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**IDA: ADVANCED  
DOCTORAL RESEARCH  
IN ARCHITECTURE**



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Antonio Tejedor Cabrera, Marta Molina Huelva (comp.)

IDA: Advanced Doctoral Research in Architecture  
Sevilla: Universidad de Sevilla, 2017.

1.408 pp. 21 x 29,7 cm

ISBN: 38765987928376375

Legal Dep.: 236235768336

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Seville, november 2017

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## **FORMATO**

### **Mesas temáticas**

Las mesas temáticas son lugares de presentación de las metodologías y las experiencias de jóvenes doctores y de estudiantes de doctorado procedentes de las diferentes universidades. Son gestionadas por los propios estudiantes de doctorado que generan unas conclusiones para ser debatidas y reelaboradas en la sesión plenaria final. Las sesiones se desarrollan de manera simultánea con la presentación de los *papers* seleccionados en la *call*, organizados en cuatro áreas o líneas temáticas:

1. Tecnologías de la Arquitectura
2. Vivienda, Ciudad y Territorio
3. Patrimonio y Rehabilitación
4. Análisis y Proyectos Avanzados

### **Taller**

El workshop del Congreso se orienta hacia el análisis de los problemas y las necesidades de gestión de los Programas de Doctorado con el fin de extraer conclusiones que pueden ser útiles a las Universidades implicadas. En el workshop participan los coordinadores de los programas de Doctorado en Arquitectura y los representantes de los doctorandos. Son temas de debate: las líneas de investigación, las metodologías, las necesidades organizativas de los programas de doctorado, el Doctorado Internacional y el Doctorado Industrial, y el futuro de la investigación doctoral.

### **Sesiones Plenarias**

Las sesiones plenarias se realizan al inicio y al final del Congreso. En la primera sesión de bienvenida e introducción al Congreso se invita a participar a expertos investigadores del panorama nacional e internacional y a los coordinadores de los programas de doctorado. En la segunda sesión plenaria se propone un debate abierto para la reelaboración de las propuestas extraídas del taller y de las mesas temáticas. Sirve también de clausura con la presentación de las conclusiones finales del Congreso IDA\_Sevilla 2017.

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## FOREWORD

The Instituto Universitario de Arquitectura y Ciencias de la Construcción (IUACC), in collaboration with the Escuela Técnica Superior de Arquitectura (ETSAS) and the Escuela Internacional de Doctorado (EIDUS) of the University of Seville are pleased to welcome the heads of research from both Spanish and overseas universities, consolidated researchers and young doctoral researchers to the First International Congress of Doctorates in Architecture IDA Sevilla, from 27th to 28th November 2017.

The **IDA\_Sevilla 2017** Congress offers a general perspective of doctoral studies in the field of Architecture and its related disciplines: urban planning, heritage, landscape, construction technologies and sustainability. In the new context generated after the elimination of the doctoral programs prior to RD 99/2011, it is necessary to carry out an analysis of the complex panorama that the former programs and the new doctoral programs have drawn up, in order to know in detail both what has been achieved so far, as well as the challenges of the future of advanced doctoral research in Spain, in the European and international context.

The startling changes that are taking place in our society call for a vision of research that is not compartmentalised into traditional disciplines or areas of knowledge. Doctoral research in Architecture must adapt to changes in society and to the sustainable productive needs of territory.

The congress will take place at the Escuela Técnica Superior de Arquitectura de Sevilla, organised in four simultaneous thematic tables, a workshop on the administration of doctoral programs and two plenary sessions.

The **thematic tables** are aimed at young doctors and doctoral students of the different participating universities who will present their experiences and methods of their research - in development or recently concluded. The participation in the thematic tables is carried out through the selection procedure with blind peer review established in the call for papers and through express invitations to the debate. The almost 70 communications have been structured in four thematic areas representative of the PhD programs in Architecture.

The **open workshop** will be held in two sessions with the participation of the coordinators of each of the collaborating programs of the Congress, and professors with extensive doctoral experience. Its objectives are multiple: to discuss the experiences undertaken in the different universities, exchange ideas about the approaches and models applied, address the challenges of internationalization and management, launch the new Industrial Doctorate with companies and public agencies, and so on.

There are two **plenary sessions**: one, a plenary session of introduction to the congress, with the participation of coordinators of national and foreign doctoral programs; and a closing plenary session, with an open debate for the going-over of the conclusions drawn from the thematic tables and the workshop, and the presentation of final conclusions.

We thank the Escuela Internacional de Doctorado of the University of Seville, and the Escuela Técnica Superior de Arquitectura de Sevilla for the support they have provided for the holding of this meeting, which contributes so much to the clarification of the future of doctoral studies in Spanish universities in the face of the great challenge of internationalization and the continuous improvement of the quality of research in Architecture. We also thank those responsible for the participating Doctoral Programs, the Architecture library of the US and all the participants and attendees.

Antonio Tejedor Cabrera  
Marta Molina Huelva

## PRÓLOGO

El Instituto Universitario de Arquitectura y Ciencias de la Construcción (IUACC), con la colaboración de la Escuela Técnica Superior de Arquitectura (ETSAS) y la Escuela Internacional de Doctorado (EIDUS) de la Universidad de Sevilla, se complacen en recibir a los responsables de investigación de universidades españolas y extranjeras, a los investigadores consolidados y a los jóvenes investigadores de doctorado en el I CONGRESO INTERNACIONAL DE DOCTORADOS EN ARQUITECTURA IDA\_Sevilla, del 27 al 28 de noviembre de 2017.

El congreso **IDA\_Sevilla 2017** ofrece una perspectiva general de los estudios de doctorado en el campo de la Arquitectura y sus disciplinas afines: urbanística, patrimonio, paisaje, tecnologías de la construcción y sostenibilidad. En el nuevo contexto generado tras la extinción de los programas doctorales anteriores al RD 99/2011 es necesario realizar un análisis del complejo panorama que han construido los programas extintos y los nuevos programas de doctorado, con el objeto de conocer con detalle tanto lo conseguido hasta ahora como los retos que depara el futuro de la investigación doctoral avanzada en España, en el contexto europeo e internacional.

Los vertiginosos cambios que se están produciendo en nuestra sociedad reclaman una visión de la investigación no compartimentada en disciplinas o áreas de conocimiento tradicionales. La investigación doctoral en Arquitectura debe adaptarse a los cambios de la sociedad y a las necesidades productivas sostenibles en el territorio.

El congreso se celebra en la Escuela Técnica Superior de Arquitectura de Sevilla organizado en cuatro mesas temáticas simultáneas, un taller sobre la gestión de los programas de doctorado y dos sesiones plenarias.

Las **mesas temáticas** están dirigidas a los jóvenes doctores y a estudiantes de doctorado de las diferentes universidades participantes que exponen sus experiencias y métodos sobre las investigaciones en desarrollo o recientemente concluidas. La participación en las mesas temáticas se realiza por el procedimiento de selección con revisión por pares ciegos establecido en la *call for papers* y por medio de invitaciones expresas al debate. Las casi 70 comunicaciones se han estructurado en cuatro áreas temáticas representativas de los programas de doctorado en Arquitectura.

El **taller** de puesta en común se realiza en dos sesiones con la participación de los coordinadores de cada uno de los programas colaboradores del Congreso y de profesores con amplia experiencia doctoral. Sus objetivos son múltiples: debatir sobre las experiencias desarrolladas en las distintas universidades, intercambiar ideas sobre los enfoques y los modelos aplicados, abordar los retos de internacionalización y de gestión, poner en marcha el nuevo Doctorado Industrial con empresas y agencias públicas, etc.

Las **sesiones plenarias** son dos: una sesión plenaria de introducción al congreso, con la intervención de coordinadores de programas de doctorado nacionales y extranjeros; y una sesión plenaria de clausura, con un debate abierto para la reelaboración de las conclusiones extraídas de las mesas temáticas y del workshop y la presentación de las conclusiones finales.

Agradecemos a la Escuela Internacional de Doctorado de la Universidad de Sevilla y a la Escuela Técnica Superior de Arquitectura de Sevilla el apoyo que han proporcionado para la realización de este encuentro que tanto contribuye a clarificar el futuro de los estudios doctorales en las universidades españolas ante el gran reto de la internacionalización y la continua mejora de la calidad de la investigación en Arquitectura. Damos las gracias también a los responsables de los Programas de Doctorado participantes, a la Biblioteca de Arquitectura de la US y a todos los participantes y asistentes.

Antonio Tejedor Cabrera  
Marta Molina Huelva



## OBJECTIVES

1. Analyze the research lines of the various programs and build a map of doctoral research in Spain with the support of coordinators, tutors / thesis supervisors, doctoral students and young doctors in the disciplines related to Architecture and their related areas.
2. To know the status of doctoral theses in progress or defended in the last three years, selected by means of a call with blind peer evaluation of the doctoral programs participating in the congress.
3. Discuss the structure and university management of doctoral programs in relation to employment challenges, collaboration with the productive sector and national research programs.
4. Exchange experiences with other international doctoral research programs on international mobility management, theses with international mention, co-supervised theses, theses with industrial mentions, etc.
5. No less important, consolidate a national and international network of Doctoral Programs related to Architecture, Urban Planning, Heritage, Landscape, Technologies and related disciplines.



## **FORMAT**

### **Thematic tables**

The thematic tables are places to present the methodologies and experiences of young doctors and doctoral students from different universities. They are managed by the doctorate students themselves, who generate conclusions to be debated and reworked in the final plenary session. The sessions are developed simultaneously with the presentation of the papers selected in the call, organized in four areas or thematic lines:

1. Architectural technologies
2. Housing, city and territory
3. Heritage and Rehabilitation
4. Analysis and advanced projects

### **Workshop**

The workshop of the Congress is oriented towards the analysis of the problems and management needs of the Doctorate Programs, with the objective of arriving at conclusions that may be useful to the Universities involved. The coordinators of the Doctorate in Architecture programs and the doctoral students' representatives will participate in the workshop. The following are topics for debate: lines of research, methodologies, organizational needs of the doctoral programs, the International Doctorate and the Industrial Doctorate, and the future of doctoral research.

### **Plenary Sessions**

The plenary sessions are held at the beginning and end of the Congress. In the first session of welcome and introduction to the Congress, researchers from the national and international scene and the coordinators of the doctorate programs are invited to participate. In the second plenary session an open debate is proposed for the going over of the proposals drawn from the workshop and the thematic tables. It also serves as a closing ceremony with the presentation of the final conclusions of the 2017 IDA\_Sevilla Congress.

## OBJETIVOS

1. Analizar las líneas de investigación de los diversos programas y construir el mapa de la investigación doctoral en España con el apoyo de los coordinadores, los tutores/directores de tesis, los doctorandos y los jóvenes doctores en las disciplinas relacionadas con la Arquitectura y sus áreas afines.
2. Conocer el estado de las tesis doctorales en marcha o defendidas en los últimos tres años, seleccionadas por medio de una *call* con evaluadores por pares ciegos de los programas de doctorado participantes en el congreso.
3. Debatir sobre la estructura y la gestión universitaria de los programas de doctorado en relación con los retos de empleo, colaboración con el sector productivo y los programas nacionales de investigación.
4. Intercambiar experiencias con otros programas de investigación doctoral a escala internacional sobre gestión de la movilidad internacional, tesis con mención internacional, tesis en cotutela, tesis con mención industrial, etc.
5. No menos importante, consolidar una red nacional e internacional de Programas de Doctorado relacionados con la Arquitectura, la Urbanística, el Patrimonio, el Paisaje, las Tecnologías y sus disciplinas afines.



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LA ARQUITECTURA

## ARCHITECTURE TECHNOLOGIES / TECNOLOGÍAS DE LA ARQUITECTURA

p. 23-30: **ANALYSIS OF INCIDENCE OF LICENSE MANAGEMENT ACTIVITIES IN THE PROCESSES OF THE INTERNATIONAL STANDARD UNE ISO 21,500** / p. 31-39: **ANÁLISIS DE INCIDENCIA DE LAS ACTIVIDADES DE GESTIÓN DE LICENCIAS EN LOS PROCESOS DE LA NORMA INTERNACIONAL UNE ISO 21.500**

*García Ruiz-Espiga, Adolfo; Soler Severino, Manuel*

p. 41-49: **ENVELOPE'S ENERGY PERFORMANCE OF UNIVERSITIES BUILDINGS LOCATED IN BAHIA – BRAZIL** / p. 50-58: **DESEMPEÑO ENERGÉTICO DE LA ENVOLVENTE TÉRMICA DE EDIFICACIONES UNIVERSITARIAS CONSTRUIDAS EN BAHIA - BRASIL**

*Santana, Bruno; Coch, Helena*

p. 59-66: **A STUDY OF THE ESSENTIAL CHARACTERISTICS OF A GLOBAL DANCE FLOOR SYSTEM** / p. 67-74: **ESTUDIO SOBRE LAS CARACTERÍSTICAS ESENCIALES DE UN SISTEMA DE SUELO GLOBAL PARA LA DANZA**

*Turiel, Claudia; García-Santos, Alfonso*

p. 75-83: **THE ROOF THERMAL BEHAVIOR IN A TROPICAL-EQUATORIAL CLIMATE** / p. 84-93: **EL COMPORTAMIENTO TÉRMICO DE LA CUBIERTA EN EL CLIMA TROPICAL-ECUATORIAL**

*Torres-Quezada, Jefferson; Coch-Roura, Helena; Isalgué, Antonio*

p. 95-103: **FRP REINFORCEMENT AND PRODUCTION OF DUO TIMBER BEAMS** / p. 104-112: **FABRICACIÓN Y REFUERZO DE VIGAS LAMINADAS DÚO CON FRP**

*Balmori, Jose Antonio; Basterra, Luis-Alfonso*

p. 113-121: **METHODOLOGY OF COMPLEMENTARY ASSESSMENT TO A LIFE CYCLE ANALYSIS OF THE SUSTAINABILITY OF USE GADUA BAMBOO IN CONSTRUCTIVE SOLUTIONS** / p. 122-130: **METODOLOGÍA DE VALORACIÓN COMPLEMENTARIA A UN ANÁLISIS DE CICLO DE VIDA DE LA SOSTENIBILIDAD DEL USO DEL BAMBÚ GUADUA EN SOLUCIONES CONSTRUCTIVAS**

*Torres Rojas, José Eduardo; Neila Gonzalez, Francisco Javier*

p. 131-141: **THERMODYNAMICS OF MEDITERRANEAN COURTYARDS: QUANTIFICATION AND APPLICATIONS IN ECO-EFFICIENT ARCHITECTURAL DESIGN** / p. 142-152: **TERMODINÁMICA DEL PATIO MEDITERRÁNEO: CUANTIFICACIÓN Y APLICACIÓN AL DISEÑO DE ARQUITECTURAS ECO-EFICIENTES**

*Rojas Fernández, Juan Manuel; Galán Marín, Carmen; Fernández Nieto, Enrique*

p. 153-160: **COMPLEMENTARY TECHNIQUES FOR THE CHARACTERIZATION OF NEW CONSTRUCTION MATERIALS: ANALYSIS AND REVIEW** / p. 161-169: **TÉCNICAS COMPLEMENTARIAS PARA LA CARACTERIZACIÓN DE NUEVOS MATERIALES CONSTRUCTIVOS: ANÁLISIS Y REVISIÓN**

*Pedreño-Rojas, M. Alejandro; Morales-Conde, M. Jesús; Rodríguez-Liñán, Carmen; Pérez-Gálvez, Filomena; Rubio-de-Hita, Paloma*

p. 171-181: **CURRENT AND FUTURE DEMAND-SIDE MANAGEMENT POTENTIAL RELATED TO THE THERMAL MASS OF RESIDENTIAL BUILDINGS IN EUROPE BACKGROUND AND METHODOLOGICAL APPROACH** / p. 182-192: **POTENCIAL ACTUAL Y FUTURO DE GESTIÓN DE LA DEMANDA ENERGÉTICA ASOCIADA A LA MASA TÉRMICA DE EDIFICIOS RESIDENCIALES EN EUROPA ANTECEDENTES Y PLANTEAMIENTO METODOLÓGICO**

*de-Borja-Torrejón, Manuel; León-Rodríguez, Ángel-Luis; Auer, Thomas*

p. 193-203: **STUDY AND ASSESSMENT OF THE SEISMIC VULNERABILITY OF PRIMARY SCHOOL BUILDINGS LOCATED AT THE ALGARVE AND HUELVA: STATE OF THE ART** / p. 204-214: **ESTUDIO Y VALORACIÓN DE LA VULNERABILIDAD SÍSMICA DE EDIFICIOS DE EDUCACIÓN PRIMARIA EN EL ALGARVE Y HUELVA: ESTADO DEL ARTE**

*Requena-García-de-la-Cruz, María-Victoria; Fazendeiro-Sá, Luis; Morales-Esteban, Antonio; Estêvão, João M.C.; Ferreira, Mónica A.; Durand-Neyra, Percy; Oliveira, Carlos Soussa*

p. 215-222: **RESEARCH ON ECO-EFFICIENT STRUCTURAL MORTARS** / p. 223-231: **INVESTIGACIÓN SOBRE MORTEROS ESTRUCTURALES ECO-EFICIENTES**

*González-Kunz, Rocío N.; Pineda, Paloma; Morillas, Leandro; Brás, Ana*

p. 233-242: **TOWARD A CONTEMPORARY PLANNING METHOD: TECHNOLOGICAL AND CITIZENSHIP COMMITMENT** / p. 243-253: **HACIA UN MÉTODO DE PLANIFICACIÓN CONTEMPORÁNEO: COMPROMISO TECNOLÓGICO Y CIUDADANO**

*Luque Martín, Irene*

# THE ROOF THERMAL BEHAVIOR IN A TROPICAL-EQUATORIAL CLIMATE

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**Abstract:** The use of construction materials in response to the climate where it is located is a priority that has lost importance in architecture, in recent years. This has had repercussions in the increasing use of active systems to reduce the thermal discomfort in the residences. This study focuses on the comparison of the two most relevant roofs of the Ecuadorian Coast: metal roof and concrete roof, and the energy repercussions on the building. The results show a completely opposite thermal behavior between these two roofs, both day and night. Finally, these results allow to determine the thermal mass and the emissivity of the roof as fundamental parameters that deserve to be analyzed in future investigations. The final purpose of the thesis will be to establish guidelines or future rules to design in these climates.

**Key Words:** Roof, Tropical-Equatorial Climate, Sola Radiation, Cloud Cover.

## 1. Introduction

The roof is defined as a part of the building envelope, which covers the highest part of this and its main objective has always been the protection to the user. Protection of animals and climate, notably from rain or snow, but also from heat, wind and solar radiation (Whitney and Smith 1901). With the primary objective of protection, the form and material of this element vary greatly from region to region. These parameters have been influenced mainly by the climate and the available resources of each zone. For this reason there are numerous roof typologies such as: dome, inclined, flat, heavy, light, etc; and a great variety of materials such as palm, straw, clay, ceramics, concrete, metal, etc. However, Dollfus shows in his study that until the end of the 19th century that the typologies of buildings were guided primarily by the local climate and the search for user comfort (Dollfus 1954). The progress of construction and technology processes of the 20th century, such as concrete, metal, cooling systems, elevator, glass, led us to the globalization of architecture. The same process and technologies are used for different climates, while the comfort of people is ensured by the use of energy systems.

The central scopus of this research is the architectural element THE ROOF contextualized in a certain area of Ecuador, the Coast Region of this country. The analysis of this architectural element lies in its close relationship with two conditions: geographical and social-urban: the tropical-equatorial climate and urban growth.

In regards to their relationship with the geographical condition, it can be observed that in regions with these climates, which are determined by their high and constant amount of solar radiation throughout the year (3 kWh/m<sup>2</sup> average), the roof is the part of the envelope most exposed to this energy flux. Because of their latitude near 0 °, the extremes points of the solar paths are practically equal, for this reason the variation of the annual solar radiation received on a horizontal surface is only of 0.8 kWh/m<sup>2</sup> (Torres et al. 2016). Moreover, these climates are also defined by high levels of humidity, which in turn have a strong influence on cloudiness, and consequently on solar radiation (Koenigsberger et al. 1975). Due to these determinants, not only direct radiation and solar paths have a great impact on the thermal behavior of the roof, but also the diffuse component, usually not observed in other studies (Beckers 2012). The diffuse radiation in this region represents 63% of the average annual radiation (Conelec 2008), so its inclusion in the analysis of this research is indispensable.

With respect of the social-urban variable, the constant population growth in the world has brought complications on the urban expansion. At present over the half of the world population lives in cities. (United Nations 2014). These urban growth statistics have intensified especially in areas with tropical climates. Ecuador in particular has had a growth rate of urban population from 1990 to 2010 of 50%, which has impacted on the demand for housing and energy consumption in this sector, with a non-proportional growth of 113% and 173% respectively (INEC 1990)(INEC 2010)(CONELEC 2011)(ARCONEL 2013). Different models of cities approach this problem through the densification of the urban area, however countries like Ecuador have faced this increase of the urban population through

the growth of the territory, resulting in dispersed cities (Downs 1999). This situation has brought about the predominance of the roof, in terms of area, within this context.

Its relation with these conditions, climatic and urban, defines the roof as the determinant element on the indoor thermal behavior within these contexts. Some studies have addressed these impacts, and it has been defined that the roof can represent up to 70% of the total heat flows into the interior of the building, depending on the typology of the building (Vijaykumar et al. 2007). Also, several strategies have been analyzed in different climates, such as: cool roof in arid climates (Simpson and McPherson 1997) (Suehrcke et al. 2008), the effect of the ventilated roof and the barrier radiant in warm-humid climates (Dimoudi et al. 2006)(Černe and Medved 2007)(Gagliano et al. 2012), the impact of the inclination-orientation of the roof over indoor thermal behavior (Jayasinghe et al. 2003).

In general terms the morphological and material characteristics of the cover that are most used in climates where research is focused, warm-humid, are high slopes and light materials (Koch-Nielsen 2002)(Olgay 1963)(Serra, R. and Coch 2001). Nevertheless, in the same period of the urban expansion that this country experiences, 1990-2010, this trend presented a change. The use of light materials until 1990 was 72% while that of heavy materials was 28% (INEC 1990), while for 2010 these percentages were 63% and 37% respectively (INEC 2010). A considerable increase in the use of heavy materials.

In this context, several questions arise from this research: what typology or roofing material should be used on the coast of Ecuador? Does the concrete roof have a better thermal performance compared to the metal roof? What is the difference, in thermal terms, between the two roofs?

Finally, the total research of this doctoral thesis deals with the thermal behavior of the two most representative types of roofing in this region: the metal roof, 55%, and the concrete roof, 37% (INEC 2010), and the use of appropriate strategies to improve its thermal performance. However, this publication will focus on a detailed description of the methodology of the study and an analysis of these roofs in their natural state, with the purpose of obtaining the most influential variables on the thermal behavior of these two typologies in this tropical-equatorial climate. From this analysis will obtain basic indexes of the thermal differences among these roofs, which will serve for the next part of the study.

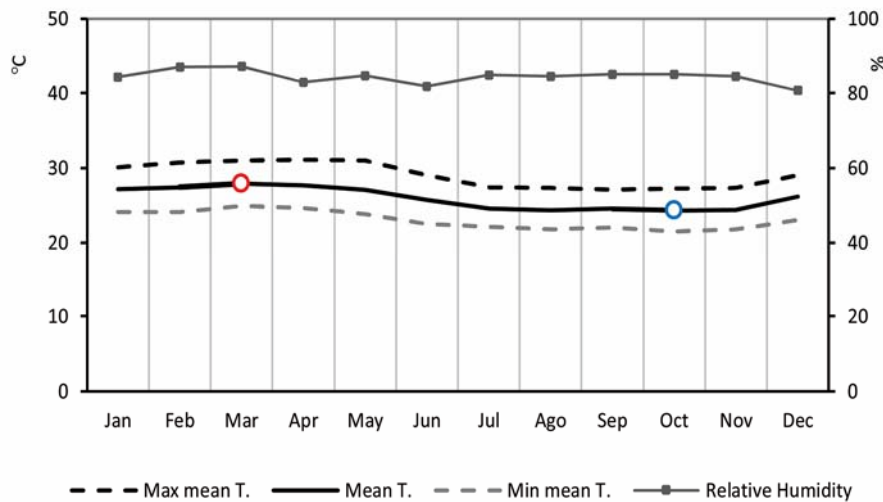
## **2. Methodology**

The methodology of the doctoral thesis on which this study is based is divided into two parts: the experimental part, and the evaluation of different variables through the simulation. The experimental work, in which this research is centered, was carried out in a city located in the south of the Coast of Ecuador (Santa Rosa). This part in turn focuses on two parts. The first deals with the detailed analysis of the climatic factors of this region as solar radiation, cloudiness, sky temperature, air temperature and humidity, through the collection of data and measurement of these parameters. The second part of the experimental analysis focuses on the measurement of the thermal behavior of the two roof types. As for the analysis by simulation, this will take as base the data obtained in the experimental evaluation, through the development of a digital model analyze the variables determined in this initial stage.

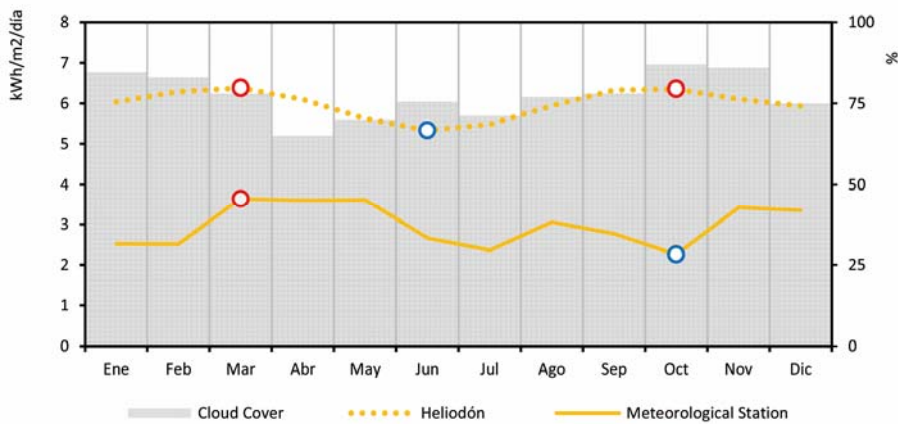
### **2.1. The study area weather**

The city where the study is carried out, Santa Rosa, is located in the south of the region of the Coast of the Equator, at a latitude 3°27'S and an altitude of 14 masl. This city is classified on the map of Köpen-Geiger as a Tropical Humid Climate (Aw). This type of climate is characterized by a negligible annual temperature variability. The annual average temperature is 26°C and a daily and annual oscillation of 6°C and 3°C respectively, Fig. 1. Another relevant feature is the high level of humidity throughout the year, which are accentuated by its proximity to the sea. The annual average of 83%, and is directly related to the high levels of precipitation in this region. These exceed 1500 mm per year and are concentrated in the months of February, March and April. On the other hand, the wind regime is low, influenced mostly by the sea breeze.





**Fig. 1** Monthly average temperatures: maximum, mean and minimum, and relative humidity of 2016. Data obtained from the meteorological station of the airport Victor Larrea, Santa Rosa city.



**Fig. 2** Solar Radiation monthly averages: data from meteorological station in 2016 (continuous line), data obtained from simulation with the use of Heliodon Software (Beckers and Masset 2003) (discontinuous line), and cloud cover obtained from the simulation with the use of EarthEnv application (Wilson and Jetz 2016) (bars)

Finally a major factor in this region, due to its geographical location and its influence on the roof, is solar radiation. The average annual average, according to the data of meteorological station ID: IELOROEL2, is 3 kWh/m<sup>2</sup>, of which 60% comes from diffuse radiation (Conelec 2008). The measured values represent 50% of the values obtained by simulation with a clear theoretical sky model, Fig. 2. The radiation levels are directly related to the percentage of the sky cover, also called cloudiness, therefore when there is higher cloudiness there is less amount of radiation received, Fig. 2. These regions are characterized by high cloudiness values, with an annual average of 78% (Wilson and Jetz 2016). In addition, due to the importance of this parameter, the cloudiness, on other climatic factors, it has been carried out a more detailed study of this through the measurements.

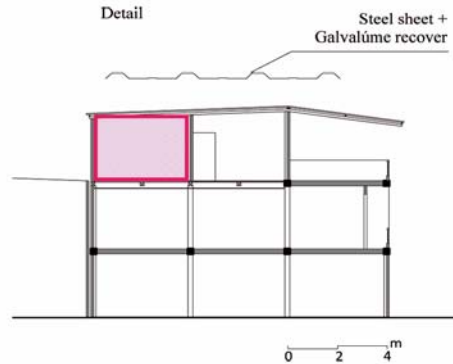
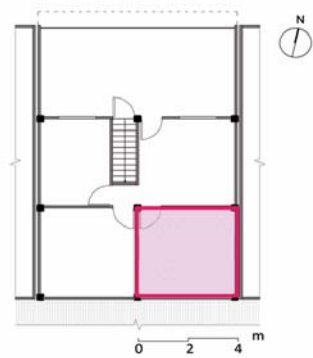
## 2.2. Study case characteristics

According to the objective, the comparison of the thermal behavior of two roof typologies in this region, the experimental work was carried out in two residential buildings with similar constructive characteristics, except the roof. The space with the sheet metal roof or light roof (LR) is located on the second floor of a multi-family building in the 3 floor. It is oriented towards the south, although it does not have windows, Fig. 3. While the space measured with the concrete roof or heavy roof (HR) is a bedroom in one floor house. The bedroom is surrounded by 3 rooms and its fourth wall is attached to the adjoining dwelling, so this space also has no window, Fig. 3. With respect to the spatial characteristics, the two spaces have a height of 3.25m, the LR volume is 36 m<sup>3</sup> and the HR volume is 29 m<sup>3</sup>.

METAL ROOF DWEELING

Plant (3th Floor)

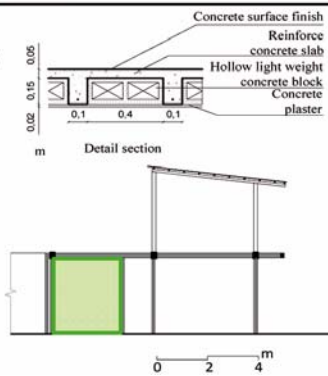
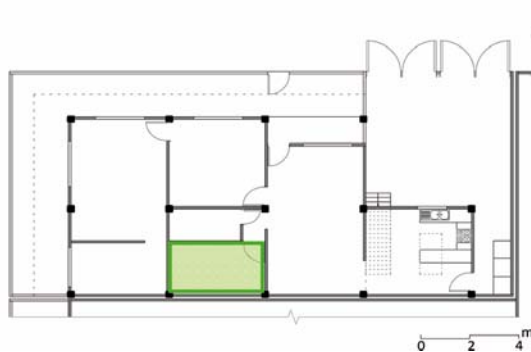
Longitudinal Section



CONCRETE ROOF DWEELING

Plant

Section



**Fig. 3** Plan and section of both dwellings used in the experimental work, and the detail of the two roofs typologies (concrete and metal roof)

In regards to the occupation, LR has a zero occupation, since it is a state of the building totally vacated, nevertheless the bottom plant is an inhabited space. While HR has an occupation of 3 people, although the measured room is used occasionally, the contributions of heat by occupation are very low. About the materials characteristics, the walls of the two spaces are 12 cm wide, built in light block and plastered with cement mortar. The floor of the LR has a wooden structure that adjoins an inhabited space, while the HR has a concrete slab on a pavement in contact with the ground. The characteristics of the roofs, which is the variable to be considered in the analysis, they have totally different thermal characteristics, however they have similar slopes 5% and 2%, for the LR and HR respectively. The LR is composed of a steel metal sheet with a coating of GALVAUMEN (aluminum and zinc alloy) and has a thickness of 0.0004 m, while the HR is 0.22 cm thick and is composed of a concrete slab of 5 cm thick, and lightweight concrete blocks. According to these characteristics, the LR has a negligible thermal resistance and a low thermal mass, while the HR will have a medium thermal resistance and a high thermal mass. It has to be considered that the two roofs have 12 years of installation or construction, and have had zero maintenance. Therefore, its factors of reflection have been reduced, especially the HR. Another difference to consider between these two covers is that the LR has a polished metal finish while the HR has a rugged finish, which will affect the emissivity factor of the covers. In Table 1, the thermal properties of the two roofs analyzed are specified.

**Table 1.** Thermal properties of the two roofs analyzed.

Roof Type	F. absorption (0-1)	F. Emissivity (0-1)	Thermal Transmittance (W/m <sup>2</sup> .K)	Thermal Mass (kJ/m <sup>2</sup> .K)
LR	0.5*	0.13*	7.14**	0.61**
HR	0.75*	0.95*	2.68**	70.51**

\* Measured Values

\*\* Calculated values from bibliography data (ASHRAE 2001) (CTE WEB 2007) (Bergman et al 2011)

### **2.3. Parameters and experimentation periods**

Measurements were made in a continuous period (24h) from September 25 to October 21, 2016. All measurements are always referred to solar time (UTC).

The parameters that have been considered, in terms of climatic factors, are: air temperature, solar radiation and percentage of sky cover. The information from the first two parameters was collected from different weather stations. For the air temperature data were used from the station of the airport Victor Larrea of the city of Santa Rosa, latitude  $-3^{\circ}18'3''$ , longitude  $-79^{\circ}53'53''$ , and for the solar radiation the data of the station ID: IELOROEL2, latitude  $-3^{\circ}18'3''$ , longitude  $-79^{\circ}53'53''$ , and an altitude of 20 masl. This information has been collected at 15-minute intervals. On the other hand, the percentage of coverage of the sky has been measured in tenths through the observation in intervals of 2 hours. In addition, solar radiation was simulated with a theoretical model of 100% clear sky and a reduction factor per atmosphere of 0.7, using the software Heliodon TM 2.6-1 (Beckers and Masset 2003).

With respect to the measured parameters of the thermal behavior of the roofs: the outer surface temperature ( $T_s$ ), the inner surface temperature ( $T_{si}$ ) and the internal air temperature ( $T_{ai}$ ). The first two were measured with the use of a thermocouple type K that stores the information in an Amprobe data logger, and for the last parameter a thermo-hygrometer Testo 174H was used. The information from these three parameters was collected every 5 min.

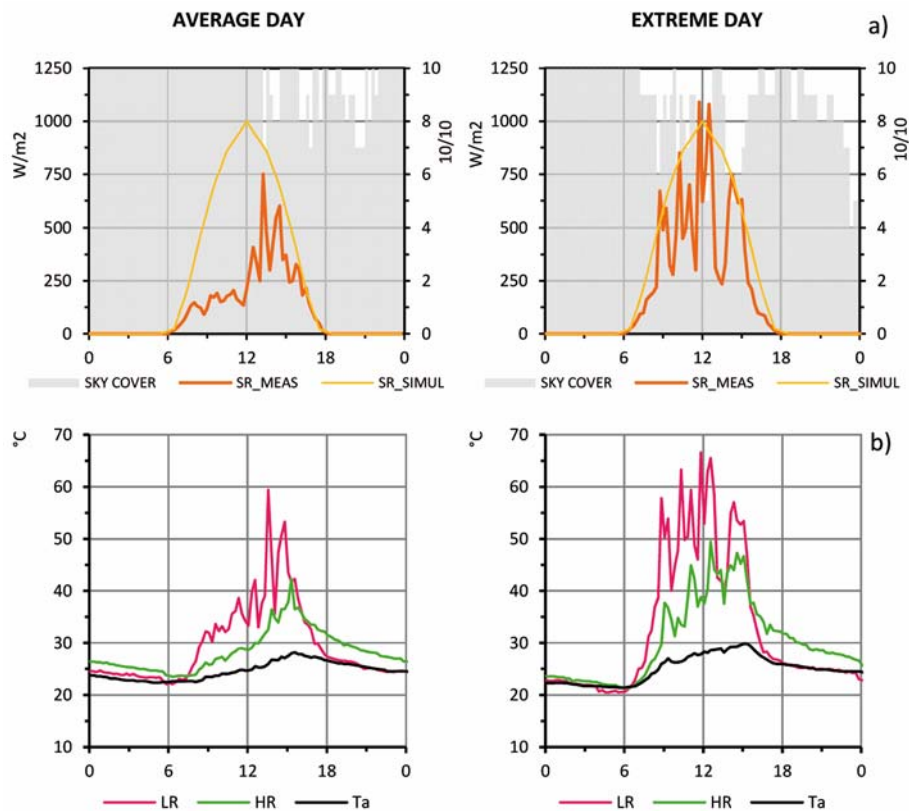
## **3. Results and Discussions**

The results of solar radiation obtained in the measurement period, from September 25 to October 21, 2016, show very varied values ranging from a very cloudy day with  $1.4 \text{ kWh/m}^2$  to a semi-cleared day with  $4.3 \text{ kWh/m}^2$ . From this period, the results of two days were chosen for the analysis. October 12 with  $2.4 \text{ kWh/m}^2$ , because it is the closest to the average value of this month,  $2.2 \text{ kWh/m}^2$ . Additionally this day is within the range,  $2\text{-}3 \text{ kWh/m}^2$ , of the days that are most recurrent throughout the year. The second day analyzed was October 10 with  $4.3 \text{ kWh/m}^2$ , because it is close to the maximum value of the standard variation of the year-round daily averages,  $4.6 \text{ kWh/m}^2$ . In this way the two chosen days can give an overview of the thermal behavior of the cover of the whole year.

### **3.1. The outdoor thermal behavior of the roof**

Figure 4 shows the results of solar radiation and external surface temperature of the two roofs analyzed, for an average day of radiation, October 12, and one day of extreme radiation, October 10.

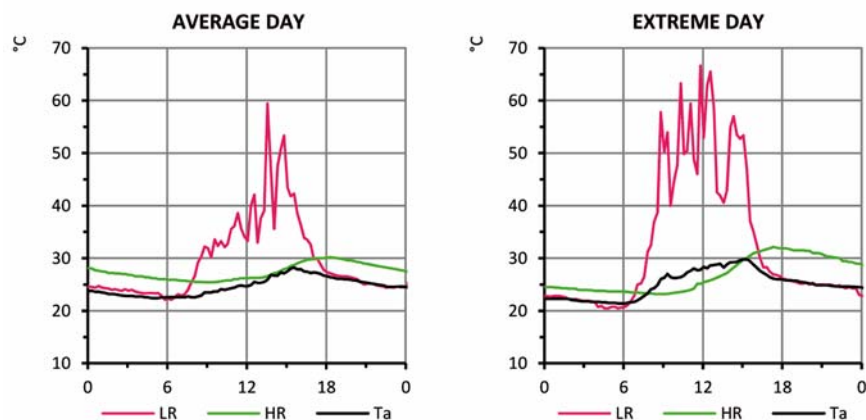
About the radiation results, Figure 4 a, on the average day, measured solar radiation does not reach  $250 \text{ W/m}^2$  in the morning period, whereas in the afternoon the radiation rises considerably, reaching its maximum,  $750 \text{ W/m}^2$ , around 13h00. This behavior is corresponding to the percentage of sky covered, in the morning 100%, in the afternoon a behavior variable between 70 and 100% until 10:00 p.m. where it is completely covered again. The extreme day on the other hand, presents a radiation with ups and downs throughout the day, and reaches its maximum at noon coinciding with simulation data, even exceeding these values,  $1150 \text{ W/m}^2$ . On this day we can see a lower percentage of covered sky that varies from 40 to 100%, during the hours of sun. As for the night period, from 00h00 to 06h00 the coverage of the sky is 100%, even precipitations less than 1 mm were registered; however after 6:00 p.m. to midnight a sky with a percentage of coverage ranging from 90% to 40% is shown. In general terms, the solar radiation has an erratic behavior, and its values are smaller than the simulated ones. Also the two days have a high percentage of cloudiness, including the extreme day, 87% daily average, and in the average day 96%. In the night period, it reflects the effect of thermal mass and its relation with the capacity of cooling radiative effect of the sky. After solar radiation disappears at 18h00, the temperature of the LR is reduced almost immediately to a temperature similar to the outside air temperature ( $T_a$ ) in the two days analyzed, while the HR keeps its temperature above the  $T_a$ , between  $4^{\circ}\text{C}$  and  $5^{\circ}\text{C}$  throughout the whole night.



**Fig. 4** a): Measured (dark orange), simulated (light orange) solar radiation, and sky cover (grey). b): exterior surface temperature of LR (magenta) and HR (green) of the two days analyzed: average day (left) and extreme day (right).

### 3.2. The indoor thermal behavior of the roof

Regarding to the results of the internal surface temperatures ( $T_{si}$ ), Fig. 5, the inner surface of LR ( $T_{si\_LR}$ ), due to its low thermal resistance, has temperatures equal to the outer surface, which is determinant for its thermal behavior in both the daytime and night time periods. In the diurnal period, the differential with the outside air temperature ( $\Delta T_{s\_LR} - T_a$ ) is  $35^\circ\text{C}$ , while the HR has a differential of  $6^\circ\text{C}$ , at the maximum temperatures of each surface. About the nocturnal period, the LR has a  $\Delta T_{si\_LR} - T_a$  almost  $0^\circ\text{C}$  in the two days analyzed, and the HR has a differential between  $+3^\circ\text{C}$  and  $+6^\circ\text{C}$ . In general terms, HR keeps lower and more constant temperatures in the daytime period, but stores energy that raises its temperature at night. In contrast the LR reaches high temperatures in the day, although in the night period it maintains temperatures lower than the HR.

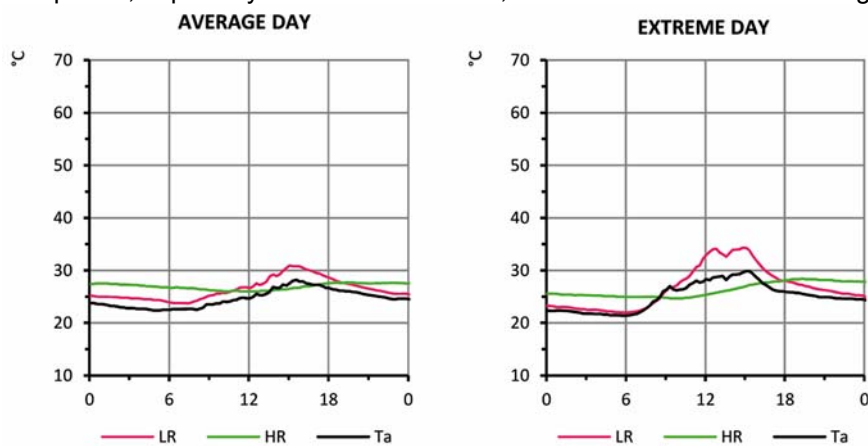


**Fig. 5** Interior surface temperature of LR (magenta) and HR (green) of the two days analyzed: average day (left) and extreme day (right).

### 3.3. Indoor ambient thermal Behavior

Finally, about the results of the indoor air temperature ( $T_{ai}$ ), Fig. 6, the LR has almost no delay with respect to the  $T_a$  in the two days analyzed. In the average day  $T_{ai\_LR}$  is above than  $T_a$  between  $1^{\circ}\text{C}$ , in the night period, until  $3.3^{\circ}\text{C}$ , at the maximum of its temperature; while in the extreme day between  $1^{\circ}\text{C}$  and  $4.5^{\circ}\text{C}$  respectively. This implies that the behavior of  $T_{ai\_LR}$  in the night period is not conditioned by the amount of solar radiation received during the day, since there is no great variation between the two days. However in the daytime period the solar radiation has a great influence on this,  $1.2^{\circ}\text{C}$ .

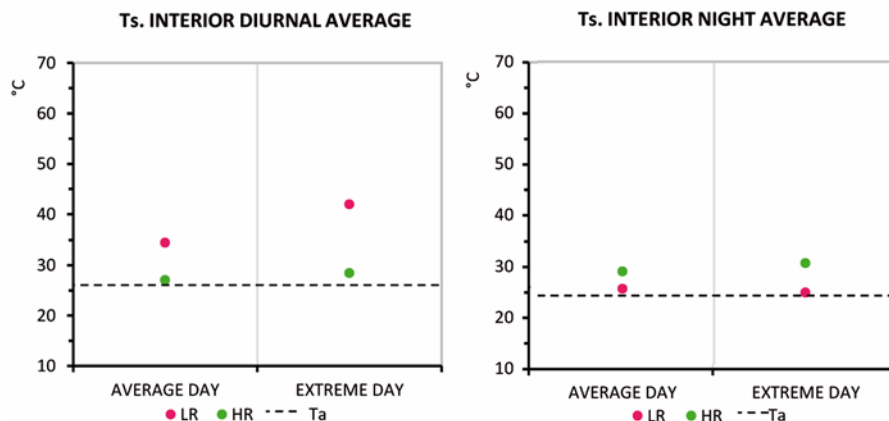
On the other hand, the results of the internal temperature of the HR ( $T_{ai\_HR}$ ) show a lag with respect to the  $T_a$  of 3 hours with its maximums around 20h00, in the two days analyzed. On the average day, the  $T_{ai\_HR}$  remains fairly constant throughout the whole day with an oscillation of about  $1.5^{\circ}\text{C}$ .  $T_{ai\_HR}$  is maintained, throughout the day, above the  $T_a$  with the exception of a lapse of 1 hour in the afternoon. In the night period this temperature is between  $3^{\circ}\text{C}$  and  $5^{\circ}\text{C}$  above the  $T_a$ . While on the extreme day the  $T_{ai\_HR}$  oscillation is  $4^{\circ}\text{C}$ , and remains below the  $T_a$  a period of seven hours, 9:00 a.m. to 6:00 p.m. On the other hand, in the night periods,  $T_{ai\_HR}$  is between  $3^{\circ}\text{C}$  and  $4^{\circ}\text{C}$  above  $T_a$  in the periods of 18h00-24h00 and 00h00-06h00 respectively. This difference between the two night periods is due to the fact that  $T_{ai\_HR}$  remains very constant throughout the night period while  $T_a$  does show a more marked oscillation in this period, especially from 00h00 - 06h00, and for this the differential is greater.



**Fig. 6** Indoor air temperature of LR (magenta) and HR (green) of the two days analyzed: average day (left) and extreme day (right).

The comparison of the  $T_{ai}$  results of these two roofs, shows that in the diurnal period a maximum differential between LR and HR ( $\Delta T_{ai\_LR} - T_{ai\_HR}$ ) of  $4^{\circ}\text{C}$  and  $8^{\circ}\text{C}$  is reached in the average day and the extreme day respectively. However in the nighttime period this differential,  $\Delta T_{ai\_LR} - T_{ai\_HR}$ , is reversed and reaches a value of  $-2.5^{\circ}\text{C}$  which remains fairly constant throughout the night, in the two days analyzed. However, if we consider the daily averages the difference between the two roofs,  $\Delta T_{ai\_LR} - T_{ai\_HR}$ , would be minimal,  $-0.5^{\circ}\text{C}$  in the average day and  $+0.5^{\circ}\text{C}$  in the extreme day.

Since the thermal behavior of these two roofs is totally different between the daytime (06h00-18h00) and the night time (00h00-06h00 + 18h00-24h00), and the most marked difference is shown in the results of the interior surface temperature of the roofs, the comparison of the averages of this parameter ( $T_{si}$ ) independently for each period is shown below, Fig. 7. Due to the presence of precipitations in the period of 00h00-06h00 that modifies the results, the average night will be only of the period from 18h00 to 24h00.



**Fig. 7** Average temperatures of diurnal period (left) and night period (right) of the  $T_{si}$  of LR (magenta) and HR (green) in both days analyzed: average day and extreme day.

From this graph you can determine the influence of the greater radiation of the extreme day in comparison with the average day. In the diurnal period, LR has a  $T_{si}$  of 34.4°C and in the extreme day 41.9°C, an increase of 7.5°C, whereas in the HR this increase is 1.4°C. On the other hand in the nocturnal period it shows the repercussion of the percentage of sky cover. The LR in the average day has a  $T_{si}$  of 25.6°C with a percentage of cloudiness in night period of 92%, and in the extreme day 24.8°C with 81%. While in the HR, values of 29°C are observed in the average day and 30.6°C in the extreme day. Therefore, the greater cooling capacity of the extreme day sky represents a reduction of 0.8°C in the LR, while in the HR an increase of 1.6°C was shown because the roof received a higher radiation in the daytime period and this accumulated more energy, hindering the losses by radiation at night.

If we compare the results of the two roofs, it is confirmed that the HR has lower temperatures than the LR, in the daytime period. The difference in this period ranges from 7.4°C in the average day and in the extreme day it is 13.5°C. While in the night period it is the LR that has temperatures lower than the HR. The differential in this period is -3.4°C and -5.8°C.

#### 4. Conclusions

The detailed knowledge of the climatic characteristics of each region is essential before choosing the materiality of a building. Climatic factors such as solar radiation or cloud cover are determinants over the thermal behavior of the roof, mainly in this region.

The low thermal mass and low thermal resistance of the light roof (LR) represents a disadvantage in the daytime period over the radiant temperatures inside the building, however these same characteristics represent a great advantage in the night period.

Based on the results of this study, the parameters that are determinant on the thermal behavior of the roof, taking into account its relation with the predominant climatic factors of these regions, are: the high emissivity of the surface of the roof that will increase the radiation losses and can mean a representative decrease of the temperature of the outer and inner surface, especially in the daytime period; and on the other hand the low thermal mass which increases the cooling capacity by radiation to the sky in the night period and therefore affects a decrease of the indoor surface temperature of the roof and the indoor air temperature. From these results, the integral investigation of this thesis proposes to evaluate the modification of the thermal parameters of these two types of roofs, and to determine which of them shows a better thermal behavior on the interior conditions of the space. These parameters will be analyzed in a future research, to establish guidelines or future design rules for these climates.

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**Acknowledgements:** This work has been supported by the Spanish Ministry of Economy under project code: BIA2016-77675-R. JTQ acknowledges to the scholarship of the SENESCYT ref. AR6C9307 from the government of Ecuador.