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Original
Mapping winter climate zoning variations in Europe under climate change scenarios / Chiesa, G., Jahanirahaei, A.. - In: JOURNAL OF PHYSICS. CONFERENCE SERIES. - ISSN 1742-6588. - ELETTRONICO. - 3140:2(2025). [10.1088/1742-6596/3140/2/022018]

Publisher:
IOP publishing

Published
DOI:10.1088/1742-6596/3140/2/022018

Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

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To cite this article: G Chiesa and A JahaniRahaei 2025 *J. Phys.: Conf. Ser.* **3140** 022018

Mapping winter climate zoning variations in Europe under climate change scenarios

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Abstract. The attribution of a specific climate zone to a Municipality or a Local Administrative Unit (LAU) level in the European Member States is fundamental to support the definition of EPBD correlated decisions, e.g. activation periods of heating systems or minimal U-values. Climate change also impacts this specific attribute, requiring progressively upgrading this indicator. The paper computes local climate zones, adopting the Italian regulation approach, based on daily heating degree days with a base temperature set to 20°C. Zoning is applied to the whole European territory with a detail of about 10km, i.e. 0.1° in both latitude and longitude. This high precision allows to understand climate change variations better. The calculation is supported by integrating, inside our new dynamic simulation platform PREDYCE, this Key Performance Indicator (KPI) and by computing it via our server facility. Different climate databases are managed: ERA5-land re-analysis (1950–2023) database and four EUROCORDEX couples of global-regional climate models (historical 1970–2005, and future projections 2010–2100). A series of maps showing the progressive variations of the local climate zone, from A (less than 600 HDD) to F (more than 3000 HDD), is produced. The study shows substantial variations in climate zoning, with a growing progressive impact from Southern European regions to Northern European ones. Outcomes suggest the need to align EPBD-correlated regulations with constantly upgraded climate databases.

1. Introduction

The attribution of climate heating (and cooling) zones to geographic regions and specific municipalities is a fundamental process for defining energy-related regulations in the European Union. These climate zones influence critical decisions related to building standards, such as the activation period for heating systems and the minimum U-value levels for retrofitting or new construction projects [1]. As the European Union continues its efforts to improve energy efficiency and reduce carbon emissions, the role of accurate climate zone classification becomes even more crucial. This classification directly correlates with heating needs and, by extension, the energy demand of buildings. Furthermore, it serves as a key parameter for energy performance regulations under the Energy Performance of Buildings Directive (EPBD), guiding policies on building construction, retrofitting, and overall energy consumption [2,3]. However, climate zones are not static; they evolve over time due to the impact of climate change. Shifts in temperature and seasonal weather patterns necessitate continuous updates to climate zone classifications in order to reflect the changing realities of heating and cooling demands across Europe. This ongoing adjustment is a complex and resource-intensive process, requiring comprehensive data collection, analysis, and revisions to national regulations that rarely arrive in reality, basing Energy Performance Certifications (EPC) and requirements on not-upgraded climate data, supporting regulations that do not include climate resilience aspects, looking at future trends. A study in Spain [4] has applied a national zoning scheme to future climates but remains limited to municipal-level analyses based on a network of morphed weather stations; in contrast, our work employs four different climate models over the entire European territory. By extending beyond a single country and a few stations to continent-wide, multi-model projections, our approach demonstrates the feasibility and necessity of high-resolution, pan-European climate zoning.

The aim of this paper is to address the need for an updated and high-resolution climate zoning system, which can be applied across the entire European territory. By leveraging data from climate re-analysis databases, such as ERA5-land [5], and projections from the EUROCORDEX initiative [6], we present a refined methodology for calculating local climate zones. The research integrates these refined climate zones into the newly developed dynamic simulation platform, PREDYCE (Python Real-time Energy DYnamics and Climate Evaluation) [7]. The paper will explore the impact of climate change on local climate zones from southern to northern Europe. Ultimately, this study highlights the importance of aligning national regulations with updated, high-resolution climate zone data to ensure that building standards remain adaptive to climate change. By doing so, we can better align heating and cooling requirements with the broader goal of achieving zero-energy buildings across Europe.

1.1. Background
The attribution of climate zones plays a crucial role in shaping energy performance regulations for buildings, particularly within the context of the EPBD in Europe. These climate zones are essential for determining the required heating (and cooling) energy needs for buildings, which are directly tied to the design of energy efficiency measures. In this section, we review existing literature related to the role of climate zones in building energy regulations, the effects of climate change on these zones, and the methodologies used to calculate and update climate zones across Europe. While the Spanish case study [4] offers valuable insights, its municipal focus and limited meteorological inputs highlight the need for a broader, more detailed European assessment.

1.1.1. Climate Zones and EPBD Regulations. Climate zones are typically defined based on a variety of climate parameters, including temperature, humidity, and heating degree days (HDD), which are critical indicators for understanding a region’s energy needs for heating [8]. The EPBD, which aims to reduce energy consumption and improve the overall energy performance of buildings across the European Union, uses in their Member State (MS) applications climate zonings to set guidelines for energy-efficient building practices. The classification of these zones, therefore, influences key regulatory measures, such as the period of activation for heating systems and the definition of minimum U-values for insulation [9].

1.1.2. Impact of Climate Change on Heating and Cooling Needs. Climate change has introduced significant variations in regional temperature and weather patterns, altering the heating and cooling requirements for buildings. Numerous studies have highlighted the growing uncertainty regarding climate predictions, particularly in the context of future building energy demands [10,11]. Global warming is expected to reduce heating needs in some northern European regions while increasing cooling demands in southern areas [12]. This change in climate dynamics necessitates the continuous updating of climate zone classifications to reflect both historical data and future projections of temperature shifts. The adoption of updated climate data is particularly important in Europe, where regions are already experiencing notable variations in temperature and precipitation patterns due to climate change [13].

1.1.3. Climate Models: EURO-CORDEX and ERA5-Land. Accurate climate zoning relies on robust climate data derived from advanced climate models and reanalysis datasets. Among the most widely used sources in Europe are EURO-CORDEX (Coordinated Regional Climate Downscaling Experiment – European Domain) and ERA5-Land, both providing high-resolution climate information essential for assessing long-term climatic trends. EURO-CORDEX offers detailed regional climate projections based on the downscaling of Global Climate Models (GCMs), allowing for finer spatial resolution and more accurate representations of local climate variability. It includes historical simulations and future projections under different greenhouse gas concentration pathways, making it a critical resource for studying the potential impacts of climate change. ERA5-Land, produced by the Copernicus Climate Change Service (C3S), is a global reanalysis dataset providing consistent, high-resolution climate data from 1950 onwards. It integrates observational data with model outputs to reconstruct past weather conditions, offering a reliable baseline for historical climate assessment. Both datasets are instrumental in this study, enabling a comprehensive evaluation of HDD and the evolution of climate zones across Europe.

1.1.4. Challenges in Updating Climate Zones. Despite the availability of high-resolution climate data, updating climate zones remains a significant challenge. One of the primary barriers is the complexity involved in processing and integrating large volumes of climate data from multiple sources. Furthermore, regulatory bodies must adopt updated climate data and adjust national or regional building codes, a task that often requires extensive coordination among various stakeholders. The need for constant updates to climate zone classifications also raises concerns about the consistency and reliability of these data for long-term energy planning. While climate models provide valuable insights, there is still uncertainty in predicting regional temperature variations and their impact on building energy needs.

2. Methodology

This section describes the approach used to calculate local climate zones for the entire European territory, using the PREDYCE. The methodology consists of several key steps: (1) data collection from climate re-analysis and projection databases and data elaboration to define climate averages, (2) integration of the climate data into the PREDYCE platform and its CDO-python light version for calculation of HDD, and (3) development of local climate zones based on Italian regulation.

2.1. Data Collection and Sources

The climate data were gathered from four different EURO-CORDEX models, covering the period from 1970 to 2100. This dataset includes both historical simulations and three future projections (RCP 2.6, 4.5, and 8.5). Additionally, ERA5-Land reanalysis data were collected from 1950 to 2022, offering a comprehensive record of past climatic conditions. The methodology described was applied uniformly across all mentioned climate models; however, this paper presents results from selected EURO-CORDEX models. While the full dataset is not shown, the general trend observed across all models consistently supports the findings discussed in this paper, reinforcing the robustness and reliability of the presented outcomes.

2.2. Integration into PREDYCE CDO-python version

Using the CDO-Python integration within the PREDYCE platform, all collected climate model data are systematically processed. The platform generates Average Meteorological Years (Av.MY) for different time periods, providing a representative climate profile for each dataset. Seven periods are produced for the EURO-CORDEX models and four periods for the ERA5-Land dataset. The integration of CDO-Python enables efficient large-scale computation, automating the generation of average climate files and preparing them for the application of the HDD KPI on the Av.MY files. The annual HDD is calculated using the following formula:

$$\mathrm{HDD} = \sum_{i=1}^{n} \max(0, T_{\mathrm{Base}} - T_{\mathrm{Daily}}) \qquad (1)$$

Where T_{base} = 20°C and T_{daily} is the daily mean temperature. The HDD calculation provides a quantitative measure of heating needs based on the temperature deviations from the base.

2.3. *Development of Local Climate Zones*

Local climate zones are defined based on the calculated HDD values, which are classified into six categories ranging from A (less than 600 HDD) to F (more than 3000 HDD), following the Italian regulation approach [14]. These categories correspond to various climate conditions, influencing energy needs for heating and cooling.

Table 1. Heating climate zoning, from hotter sites (Zones A and B) to colder ones (Zone F) [8,14].

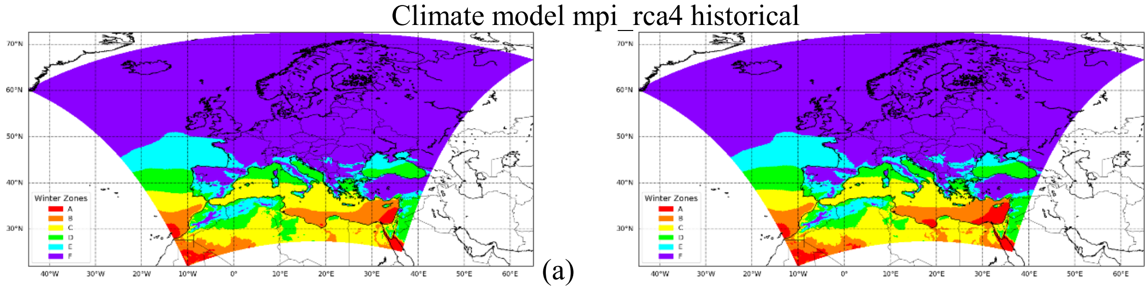
Zone	HDD range	Description
A	< 600	Municipalities with degree days not exceeding 600
B	601 - 900	Municipalities with degree days greater than 600 and not exceeding 900
C	901 - 1400	Municipalities with degree days greater than 900 and not exceeding 1400
D	1401 - 2100	Municipalities with degree days greater than 1400 and not exceeding 2100
E	2101 - 3000	Municipalities with degree days greater than 2100 and not exceeding 3000
F	> 3000	Municipalities with degree days greater than 3000

The resulting local climate zones are mapped for the European territory, with special attention to regional variations and the progressive impacts of climate change over time. This is visualised (section 3) through a series of maps showing the changes in local climate zones for different periods.

3. Results

The following figures present the winter heating zones across Europe based on the climate data from the mpi_rca4 model. Figure 1 illustrates the historical periods (1970-1989 and 1990-2005), while Figure 2 depicts future projections under the RCP 8.5 scenario for the periods 2010-2029, 2030-2049, 2050-2069, 2070-2089, and 2090-2100.

Climate model mpi_rca4 historical



(a) (b)

Figure 1. Winter heating zones classification of the climate model mpi_rca4 in two historical periods; (a): 1970-1989, (b): 1990-2005

A clear transition toward zones with lower winter heating needs is observable, progressing from North Africa toward the northern European territories. Notably, during the 1970-89 period, zones A, B, and C were almost entirely absent in Southern Europe. However, by the 2090-2100 period, these zones emerge across the same regions, reflecting a substantial reduction in heating demand. A significant shift is also evident in Central Europe, where large portions transition from Zone F to Zone E over time. Specific regions, such as southern France, exhibit further changes, with some areas moving into Zone D, indicating a consistent decrease in heating requirements over the studied periods.

Journal of Physics: Conference Series **3140** (2025) 022018 doi:10.1088/1742-6596/3140/2/022018

Climate model mpi_rca4 projection 8.5

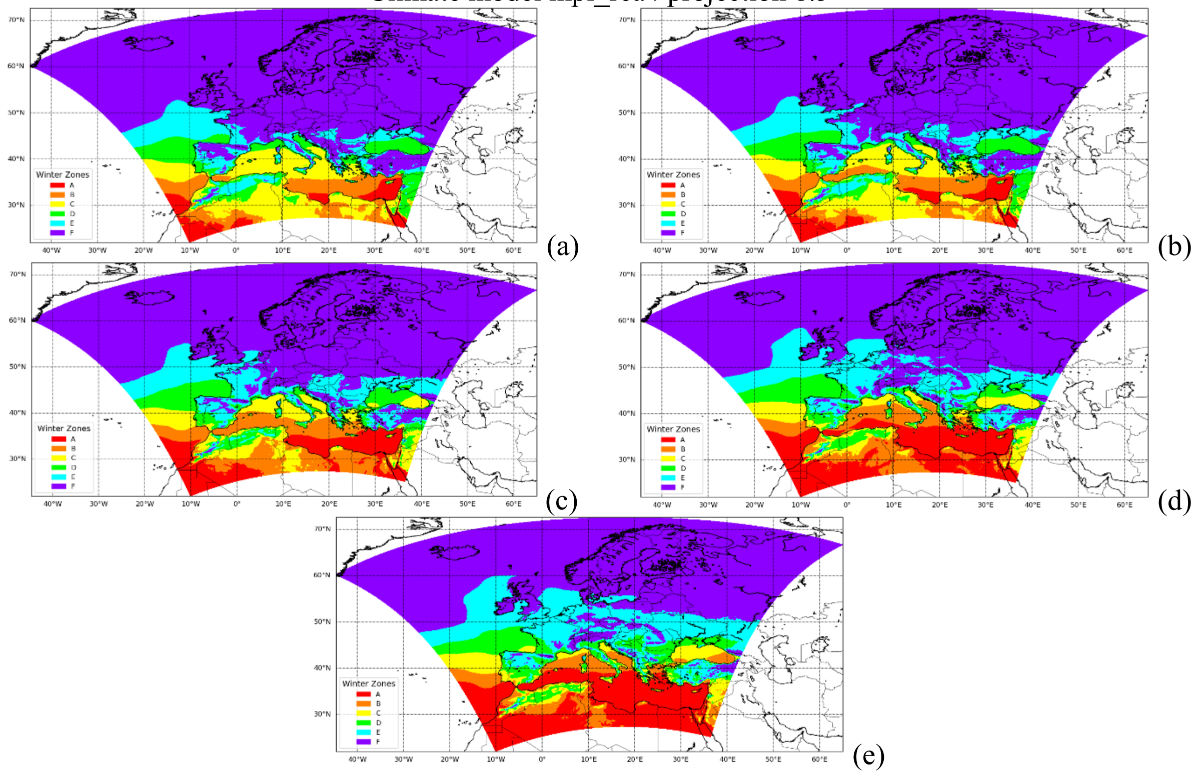


Figure 2. Winter heating zones classification of the climate model mpi_rca4 projection 8.5 in 5 future periods; (a): 2010-2029, (b): 2030-2049, (c): 2050-2069, (d): 2070-2089, (e): 2090-2100.

In Figures 3, 4, and 5, three additional climate models are used: cnrm_racmo22e, mohc_rca4, and ncc_rca4, respectively. These figures compare the historical period (1970-89) with the far future (2090-2100) under the RCP 8.5 projection. The overall trend is consistent, revealing a general shift toward warmer climate zones with reduced heating demands. Mohc_rca4 projects the most substantial changes, particularly in Central Europe, where the classification transitions from Zone F during the historical period to Zone E in the far future. Ncc_rca4 shows a slightly less pronounced impact. cnrm_racmo22e exhibits the least variation among the three models, although significant changes still occur. For instance, southern Italy transitions from Zone E to Zone D, while central Italy shifts from Zone F to both Zones E and D, signalling a progressive reduction in heating requirements. These results highlight the robustness of the observed trends across multiple climate models while emphasising the variability in the magnitude of change. The findings reinforce the necessity of regularly updating national climate zoning frameworks to support more accurate EPBD measures.

Climate model cnrm_racmo22e projection 8.5

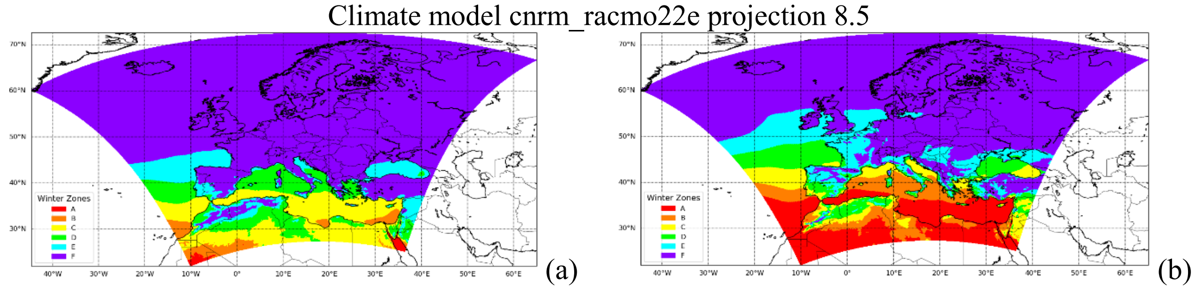
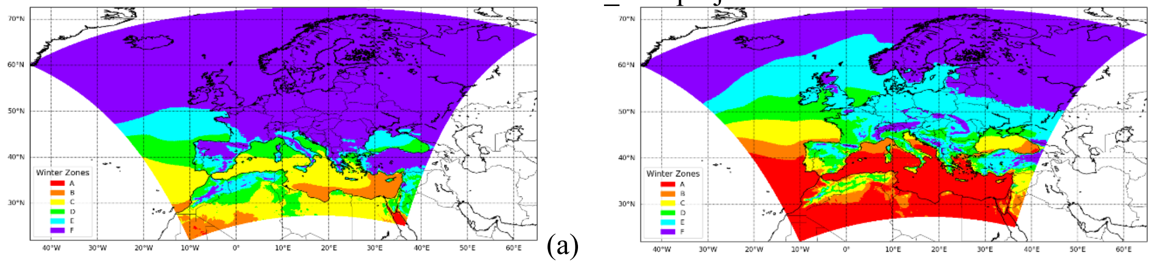


Figure 3. Winter heating zones classification of the climate model cnrm_racmo22e projection 8.5 in 2 periods; (a): 1970-1989, (b): 2090-2100

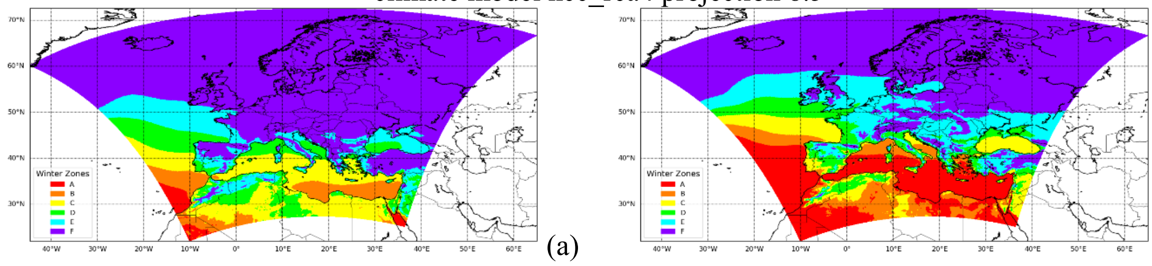
Climate model mohc_rca4 projection 8.5



(a) (b)

Figure 4. Winter heating zones classification of the climate model mohc_rca4 projection 8.5 in 2 periods; (a): 1970-1989, (b): 2090-2100

climate model ncc_rca4 projection 8.5



(a) (b)

Figure 5. Winter heating zones classification of the climate model ncc_rca4 projection 8.5 in 2 periods; (a): 1970-1989, (b): 2090-2100

4. Conclusion

This study applies the existing Italian heating zone classification approach, based on HDD, adopted for EPBD implementation and for managing building energy efficiency management, to the entire European territory using future climate projections from ERA5-Land and EURO-CORDEX models. The analysis highlights significant shifts in local climate zones across Europe, driven by climate change, and underscores the importance of regularly updating these zones to reflect evolving climatic conditions. These findings are consistent with those of [4] for the Spanish territory, who similarly reported a shift toward warmer zones at the municipal level, yet our study confirms and expands this trend across all of Europe. The results reveal a clear trend toward warmer climate zones, with many regions experiencing a reduction in heating needs over time. This shift suggests that current national regulations, particularly those under the EPBD, may no longer fully align with future climate realities. As climate zones continue to evolve, updating energy performance standards and heating system activation periods will be crucial to ensure buildings remain energy-efficient and adaptable to future conditions. The study emphasises the need for continuous updates to climate zone classifications, reflecting the impact of climate change on regional heating and cooling demands. By integrating high-resolution climate data into policy frameworks, countries can better align their building regulations with future energy needs, contributing to the goal of nearly zero-energy buildings (nZEB) and resilient urban planning.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement N° 958345 (PRELUDE project). P. Carrisi is thankfully acknowledged for supporting EPW generations and PREDYCE tool integration.

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