Climate Services 30 (2023) 100391

Contents lists available at ScienceDirect

Climate Services

journal homepage: www.elsevier.com/locate/cliser

Harmonised procedure to update thermal loads in the Eurocodes. Case study for Italy

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HIGHLIGHTS

- European climatic loads for structural design need to be updated and harmonised.
- European climate datasets (E-OBS, ERA5-Land) can be used to update thermal maps.
- Methods to update thermal loads for design with the Eurocodes are tested for Italy.
- European maps of climatic actions will help setup of national safety requirements.
- Updated climatic actions will speed climate change adaptation of built environment.

ARTICLE INFO

Keywords:
Climate change
Climatic actions
Eurocodes
Reanalysis
Thermal load maps

ABSTRACT

The characteristic values of temperature corresponding to the maximum and minimum shade air temperature with an annual probability of being exceeded 0.02, used in the European construction standard for thermal actions (EN 1991-1-5:2003), are usually assessed at a country level and included in the National Annexes to that Eurocode part.

The paper aims to support national authorities on elaborating maps for thermal actions using publicly available datasets, consistent at a European level, and harmonised modelling approaches. In addition, these datasets are continuously updated, reflecting the current climate and capturing potential global warming variations.

The work investigates how updates in data and modelling could affect the characteristic values currently adopted in the Italian National Annexes to the Eurocodes. The main results show that: (i) the currently adopted number and locations of the weather stations result fairly representative of the patterns detected by exploiting additional datasets; ii) the statistical method plays an essential role in the assessment of characteristic values, i.e., the method adopted in the current Italian standard evaluates more conservative characteristic values of maximum temperature than Gumbel or Generalized Extreme Value distributions, but could err on the unsafe side for minimum ones; (iii) both E-OBS and ERA5-Land datasets represent two optimal products to be used as a common source of temperature values at European scale; (iv) moving towards an updated period for temperature data results on an increase of characteristic values of maximum temperature and limited variations in spatial extent and magnitude of characteristic values of minimum ones.

Practical implications

The study aims at paving a way to updating the climatic loading used in the European countries to design and reconstruct buildings and infrastructures. Such updates are of central importance for adaptation of the built environment to climate change, as they give opportunity to apply the most-up-to-date climatic

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https://doi.org/10.1016/j.cliser.2023.100391
Received 10 August 2022; Received in revised form 11 April 2023; Accepted 3 May 2023
Available online 12 May 2023

information in the structural design and retrofitting. The study makes a bridge between the ad-hoc maps for design to climatic actions (most of them created more than 20 years ago) and the latest available climatic information. It is aimed to explain and separate the differences in the climatic loading resulting from the new way of representation of climatic datasets (e.g. use of gridded data, reanalysis, etc.), from the probabilistic models implemented, and from historical or contemporary changes in the climate. The paper showcases the possible way of updating the Eurocodes maps for thermal design in Italy by using the datasets currently and freely available at a European scale.

The Eurocodes are a set of 10 European technical standards providing common rules for the structural design of buildings, other civil engineering works and construction products. The wide international adoption of the Eurocodes, as well as their extensive harmonisation among the European Committee for Standardization (CEN) Member States, contribute to more uniform safety levels in the built environment and reduce barriers resulting from national practices facilitating the free circulation of construction products and engineering services in the EU and abroad.

The publication of National Standards transposing the Eurocodes to a national level, involves the preparation of the National Annexes containing the Nationally Determined Parameters (NDPs), which are the parameters used for structural design that were left open in the Eurocodes for national choice. Countries implementing the Eurocodes should lay down their NDPs to consider local differences in geographical, geological, and climatic conditions, or in traditional building practices and design procedures.

The EN 1991, or "Eurocode 1: Actions on structures", has three parts dedicated to climatic actions, i.e., snow (EN 1991-1-3: 2003), wind (EN 1991-1-4: 2005E) and thermal actions (EN 1991-1-5: 2003).

The characteristic values are the fundamental representative values of a given climatic action for design calculations. Probabilistic approaches are usually applied to assess characteristic values based on adequate climate data. Their determination is the sole responsibility of the CEN Member States' regulatory authorities, being included in the National Annex to each Eurocodes part, as are other parameters related to safety issues.

Most of the existing European maps for climatic loads were based on observations collected in the last century and disregard the potential effects of climate change. A number of pilot studies on the implication of climate change on the climatic loading for design with the Eurocodes prove an urgent need to update the European climatic load maps currently used for structural design (Athanasopoulou et al., 2020; Croce et al., 2021a,b).

This work addresses the methodology for extracting climatic loading from available datasets for updating current European maps for the thermal design of structures. The goal is supporting national authorities and standardisation bodies in preparing their national maps for design thermal actions based on publicly and freely available datasets, consistent at a European level, and on harmonised modelling approaches.

Moreover, it is proposed to develop readily available tools for post-processing climate data, which apply probabilistic modelling of climatic actions compatible with the requirements of standards for structural design. For example, the most up-to-date climate datasets and harmonised modelling tools of climatic actions for structural design could be offered on authoritative websites, such as those hosted by the Climate Data Store of Copernicus Climate Change Service (CDS, 2022) or the European Climate Data Explorer of the Climate-ADAPT platform (Climate-ADAPT, 2022).

Considering the upcoming second generation of the Eurocodes, the implementation of such proposal represents a timely and unique opportunity to assist national organizations incorporating up-to-date climate data into their standards, capturing recent and future climate trends. Additionally, informed and properly grounded modelling tools will help minimise inconsistencies in climate maps across the country borders, representing further benefits to the national standards of the EU Member States and other countries.

In conclusion, it is crucial to implement such innovative instruments accompanied by educational programmes and user guidance on the usage of climate data and modelling tools with the goal to make the new and existing infrastructures and buildings more resilient to climate change over their entire lifetime.

Data availability

Data will be made available on request.

1. Introduction

The EU is committed to achieve greenhouse gas emissions neutrality by 2050, which requires the engagement of all economic sectors. The construction sector must play its part to deliver climate-neutrality, being a priority under the umbrella of the *European Green Deal* (COM(2019) 640)) and related initiatives, noteworthy: (i) the *New Circular Economy Action Plan* (COM(2020) 98) and the *New Industrial Strategy for Europe* (COM(2020) 102) both focused on the transition of the EU industry to sustainability based on circular economy principles; (ii) the *Renovation Wave for Europe* (COM(2020) 662) aiming to at least double till 2030 the annual energy renovation rates (currently around 1%) in the European building stock by increasing energy efficiency and affordability and reducing emissions of around 35 million buildings; (iii) the *New European Bauhaus* (COM(2021) 573) concerned with sustainable techniques, materials and processes for construction and design, bridging science and technology to art and culture; (iv) the review (COM(2022) 144) of the *Construction Products Regulation* (Regulation (EU) No 305/2011) addressing the challenges of circular economy and digitalization of the building stock; and (v) the proposal for recasting the *energy performance of buildings directive* (COM(2021) 802) to reduce lifecycle carbon emissions in buildings.

Moreover, it is well known that standards are important mechanisms for regulating the construction sector, guiding adaptation measures to the inevitable impacts of climate change (EEA, 2020) and avoiding potential long-term costs. In this context, the *new European Strategy on Adaptation to Climate Change* (COM(2021) 82) stresses the importance of mainstreaming climate change adaptation solutions into standards. It explicitly encourages the Member States to involve their Standardization Organizations in implementing their National Adaptation Strategies to complement the EU-level standardisation work.

Recently, the European Commission recognised the need to leverage the European standardisation system to achieve a climate-neutral, resilient and circular economy and presented a *new Standardization Strategy* (COM(2022) 31) aiming to enable EU standards to take the lead on a global scale and promote a greener, more resilient and Digital Single Market.

Nonetheless, the EU had already created a broad legislative and regulatory framework for the construction sector, encompassing the European Standards (EN) for structural design. They are the Eurocodes, a set of 10 European standards, EN 1990 to EN 1999, comprising 59 parts providing common rules for the design of buildings and other civil engineering works and construction products (European Commission, 2022).

The Eurocodes comprehensively cover the basis of structural design, actions on structures, the design of the principal construction materials such as concrete, steel, composite steel–concrete, timber, masonry and aluminium, together with the geotechnical, seismic and fire design.

Three parts of "Eurocode 1: Actions on structures" (EN 1991) are dedicated to climatic actions, i.e. snow (EN 1991-1-3: 2003), wind (EN 1991-1-4: 2005) and thermal actions (EN 1991-1-5: 2003). EN 1990

'Basis of structural design' (EN 1990:2002) gives the provisions for evaluating the design effects of actions combining climatic actions with other actions, namely permanent, accidental and other variable actions. The design effects of actions are compared with the structural resistance evaluated according to the rules provided in the so-called material Eurocodes (EN 1992 to EN 1996 and EN 1999) and the geotechnical and earthquake resistance Eurocodes (EN 1997 and EN 1998) (Formichi, 2016). Fig. 1 shows the interrelation between the EN Eurocodes at a glance.

The principal representative value of a given climatic action for design calculations is its characteristic value, which is usually assessed by probabilistic approaches based on appropriate climatic data. The characteristic values of climatic actions are left open in the Eurocodes for national choice, and their determination is the sole responsibility of CEN Member States' regulatory authorities, being included in the National Annex to each Eurocode part, similarly to other parameters related to safety issues.

Alterations in weather patterns due to climate change may impact the characteristic values of climatic actions. They should be carefully considered in the design of new structures and infrastructures as well as in assessing the reliability of existing ones. Indeed, one of the main concepts of the Eurocodes is the *design working life*, which is defined as "the assumed period for which the structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary" (EN 1990, section 1.5.2.8, EN 1990:2002). The indicative design working life of buildings and other common structures is 50 years (EN 1990, Table 2.1 section 2.3(1), EN 1990:2002), so buildings constructed in 2022 shall withstand climatic actions, such as snow, wind, and thermal actions, and extreme events expected to occur in the period 2022–2072. In contrast, bridges and monumental buildings, which have an indicative design working life of 100 years, should withstand climatic actions at least till 2122. In short, both new and existing infrastructures and buildings should be made resilient to climate change throughout their service life, even more, when the actual service life of most structures is longer than their design life (Croce et al., 2018).

According to the Commission Recommendation 2003/887/EC (European Commission, 2003) on the implementation and use of the Eurocodes, the latest developments in science and technology should be integrated into the Eurocodes. In this context, in 2012, the European Commission issued to CEN the Mandate M/515 (2012) for a detailed work programme to amend the existing Eurocodes and extend their scope leading to a second generation of the Eurocodes. The Mandate includes standardisation works relevant to climatic actions and climate change. The second generation of the Eurocodes, being prepared by the CEN/Technical Committee (TC) 250 "Structural Eurocodes" (CEN/TC250), is expected to be published by 2026.

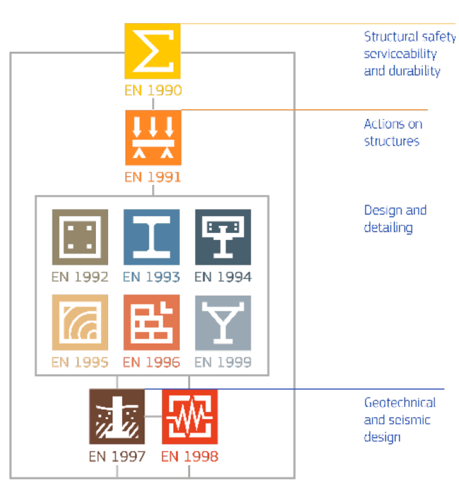

Fig. 1. Eurocodes at a glance; interrelations between the European standards for structural design.

In addition, in 2014, the European Commission issued the Mandate M/526 (2014) aiming to build and maintain a more climate-resilient infrastructure in three priority sectors: transport infrastructure, energy infrastructure, and buildings/construction (about aspects not covered by the Eurocodes) and accelerate the standardisation of adaptation solutions.

More recently, a study commissioned by the European Commission will produce by the end of 2022 an "EU–wide technical guidance on adapting buildings to climate change", providing relevant practical advice to different actors in the construction sector on the climatic resilience of buildings (Ramboll, 2022).

On the other hand, the works of the Joint Research Centre scientific network on implications of the climate change to structural design provide important synergies with the activities of Mandates M/515 (2012) and M/526 (2014), intending to respond to the challenge of making standards for buildings and construction more resilient to climate change. The network identified the urgent need to update European maps of climatic loads currently used for the structural design of civil engineering works. Specifically, the network and the JRC recognised the necessity of harmonising climatic maps across countries borders and of using new available data to capture recent trends in the climate and future variations of climatic actions (Croce at al., 2018, Sousa et al., 2019). In fact, with a few exceptions, current European maps for climatic loads were based on observations collected in the last century and neglect the potential effects of climate change (Athanasopoulou et al, 2020).

Several recent works suggest approaches to update the characteristic values of the main climatic actions included in the Eurocodes. For snow loading, Croce et al. (2018) present a procedure to derive snow load on the ground by exploiting daily temperatures and precipitation provided by the gridded observational dataset E–OBS (Haylock et al., 2008; Cornes et al., 2018) for recent decades (1951–2010) and climate projections included in the EURO-CORDEX initiative (Jacob et al., 2014) for future decades. Croce et al. (2021a) again exploit climate projections in EURO-CORDEX to derive the characteristic values of past ground snow load in Europe from 1950 to 2100, under several concentration scenarios of climate-altering gases. The approach was validated using relevant observations for Germany and Switzerland test cases. Croce et al. (2019) suggest and validate a general methodology to evaluate the influence of climate change on climatic loadings by using observations in Germany and Italy; they assess the effect of climate change on the long–term–time-dependent structural reliability and highlight the need for adaptation measures to maintain the required target reliability of the structure during its lifetime. Athanasopoulou et al. (2020) adopt Italy as a test case for approaches aimed at evaluating future variations in characteristic values of temperature by exploiting the ensemble mean value from EURO-CORDEX projections. Finally, Croce et al. (2021b) investigate the suitability of available gridded datasets of observations (E-OBS) and regional reanalysis (Uncertainties in Ensembles of Regional Re-Analyses, UERRA) to retrieve the current trends of climatic actions in Europe; the adoption of such pan–European datasets facilitates cross border harmonisation of climatic maps in European, and minimise inconsistencies in climate maps across countries borderlines that currently exist in the National Annexes of EN 1991 parts (Sousa et al., 2019).

The current work addresses the need to update the current European maps for the thermal design of structures, considering the following main issues: (i) the role of density and distribution of observations, (ii) the adopted statistical method (from normal distribution to extreme value analysis, e.g. Gumbel and GEV), (iii) the choice of the temperature dataset (including pan-European gridded observations, e.g. E-OBS, and reanalyses, e.g. ERA5-Land) and (iv) the use of more recent data. The aim is to provide support to national authorities and standardisation bodies on elaborating maps for thermal actions based on publicly available datasets, consistent at a European level, and on harmonised modelling approaches.

These issues are tackled by performing an investigation using Italy as a test case focused on the characteristic values of thermal actions, defined in EN–1991–1–5:2003 as the maximum and minimum shade air temperature with an annual probability of being exceeded of 0.02. The investigation framework could, in any case, be tested and extended to other countries and types of climatic actions.

The paper is structured as follows. Firstly, it introduces the approach currently used for Italy to retrieve isotherms of national minimum and maximum shade air temperatures (§2.1), the statistical approaches commonly adopted to retrieve characteristic values at the European scale (§2.2), and the temperature datasets available at National and European scale adopted in this work (§2.3). Then, the paper outlines and presents the effects of a step-by-step investigation carried out by modifying the density and distribution of observations (§3.1), statistical approach (§3.2), temperature dataset (§3.3), time span (§3.4) and the potential impact of the combined variations (§3.5). Finally, it discusses the main findings and draws conclusions (§4).

2. Data and methods

2.1. Isotherms of national minimum and maximum shade air temperatures for Italy

In line with clause 4.1.2(7)P Note 2 of chapter 4 of EN 1990:2002, "the characteristic value of climatic actions is based upon the probability of 0.02 of its time-varying part being exceeded for a reference period of one year. This is equivalent to a mean return period of 50 years for the time-varying part. The characteristic values of minimum ($T_{min50ys}$) and maximum temperatures ($T_{max50ys}$) for Italy follow the investigation carried out by Froli et al. (1994). The authors exploited a pool of observations over 1951–1990, including about 370 meteorological stations for which only mean and standard deviation of daily maximum and minimum temperature are available. Such constraint drives the selection of the statistical approach. They assume that daily maximum and minimum temperatures can be treated as random variables following a Normal distribution. Then, linear relationships between the characteristic values retrieved at each site and the related altitude (z) are retrieved over climatically homogeneous areas (from now on, also referred to as "Zone", see Fig. 2).

Fig. 2. Homogeneous climatic regions for the current Italian thermal map (Froli et al., 1994).

2.2. Statistical methods for extreme value analysis: GEV and Gumbel

As discussed above, the characteristic values of maximum and minimum temperatures over Italy adopt a statistical approach (based on the Normal distribution) associated with the availability of a limited number of statistical measures (mean and standard deviations values) for the pool of exploited weather stations. On the other side, for other European countries, the availability of data series of maximum and minimum yearly values enables the adoption of more reliable and widely adopted statistical approaches based on Extreme Value Theory (EVT), representing a rigorous and authoritative framework for the analysis of climate extremes and their level for a given return period.

In more detail, in EVT, the Extremal Types Theorem (Coles, 2001) ensures the convergence of the distribution to one of three possible distributions, namely Gumbel, Fréchet and Weibull distributions or extreme value type I, II and III distributions, respectively.

Even though very different, the three distributions can be combined within the family of continuous probability distributions known as Generalized Extreme Value (GEV), in which cumulative distribution function (CDF) for a random variable × has the form:

$$F(x) = \exp\left\{ -[1+\xi(x-\mu/\sigma)]^{-\frac{1}{\xi}} \right\} \quad (1)$$

with μ, σ, and ξ representing location, scale, and shape parameters, respectively.

The families defined by $\xi = 0$, ξ greater than 0,and $\xi < 0$ correspond respectively to the Gumbel (type I), Fréchet (type 2) and Weibull (type III) classes of extreme value distributions. The CDF of the Gumbel family is formulated as follows:

$$F(x) = \exp\{ -\exp[-(x-\mu/\sigma)] \} \quad (2)$$

where μ, the location parameter, specifies the centre of the distribution and σ permits identifying the size of deviations around μ.

The block maxima approach is pursued to model extremes of a series of independent observations. The observation period is divided into non-overlapping periods of equal size, in this case, a block period of one year. The new data series is restricted to the maximum observation in each block, i.e., the annual maxima. According to this approach, annual maxima are used to estimate model parameters. They are then adopted to derive the extreme quantiles x_p of the annual maximum distribution (i.e., $p = 0.02$ corresponds to a return period of 50 years as prescribed for climatic actions in EN 1990:2002). It is worth pointing out that the block maxima approach requires the use of a series of maxima; therefore, if for $T_{max50ys}$ the extracted maxima series respect precisely this requirement, for $T_{min50ys}$ it is necessary to change the sign of the values in the sample before estimating the distribution parameters.

2.3. Datasets for recent climate over Italy: Observations and reanalysis

In-situ weather station measurements with dense networks over long time spans are the optimal support to assess the current evolution of thermal actions. However, they are seldom available for long periods and often feature a scarce (spatial and temporal) homogeneity and density of observation points. A potential alternative solution is gridded observational datasets. These products have been significantly improved in recent years on European and national scales. They outline different temporal (e.g., from hourly to daily) and spatial (e.g., from ≃ 1 km to ≃

10–20 km) resolutions, covering different time spans. Their reliability is strictly related to the density of station networks they derive. A further resource is represented by climate reanalysis, providing a complete and consistent picture of past weather by adopting a numerical weather prediction model to assimilate historical observations provided by diverse but unevenly distributed sources (e.g., satellite data, in situ observations) across the domain of interest. In this work, the selected datasets are:

- **SCIA-ISPRA** (Desiato et al., 2011): a dataset of precipitation and temperature observations resulting from the systematisation of different national and regional monitoring synoptic, hydrographic and agro-meteorological networks over Italy. They were included in the dataset after applying rigorous data quality control procedures and the reconstruction of partial series from different sources. Over the years, the density of the number of stations has increased almost twofold from the first 40 years (1951–1990) to the most recent ones (1981–2020), if only stations with at least 20 years for each time span of measurements are considered.
- **E-OBS** (Cornes et al., 2018; Haylock et al., 2008): a European daily gridded observational dataset at a horizontal resolution of 0.1° (≃11 km). It includes data for precipitation, temperature, relative humidity, sea level pressure, and surface shortwave downwelling radiation over 1950–2021. E-OBS relies on the blended time series collected from the station network of the European Climate Assessment & Dataset (ECA&D) project. All station data are sourced directly from the European National Meteorological and Hydrological Services or other data holding institutes. Local point observations are turned into gridded information according to a two-stage process to derive the daily field and assess the uncertainty in such estimates.
- **ERA5-Land** (Muñoz-Sabater et al., 2021): an hourly land-only ERA5-driven reanalysis, giving a consistent view of the land variables evolution from 1950 onwards at an enhanced horizontal resolution (∼9 km) compared to ERA5 (≃ 31 km), the new generation of global reanalysis recognised as the most plausible description for the current climate (Hersbach et al., 2020). ERA5–Land has been produced by replaying the land component of the ERA5 climate reanalysis. To control the simulated land fields, it assumes as atmospheric forcing a set of ERA5 atmospheric variables (e.g., air temperature, air humidity, and pressure), properly corrected through a lapse rate factor to account for the altitude difference between the grid of the forcing and the higher resolution grid of ERA5-Land. For this reason, while observations are not directly used in producing ERA5-Land, they have an indirect influence through the atmospheric forcing used to run the simulation.

3. Results

3.1. Density and distribution of observation points

The procedure described in Froli et al. (1994) is replicated using the observational dataset SCIA–ISPRA over the reference period 1951–1990. Considering local observations, SCIA-ISPRA represents the most similar dataset to the one adopted to derive the climatic Zones in the current Italian National Annex to EN 1991-1-5:2003, sharing several local stations adopted by Froli et al. (1994). In particular, from this dataset, 631 stations with at least 15 values of mean yearly T_{max} and T_{min} have been considered, deriving for each station the mean and the relative standard deviation over the reference period.

The altitude (z) of the single stations is not included as metadata in SCIA- ISPRA, and it has been taken from EUDEM (EEA, 2021), the digital surface model of the European Environment Agency (EEA) at 25 m resolution, available on the Copernicus Land Monitoring Service.

After computing the characteristic values for each site (see section 2.1), the samples of pairs $T_{max50ys}$/$T_{min50ys}$ - altitude are aggregated on the same climatic Zones for temperature identified in the National Annexes (see Fig. 2) and interpolated using a linear regression function. Fig. 3 compares the curves given by Froli et al. (1994) for the four homogeneous climate regions to those obtained using the same methodology applied to SCIA–ISPRA observations.

In general, limited variations are recognisable between the two curves regardless of the Zone and if minimum or maximum temperature is considered. At sea level (i.e., z = 0 m), $T_{max50ys}$ values are essentially coincident (≈ 42 °C) for all Zones, while for $T_{min50ys}$ they vary according to the Zone being approximately −15 °C in Zone I, −8 °C in Zones II and III, and −2 °C in Zone IV. Furthermore, the original curves have a more pronounced slope for z-$T_{max50ys}$ in Zone I than in Zones II and IV, being practically zero in Zone III, while for z-$T_{min50ys}$ the maximum and minimum slopes concern Zone IV and Zone I, respectively. The reconstructed curves almost coincide with the original ones for $T_{min50ys}$, with slight differences only in Zone III and Zone IV. The same is retrieved for $T_{max50ys}$ in Zone I and Zone IV. At the same time, there is a pronounced divergence in the other Zones, where the lapse rate becomes higher in the case of the reconstructed curves, returning a higher reduction of the characteristic values as the altitude increases.

3.2. The statistical approach

This section is aimed at comparing the characteristic values as returned by three different approaches: i) the Normal distribution adopted by Froli et al. (1994) and included in the Italian National Annex; ii) the Gumbel distribution and iii) the more general GEV. The former only requires mean and standard deviation values for each station, whereas the latter two approaches require the yearly maximum/minimum values of temperatures over the investigated time span. The values retrieved over 1951–1990 from the SCIA-ISPRA dataset are used as a common benchmark.

Fig. 4 compares the characteristic values Tmax50ys (Fig. 4a) and Tmin50ys (Fig. 4b) over Italy carried out using the aforementioned statistical methods (i.e. Normal, Gumbel and GEV) in terms of the box-whisker plot.

For $T_{max50ys}$, the adoption of the Normal probability distribution function returns a mean value of 41.3 °C with an interquartile range (IQR) of 4.7 °C, while for Gumbel and GEV, it reduces by 1.9 °C (IQR = 5.0 °C) and 3.6 °C (IQR = 4.5 °C), respectively. Concerning $T_{min50ys}$, according to the Normal distribution, a mean value of −11.5 °C (IQR = 7.3 °C) is estimated, but, in this case, the Gumbel has a more marked decrease (2.5 °C) than the GEV (1.2 °C). At the same time, both approaches show more significant variability (IQR ≈ 9.5 °C) than the Gaussian.

The results are spatially mapped in Fig. 5; specifically, the Figure shows the spatial distribution of $T_{max50ys}$ and $T_{min50ys}$ obtained by Normal distribution over 1951–1990 (Fig. 5a and Fig. 5d, respectively), while the variations emerged by adopting Gumbel and GEV concerning this statistical approach are mapped in Fig. 5b and Fig. 5c for $T_{max50ys}$ and Fig. 5e and Fig. 5f for $T_{min50ys}$.

Regarding $T_{max50ys}$, the Normal distribution (Fig. 5a) provides characteristic values varying in-between 32 °C and 48 °C (5th-95th percentiles of distribution). In particular, Zone I has an average value of 38.8 °C with a standard deviation of ± 5.7 °C with higher values in the Po Valley, decreasing in the Alpine region. The average values increase in Zone II, Zone III, and Zone IV (40.9 °C, 42.1 °C, and 41.8 °C, respectively) with standard deviations of 1.5 °C, 1.7 °C, and 0.6 °C. Fig. 5b shows a colder behaviour in the northern areas (especially in Zone I) by replacing the Normal with the Gumbel statistical function. Such a tendency attenuates from the north to the south of Italy with a warmer behaviour in Zone IV. On the other hand, moving to GEV (Fig. 5c), a general reduction in $T_{max50ys}$ is estimated over the Italian peninsula except for part of the south of Italy, mainly in Zone IV.

Regarding $T_{min50ys}$, the Normal distribution (Fig. 5d) provides characteristic values varying in-between −20 °C and −2°C (5th-95th

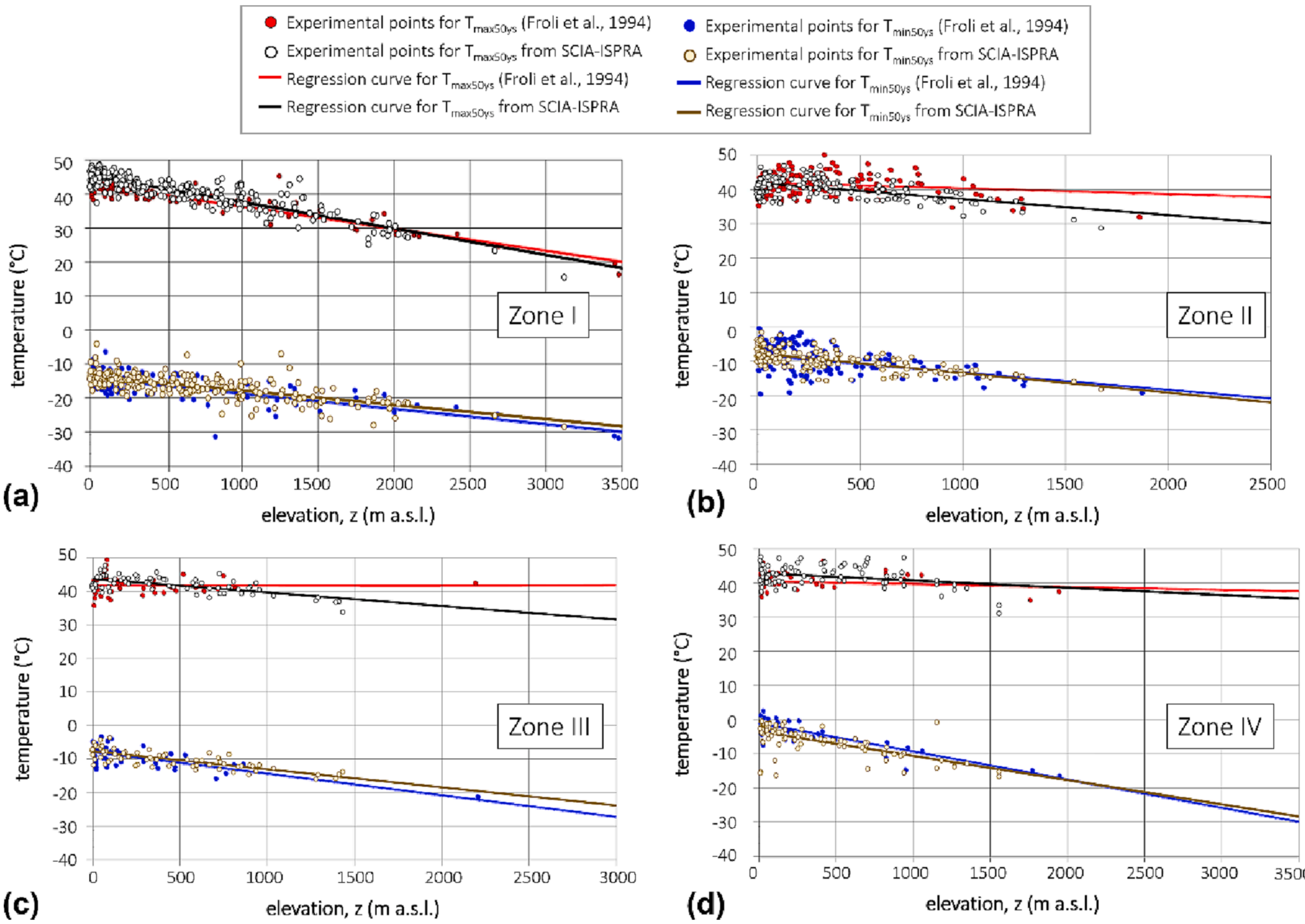

Fig. 3. Comparison of characteristic values and curves of temperature ($T_{max50ys}$ and $T_{min50ys}$) against altitude provided by Froli et al. (1994) and carried out using SCIA-ISPRA observations and Normal distribution for different homogeneous climatic Zones in Italy; m a. s. l. stands for meter above sea level.

percentiles of distribution). Zone I returns an average value of −16.9 °C with a standard deviation of ± 3.4 °C. Of course, the minimum values are retrievable in the Alpine region. For the other Zones, the average values significantly increase, with values similar between Zone II and Zone III (~-9.7 °C) and even higher in Zone IV (~-6.2 °C). Standard deviations for these cases are in the same range as Zone I. From Normal to Gumbel function, Fig. 5e highlights a general reduction of $T_{min50ys}$ sharpened along the west coast and the Alpine region.

In contrast to $T_{max50ys}$, the GEV (Fig. 5f) returns a spatial distribution much closer to the Normal than to the Gumbel (Fig. 5e). Generally, the differences between GEV and the reference are negligible in several areas. There is still a tendency for reductions on the west coast, but less marked. In addition, slight warming is noticed for zone IV, especially in coastal areas.

3.3. *Temperature dataset*

To investigate the significance of the temperature dataset selected to retrieve isotherms of national minimum and maximum shade air temperatures, two datasets covering the entire Europe are selected: E-OBS and ERA5-Land. Of course, such a selection primarily aims to investigate the potential impact of exploiting pan-European datasets (and then pursuing the harmonisation target) instead of the national assessments.

These requirements are currently fulfilled by gridded datasets of observations or by reanalyses (§2.3). In Europe, the reference gridded datasets that could be used are E-OBS as observations and ERA5-Land as atmospheric reanalysis. To this end, the maximum and minimum temperature values provided by the stations included in the SCIA-ISPRA dataset have been compared over 1951–1990 with those returned by E-OBS and ERA5-Land. Over Italy, for each station, the nearest representative grid point has been obtained from both grids, and simple statistics have been calculated, i.e. the mean of the annual maxima and the mean for the maximum temperature, and the mean of the annual minima and the mean for the minimum temperature. The data thus processed are shown in Fig. 6 as box whisker plots.

The comparison shows that E-OBS can better reproduce the local observations provided by SCIA-ISPRA for both maximum and minimum temperature. Specifically, concerning the mean of the annual maxima of T_{max} (Fig. 6a), SCIA-ISPRA returns an average value of 33.4 °C, which is reduced to 31.9 °C for E-OBS and 30.5 °C for ERA5-Land. In terms of median value, the differences between SCIA-ISPRA and E-OBS are further reduced. Regarding spatial variability, a higher variability returned by both the gridded datasets (IQR for E-OBS = 4.7 °C; IQR for ERA5-Land = 5.7 °C) compared to the observations (IQR = 3.9 °C) can be retrieved. Similar patterns emerge by averaging the T_{max} over 1951–1990 (Fig. 6b), keeping the same rank of the different information that sees E-OBS more in line with SCIA-ISPRA than ERA5-Land.

In terms of annual T_{min} minima (Fig. 6c), the ability of E-OBS to replace SCIA-ISPRA compared to ERA5-Land is even more evident. Specifically, E-OBS returns an average value (-7.8 °C with IQR = 4.1 °C) similar to SCIA-ISPRA (-6.7 °C with IQR = 4.6 °C) and definitely different from ERA5-Land (-9.7 °C, with IQR = 4.6 °C). Finally, the average T_{min} (Fig. 6d) shows similar behaviour to that returned for the mean of the annual minima temperatures: also such case, however, E-OBS experiences a lower spatial variation compared to SCIA-ISPRA. The maps in Fig. 7 report the differences between gridded datasets and the reference SCIA-ISPRA. In this regard, not clear geographical patterns are retrievable. In general terms, both gridded datasets return lower

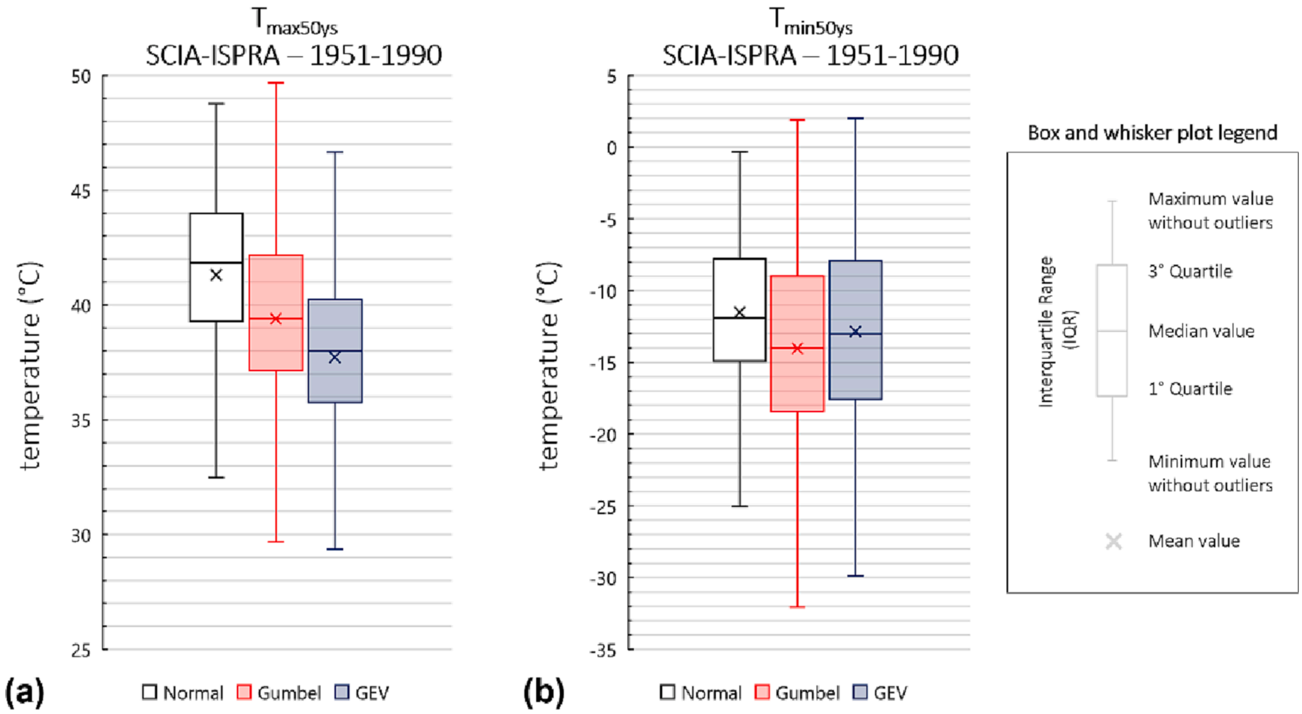

Fig. 4. Box-whisker plots of $T_{max50ys}$ (a) and $T_{min50ys}$ (b) carried out using Normal, Gumbel and GEV as statistical methods on temperature data provided by SCIA-ISPRA over 1951–1990. Maximum (Minimum) values without outliers correspond to the minimum (maximum) between the highest (lowest) sample value and 3rd (1st) quartile + (-) 1.5 times the interquartile range.

(colder) values for T_{max}, especially in the Alpine area. At the same time, for T_{min}, E-OBS and ERA5–Land usually assess higher values along the coasts and Sardinia island and lower in the internal areas.

Several reasons can be assumed contributing to the displayed results. First, E-OBS is a daily gridded land-only observational dataset; then, it is built exploiting a significant part of observations also included in the reference SCIA-ISPRA dataset. In this regard, its performances are strictly related to the density of stations available in the investigated area. In general terms, it means that, in areas not properly covered by observations or where available observations are not exploited for E-OBS, the biases could be significant. On such areas, the adoption of physically based approaches as atmospheric reanalysis could be crucial. On the other side, ERA5-Land has only a nominal resolution of about 9 km for atmospheric variables, but the relative fields are obtained by means of statistical-physical downscaling approaches from ERA5 (horizontal resolution of about 32 km over Italy); for example, for air temperature, simple lapse rate relationships are implemented to downscale the variables.

3.4. The time span

The section investigates the effects of updating the reference period from 1951 to 1990 to 1981–2020. To this aim, E-OBS is assumed as the source of climatic information while GEV as the statistical approach. The goal is to make such results readily suitable for harmonisation at the European scale.

Firstly, Fig. 8 shows the spatial distribution of $T_{max50ys}$ (Fig. 8a) and $T_{min50ys}$ (Fig. 8b) over 1951–1990, obtained by deriving the GEV parameters for each grid point in relation to the series of annual temperature maxima (minima) provided by E-OBS. The great advantage, in this case, is that the dataset does not present missing data and covers the whole of Italy (3316 grid points) homogeneously, thus making it possible to move away from the concept of homogeneous climatic areas and linear relationships between characteristic values and altitude.

The data shown in Fig. 8 have been summarised in terms of box-whisker plots in Fig. 9 and compared with those obtained considering three additional periods (i.e. 1961–2000, 1971–2010, and 1981–2020), derived as a 10-year forward shift from 1951 to 2020.

Over the period from 1951 to 1990, the spatial mean of $T_{max50ys}$ (Fig. 9a) and $T_{min50ys}$ (Fig. 9b) returns values of 35.7 °C and −12.6 °C, respectively. Of course, from the spatial point of view, the characteristic values decrease with altitude (see Fig. 7). The spatial variability is generally more significant for $T_{min50ys}$ than for $T_{max50ys}$. For such analysis, we exploit the full E-OBS dataset over Italy and not a limited number of stations as carried out in previous elaborations.

Moving forward the 40-year reference period, an expected increase in temperature (both maximum and minimum) can be noted. Very different causes can potentially induce such variations: variations in temperature patterns induced by climate change, variations in land use (for example, entailing Urban Heat Islands phenomena in urban settlements, Oke et al., 2017; Reder et al., 2018). Nevertheless, the number of observation points feeding the gridded datasets E-OBS has substantially increased over the years, improving the evaluations. Anyway, the resulting increase is, on average, more marked for $T_{max50ys}$ (Fig. 9a) with a variation of 0.3 °C over 1961–2000, 1.1 °C over 1971–2010, up to 1.5 °C over 1981–2020, compared to the reference period 1951–1990. As for $T_{min50ys}$ (Fig. 9b), the increase reduces to values of 0.1 °C, 0.6 °C, and 0.8 °C for the analysed three periods with respect to the reference one. While a reduction in the spatial variability of the characteristic values can be observed for $T_{max50ys}$ from 1951 to 1990 to 1981–2020, the same does not appear for $T_{min50ys}$, for which the spatial variability seems to be slightly affected. In particular, for $T_{max50ys}$, this reduction in spatial variability occurs due to an increase in the lower whisker boundary of the plot that corresponds to the smallest data value increasing from 27 °C to 32 °C, which translates into a more marked increase in characteristic temperature values, especially in areas at higher altitude.

Furthermore, Kolmogorov-Smirnov K-S (Kolmogorov, 1933; Smirnov, 1939) and Mann-Kendall M−K (Mann, 1945; Kendall, 1975) tests are exploited to retrieve the areas where the variations can be

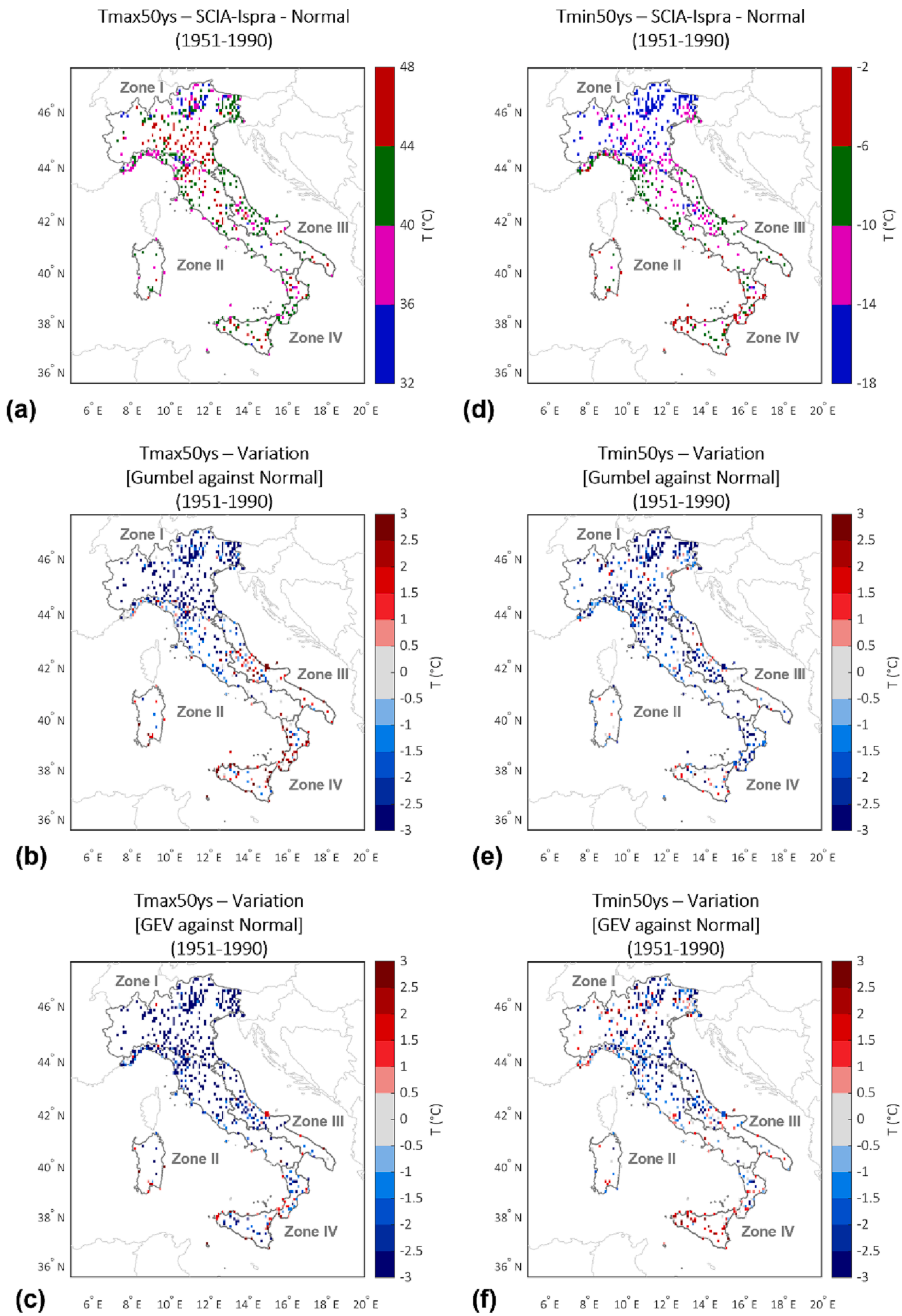

Fig. 5. Maps of $T_{max50ys}$ (a) and $T_{min50ys}$ (d) carried out using Normal as the statistical method on temperature data provided by SCIA-ISPRA over 1951–1990. For the same data and period, variations of Normal against Gumbel (b - for $T_{max50ys}$; e - for $T_{min50ys}$) and GEV (c - for $T_{max50ys}$; f - for $T_{min50ys}$).

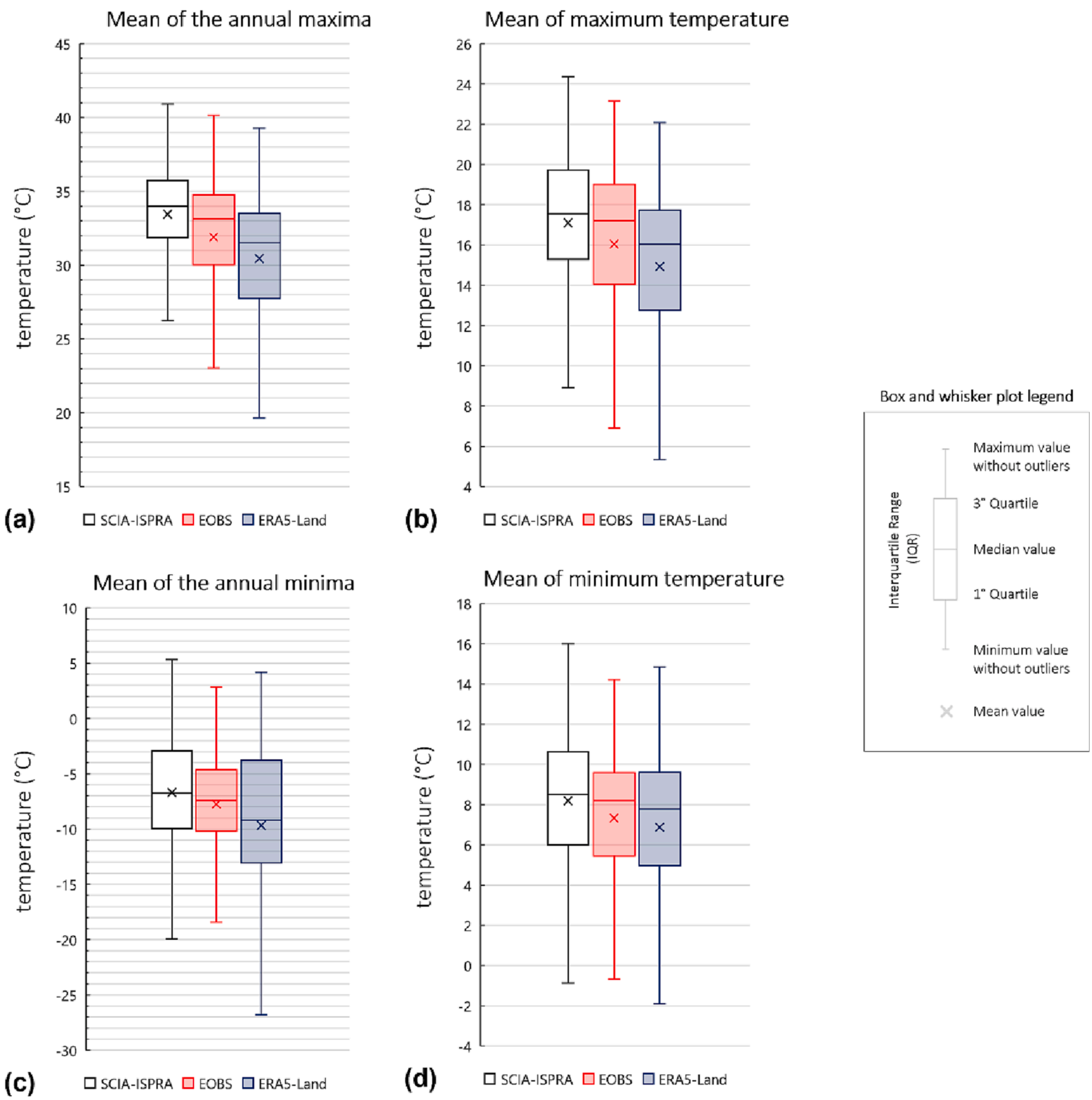

Fig. 6. Box-whisker plots of mean annual maximum T_{max} (a), mean T_{max} (b), mean annual minimum T_{min} (c), and mean T_{min} (d) provided by SCIA-ISPRA, E-OBS (nearest points against SCIA-ISPRA), and ERA5-Land (nearest points against SCIA-ISPRA) over 1951–1990.

recognised as statistically significant (with a significance level < 0.05). The null hypothesis are: for (K-S) the characteristic temperature values for the periods 1991–2020 and 1951–1980 are drawn from the same distribution; for (M−K) there is no monotonic increase in the series of the characteristic values of temperature from 1951 to 2020. The results of this statistical analysis are shown in Fig. 9 for both $T_{max50ys}$ and $T_{min50ys}$. The results are shown in Fig. 10a for $T_{max50ys}$ and Fig. 10b for $T_{min50ys}$. As for the M−K test, it has been applied to the whole pool of annual temperature maxima (minima) over the period 1951–2020. The results are shown in Fig. 10c and Fig. 10d for $T_{max50ys}$ and $T_{min50ys}$, respectively.

There is significant evidence to reject the null hypotheses in both statistical tests over most of the Italian territory with regard to $T_{max50ys}$ (Fig. 10a and Fig. 10c). In particular, such behaviour is strongly marked in the north and centre of Italy, while in the South, and especially on the islands, the variations and increasing trends of $T_{max50ys}$ (shown in Fig. 8) are not statistically significant. For $T_{min50ys}$ (Fig. 10b and Fig. 10d), the areas characterised by statistically significant values are smaller (in a particular way for the K-S test). They are located in Po River Valley, sub-Alpine chains and central Italy. Again, on the islands, no clear patterns are recognisable.

Fig. 11 maps the magnitude of the variation (1981–2020 against 1951–1990) of the characteristic values of the maximum and minimum shade air temperature for the grid points at which the K-S test was statistically significant over the climatic Zones for temperature in Italy (Froli et al., 1994).

Concerning $T_{max50ys}$ (Fig. 11a), the main changes are estimated in Zone I and Zone III, with values that, on average, increase by 2 °C (standard deviation = 1.0 °C) and 2.5 °C (standard deviation = 1.3 °C) respectively, and in some cases even exceed 5 °C. However, 92% of the

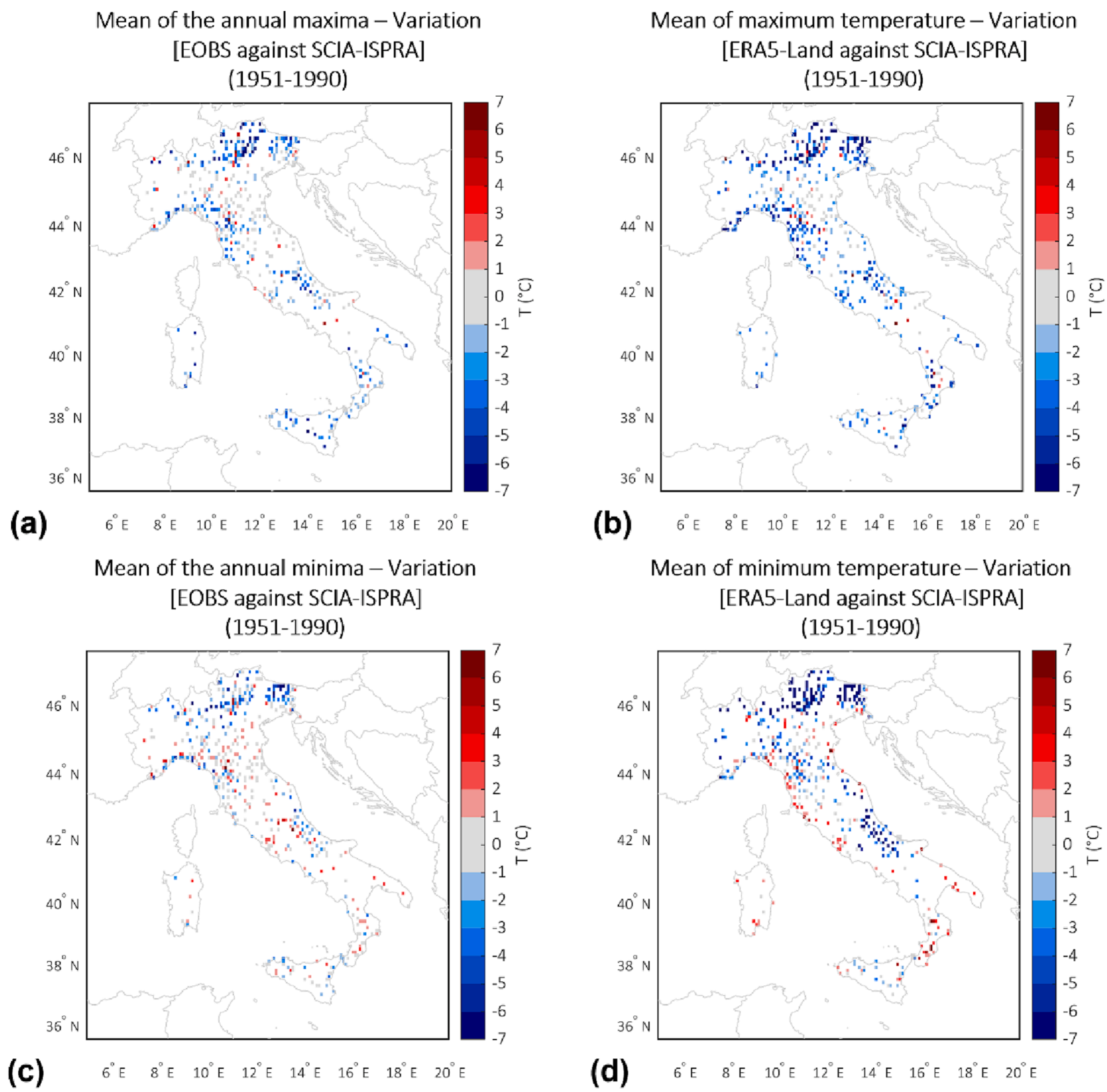

Fig. 7. Spatial variation of mean annual maximum T_{max} (a, b) and mean annual minimum T_{min} (c, d) for E-OBS against SCIA-ISPRA (a, c) and ERA5-Land against SCIA-ISPRA (b, d) over 1951–1990.

points in Zone I show statistically significant differences, while Zone III has only 58% of the points with statistically significant differences. In the other Zones, changes in $T_{max50ys}$ are more reduced in both extent and magnitude. In Zone II, half of the points show statistically significant differences with a mean variation of 1.3 °C (standard deviation = 1.0 °C); in contrast, Zone IV has only 29% of the grid points that have statistically significant differences with a mean variation of 0.8 °C (standard deviation = 0.8 °C).

The changes are more limited both in extension (<50% of the grid points) and magnitude when investigating $T_{min50ys}$ (Fig. 11b). Compared to $T_{max50ys}$, Zone IV exhibits the highest percentage of grid points showing statistically significant differences (44%) with a mean value of 1.1 °C (standard deviation = 1.0 °C). The largest change is estimated in Zone III (mean value = 1.9 °C; standard deviation = 0.7 °C), albeit over a reduced percentage of grid points (27%). Zone I shows similar behaviour to Zone IV, with a higher standard deviation (1.5 °C); finally, in Zone II, 37% of the grid points display statistically significant differences with a limited variation (0.6 °C with standard deviation = 1.0 °C).

3.5. *The potential impact of the different variations*

An exemplification of the overall impact of the different contributions (probability distribution, temperature datasets, and time span) is reported in Fig. 12 for the four climate homogeneous Zones. The graphs illustrate the reference curves for maximum and minimum temperature and the potential update due to the three improvements, then using GEV forced by E-OBS temperature values over the most recent 40 years (1981–2020). For comparison, the graphs show the temperature curves computed by updating the dataset (E-OBS) and the probability distribution approach (GEV) but maintaining the reference time span (1951–1990). Concerning the characteristic values of maximum temperature, the overall impact of the updates entails that the revised curves are below the standard ones for all the four Zones. Then, the expected warming and increase in maximum temperatures are compensated by the variations due to the dataset and probability distribution approach. For Zone I, the three lines are pretty parallel. At the same time, for the other zones, a better characterisation of the areas in terms of observation points, mountain regions included, permits a better representation of the reduction in temperature induced by an increase in altitude (lapse rate).

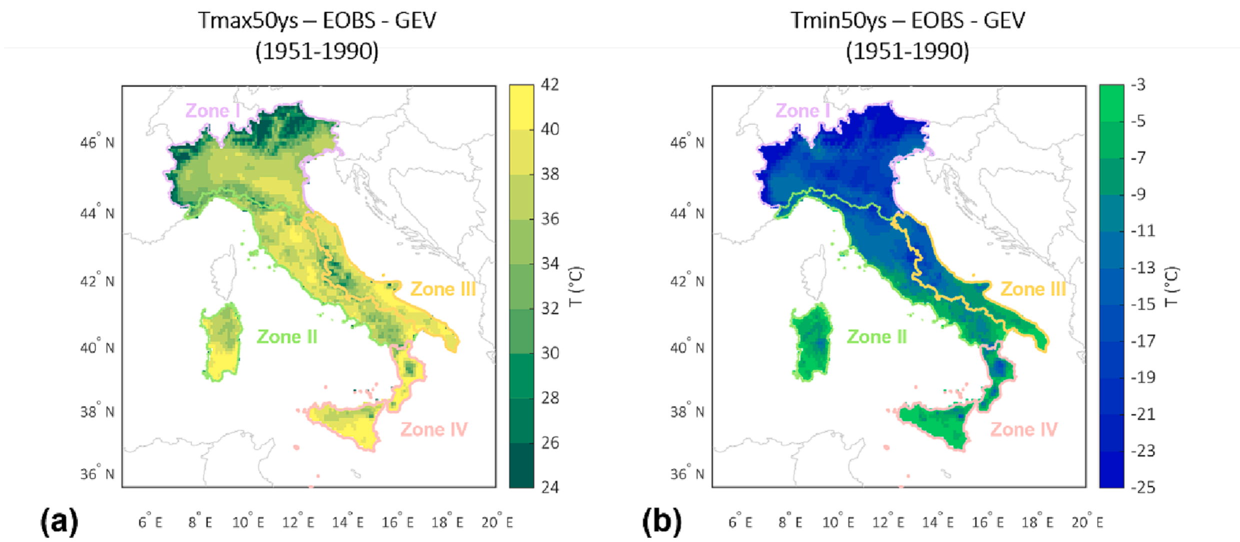

Fig. 8. Spatial distribution of $T_{max50ys}$ (a) and $T_{min50ys}$ (b) obtained using GEV as the statistical method on temperature data provided by E-OBS over 1951–1990.

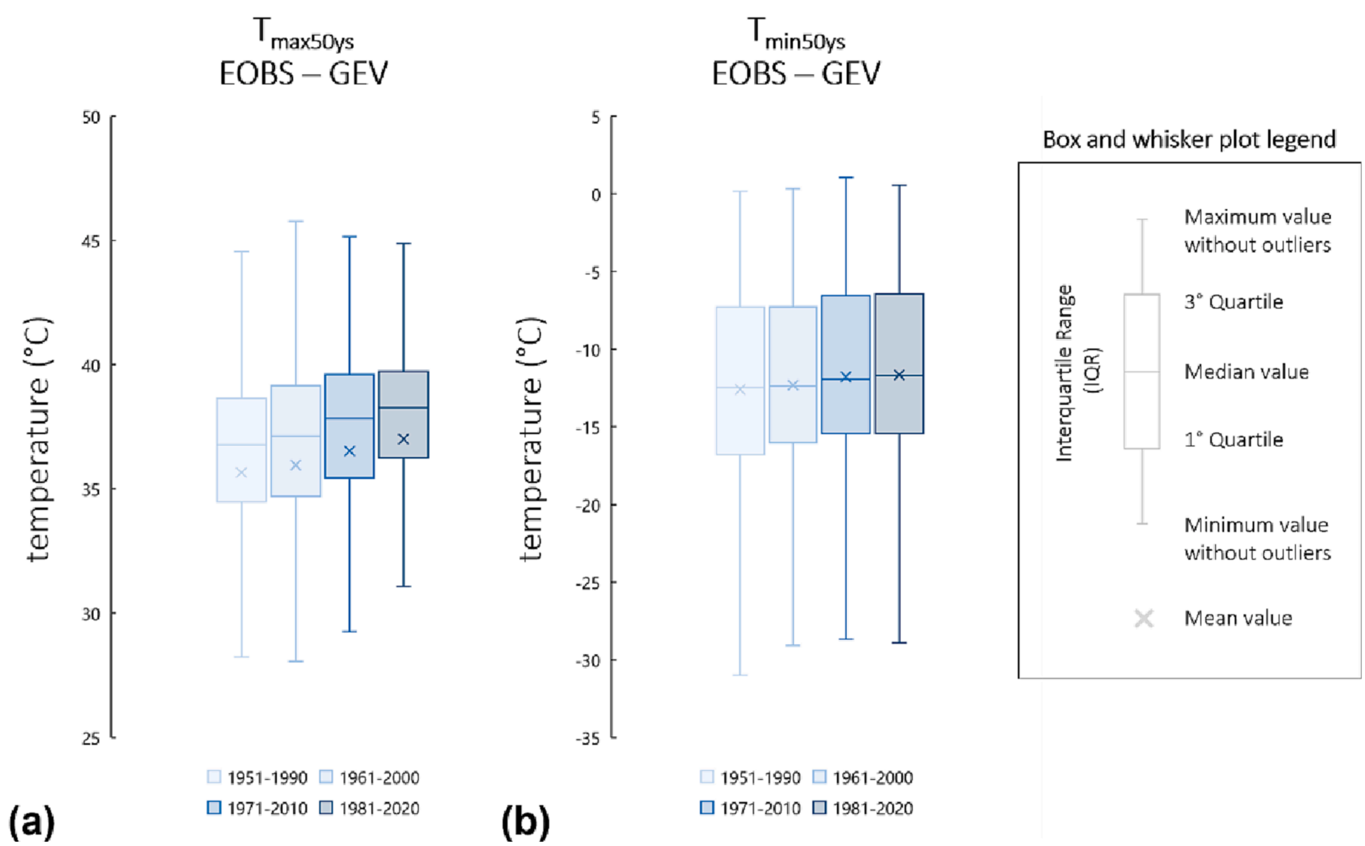

Fig. 9. Box-whisker plots for Tmax50ys (a) and Tmin50ys (b) obtained considering three additional periods (i.e. 1961–2000, 1971–2010, and 1981–2020), derived as a 10-year forward shift from 1951 to 2020. Temperature data are provided by E-OBS, and GEV is adopted as the statistical method.

Also, for low altitude regions, the differences are limited. For what concern the characteristic values of minimum temperatures, the differences are minimal, and they do not have the same trend: for Zone I, the reference values slightly exceed the new curves. In contrast, the opposite is observed for Zone III and IV. Clearer insights about the significance of the different assumptions require careful testing and validation in other European Countries.

4. Discussion and conclusions

Under the assumption of stationary climate, it is assumed that the longer the time span used to fit the distribution, the more robust the assessment. Such an assumption is no longer valid in a climate change perspective where long periods may be characterised internally by statistically significant trends. Old data could not be adequate to describe current or near-future conditions.

In this context, the present work analysed (i) the potential impact of

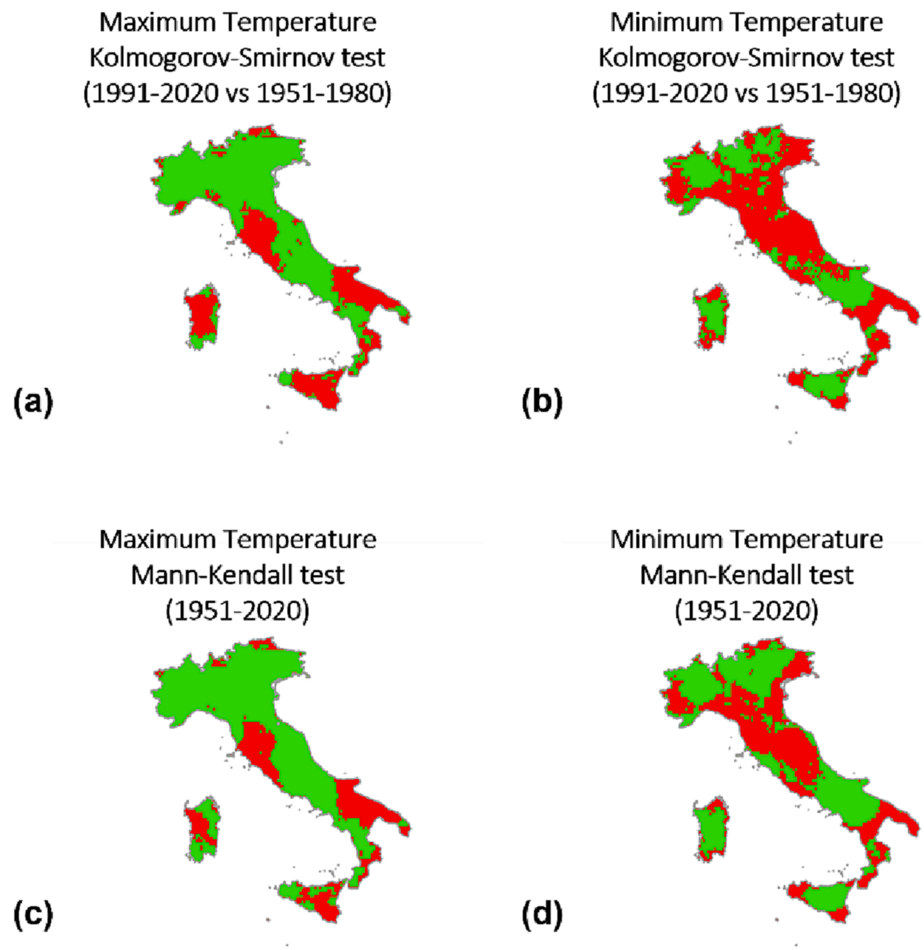

Fig. 10. Two sample Kolmogorov Smirnov test comparing 1951–1980 against 1991–2010 for $T_{max50ys}$ (a) and $T_{min50ys}$ (b), and Mann–Kendall test over the 1951–2020 period for $T_{max50ys}$ (c) and $T_{min50ys}$ (d). The characteristic values are derived using GEV as a statistical method and E-OBS as a temperature dataset. The null hypothesis was rejected in green areas, while the statistical test failed to reject it in red areas.

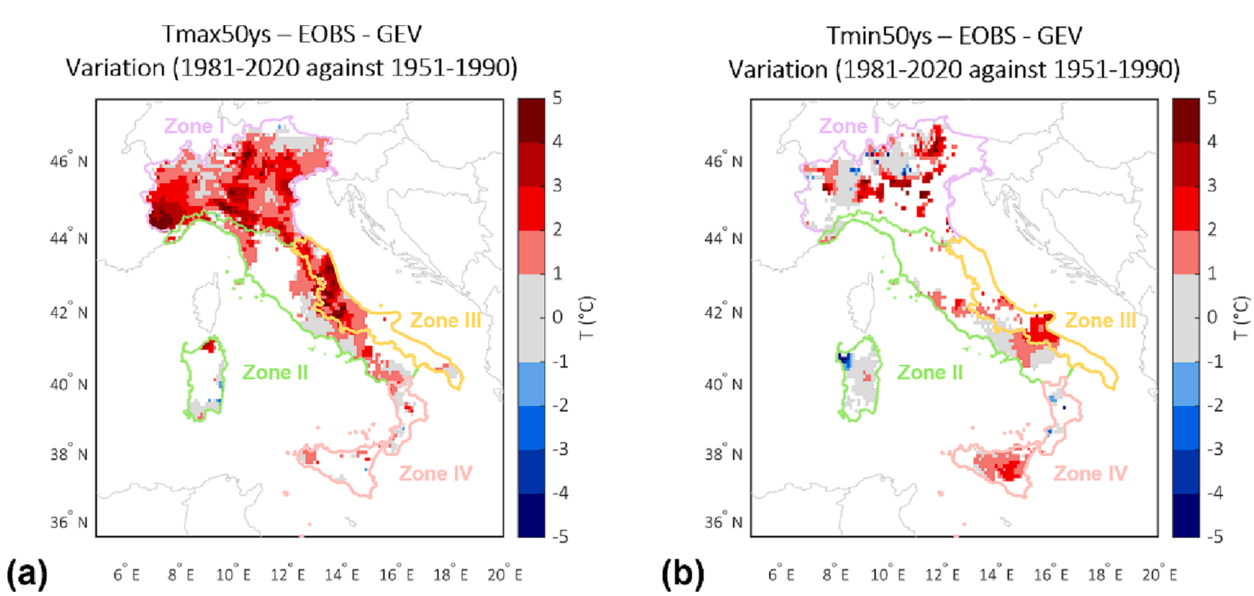

Fig. 11. Map of the variation of Tmax50ys (a) and Tmin50ys (b) comparing the 1981–2020 period against 1951–1990. Data are obtained using GEV as a statistical method and E-OBS as a temperature dataset. Plots show the variations for the grid points where the K-S test rejected the null hypothesis (Fig. 9a for $T_{max50ys}$ and Fig. 9b for $T_{min50ys}$).

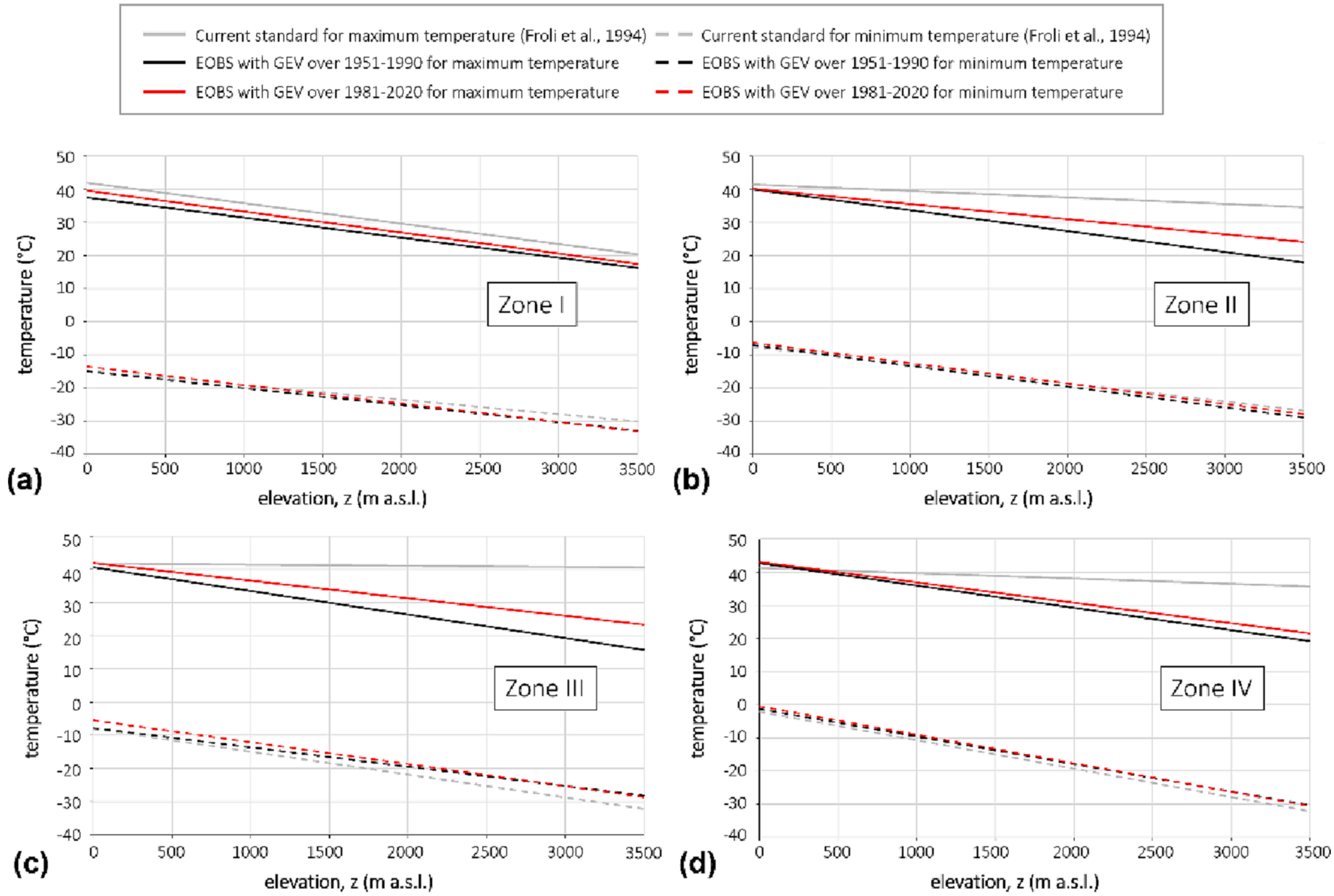

Fig. 12. Comparison of characteristic values of temperature against elevation above sea level provided by Froli et al. (1994) [grey] and carried out by using temperature values provided by E-OBS over 1951–1990 [black] and 1981–2020 [red] using the GEV approach.

climate change (and or concurrent local causes), (ii) the choice of temperature datasets available at the pan-European scale and (iii) the probabilistic models on the characteristic values of temperature for thermal actions in standards for structural design.

To address these issues, an investigation has been performed, using Italy as a test case. The main findings of this investigation are summarised below:

- enlarging the number of observation points (compared to those used originally in Froli et al., 1994) over 1951–1990 does not substantially impact the assessment;
- the statistical approach plays an important role. At present, on a European level, Gumbel is the most frequently used approach to determine characteristic design values; nevertheless, GEV has a higher degree of freedom in the number of parameters to be calibrated, making it more versatile. Both approaches can entail an average reduction in the Italian characteristic values of maximum and minimum temperatures in terms of impacts. In this way, the current standard could be more conservative for the maximum temperatures, but it could err on the unsafe side for the minimum one;
- for what concerns the selection of the temperature dataset, E-OBS could return values closer to those estimated by using observation point stations. The good performances of E-OBS are also reported by Croce et al. (2019). An analogous discourse should be reiterated in other countries to designate E-OBS as the uniform dataset for harmonising standards. This further investigation should also take into account the density of local stations from which E-OBS is generated;
- in terms of time span, the comparison between the assessments carried out on the most recent 30 years 1991–2020 and the less recent period 1951–1980 (about coincident with those used in the Italian national standard) stress substantial variations for maximum temperatures and more limited in spatial extension and magnitude for minimum temperatures. It entails that the current values could be conservative for minimum temperatures but not for maximum temperatures.
- The superimposition of the different contributions result in limited variations compared to the current national standard; they are more significant for maximum temperatures where the altitude plays a key role in the different assessments. Nonetheless, a precise evaluation of the magnitude associated with such variations may be useful support for standard writers and decision-makers.
- Finally, the analysis clearly shows how datasets currently and freely available at a European scale can support the works of national standardisation bodies on preparing the National Annexes to the Eurocodes. The development of readily available tools for post-processing data and statistical modelling of characteristic values could assist national organizations in leaping from static to continuously updated data for climatic actions. In this regard, the datasets with the calculated climatic loading could be made available in the form of georeferenced data and tools exploitable, and included, for example, on authoritative websites as those hosted by the Climate Data Store of Copernicus Climate Change Service (CDS, 2022) or the European Climate Data Explorer of the Climate-ADAPT platform (Climate-ADAPT, 2022). This proposal would simplify and speed up the retrieval of reliable and continuously updated characteristic values for climatic actions used in the design of structures.

Considering the upcoming second generation of the Eurocodes, the implementation of such proposal would represent a timely and unique opportunity to assist national organizations incorporating up–to–date climate data into their standards, capturing recent and future climate trends. Additionally, informed and properly grounded modelling tools will help minimise inconsistencies in climate maps across the country borders, representing further benefits to the national standards of the EU Member States and other countries.

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

Data will be made available on request.

Acknowledgements

ERA5-Land data have been generated using Copernicus Climate Change Service Information and downloaded from the C3S CDS (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab = overview).

The authors are grateful to Sistema nazionale per l'elaborazione e diffusione di dati climatici SCIA (http://www.scia.isprambiente.it/wwwrootscia/Home_new.html). Finally, we acknowledge the E-OBS dataset from the EU-FP6 project UERRA (http://www.uerra.eu) and the data providers in the ECA&D project (https://www.ecad.eu)

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