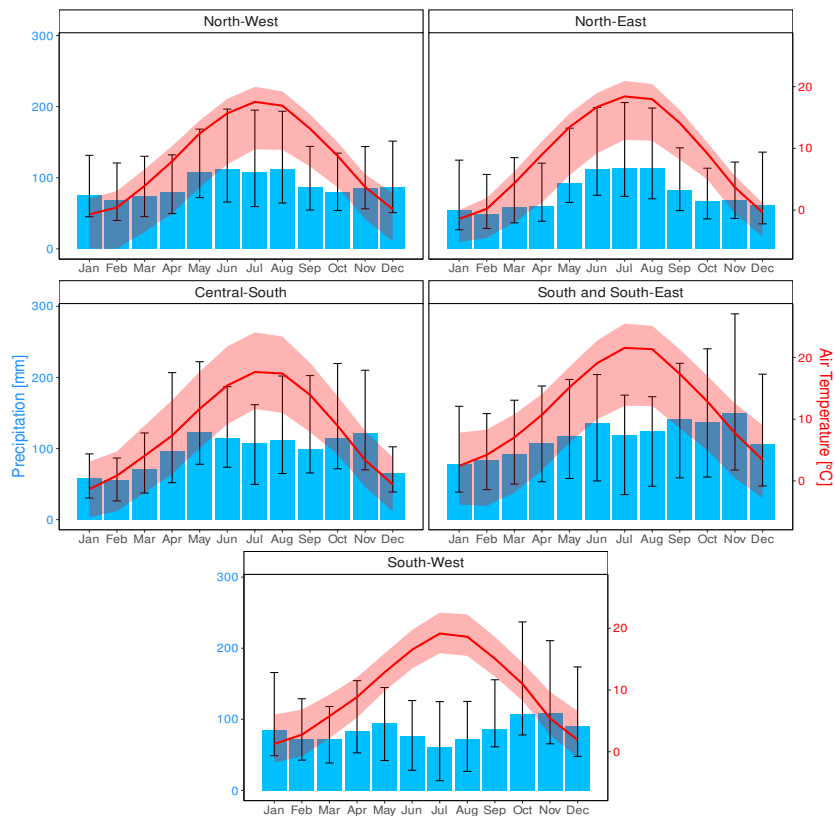


Figure 3 Average annual cycle of air temperature (red line) and precipitation (blue bars) of each CSR based on EEAR-Clim-30 subset over 1991-2020. Red area and error bars show the 5th-95th percentile spread of multi-year average across stations for air temperature and precipitation, respectively.

The South&South-East (S&SE) sub-region shows the highest average temperatures, with a maximum of $+25.5^{\circ}\text{C}$ in summer. In contrast, sub-regions covering northern Alps, including North-West (NW) and North-East (NE), experience colder temperature ranging from -6.3°C in winter to $+20.9^{\circ}\text{C}$ in summer, with widespread winter frosts. Intermediate temperatures were shown in South-West (SW) and Central-South (CS), between -5.9°C and $+24.1^{\circ}\text{C}$, aligning to EEAR average. However, S&SE and CS exhibit the highest variability across stations, mostly during summer, with the widest differences observed from $+12.0^{\circ}\text{C}$ at Krvavec (1610 m a.s.l.) to $+25.5^{\circ}\text{C}$ at Bologna (53 m a.s.l.) in S&SE, and from $+9.3^{\circ}\text{C}$ at Lago Gabiet (2379 m a.s.l.) to $+22.3^{\circ}\text{C}$ at Milan (134 m a.s.l.) in CS.

Precipitation patterns significantly differ across the CSRs. The Northern Alps (NW and NE) experience moderate yet frequent wet conditions, with total precipitation peaking in late spring and summer. In the SW, precipitation exhibits more fluctuations throughout the year, with a distinct summer minimum. The highest monthly precipitation totals were observed during spring and autumn in the CS and S&SE, often exceeding 100 mm with peaks near 300 mm. However, similarly to air temperature, precipitation in CS and S&SE shows the highest variability among stations in such seasons. In S&SE the precipitation totals show the widest differences in autumn, from 290 mm at Bohinjska Bistrica (509 m a.s.l.) to 68 mm at Ferrara (15 m a.s.l.), while in CS similar uncertainties were observed in both spring and autumn, from 72 mm at Diga di Vizzate (1365 m a.s.l.) to 220 mm at Oropa (1186 m a.s.l.).

Large differences among sub-regions also emerge from quantile-quantile analyses, elevation-dependent climatologies and inter-regional correlation coefficients (S13 and S14). A marginal agreement was shown only for the pairs NW-NE and SW-CS, with similar lapse rates and high time correlation coefficients, but exhibiting marked differences in their statistical distributions.

3.3 Observed Changes over 1961-2020

3.3.1 Trends in Mean Values

Seasonal trends over 1961-2020 in each CSR are displayed in fig. 4, with average EEAR rates highlighted. Further information on the magnitude and significance of trends is summarized in tables S2 and S3.

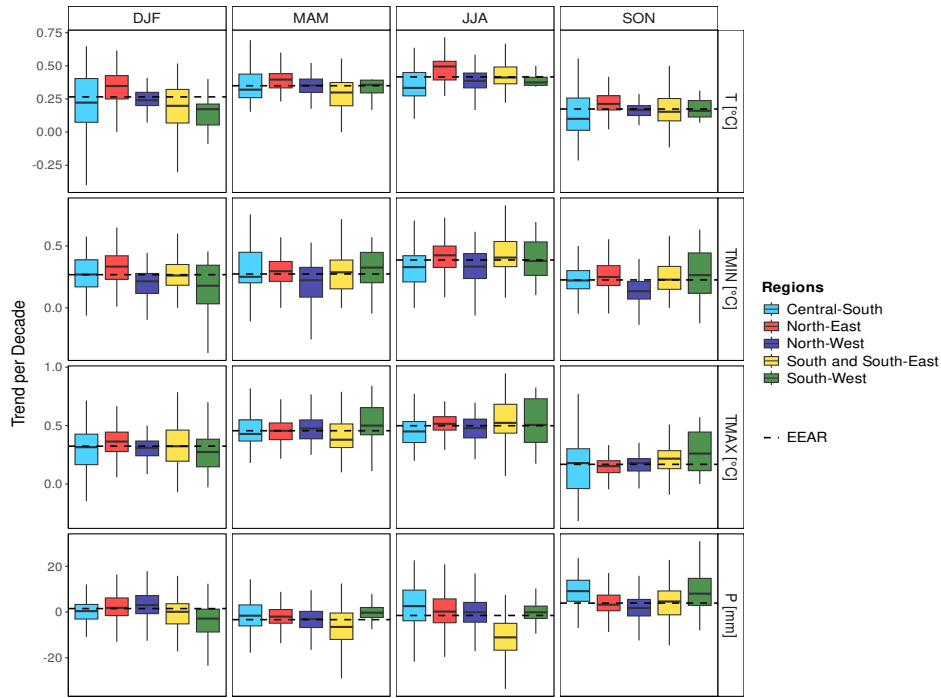


Figure 4 Boxplots showing the 1961-2020 trend distribution among stations for precipitation (P) and minimum (TMIN), mean (T), and maximum (TMAX) temperature in each sub-region. Black dashed horizontal line highlights the EEAR average.

Air temperature trends in all sub-regions (table S2 show a highly significant ($p < 0.01$) warming from 1961 to 2020, stronger between mid-spring (April) and late summer (August). The highest warming rates are found in the North-East, South-West, and S&SE, with overall increases over 1961-2020 from about $+2^{\circ}\text{C}$ for TMIN, to $+2.4^{\circ}\text{C}$ (NE and S&SE) and $+2.8^{\circ}\text{C}$ (SW) for TMAX. The robustness of such warming

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rates is supported by number of stations with statistical significant ($p < 0.05$) trends (S2), 88 – 96% for TMIN and 94 – 100% for TMAX, higher as the magnitude of the trend increases. Trends in Central-South, $+1.6^{\circ}\text{C}$, and North-West, $+1.4^{\circ}\text{C}/+2.3^{\circ}\text{C}$, are close to the EEAR average. Sub-regional trends also show a limited evidence of the faster warming of TMIN compared to TMAX, the so-called asymmetric warming phenomenon (Karl et al., 1993), restricted to September-December in CS and NE. Moreover, a further asymmetry between TMIN and T was observed over SW and S&SE.

However, sub-regional trends exhibit a high inter-station spatial variability, more pronounced in S&SE and SW, across all seasons, CS, mostly in winter and autumn, and NW, in spring and summer but limited to TMIN. A longitudinal dependency is noted in the magnitude of TMIN trends and their distribution over the year. The strongest TMIN rate, $+0.46^{\circ}\text{C}/\text{decade}$, was observed over NE and S&SE, in December for the former and in August for the latter. On the other hand, western sub-regions agree in reporting the greatest TMIN trends in June, with $+0.43^{\circ}\text{C}/\text{decade}$ in SW and $+0.36^{\circ}\text{C}/\text{decade}$ in CS and NW. A latitudinal dependency was observed mostly in terms of the seasonal variability of trends (fig. 4), with a consistent warming across seasons in NW and NE. Instead, southern Alps show more pronounced seasonal distinctions, with smaller warming rates mostly in CS during summer and SW during winter, and more positive in spring and autumn.

Precipitation time series exhibit a large temporal and spatial variability, limiting the statistical significance of trends across most periods and sub-regions, in particular over northern Alps. However, in S&SE annual rainfall trends show the largest decrease, $-16.96 \text{ mm}/\text{decade}$, mostly significant in summer ($-12.39 \text{ mm}/\text{decade}$). Conversely, Central-South shows the largest positive tendency annually with $+15.55 \text{ mm}/\text{decade}$, mostly in JJA and SON.

3.3.2 Trends in Extreme Indices

In addition to the trend analysis of mean climate, trends in extreme climate indices were also calculated (table S1) and reported for each sub-region in fig. 5 and table S4.

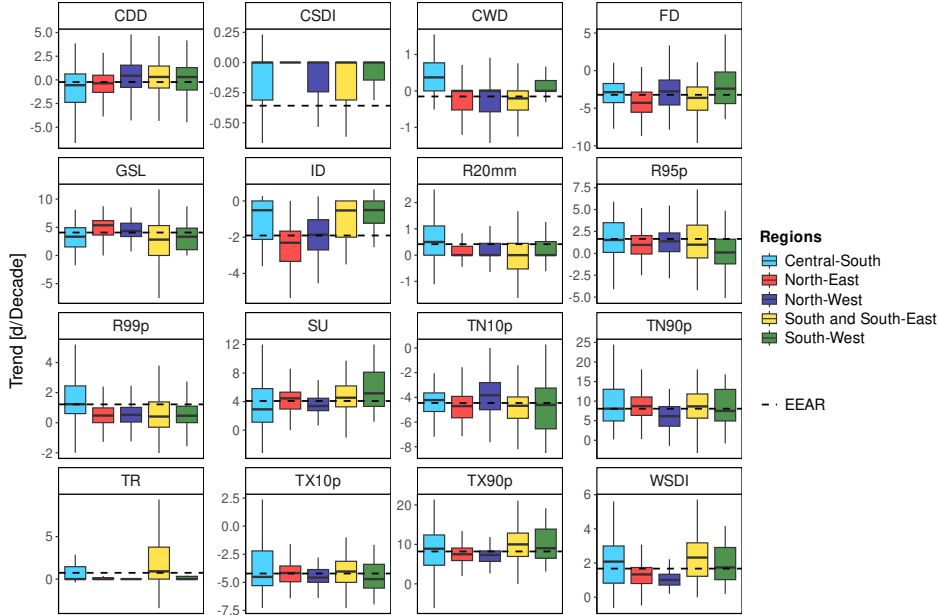


Figure 5 Boxplots showing the trend distribution among stations for the selected extreme indices in each sub-region. Black dashed horizontal line highlights the EEAR average.

Warm days (TX90p) and warm nights (TN90p) increased consistently in southernmost sub-regions, with the highest trends observed in South-West, +10.35 days per decade, and Central-South, +9.29 days per decade (table S1), respectively. The South-West also shows the most pronounced increase in summer days (SU), at a rate of +5.59 days per decade. However, the warming in the EEAR was also shown by the increase in tropical nights (TR), mostly in the S&SE where a trend of +2.18 nights per decade, three times the EEAR average, was observed. Central-South and S&SE also experience more persistent warming conditions compared to other sub-regions, with both showing notable increases in the length of warm spells (WSDI), reaching +2.51 days

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per decade in S&SE, and decreases in cold spells (CSDI), -0.51 days per decade in CS, respectively. Conversely, cooling indices exhibit a more marked reduction in northern Alps compared to the southernmost sub-regions. Frost days (FD) and icing days (ID) show pronounced decreases, primarily in the North-East, of about -3.9 and -2.5 days per decade, respectively. Instead, cold days (TX10p) and cold nights (TN10p) mostly align to the EEAR average, though TN10p shows a slightly reduced decrease in the North-West. The North-South contrast across the Alps was also shown in the growing season length (GSL) index, with a more uniform positive signal shown across the northern Alps, about +4.6 days per decade for both North-West and North-East compared to southernmost sub-regions (+2.59, S&SE, +4.18, SW, days per decade). In all sub-regions, spring and summer are the seasons with stronger rates in temperature extremes (table S5). However, stronger and statistically significant ($p < 0.05$) trends were observed also in winter and autumn for the TX90p index, mostly in South-West, Central-South, and S&SE.

Precipitation extremes (R95p, R99p) show positive and statistically significant ($p < 0.05$) trends in most of the sub-regions, with marked increases of about +2.03 and +2.34 days per decade observed for R95p in the North-East and North-West, respectively. These increases are more pronounced in spring, especially in the North-West where a statistically significant ($p < 0.05$) trend of +1.33 mm/decade was detected (table S5). Notable increasing trends are also shown in the South-West for both R95p and R99p indices, with a statistically significant ($p < 0.05$) rate of 1.11 days per decade detected in autumn. R95p shows marked increases also in southern sub-regions, already affected by drier conditions, such as S&SE (+1.96 days per decade, $p < 0.10$). The sensitivity of S&SE and Central-South, to extreme precipitation events (R95p) is tending to increase without any statistical significance especially during autumn, about +0.79 %days per decade for both sub-regions and winter, respectively +1.15 and +1.51 %days per decade. Central-South also exhibits an increase (+2.99 days per

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decade) in R99p index, signal shared by 40% of the stations with moderate statistical significance ($p < 0.10$), mostly in winter when a rate of $+2.02$ %days per decade was detected (table S5). Precipitation in the Central-South are also becoming more persistent, showing reduced duration of dry spells (CDD) and increased duration of wet spells (CWD), though not statistically significant.

4 Discussion

The combination of the EEAR-Clim dataset and the proposed regionalization provided a refined framework for analyzing climate trends and extremes at a sub-regional scale, and enhance our understanding of local climatic processes, especially in areas with high orographical complexity.

The proposed regionalization shows differences to the HISTALP approach (Auer et al., 2007), the key-reference for Alpine climate studies, in underlying data and methods. The HISTALP regionalization provides a long-term perspective incorporating monthly time series of several climate variables, whereas our CSRs are based on a denser network of daily air temperature and precipitation measurements only covering a 30-year period. Taking these differences into account, a brief comparison between the two regionalizations can be made. The main differences arise in the number and size of CSRs and in the clustering of the southern and western parts of the domain. In our regionalization, the higher spatial coverage of stations of the EEAR-Clim dataset (Bongiovanni et al., 2024a) for the Northern Italy revealed a more marked North-South division across Po Valley compared to HISTALP, with the introduction of a specific sub-region covering the southern Alps. The West-East separation across the Apennines presented in HISTALP, here does not result in distinct clusters, agreeing to regionalizations over Italy (Lanfredi et al., 2020; Di Giuseppe et al., 2013). Possible explanations may be the higher density of stations used here, revealing the Apennines

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separation as a secondary regionalization, and the more recent period considered, suggesting more coherent North-South rather than West-East patterns. Over the Western Alps, the higher amount of available measurements with respect to HISTALP allowed us to better distinguish the South-East of France from the North-West of Italy, consistent with the significant mountain barrier separating these regions. The additional separations identified in the proposed regionalization are further supported by marked differences in climatological distributions among the involved sub-regions (figs. S13 and S14).

In the last six decades air temperature increased in all sub-regions of the EEAR, with higher rates between mid-spring (April) and late summer (August). However, the average increase of about 2°C since the 1960s observed over the EEAR (Bongiovanni et al., 2024c) varies in both timing and magnitude by variable and sub-region, reflecting complex regional differences in the Alpine climate (Fischer and Knutti, 2016; Gulev et al., 2021). In particular, the highest warming rates are found over NE, SW, and S&SE mostly aligning with the scientific literature considering the same region (Auer et al., 2007; Durand et al., 2009; Gobiet et al., 2014; Pepin et al., 2022). Also at sub-regional scale, the asymmetric warming (Karl et al., 1993) between TMIN and TMAX shown a limited evidence, aligning with the EEAR average tendency (Bongiovanni et al., 2024c) and recent findings in global and European databases (Curci et al., 2021).

The high spatial variability observed in air temperature trends at sub-regional scale, mostly in S&SE and SW, could be linked to the influence of the Mediterranean Sea warming, strongest along coastlines, that acting as a thermal engine amplifies warming and variability of trends (Pastor et al., 2018; García-Monteiro et al., 2022). However, other possible mechanisms could play a key role, including i) the changes of snow and ice albedo in high-elevated areas due to reduction of snow covered areas and retreat of Alpine glaciers (Valt and Cianfarra, 2010; Beaumet et al., 2021; Matiu et al., 2021), ii) land-use changes that can alter energy balance, moisture availability and

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local weather patterns (Pijl and Tarolli, 2022), and iii) the aerosol-radiation feedback that can lead to trend variability depending on aerosol concentrations (Carnevale et al., 2015; Diémoz et al., 2019).

Since 1961 the EEAR experienced an overall amplification in extreme temperature conditions. As other recent studies report (Tank and Können, 2003; Auer et al., 2007; Bartolini et al., 2012; Ceppi et al., 2012; Acquafredda et al., 2015; Scorzini et al., 2018; Hock et al., 2019; Nigrelli and Chiarle, 2023), the amplification has been manifested through different mechanisms in southern and northern Alps, as changes in the hot and cold tail of the temperature distribution, respectively. Central-South and S&SE experience more persistent warming conditions compared to the Northern part of the Alps, about 50% higher than EEAR average, suggesting an increased vulnerability to climate change on the southern side of the Alps (Moberg and Jones, 2005; Toreti and Desiato, 2008; Acquafredda et al., 2015; Pepin et al., 2022). This latitudinal contrast across the Alps was also shown in the growing season length (GSL) index, with the stronger positive signal over NW and NE leading to more advanced leaf unfolding and delayed leaf coloring in northern Alps (Gordo and Sanz, 2010; Güsewell et al., 2017; Piao et al., 2019). The observed trends in mean and extreme conditions thus highlights the role of ongoing climate change to amplify the already existing differences in climate between northern and southern Alps, enhancing climatic-environmental changes on the southernmost part of the EEAR.

The seasonal distribution of trends in temperature extremes supports the attribution of most of the recent warming to summer temperatures (Bartolini et al., 2012; Scorzini et al., 2018; Bongiovanni et al., 2024c), though increases in winter temperatures and related extremes are also emerging, mostly over the main Alpine ridge. Stronger and significant increases over SW, CS and S&SE suggest a probable linking to the decrease in snow cover, particularly relevant also at mid and low-elevations, and glacier retreat at higher elevations. Both, further enhanced by shifts in snowfall

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timing, favor the transition from glacial to proglacial environment with consequent changes in ice and snow-albedo feedbacks (Brugnara et al., 2012; Stocker et al., 2013; Matiu et al., 2021; Monteiro and Morin, 2023; Nigrelli and Chiarle, 2023). These mechanisms jointly contribute to an increase of air temperature, with greater changes in daytime temperatures compared to the climatological mean.

The large temporal and spatial variability in precipitation trends observed over the EEAR (Bongiovanni et al., 2024c) and also in the all sub-regions, limit their statistical robustness. The northern Alps are characterized by high uncertainty in mean rates of precipitation, aligning to the findings of Brugnara and Maugeri, 2019, thus failing to show the increasing trend reported by other studies (Brunetti et al., 2009; Monteiro and Morin, 2023). Conversely, the decreasing trend observed in S&SE is more consistent with the scientific literature (de Luis et al., 2012; Gobiet et al., 2014; Kotlarski et al., 2022). The positive tendency in Central-South, above the EEAR average except for winter, is linked to changes in October, when 20-30% of stations record significant increasing rates, and in December, when wetter conditions were observed, also affecting also elevations up to 2000 m a.s.l.

Conversely, trends in precipitation extremes are statistically significant, with more pronounced increases in spring, in agreement to other studies over the region (Ménégoz et al., 2020; Blanchet et al., 2021; Bauer and Scherrer, 2024; Peter et al., 2024). The increase of extreme precipitation in sub-regions affected by drier conditions, such as S&SE and CS, can exacerbate soil dryness post-event, contributing to local flooding and increased runoff (Trenberth, 2011). This raises the risk of landslides and related phenomena, enhancing the vulnerability of the area. The sensitivity of S&SE and Central-South to extreme precipitation events is increased especially during autumn and winter, as also noted by Frei and Schär (2001). Precipitation in the Central-South is also becoming more persistent, though the reduced duration of dry spells (CDD) and the increased duration of wet spells (CWD) are not statistically significant,

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in agreement to previous studies (Brugnara and Maugeri, 2019; Bongiovanni et al., 2024c).

The regionalization proposed here might be expanded to include additional climate variables, made available in a gridded version, for instance using the interpolated version of the EEAR-Clim dataset planned to be released, or be used for sub-regional analyses in climate models studies. For those purposes, we also provide a geospatial vector data format of the EEAR sub-regions boundaries.

5 Conclusions

This study aimed to provide a detailed climate analysis of the Extended European Alpine Region (EEAR) at sub-regional scale during the 1961-2020 period, exploiting an updated regionalization of the European Alps developed herein.

Leveraging the high-density observational dataset EEAR-Clim, the regionalization of air temperature and precipitation shown five distinct climatic sub-regions over the EEAR, namely North-West (NE), South-West (SW), North-East (NE), Central-South (CS) and South&South-East (S&SE). The proposed regionalization revealed a marked separation across the Po Valley introducing a distinct cluster covering the Italian Alps, more sensitive to extreme weather events and elevation-dependent variability (Isotta et al., 2014). In addition it provides a better separation between South-East France and North-West Italy, reflecting differences in local weather, thermal and precipitation patterns (Isotta et al., 2014; Ménégoz et al., 2020).

The average warming of about 2°C observed over the EEAR from 1961 to 2020, already observed in Bongiovanni et al., 2024c exhibits clear spatial patterns, accordingly to Alpine climate features (Fischer and Knutti, 2016; Gulev et al., 2021), and an amplification driven by different mechanisms. The North-East, South-West, and S&SE experienced the most pronounced warming, mostly in spring and summer, with a reduction in cold extremes in NE and an increase of warm extremes in SW, CS

This manuscript is an original research preprint and has not undergone peer review and S&SE. Moreover, more persistent warming patterns were shown in S&SE and CS, that, coupled with increased frequency of heavy rainfall events, heighten the vulnerability of such sub-regions to extreme events. This suggests to carefully monitor these tendencies for the EEAR in the future, also from climate change projections.

This study, complements previous analyses (Bongiovanni et al., 2024c), providing an improved spatial characterization of climate and trends in the EEAR and enhancing our understanding of the underlying phenomena. The findings of this study clearly highlights the importance of a robust regionalization of the EEAR for an accurate detection of local climate and trend patterns, otherwise hidden at larger spatial scale. Thus, the proposed regionalization framework coupled with a robust analysis of climate and trend patterns at a more local scale offer a valuable basis for future research and targeted climate impact assessments and adaptation strategies, informing region-specific policies to mitigate climate risks.

The methodology presented can be readily applied to other regions or time periods and extended to additional essential climate variables. For instance, incorporating such variables into the regionalization framework will help to better understand their influence on local climate patterns and the mechanisms driving the observed trends in the EEAR. A deeper understanding of climate change drivers and dynamics, especially in regions with complex terrain, is crucial for advancing more comprehensive studies and integrating models with high spatially and temporally resolved observational products.

Supplementary information

The online version contains supplementary material available at [link](#).

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Author contributions

The original idea of the work was conceived by Giulio Bongiovanni, Dino Zardi and Bruno Majone with the help of other co-authors. The methodology was elaborated by Giulio Bongiovanni and Michael Matiu with the help of all co-authors. The analysis of results was performed by Giulio Bongiovanni with the help of all co-authors. The first draft of the paper was prepared by Giulio Bongiovanni. All co-authors revised and refined the manuscript.

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Availability of data and materials

The geospatial vector data format (shape file) of the sub-regional borders is available at link <https://github.com/Hoiya1985/EEAR-Clim/>. Source of analyzed data can be found in the methods description (<https://doi.org/10.5281/zenodo.10951609>, Bongiovanni et al., 2024b).

Code availability

All code used in the analysis is available upon request to the corresponding author.

Declarations

Conflict of interest

The contact author has declared that none of the authors has any competing interests.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

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