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Bioclimatic Conditions in a Contrasted Coastal Environment: An Inductive Approach on the Grand-Popo Peninsula (South-West Benin)

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Abstract

Tropical sandy-lagoonal coastal strips concentrate thermal-comfort challenges because of their limited width, high radiative exposure and simultaneous proximity to water bodies with contrasting thermal properties. This configuration is particularly pronounced on the Grand-Popo peninsula, where the Atlantic Ocean, the Gbaga Channel and a progressively densifying urban fabric structure a discontinuous microclimatic system. The general objective is to characterize local bioclimatic conditions and determine their relationship with thermal comfort and adaptation strategies among riparian populations. The study combines hourly and daily meteorological data, in-situ microclimatic measurements conducted from 06:00 to 18:00, remote-sensing data and a survey of 384 respondents. Thermal conditions are assessed using the Universal Thermal Climate Index (UTCI), complemented by analysis of thermal perception, reported effects on activities, and spatial and architectural responses. The results show a regular thermal gradient between the two interfaces: the mean daily difference reaches 1.8 °C between ocean-facing and lagoon-facing sectors, with a maximum of 2.7 °C at 14:00. Mean UTCI reaches 34.6 °C at 14:00 during the hot season, corresponding to strong thermal stress, compared with 31.8 °C on the ocean-facing sector. Across hourly observations, 42.6% fall within strong to very strong thermal-stress classes. The survey indicates that 78.1% of respondents frequently experience uncomfortable heat and 72.4% report adapting their location or activity schedules.

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Keywords

Bioclimatology, Thermal index (UTCI), Peninsula, Grand-Popo, Benin

Introduction

Thermal comfort is a major determinant of the habitability of tropical coastal areas, where sensible heat results from the interaction between temperature, humidity, wind, radiation and urban morphology. Densified coastal environments show particularly marked thermal contrasts where mineral surfaces, water bodies and vegetated spaces are juxtaposed. Recent work on hot urban environments shows that physiological exposure depends as much on the local microclimate as on morphological characteristics and adaptive capacities (Coccolo *et al.,* 2016; Lai *et al.,* 2020; Obe *et al.,* 2023). In West Africa, the recent increase in the frequency, duration and intensity of urban heat waves reinforces the relevance of such approaches (Ngoungue Langue *et al.,* 2023). On the Beninese coast, human bioclimatology studies have highlighted the thermal constraints of coastal areas and their health and tourism implications (Boko, 2014; Houssou *et al.,* 2015).

On the Grand-Popo peninsula, the narrowness of the sand barrier, the proximity of the Atlantic Ocean and the Gbaga Channel, and the extension of built-up surfaces

create a thermal interface where sea-breeze effects interact with the thermal inertia of land and lagoon surfaces. The research question is therefore: to what extent do the microclimatic specificities of the Grand-Popo peninsula influence bioclimatic comfort and the adaptation strategies of riparian populations? The hypothesis is that the interface position between the Atlantic Ocean and the Gbaga Channel generates a sharp microclimatic gradient that accentuates daytime thermal stress despite the breeze regime. The specific objective is to assess local bioclimatic conditions and to analyse the level of thermal vulnerability perceived by users of the peninsula.

Materials and Methods

Study Area

The Grand-Popo peninsula is located in South-West Benin, approximately between 6°16′ and 6°18′ N and 1°48′ and 1°54′ E, in a coastal sector directly exposed to Atlantic influences. The study area is a narrow sand barrier between the ocean front and the lagoon system associated with the Gbaga Channel. This hydro-morphological organisation imposes a close proximity between water bodies, housing and roads (Figure 1).

The coastal barrier is characterized by sandy soils, a low water-retention capacity and high exposure to radiation. The Gbaga Channel acts as a humid surface with high thermal inertia, while the Atlantic Ocean is a permanent source of turbulent exchanges and breezes. Densification of housing, soil sealing and the reduction of vegetated areas modify radiative and convective exchanges at the local scale. These transformations reinforce the contrasts between open sectors, shaded spaces and built fronts, with direct implications for ventilation and housing comfort.

The spatial configuration of the peninsula reveals a structural confinement of the urban fabric on a narrow sand strip. The ocean and the channel limit lateral expansion, while housing develops longitudinally along the roads. This organisation brings buildings closer to the water interfaces and concentrates sealed surfaces. Built-up areas alternate with vegetated pockets and open sandy sectors, producing a mosaic of exposure conditions. The proximity of the channel favours air humidification, whereas built surfaces and bare soils store and release part of the radiation received. Morphology is therefore a key factor of local thermal differentiation.

Studies of the Beninese coast and its lagoon systems highlight the importance of interactions between coastal dynamics, land use and local hydrology (Lawson *et al.,* 2021; Oumbouke *et al.,* 2026).

Data Used

The climatic data used in this study are air temperature (°C), relative humidity (%), wind speed (m/s) and solar radiation (W/m²), extracted from the Météo-Bénin database at hourly and daily time steps for the 1991–2020 reference period and the 2024–2025 field campaign.

These data are complemented by field microclimatic data, namely in-situ records of air temperature, relative humidity and surface parameters obtained with thermo-hygrometric sensors at an hourly time step between 06:00 and 18:00 in the sectors exposed to the ocean and to the Gbaga Channel.

Finally, socio-demographic data focus on population perception: perceived heat, reported effects on activities, perceived health manifestations and housing arrangements.

Data Collection

The literature review covered scientific publications on urban bioclimatology, thermal comfort in tropical environments, physiological indices and adaptation strategies in coastal environments. Fieldwork combined microclimatic observations and a structured survey.

The target group consisted of household heads and regular users of the peninsula whose daily activities expose them to local thermal conditions.

The sample size was determined using the Schwartz formula:

$$n = (Z^2 \times p \times (1 - p)) / e^2$$

Where $Z = 1.96$ for a 95% confidence level, $p = 0.50$ for maximum variability and $e = 0.05$ for a 5% margin of error. The calculation gives $n = (1.96^2 \times 0.50 \times 0.50) / 0.05^2 = 384.16$. The operational sample size was therefore 384 respondents, distributed across the different exposure sectors to capture the contrasts between the ocean front, the lagoon environment, residential sectors and activity areas.

Data Processing and Analysis

The UTCI was used as the main physiological indicator of thermal stress, in line with its use in bioclimatic studies conducted in Benin (Mehinto-Dovonou *et al.,* 2018; Boko *et al.,* 2021). The simplified formula applied is given in equation (1):

$$UTCI = 3.21 + 0.872\,t + 0.2459\,Mrt - 2.5078\,v - 0.0176\,RH \quad (1)$$

Where t is air temperature (°C), Mrt the mean radiant temperature (°C), v the wind speed 10 m above ground (m/s) and RH the relative humidity (%).The UTCI is a complex multi-node model simulated from several input variables (adapted from Błażejczyk *et al.,* 2010, see Figure 2).

The UTCI values obtained were interpreted according to the assessment scale presented in Table 1 and were used to analyse the seasonal variability of thermal comfort. Thermal comfort corresponds to UTCI values between 9 and 26 °C. Below this range, conditions become cold; above it, conditions become warm and range from moderate to extreme heat stress.

Statistical analyses include means, minima, maxima, thermal ranges, inter-sector differences, relative frequencies and hourly distributions. Differences between sectors are examined by comparing means and relative differences. Survey responses are expressed as frequencies and percentages. Spatial analysis of satellite images relates thermal contrasts to built, sandy and vegetated surfaces.

Results and Discussion

Spatio-temporal Variability of Microclimatic Parameters on the Peninsula

Table 2 presents the mean hourly variations of air temperature and relative humidity according to exposure to the Atlantic Ocean or to the Gbaga Channel.

The thermal gradient is weak at 06:00 (0.9 °C), then increases steadily up to 2.7 °C at 14:00 before decreasing to 1.2 °C at 18:00. The maximum temperature reaches 32.0 °C on the ocean side against 34.7 °C on the Gbaga side, a relative difference of 8.4%. Humidity remains systematically higher on the channel side, from 3 points at 06:00 to 8 points at 14:00, then 6 points at 18:00. The daily range is 5.9 °C on the ocean side and 7.7 °C on the channel side. The lagoon sector therefore combines the thermal maximum with higher humidity in the middle of the day, a configuration likely to increase physiological stress despite the regulating influence of water bodies.

Assessment of Thermal Comfort and Bioclimatic Indice (UTCI)

Figure 3 presents the seasonal and hourly distribution of thermal-stress classes assessed with the UTCI. The UTCI shows a clear increase towards midday. The maximum mean UTCI value of 34.6°C is observed in July between 13:00 and 15:00 -7.2°C higher than the 27.4°C recorded in the morning in January (06:00–09:00). Periods of strong stress represent 42.6% of hourly observations, whereas no-stress situations account for only 18.7%. The hot season concentrates the highest values: 32.8 °C between 10:00 and 12:00, then 34.6 °C between 13:00 and 15:00.

Local Perception and Adaptation Strategies to Thermal Constraints

Figure 4 Summarises the spatial and architectural adaptation strategies reported by households in response to thermal stress.

Natural ventilation is the most frequent strategy, reported by 87.8% of respondents (n = 337), followed by changes in activity schedules (72.4%, n = 278), the use of traditional materials (70.1%, n = 269), and the search for vegetation or shade (65.4%, n = 251). The gap between the most and the least frequent strategy reaches 22.4 percentage points. Adaptation thus relies primarily on ventilation and temporal mobility before physical transformations of the dwelling. Proximity to vegetated areas or to water is also a spatial option sought when thermal conditions become constraining.

The contrasts observed on the peninsula are consistent with the mechanisms described for hot urban environments, where surface geometry, the presence of water, vegetation and radiative properties jointly control temperature and physiological exposure. Lai *et al.,* (2020) show that the configuration of open spaces strongly modulates local thermal conditions. Gunawardena *et al.,* (2017) also establish the importance of blue and green spaces in microclimatic regulation, while in Cotonou, Teka *et al.,* (2017) highlight the mitigating effect of tree cover on air temperature.

Figure.1 Geographical and hydro-morphological location of the Grand-Popo peninsula (South-West Benin)

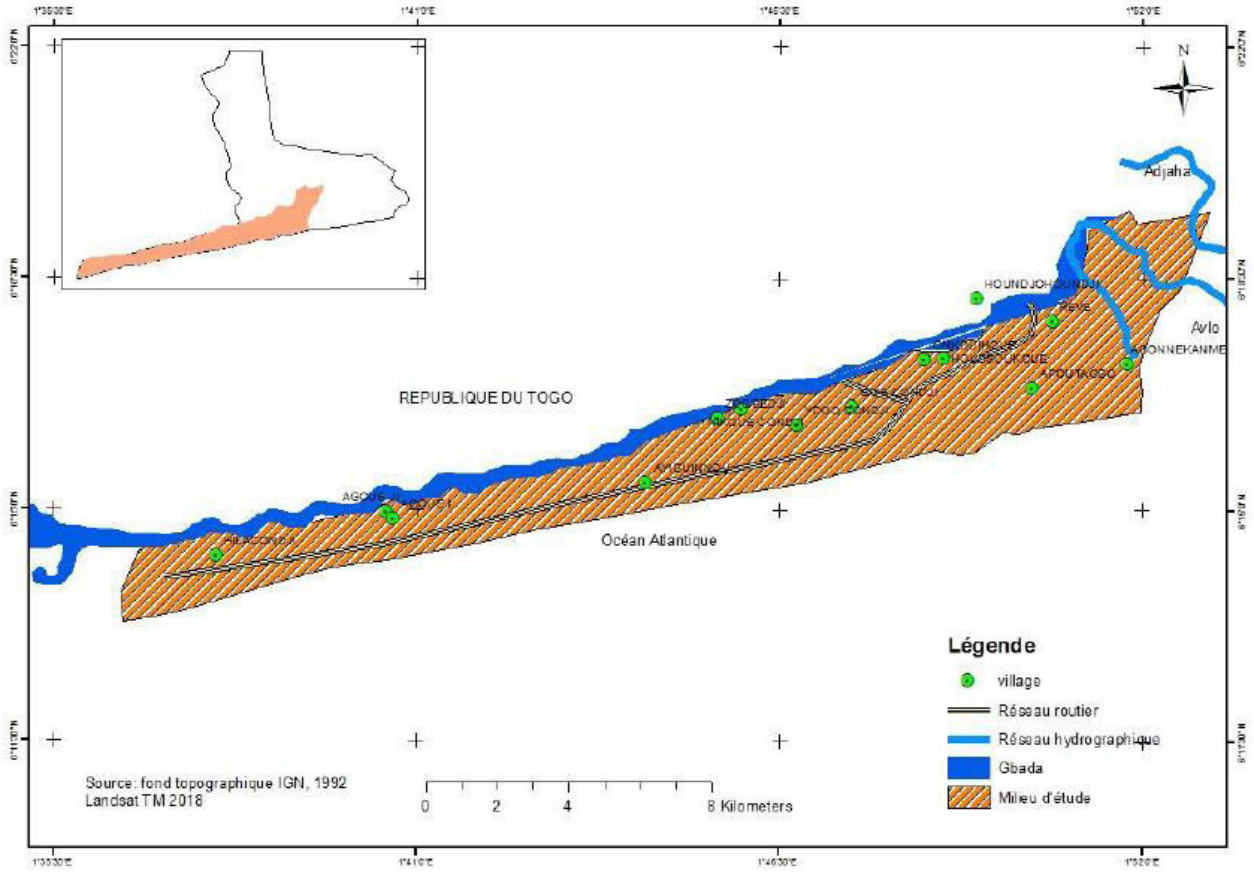
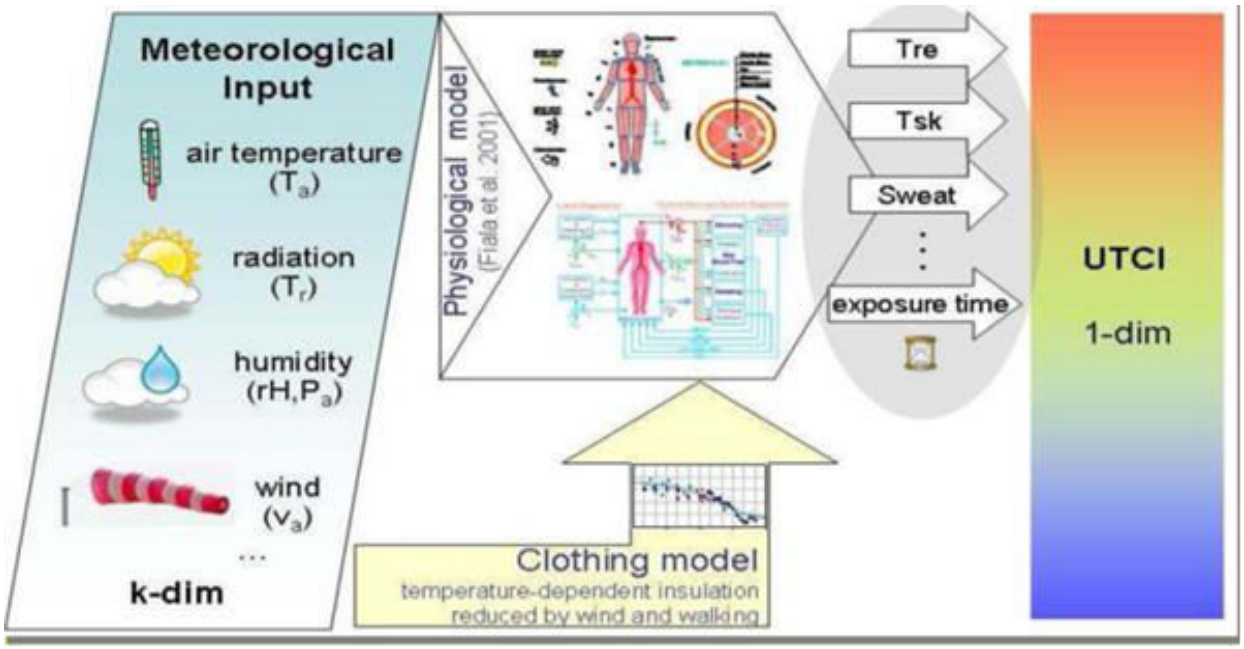
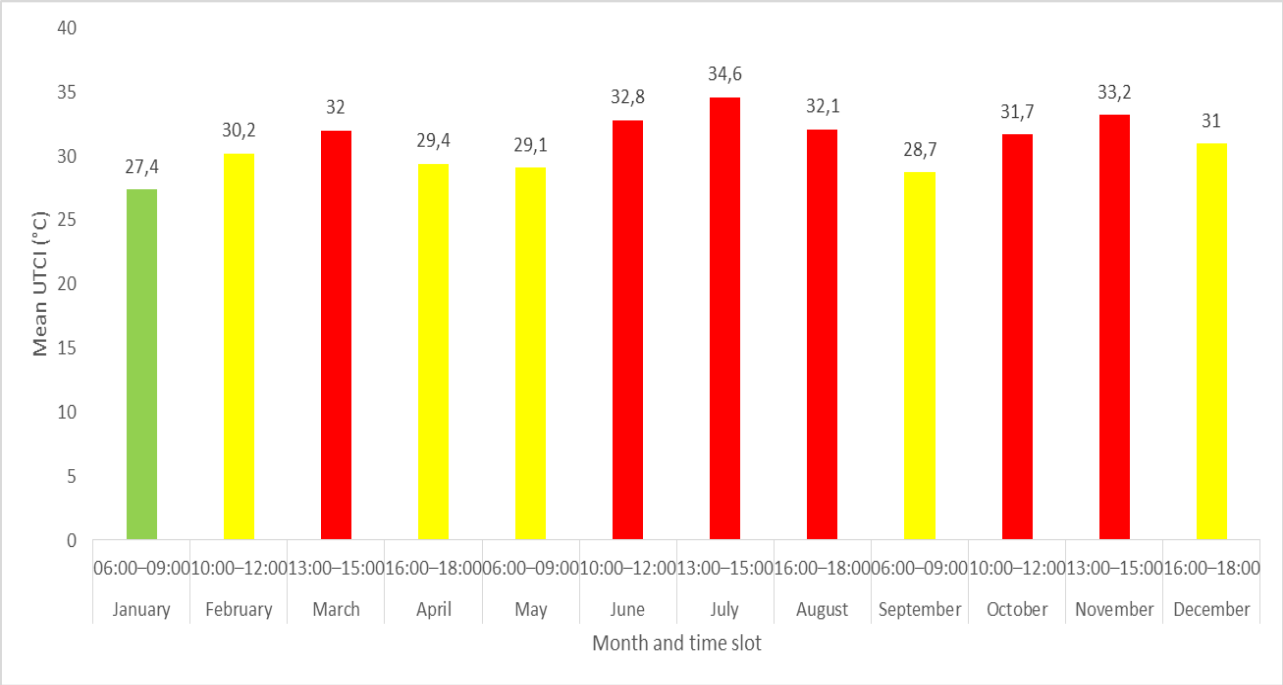


Figure.2 Main modelling parameters of the UTCI



Source: Błażejczyk et al., (2010) and Havenith et al., (2012)

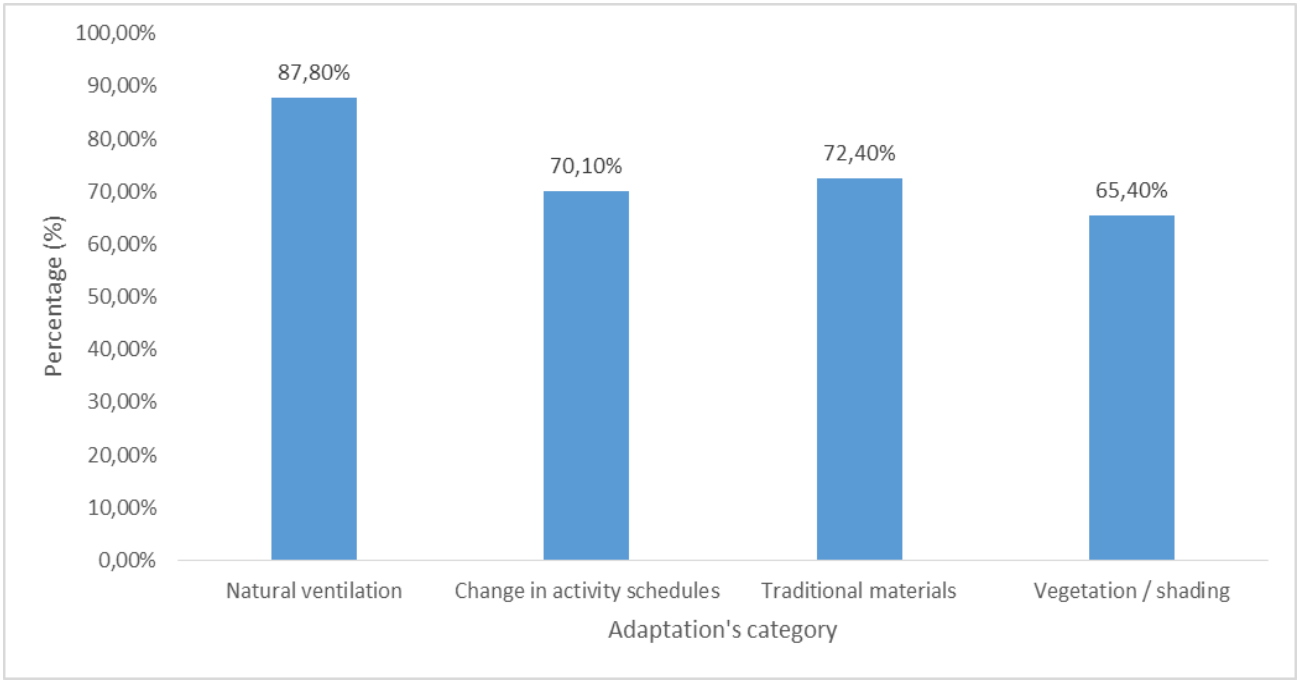
Figure.3 Seasonal and hourly distribution of thermal-stress classes (UTCI, °C) on the Grand-Popo peninsula



Source: Data processing, 2026

CAPTION	CATEGORY
	No stress
	Moderate stress
	Strong stress

Figure.4 Spatial and architectural adaptation strategies reported by households



Source: Field surveys, 2026

Table.1 UTCI assessment scale

UTCI (°C) range	Stress Category
above +46	extreme heat stress
+38 to +46	very strong heat stress
+32 to +38	strong heat stress
+26 to +32	moderate heat stress
+9 to +26	no thermal stress
+9 to 0	slight cold stress
0 to -13	moderate cold stress
-13 to -27	strong cold stress
-27 to -40	very strong cold stress
below -40	extreme cold stress

Source: Błażejczyk et al., (2010)

Table.2 Mean hourly variations of air temperature (°C) and relative humidity (%) by exposure (ocean side vs Gbaga Channel side)

Hour	T Ocean (°C) (ocean-facing sector)	T Gbaga (°C) (lagoon-facing sector)	Difference (°C)	RH Ocean (%)	RH Gbaga (%)
06:00	26.1	27.0	0.9	86%	89%
08:00	27.8	29.1	1.3	82%	86%
10:00	30.2	31.5	1.3	75%	81%
12:00	31.6	33.0	1.4	70%	77%
14:00	32.0	34.7	2.7	68%	76%
16:00	31.0	33.0	2.0	71%	79%
18:00	29.0	30.2	1.2	78%	84%

Source: Field data / Météo-Bénin, 2025

In tropical regions, the effects of humidity on comfort become decisive when temperatures exceed physiological tolerance thresholds. Raymond *et al.,* (2020) show that combinations of heat and humidity close to the limits of human tolerance are becoming more frequent, and Ngoungue Langue *et al.,* (2023) underline the important role of humidity in night-time heat events in West African cities. These findings are in line with thermal-comfort assessments conducted on other coasts of the Gulf of Guinea, in Lagos (Komolafe and Akingbade, 2004; Obe *et al.,* 2023), on the Ghanaian coast (Frimpong, 2025) and in Pointe-Noire (Golo Bandzouzi *et al.,* 2025). The results obtained in Grand-Popo extend this reading by showing that the channel sector combines high temperature, higher humidity and morphological confinement.

The reported strategies are consistent with the conclusions of Santamouris (2020) on the importance of urban overheating mitigation strategies, and with the work of Besancenot (1990), Houssou (1998) and Boko (2014) on the socio-economic and tourism implications of human bioclimates. The perceived health manifestations echo the links established between bioclimatic conditions and health in southern Benin (Boko, 1992; Houssou *et al.,* 2015; Boko *et al.,* 2025). Finally, the results confirm the value of physiological indices for going beyond air temperature alone, in line with the methodological work of Bröde *et al.,* (2012), Błażejczyk *et al.,* (2012) and Di Napoli *et al.,* (2018). The integrated UTCI approach thus provides a more operational reading of the contrasts between oceanic and lagoon interfaces.

In conclusion, this study establishes a clear bioclimatic differentiation between the two interfaces of the Grand-Popo peninsula. The sector exposed to the Gbaga Channel has the highest daytime temperatures and simultaneously retains higher relative humidity, whereas the ocean sector benefits from a better-ventilated environment and a less marked thermal gradient. The maximum of 34.7 °C recorded on the channel side at 14:00 corresponds to a difference of 2.7 °C with the ocean sector. The UTCI confirms this pattern, with a maximum mean value of 34.6 °C during the hot season.

The main contribution lies in linking microclimatic variability, thermal indices and population perception. Reported responses show that natural ventilation, changes in schedules, traditional materials and vegetation are the main adaptation strategies. These results provide an operational basis for coastal planning, emphasising the continuity of ventilation corridors, the conservation of vegetated spaces and the control of soil sealing.

From a theoretical standpoint, the approach confirms the value of an analysis based on hydro-morphological interfaces rather than on a single mean temperature. Future research should integrate longer microclimatic series, high-resolution thermal mapping, physiological measurements and a detailed seasonal analysis of building characteristics in order to clarify the mechanisms of thermal vulnerability at neighbourhood scale.

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