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GIS-based approach to identify climatic zoning: A hierarchical clustering on principal component analysis

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ABSTRACT

In tropical environments, the design of bioclimatic houses adapted to their environment represents a crucial issue when considering thermal comfort and limiting energy consumption. A preliminary aspect of such design endeavors is the acquisition of accurate knowledge regarding the climatic conditions in each region of the studied territory. The objective of this paper is to propose a climatic zoning for Madagascar from a database of 47 meteorological stations by performing hierarchical clustering on principal components (HCPC). The results are then combined with spatial interpolation using geographic information system (GIS) tools, enabling us to define three climate zones corresponding to dry, humid and highland areas. These results make it possible to define standard meteorological files to evaluate the thermal performance of traditional Malagasy houses. Regardless of the type of house and the areas considered, the percentage of thermal comfort according to the Givoni bioclimatic chart varies from average values of 20% without ventilation to 70% with an air velocity of 1 m/s. In summary, Madagascar's traditional habitat typologies have adapted over time to the constraints of their environment.

1. Introduction

Climatic zoning is an essential prerequisite for the design of climate-responsive buildings [1–3]. As a consequence, the importance of accurate knowledge regarding climate conditions for simulating the energy efficiency of a building is widely known. According to the IEA[1] flagship publication, World Energy Outlook 2018, the global energy consumption in the building sector was 3047 Mtoe, accounting for 31.4% of the total final energy consumption in 2017 [4]. Environmental issues are at the forefront of regulatory requirements; correspondingly, the future will require a logical approach that considers both the energy and the environmental performance of buildings worldwide. These issues are all the more important for developing countries such as Madagascar because they can either weaken or boost their economic development. By 2020, developing and emerging countries will be more energy-intensive than developed countries, [5]. Thus, minimizing energy demand in the construction sector by erecting climate-resilient buildings is an appropriate option to decrease the energy vulnerability of these countries due to their dependence on fossil fuel imports.

Like many developing countries, Madagascar is experiencing rapid urbanization. Out of a total population of 25.57 million (2017), the country is currently composed of nearly 7 million urban dwellers compared with 2.8 million in 1993. Over the past 20 years, the combined effect of population growth, rural exodus and interurban migration on capital has led to a 50% increase in building construction. The 2017 National Energy Balance of Madagascar [6] shows that the residential sector alone consumes 3245 ktoe, which represents 59% of the final energy consumption. Consequently, urban areas must face the challenges of sustainability and mitigating energy consumption due to urban population growth and economic development [7]. One possible solution is to construct buildings that are adapted to their environment and therefore consume less energy.

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1.1. Statement of significance

This study aims to make an original contribution to climatic zoning by exploring a new combined approach. The review conducted by Walsh [8], has shown that most approach for climatic zoning are based on the supervised methods. In that case, the assumption is made to have some knowledge of the data and the study area. Thus, index can be defined and thresholds set that will allow to assign a class. The present study set out to focus on unsupervised approach which does not assume a priori knowledge to define classes. There is actually no real consensus on an acceptable method to define climatic zoning. Our work intends to fill the gap in proposing a framework based on quantitative data that is easily replicable.Our approach is based on a combination of zoning through interpolation coupled with clustering on principal components. Another relevant result is the application of the method for the zoning of Madagascar. Thus, the boundaries of climate zones have been redefined based on multivariate data analysis. Finally, to complete the zoning objective, the results are then applied to traditional houses to evaluate their thermal comfort performance. The illustration of these zoning results will allow the thermal comfort of traditional Malagasy houses to be evaluated and typical meteorological files to be defined.

1.2. State-of-the-art climate zoning methods

Climate zones can be identified in numerous different ways based on different criteria using either clustering methods (i.e., performing statistical analysis by grouping observations and analyzing possible groupings; also called “modern methods”) [9] or class methods (i.e., using thresholds for climate variables and indices; also called “traditional methods”) [9]. The selection of the method depends largely on the climate classification objective. Among the most recognized classification methods, the Köppen-Geiger climate classification is often considered a reference in the field and has supported many multidisciplinary studies [10,11]. Köppen established five climate zones based on natural vegetation cover: an equatorial zone (A); an arid zone (B); a temperate warm zone (C); a snow zone (D); and a polar zone (E). This classification approach introduces nuances through the addition of second and third letters related to precipitation and temperature, respectively. The Köppen classification is a powerful classification technique for global analysis [12] and is often employed as a diagnostic tool to monitor climate change across different time scales and for different aspects. For example, the Köppen classification was used to highlight the effects of climate change on ecosystems, energy consumption or climate variability on different time scales [13–16]. Nevertheless, this method is not unanimously accepted for other purposes; many authors have shown that this approach has limitations under specific conditions. Hence, other methods, namely, clustering methods, are more precise and more consistent with the identified climate zones for local problems. In this regard, a comparative study was carried out by Zscheischler [17], who proposed a comparison between the accuracy of the Köppen-Geiger classification and that of principal component analysis (PCA) using the “k-means” clustering method; the study verified that climate and vegetation variables composed similar groupings and further showed that the parameters utilized in the Köppen-Geiger classification are not optimal for categorizing the local climate. In contrast, the use of clustering based on meteorological data allows better results to be achieved. Other comparisons have been conducted in recent years [18–20], some of which even showed that the Köppen classification does not permit the use of specific information necessary for building design and thermal comfort problems [21–23]. Accordingly, other classification methods have been used for the purpose of studying the thermal comfort of a building [3,21,23] or for performing climate classifications of urban and rural sites [24–27]. Moreover, the use of multivariate statistical analysis based on clustering makes it possible to obtain an efficient climate classification [28] that seems more coherent for building concerns [9]. Other studies have confirmed the applicability of clustering [29,30], specifically, k-means clustering with the Euclidean distance correlation as a similarity measure, to the classification of a local climate in general [17,19] or to the adaptability of a building [1,2,8,23,31–33].

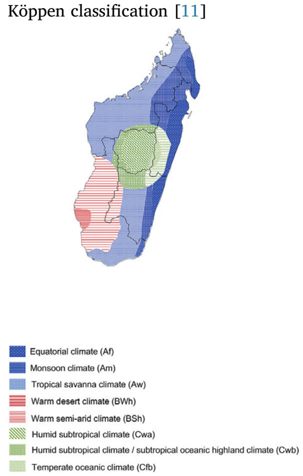
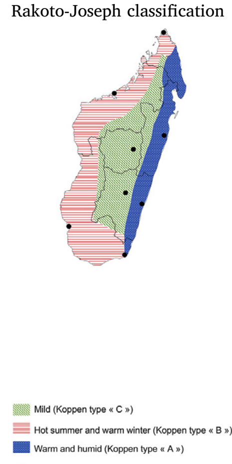
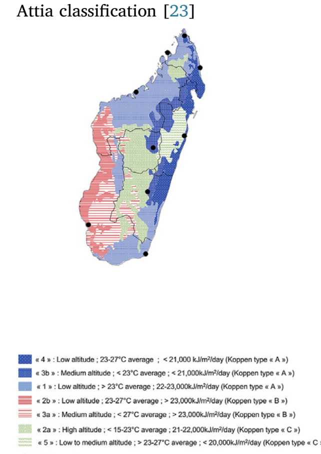
The quality and availability of the parameters used for climate classification are essential. The literature has revealed a multitude of parameters from various origins that make it possible to guide a climate classification to its final objective. In this regard, the representativeness of the data is a significant criterion in climate analysis, especially for clustering methods. Clustering and class methods use any of the following sources of data (i) climate data (e.g., the outdoor air temperature, outdoor relative humidity, global solar irradiation, precipitation, altitude, wind velocity, wind direction, and atmospheric pressure): [21,22,28] (ii) climate indexes (e.g., the sky clearness index kt); [34]; (iii) topographic parameters [34]; or (iv) thermal comfort indexes (e.g., Terjung's comfort index [35,36] and the physiological equivalent temperature (PET) [24]). Among these parameters, global solar irradiation, outdoor air temperature, and wind velocity seem to be optimally correlated to analyze the climate [21]. The temporal dimension is an important factor in ensuring a high-quality climate classification. All the authors of the abovementioned studies seem to agree on the need for a climate study to utilize a database spanning an average of ten years [9,37]. If the time span of the database is too short, it will not be possible to rule out occasional climatic events; conversely, if the time span is excessively long, the classification may not take the effects of climate change into account.

1.3. Existing climatic zoning of Madagascar

Madagascar is in a humid tropical zone influenced by four types of wind; among them, trade winds that bring rain to the coastal region and eastern slopes are the most predominant. The region is divided into nine areas according to the Köppen classification; these areas were reexamined by Peel in 2007 [11]. Subsequently, in 2009, Rakoto-Joseph [21] presented a climate classification of Madagascar based on 29 years of meteorological data (without geographical precision) with a focus on the cities considered by the author to be the most representative of the established climate zones. This classification used temperature, solar irradiation, wind velocity and altitude data to define overlapping layers, thereby constructing coherent geographic areas and enabling the author to delineate six climate zones, which were further divided into three zones for coherence considering the “building” problem. The average temperatures and humidities used in this classification were those of the coldest and hottest months of the year. Unlike the Peel-Köppen classification, which serves a global objective, Rakoto-Joseph's classification makes it possible to propose passive technological solutions for buildings. Most recently, Attia [23] proposed a new classification for Madagascar in 2019 based on the Rakoto-Joseph and Peel approaches. Using solar irradiation, temperature and topography data from Madagascar that were synthesized within the Prieto equation [38], Attia defined six characteristic climate zones; Attia's approach employed a threshold-based method to define layers and infer zoning and utilized the data from 9 stations spread throughout the territory (Tolagnaro, Toliary, Antananarivo, Mahajanga, Nosy-Be, Antsiranana, Sambava, Toamasina, and Fianarantsoa).

Table 1 compares the approaches and results of the three existing climate classifications. The climatic zoning maps were reissued herein with the outlines proposed by each author but in colors that allow contrast. Compared with the Rakoto-Joseph scheme, the Peel and Attia classifications offer a higher level of detail. In addition, we are able to notice similarities among the classifications based on the size and shape of each climate zone. For instance, the eastern zone is a warm and humid zone with an equatorial climate. The central zone of Madagascar situated at high altitude is also classified as a type “C” (temperate) climate zone where the climate can range from mild to cool. For the southwestern zone, the classifications all agree on a type “B” (dry)

Table 1
Comparative analysis of Madagascar's three existing climate classifications.

Existing climate classifications			
Reference	Köppen classification [11]	Rakoto-Joseph classification [21]	Attia classification [23]
Number of zones	9 climate zones	6 climate zones (global approach) 3 climate zones (for building concerns)	7 climate zones
Classification parameters	Rainfall outdoor air temperature Temperature variations	Global approach: Solar irradiation Dry bulb temperature Wind speed – For building concerns: Average temperature and average humidity of the hottest and coldest months	Altitude Solar irradiation Dry bulb temperature
Period and/or Weather stations	Several stations worldwide with an interpolation between each station pair	Period of 29 years that lacks geographical precision For building concerns: six local meteorological stations representative of the established climate zones (Antananarivo, Fianarantsoa, Antsiranana, Mahajanga, Toliary and Toamasina)	Nine local meteorological stations with data available between 1991 and 2008 (Tolagnaro, Toliary, Antananarivo, Mahajanga, Nosy-Be, Antsiranana, Sambava, Toamasina and Fianarantsoa)
Classification method	Based on limits + layers		
Existing climate classifications			
Reference	Köppen classification [11]	Rakoto-Joseph classification [21]	Attia classification [23]
Results			

climate tendency according to Köppen. In contrast, the northwestern zone shows disparate results among the Rakoto-Joseph method, which classifies the area as a savannah climate with a dry winter; the Peel method, which classifies the area as a type "A" zone according to the Köppen classification; and the Attia method, which classifies the area as having hot summers and winters (type "B" according to the Köppen classification).

The work performed by Rakoto-Joseph and Attia constituted research on adapting the needs of buildings with the climatic zoning accuracy as a constraint. In this regard, Attia noted that increasing the number of data points would enable climate trends to be either confirmed or disproved.

Our study aims to highlight a recurring problem in modern climate zoning methods. The literature demonstrates that these methods have been heavily preferred due to the quality and validity of their results. However, the lack of distributed meteorological data throughout a territory can lead to climate zoning errors. To overcome this problem, which was a recurring obstacle in previous studies, we propose to identify a standard meteorological file representative of a given climate zone. This is achieved by combining the statistical analysis of weather conditions with the geolocation of measuring stations and the interpolation of data by the GIS tool.

2. Methods

This study is split into two main parts. The first part describes a weather-centered clustering technique that defines the climatic zoning of Madagascar, while the thermal performance of traditional Malagasy houses among different zones and the main results of this study are discussed in the second part. Fig. 1 provides an overview of the proposed method and the objective of this article.

One of the ambitions of this work is to propose a global approach in which meteorological data not readily available are employed to define standard files, thereby allowing building simulations to be carried out. To achieve this goal, our approach classifies meteorological data and then identifies the meteorological station most representative of a given climate zone.

2.1. Data collection

The first task in defining a climatic zoning map is the acquisition of meteorological data. Madagascar is a unique case study because of the poor availability of hourly weather files. Our study is based on a database of 47 stations spread across the entire country, and the sparse data available during a given year are monthly files. The database used for PCA consists of five meteorological parameters: outdoor temperature, relative humidity, wind speed, daily global horizontal irradiation

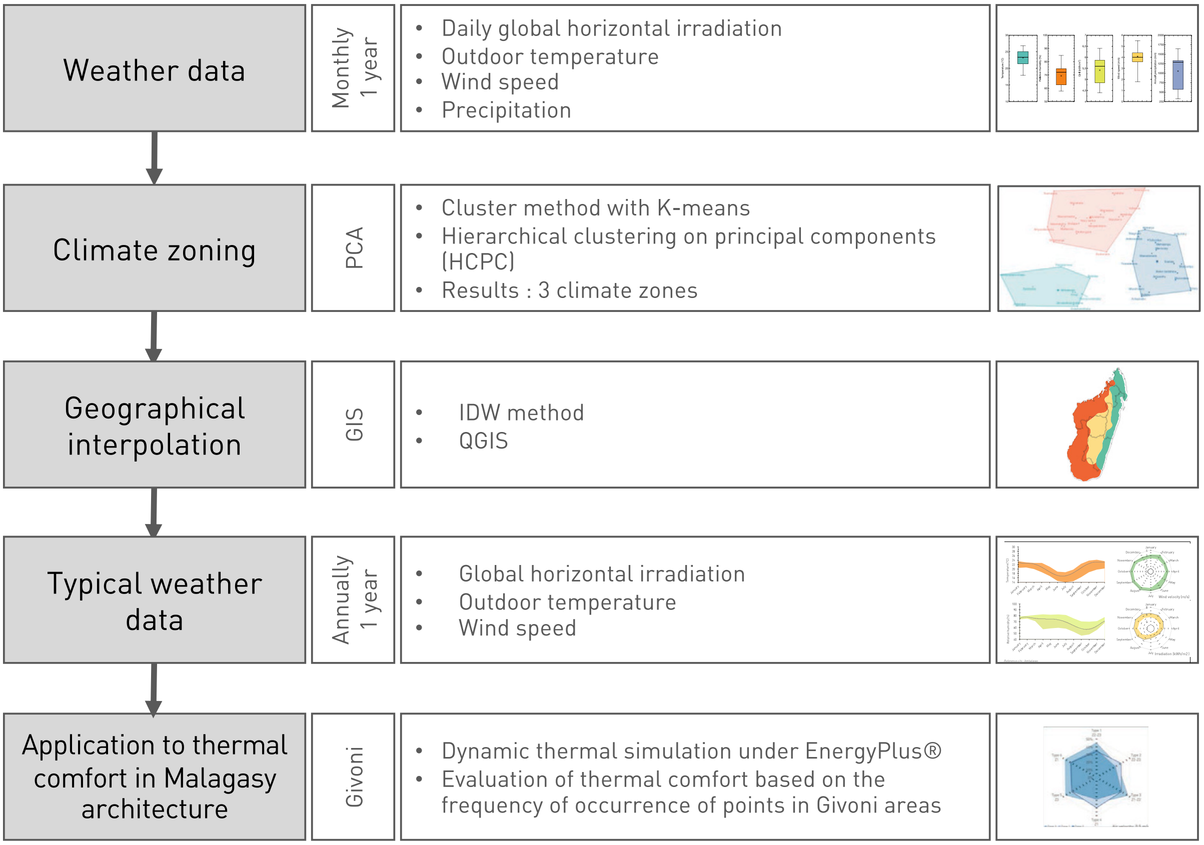


Fig. 1. Synoptic view of the proposed methodology.

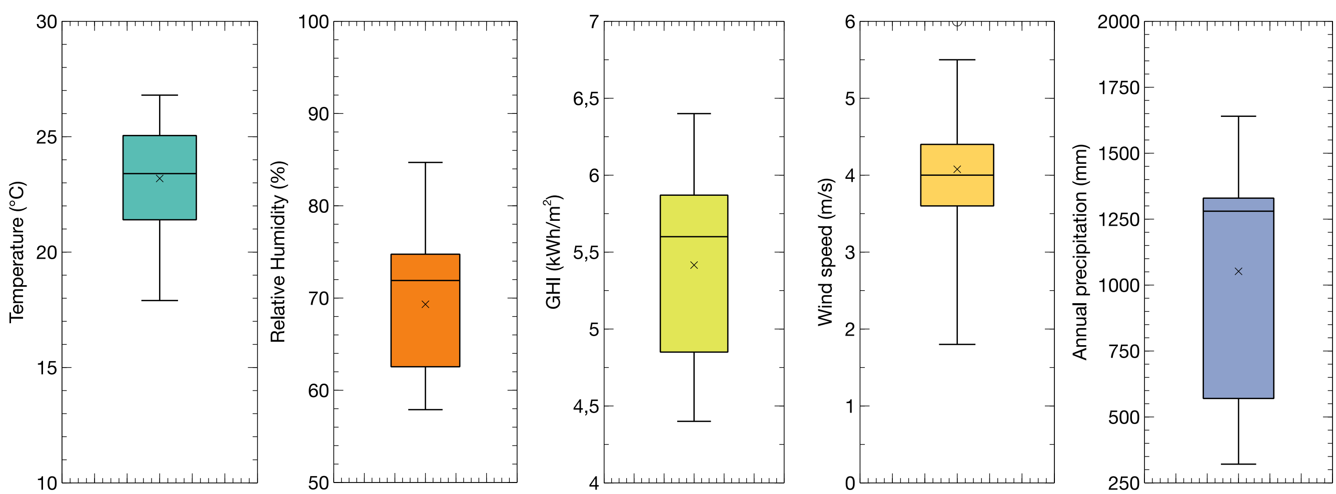


Fig. 2. Boxplot of climatic data for the 47 meteorological stations in the study area of Madagascar.

(GHI) and precipitation. Geographic information, such as longitude, latitude, and altitude, is also considered. Fig. 2 shows the range of variation in each meteorological parameter. In the case of the daily GHI, relative humidity and precipitation, the median is shown at the top of the box, which implies an asymmetric distribution toward the higher values of each variable.

The results of the boxplot show that these three variables will play an essential role in the partitioning of the data and therefore in our unsupervised classification.

2.2. *Hierarchical k-means clustering on principal components (HCPC)*

As noted by Kassambara in [39], the HCPC approach is the combination of three fundamental techniques used in multivariate data analysis, namely, hierarchical clustering analysis (HCA), k-means partitioning, and PCA. This analysis is a dimension reduction method that allows quantitative variables to be utilized to explore and visualize a matrix composed of individual data. The main purpose of PCA is to maximize the total variance of the projected points, i.e., to define the subspace that best represents the diversity of individuals. One of the significant advantages of this method is its ability to extract characteristics and summarize the information contained in a dataset

[40,41]. In our study, this first step (which can be considered a preliminary step) is to increase the stability of the classification, thereby reducing the noise in the data. After defining the number of dimensions (principal components) to retain for our analysis, a hierarchical tree is constructed without any prespecified number of clusters. The optimum height at which to cut the dendogram is defined by Silhouette method optimization. Additionally, partitioning is made more robust by applying k-means clustering, the objective of which is to heuristically highlight groups (called clusters) of similar objects in a dataset. Using this method, the 47 weather stations are automatically classified into homogeneous groups according to Ward's criterion [42]. Thus, this algorithm makes it possible to group the individuals closest to a station in the projection plane of the first two principal components. Compared with the work of Zscheischler [17], our classification is a two-step process: the first step is HCA, which allows us to define the first partition of our projected data on the two best principal components; then, k-means partitioning, which is a centroid-based algorithm, is employed to consolidate the partition.

All statistical analyses investigated in this work are performed with R freeware using the package FactoMineR developed by F. Husson [43,44].

2.3. GIS-based mapping

Spatial interpolation involves the reconstructing of values corresponding to a georeferenced variable over a defined territory from a limited number of sampling points. This step is particularly interesting in a territory lacking a spatial grid of data possessing sufficient or equal quality. The interpolation process is validated by the hypothesis that spatially distributed objects are correlated. The probability of likelihood then employs the fact that the values of objects close to the sampling points are higher than those of distant objects.

Several interpolation methods are applicable, but the difference in the abstraction ability between interpolation methods is affected by the phenomenon under study. The proposed methodology uses inverse distance weighting (IDW), which is based on the principle of a weighting coefficient; in other words, the calculation of the value of a point is achieved by averaging the values of points located in its vicinity weighted by the inverse of each point's distance. In contrast, reverse distance weighting (RDW) works according to the principle of the first law of geography: close things are more related than more distant things. Contrary to geostatistics, the so-called deterministic IDW method is well suited to the dataset in this study and demonstrates the advantage of usually being both sufficient and appropriate [45–47]. The starting point here is a set of point data corresponding to climatic clustering level values for Madagascar. The purpose of this investigation is ultimately to obtain spatial estimations of the values from the sampling points to generate a climatic zoning map of the study area.

To create spatial distribution maps of the meteorological parameters (through the cluster number), an IDW interpolator was used. The generic formulation, which is expressed in Eq. (1) [48], was defined by Bartier and Keller [49]. Thus, the power parameter p determines the most appropriate value closest to the interpolated point. In the interpolation process, several interpolator values (1, 1.5, 1.9, 2, 5, 10, and 20) were tested in accordance with the examples in the literature [50,51].

$$\mathbf{z}_{x,y} = \frac{\sum_{i=1}^{n} z_i \mathbf{d}_{\mathbf{x,y,i}}^{-\beta}}{\sum_{i=1}^{n} \mathrm{d}_{\mathbf{x,y,i}}^{-\beta}} \tag{1}$$

where z_i is the sample value at point i, $z_{x,y}$ is the point to be estimated, and $d_{x,y}$ is the distance from the sample point to the estimated point. The variable β called the exponent value improves the accuracy of the IDW interpolator between the measured and estimated data [52].

2.4. Traditional housing simulation

The objective of a thermal comfort study is to depict a link between established climate zones and thermal comfort conditions according to traditional habitat typologies. To achieve this, we choose cities with available data that are representative of the weather conditions in each thermal zone Table A.5. Weather files in an "epw" format are used. As a reminder, the meteorological files used during the simulations are those of the paragons, which represent the average behavior (i.e., center) of each cluster. Comparisons are established between all cases with a study of the indoor operative temperature, indoor relative humidity and comfort rates associated with each configuration.

The computer simulations are conducted with the well-recognized software EnergyPlus [53], which has been used in many studies to evaluate the thermal comfort of occupants in buildings [54–56].

A typical Malagasy house is considered for the simulations. The house has a gabled roof whose gables (350 cm long and 350 cm high) are oriented north-south. In addition, the west and east facades (450 cm long and 200 cm high) contain two openings (a door that is 180 cm high by 90 cm wide and a window that is 80 cm high by 60 cm wide). For our study, traditional Malagasy houses are divided into six types created for the simulations from building materials that are commonplace in Madagascar. The details of all these types are presented in Table 2.

The building materials of the 6 house types are implemented according to their physical and thermal properties (Table 3).

The occupants of each house constitute a family comprising a couple with four children. The family occupancy schedule is based on a typical day of the Malagasy people. The occupants of the house are absent from 8 a.m. to 12 p.m. and from 1 p.m. to 6 p.m. The metabolic rate of each occupant is based on the ASHRAE 55 standard [58] and is fixed at 131 W. The natural ventilation implemented in the EnergyPlus model corresponds to the opening of doors and windows during the day.

To provide a fair comparison, we study the adaptability of traditional architecture to climate zones as needed. Accordingly, we employ a method that can clearly describe the thermal impact of architecture on comfort: the psychrometric chart of Givoni.

In 1978, Baruch Givoni established a psychrometric diagram in which he assessed the physiological requirements of comfort. This approach, commonly used in hot climates, is one of the so-called "rational" or "analytical" methods for assessing thermal comfort. Givoni recommended two passive cooling approaches: either by ventilation or by reducing indoor temperatures relative to the outside temperature. For the assessment, this approach utilizes three of the leading environmental parameters (operating temperature, relative air humidity, and air velocity) and analyzes thermal comfort situations while considering physiological evapotranspiration phenomena under sedentary activity and light clothing (i.e., summer clothing). This method allows the definition of 4 comfort zones linked to 4 different wind speeds from 0 to 1.5 m/s. Above 1.5 m/s, the air velocities are too high and are considered a draught. In reality, we will focus on the first three comfort zones (0 m/s, 0.5 m/s and 1 m/s). The Givoni areas are designed for summer clothing (0.5 clo) and for office metabolic activity (1.2 met). The results obtained in this fashion are very intuitive and make it possible to quantify the percentage of points in an area and thus deduce the number of hours of discomfort over the period studied.

Table 2
Descriptions of the six types of Malagasy housing used.

Type	Floor	Walls	Roof
1	Wooden floor on stilts (0.4 m)	Thatch	Thatch
2	Wooden floor on stilts (0.4 m)	Wood	Thatch
3	Dirt floor	Mud and earthen	Thatch
4	Dirt floor	Red brick	Metal sheet
5	Dirt floor	Thatch	Thatch
6	Dirt floor	Red brick	Thatch

Table 3
Physical and thermal properties of the building materials (1) similar to a Ftimi date palm tree with intertwined fibers whose thermophysical properties are described in [57].

Component	Material	Thermal conductivity	Density	Specific heat	Thickness
		(W/m.K)	(kg/m^3)	(J/kg.K)	(m)
Ravenala wood (1)	Ftimi date palm	0.103	700	1145	0.02
Thatch	Ravenala sheet	0.045	120	1980	0.25
Dirt	Earth	0.84	1900	850	∞
Cob wall	Mud and straw	0.1	350	800	0.3
Red brick	Baked clay	0.26	1950	836	0.25
Metal sheet	Steel	163	2787	450	0.001

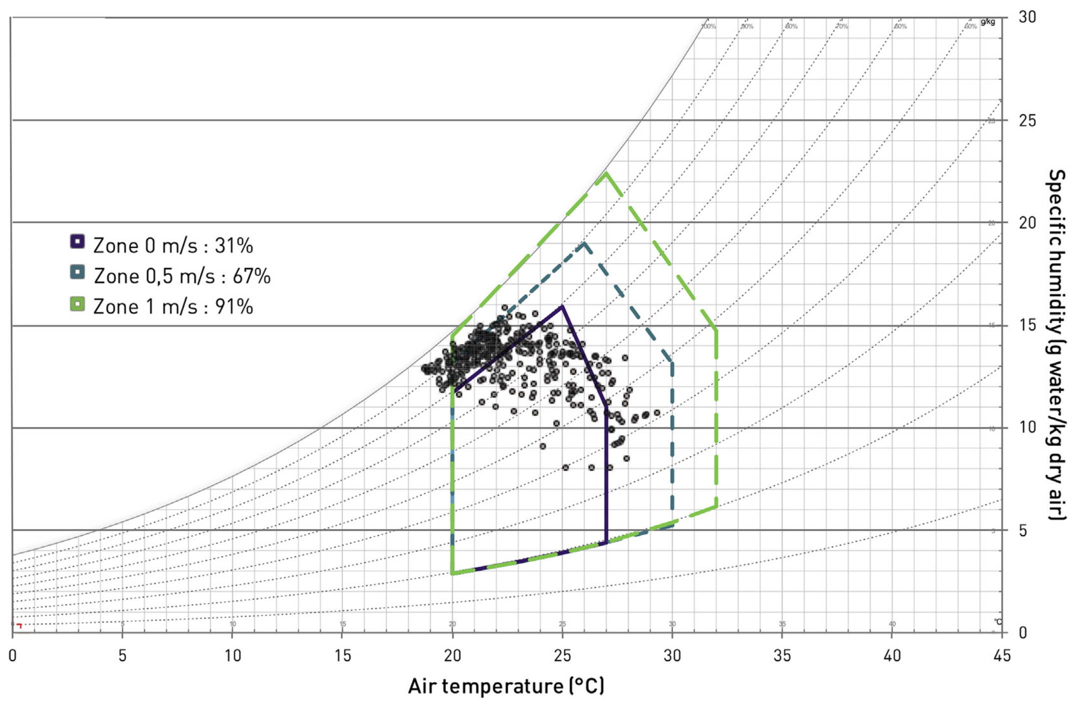


Fig. 3. Psychrometric chart of Givoni with the first 3 areas (0 m/s, 0.5 m/s and 1 m/s) and the associated occurrence frequencies.

The percentages obtained correspond to the frequency of occurrence of the temperature-humidity pairs in each Givoni zone, as shown in Fig. 3.

3. Results and discussion

3.1. Climatic zoning

Considering the methodology presented in section 2.2 and shown in Fig. 1, PCA is conducted on a matrix of 47 weather stations characterized by nine variables. Prior to determining the clusters, a preliminary investigation of the map projection of the principal components (as shown in Fig. 4) is necessary to understand the main characteristics of the weather stations and to detect any aberrant data.In the decomposition of the total inertia, the first two principal components (PC1 and PC2) account for 67.58% of the total data variance. As a result, the variability of the data is well reflected in the first projection plane, which will therefore be more than sufficient to interpret the data for the next classification step. The main characteristics of this first plane are summarized in Table 4.

The PCA results for the weather stations are depicted in Fig. 4. Evidently, the stations are organized into four main regions: midlands, highlands and two coastal areas. The dataset appears to be organized into three groups, which will be verified during the clustering step. Fig. 4 shows the projection plane of the first two components; the general layout of the projection plane does not appear to highlight any outliers. The first component (to the right of the PC1 axis) encompasses regions characterized by high temperatures and high solar irradiation at low altitudes. For the second component, the upper part of the graph is characterized by areas that experience rather heavy rainfall with high relative humidity and are exposed to strong winds. The data projection quality is represented by the variable cos^2, which is the cosine of the projection angle of each station on the two best principal components. As a result, the only single point with a low projection quality is the city of Bealanana, which is located almost at the origin of the principal component coordinate system, indicating that the position of Bealanana on this plane cannot be correctly interpreted.

This first step allows us to observe the initial clusters of the weather stations. In addition, we are able to define the main characteristics of the PC1-PC2 projection plane, upon which the clustering results will be subsequently projected. These details are provided below in the descriptions of the clusters.

The clustering results projected on the PC1-PC2 plane are presented in Fig. 5. The results highlight three clusters that exhibit very different characteristics. The cluster analysis is performed first according to variables and then according to individuals (weather stations). As shown in Fig. 5, all clusters are well separated. Cluster 1 corresponds to highland areas, which are characterized by precipitation, wind and temperature variables; these areas are subject to lower rainfall than the average for Madagascar. In contrast, the variables that most

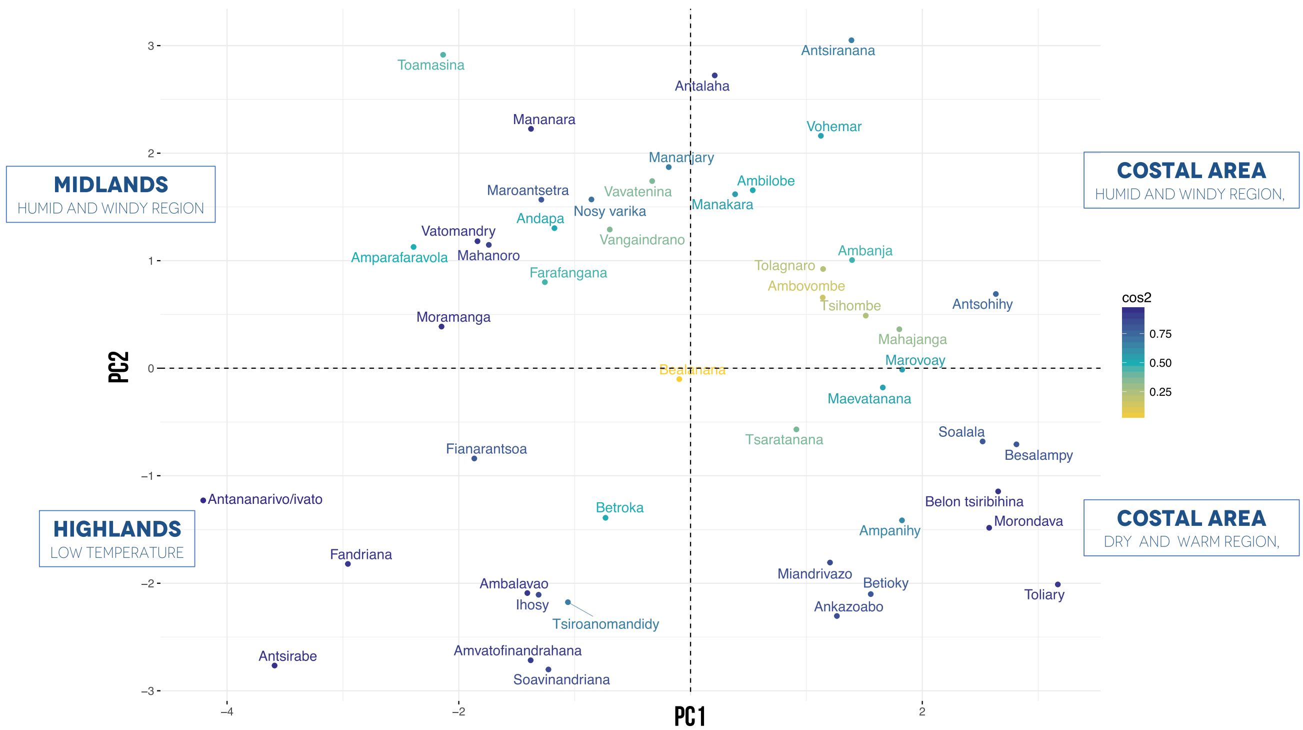


Fig. 4. The individual factor map (PCA).

Table 4
PCA results.

Principal component	Eigenvalue	Variance (%)	Cumulative (%)
PC 1	3.302	36.685	36.685
PC 2	2.781	30.896	67.582

characterize the second cluster, which corresponds to the eastern region, are relative humidity and precipitation; the mean values of these two variables in this cluster are higher than the overall corresponding means. Considering all variables, the third cluster is mostly described by the highest temperatures, the highest solar irradiation and a low altitude; this cluster corresponds to the western zone of Madagascar, which is characterized by hot and dry climatic conditions, particular regarding the southern extent of the island, where this area reaches arid conditions. Thus, the characteristics inherent to each cluster make it possible to highlight three very different climate zones as follows from west to east: a dry zone, a highland region, and a wet-humid area (see Fig. 6).

Clustering is interpreted not only according to variables but also according to individuals. Indeed, it should be recalled that the purpose of this study is to develop a classification application in the field of thermal comfort, specifically regarding the case of traditional housing. Madagascar, similar to many developing countries, does not always have meteorological data covering its entire territory. Thus, clustering allows us first to define and then characterize these climate zones, particularly their boundaries. The second round of clustering involves the identification of paragons. For each group, the individual whose coordinates are closest to the barycenter is called the paragon; accordingly, the profile of this individual best characterizes the cluster to which the individual belongs. The paragons are *Ambalavao* (Cluster 1), *Mananara* (Cluster 2), and *Belon'i Tsiribihina* (Cluster 3). These paragons are significant, as they make it possible to define typical weather files for each area. In this work, each paragon is taken to reflect the average behavior of the individuals within that paragon's cluster rather than the cluster's center of gravity, which is a fictitious element. Throughout the remainder of this article, we will therefore consider the files pertaining to these three paragons to evaluate the thermal comfort of traditional Malagasy houses.

Considering these clustering results, climatic zoning is carried out next through interpolation. The estimated data are obtained with a spatial resolution of approximately 500 m per cell, i.e., a total area of 25 ha. The interpolation result is then discretized at the exclusion limits of the maximum values to obtain a 3-class climatic mapping of Madagascar's territory. Compared with previous work on Madagascar, our results partly match those of the Rakoto-Joseph classification [21]. However, similar to Attia's classification [23], the two previous classifications set thresholds to define categories; furthermore, the mapping is performed by overlapping raster data sets. Therefore, this approach presumes that the users of the proposed method have some knowledge of the studied territory to define the category thresholds. This represents a crucial difference because clustering is an unsupervised method, and thus, our climatic zoning is based on the similarity among station characteristics rather than on our own preferred grouping.

Our climatic zoning reveals two significant differences. First, the delimited highland area coincides well with the topography, which is appealing considering that a topography variable was not used during the interpolation process. The other difference is observed in the northern part of the island: whereas our results suggest a more equatorial/tropical climate zone, the previous classifications show either a semi-arid or a tropical warm climate. In addition, the particular case of Bealanana (noted earlier in the PCA discussion) is better understood in light of these mapping results; indeed, this city is located almost at the intersection of the three climate zones. This explains why it has been difficult to characterize the city of Bealanana in the past.

3.2. Typical weather data

In this section, we propose a synthesis of the climatic characteristics of the identified zones. The meteorological data presented are derived from the data of the most representative city of each cluster, namely,

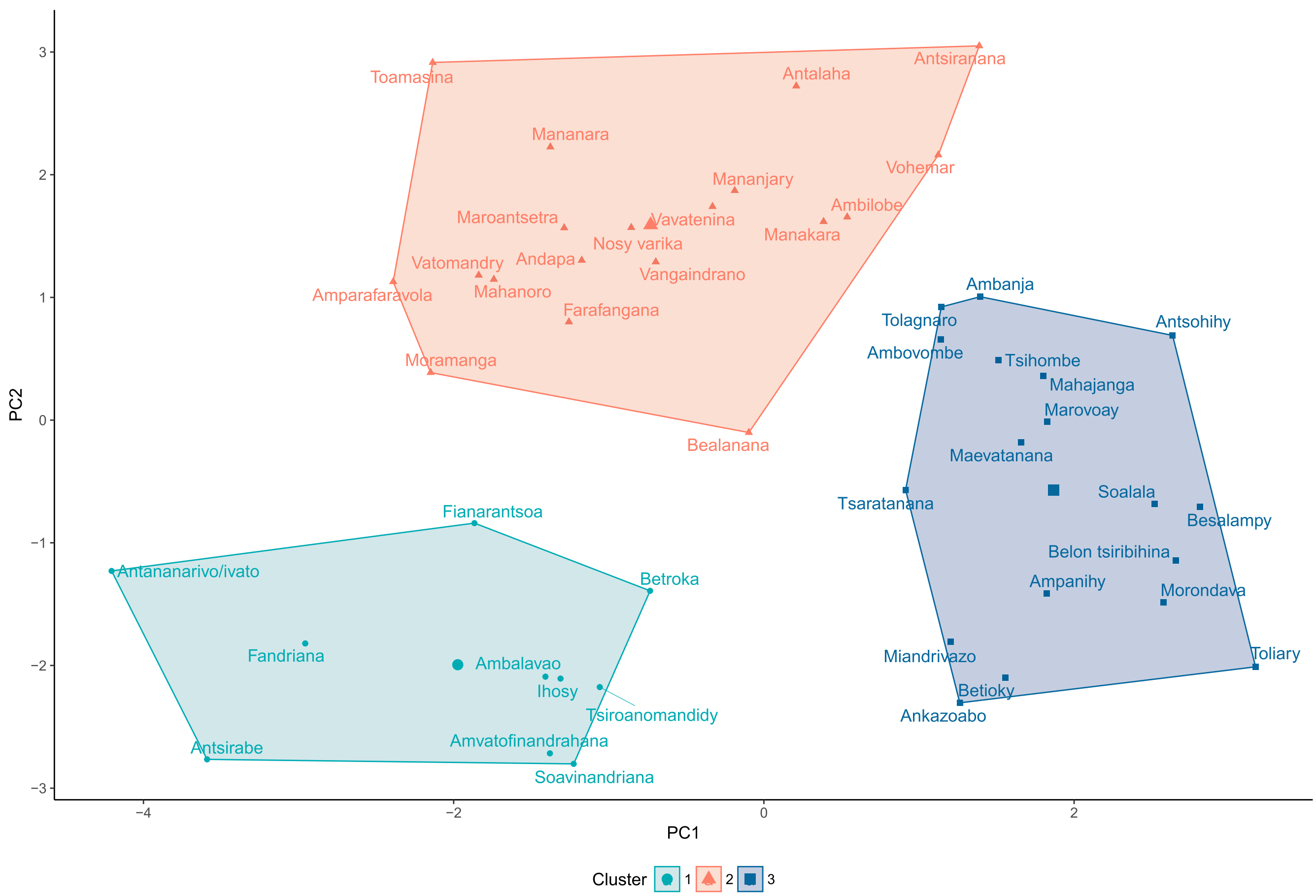


Fig. 5. Hierarchical clustering results for the weather stations.

the paragon. The yearly maximum and minimum values of each parameter are defined from the extreme values recorded in each cluster among the meteorological data from the studied cities. Table B.6 summarizes these climatic characteristics based on monthly average data. We also provide a link to the numerical data for each area in the table.

The city of Ambalavao presents the most representative data for zone 1 (see Table B.6). The average annual temperature is 20.7 °C with a cold period from June to July and a warm season from October to January. The wind speed is low and reaches a maximum between August and October. The solar irradiation evolves according to the same annual trend as the temperature, guaranteeing an accumulated global irradiation of approximately 7 kWh/m^2.

The cluster of climate zone 2 has a barycenter close to the data from the city of Mananara. Table B.6 presents the main characteristics of this zone located in the center of Madagascar. The temperatures in climate zone 2 are warmer than those in climate zone 1 with an annual average of 23 °C. The wind intensity is more important in this zone with a peak value reaching 5 m/s, and the accumulated global irradiation peaks in March (approximately 7 kWh/m^2).

Climate zone 3 can be represented by the city of Belon'i' Tsiribihina. Consistent with the findings of the previous sections, this zone is the hottest (average annual temperature of 25.8 °C) and receives significant solar irradiation during the October–January period. Table B.6 summarizes the main characteristics of climate zone 3. The standard weather files are provided as additional data for this article.

Our methodology proposes a different climatic zoning for some cities. For example, in this paper, the city of Bealanana is located in zone 2, while this same city is placed in zone 3 in the study of Rakoto-Joseph [21]. Boxplots of the annual atmospheric temperature and relative humidity are shown in Fig. 7. Three weather stations are compared: Bealanana, the city being discussed in this section, and Mananara and Belon'i Tsiribihina, which are the barycenters of zones 2 and 3, respectively. The distribution of annual temperatures confirms that the city of Bealanana has a temperature pattern much closer to that of the city of Mananara than to that of the city of Belon'i Tsiribihina. Our classification of the city of Bealanana in zone 2 seems more appropriate. However, the distribution of the annual relative humidity does not reflect the same result. According to the relative humidity, the city of Bealanana is more similar to Belon'i Tsiribihina than to Mananara and should therefore belong in zone 3. However, cross-analysis of these two parameters through the thermal comfort can reinforce the suitability of climate zone 2; the thermal discomfort shown by the Givoni chart in this area is associated mainly with elevated temperatures. The choice of zone 2 for the city of Bealanana is therefore affirmed by the air temperature criterion.

3.3. Thermal comfort

In this section, the thermal comfort results are presented for typical Malagasy houses, and the thermal comfort is evaluated for the climatic zoning established above through the method developed in this paper.

For this purpose, the cities in Fig. (A5) are chosen for their data availability and their affiliation as paragons of the 3 previously identified climate zones.

The types of buildings in each climate zone are examined first. In climate zone 1, it is common to find constructions of type 3 (very low thermal inertia), type 4 (medium thermal inertia) and type 6 (very high thermal inertia) buildings. In contrast, type 1 and type 2 (using stilt technology) buildings are preferred in climate zone 2 because of their

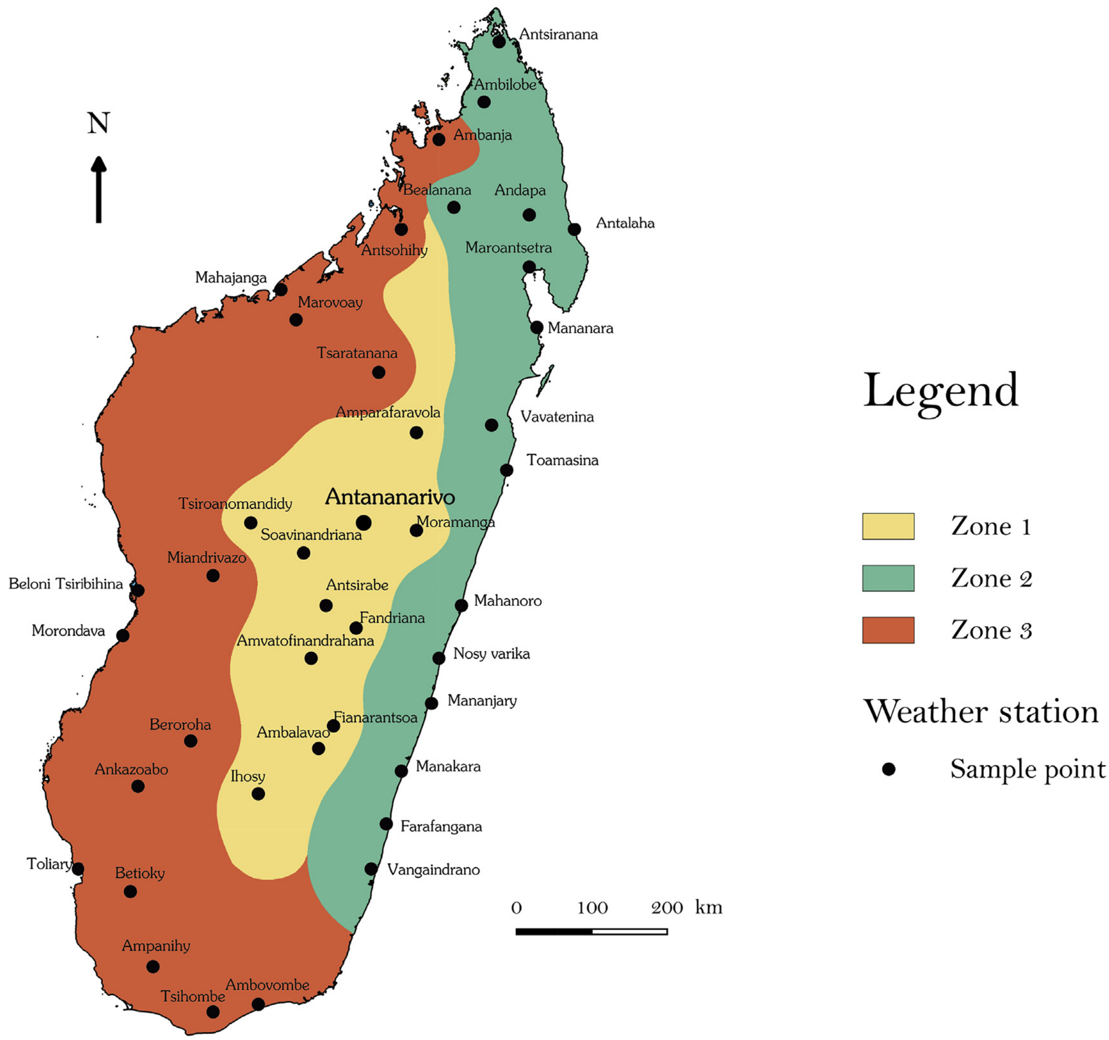


Fig. 6. Climatic zoning results.

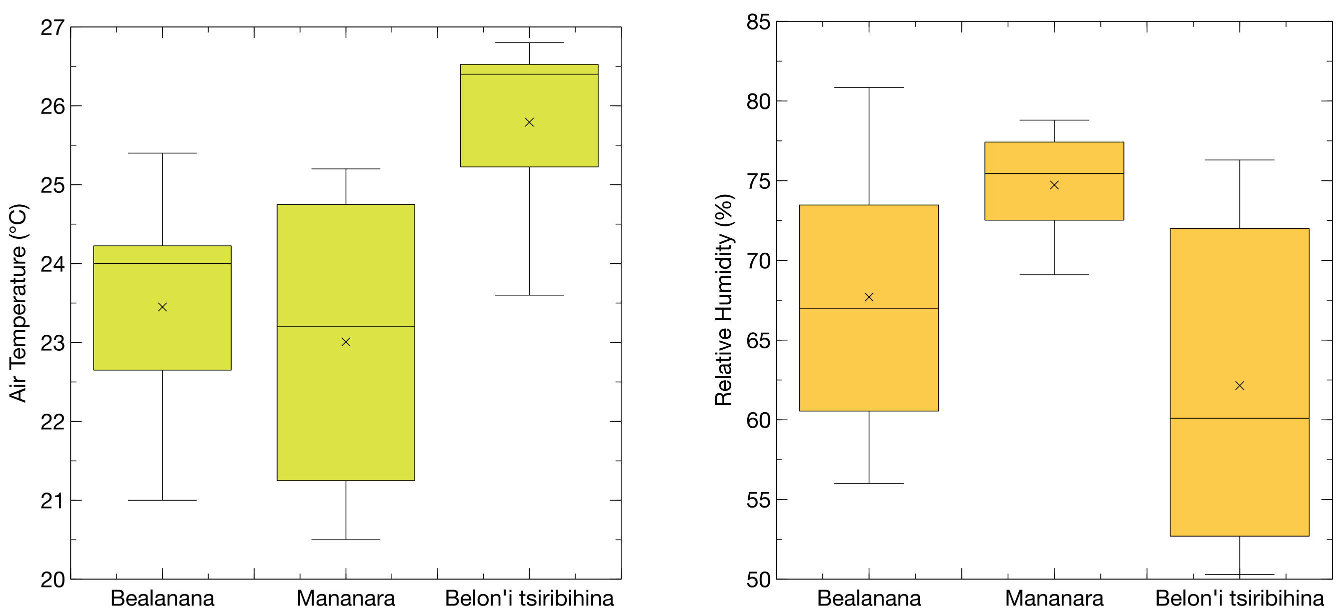
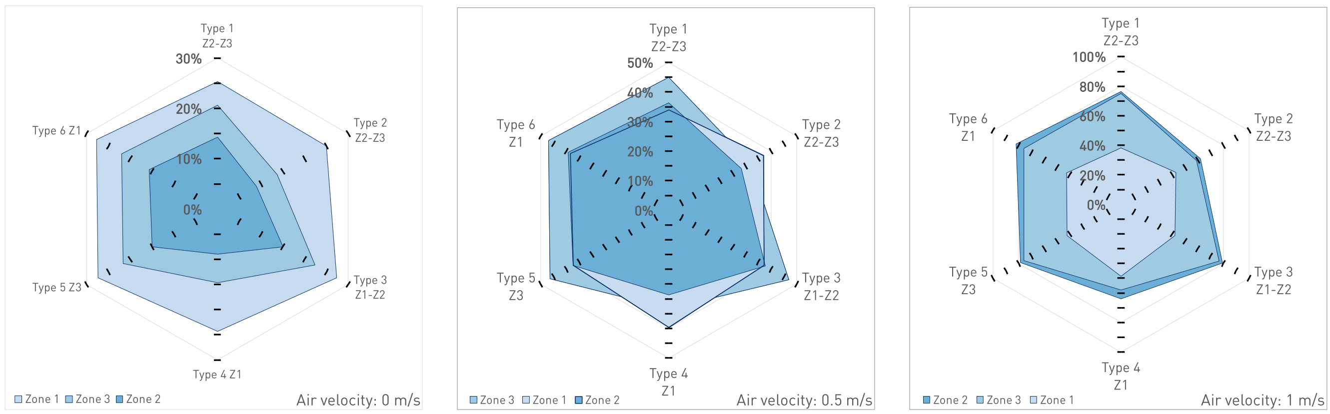


Fig. 7. Boxplots of the annual temperature and relative humidity for the weather stations at Bealanana, Mananara and Belon'i Tsiribihina.



(a) (b) (c)

Fig. 8. Percentage of the thermal comfort time in each climate zone for each type of building and air velocity (where each type is evaluated for each climate zone): (a) air velocity at 0 m/s; (b) air velocity at 0.5 m/s; (c) air velocity at 1 m/s.

possible exposure to rising water levels; in the same zone, however, type 3 buildings (involving the combination of a dirt floor with mud and earthen walls and a thatched roof) are used in drier areas. Type 2 and type 5 buildings are commonly found in climate zone 3 (i.e., in the northeastern, eastern and southeastern regions of the island of Madagascar).

As shown in Fig. 8, the thermal comfort results are presented in a radar diagram as a percentage of time for each type of Malagasy house (the percentages obtained correspond to the frequency of occurrence of the temperature-humidity pairs in each Givoni zone). Radar diagrams are plotted for the three specific air velocities presented previously (0 m/s, 0.5 m/s and 1 m/s), where Fig. 8 a) illustrates the results of a thermal comfort zone without any ventilation.

The results show that for climate zone 1, for all types of Malagasy houses, it is possible to reach a percentage of comfort time between 24 % and 28 %. Hence, even if the building materials used for the walls differ, the levels of comfort achieved are similar. These simulations thus show that for climate zone 1, which is the coldest zone in terms of temperature, the annual results exhibit a similar level of thermal comfort among all types of buildings.

For climate zone 2, the annual percentage of comfort time is between 9% and 16%. This climate zone contains areas exhibiting a high relative humidity that continuously exceeds 60%; accordingly, the results reveal that the investigated habitats in these areas have difficulty limiting the impacts of high humidity and temperature. The absence of ventilation in this climate zone limits the circulation of air in a building, and therefore, the occupants experience thermal discomfort. The type 2 and type 4 buildings studied herein display comfort time percentages of less than 15%. Here, thermal discomfort is related to the roof and wood-type materials used in type 2 and 4 buildings.

Nevertheless, at an air velocity of 0.5 m/s, which could correspond to the air velocity of natural ventilation (possibly a draught), the results show an increase in thermal comfort. In climate zone 1, each type of building can achieve the same average level of comfort, although the literature reveals that building types 3, 4 and 6 are the most commonly used. The most suitable architecture for climate zone 1 seems to be type 4, where the thermal inertia is marked by red brick walls and a clay floor and the buildings are covered by a low-inertia surface (sheet metal roofing).

In climate zone 2, the effectiveness of building types 1 and 3 (low thermal inertia), used frequently in this zone, is superior to that of type 2 buildings, which are also deployed throughout this climate zone and are characterized by a comfort time percentage of less than 30%. Therefore, it would seem that type 2 buildings are less adapted to this climatic configuration. Type 4 (medium thermal inertia) buildings achieve the same results as type 2 buildings; the sheet metal roofing causing a reduction in the thermal inertial potential of the red bricks. Type 6 buildings, defined by a dirt floor, red brick walls and a thatched roof, are not commonplace in this climate zone. Nevertheless, type 6 buildings offer the best results in terms of thermal comfort. This zone becomes rather hot in summer and cold in winter, and thus, the strong thermal inertia of the type 6 configuration is a major asset for regulating heat waves.

The results for climate zone 3, marked by temperatures displaying a significant regularity throughout the year, show that building types 1 and 5, which are popular in this territory, offer very good thermal comfort over almost half of the year. In contrast, type 2 buildings, also commonly distributed, are revealed to be unsuitable for climate zone 3 with a thermal comfort of nearly 32% over a full year. The best configuration is type 3 (medium thermal inertia), which involves the combination of a dirt floor with mud and earthen walls and a thatched roof; the porosity of the walls and the medium thermal inertia of the building make it possible to benefit from the regularity of the ground and outdoor air temperatures.

At 1 m/s, the air velocity is similar to that produced by mechanical ventilation or a fan. In this scenario, climate zones 2 and 3 offer very similar results for each type of building with year-round thermal comfort rates exceeding 70%. Because these climate zones are the warmest, it is expected that they present suitable results when the air velocity circulates the volumes of warm air in the buildings therein. We note, however, that building types 3, 5 and 6 offer significant results. The linearity of the temperature of the dirt floor is a very interesting cold thermal source in the regulation of temperature within buildings. In contrast, type 4 buildings, which are equipped with sheet metal, thereby limiting the benefit of the thermal inertia inherited from the red bricks, have a negative impact on thermal comfort (the sheet metal, which is highly exposed, will accentuate the high heat loss). In climate zone 1, the comfort results are poor. An air velocity of 1 m/s does not improve the results previously noted at 0.5 m/s. Nearly 60 % of the year, The occupants experience thermal discomfort throughout nearly 60 % of the year where even passive cooling (e.g., a fan) is ineffective. Nevertheless, building types 3, 4 and 6, which are frequently installed in this area, offer the optimal results.

Traditional construction methods have historically been assigned to climate zones. Some design choices are relatively well adapted, while others limit the annual proportion of thermal comfort. We note that for all climate zones combined, building types 3 and 6 are, on average, the most effective. By focusing on each climate zone, we can analyze the frequency of occurrence of the efficiency of each building type for the three air velocities studied. Thus, in climate zone 1, we recommend erecting buildings according to the construction method of type 4 (dirt floor + red brick + sheet metal roofing) to reach an annual comfort time of 38%. In climate zone 2 (mild to cool climate), the high thermal inertia of type 6 buildings (dirt floor + red brick + thatched roof) seems to guarantee an annual comfort rate of 46% . Finally, type 3 buildings (dirt floor + mud and earthen walls + thatched roof) are associated with guaranteeing the longest average thermal comfort time in climate zone 3. Overall, the results of this study are promising; however, they will require further analysis to validate the overall relationship between the construction mode and climate association in Madagascar.

4. Conclusion and policy implications

The issues of housing construction and construction quality are major challenges for a developing country such as Madagascar. Indeed, Madagascar must meet growing housing needs in important urban areas due to a gradual demographic transition. This population growth leads to a new influx of people to major Malagasy cities. The capital alone possesses more than 2.6 million inhabitants. In addition, construction in a tropical environment also requires effective practices that adapt to different climates. It thus seems indisputable that the climate zones of Madagascar should be characterized for the adaptation of building construction practices throughout the territory. Correspondingly, the objective of this work was to propose an unsupervised zoning method applicable in areas with low data availability.

The literature revealed no consensus on the appropriate methodology for climate zoning. Two categories of state-of-the-art methods were identified: clustering and class methods. The choice of method is highly dependent on the objectives of the study and the availability of data. Our case study focused on describing three existing climate zoning schemes based on a classic approach. The results obtained showed some consistency in the characteristics of the areas with variations in their location.

Therefore, our objective was to analyze Madagascar's climate using a clustering method coupled with PCA. We used a new database of 47 weather stations spread across Madagascar to identify 3 climate zones: climate zone 1, which encompasses the central highland region of the island with mild summers and cold winters; climate zone 2, which is slightly hot and humid; and climate zone 3 incorporating the western part of the island with a warm tendency in summer and a mild tendency in winter.

The use of GIS enabled us to establish a climatic zoning of the entire territory of Madagascar. The three climate zones were defined through a combination of multivariate analysis and spatial interpolation. The results seem consistent with the reality of the territory. We thus delineated the following organization: the highlands of Madagascar separate a dry area in the west from a wet area in the east. To illustrate this climate zoning, we studied the links between established climate zones and the thermal comfort conditions therein according to traditional habitat typologies. The results showed that certain types of buildings make it possible to guarantee a superior annual comfort rate. For example, we demonstrated that type 3 (clay floor + mixed walls (earth + mud) + thatched roof) and type 6 (clay floor + red brick + thatched roof) buildings were the most efficient annually (with all climate zones combined).

This work has highlighted that traditional construction practices are well adapted to their environmental constraints. Unfortunately, these practices tend to give way to the modernization of new construction in urban areas. This study is the first part of a more global investigation of traditional and modern Malagasy construction practices. Future studies will assess the performance of buildings in the climatic zoning developed herein to implement specific thermal regulations for Madagascar. In particular, future studies will address the application of our methodology to other islands in the Indian Ocean.

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Appendix A. Weather files used for the thermal comfort simulation

Table A.5
Weather files used for the application

Climatic zone	Town	Geographical coordinates	Location	City type	Weather file
1	Morondava	20° 17′ S 44° 19′ E Elevation: 8 m		Urban and rural areas Plain and cottage town	MDG_TL_Morondava .AP.671170_TMYx.epw
	Toliara	23° 21′ S 43° 40′ E Elevation: 11 m		Urban area Cottage town	MDG_TL_Toliara .AP.671610_TMYx.epw
	Antsohihy	14° 53′ S 47° 59′ E Elevation: 120 m		Urban and rural areas Plain	MDG_MA_Antsohihy .AP.670200_TMYx.epw

(*continued on next page*)

Table A.5 (*continued*)

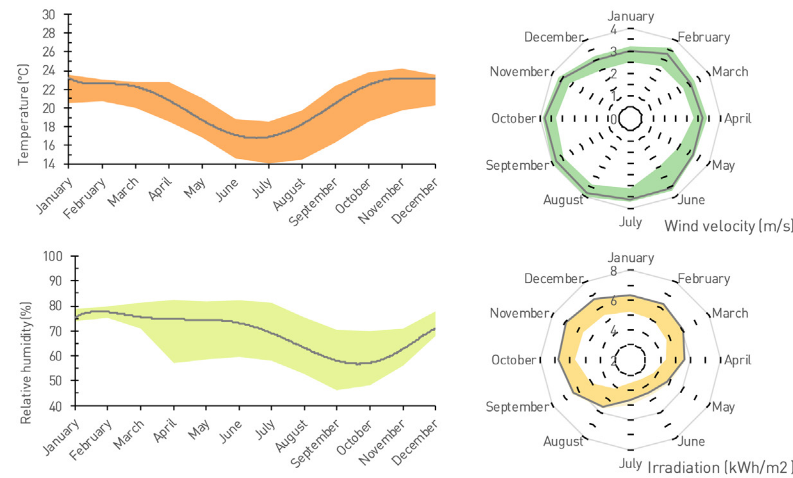
Climatic zone	Town	Geographical coordinates	Location	City type	Weather file
2	Antananarivo	18° 54′ S 47° 31′ E Elevation: 1275 m		Urban area Highlands	MDG_AV_Antananarivo-Ivato .Intl.AP.670830_TMYx.epw
	Antsirabe	19° 52′ S 47° 02′ E Elevation: 1500 m		Urban area Highlands	MDG_AV_Antsirabe .AP.671070_TMYx.epw
	Fianarantsoa	21° 27′ S 47° 05′ E Elevation: 1200 m		Urban area Highlands	MDG_FI_Fianarantsoa .AP.671370_TMYx.epw
3	Farafangana	22° 49′ S 47° 49′ E Elevation: 10 m		Urban area Cottage town	MDG_FI_Farafangana .AP.671570_TMYx.epw
	Mananjary	21° 13′ S 48° 20′ E Elevation: 10 m		Urban area Cottage town	MDG_FI_Mananjary .AP.671430_TMYx.epw
	Mahanoro	19° 54′ S 48° 48′ E Elevation: 10 m		Urban and rural areas Cottage town	MDG_TM_Mahanoro .AP.671130_TMYx.epw

Appendix B. Main characteristics of each climate zone

Table B.6
Main characteristics of each climate zone.

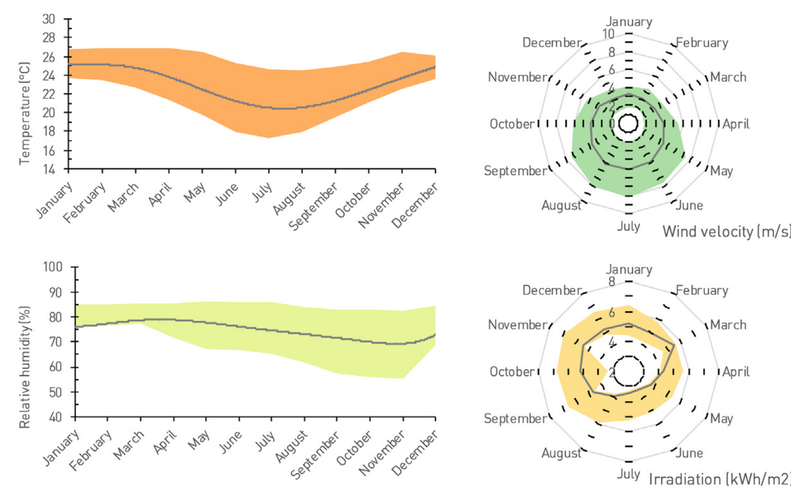
Climate zone	Main characteristics

1



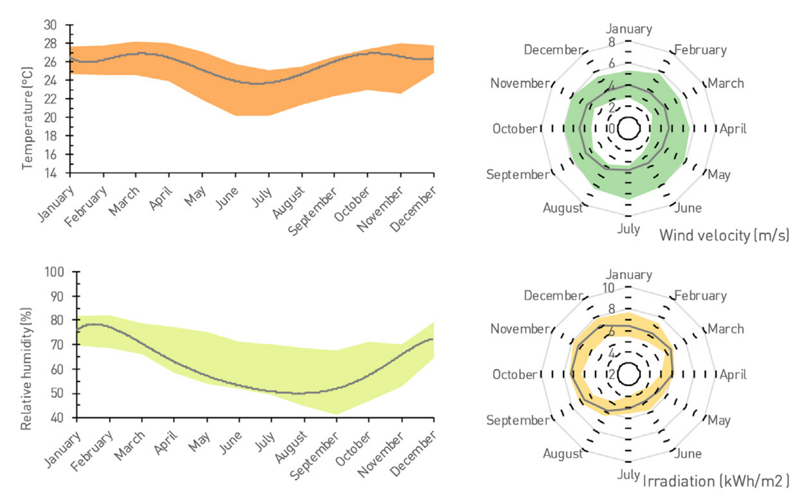
Reference city: Ambalavao

2



Reference city: Manara

3



Reference city: Belon'i'tsiribihina

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