Open Access Library Journal
2026, Volume 13, e15529
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Development of Maps for the Design of Bioclimatic Housing in Madagascar Based on Mahoney's Table

Sitraka Ravelomanantsoa, Bienvenue Raheliarilalao

Doctoral School of Engineering and Geosciences (INGE), Higher Polytechnic School of Antananarivo (ESPA), Antananarivo, Madagascar
Email: sitraka.strk@gmail.com, rahelbi2001@yahoo.fr

How to cite this paper: Ravelomanantsoa, S. and Raheliarilalao, B. (2026) Development of Maps for the Design of Bioclimatic Housing in Madagascar Based on Mahoney's Table. *Open Access Library Journal*, **13**: e15529.
https://doi.org/10.4236/oalib.1115529

Received: May 20, 2026
Accepted: June 23, 2026
Published: June 26, 2026

Abstract

Housing design, which has become highly complex, requires integrated approaches that combine functionality, sustainability, and aesthetics in residential buildings. The central focus of bioclimatic design is passive thermal comfort. In Madagascar, the use of such systems in housing is minimal. In a bioclimatic home, climate control makes optimal use of solar radiation and natural air circulation. This concept is based on the bioclimatic profile. This profile is described by bioclimatic variables representing annual trends such as average annual temperature, annual precipitation, seasonality, and extreme or limiting environmental factors. The diversity of Madagascar's tropical climate makes thermal comfort particularly difficult to achieve. This article aims to identify recommendations for designing bioclimatic housing adapted to local conditions. The Mahoney Table is a structured method that integrates orientation, openings, and material selection. Our meteorological data covers Madagascar from 1991 to 2020. In the Boeny region (humid, very rainy, with hot and cold winds), openings must be strategically oriented with moderate spacing and wind protection (awnings, horizontal sunshades). The hot and humid regions of the Central East and Southeast (Ambatosoa, Atsimo Atsinanana, Atsinanana) require lightweight materials (wood/straw sandwich panels, wooden houses with ventilated air gaps under the roof) and thermal insulation of the walls (wood frame plus plant-based panels). They also require appropriate management of openings to limit overheating in summer and heat loss in winter.

Subject Areas

Atmospheric Sciences

Keywords

Climate Zones, Mahoney Table, Madagascar, Site Plan, Air Circulation

1. Introduction

The study of climatic conditions and their impact on human habitation is a major focus in bioclimatology and sustainable housing. The Mahoney method, developed in 1967 in "Tables for the Estimation of Indoor Thermal Comfort," allows for the assessment of thermal comfort requirements in buildings based on local climate data. This approach relies on the analysis of parameters such as temperature, humidity, and precipitation to define appropriate architectural recommendations [1].

Globally, research such as that conducted by Olgyay in 1963 has demonstrated the importance of adapting buildings to specific climatic conditions in order to reduce energy consumption and improve occupants' well-being [2]. In tropical regions such as Madagascar, where seasonal variations and extreme weather events (cyclones, droughts) are pronounced, this approach is particularly relevant [3].

The design of bioclimatic housing requires a detailed understanding of the interactions between climate, the local environment, and building materials. The Mahoney Table provides a simple yet effective methodological framework for analyzing these interactions by combining decades of meteorological data with planning and design criteria. The study conducted in Madagascar is of major interest given that the island is divided into different climate zones. It aims to compile strategies tailored to each zone in the form of recommendations based on local climate analysis and defined using indicators. The primary objective was to design buildings that provide a significant level of thermal comfort throughout the year, using passive methods.

2. Methods and Materials

The sequence of operations is illustrated in the flowchart below (See **Figure 1**).

2.1. Mahoney's Method

The Mahoney method is a four-step bioclimatic analysis tool that translates meteorological data into architectural recommendations for optimizing thermal comfort. Used primarily for arid and tropical climates, it guides the design of the building envelope, openings, and site layout. Based on basic climate data, it enables the identification of a site's constraints and potential and the formulation of bioclimatic design recommendations to ensure the thermal comfort of occupants.

Diagnostic Tables

Diagnostic tables are used to collect and organize essential monthly climate data for the regions under study. They lay the groundwork for comfort analysis and subsequent recommendations.

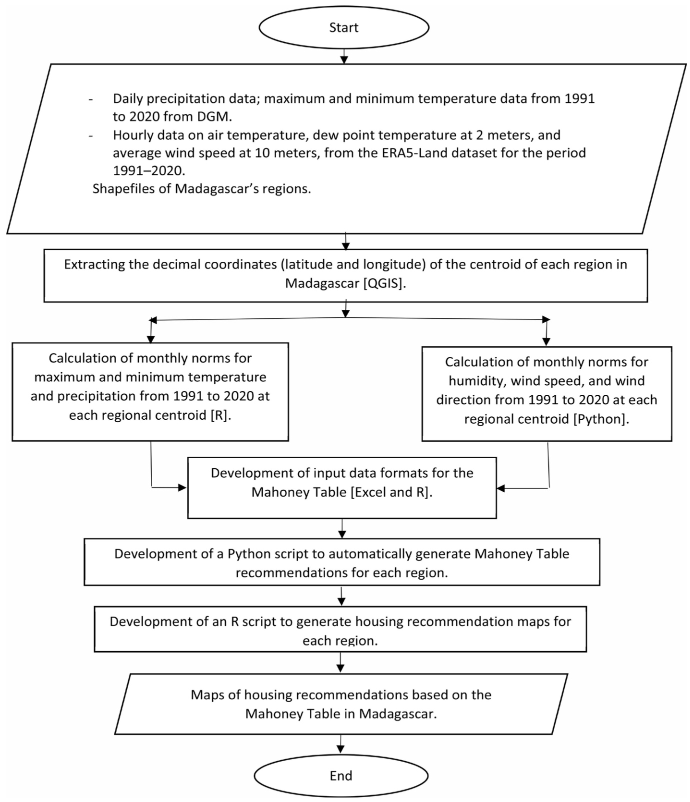

Figure 1. Flowchart of the method for designing housing recommendation maps based on the Mahoney Table.

❖ The meteorological data used are based on the centroid of each region (see Figure 1):

- Monthly average maximum and minimum temperatures. This data is crucial for understanding daily and annual temperature variations. Maximum temperatures indicate the level of daytime heat to which the building will be exposed, influencing solar shading and ventilation strategies. Minimum nighttime temperatures are important for assessing the potential for passive cooling and the risk of cold-related discomfort [4] [5].
- Monthly average precipitation is critical for water management and protection against moisture. High precipitation levels require effective drainage systems, roofs with adequate slopes, and protective measures for openings and walls. The seasonal pattern of rainfall also influences landscape design and the choice of materials [6] [7].
- The average monthly relative humidity has a significant impact on the perception of thermal comfort. High humidity intensifies the sensation of heat by limiting the evaporation of sweat. It also promotes mold growth. Effective ventilation strategies are crucial in humid climates to remove moisture-laden air [8] [9].

- The prevailing wind direction and average monthly wind speed, which are essential for optimizing natural ventilation. The prevailing wind direction helps determine the building's orientation and the placement of openings to promote air circulation within the spaces. Wind speed influences the efficiency of ventilation [10] [11].

For illustrative purposes, consider the example of Alaotra Mangoro region, which falls within climate zone B (very humid, influenced by moderate trade winds, with an average annual temperature of 18˚C to 22˚C and annual precipitation of 1350 to 2500 mm (see **Figure 2**).

Table 1 of meteorological data for Alaotra Mangoro region is as follows:

Table 1. Table of meteorological data for Alaotra Mangoro region.

	Jan	Fev	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp. Max.	28.1	27.9	27.9	27.3	25.8	23.6	22.5	23.3	25.4	27.3	28.6	**28.9**
Temp. Min.	18.2	18.2	17.7	16.2	14.4	12.2	**11.2**	11.5	12.6	14.4	16.2	17.6
Hu. Moy	78.8	80.8	79.4	76.0	74.2	74.3	73.6	70.7	66.4	64.0	64.5	82.4
Precip.	221.2	208.2	132.3	20.5	4.8	0.5	1.8	0.3	1.3	16.8	42.6	146.8
Vit. Vent	0.7	0.8	1.6	2.1	2.0	2.6	2.9	2.7	2.5	2.1	1.8	1.2
Dir. Vent	E	SE	SE	SE	SE	SE	SE	SE	SE	E	E	E

❖ Comfort Table [12] [13]

This table is used to determine the thermal comfort limits for the site under study based on the Annual Mean Temperature (TMA) and the humidity group.

$$\text{TMA} = \frac{\text{Highest annual maximum temperature} + \text{Lowest annual minimum temperature}}{2} \quad (1)$$

The average temperature in Alaotra Mangoro region is 20.1˚C (See **Table 2**).

Table 2. Moisture group table.

		TMA ≥ 20˚C		15 ≤ TMA < 20˚C		TMA < 15˚C	
Hu. Moy. (%)	G.H.	Day	Night	Day	Night	Day	Night
[0, 30[	1	26 - 34	17 - 25	23 - 32	14 - 23	21 - 30	12 - 21
[30, 50[	2	25 - 31	17 - 24	22 - 30	14 - 22	20 - 27	12 - 20
[50, 70[	3	23 - 29	17 - 23	21 - 28	14 - 21	19 - 26	12 - 19
≥70	4	22 - 27	17 - 21	20 - 25	14 - 20	18 - 24	12 - 18

Using the TMA and the humidity group table, we can define the daytime and nighttime comfort zones. These limits are not universal but are tailored to populations acclimated to specific conditions (see **Table 3**). They take into account the fact that people living in hot climates can tolerate higher temperatures.

To fill out this comfort table for each month, let's take January as an example; first, fill in the humidity group using **Table 2**. Next, enter the maximum temperature value. Next, find the maximum and minimum TMA values for the day corresponding to the month's humidity group to fill in the maximum and minimum daytime comfort levels; the same principle applies to filling in the maximum and minimum nighttime comfort levels, but using the TMA for the night. Finally, to fill in the daytime (nighttime) thermal stress, compare the average maximum (minimum) temperature value to the maximum and minimum daytime (nighttime) comfort levels; if the average maximum (minimum) temperature falls between the maximum and minimum daytime (nighttime) comfort levels, we have "comfort ©"; if it is lower, the sensation is "too cold (TF)"; otherwise, the sensation is "too hot (TC)".

Table 3. Comfort table for Alaotra Mangoro region.

		Jan	Fev	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
G.H.		4	4	4	4	4	4	4	4	3	3	3	4
Temp. Max.		28.1	27.9	27.9	27.3	25.8	23.6	22.5	23.3	25.4	27.3	28.6	**28.9**
C.D.	Max	27	27	27	27	27	27	27	27	29	29	29	27
	Min	22	22	22	22	22	22	22	22	23	23	23	22
Temp. Min.		18.2	18.2	17.7	16.2	14.4	12.2	**11.2**	11.5	12.6	14.4	16.2	17.6
C.N.	Max	21	21	21	21	21	21	21	21	23	23	23	21
	Min	17	17	17	17	17	17	17	17	17	17	17	17
S.T.	Jour	TC	TC	TC	TC	C	C	C	C	C	C	C	TC
	Nuit	C	C	C	TF	TF	TF	TF	TF	TF	TF	TF	C

❖ Tables of indicators [14]-[18]

The first indicator table is used to populate the second indicator table. Recall the following definitions of the Koenigsberger indicators:

- H1 (Essential ventilation): Daytime temperature ≥ 32˚C for 4 or more months, consecutive or otherwise.
- H2 (Ventilation desirable): Daytime temperature 29˚C - 32˚C for 4 months or more.
- H3 (Rain protection): Annual rainfall ≥ 1000 mm with a dry season < 3 months.
- A1 (Thermal inertia desirable): Annual temperature range (Tmax warmest month – Tmin coldest month) ≥ 10˚C.
- A2 (Sleeping outdoors possible): Nighttime temperature ≥ 22˚C for 4 months or more.
- A3 (Cold season issue): Minimum temperature of the coldest month < 10˚C.
- W1 (Strong, disruptive wind (protection)): Wind > 4 m/s for 4 months or more, or gusts > 10 m/s.
- W2 (Wind useful for ventilation): Moderate wind (2 - 4 m/s) for 4 months or more.

In order to preserve seasonal information, temperature ranges and precipitation were analyzed on a monthly rather than an annual basis. This approach is consistent with the principles of bioclimatic design, which require a detailed consideration of seasonal climate variations in order to adapt architectural strategies to local conditions [18]. Therefore, we use the monthly value instead of the annual value for A1 (Monthly Temperature Range or MTR) and H3 (Monthly Precipitation), because the annual range is a single value that smooths out seasonal variations.

$$\text{ATM} = \text{Monthly high temperature} - \text{Monthly low temperature} \quad (2)$$

The first indicator table becomes **Table 4**.

Table 4. First table of indicators.

	Thermal Stress	G.H.	ATM (˚C)	Monthly precipitation (mm)	Wind/Additional Conditions
H1	C.D. too hot	4			Essential ventilation
	C.D. too hot	2-3	<10		
H2	C.D. Comfort	4			Recommended ventilation
H3				>200	Rain protection
A1		1-2-3	>10		Thermal inertia
A2	C.D. too hot and C.N. Comfort	1-2	> 10		Sleeping outdoors
A3	C.D. too cold or C.N. too cold				Cold season
W1	Inconvenient strong winds (≥1 month)				Windbreaks (hedges, walls, rows of trees)
	W1 + A3 (cold season)				Dense windbreaks (solid walls)
	W1 + H1 (essential ventilation)				Permeable windbreaks (hedges, trellises)
W2	Moderate prevailing wind (≥1 month)				Openings perpendicular to the prevailing wind
	W2 + H1 (essential ventilation)				Wind sensors + opposite outputs
	W2 + A3 (cold season)				Do not face the cold wind; keep the opening on the leeward side
W1 + W2	(W2 + H1 or H2) + (A3 = 0 to 5 months)				Dual orientation for maximum span
	(W2 + A3 = 6 to 12 months)				Dual-orientation with adjustable openings
	W1 = 1 to 12 months (strong winds)				Double orientation not recommended; single orientation + windbreak

The second table of indicators is **Table 5**.

Based on the assessment and indicators, the recommendation tables propose specific bioclimatic design strategies to address the identified thermal stresses and optimize comfort. Columns H1 through A3 indicate the combinations of indicators for which the recommendation in the row applies (See **Table 6**).

Table 5. Second set of indicators for Alaotra Mangoro region.

	Jan	Fev	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	TOTAL
H1													0
H2	*	*	*									*	4
H3	*	*											2
A1									*	*	*		3
A2													0
A3				*	*	*	*	*	*	*	*		8
W1													0
W2				*	*	*	*	*	*	*			7

Recommendation Tables [19] [20].

Table 6. Site plan.

Conditions	Recommendation	Explanation
A1 = 0 - 10	Buildings oriented along an east-west axis.	If the thermal inertia (A1) is not very high (0 - 10), the orientation is optimized to capture sunlight in the winter and block it in the summer.
A3 = 5 - 12	Compact floor plans with courtyards.	During the cold season (A3 active), compact layouts reduce heat loss. Interior courtyards provide protection from the cold wind.
A1 = 11 - 12 and A3 = 0 - 4	Compact floor plans with courtyards.	When thermal inertia is very high (high A1) and the cold season is short (low A3), thermal mass remains useful for stabilizing the temperature.

The orientation and compactness of the layout depend primarily on the requirements for thermal mass (A1) and protection against the cold (A3).

The spacing is determined almost exclusively by H1 (essential ventilation) (See **Table 7**).

Table 7. Spacing between buildings.

Conditions	Recommendation	Explanation
H1 = 11 or 12	Wide spacing to allow for better airflow.	When natural ventilation (H1) is required, buildings are spaced apart so as not to block the wind.
H1 = 2 - 10	Same as above, but with protection against hot/cold winds.	Need for ventilation (H1) but protection from unwanted winds (windbreaks, orientation).
H1 = 0 or 1	Compact design.	If H1 is not active (0 or 1), ventilation is not a priority → the buildings can be sealed off.

The ventilation strategy depends on H1 and H2 (ventilation requirements) and A3 (cold weather may limit the opening) (See **Table 8**).

The size of the openings depends on A1 (inertia) and A3 (cold). The lower the inertia and the less cold there is, the larger the openings can be (See **Table 9**).

Table 8. Airflow.

Conditions	Recommendation	Explanation
H1 = 3 - 12	Single-aspect building. Continuous air circulation.	Requires essential ventilation (H1) for at least 3 months; the design allows for continuous air circulation (simple cross-ventilation).
(H1 = 1 - 2) + (H2 = 2 - 12) + (A3 = 0 - 5)	A dual-aspect building designed for intermittent traffic.	If H1 is low but H2 is active, and it's not very cold (A3 is low), intermittent ventilation will suffice, so you can open the vents in either direction as needed.
H1 = 0 et (A3 = 0 ou 1)	Unnecessary air circulation.	No need for ventilation (H1 = 0) and it's not cold, so we can even close it.

Table 9. Opening dimensions.

Conditions	Recommendation	Explanation
A1 = 0 - 1 et A3 = 0	Large openings (40% - 80% of north-south facades).	Low thermal mass (A1) and no cold (A3) allow for very large openings.
A3 = 1 - 12	Moderate openings (25% - 40% of the walls).	As soon as cold weather sets in (A3), we close the openings to minimize heat loss.
A1 = 2 - 10	Intermediate (20% - 35% of the walls).	Moderate inertia, moderate aperture size.
A1 = 11 - 12 and A3 = 0 - 3	Small openings (20% - 35% of the walls).	High thermal mass and low heat gain, with small openings to regulate heat flow.
A3 = 4 - 12	Moderate openings (25% - 40%).	If the cold spell lasts longer (A3: 4 to 12 months), we return to the average.

The position of the openings is controlled by H1 and H2 (ventilation) and limited by A3 (cooling) (See Table 10).

Table 10. Position of the openings.

Conditions	Recommendation	Explanation
H1 = 3 - 12	Openings in the north-south walls, at chest height on the windward side.	Essential ventilation is required (H1); openings are positioned to capture the prevailing wind.
(H1 = 1 - 2) + (H2 = 2 - 12) + (A3 = 0 - 5)	As above, with openings in interior walls.	Good ventilation is desirable; avoid extreme cold; add interior openings to allow for air circulation.
H1 = 0 et A3 = 0 - 1		No ventilation is required; the openings can be positioned as desired.

Two distinct needs: protection from the sun (if it's not cold) or from the rain (if H3 is active) (See Table 11).

Table 11. Opening controls.

Conditions	Recommendation	Explanation
A3 = 0 - 2	Protect yourself from direct sunlight.	When the cold season is short or nonexistent (A3 = 0 - 2), the problem is excessive sunlight, so sun protection measures (sunshades, awnings) are needed.
H3 = 2 - 12	Plan for rain protection	If it rains (H3) for at least two months, protective measures are needed (awnings, overhanging roofs, waterproof shutters).

The thermal mass is directly determined by A1 (See Table 12).

Table 12. Walls and floors.

Conditions	Recommendation	Explanation
A1 = 0 - 2	Lightweight construction, low thermal inertia.	If inertia is undesirable (low A1), the structure is built using lightweight materials (wood, metal, thin walls).
A1 = 3 - 12	Major construction, time difference > 8 hours.	If thermal mass is desirable (A1 active), thick walls (concrete, stone, adobe) are used to delay the transfer of heat.

Roofs are either lightweight and insulated (for hot or humid climates) or heavy-duty (for dry climates with significant temperature fluctuations) (See Table 13).

Table 13. Roof.

Conditions	Recommendation	Explanation
H1 = 10 - 12 et A1 = 0 - 2	Lightweight roof, reflective coating, and more air space.	Essential ventilation at the end of the year with low thermal mass, a lightweight roof to allow heat to escape, and reflective insulation.
A1 = 3 - 12	Lightweight, well-insulated roof.	If thermal mass is desired, the (lightweight) roof is insulated so that the mass of the walls can be effective.
H1 = 0 - 9 and A1 = 0 - 5	Lightweight or heavy roof, time difference > 8 hours.	If thermal mass is desirable, the roof (lightweight) is insulated. If thermal mass is not desirable, the heavy roof acts as a temperature regulator (dry climate).
H1 = 0 - 9 and A1 = 6 - 12	Heavy snowfall, time difference > 8 hours.	The solid roof acts as a temperature regulator (dry climate).

Outdoor spaces must comply with A2 (nighttime use) and H3 (rainwater management) (See Tables 14-17).

Table 14. Outdoor spaces.

Conditions	Recommendation	Explanation
A2 = 1 - 12	Spot for sleeping outdoors.	If sleeping outdoors (A2) is possible for at least one month, outdoor spaces (courtyards, terraces, camp beds) are set up.
H3 = 1 - 12	Proper rainwater drainage.	If rain protection (H3) is required for at least one month, a rainwater drainage system (slopes, gutters, soakaways) must be provided.

Table 15. Wind protection (W1: Strong, disruptive wind).

Conditions	Recommendation	Explanation
W1 = 1 to 12 months (strong winds for ≥1 month)	Provide windbreaks (hedges, walls, rows of trees) on the side from which strong winds come.	Protects the building and outdoor areas from annoying gusts of wind.
W1 = 1 to 12 months (strong winds) and A3 = 1 to 12 months (cold season)	Windbreaks should be solid (such as solid walls) to block the cold wind.	In cold weather, we completely block the wind.
W1 = 1 to 12 months (strong wind) and H1 = 1 to 12 months (essential ventilation)	Windbreaks should be permeable (e.g., hedges, trellises) to slow down the wind without stopping it completely.	We want to reduce the wind speed but maintain ventilation.

Table 16. Use of usable wind (W2: Usable wind for ventilation).

Conditions	Recommendation	Explanation
W2 = 1 to 12 months (moderate wind for ≥1 month)	Position the main openings perpendicular to the prevailing wind direction to catch the wind.	Promotes natural cross-ventilation.
W2 = 1 to 12 months and H1 = 1 to 12 months (essential breakdown)	Use wind sensors (roof vents, solar chimneys) and opposing exhaust vents.	Optimizes airflow when ventilation is critical.
W2 = 1 to 12 months and A3 = 1 to 12 months (cold season)	Do not position openings to face the cold wind; instead, use pressure-differential ventilation (openings on the leeward side).	Avoid letting cold air enter living spaces directly.

Table 17. Dual orientation based on wind direction and temperature.

Combined terms and conditions	Recommendation	Explanation
(W2 = 1 - 12) et (H1 = 1 - 12 ou H2 = 1 - 12) and (A3 = 0 - 5)	Buildings are oriented in two directions (with openings on two opposite facades) to maximize cross-ventilation.	A gentle breeze, a need for ventilation, and no extreme cold—so we're designing for airflow.
(W2 = 1 - 12) and (A3 = 6 - 12)	Dual-orientation design with adjustable openings (shutters, tilt-and-turn windows) to limit the entry of cold air.	We can still ventilate when the weather is mild, but we can close it up in winter.
W1 = 1 - 12 (strong wind)	A dual orientation is not recommended; instead, opt for a single orientation with openings protected by windbreaks.	

2.2. Climate Zones of Madagascar

Madagascar's climate is primarily tropical, characterized by a dry season (southern winter, April through October) and a rainy season (southern summer, November through March). It varies significantly by region (indicated by the red dots), which has led the General Directorate of Meteorology to define 10 climate zones (**Figure 2**).

Figure 2. Climate classification of Madagascar. Source: [21].

To simplify the representation of bioclimatic design at the regional level, a red centroid point was used for each region (Figure 2 and Table 18). However, a single region may encompass multiple climate zones, whereas the centroid belongs to only one of them and therefore does not fully represent the region's climatic diversity. The geographic coordinates (latitude and longitude) of the centroid were used to extract the meteorological data needed to develop the Mahoney table. This approach provides a simplified representation of each region. For a more accurate analysis, it is recommended to use the exact coordinates of the bioclimatic design site, which can be easily obtained using a GPS device.

Table 18. Geographic coordinates of meteorological data and climate zones for the 24 regions.

Regions	Longitude	Latitude	Climate zones for the points marked in red
Ambatosoa	49.505	−15.764	Zone A (very humid year-round, directly exposed to trade winds, annual precipitation: 2500 to 3700 mm, average annual temperature: ≥23.6˚C).
Analanjirofo	49.214	−17.061	
Atsinanana	48.686	−19.102	
Fitovinany	47.668	−21.986	
Sava	49.824	−14.312	
Vatovavy	47.977	−20.984	
Alaotra Mangoro	48.324	−17.905	Zone B (very humid, with reduced influence from trade winds; annual precipitation: 1350 to 2500 mm; average annual temperature: 18˚C to 22˚C).
Sofia	48.292	−15.334	
Betsiboka	47.028	−17.236	Zone C (humid region with high rainfall, directly exposed to the monsoon season in summer, annual precipitation 1200 to 2000 mm, average annual temperature: ≥26˚C).
Boeny	46.2	−16.293	
Diana	48.926	−13.342	
Amoron'i Mania	46.683	−20.498	Zone D (humid, climate moderated by the terrain, rainfall concentrated in the summer, annual precipitation: 1250 to 1500 mm, average annual temperature: ≥19˚C).
Analamanga	47.423	−18.425	
Bongolava	46.133	−18.604	
Itasy	46.887	−19.051	
Matsiatra Ambony	46.599	−21.444	
Vakinankaratra	46.847	−19.735	
Atsimo Atsinanana	47.249	−23.295	Zone E (humid year-round, directly exposed to the trade winds, annual precipitation: 1400 to 1700 mm, average annual temperature: ≥21˚C).
Ihorombe	46.149	−22.523	Zone F (humid with low precipitation, dry winters, annual precipitation: 800 to 1100 mm, average annual temperature: 18˚C to 25˚C).
Melaky	44.809	−17.715	
Androy	45.445	−24.822	Zone G (windy semi-humid, influenced by trade winds, annual precipitation: 700 - 1200 mm, average annual temperature: ≥23˚C).
Anosy	46.256	−23.986	
Atsimo Andrefana	44.428	−23.06	Zone H (semi-humid, influenced by local factors (breezes), annual precipitation: 600 to 800 mm, average annual temperature: ≥23˚C).
Menabe	44.89	−20.243	
			Zone I (semi-humid with low rainfall, annual precipitation: ~500 mm, average annual temperature: ≥23˚C).
			Zone J (annual number of rainy days < 50, annual precipitation < 500 mm, average annual temperature ≥ 22˚C).

2.3. Data Used in Mahoney's Table

The period covered by the meteorological data spans 30 years (1991 to 2020). The parameters used in the Mahoney table are: daily precipitation data; maximum and minimum temperatures from DGM (4 km resolution, in collaboration with the International Research Institute for Climate and Society (IRI) at Columbia University); monthly humidity calculated using hourly air temperature and dew point temperature data at 2 m (Equation (3) [22]) and hourly wind data at 10 m from ERA5-Land (9 km resolution).

$$RH = 100\frac{e^{\frac{17.625T_d}{243.04+T_d}}}{e^{\frac{17.625T}{243.04+T}}} \quad (3)$$

- *RH*: Relative humidity (%);
- *T*: Air temperature (˚C);
- T_d: Dew point temperature (˚C).

The datasets we used underwent prior quality control. According to the WMO Guidelines on the Calculation of Climate Normals (WMO-No. 1203, 2017) [23], climate normals are calculated from monthly values, which are themselves derived from daily or hourly observations. They correspond to the average of monthly values over a 30-year period, in this case from 1991 to 2020. For parameters such as temperature, humidity, or wind speed, a month is included only if no more than 10 days are missing and if there are no 5 consecutive missing days. For precipitation, the month must be complete. Months that do not meet these criteria were excluded from the calculations (See **Table 19**).

Table 19. Method for calculating climatological norms [23].

Parameter	Aggregation by hour → by day	Daily aggregation → monthly aggregation	Calculation of the monthly mean (1991-2020 reference period)
Average air temperature (dew point)	The daily average air (dew point) temperature is calculated based on the average of the available hourly air (dew point) temperatures.	The monthly average (dew point) air temperature is calculated by averaging the daily average (dew point) air temperatures for the month.	The monthly average is the mean of the monthly air (dew point) temperatures calculated over the 30-year reference period.
Maximum (Minimum) temperature	The daily maximum (minimum) temperature is the highest (lowest) temperature recorded that day.	The monthly maximum (minimum) temperature is calculated as the average of the daily maximum (minimum) temperatures for the month.	The monthly average maximum (minimum) temperature is the average of the monthly maximum (minimum) temperatures over the reference period.
Precipitation	The daily total is calculated by adding up the hourly precipitation amounts for the day.	The monthly total is calculated by adding up the daily precipitation amounts for the month.	The monthly normal precipitation value corresponds to the average of the monthly totals observed over the 30-year reference period.

Continued

Relative humidity	Hourly relative humidity is calculated based on air temperature and dew point, and then averaged to obtain the daily value.	The monthly average is calculated based on daily relative humidity readings.	The monthly average is calculated as the mean of the monthly relative humidity values over the 30-year reference period.
Wind speed (V)	The average daily speed is calculated based on the average of the hourly speeds.	The monthly average speed is calculated based on the average of the daily speeds.	The monthly average is calculated as the average of the monthly speeds over the 30-year reference period.
Wind direction (θ)	The hourly directions are converted into vector components (u, v), and then averaged to obtain the daily direction (Equation 4).	The daily components are averaged to calculate the monthly average direction.	The monthly mean is calculated based on the average monthly directions obtained using the vector method.

The vector components are calculated according to [23]:

$$u = -V\sin(\theta) \text{ and } v = -V\cos(\theta) \tag{4}$$

- V: wind speed;
- θ: meteorological wind direction (the direction from which the wind is coming).

3. Results

The results reveal common trends and regional specificities in housing design and layout.

3.1. Site Plan and Orientation

Most regions are oriented east-west to minimize solar exposure, with the exception of the ANDROY region (semi-humid and windy, influenced by trade winds), which features a compact layout with interior courtyards to minimize heat loss (**Figure 3**).

Regions requiring specific air circulation (**Figure 4**):

- Dual orientation with adjustable openings (shutters, tilt-and-turn windows) to limit the entry of cold air: BONGOLAVA, ITASY, VAKINAKARATRA, AMORIN'I MANIA, MATSIATRA AMBONY, and IHOROMBE have humid climates moderated by the terrain; ALAOTRA MANGORO (very humid, with the influence of trade winds mitigated); ANALANJIROFO and AMBATOSOA (very humid year-round, directly exposed to trade winds).
- Dual orientation (intermittent airflow, opposing windows for cross-ventilation): SOFIA (very humid, trade wind influences mitigated), BOENY (humid with heavy rainfall, directly exposed to the monsoon in summer), BETSIBOKA (humid with heavy rainfall, directly exposed to the monsoon in summer),

ANALAMANGA (humid, climate moderated by the terrain), and ANDROY (semi-humid and windy, influenced by trade winds).

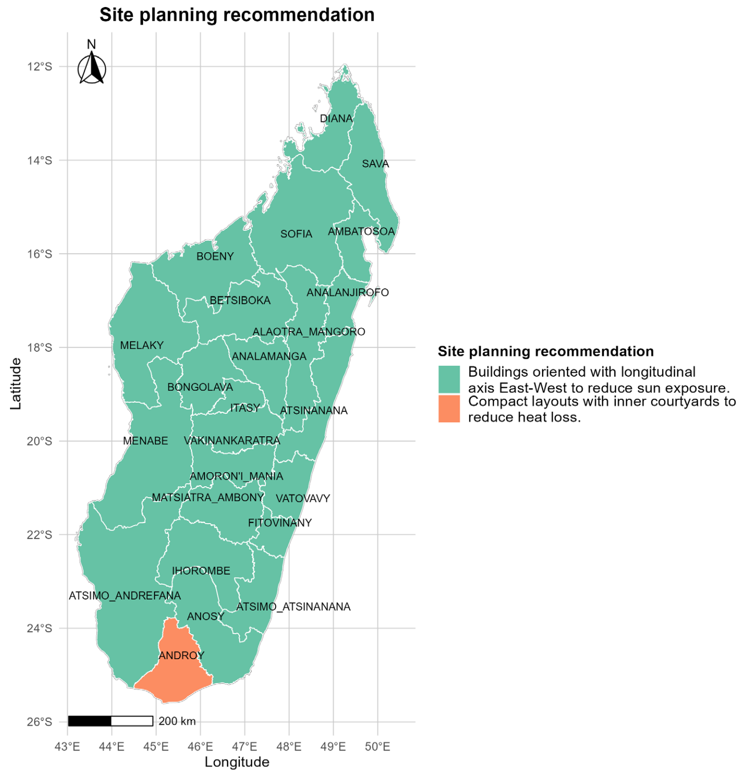

Figure 3. Site planning recommendation.

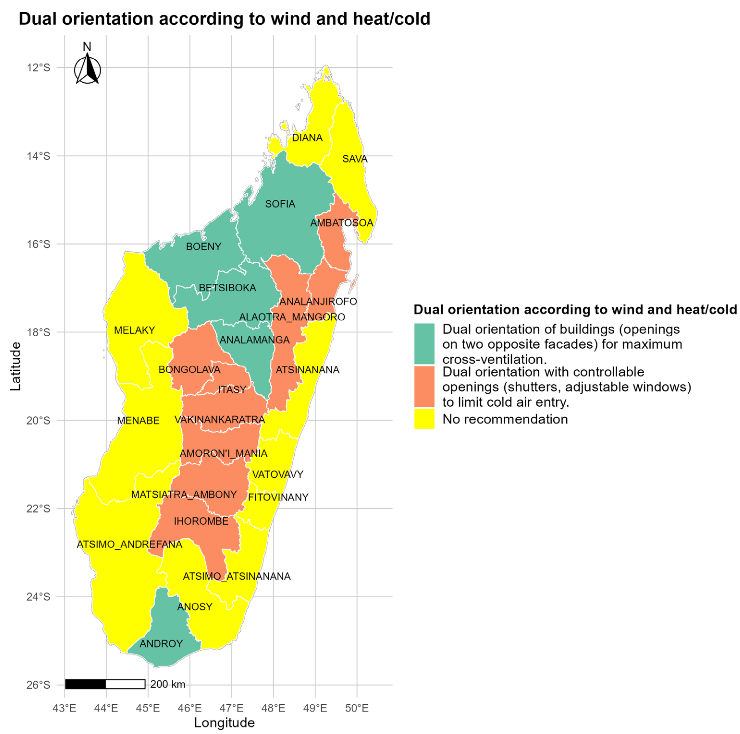

Figure 4. Dual orientation according to wind and heat/cold.

3.2. Spacing and Compactness

The compact layout is recommended for ANDROY region (semi-humid, windy) where ventilation is not a priority. For other regions, use medium spacing with protection against hot/cold winds (Figure 5).

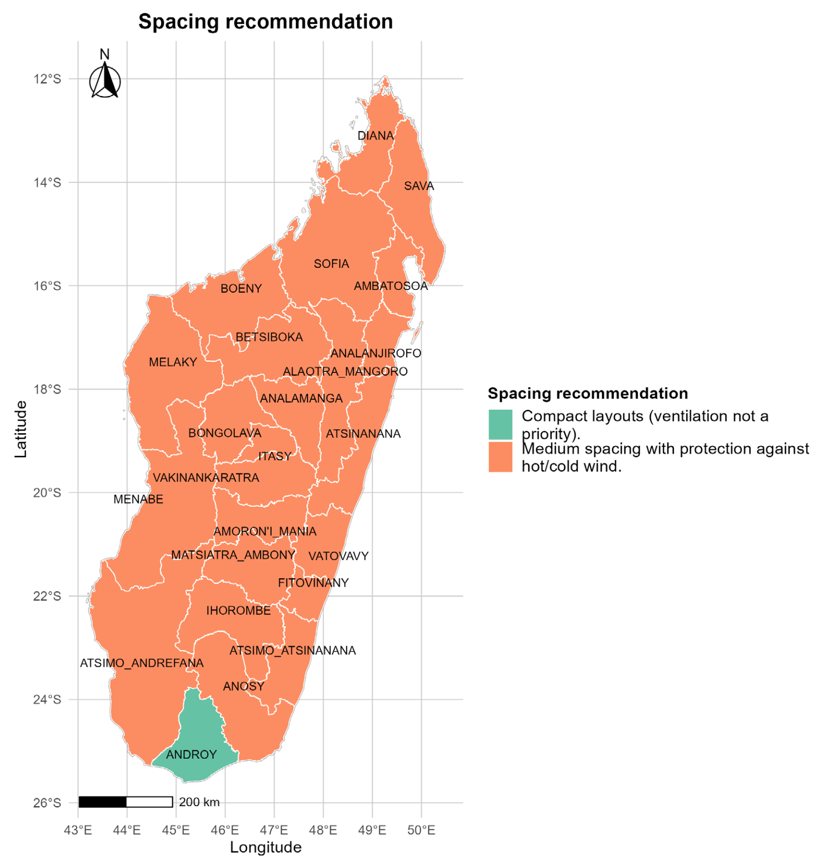

Figure 5. Spacing recommendation.

3.3. Openings

Most buildings have moderate openings (25% - 40% of wall area), except in hot/dry regions: BOENY (humid with high rainfall, directly exposed to the monsoon regime in summer), SOFIA (very humid, with limited influence from trade winds), DIANA (humid with high rainfall, directly exposed to the monsoon regime in summer) and MELAKY (humid with low precipitation, dry winter), which have intermediate openings (20% - 35% of the walls). Note that a 30% opening on a 10 m^2 wall represents 3 m^2 of windows or doors (Figure 6).

Protection from rain (awnings, overhanging roofs, waterproof shutters) is necessary in central and eastern Madagascar (humid and very humid zones). Protection from direct sunlight, such as exterior blinds, horizontal sunshades, and verandas, is essential in the following regions: BOENY (humid zone with high rainfall), DIANA (humid zone with high rainfall), MELAKY (humid zone with low rainfall and a dry winter), and SOFIA (very humid zone) (Figure 7).

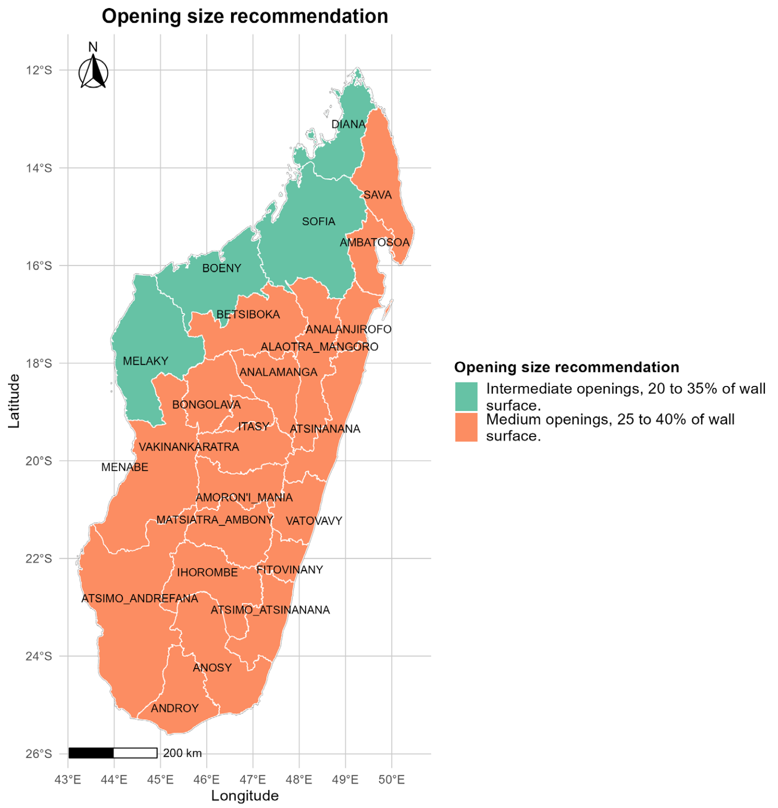

Figure 6. Opening size recommendation.

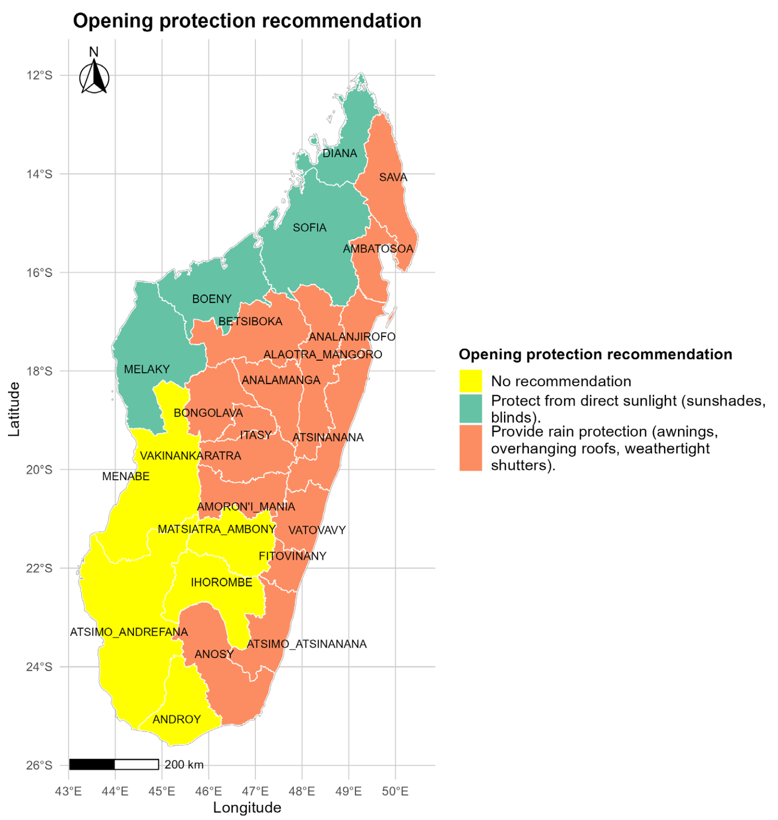

Figure 7. Opening protection recommendation.

3.4. Walls and Floors

Solid construction, such as 40 cm thick stone walls or compressed earth bricks (thermal lag > 8 hours), is essential in regions with large daily temperature ranges, such as ALAOTRA MANGORO (daily temperature range > 12˚C), ANALAMANGA (temperature range between 8˚C and 10˚C), and ANDROY (temperature range > 15˚C). Lightweight construction, such as wood-frame structures with plant fiber panels (low thermal mass) and/or wood/straw sandwich panels, or wooden houses with a ventilated air gap under the roof, is recommended in the hot/humid areas of AMBATOSOA (average temperature > 23.6˚C and humidity > 85%), ATSIMO ATSINANANA (average temperature > 21˚C and humidity between 75% and 85%), ATSINANANA (average temperature > 23.6˚C and humidity > 85%), FITOVINANY (average temperature > 23.6˚C and humidity > 85%) and SAVA (average temperature > 23.6˚C and humidity > 85%) (Figure 8).

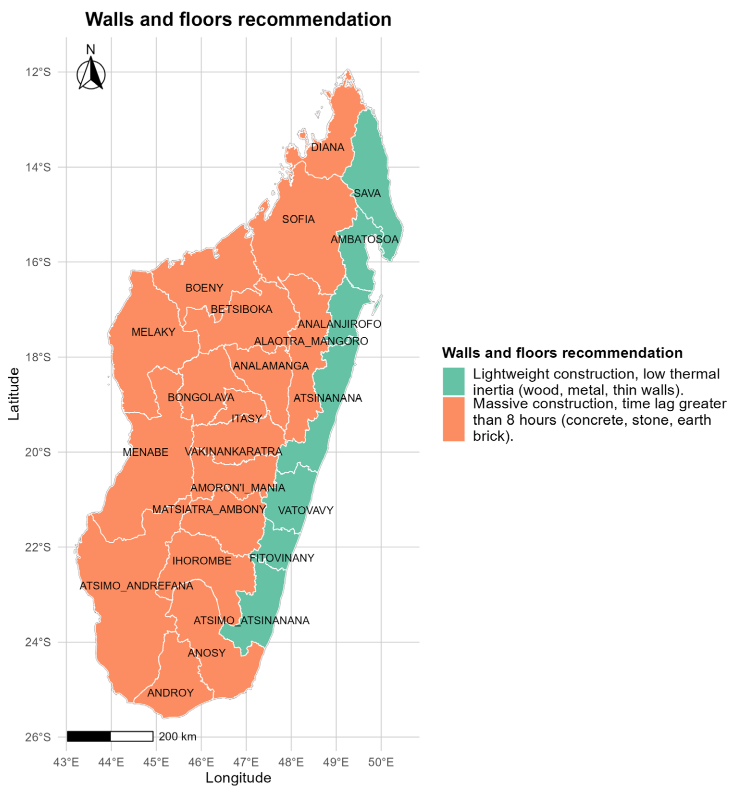

Figure 8. Walls and floors recommendation.

4. Discussion

This study is based on a map of housing construction recommendations using the Mahoney table. It recommends that most regions adopt an east-west orientation to reduce solar exposure. SOFIA, BOENY, BETSIBOKA, and ANALAMANGA require air circulation, so buildings with dual orientations are needed to promote ventilation. For DIANA region, recommendations include intermediate openings, representing 20% to 35% of the wall surface area, as well as moderate spacing combined with protection against hot or cold winds. These conclusions align with those of Rivel *et al.* (2024), who combine thermal mass with well-oriented natural ventilation, drawing inspiration from the old schools of Diego-Suarez [24].

For ANALAMANGA, the specifications call for openings of moderate size (25% to 40%), such as 1.2 m × 1.2 m casement windows on a 12 m^2 wall (*i.e.*, 4 windows = 5.76 m^2, or 32%), a structure with high thermal mass (40 cm cut-stone wall plus lime plaster, terracotta floor on a concrete slab (thermal lag exceeding 8 hours)) to cope with a significant temperature range (reaching 10˚C). These data are consistent with the work of Razanamanampisoa (2007), who recommends optimizing components and dual orientation to minimize nighttime heat loss in a context of significant daily temperature variation [25]. The findings regarding high thermal inertia align well with the results of Rabemanantsoa's thesis, which proposes using rammed earth or coated fired brick [26]. The findings of the study by Dowou *et al.* (2025) suggest using local materials such as wood fiber, reed panels, and straw bales to reduce the indoor temperature by an average of 17.5%, which aligns with our finding regarding lightweight construction (wood frame plus plant fiber panels for humid zones (AMBATOASOA, ANALANJIROFO, ATSINANANA, FITOVINANY, SAVA)) [27].

A qualitative validation shows that the recommendations for high thermal inertia in the Central Highlands are consistent with the traditional use of thick brick or stone walls in Merina and Betsileo architecture [28]. Similarly, recommendations for natural ventilation and lightweight structures in the humid eastern regions align with vernacular dwellings that use wood and plant-based materials to improve thermal comfort [29]. However, unlike the east–west bioclimatic orientation recommended by Mahoney's table, traditional Malagasy housing generally favors a north–south orientation for primarily cultural and symbolic reasons [30].

Mahoney's table is a key tool for bioclimatic design, enabling buildings to be adapted to local weather conditions in order to optimize thermal comfort. However, relying solely on this table is insufficient for a thorough analysis: combining it with sustainable energy solutions and specialized software (Climate Consultant and EnergyPlus) is essential for accurately assessing the effectiveness of passive strategies.

5. Conclusion

Applying the Mahoney method to climate data from Madagascar (1991-2020) provides a valuable tool for guiding sustainable architecture in Madagascar. The maps produced highlight the need to adopt strategies adapted to local climate conditions, particularly natural ventilation in the humid regions of the east and northeast, as well as the use of materials with high thermal inertia in the Central Highlands. Incorporating these recommendations into planning and building policies could help improve occupants' thermal comfort, enhance the resilience of buildings to climate change, and promote more sustainable architecture. When combined with the use of local materials such as earth, wood, and plant fibers, this approach offers significant potential for reducing the energy requirements associated with building thermal insulation while highlighting Madagascar's architectural heritage. However, detailed thermal and energy simulations are still needed to accurately quantify the energy savings that can be achieved.

Acknowledgements

First of all, we would like to thank the Madagascar Meteorological Directorate for providing us with daily data on temperature and precipitation. We would also like to thank ERA5-Land for providing us with hourly data on air temperature, dew point temperature, and average wind speed at 10 m.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Givoni, B. (1998) Climate Considerations in Building and Urban Design. Wiley.

[2] Olgyay, V. (1963) Design with Climate: Bioclimatic Approach to Architectural Regionalism. Princeton University Press.

[3] Kottek, M., Grieser, J., Beck, C., Rudolf, B. and Rubel, F. (2006) World Map of the Köppen-Geiger Climate Classification Updated. *Meteorologische Zeitschrift*, **15**, 259-263. https://doi.org/10.1127/0941-2948/2006/0130

[4] Koenigsberger, O.H., Ingersoll, T.G., Mayhew, A. and Szokolay, S.V. (1973) Manual of Tropical Housing and Building: Climatic Design. Orient Longman Private Limited.

[5] Givoni, B. (1998) Climate Considerations in Building and Urban Design. Van Nostrand Reinhold.

[6] Littlefair, P. (2000) Site Layout Planning for Daylight and Sunlight: A Guide to Good Practice. BRE Bookshop.

[7] Oke, T.R. (1987) Boundary Layer Climates. Methuen.

[8] Szokolay, S.V. (2008) Introduction to Architectural Science: The Basis of Sustainable Design. Architectural Press.

[9] Watson, D. and Labs, K. (1983) Climatic Design: Energy-Efficient Building Principles and Practices. McGraw-Hill.

[10] Brown, G.Z. and DeKay, M. (2001) Sun, Wind, and Light: Architectural Design Strategies. Wiley.

[11] Aynsley, R.M., Melbourne, W. and Vickery, B.J. (1977) Architectural Aerodynamics. Applied Science Publishers.

[12] Mahoney, C. (1971) Climate and House Design. United Nations.

[13] Fanger, P.O. (1970) Thermal Comfort: Analysis and Applications in Environmental Engineering. Danish Technical Press.

[14] Baker, N. (1987) Passive and Low Energy Building Design for Tropical Island Climates. Commonwealth Secretariat.

[15] Evans, M. (1980) Housing, Climate and Comfort. Architectural Press.

[16] Milne, M. and Givoni, B. (1979) Architectural Design Based on Climate. In: Watson, D. Ed., *Energy Conservation through Building Design*, McGraw-Hill, 96-113.

[17] Koenigsberger, O.H., Ingersoll, T.G., Mayhew, A. and Szokolay, S.V. (1974) Manual of Tropical Housing and Building. Part 1: Climatic Design. Longman.

[18] Szokolay, S.V. (2004) Introduction to Architectural Science: The Basis of Sustainable Design. Architectural Press.

[19] Givoni, B. (1976) Man, Climate and Architecture. Applied Science Publishers.

[20] Khalissa, H. (2007) Sciences Pour l'architecture. Master I: Architecture et Environnement.

[21] Météo Malagasy (2014) Atlas climatologique de madagascar.

[22] World Meteorological Organizatio (2018) Guide to Meteorological Instruments and Methods of Observation (WMO-No. 8).

[23] World Meteorological Organization (2017) WMO Guidelines on the Calculation of Climate Normals, WMO-No. 1203.

[24] Rivel, S., Nematchoua, M.K., Chrysostome, R.J. and Sambilason Richard, R. (2024) Study of Thermal Comfort in Some Standard School Buildings: A Case of Madagascar Island. *Health and Environment*, **5**, 237-245. https://doi.org/10.25082/he.2024.01.001

[25] Razanamanampisoa, H., Randriamanantany, Z.A., Rakotondramiarana, H.T., Garde, F. and Boyer, H. (2007) Simulation of a Typical House in the Region of Antananarivo, Madagascar. Determination of Passive Solutions Using Local Materials. 3rd *International Madagascar Conference in High-Energy Physics* (HEP-MAD 07). http://www.slac.stanford.edu/econf/C0709107/pdf/312.pdf

[26] Rabemanantsoa, H.N. (2021) Etude de l'inertie thermique de parois: Cas des murs typiques de maisons d'habitation de Madagascar. Ph.D. Thesis, Université d'Antananarivo.

[27] Dowou, K., Nougbléga, Y., Toka, K.A. and Amou, K.A. (2025) Numerical Study of Integrating Thermal Insulation Local Bio-Sourced Materials into Walls and Roofs for Thermal Comfort Improvement in Buildings in a Tropical Climate. *Construction Materials*, **5**, Article 4. https://doi.org/10.3390/constrmater5010004

[28] Ottino, P. (1986) L'étranger intime: Cosmologie, rituel et société chez les malgaches. Éditions des Archives Contemporaines.

[29] Kus, S. and Raharijaona, V. (2000) House to Palace, Village to State: Scaling Up Architecture and Ideology. *American Anthropologist*, **102**, 98-113. https://doi.org/10.1525/aa.2000.102.1.98

[30] Copalle, A. (1970) La cosmographie malgache. *Taloha*, **1**, 85-197.

List of Abbreviations

DGM:	Directorate General of Meteorology (Direction Générale de la Météorologie)
ECMWF:	European Centre for Medium-Range Weather Forecasts
ERA5-Land:	ECMWF Reanalysis version 5 - Land
IRI:	International Research Institute for Climate and Society
QGIS:	Quantum Geographic Information System (Système d'information géographique)

List of Notations

A1:	Thermal inertia
A2:	Sleeping outdoors
A3:	Issues Related to the Cold Season
ATM:	Monthly Temperature Range
C:	Comfort
C.D.:	Daytime Comfort
C.N.:	Nighttime Comfort
Dir. Vent:	Prevailing Wind Direction
G.H.:	Humidity Group
H1:	Essential Ventilation
H2:	Desirable Ventilation
H3:	Rain Protection
Hu. Moy.:	Average Humidity
Precip.:	Precipitation
Prob.:	Problem
RH:	Relative Humidity (%)
S.T.:	Thermal Stress
T:	Air Temperature (˚C)
TC:	Too Hot
Td:	Dew point temperature (˚C)
Temp. Max.:	Maximum temperature
Temp. Min.:	Minimum temperature
TF:	Too Cold
TMA:	Annual Average Temperature
Vit. Vent:	Wind speed
W1:	Strong, disruptive wind (1 to 12 months = present for ≥ 1 month)
W2:	Moderate wind useful for ventilation (1 to 12 months = present for ≥ 1 month).