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Research Article

Building Thermal, Lighting, and Acoustics Modeling

Impact assessment of climate change on buildings in Paraguay—Overheating risk under different future climate scenarios

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Abstract

This research seeks to evaluate the impact of climate change (CC) on the thermal performance of buildings. In particular, it is focused on historical residential buildings located in Asunción, Paraguay, a city characterised by a humid subtropical climate. Energy dynamic simulations of a representative building in its original state and an energy efficient version were assessed to evaluate the effectiveness of common energy retrofit measures under future climate conditions. Low and high Representative Concentration Pathways climate scenarios for 2030, 2050 and 2070 are employed with a CORDEX climate model and compared with observed weather data of 2009. Two thermal comfort assessment methods are considered, the statistic and the adaptive thermal comfort approach, where operative temperatures and overheating and underheating rates are analysed. As expected, the results show that the projected temperature rise will lead to an increment of discomfort rates, but it could be mitigated by energy refurbishment measures. Thus, CC effects on thermal performance of buildings are relevant and must be considered for the development of adaptation strategies able to manage this phenomenon. At present, Paraguay does not have any energy building codes and, instead, the results of this paper underline their needs with a substantial impact on society and building industry of Paraguay since it demonstrates that the creation of energy buildings codes is highly necessary to face CC impact on buildings.

Keywords

climate change,
building thermal performance,
comfort assessment methods,
humid subtropical climate,
CORDEX

Article History

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1 Introduction

Nowadays, climate change (CC) is one of the biggest challenges the world is facing. In the last seventeen years, humankind has lived fifteen of the warmest years on record, as rising carbon emissions continue to trap heat and drive global warming (NOAA 2017). Over the period 1880–2012, a warming of 0.65 to 1.06 °C was detected in the globally averaged combined land and ocean surface temperature and, considering the worst climate scenario, it is projected to increase by 2.6–4.8 °C by the period 2081 to 2100, when compared to the 1986 to 2005 period. One of the most alarming statements of the Intergovernmental Panel on Climate Change (IPCC) fifth assessment report is that due to the past, present and future emissions of CO_2, CC is inexorable and irreversible, and most of its consequences will persist for many centuries even if emissions of CO_2 are stopped (IPCC 2014). Thus, the global objective is reducing greenhouse gas emissions (GHG) to stop global warming.

The energy sector is one of the main contributors to global emissions, and reducing the energy demand in end-use sectors represents a key mitigation strategy for the global challenge of reducing emissions from the energy supply sector (Edenhofer et al. 2014). In 2010, the building sector absorbed about 32% of total global final energy consumption, being one of the largest end-use sectors worldwide, and a large share of this consumption is used for space conditioning (Lucon et al. 2014). Generally, building energy use in developed countries is very wasteful and inefficient, and the risk that this tendency could be diffused among developing countries is high. Thus, considering business-as-usual projections, globally, the energy use in the building sector can double or even triple by 2050 (Chalmers 2014). Considering this, Levine et al. (2007) analysed the potential global reduction of

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greenhouse gas (GHG) emissions around the world for the building sector, through a review of several recent studies from different countries. Thus, using as baseline the estimated CO_2 emission projections for the year 2020, those authors found that there is a global potential to reduce approximately 29% of these emissions cost-effectively in this sector, through the implementation of energy efficiency (EE) measures.

Some developed countries have already managed to reduce their total energy use through the implementation of stricter building codes and appliance standards. However, to reach the established goal for reduction requires applying sustained policies and actions considering all aspects of the design, construction and operation of buildings and their equipment, as well as the changing user behaviours, which represents a complex task (Chalmers 2014). In developing countries like Paraguay, GHG emissions from building sector are not very representative, however, a study which assessed the risk of exposure to climate change with respect to human sensitivity and adaptive capacity of 33 countries in the Latin-American region, placed Paraguay in eighth position and classified it in the category of "extreme risk" (Mapplecroft 2014).

According to a research carried out by the Economic Commission for Latin America and the Caribbean (ECLAC), for Paraguay it is projected an average increase of the temperature of 4.2 °C considering the climate scenario A2 and of 3.4 °C for the climate scenario B2 by the year 2100, taking as a basis the period of 1961–1990 (ECLAC 2014). A research developed by the United Nations Development Programme (UNDP) estimated that the thermal oscillation will be greater in the future and that the summers and winters will be warmer. In this research is also highlighted that if the current average annual temperature in the country is 22 °C, it is likely to increase by between 23.2 and 27.8 °C by the year 2100 (UNDP 2007).

In the Second National Communication on Climate Change of Paraguay, developed by the country's Secretary of the Environment (SEAM, by their Spanish initials), different climate scenarios were analysed, considering two socio-economic scenarios SRES A2 (high) and B1 (low), selecting 2020 and 2050 as time horizons and using four different climate models. The outcomes were an increase in temperature of around 1 °C for the year 2020 and 2.5 °C for the year 2050, according to the average of the four climate models analysed (SEAM 2011). Nonetheless, resorting the climate scenarios recommended by the IPCC Fifth Assessment Report, the increase in the country's temperature can reach up to 3 °C considering RCP 4.5 and up to 4 °C for the RCP 8.5 over the period 2041–2050, using the average temperature values over the period 1961–1990 as a basis (CEDIC and ID 2016). Thus, considering forecasting climate scenarios, several scientific researches have shown that is very likely that the air temperature in the country will increase due to climate change effects. As a consequence, this temperature increase will affect the building indoor thermal comfort and would lead to higher energy consumption in the building sector for space cooling (ECLAC 2014; UNDP 2007), especially for hot summer and warm winter climates (Li et al. 2012), which is the Paraguayan case.

Thus, globally, one of the main CC effects on buildings sector is that the global warming will increase the buildings overheating risk affecting the indoor temperature and causing users discomfort, leading to a decrease of energy demand for space heating but increasing the cooling demand, especially in countries with hot climates, as shown by several scientific research (Aebischer et al. 2007; Alves et al. 2016; Aries and Bluyssen 2010; Crawley 2008; de Wilde and Tian 2009; Dirks et al. 2015; Dodoo and Gustavsson 2016; Frank 2005; Patidar et al. 2013; Pierangioli et al. 2017). The implementation of energy efficiency measures to retrofit buildings, as well as to get highly efficient new buildings, is essential to mitigate the climate change impact (Triana et al. 2018; van Hooff et al. 2016; Wan et al. 2011). Therefore, the implementation of measures to improve the EE of buildings beyond being an opportunity to improve their thermal performance is a mitigation and adaptation strategy to the effects/impacts of CC. Most of the scientific investigations developed about climate change impact on buildings have focused on the potential changes in energy use and how it could affect the buildings' indoor temperature, taking as case study different climates of several countries. Unfortunately, fewer studies have taken Paraguay as a case study and have analysed how prepared its building stock is to face the effects of climate change in the country.

The National Environment Public Secretary published several studies related to the mitigation of greenhouse gas emissions developed in the country, where are also highlighted the importance of adaptation measures. Despite policymakers aware that adaptation is essential to face climate change impact, the scarce information and the lack of knowledge about strategies to deal with these impacts, are stated as the main barriers (SEAM 2014). It is known that the building's useful lifetime is expected to last at least 50 years, the reason why comfortable internal conditions need to be ensured over a considerable time frame, under a climate that will change significantly, even more, considering climate change effects (Liu et al. 2016). Adaptation measures will allow reducing the climate change impacts and, in the building sector, adaptation can be reached by improving their energy performance. However, for this purpose, firstly is necessary to evaluate and quantify the impact of climate change on buildings, in order to develop a suitable adaptation strategy plan.

In this framework, this research seeks to evaluate and quantify the impact of climate change on the thermal performance of an historical residential building located in Asunción, Paraguay, a city characterised by a humid subtropical climate with sweltering summers. To this end, energy dynamic simulations of a representative building in its original state and an energy efficient version are assessed, in order to evaluate the effectiveness of refurbishment measures under future climate conditions. Low and high Representative Concentration Pathway (RCP) climate scenarios for the time horizons of 2030, 2050 and 2070 from the IPCC Fifth Assessment Report are used and compared with observed weather data of the 2009 year. For each time horizon selected, a weather data file is created considering the weather dataset obtained for that year by the regional downscaling climate model and according to the RCP selected. Furthermore, a simulated temperature dataset for the years 1990 and 2009 are acquired to describe the trends in temperature briefly and to evaluate the accuracy of the climate model.

The evaluation of the results was developed considering two different comfort assessment methods, the statistic model (STAT) and the adaptive comfort approach addressed in the European standard 15251:2014 (ADAPT) (CEN 2014), where operative temperatures and overheating and underheating rates are analysed. Furthermore, the potential changes in heat gains and losses through buildings' envelope components are also shown, in order to detect the building components with the greatest influence on its thermal performance under different time horizons. Thus, this research aims to provide a scientifically based approach to demonstrate the importance to implement building energy retrofit measures, as an adaptation strategy considering future climate conditions, that will contribute as support for the development of building energy codes, energy efficiency policies and decision-making processes, regarding adaptation strategies for climate change in Asunción.

This paper is structured as follows: after this introduction, the methodology is described in Section 2, where the climate models and scenarios employed are explained, as well as the basis of the adaptive thermal comfort approach. Subsequently, Section 3 portrays the case study, describing the building under analysis and the input parameters for the dynamic energy simulations. Section 4 involves the buildings dynamic simulations, where the results are depicted, and the discussions are drafted. Finally, in Section 5 the main conclusions are drawn.

2 Methodology

In the first stage of this paper, the weather datasets selected for each time horizon were created, being employed the weather data source that corresponds to the Coordinated Regional Climate Downscaling Experiment (CORDEX) (CORDEX n.d.). The regional climate model "Hadley Global Environment Model 2 - Earth System" (HadGEM2-ES) is used as forecasting model and to obtain the dataset for the year 1990 (hereafter referred as "historical"). Observed meteorological data for the city of Asunción were collected from a weather station, which corresponds to the year 2009 (hereafter referred to as "recent"). Simulated weather datasets for the year 2009 were also obtained from CORDEX employing the "Hadley Centre Regional Climate Model", version 3, which improved physics parameterisations (HadRM3P) in order to briefly compare simulated and observed data.

The climate parameters obtained by the climate models are temperature, atmospheric pressure, relative humidity, wind speed and global solar radiation. The correlation model developed by Marques Filho et al. (2016) is used to obtain the diffuse and direct components of the global solar radiation to create the weather data file for the dynamic simulations. For acquiring the weather datasets for future climate conditions, RCP 4.5 and RCP 8.5 were employed as low and high CO_2 concentration pathways climate scenarios, respectively. Table 1 represents an overview of the weather datasets used for this research. The first two rows described as Historical – 1990 and Simulated – 2009 correspond to simulated temperature dataset used to briefly describe the trends in temperature and to evaluate the accuracy of the climate model. Unfortunately, temperature dataset for the year 2009 for the driving model MOHC-HadGEM2-ES is not available in the CORDEX project for the South America domain. For this reason, the driving model ECMWF-ERAINT was employed, but it is important to note that the regional climate model used for all the datasets was the RCA4. The other datasets depicted in Table 1 correspond to weather data files used for the building energy simulations. Further information about the weather data sources, the climate models employed, and the RCP scenarios selected are given in the next subsections.

The second stage analyses the climate change impact on buildings energy performance, using the different weather datasets created through dynamic simulations resourcing EnergyPlus software (Department of Energy U.S. n.d.) and DesignBuilder interface (DesignBuilder Software 2018). The building is analysed both in its original state and an energy efficient version, and the simulations were made on an annual basis analysing the thermal zone with the worst thermal performance. The aim of these simulations is to represent how climate change effects might change the discomfort rates during the period of simulation, which is computed considering two methods. The first one, according to the acceptable indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially-weighted running mean of the external

Table 1 Weather datasets used in this research

Weather dataset	Description
Historical – 1990	Temperature dataset for the year 1990, extracted with the regional model RCA4 and MOHC-HadGEM2-ES
Simulated – 2009	Temperature dataset for the year 2009, extracted with the regional model RCA4 and ECMWF-ERAINT
Observed – 2009	Dataset for the year 2009, collected from a weather station in Asunción
RCP 4.5 – 2030	Dataset for the year 2030, extracted with the regional model RCA4 and MOHC-HadGEM2-ES, using RCP 4.5
RCP 4.5 – 2050	Dataset for the year 2050, extracted with the regional model RCA4 and MOHC-HadGEM2-ES, using RCP 4.5
RCP 4.5 – 2070	Dataset for the year 2070, extracted with the regional model RCA4 and MOHC-HadGEM2-ES, using RCP 4.5
RCP 8.5 – 2030	Dataset for the year 2030, extracted with the regional model RCA4 and MOHC-HadGEM2-ES, using RCP 8.5
RCP 8.5 – 2050	Dataset for the year 2050, extracted with the regional model RCA4 and MOHC-HadGEM2-ES, using RCP 8.5
RCP 8.5 – 2070	Dataset for the year 2070, extracted with the regional model RCA4 and MOHC-HadGEM2-ES, using RCP 8.5

temperature, recommended by the EN 15251:2014 (CEN 2014) and the second, using fixed threshold values of comfort temperature.

2.1 Climatic data

2.1.1 Climate change—RCPs scenarios

Since IPCC identified the CC as an urgent global problem, several climate scenarios have been developed considering different factors to predict the climate variability. The main objective is to detect and analyse the likely climate change to subsequently estimate their impacts, in order to develop the mitigation and adaptation strategies for the most vulnerable zones. Since its creation in 1988, IPCC has published five assessment reports about climate change, besides several technical articles and methodological reports. Over this time, knowledge about future emissions of greenhouse gases and climate change has changed considerably. Furthermore, political developments have been conducted, protocols and international agreements on climate change have been created. All these actions have given a pattern of the possible tendencies of the phenomenon. As a result, the possible future climate scenarios have been updated several times.

The last two sets of scenarios launched by the IPCC correspond to the SRES (Special Report on Emissions Scenarios) and the RCPs (Representative Concentration Pathways). Being the last one the most recommended currently, since they were updated and expanded in scope (regarding the SRES) and they cover a range of radiative forcing levels examined in the open literature containing relevant information for climate model runs (van Vuuren et al. 2011a). These scenarios are not a complete package of socio-economic, emission and climate projections since the expression "concentration pathway" refers to internally consistent sets of projections of the components of radiative forcing, where concentrations are used as the primary product of the RCPs, designed as input to climate models. With these conditions, a set of four pathways were created that lead to radiative forcing levels of 8.5, 6.0, 4.5 and 2.6 W/m^2 by the end of the century, where each of the RCPs covers the 1850–2100 period (van Vuuren et al. 2011b). Figure 1 depicts the projected trends in global CO_2 emissions under the RCPs scenarios.

The creation of climate projections scenarios represents key tools for the development of adaptation and mitigation strategies facing Climate Change threats, considering that

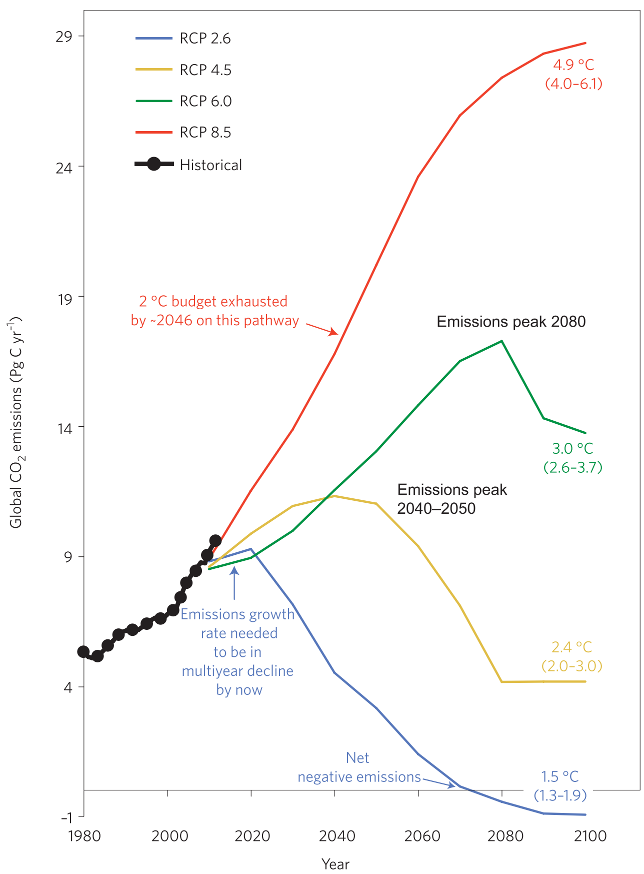


Fig. 1 Projected trends in global CO_2 emissions under the RCPs scenarios (Sanford et al. 2014; reproduced with permission ©Springer Nature)

they allow identifying the potential impacts by geographical area and considering a specific sector. The climate scenarios analyse how anthropogenic activities might influence the concentrations of greenhouse gases in the atmosphere and then they predict how it will affect the climate system (Camilloni et al. 2006; Comisión Nacional de Cambio Climatico Paraguay 2016).

Currently, the use of climate models to generate weather datasets for buildings energy simulation represents a robust strategy to evaluate their thermal performance under future climate conditions, being a key role for the updating or the creation of construction standards. Thus, the present study addressed climate change in terms of the variables that influence thermal performance of a residential building in Paraguay. The RCP 4.5 and RCP 8.5 scenarios have been selected as the best and worst scenario respectively. The RCP 8.5 is consistent with a future with no policy changes to reduce emissions, and the RCP 4.5 is consistent with a future with relatively ambitious emission reductions. The choice of these scenarios is justified by the need to detect the possible impact of climate change on buildings to support future building design projects or for energy retrofit of existing buildings in Asunción. The RCP 2.6 scenario was not considered in this research since some authors believe that this scenario is unrealistic. This is because the RCP 2.6 considers a future with low radiative forcing (drops to below current levels), which requires ambitious decreases of GHG emissions (Talukdar and Banthia 2016).

This research is aware of the uncertainties involved in the use of projections for future weather data since the climate models and scenarios might have some limitations regarding the level of confidence in the predictions of the climate parameters used for the building simulation. However, the climate scenarios and the weather datasets obtained by simulation with climate models, represent the sole decision-making tool currently available to predict the impact of climate change and subsequently, to develop different adaptation initiatives and mitigation strategies.

2.1.2 Coordinated Regional Climate Downscaling Experiment (CORDEX)

CORDEX is a project created with the objective of developing a coordinated framework for evaluating and improving Regional Climate Downscaling (RCD) techniques and producing a new generation of RCD-based fine-scale climate projections for identified regions worldwide (Giorgi et al. 2009).

For the South America CORDEX domain, a 3-hour time-frequency and for the year 2009, the regional climate models employed corresponds to the fourth version of the Rossby Centre Regional Atmospheric Climate Model (RCA4) developed by the Swedish Meteorological and Hydrological Institute (SMHI), which operates on a rotated longitude-latitude grid of 0.11° and 0.44° horizontal resolution and 40 vertical levels (Kotlarski et al. 2014). The model uses the ERA-Interim global driving model, a global atmospheric reanalysis with a spatial resolution of the data set of approximately 80 km and 60 vertical levels from the surface up to 0.1 hPa, which was developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Berrisford et al. 2009). The forecasting model also corresponds to the RCA4 regional climate model, which also provided the temperature dataset for the historical representative year 1990. However, in this case, the driving model corresponds to the MOHC-HadGEM2-ES. This driving model uses a horizontal resolution of 1.25° × 1.875° in latitude and longitude with 38 layers in the vertical extending to over 39 km in height (Collins et al. 2011).

The meteorological parameters available are temperature, atmospheric pressure, relative humidity, wind speed and global solar radiation. The dataset was drawn from the nearest grid point to Asunción, which is 25°11′ Southern latitude, 57°51′ Western longitude, 13.54 km away from the airport met mast.

2.1.3 Observed weather data

The observed meteorological data of Asunción corresponds to the climate parameters of temperature, atmospheric pressure, relative humidity, wind speed, wind direction and cloud cover. These collected data come from the Directorate of meteorology and hydrology of the National Paraguay's Directorate of Civil Aeronautics (DINAC, by their Spanish initials), and corresponds to 5-minute interval records from 1st January to 31st December of 2009. The weather station is located at the Silvio Pettirossi Airport of Asunción at 25°14′ Southern latitude, 57°30′ Western longitude and 83 meters above the sea level. Regarding the climate under analysis, Paraguay has a tropical to a subtropical climate with an annual average temperature of 24 °C. The country has springs and winters with pleasant temperatures, normally, without frost, with average temperatures of 19 °C. Summers are sweltering with a high percentage of humidity, and in some regions, including Asunción, the temperature may exceed 41 °C (SEAM, UNDP, and GEF 2017). According to the climate classification system developed by Köppen-Geiger (Peel et al. 2007), Asunción has a Humid subtropical climate denominated **Cfa**. The group **C** corresponds to "Warm Temperate" climates, **f** means "fully humid" and indicate the lack of a dry season and **a** corresponds to a "hot summer".

2.2 Comfort assessment models

Thermal comfort is a complex concept to define due to its subjective character and its reliance on human sensations, which can depend on multiple factors (habits, culture, individual and social variables, etc.). Nonetheless, generally is defined as the condition of a person's mind that expresses satisfaction with the environment that surrounds it (ASHRAE 2010). Basically, two different approaches to study comfort criteria are worth noting, the adaptive models (based on field studies) (McCartney and Nicol 2002) and the analytical or static models (using climate chambers) (Fanger 1970). The static models usually set fixed thresholds values of comfort temperatures, and they have been widely used in a significant number of thermal regulations around the world. In Portugal, the thermal regulation sets as acceptable temperatures the range between 18 and 25 °C (Ministerio da Economia e do Emprego 2013). In Chile, the Sustainable Construction Code considers acceptable the temperatures between the range of 18–26 °C (Ministerio de Vivienda y Urbanismo del Gobierno de Chile 2018). In Brazil, the NBR 16401-2 (ABNT 2008) sets as acceptable temperatures the range between 23 and 26 °C in the summer season and with a relative humidity of 35%. The Chartered Institution of Building Services Engineers (CIBSE) (CIBSE 2006) recommends a benchmark summer peak temperature of 28 °C for dwelling's living areas. In addition, several scientific investigations have been developed to set thresholds values of comfort temperature considering the climate under analysis.

Lu et al. (2018) developed a field study of thermal comfort in non-air-conditioned buildings in a tropical island climate in China; the results suggest the acceptable temperature range of thermal comfort for the residents was from 23.1 to 29.1 °C. Djamila (2017) explored the thermal perceptions of people in the humid tropics of Malaysia employing different thermal perception approach; the results suggest that the optimum temperature was found to be about 30 °C. Maybe the only work assessing thermal comfort conditions taking as case study Paraguay is the developed by Lopez et al. (2015), for which three naturally-ventilated buildings in Asunción were evaluated, and the results were compared to three different methodologies. The outcomes of the research proven that heat discomfort was overestimated by the ISO 7730 Standard when air temperature values exceeded 30 °C since users reported neutral thermal conditions, while the method indicated intense heat discomfort. Furthermore, it was stated that methods employing equations as a function of the outdoor climate variables could successfully adjust to the hot-humid climatic context. In this way, it is possible to assert that occupants of naturally-ventilated buildings have a higher tolerance of high temperatures and greater thermal comfort range.

The adaptive model introduces the principle that if there is a change causing a sense of discomfort, people react in a way that tends to restore their comfort (ASHRAE 2010). Thus, this model considers the users as an active agent facing the thermal conditions offered by the building environment. For example, the user is able to interact with the environment by opening windows, changing clothes, posture, physical activity, etc., aiming to achieve comfortable thermal sensations (McCartney and Nicol 2002). Furthermore, this model considers that the acceptable indoor temperatures are linked to the mean outdoor temperatures. Nevertheless, the application of this model is recommended for naturally ventilated buildings mainly used for near-sedentary physical activities (1.0 and 1.3 met) with easy access to operable windows and where users can adapt their clothing to indoor thermal oscillation (0.5 to 1 clo) (ASHRAE 2010).

Thus, there are different methodologies allowing to assess comfort conditions in a building, as well as several international standards setting threshold temperatures to establish comfort range. Since in Paraguay, currently, no standards define acceptable indoor thermal conditions for buildings, for this research, two approaches were considered, in order to compare the results obtained from simulations with the widely used models for comfort assessment. Thus, considering the review previously herein presented, for the static model, an upper threshold of 28 °C and a lower threshold of 18 °C is considered, above or below which the thermal zone is over or underheating, respectively, independently of exterior conditions. For the adaptive approach, the acceptable indoor temperatures for the design of buildings without mechanical cooling systems recommended by the European Standard 15251:2014 is employed (CEN 2014), which is based on the adaptive thermal model developed in the ASHRAE Standard 55 (ASHRAE 2010).

This standard sets four buildings categories for which it defines the upper and lower temperature threshold values considered as comfortable that are related to the outdoor running mean temperatures. Table 2 describes the buildings categories and the formulas to be used according to each category. For calculating the running mean external air temperature (θ_{rm}) for a certain day Eq. 1 is employed, where the outside average temperatures of the previous 7 days are used ($\theta_{\text{ed-1}}$ is the daily outdoor average temperature of the previous day; $\theta_{\text{ed-2}}$ the daily outdoor average temperature two days before, and so on). In addition, Eq. 2 is used to calculate the optimal operative temperature (θ_{c}).

$$\theta_{\mathrm{rm}} = (\theta_{\text{ed-1}} + 0.8\theta_{\text{ed-2}} + 0.6\theta_{\text{ed-3}} + 0.5\theta_{\text{ed-4}} + 0.4\theta_{\text{ed-5}} + 0.3\theta_{\text{ed-6}} + 0.2\theta_{\text{ed-7}})/3.8 \quad \text{Eq. 1}$$

$$\theta_{\mathrm{c}} = 0.33 \times \theta_{\mathrm{rm}} + 18.8 \quad \text{Eq. 2}$$

The applicability of this model is limited to daily mean outdoor temperatures within the range of 10 to 30 °C. Considering that the summer temperatures in Asunción can sometimes be outside of this range and that the standard

Table 2 Comfort temperature ranges per buildings category according to the EN 15251:2014 (CEN 2014)

Category	Description	Allowable indoor operative temperatures		
I	High level of expectation (spaces with special requirements)	Upper limit	$\theta_o = 0.33 \times \theta_{rm} + 18.8 + 2$	Eq. 3
		Lower limit	$\theta_o = 0.33 \times \theta_{rm} + 18.8 - 3$	Eq. 4
II	Normal level of expectation (new buildings or renovations)	Upper limit	$\theta_o = 0.33 \times \theta_{rm} + 18.8 + 3$	Eq. 5
		Lower limit	$\theta_o = 0.33 \times \theta_{rm} + 18.8 - 4$	Eq. 6
III	An acceptable, moderate level of expectation (existing buildings)	Upper limit	$\theta_o = 0.33 \times \theta_{rm} + 18.8 + 4$	Eq. 7
		Lower limit	$\theta_o = 0.33 \times \theta_{rm} + 18.8 - 5$	Eq. 8
IV	Low level of expectation	Values outside the criteria for the above categories		

does not provide information regarding how to obtain the comfort temperature outside this range, for the development of this work, for daily mean outdoor temperatures higher than 30 °C, a comfort temperature identical to that obtained for 30 °C is considered, setting thus the maximum admissible temperature. The same procedure is adopted for minimum daily mean outdoor temperatures below 10 °C.

This research aims to estimate the sensitivity of a residential building to underheating and overheating, subjecting it to thermal stress conditions due to climate change effects. To this purpose, annually indoor air temperature profiles are hourly modelled for the thermal zone presenting the worse thermal performance and, the percentage of the simulated time in which the operative temperatures exceed the upper limit of 28 °C or such recommended by the EN 15251:2014 for buildings in the Category II (Eq. 5), corresponds to the overheating rate. Similarly, the percentage of the simulated time in which the operative temperatures are lower than the lower limit of 18 °C or such recommended by the EN 15251:2014 for buildings in the Category II (Eq. 6), corresponds to the underheating rate.

3 Case study description

The building taken as case study consists in a historical building located in the Historic Centre of Asunción (CHA, by its Spanish initials). According to a statistical analysis (Facultad de Arquitectura de la Universidad Nacional de Asunción 2005), most of the buildings located in the CHA corresponds to buildings originally built for a residential use (most of them currently abandoned). Almost 60% of residential buildings in the CHA have an Italianate architecture style and were constructed between 1880 and 1930. Thus, the case study herein analysed is a residential building with the referred architecture style, representative of most of the CHA's residential buildings, for which it was possible to characterise the building envelope components and materials employed.

The building consists of a two-storey structure and, according to the area (188.8 m²) and geometry, corresponds to a single-family dwelling. The ground floor is composed of four thermal zones (lounge, circulations, bathroom, dining room and a kitchen) and the first floor has three thermal zones (two bedrooms and one lounge) (see Fig. 2). The main thermal zone under analysis and for which the results are depicted corresponds to the Bedroom 2 (19 m²), a thermal zone on the first floor and with an east orientation. First, the building was simulated in its original state with the seven weather data files previously created. Subsequently, an energy efficient version of the building was simulated to figure out how weather files created considering climate change effects can influence the design and correct setting of energy retrofit solutions. The thermal properties of the building's envelope in the original state and the improved solutions are summarised in Table 3. For the dynamic simulations, the metabolic factor was set to 1 for all thermal zones, the values used for insulation clothing were 0.5 clo for the summer season and 1 clo for the winter season. The input parameter values varying according to each thermal zone are shown in Table 4.

For the thermal comfort evaluation, it is considered that the selected building does not have any heating or cooling systems. However, a natural ventilation strategy is

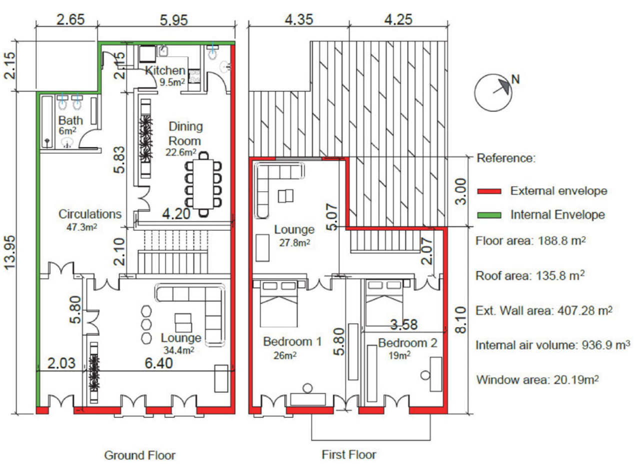
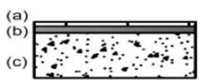
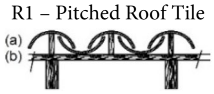
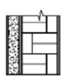
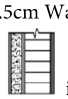
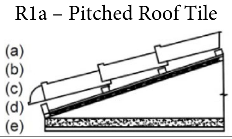


Fig. 2 Case study architectural blueprints and thermal envelope definition

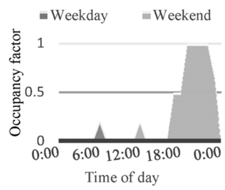
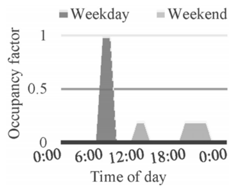
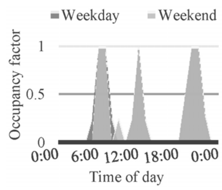
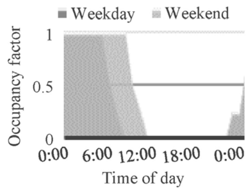
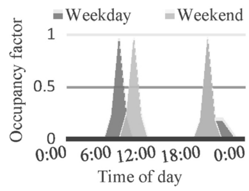
Table 3 Description of the building's envelope components in the original state. For each layer, the values of *s* (thickness), *λ* (thermal conductivity), *c* (specific heat), *ρ* (density), *U* (thermal transmittance) and M_s (thermal mass) are depicted

Building component	Material [outer to inner]	*s* (m)	*λ* (W/(m·K))	*c* (J/(kg·K))	*ρ* (kg/m³)	*U* (W/(m²·K))	M_s (kg/m²)
Configurations in the original state							
W1 – Façade SE orientation 30cm Wall outer  inner (a)(b)(c)	(a) Sand-lime plaster	0.015	1.15	1000	1800	1.95	459
	(b) Solid brick burned	0.270	0.85	840	1500		
	(c) Sand-lime plaster	0.015	1.15	1000	1800		
W2 – NE orientation 20cm Wall outer  inner (a)(b)(c)	(a) Sand-lime plaster	0.015	1.15	1000	1800	2.53	309
	(b) Solid brick burned	0.170	0.85	840	1500		
	(c) Sand-lime plaster	0.015	1.15	1000	1800		
W3 – NE, NW and SW 15cm Wall outer  inner (a)(b)(c)	(a) Sand-lime plaster	0.015	1.15	1000	1800	2.93	234
	(b) Solid brick burned	0.120	0.85	840	1500		
	(c) Sand-lime plaster	0.015	1.15	1000	1800		
F1 – Calcareous Floor 	(a) Calcareous tile	0.010	2.21	840	2550	2.92	277
	(b) Soil-sand screed	0.015	1.15	1000	1800		
	(c) Granular subbase	0.100	1.80	840	2240		
R1 – Pitched Roof Tile 	(a) High density wood	0.025	0.29	1340	850	4.20	40
	(b) Ceramic clay tile	0.010	0.84	800	1900		
G1 – Glazing outer  inner (a)	(a) Single clear glazing	0.006	0.90	880	2500	5.78	5
Configurations of the energy efficient version[1,2]							
W2a – NE orientation 29.5cm Wall outer  inner (a) (b) (c) (d) (e)	(a) Thin clay plaster	0.015	0.35	2100	3000	0.45	368
	(b) Glass wool felt	0.080	R_t=1.80	840	175		
	(c) Sand-lime plaster	0.015	1.15	1000	1800		
	(b) Solid brick burned	0.170	0.85	840	1500		
	(e) Sand-lime plaster	0.015	1.15	1000	1800		
W3a – NE, NW and SW 24.5cm Wall outer  inner (a) (b) (c) (d) (e)	(a) Thin clay plaster	0.015	0.35	2100	3000	0.46	293
	(b) Glass wool felt	0.080	R_t=1.80	840	175		
	(c) Sand-lime plaster	0.015	1.15	1000	1800		
	(b) Solid brick burned	0.120	0.85	840	1500		
	(e) Sand-lime plaster	0.015	1.15	1000	1800		
R1a – Pitched Roof Tile 	(a) Ceramic clay tile	0.010	0.84	800	1900	0.43	1281
	(b) High density wood	0.025	0.29	1340	850		
	(c) Air gap	1.000	R_t=0.15	1000	1200		
	(d) Glass wool felt	0.080	R_t=1.80	840	175		
	(e) Plasterboard	0.030	0.25	1000	900		
G1a – Double Glazing outer  inner (a)(b)(c)	(a) Single clear glazing	0.006	0.90	2500	880	2.76	10
	(b) Air gap	0.010	R_t=0.15	1000	1200		
	(c) Single clear glazing	0.006	0.90	2500	880		

1. To calculate the thermal parameters of the roof R1a, an equivalent constant thickness was used for the air gap.

2. For some constructive elements were considered their thermal resistance (R_t) instead their thermal conductivity.

Table 4 Input parameters used for the simulations. For each thermal zone the occupation density (m^2/person), the minimum fresh air (L/(s·person)), the target illuminance (lx), the internal gains (W/m^2) and the occupation schedules are shown

Thermal zone	Lounge	Circulations	Kitchen & dining	Bedroom	Bathroom
Occupation density	53.32	64.50	59.12	43.59	53.37
Fresh air	4	4	14	4	10
Illuminance	200	100	300	100	150
Internal gains	3.9	1.57	30.28	3.58	1.67
Schedule					

considered, where the minimum natural ventilation rate is defined using minimum fresh air requirements as was set in Table 4. It is important to bear in mind that mechanical heating/cooling systems are not considered in the present research because, as indicated in the introduction, buildings energy expenditure is one of the main responsible for climate change effects. In this way, it is intended to demonstrate that resourcing natural ventilation and the proposed configurations for walls and roofs, it is possible to significantly improve the thermal performance of the building without large energy expenditure.

In this way, the implemented strategy was focused on the addition of insulation materials aiming to increase the thermal mass of the building causing a delay and a decrease in the indoor temperatures. As the operation of natural ventilation is linked to the outdoor and indoor temperatures (it only operates when the outdoor temperature is lower than indoor temperature), a decrease in terms of indoor temperatures will allow an increase of natural ventilation inside the building. Thus, the strategy of increase the thermal mass coupled with the use of natural ventilation is evaluated in this research work.

The windows operation schedule defines the operation of natural ventilation. Thus, for summer season windows are open and allow natural ventilation only when the outdoor temperature is lower than indoor temperature, but it is restricted when the outdoor temperature is lower than 20 °C. For the winter season, windows are open only when the operative temperature is higher than the comfort temperature calculated from the CEN 15251:2014 adaptive comfort model (CEN 2014), considering that some days in winter season can reach high values of temperature. Regarding the window shading (exterior venetian blinds), the aperture operation is scheduled for winter season: 100% open from 8 a.m. to 6 p.m. and fully closed the rest of the day. For the summer season, the shading is on when solar radiation on the window reaches the medium solar setpoint of 189 W/m^2 (Wankanapon and Mistrick 2011), aiming to reduce thermal discomfort due to direct solar radiation but taking advantage of natural daylight.

4 Dynamic simulations—results and discussions

4.1 Comparison between observed and simulated weather data

Once the weather datasets were extracted, and all the input parameters were set, the dynamic energy simulations were carried out, and the outcomes are depicted and discussed in this section. The dynamic simulations were performed using EnergyPlus Software (v8.6.0) and DesignBuilder interface (v5.5). Figure 3(a) depicts the comparison between the observed monthly mean temperatures (black dots) against the simulated ones (yellow squares). In addition, the weather dataset presented by DesignBuilder and EnergyPlus software as typical and representative of Asunción's climate is depicted (red triangles), aiming to briefly analyse the accuracy of the datasets under study with reference to a dataset normally assumed for building energy assessment. This weather datasets correspond to the default weather file available in the mentioned software for Asunción, which has hourly weather data obtained from the International Weather for Energy Calculations (IWEC) (ASHRAE 2001). The weather station corresponds to the Silvio Pettirossi Airport, and the dataset is derived from up to 18 years (1982–1999 for most stations).

Figure 3(b) illustrates the temperature distribution for the year 2009 according to the observed collected data (orange line) and those obtained for such year from the RCA4 climate model (blue line). The model results present a positive,

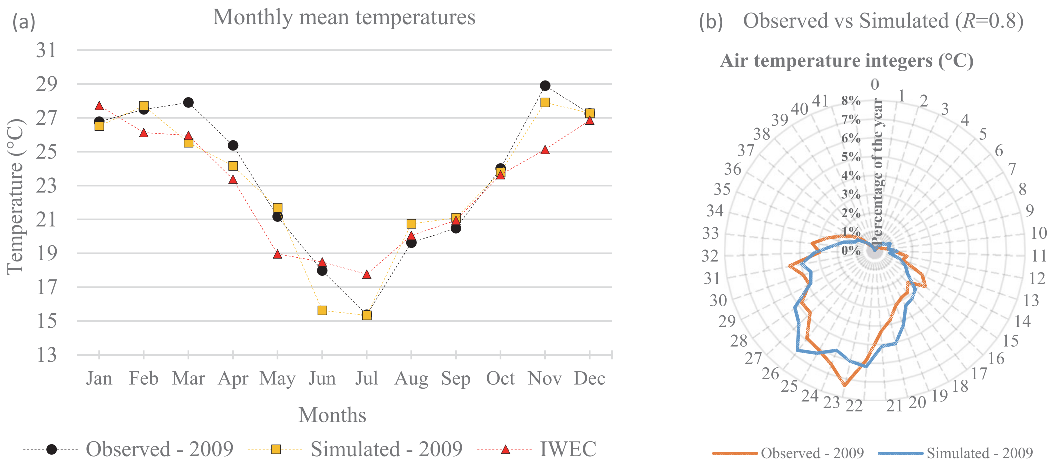


Fig. 3 Monthly mean temperatures (a) and temperature distribution (b) of simulated and observed weather datasets for the year 2009

acceptable correlation coefficient (R) of 0.8 when compared to observed data and show a good ability to capture the seasonal variation trend. In detail, the simulated model tends to describe with high accuracy the mean monthly temperature for the summer period (December, January and February), recording acceptable underestimated values for the autumnal transitional months (March and April). For the wintertime, the accuracy becomes lower, and the simulated values tend alternatively to underestimate (June) and overestimate (August) the recorded data. As expected, the IWEC dataset, due to it considers long-term averaged years, overestimates some months and underestimates others, presenting relatively accurate values only for the Spring-like transition months. On the basis of these considerations, and when compared with the commonly used IWEC weather file, it is possible to affirm that the RCA4 model is able to predict with a good approximation the temperature pattern for a specific year. Excluding only three months, March, April and June, the simulated weather dataset almost matches observations in the remaining months.

4.2 Trends in temperature according to the RCP scenarios

Figures 4(a) and (b) depict the temperature distribution according to the datasets obtained by the RCP 4.5 and RCP 8.5, respectively, for the time horizons and the city under analysis. Comparing the percentage of the time during the year in which a certain temperature is presented, the scenario that considers a future with significant emissions reductions clearly projects a limitation in terms of temperature increase (RCP 4.5) (Fig. 4(a)). So, no large increases in temperature can be noted when comparing the circles of the historical (grey lines) and the 2030 (yellow) datasets. With this climate scenario, the increase in temperature starts to be noted

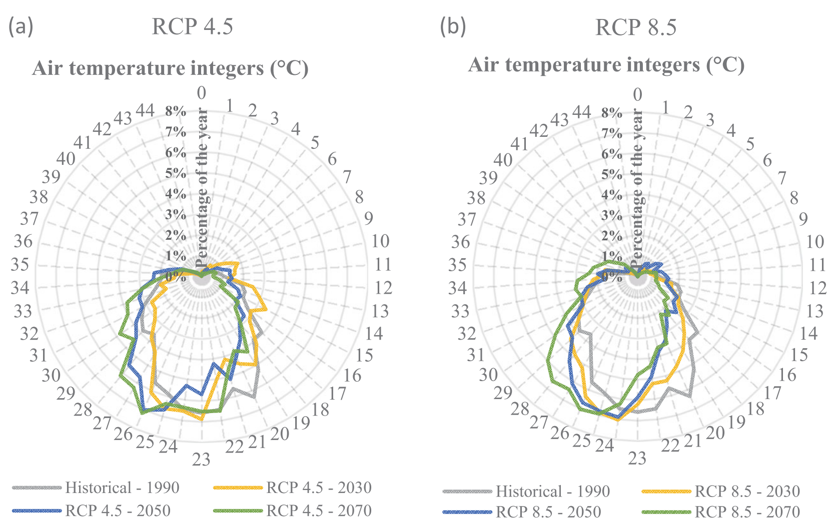


Fig. 4 Temperature distribution for the years 1990, 2030, 2050 and 2070 according to (a) RCP 4.5 and (b) RCP 8.5. The graphs depict the percentage of the time during the year (circumferences) in which a certain temperature is presented (radius)

with the 2050 and 2070 weather datasets, since the circles tend to turn to the left, which indicates the occurrence of higher temperatures. In the same line, the trend of temperature increase is better appreciated with the RCP 8.5 (Fig. 4(b)) since the differences among each weather dataset are accentuated, and the circles tend to turn to the left according to the time horizon considered, indicating the occurrence of higher temperatures.

The historical dataset, referred to the 1990 year, shows for the temperature recorded that the highest percentage of occurrences is 23 °C. This trend is maintained for the estimation coming from the RCP 4.5 scenario for the year 2030. For the years 2050 and 2070, the highest percentage corresponds to a temperature of 26 °C. For the RCP 8.5, the 2030 and 2050 weather datasets estimate a temperature of 24 °C as the highest percentage of occurrence. Considering the year 2070, the highest percentage of occurrences for temperatures is also 26 °C. Nonetheless, the 2070-year forecasts estimate maximum temperature values equal to 38 °C and 40 °C, for the RCP 4.5 and RCP 8.5 climate scenarios, respectively.

The temperature frequencies according to the datasets considered for Asunción are depicted in Fig. 5. On the base of comparisons between the datasets referred to 1990 and the simulated 2009, a decrease regarding the number of hours with temperature values lower than 28 °C and a parallel increase of higher values are recorded. Through the comparison between the simulated and the observed data referred to 2009, it is possible to evaluate the accuracy of the model which estimates with good approximation the number of hours for each range, recording few differences between each other. A slight tendency to overestimate the number of hours with temperatures higher than 28 °C can be noted, but with a very good estimation of those with lower than 18 °C temperatures.

Analysing the results with the forecasting scenarios, a general increase in terms of temperatures is projected, where the tendency that the number of hours with higher temperatures will increase and the number of hours with lower temperatures will decrease is outlined. Nonetheless, both RCP climate scenarios estimate that the highest number of hours during the year will have a temperature value between the acceptable range (18–28 °C). With the RCP 8.5 scenario, where no emission reduction policies are taken into account for the future, a significant increase in temperatures is highlighted which are outside of the comfort range, especially for the 2070-year. Taking as a base the observed data of the 2009-year, the number of hours with temperatures higher than 28 °C will increase considering climate change effects by the year 2070 in around 20% and 34% for the RCP 4.5 and RCP 8.5, respectively. This specific analysis has been carried out in order to evaluate the boundary conditions for the definition of the comfort rate for the energy simulations, and to briefly display how, according to every forecasting scenario, the temperature frequency will change for the time horizons selected, as it happens respectively for the scenario RCP 4.5 or RCP 8.5.

4.3 Thermal comfort evaluation of the building in the original state and the energy efficiency version

Figures 6 and 7 depict the results of the annual thermal comfort evaluation of the case study employing the different weather datasets, considering both the original state and the energy efficient version of the building. Through the analysis of the results using the different forecasting scenarios, the projected increase in temperature leads to a consequent increment of the overheating rates with a parallel decrease of the underheating percentage, which is recorded using both the adaptive thermal comfort approach (Fig. 6) and the static one (Fig. 7).

In order to analyse the differences between the employed thermal comfort approach, it can be said that when considering a fixed temperature comfort range, independent of the outdoor conditions, the overheating rates are more significant for both, the original and the energy efficient version of the building (these findings were also found by Barbosa et al. (2015)). In fact, even with the energy efficient version, the overheating rates for both climate scenarios are very significant from the year 2030, indicating the imminent need to use HVAC systems to achieve better comfort conditions, which will lead to higher energy consumption

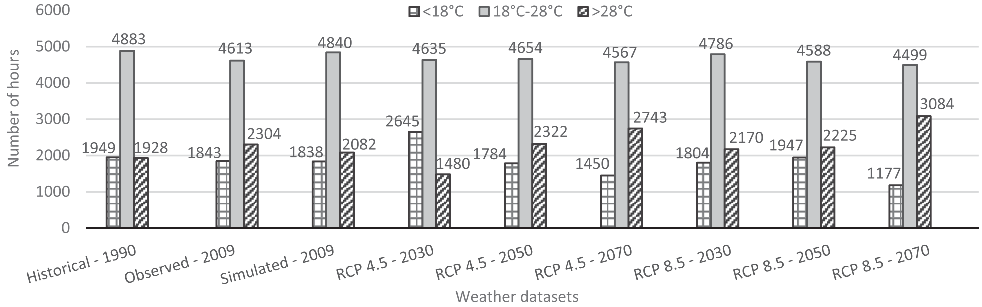


Fig. 5 Temperature frequency according to the datasets and time horizon considered for Asunción

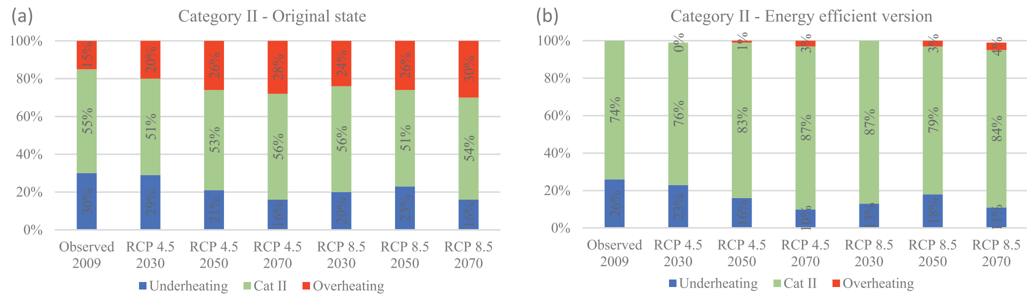


Fig. 6 Annual average comfort rates according to the adaptive thermal comfort model for Category II, for the building in the original state (a) and in the energy efficient version (b)

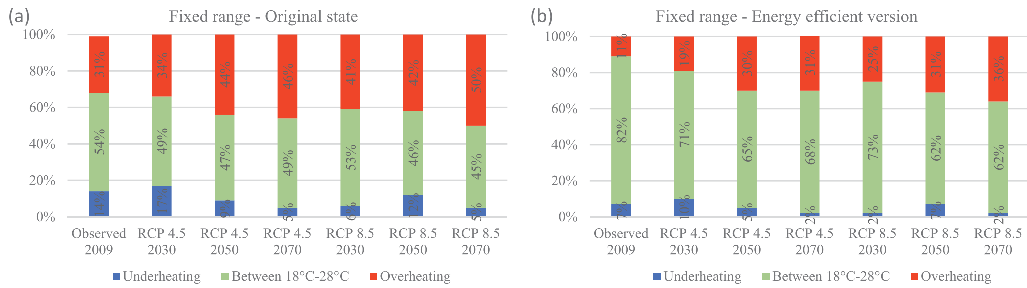


Fig. 7 Annual average comfort rates according to the static thermal comfort approach, for the building in the original state (a) and in the energy efficient version (b)

in the building. Nonetheless, the overheating rates in the original state of the building are significantly greater, indicating that if no retrofit measures are considered, the building will have uncomfortable conditions most of the year, mainly from the 2050 and considering the RCP 8.5 scenario.

It is also important to note that the underheating rates are less substantial in the static approach. This is because the adaptive approach tends to be permissive with high temperatures but not with low temperatures, since for example, for a running mean outdoor temperature of 26.4 °C, the optimal operative temperature is 27.5 °C, and the upper and lower limits are 30.5 °C and 23.5 °C respectively. In this way, an operative temperature of 22.0 °C is recorded as underheating rate, when in fact 22 °C is in the comfort range of the static model. This situation can be better understood by examining the Fig. 8.

The simulations results employing the different datasets are also depicted regarding the outdoor mean running temperature versus the operative temperature (Fig. 8), in order to represent more accurately the impact that the forecasting datasets have on the selected comfort approaches. The outcomes of these graphs are quantified in terms of comfort rates in Fig. 6 and Fig. 7. Considering the observed 2009 dataset and the case study in the original state, a high number of values are outside of the acceptable comfort range, both for the fixed and adaptative approach, as depicted in Fig. 8(a). In the energy efficient version, a consistent reduction of the operative temperature outside the acceptable range is recorded, assuming as upper and lower limits the two comfort conditions. In this case, the adaptive comfort approach does not record operative temperature higher than the upper limit as happens for the underheating condition. Regarding the static approach, the method records with the same trend the overheating and underheating rates but with a significant improvement in the rate of the comfortable range.

The described trend is also outlined with the forecasting datasets when comparing the energy efficient version results with those of the building in the original state. Thus, considering the original state (for example, Figs. 8(c), (d), (e)), the building is not able to face the outdoor conditions through the years, and the climate change effects lead to an increase of the operative temperature, which has consequences on the discomfort rate, especially of the overheating, and this is emphasised in the RCP 8.5 (Figs. 8(i), (j), (k)). With the energy efficient version, the building has a better capacity to maintain its indoor temperatures without being too affected by the outside temperature, as it is depicted in Figs. 8(f), (g), (h) for the RCP 4.5, and in Figs. 8(l), (m), (n) for the RCP 8.5. In the referred figures, it can be seen that the large spread of the recorded hourly operative temperatures values is reduced, fitting better within the comfort ranges considered. Thus, the introduction of passive energy efficiency measures to improve the thermal performance of the building can ensure a restraint on the variability of the operative temperatures through the years, and to collaborate for the steadiness of comfort conditions inside the building.

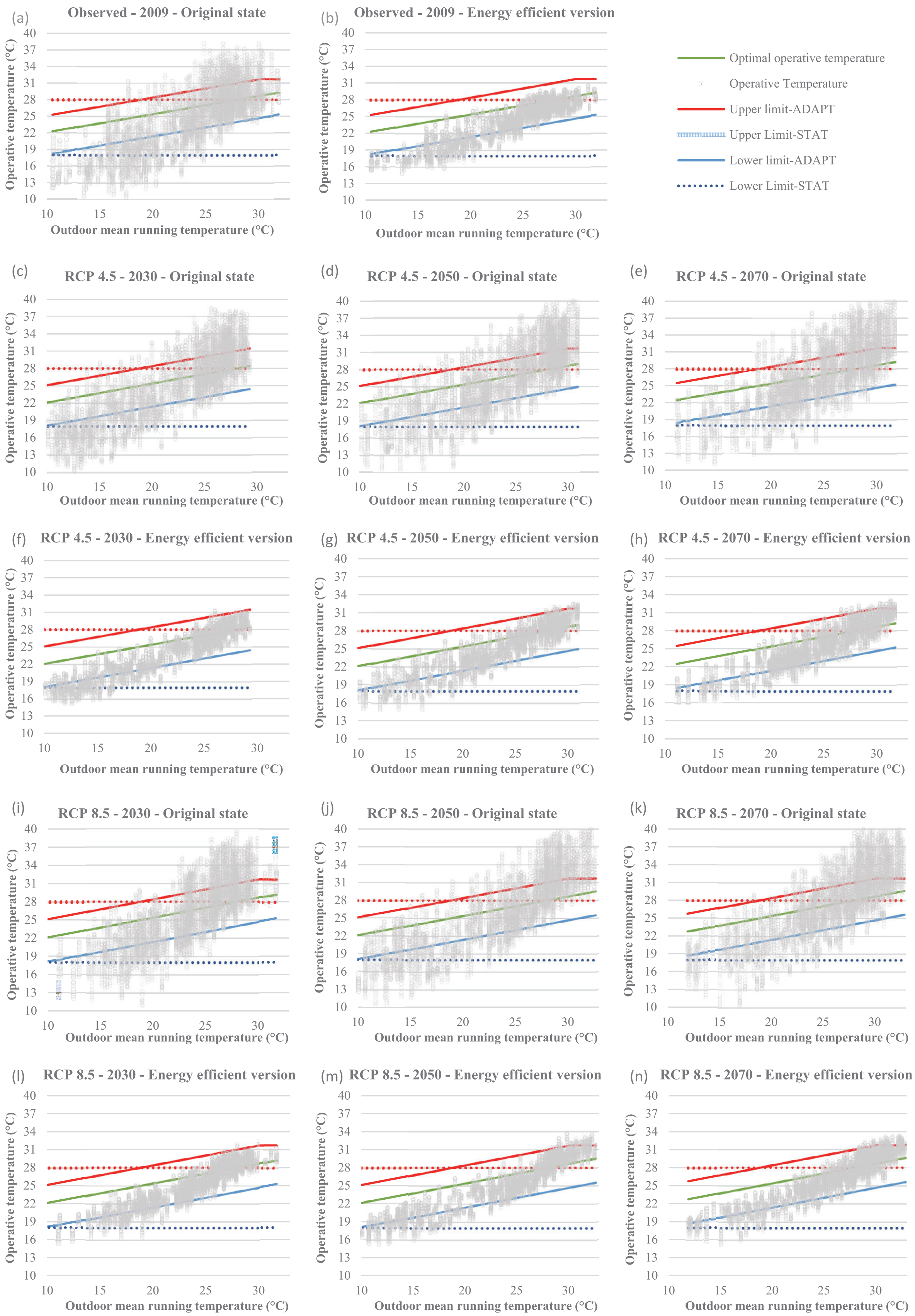


Fig. 8 Distribution of operative temperatures according to the static and adaptive thermal comfort model, for the two configurations of building design and the different weather datasets

The impact of the forecasting datasets has also been analysed regarding heat transfer through building envelope components, as reported in Figs. 9 and 10. While significant changes can be noted comparing the heat transfer of the building envelope components in the original state versus the energy efficient version, no major differences can be pointed out in the trend regarding the forecasting scenarios and through the years. Looking at the original state (Fig. 9), the highest amount of heat losses is through the ground floor, both for the dataset referred to 2009 and for the forecasting scenarios, which are recorded mainly during the warmer months. Considering that the highest discomfort rates are due to overheating issues, this is a good feature for the hot-humid climate under analysis, and for this reason, energy efficiency measures were not considered for the ground floors. On the other hand, the roof is the main responsible for heat gains during the summer period and heat losses during the winter period. The external walls, because of the absence of insulation, do not have good thermal performance, both for gains and losses. Considering the energy efficient version (Fig. 10), a general reduction of the annual heat transfer through the building components is recorded. In fact, the introduction of insulation in the external walls and the roof allows a decrease of the heat transfer during the summertime (heat gains) and the winter period (heat losses). The adoption of passive energy efficient measures has consequences on the living comfort and operative temperatures of the building. This leads to better control of the heat transfers also through building components not intervened with an improved solution, as it happens with the ground floor, through which the heat losses regarding the original state and the energy efficient version have decreased.

4.4 Admissible thermal transmittance values recommended by international standards

Finally, considering that Paraguay does not have standards for the thermal comfort evaluation of buildings, and in order to contribute to the regulation of thermal parameters aiding to improve the energy efficiency of buildings, Table 5 summarises the thermal transmittance values of the energy efficient version compared to those of the building in the original state. Furthermore, aiming to make a quick comparison between the thermal performance requirements for building components, the admissible thermal transmittance values recommended by Italian, Argentine and Brazilian Standards for the thermal performance of buildings for cities with climatic conditions similar to Asunción are also depicted.

The analysed standards currently in force are for Italy the thermal standard DM 26/06/2015 No.162 (Ministero dello Sviluppo Economico 2015), for Argentina, the IRAM 11605:1996 (IRAM 1996) and for Brazil, the NBR 15575:2013 (ABNT 2013). Thus, Table 5 shows the maximum admissible thermal transmittance values set by these standards for buildings envelope components. For Brazil, no specific requirements about thermal performance of windows were found, since within the pre-requirements for the envelope

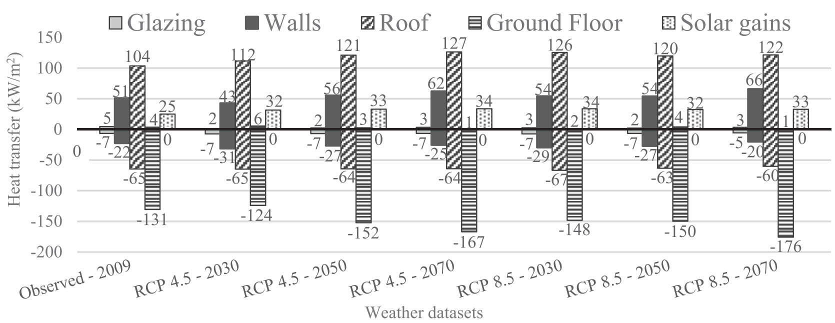


Fig. 9 Original state—annual heat gains and losses through building envelope components during the year, in different time horizons

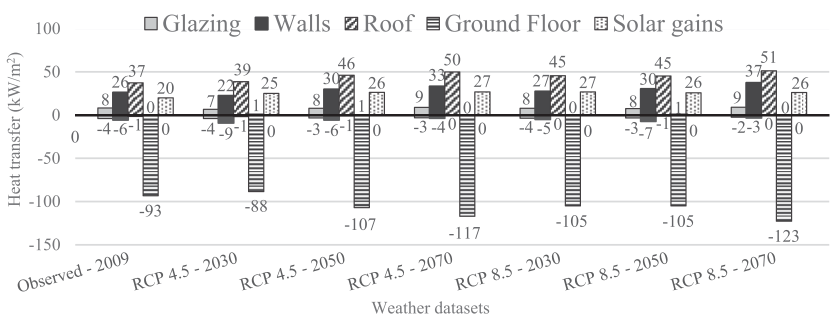


Fig. 10 Energy efficient version—annual heat gains and losses through building envelope components, in different time horizons

Table 5 Average values of thermal parameters of the building envelope in the original state, with retrofit measures and the values recommended by Italian, Argentine and Brazilian standards

	U (W/(m²·K))		
	Glazing	Walls	Roofs
Original state	5.78	2.53	4.20
Energy efficient version	**2.76**	**0.46**	**0.43**
Italian standard	3.20	0.45	0.34
Argentine standard	4.00	1.32	0.45
Brazilian standard	5.70	3.70	1.50

only conditions for walls and roofs are established. Nonetheless, aiming to have a reference value, the window thermal transmittance depicted in Table 5 corresponds to the most used type of window in residential buildings of Brazil, as suggested by Melo et al. (2016).

For the comparison, one city from each country was considered. For Argentina, the city of Pilcomayo, Formosa (zone Ib—humid subtropical climate with an average temperature of 24 °C) and for Brazil, the city of Foz do Iguaçu (zone 3—humid subtropical climate with average temperature of 21.6 °C). These cities were chosen because besides to have similar average annual temperatures, they are in the same climatic area than Asunción according to the Köppen-Geiger classification system. Thus, these cities also have a humid subtropical climate denominated **Cfa** (Peel et al. 2007; Rubel and Kottek 2010). For Italy instead, the city of Porto Empedocle was considered, which is under the climatic zone A, according to the climate classification system of the country, and has an average annual temperature of 17.7 °C. This city is under the climate zone **Csa** according to the Köppen-Geiger classification system, where the capital letter **C** refers to a temperate climate, the small letters **s** and **a** indicate a dry and hot summer, respectively. Although the climate of this European country can be different to Asunción's climate, the values are stated to have a reference of the buildings thermal performance levels required in other parts of the world, also taking into account that Italy is considered one of the leading countries regarding overall energy efficiency levels (Kallakuri et al. 2016). Furthermore, analysing Italy's climate zones, the climatic zone A can be considered the least severe cold climatic zone of the country.

Analysing the values referred in Table 5, the constructive solutions considered for the energy efficient version accomplish the requirements regarding U values recommended by the Argentine and Brazilian standard, the walls in their original state already had fulfilled the Brazilian standard but roofs, on the contrary, had extremely high thermal transmittance value. However, the Italian requirements are even more demanding regarding the performance of roofs and walls, which indicates the energy efficiency targets the country set for the buildings sector.

It must be noted the high thermal transmittance values of the building in its original state, which lead to the high values of discomfort rates during the observed 2009-year and became even worse over time considering the climate change scenarios. Even more concerning is that the buildings currently being constructed in the country (new buildings) could have even worse thermal performance, considering that the building under analysis has a relatively high thermal mass (compared with new buildings of the country), since regarding walls, it has 30cm and 20cm thick walls, while the commonly wall thickness used in the country is only 15 cm. This is due to the lack of standards requiring a minimum level of thermal performance or energy efficiency of buildings, causing that the Paraguayan building envelope has a poor constructive design, with a minimum or no presence of thermal insulation materials, which affect the indoor thermal comfort creating high sensations of discomfort. For this reason, users are forced to use mechanical systems for air conditioning to achieve acceptable comfort conditions, which causes a greater energy expenditure and driving up the electric bills. Therefore, it is important to highlight that this situation will worsen over time due to climate change effects, as it was demonstrated in the present research. For this reason, energy policy-makers and construction technicians should prioritise the actions focused on the creation of building energy codes. Thus, this research demonstrated the low thermal performance of the building analysed in its original state, the effectiveness of the implementation of passive strategies to improve the thermal performance considering current and future climate conditions, and the importance to create standards setting minimum requirements of thermal performance for Paraguayan buildings.

5 Conclusions

In this work, the impact of climatic change on the thermal performance of an historical residential building in Paraguay is investigated. Low and high Representative Concentration Pathway climate scenarios for the time horizons of 2030, 2050 and 2070 from the IPCC Fifth Assessment Report are employed and compared with observed weather data of the year 2009. The first analysis involved the comparison between the observed meteorological data of the city of Asunción with the simulated values obtained from the regional climate model (RCA4) for the same year, with the objective to analyse the accuracy of the model. The second analysis describes the trends regarding temperature distribution and increments considering the weather datasets for future climate conditions. Subsequently, the RCP 4.5 and RCP 8.5 forecasting scenarios were selected as the best and worst scenario, respectively, and were used for the dynamic simulations to evaluate how climate change will impact discomfort rates.

The case study is analysed both in its original state and in an energy efficient version, and the energy simulations are carried out to compute annual comfort rates considering two assessment methods, the statistic and the adaptive thermal comfort approach addressed in the European standard 15251:2014.

Thus, the three main goals established were: to figure out the accuracy of climate models to describe the climatology of the city under study; to evaluate the impact of the climate change on buildings in terms of discomfort rates, and to verify the effectiveness of passive retrofit measures under future climate conditions. In this way, the main conclusions of the investigation are summarised as follows:

- From the intercomparison between the observed and simulated temperature distribution of the year 2009 for Asunción, the regional model estimates with high accuracy the temperature values, presenting an acceptable correlation coefficient equal to 0.8 if compared to collected data. The precision of the RCA4 model is higher for the summer period and becomes lower for some of the colder months, mainly during the autumn period. However, the analysis presented in this research suggests that the RCA4 climate model is able to reproduce with a good approximation the climatology of Asunción, describing the temperature pattern accurately.
- From the intercomparison between historical, observed and predicted weather datasets according to different scenarios, the analysis projects a general increase in terms of temperature, where the tendency of the number of hours with higher temperatures will increase and the number of hours with lower temperatures will decrease is outlined. The projected temperature rise due to climate change effects will lead to a consequent increment of the discomfort rates, which will be even worse if no energy retrofit measures are adopted. Furthermore, the overheating rates on buildings can deeply increase due to climate change if no emission reduction policies are introduced, considering both the adaptive and the static thermal comfort approach. In fact, considering the RCP 8.5 scenario, the discomfort rate reaches in 2070 30% and 50% respectively for the adaptive and static method, and these percentages could be reduced to 4% and 36% introducing energy efficiency measures.
- From the analysis of discomfort rates estimated for the case study in the original and energy efficient version, the results allow asserting that the strategy implemented contributes for reducing the overheating phenomena significantly and enables to maintain comfortable indoor conditions contributing to the improvement of occupant wellbeing. In this way, through the retrofit measures, the building thermal performance has been significantly improved, and the building has a better capacity to face the climate change effects. Considering this, the introduction of building energy codes in Paraguay can represent a key adaptation strategy for the country to tackle the climate change effects, in order to evade their great impact on buildings and to avoid the increase in energy consumption at which the projected overheating rates will lead.

Based on the above conclusions, the impact of the climate change on the thermal performance of buildings, according to projections of future weather data, is relevant and must be considered to develop the different adaptation initiatives and mitigation strategies able to limit and control this phenomenon. Compared to other South American countries, Paraguay is still far from mandatory energy labelling of buildings. Thus, this kind of research can have a substantial impact on society and building industry of the country, since it demonstrates that passive rehabilitation strategies are effective for the severe climate of the country, even more considering the projected temperature rise due to climate change effects. Furthermore, the strategy herein presented were focused on the improvement of building envelope components; nonetheless, considering the hot-humid climate of the city, introducing strategies to improve natural ventilation rates and shading systems could improve even more the thermal performance of the building, which should be considered in further research in this area for the country.

In summary, this study has demonstrated that for the current and future climate conditions of Asunción, it is necessary to introduce regulations for the thermal performance of buildings and particularly, consider the use of thermal insulation materials since for the climate characteristics of the country, it is essential to require buildings with better thermal performance, which have the capacity to manage the high outside temperatures and keeping comfortable indoor conditions. Nevertheless, the most important is that leaders and citizens realise that buildings energy efficiency can reap multiple benefits, as having more valuable and resilient buildings that offer better living conditions for owners, better indoor air quality and indeed, healthier environments; finally, also reducing energy bills and energy expenditure without affecting the quality of life.

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