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GIS-based approach to define 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 is a crucial issue when considering comfort and limiting energy needs. A preliminary part of such design is an accurate knowledge of the climatic conditions in each region of the studied territory. The objective of this paper is to propose climatic zoning from a database of 47 meteorological stations in Madagascar by investigating hierarchical clustering on principal components. Then, theses results are combined with a spatial interpolation using a *Geographic Information System* approach. This step allows us to define three climatic zones corresponding to dry, humid and highland zones. These results make it possible to define standard meteorological files that are used to evaluate the thermal performance of traditional Malagasy houses. Regardless of the type of house and the areas considered, the percentage of comfort, according to Givoni bioclimatic chart, varies from an average value of 20 % to 70 % without ventilation and with an air velocity of 1 m/s, respectively. It can be concluded that Madagascar's traditional habitat has adapted over time to the constraints of its environment.

Keywords: Madagascar, Climate zone, Clustering, PCA, Givoni Bioclimatic Chart, GIS

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1. Introduction

Climatic zoning is an essential prerequisite for climate responsive building design [1–3]. The importance of an accurate knowledge of climate conditions for building energy efficiency simula-

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tion is widely known. According to the World Energy Outlook 2018 by IEA[1], the world energy consumption for building sector was 3,047 Mtoe which accounted for 31.4 % of the total final consumption in 2017 [4]. Environmental issues are at the forefront of regulatory requirements. Taking into account both the energy and environmental performance of buildings is a logical approach which will become widespread and the rule for all in the future. For developing countries like Madagascar, these issues are all the more important because they can weaken or boost the country's development. By 2020, developing and emerging countries will be more energy-intensive than developed countries, [5]. Thus minimizing energy demand in the construction sector through building in a climate-resilient manner is an appropriate option to decrease their energy vulnerability due to fossil fuel imports.

Like many developing countries, Madagascar is experiencing rapid urbanization. Out of a total population of 25.57 million (2017), the country has now nearly 7 million urban dwellers, compared to 2.8 million in 1993. In 20 years, the combined effect of population growth, rural exodus and interurban migration to the capital have led to a 50 % increase in building construction. The national energy balance 2017 of Madagascar [6] shows that the residential sector represents 3,245 ktoe that is 59 % of the final energy consumption. Urban areas must therefore face the challenge to sustain and mitigate energy consumption due to urban population growth and economic development [7]. One of the possible actions would be to build buildings that are adapted to their environment and therefore low in energy consumption.

The purpose of this research is to investigate a new approach to define climatic zoning in the case of low data availability. Our approach is based on a combination of zoning from GIS interpolation coupled with clustering. Another objective of the study is to update the Malagasy climatic zoning by redefining the geographical boundaries of climatic zones 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. Finally, the illustration of this zoning will allow the evaluation of the thermal comfort of traditional Malagasy houses and also the definition of typical meteorological files.

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[1] International Energy Agency

1.1. State-of-the-art in climate zoning

There are different ways to identify climatic zones based on different criteria using clustering methods (statistical analysis by group observation and analysis of possible groupings, also called “modern methods”) [8] or class methods (with the use of thresholds for climate variables and indices, also called traditional methods) [8]. The selection of the method largely depends on the objective of the climate classification. Among the most recognized classifications based on class method, the Köppen-Geiger classification is often considered as a reference in the field and supports many multidisciplinary studies [9, 10]. This classification established climatic zones based on natural vegetation cover. Köppen decomposed the zones into five climatic zones: an equatorial zone (A); an arid zone (B); a temperate warm zone (C); a snow zone (D); and a polar zone (E). The classification added nuances through second and third letters related to precipitation and temperature. Köppen classification is a powerful classification for global analysis [11]. It is often illustrated as being a diagnostic tool to monitor climate change on different time scales and for different aspects. It was used to highlight the effect of climate change on ecosystems, energy consumption or climate variability at different time scales [12–15]. This method was not unanimously accepted when used for other purposes. Many authors showed that in specific use cases this approach has limitations. For a local problem, other methods were more precise and more consistent with the identified climate zones : clustering methods. A comparative study was carried out by Zscheischler [16]. This author proposed to compare the accuracy of the Köppen-Geiger classification to that of principal component analysis (PCA) using the ”k-means” clustering method. The study verified that climate and vegetation variables constructed similar groups and then showed that the parameters used in the Köppen-Geiger classification are not optimal for categorizing a climate. The use of clustering based on meteorological data allows better results to be achieved. Other comparisons were also conducted in recent years [17–19] and some even showed that Köppen did not allow to obtain specific information necessary for the problem of building design and thermal comfort [20–22]. Other class methods also used for climate classification to study comfort in the building [3, 20, 22] or for climate classification of urban and rural sites [23–26]. Multivariable statistical analysis based on clustering methods makes it possible to obtain an efficient climate classification [27] and seem more coherent for building concerns [8]. Other studies confirmed the interest of clustering [28, 29] and specifically of k-means clustering with Euclidean distance correlation as a measure of similarity for the classification of a climate in general [16, 18] or adapted to a building [1, 2, 22, 30–33]. The quality and availability of the parameters used for climate classification are essential. The literature reveals that many parameters, from various origins, make it possible to guide the climate classification according to its final objective. The representativeness of the data in the climate analysis is a significant criterion, especially for clustering methods. Clustering methods or class methods use (i) climate data (outdoor air temperature ; outdoor relative humidity ; global solar irradiation; precipitation; altitude; wind velocity and direction; atmospheric pressure) [20, 21, 27] (ii) climate indexes (sky clearness index kt) [34] (iii) topographic parameters [34] or (iiii) thermal comfort indexes (Terjung's comfort index [35, 36] ; Physiological Equivalent Temperature PET [23]). The global solar irradiation, outdoor air temperature, and wind velocity seem to be the best correlated to analyze a climate [20]. Temporality is an important factor which could attest the quality in a climate classification. All the authors seem to agree on the need to base a climate study on a database averaging ten years [8, 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 too long, the classification may not take into account the effect of climate change.

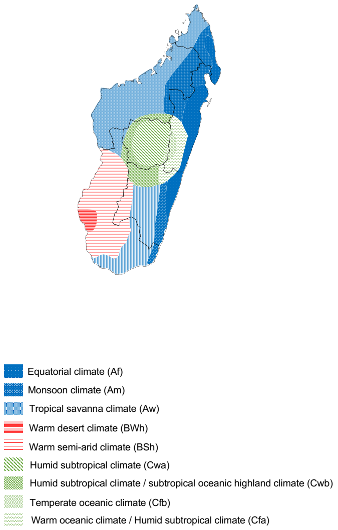
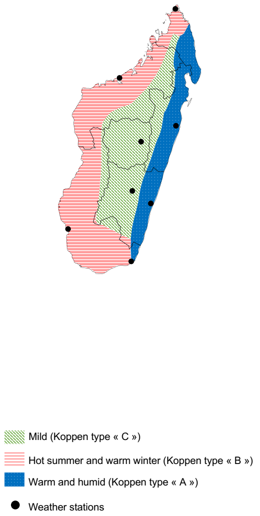
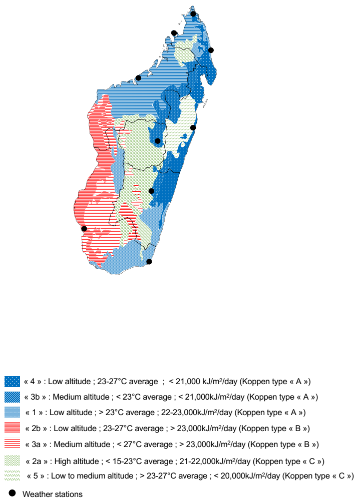
1.2. Existing climatic zoning of Madagascar

Madagascar is in a humid tropical zone under the influence of four types of wind. The trade winds that bring rain to the coastal region and eastern slopes are the most predominant. The region is divided into nine Köppen areas; the areas were re-examined by Peel in 2007 [10]. In 2009, [20] 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 as the most representative of the established climate zones. The classification used temperature, solar irradiation, wind velocity and altitude data to define layers that overlay to bring together coherent areas. This classification allowed the author to obtain six climatic zones, which he divided again into three zones for coherence with the "building" problem. The average temperatures and humidities used were those of the coldest and hottest months of the year. Unlike Peel-Köppen which serves a global objective, Rakoto-Joseph's classification makes it possible to propose passive technological solutions for buildings. In 2019, Attia [22] proposed a new classification of the island based on the Rakoto-Joseph and Peel approaches. Using solar irradiation, temperature and topography data from Madagascar, synthesized within the Prieto equation [38], Attia defined six characteristic climatic zones. This approach used a threshold-based method to define layers and infer zoning and used the databases of 9 stations spread over the territory (Tolagnaro, Toliary, Antananarivo, Mahajanga, Nosy-Be, Antsiranana, Sambava, Toamasina, and Fianarantsoa).

Table 1 compares the approaches and results of the three existing studies. The climatic zoning maps were reissued with the outlines proposed by each author but in colors that allow contrast. Compared to the Rakoto-Joseph study, the Peel and Attia classifications offer a higher level of detail. With the size and shape of the climatic zones, we notice similarities: the Eastern zone is a warm and humid zone of equatorial climate type. The central zone of Madagascar, at high altitude, is also classified as a ”C” (temperate climate) zone where the climate can be mild to cool. For the Southwest zone, the classifications also agree on a climatic classification with a ”dry climate” tendency of type ”B” according to Köppen. The Northwest zone shows disparate results for the Rakoto-Joseph method which classifies an area considered as a savannah climate with a dry winter by Peel and Attia (type ”A” according to Köppen) as an area where summer and winter are hot (type ”B” according to Köppen).

Table 1: Comparative analysis of Madagascar’s three existing climate classifications

	Existing climate classifications		
Reference	**Köppen classification [10]**	**Rakoto-Joseph classification [20]**	**Attia classification [22]**
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 humidity of the hottest and coldest months	Altitude Solar irradiation Dry bulb temperature

	Existing climate classifications		
Reference	**Köppen classification [10]**	**Rakoto-Joseph classification [20]**	**Attia classification [22]**
Period and/or Weather stations	Several stations worldwide with an interpolation between each station	Period of 29 years that lacks geographical precision For building concerns: six local meteorological stations are representative of the established climate zones (Antananarivo, Fianarantsoa, Antsiranana, Mahajanga, Toliary and Toamasina)	Nine local meteorological stations available between 1991 and 2008 (Tolagnaro, Toliary, Antananarivo, Mahajanga, Nosy-Be, Antsiranana, Sambava, Toamasina et Fianarantsoa)
Classification method	Based on limits + layer		
Results			

The work of Rakoto-Joseph and Attia offers a study adapted to building needs with a limit on the accuracy of climatic zoning. As Attia points out, increasing the number of data points would enable to confirm or disprove climate trends.

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

2. Methods

This study is split into two main parts. The first part describes a weather centered clustering which defines the climatic zoning of Madagascar while the thermal performance of traditional Malagasy housing in the different zones and discusses the main results of the study are investigated in the second part. Figure 1 provides an overview of the method and objective of the article.

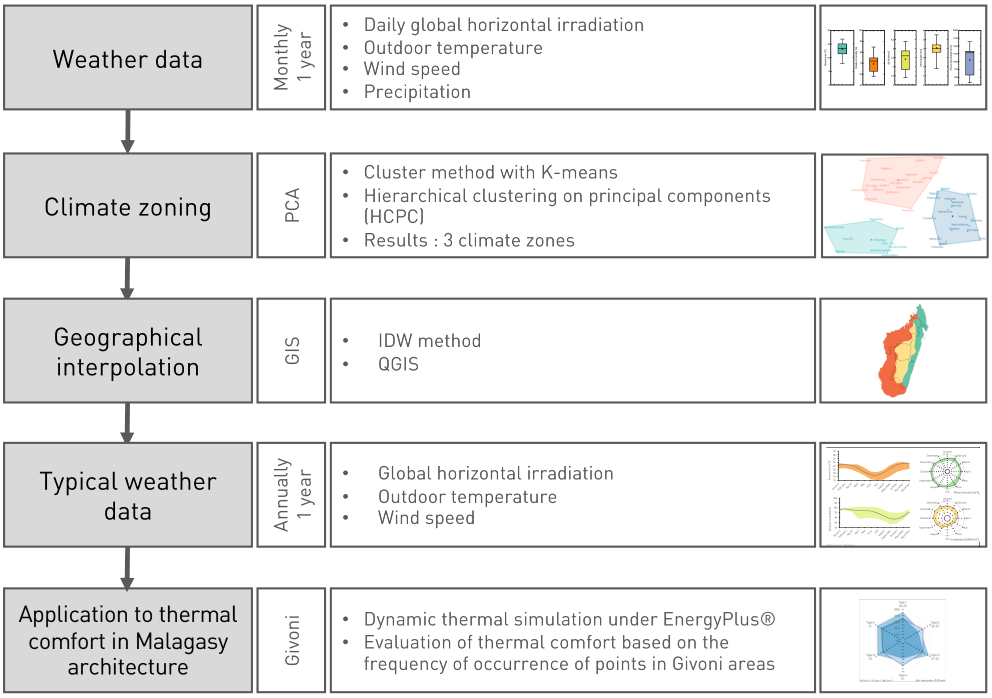


Figure 1: Synoptic view of our overall methodology

One of the ambitions of this work is to propose a global approach where meteorological data are not readily available, to define standard files allowing building simulations to be carried out. To do this, our approach was to classify the meteorological data and then identify the meteorological station most representative of a given climate zone.

2.1. Data collection

The first task in defining climatic zoning map is the meteorological data collection. Madagascar is a particular case because of the low availability of hourly weather files. Our study is based on a database of 47 stations spread over the entire country. The few data available over a year are monthly files. The database used for the principal component analysis consists of five meteorological data: outdoor temperature,relative humidity, wind speed, daily Global Horizontal Irradiation (GHI) and precipitation. Geographic informations such as longitude, latitude, and altitude were also considered. Figure 2 shows the amplitude of variation of the meteorological data. In the case of GHI, relative humidity and precipitation, the median is at the top of the box, which implies an asymmetric distribution towards the high values of each of the variables. The results of the boxplot show us that it will be these three variables that will play an essential role in the partitioning of the data and therefore in our unsupervised classification.

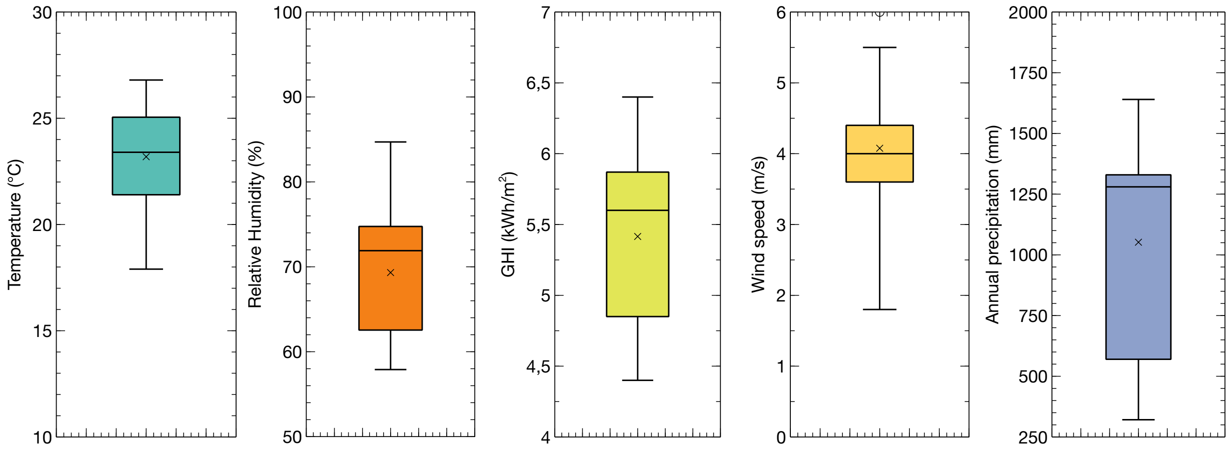


Figure 2: Boxplot of climatic data for 47 meteorological stations in study area of Madagascar.

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

As pointed out by Kassambara in [39], the HCPC approach allows the combination of three techniques basically used in multivariate data analysis, namely hierarchical clustering (HCA), the k-means partitioning method, and PCA.

PCA is a dimension reduction method that allows the exploration and visualization of a matrix of individual data by quantitative variables. 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 can be considered as a preliminary step to increase the stability of the classification, 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 pre-specified numbers of clusters. The optimum height to cut the dendogram is defined by Silhouette method optimization. Partitioning is made more robust by applying the K-means. The objective is to highlight groups (called clusters) of similar objects in a dataset heuristically. This method automatically classifies the 47 weather stations into homogeneous groups according to Ward's criterion [42]. The algorithm thus makes it possible to group the individuals closest to them in the projection plane of the first two principal components. Compared to the work of Zscheischler, [16], our classification is a two-step process, first the HCA which allows us to define the first partition of our projected data on the two best principal components. Then the K-means which is a centroid-based algorithm 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 is a process of reconstructing the values of a georeferenced variable over a territory from a limited number of sampling points. This step is particularly interesting in the case where a territory does not have a spatial grid of data of sufficient or equal quality. The hypothesis that validates a process such as interpolation is 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 abstraction between the interpolation methods is affected by the phenomenon under study. In this proposal, the inverse distance weighting (IDW) is used. The principle of this technique is that it uses a weighting coefficient so that the calculation of the value of a point is achieved by averaging the values of points located in the vicinity weighted by the inverse of the distance. Reverse distance weighting (RDW) works according to the principle of the first law of geography, according to which close things are more related than more distant things. In contrast to geostatistics, the so-called deterministic inverse distance method is well suited to this dataset and demonstrates the advantage of being usually 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 the investigation is to obtain, in the end, a spatial estimation of the values from the sampling points in order to consider a mapping of the study area.

In order to create spatial distribution maps of the meteorological parameters (through the cluster number), an inverse distance weighted (IDW) interpolator was used. The generic formulation was defined by Bartier and Keller, [48] as defined in Eq. 1, [49]. Thus, the power parameter p determines the more appropriate value closest to the interpolated point. In the implementation of 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 of the sample point to the estimated point. The variable β called the exponent value improves the accuracy of the IDW between the measured and estimated data [52].

2.4. Traditionnal housing simulation

The objective of the comfort study is to depict a link between established climatic zones and thermal comfort conditions according to the traditional habitat typology. To do this, we choose cities that are representative of the weather conditions in each thermal zone and for their data availability. Weather files in "epw" format are used. As a reminder, the meteorological files used during the simulations are those of the paragons, which represent the average behavior 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.

Computer simulations are conducted with the well-recognized software EnergyPlus [53]. EnergyPlus 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. Its gables (350 cm long and 350 cm high) are oriented north and south. The west and east facades

(450 cm long and 200 cm high) contain the openings (180 cm high by a 90-cm-wide door and 80 cm high by a 60-cm-wide window). For our study, traditional Malagasy houses have been divided into six types. The six types of houses created for simulations were made from building materials that are often found in Madagascar. The details of all these types are presented in Table 2.

Table 2: Description of the six types of 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

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

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

Component	Material	Thermal conductivity $\mathrm{W/m\,K}$	Density $\mathrm{kg\,m^{-3}}$	Specific heat $\mathrm{J\,kg^{-1}\,K^{-1}}$	Thickness 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

The occupants are 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 8am to 12am and from 13pm to 18pm. The metabolic rate of the occupants is based on the ASHRAE 55 [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 an understandable comparison, we propose to study the adaptability of traditional architecture to the climate zoning found. To do this, we use 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 part 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). To do so, the approach used four of the leading environmental parameters (operating temperature, relative air humidity, and air velocity) and analyzed comfort situations taking into account physiological evapotranspiration phenomena for a sedentary activity and light clothing (summer clothing). This method allows defining 4 comfort zones linked to 4 different wind speeds from 0 to 1.5 $\mathrm{m\,s^{-1}}$. Above 1.5 $\mathrm{m\,s^{-1}}$, the air velocities are too high and are considered a draught. In reality, we will focus on the first three comfort zones (0 $\mathrm{m\,s^{-1}}$, 0.5 $\mathrm{m\,s^{-1}}$ and 1 $\mathrm{m\,s^{-1}}$). The Givoni areas are designed for summer clothing (0.5 clo) and for office metabolic activity (1.2 met). The results obtained, which are very intuitive, 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.

The percentages obtained correspond to the frequency of occurrence of the Temperature-Humidity pairs in each Givoni zone, as shown in Figure 3.

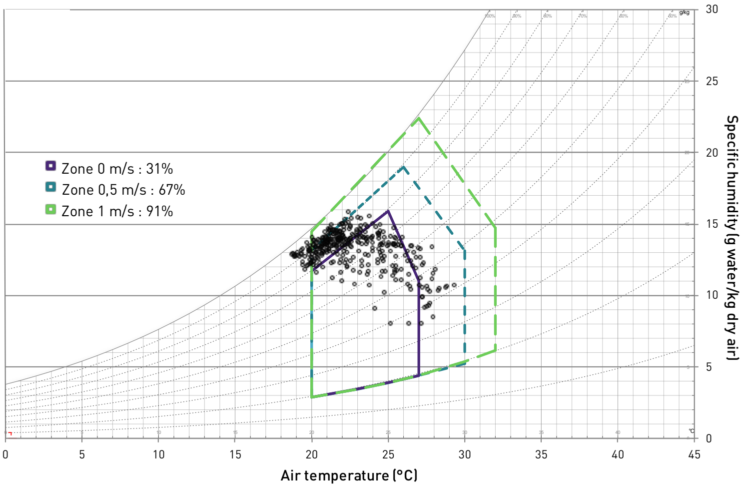


Figure 3: Psychrometric chart of Givoni with 3 areas (0 $\mathrm{m\,s^{-1}}$, 0.5 $\mathrm{m\,s^{-1}}$ and 1 $\mathrm{m\,s^{-1}}$) and the associated occurrence frequencies

3. Results and discussion

3.1. Climatic zoning

Considering the methodology presented in Fig. 1 in section 2.2, a PCA is conducted on a matrix of 47 weather stations characterized by nine variables. Previous to the determination of the clustering, a preliminary investigation of the individual's map projection in Figure 4, was necessary to understand the main characteristics of the weather station and also and detect any aberrant data.

In the decomposition of the total inertia, the first two principal components 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. This plan 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 the following Table 4. The results of PCA for the weather stations are depicted in Fig. 4. Thus, as can be observed, the stations are organized into four main parts: Midlands, Highlands and two Costal area. The general layout of the projection does not highlight any outliers. The dataset appears to be organized into three groups, which will be verified during the clustering step. Fig. 4 shows the projection on the first two components. The first component opposes regions characterized by high values for temperature and solar irradiation and also low altitude, on the right part of the PC1 axis. For the second component, the upper part of the graph is characterized by rather heavy rainfall areas exposed to wind with high relative humidity. The data projection quality is represented by the variable cos^2 which is the cosinus 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 almost located on the origin of the principal components. Consequently, this indicates that Bealanana's position cannot be correctly interpreted in this first plane.

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

This first step allowed us to observe the first organization of the weather stations. In addition, we were able to define the main characteristics of the projection plane (PC1, PC2), on which the clustering results are projected later on. These details are provided below in the description of the clusters.

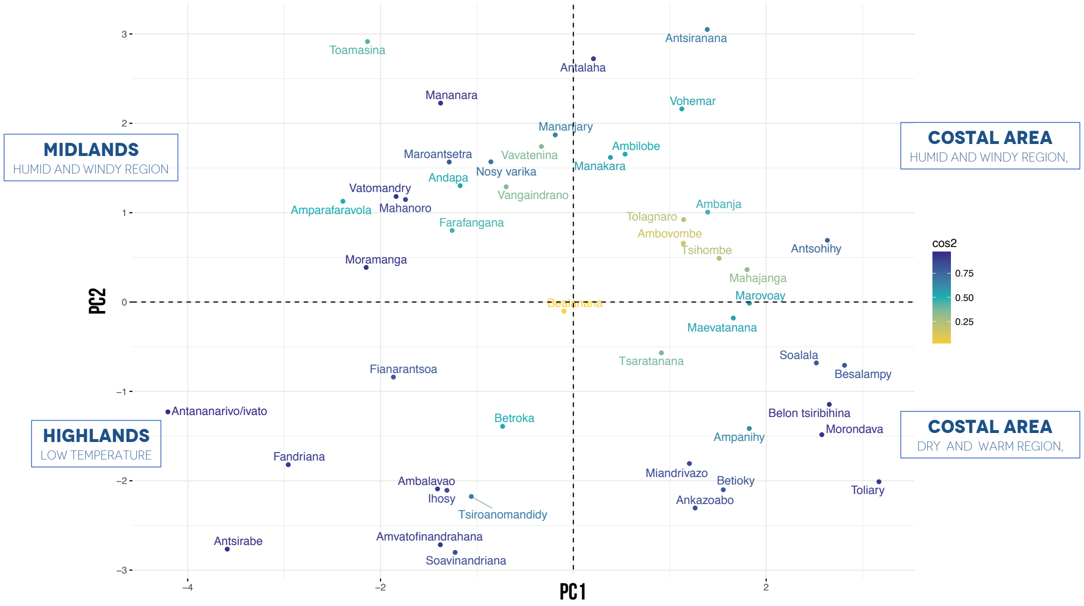


Figure 4: The individual factor map (PCA)

The clustering results projected on the plane (PC1, PC2) are presented in Fig. 5. The results highlight three clusters that have 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 the highland areas, characterized by the precipitation, wind and temperature variables. These regions are subject to low rainfall compared to the average for Madagascar. The variables that most characterize the second cluster are relative humidity and precipitation. This cluster corresponds to the eastern region. The mean value of these two variables in the cluster is higher than the overall mean. The third cluster considering all variables is mostly described by the highest values for temperature and solar irradiation and low altitude. This cluster corresponds to the western zone of Madagascar with hot and dry climatic conditions. This area is a dry or even arid region if we consider in particular the south of the island. Thus, the characteristics inherent to each cluster have made it possible to highlight three very different climatic zones, correspondingly, from the west to the east: a dry zone, highlands and a wet-humid area. Clustering is not only interpreted according to variables but also according

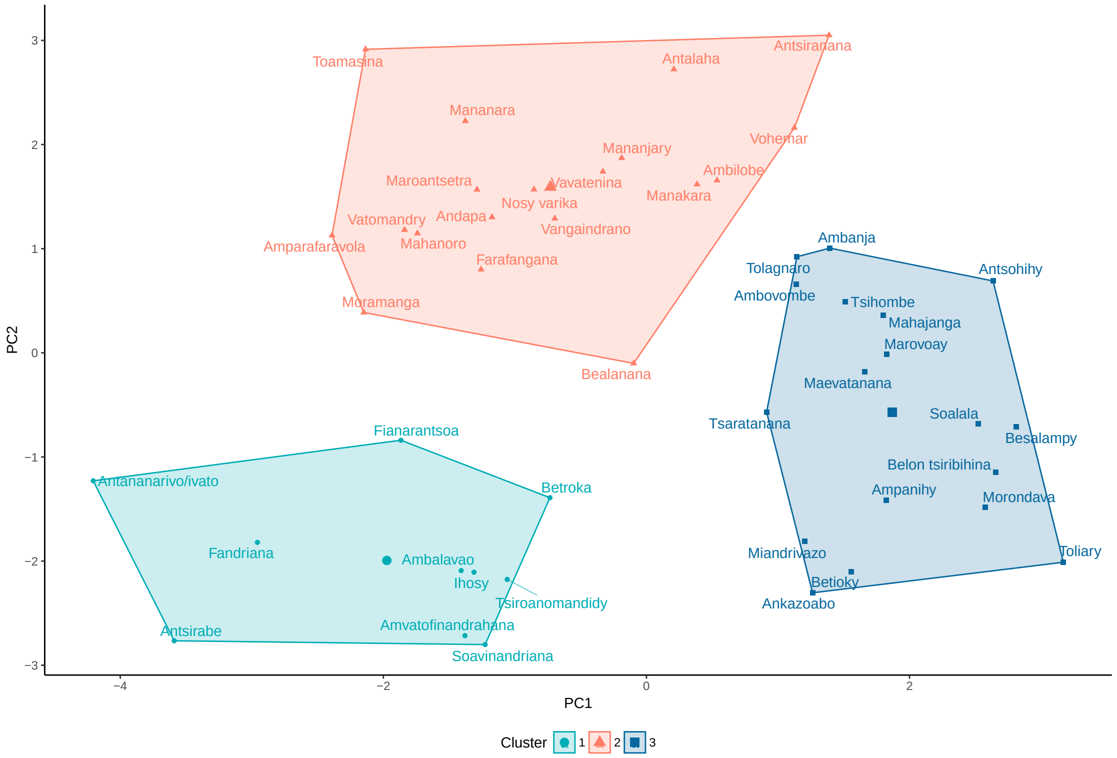


Figure 5: The result of the hierarchical clustering of the weather stations.

to individuals. Indeed, it should be recalled that the purpose of this study is an application of classification in the field of thermal comfort in the specific case of traditional housing. Madagascar, like many developing countries, does not always have meteorological data for its entire territory. Thus, this clustering allows us first to define and characterize these climatic zones, in particular these borders. The second result of clustering is an identification of paragons. For each group, the individual whose coordinates are closest to the barycenter is called the paragon. The profile of this individual then 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 a significant result, as they make it possible to define typical weather files for each area. In this work, the choice was made to take the paragon as the average behavior of individuals of a cluster rather than the center of gravity, which is a fictitious individual. In the rest of this article, we will, therefore, consider these three files for the evaluation of the thermal comfort of traditional Malagasy houses.

Considering this clustering, zoning is carried out in the next part by performing an interpolation. The estimated data are obtained with a spatial resolution of approximately 500 m per cell, i.e., a total area of 25 hectares. The interpolation result is then discretized at the exclusion limits of the maximum values in order to obtain a 3-class climate mapping of Madagascar's territore. Compared to previous work on Madagascar, our results partly match those of Rakoto-Joseph, [20]. However, like Attia's research [22], the two previous approaches are classifications that set thresholds for defining categories. The mapping is done by overlapping raster data sets. This, therefore, presumes that users of the proposed methods have some knowledge of the territory studied to define category thresholds. This point is a crucial difference because clustering is an unsupervised method, so our zoning is based on the similarity of station characteristics and not on our own choice of grouping.

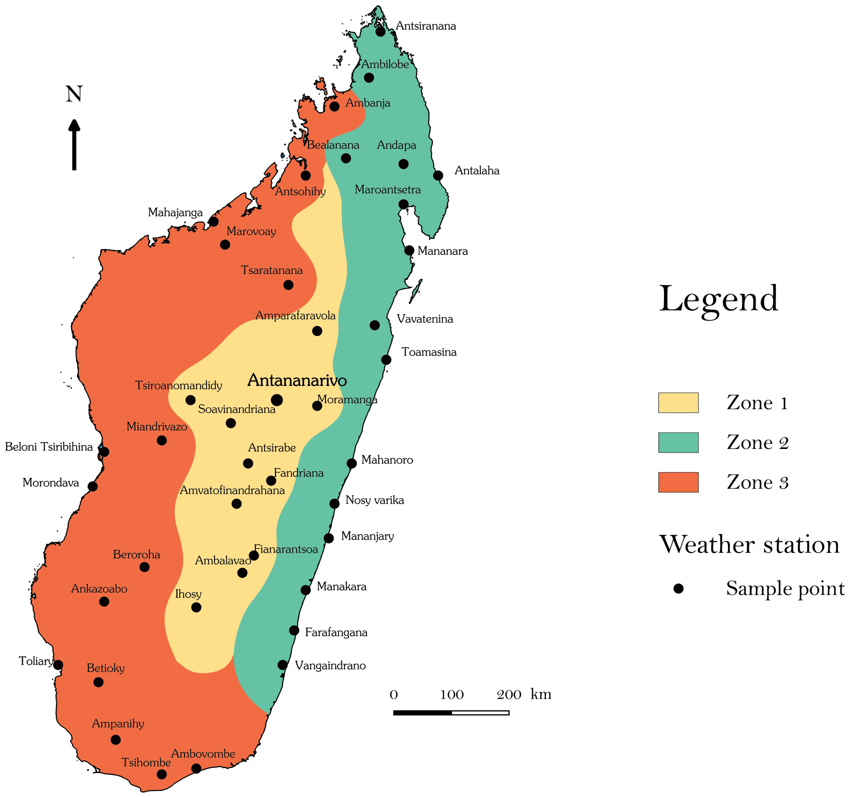


Figure 6: Climatic zoning results

Our zoning shows two significant differences. First of all, the delimitation of the highland area, which is in good coincidence with the topography, considering that topography was not used during the inteprolation process. The other difference is in the north of the island. Our results suggest a more equatorial/tropical climate zone, while the other classifications are more similar to a semi-arid or tropical warm climate. The particular case of Bealanana, as seen in the PCA, is better understood in the light of the mapping results. Indeed, this city is located almost at the intersection of the three climatic zones. This explains why it has been difficult to characterize it easily 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, called the paragon. The yearly maximum and minimum values of each parameter are defined from the extreme values recorded in the cluster among the meteorological data of the studied cities. Table B.6 summarizes these climatic characteristics based on of monthly average data. We also provide a link to the numerical data for each area (a link in each 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. Wind speed is low with a maximum between August and October. The solar irradiation yearly evolves in the same trend as the temperature, guaranteeing accumulated global irradiation of approximately 7 $\mathrm{kWh/m^2}$.

The climate zone 2 cluster has a barycenter close to the data for the city of Mananara. Table B.6 presents the main characteristics of this zone located in the center of Madagascar. Temperatures are warmer than in climate zone 1 with an annual average of 23 °C. The wind intensity is more important in this case with a peak value up to 5 $\mathrm{m\,s^{-1}}$. The accumulated global irradiation is at its maximum in March (approximately 7 $\mathrm{kWh/m^2}$).

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) for a significant solar deposit during the October-January period. Table B.6 summarizes the main characteristics of climate zone 3. These standard weather files are provided as additional data to this article.

Our methodology proposes a different zoning for some cities. For example, in this paper the

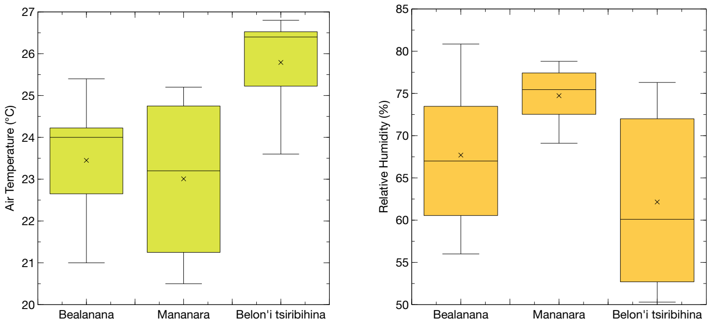


Figure 7: Boxplot of annual temperature and Relative humidity for Bealanana, Mananara and Belon'i tsiribihina weather stations.

city of Bealanana is in the zone 1 while in the study of Rakoto [20] this same city is classified in the zone 3. A boxplot of annual outside temperature and relative humidity is shown in Figure 7. Three weathers stations are compared, Bealanana which is the discussed city, Mananara and Belon'i tsiribihina that are respectively the barycenters of zone 2 and 3. The distribution of annual temperatures confirms that the city of Bealanana has a temperature pattern much closer to city of Mananara than 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 annual relative humidity does not reflect the same result. According to relative humidity, the city of Bealanana is closer to Belon'i tsiribihina and therefore to an attachment to zone 3. Cross-analysis of these two parameters through thermal comfort can therefore reinforce the choice of climatic zone 2. Thermal discomfort shown by the Givoni chart in this area is associated mainly with elevated temperatures. The choice of zone 1 for the city of Bealanana is therefore affirmed by the criterion of the air temperature.

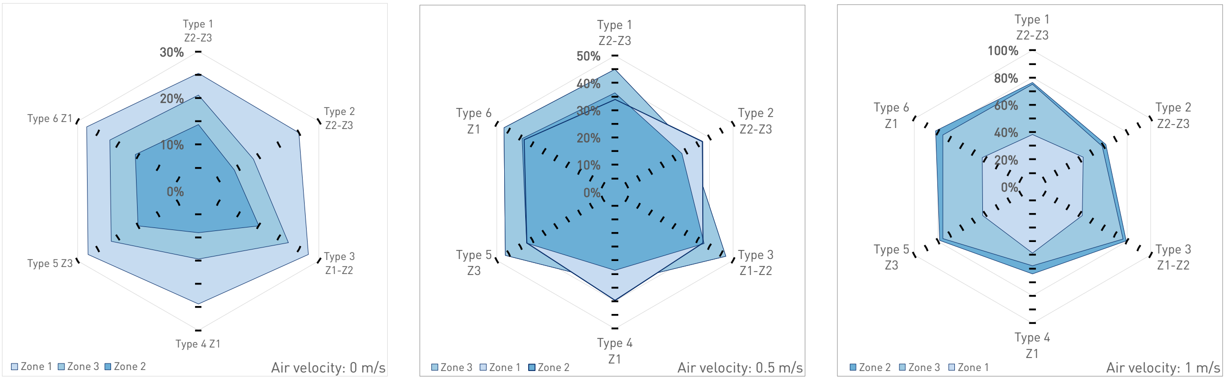
3.3. Thermal comfort

In this section, the result of thermal comfort is presented for the typical Malagasy houses. The thermal comfort is evaluated for the climatic zoning that we could establish thanks to the method developed in this paper.

The cities that followed Fig. (A.5) were chosen for their data availability and their affiliation as a paragon of the 3 previously identified climate zones.

The types of buildings are studied in certain climatic zones. In climatic zone 1, it is common practice to find constructions of type 3 (rather low thermal inertia), type 4 (medium thermal inertia) and type 6 (rather high thermal inertia). In climate zone 2, types 1 and 2 (using stilt technology) are preferred because of their possible exposure to rising water levels. In the same area, type 3, combining a dirt floor, mud and earthen walls and a thatched roof, is used in drier areas. Types 2 and 5 are part of the architectures commonly found in climate zone 3 (northeast, east and southeast zones of the island of Madagascar).

As shown in Figure 8, thermal comfort results are presented in a radar diagram in percentage of time for each types of Malagasy houses (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 velocity that are previously presented (0 $\mathrm{m\,s^{-1}}$, 0.5 $\mathrm{m\,s^{-1}}$ and 1 $\mathrm{m\,s^{-1}}$). The Fig. 8 a) illustrates the results of thermal comfort zone without any ventilation.



(a) (b) (c)

Figure 8: Percentage of thermal comfort time for each climatic zone according to the type of architecture and air velocity (for each type, the climatic zones actually concerned) (a), Air velocity at 0 $\mathrm{m\,s^{-1}}$ (b) Air velocity at 0.5 $\mathrm{m\,s^{-1}}$ (c) Air velocity at 1 $\mathrm{m\,s^{-1}}$

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%. These results show that even if the building materials of the walls are different, the levels of comfort achieved are similar. These simulations thus show that for climate zone 1, which is the zone defined

as the coldest in terms of temperature, the annual results exhibit a similar level of thermal comfort among the buildings.

For climate zone 2, the annual percentage of comfort time is between 9% and 16%. This climatic zone is an area with a high relative humidity of the air that continuously exceeds 60%. The results show that the habitats studied have difficulty limiting the impacts of humidity and temperature.

The absence of ventilation in this comfort zone thus limits the renewal of air in the building, which leads to thermal discomfort of the occupants.

In climate zone 2, the weather conditions highlight a hot and dry climate. The type 2 and type 4 buildings studied have comfort time percentages less than 15%. Discomfort is related to the roof and wood-type materials used in the type 2 and 4 buildings.

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 the thermal comfort. In climate zone 1, each typology makes it possible to achieve the same average level of comfort, whereas in this zone the literature revealed that types 3, 4 and 6 were the most commonly used. The most suitable architecture seems to be type 4, where the thermal inertia is marked by red brick walls and a clay floor and the building is covered by a low-inertia surface (sheet metal roofing).

In climate zone 2, types 1 and 3 (low thermal inertia), frequently used in this zone, confirm their effectiveness against type 2, also installed in this climate zone, revealing a percentage

of comfort time less than 30%. It would therefore seem that it is less adapted to this climatic configuration. Type 4 (medium thermal inertia) has the same results as type 2, with the sheet metal roofing causing a loss of the thermal inertial potential of the red bricks. Type 6, defined by a dirt floor, red brick walls and a thatched roof, is not frequently used in this climate zone. Nevertheless, type 6 offers the best results in terms of comfort. As this zone is a rather hot zone in summer and cold in winter, the strong thermal inertia of this configuration is a major asset to regulate heat peaks.

Climate zone 3, marked by a significant regularity of the temperatures throughout the year, shows that types 1 and 5, used in this territory, offer very good results with almost half of the year in a situation of thermal comfort. Type 2, also commonly installed, reveals an unsuitability for the climatic zone with nearly 32% comfort over a full year. The best configuration is type 3 (medium thermal inertia) combining a dirt floor, 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 outside air temperatures.

At 1 m/s, the air velocity is similar to what can be 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 of more than 70%. Since these climatic zones are the warmest, it is consistent that they present suitable results when the air velocity allows the volume of warm building air to be renewed. We note, however, that 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. Type 4, equipped with sheet metal limiting the benefit of the thermal inertia of the bricks, has a negative impact on thermal comfort. This element, which is highly exposed, will radiate and 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, occupants are in a situation of thermal discomfort where even passive cooling (such as a fan) would be ineffective. Nevertheless, types 3, 4 and 6, frequently installed in this area, offer the most correct results.

Overall, we can understand that traditional construction methods have historically been assigned to climate zones. Some design choices are relatively well adapted, and others serve users by limiting the annual time share of thermal comfort. We will note that, for all climatic zones combined, 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 type for the three air velocities studied. Thus, it would be recommended in climatic zone 1 to build according to the construction methods of type 4 (dirt floor + red brick + sheet metal roofing) to reach a 38% annual comfort time. In climate zone 2 (milder to cooler climates), the high thermal inertia of type 6 (dirt floor + red brick + thatched roof) seems to be an asset to guarantee an annual comfort rate of 46% . Finally, type 3 (dirt floor + mud and earthen walls + thatched roof) is associated with climate zone 3 to guarantee the longest average thermal comfort time. The results of this study are promising. However, they will require further analysis to validate the overall constructive mode/climate association in Madagascar.

4. Conclusion and policy implications

The issue of housing construction and its quality are major challenges for a country like Madagascar. Indeed, Madagascar must meet the housing needs in important urban areas due to a demographic transition that is slowly occurring. This population growth is leading to a new influx of people to the main Malagasy cities. The capital alone represents more than 2.6 million inhabitants. In addition, building in a tropical environment also requires adapting effective practices to different climates. Thus, it seems indisputable that the climatic zones of Madagascar should be characterized in order to adapt the construction of buildings in the territory. The objective of this work was to propose an unsupervised zoning method applicable in cases where data availability is low.

The literature revealed that there was no consensus on the appropriate methodology for climate zoning. The state of the art highlighted two categories of methods: clustering and classification 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.

Our objective was, therefore, to analyze Madagascar's climate using a clustering method coupled with PCA. We used a new database from 47 weather stations spread over Madagascar. Our results showed that 3 climate zones could be identified: climate zone 1, which is slightly hot and humid, climate zone 2, in the west of the island with mild summers and cold winters, and climate zone 3, in the east of the island, with a warm tendency in summer and a mild tendency in winter.

The use of GIS tools has enabled us to establish climatic zoning of the entire Malagasy territory. The combination of multivariate analyses and spatial interpolation defined three climate zones. The results seem consistent with the reality of the territory. We can thus find the following organization: the highlands separate a dry area in the west from a wet area in the east. To illustrate the value of climate zoning, we studied the link between established climate zones and thermal comfort conditions according to the traditional habitat typology. We understood that certain types of buildings make it possible to guarantee a better annual comfort rate. For example, we showed that buildings of type 3 (clay floor + mixed walls (earth + mud) + thatched roof) and type 6 (clay floor + red brick + thatched roof) 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 constructions. Future studies will investigate the assessment of building performance in the developed the climatic zoning in order to implement specific thermal regulations for Madagascar. In particular, future studies will address the deployment of our methodology in the case of other islands in Indian Ocean.

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Appendix A. Weather files used for thermal comfort simulation

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`
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`

Table A.5: Weather files used for the application

Appendix B. Main characteristics of each climate zone

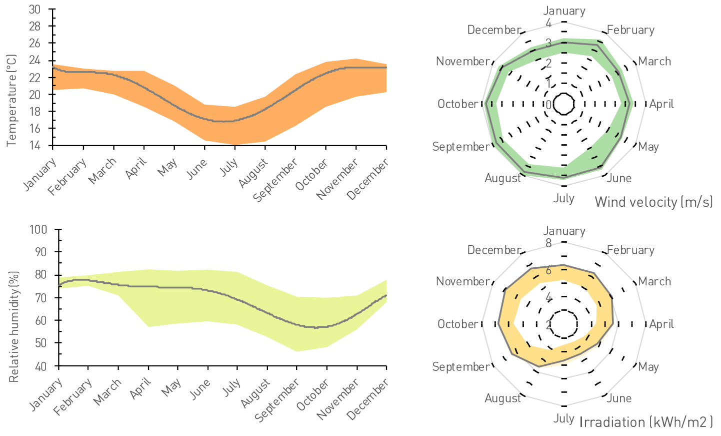
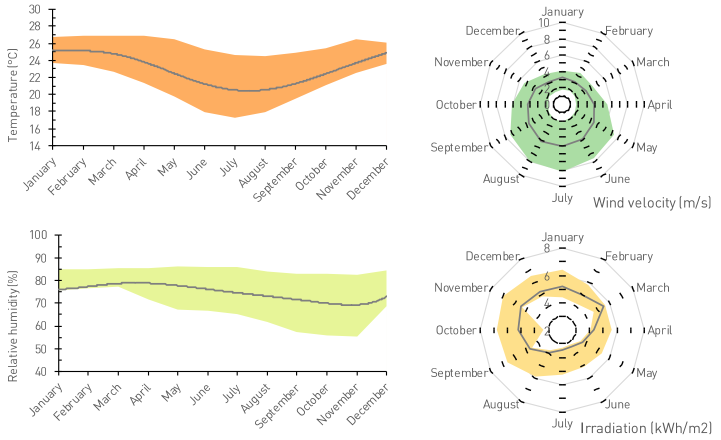
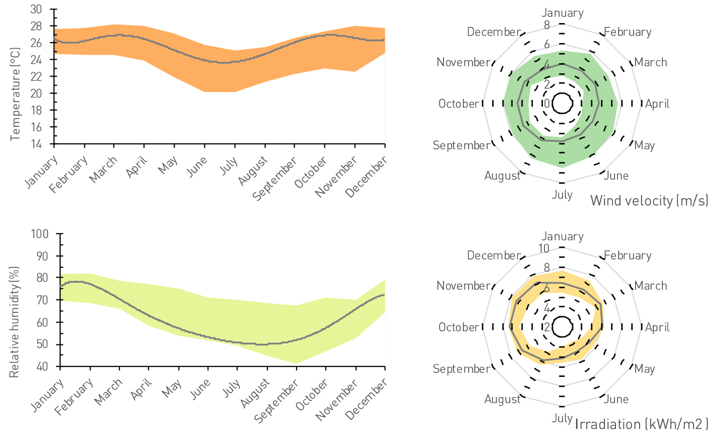
Climate zone	Main characteristics
1	 *Reference city :* Ambalavao
2	 *Reference city :* Manara
3	 *Reference city :* Belon'i'tsiribihina

Table B.6: Main characteristics of each climate zone