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Planning Post Carbon Cities

Editors:
Jorge Rodríguez Álvarez
&
Joana Carla Soares Gonçalves

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The energy demand of a social dwelling for acclimatization

Sensitivity to climate change and interventions

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ABSTRACT: Buildings energy simulation is a powerful tool that allows addressing climate change impact studies on the Built Environment. Future weather files are required as forcings, so a methodology to generate them based on outputs from several climate models was proposed in this work. This approach retains both physical and temporal consistency from climatic variables and removes the climate models' systematic errors. The variety of models allows assessing the uncertainties that are related to models and projections. The generated weather files were employed to evaluate the sensitivity of a social dwelling in Rosario city (Argentina) to design modifications and climate change projections. The proposed interventions are found to produce higher energy demand savings when the projected greenhouse gases concentrations are lower. As such concentrations increase, addressing impact studies becomes more difficult since the uncertainties associated to the results increase as well. However, as the house's efficiency enhances, experiments start to converge and related uncertainties diminish.
KEYWORDS: building simulation, climate change, weather file, uncertainties, energy demand

1. INTRODUCTION

As one-third of the total energy demand in Argentina corresponds to the residential sector [1], there is an urgent need to improve the energy efficiency of the Built Environment. Buildings energy simulation (BES) emerges as a powerful resource since it allows estimating the energy consumption associated with the use of housing, among other things. Therefore, design improvements and modifications can be evaluated for new and already built dwellings. The energy requirement is strongly dependent on the climatic conditions of the place where the house is located. The climatic trends observed since the second half of the past century are expected to maintain or worsen in the upcoming years. In particular, in central-eastern Argentina, both the mean temperature and its extremes are expected to keep rising, with warm spells becoming more frequent, longer and more severe [2]. Such future climate conditions may cause overheating of buildings and serious discomfort issues [3,4]. Therefore, it is essential to incorporate climate change impact studies when planning and designing the Built Environment.

BES experiments require a description of the building's infrastructure and the physical properties of the involved materials. In addition, the *weather forcing* of BES (i.e., a full-year climate file of hourly data of several climatic variables for the desired location) is necessary. The results of the simulations will be directly influenced by such file, so the quality of the climatic information is crucial.

Present climate weather files have mainly been used to conduct BES. However, the need to estimate the response of the energy demand to climate change also leads to the construction of appropriate future climate weather files. This involves using climate projections derived from climate models. Such projections follow to different greenhouse gas emissions' scenarios (Representative Concentration Pathways, RCPs), which are based on different global socio-economic factors [5]. Climate models' outputs must be utilized properly to create future weather files. They have high levels of uncertainty which derive from different sources: estimates of future anthropogenic forcings, the response of the models to a given forcing and the natural variability of the climate system [6]. The assessment of such uncertainties can result in economics benefits when facing adaptation costs.

Overall, regional climate models (RCMs) can capture the physics underlying the climate system and reproduce the detailed behavior of particular locations. Moreover, the use of high-frequency (hourly) outputs from several RCMs as forcing to BES can a provide a measure to assess the aforementioned uncertainties and they capture climate change signal at high temporal resolutions (e.g., diurnal cycle). The implementation of RCMs' outputs has been explored in previous works in which

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the forcing time series were the result of concatenating typical months or calculating the models' mean ensemble [7,8]. These manipulations can lead to physical inconsistencies, misrepresenting the natural climate variability and potentially negatively impacting on the assessment study. In addition, the lack of uncertainty analysis limits the BES' outputs analysis and interpretation. Finally, climate models possess intrinsic systematic errors that are not accounted for in most literature. They may result in underestimating or overestimating the climatic variables [9], so they must be removed when addressing impact studies.

In Argentina, climate change impacts studies on the built environment are incipient. In the most recent research, to the best of the authors' knowledge, a house's behavior under climate change projections for different cities is analyzed [10]. However, outdated climate projections with a coarse grid resolution were used, while uncertainties were left unaddressed. Santa Fe province has recently approved a legislation to classify buildings according to their energy performance [11], which emphasizes the relevance of such impact studies. Therefore, a methodology to create weather files with RCMs' outputs is proposed in this work. Such files are used to conduct BES experiments that allow analyzing the behavior of a social dwelling in Rosario City (Santa Fe).

In this work, we (i) evaluate design improvements and (ii) estimate changes in the future cooling energy demand due to climate change projections, based on two greenhouse gases (GHGs) concentrations´ scenarios. The analyses are for a near future period, and include considerations about the uncertainty of the results.

2. DATA AND METHODOLOGY

2.1. Climate data and weather files

To perform BES studies for Rosario city (32° 57' S, 60° 37' W, Fig. 1), 21-years of high frequency data (three-hour or hourly) from four CORDEX RCMs [12] were adapted to generate present and future weather files. The 1985-2005 and the 2045-2065 periods were chosen as representative of present and near future climate, respectively. Climate projections follow to two greenhouse gas emissions' scenarios, an intermediate one (RCP4.5) and another with high emissions (RCP8.5). Overall, the proposed methodology consists of forcing multiple BES experiments with individual RCMs to assess the potential future energy demand and the associated uncertainties.

For each RCM, several climatic variables were retrieved: surface temperature (T), surface pressure (SP), relative humidity (RH), downward shortwave radiation (SWR), downward longwave radiation (LWR), zonal wind component (U-wind) and meridional wind component (V-wind). The employed models and scenarios were: WRF (present, RCP4.5), RCA4 (present, RCP4.5, RCP8.5), REMO (present, RCP4.5, RCP8.5) and RegCM (present, RCP8.5). Also, hourly data from the Argentinian Meteorological Service was collected for the present period. Argentina lacks a solarimetric network, so radiation hourly outputs from the ERA5 reanalysis were retrieved as well [13]. The combination of both data sets was taken as an observational reference (OBS).

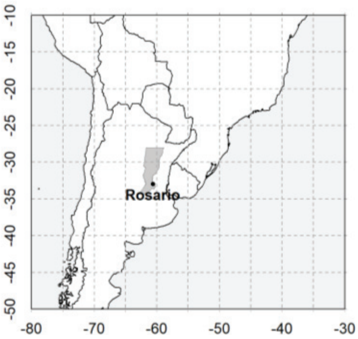

Figure 1: Rosario city (Santa Fe, Argentina).

The hourly climatology of each variable was calculated to construct weather files for mean climate conditions. That is, the 1st of January at 00:00 a.m. for present conditions was obtained as the mean value of all the twenty-one values corresponding to the 1985-2005 period, and so on. Analogously, the hourly climatology of each variable was obtained for the two future scenarios. Climatological time series were implemented to maintain temporal coherence and consistent climate variability. This procedure was applied to all RCMs' outputs and observations.

For the eleven datasets, the resulting 8760 time-step series of all climatic variables were employed to construct present and future weather files with the Weather Converter software [17], choosing the closest point to Rosario for each RCM.

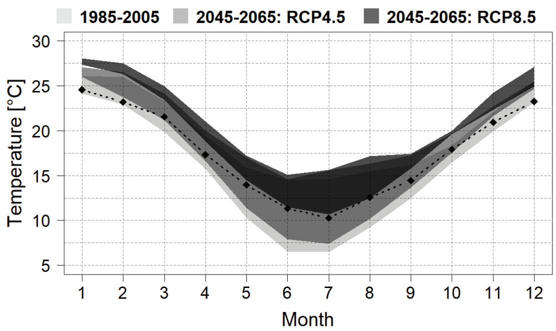

Figure 2: The annual cycle of mean surface temperature for Rosario city. Belts show the models' spread for present (1985-2005, light grey) and future climate conditions (2045-2065) according to RCP4.5 (dark grey) and RCP8.5 (light black) scenarios. Diamonds are observations. Units are °C.

Figure 2 shows the ranges of the annual cycle of mean surface temperature as spanned by the models available for each scenario. The observational

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monthly mean values are also displayed. Overall, a raise in the mean temperature throughout the all year is evident in the future. The RCMs span widens during cold months, which is an indicator that forcing BES with a models' ensemble mean could result in loss of information, especially during the winter. On the other hand, observations are confined within the present period range, which is a positive indicator of the utilized RCMs. Temporal scales are downscaled in Figure 3, which shows the climatological diurnal cycle of mean surface temperature for January. Models overestimate temperature during daytime hours, especially in the afternoon. If unaddressed, such misrepresentation could result in overestimation of the needed cooling energy when carrying out BES.

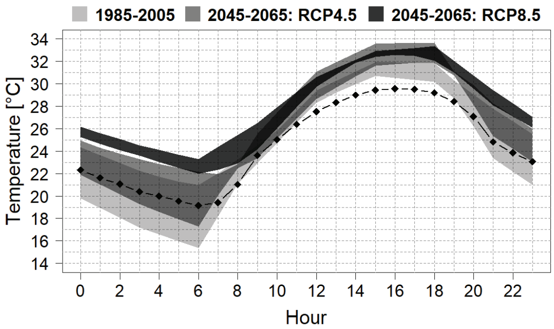

Figure 3: The diurnal cycle of mean surface temperature for January. Belts show the models' spread for present (1985-2005, light grey) and for future climate conditions (2045-2065) according to RCP4.5 (dark grey) and RCP8.5 (light black) scenarios. Diamonds show observations. Units are °C.

The implementation of several RCMs allowed for the creation of representative weather files for present and near future periods, while maintaining physical consistency among climatic variables. Temporal coherence was also conserved while the mean state of the climate system was properly represented. Moreover, with this approach, the number of realizations depends on the number of available RCMs alone, independently of the number of years of the study period.

2.2. Building energy simulation (BES)

BES experiments were performed using Energy Plus (E+) [18]. In addition to the full-year climate file of hourly data, E+ requires a description of the building infrastructure and the materials' physical properties (e.g., conductivity, density, etc). It is optional to specify Heating, Ventilation and Air Conditioning (HVAC) systems and the Ideal Loads System (ILS) option is available when they are not defined. ILS object consists of an ideal unit that supplies conditioned air to the zone and consumes no energy. It allows for a primary analysis of the building's performance since it is used for loads calculations, and can be thought as a previous step to a more realistic model [18]. As evaluating the performance of HVAC systems was beyond the scope of this study, the ILS object was utilized in this work.

2.2.1. Case study

The floor plans of a social dwelling were provided by Santa Fe's Department of Urbanism and Housing. It is a one-storey house, consisting of a living room and kitchen connected with the bathroom and two bedrooms through a hallway (Fig. 4). It has two inclined metal roofs with air chambers, covering the kitchen-dining room and the bedrooms, respectively. The bathroom has a horizontal reinforced concrete roof without any insulation. Each room was modelled as a thermal zone, with the main one oriented northward. The air chambers were defined as sealed thermal zones without air infiltrations. Traditional construction materials were used for defining the walls, blinds were set to optimize solar gains and infiltrations were set to 2 air changes per hour [19].

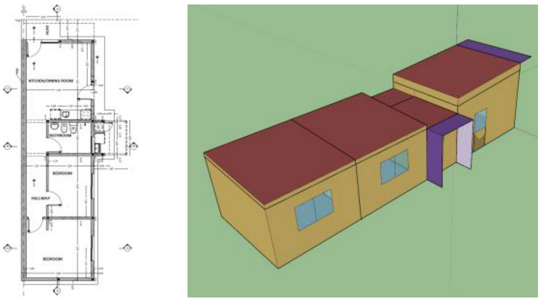

Figure 4: Floor plans and simulation design of the case study

2.2.2. Experiments

The energy needed to maintain the house's temperature below 26 °C during January was calculated for two set of experiments. This threshold is used in literature as a domestic comfort value [20].

Firstly, the house's sensitivity to design improvements was evaluated for present climate conditions. The original specifications of the social dwelling do not comply with Rosario's legislation [21], so the four RCMs' outputs and the observational set were employed to conduct the following BES:

(i) *Base Case* (BC) where the house's specifications remained unchanged

(ii) *Roof Intervention* (RI): insulation in roofs was increased to comply with the legislation (thermal transmittance U_{roof} < 0.32 W/m^{2}K)

(iii) *Roof-Wall Intervention* (RWI): insulation in walls was increased as well to comply with the legislation (U_{walls} < 0.5 W/m^{2}K).

Then, to evaluate sensitivity to changes in the mean climate conditions, the same set (i-iii) was forced by climate change projections from the available RCMs, according to the emission scenarios.

It is crucial to proper deal with the systematic errors from climate models (e.g., overestimation of

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daytime temperature, Fig. 3). Therefore, a BES future climate experiment driven by a particular RCM was compared to the BES present climate experiment driven by the very same RCM. If the results of future climate experiments were contrasted to those from conducting with observations, systematic errors from the forcing RCM would be kept intact and overestimations or underestimations of the energy demand may occur. Therefore, the estimated future energy demand (FED) was calculated as follows:

$$\Delta E_{model,scenario,case} = ED_{model,scenario,case} - ED_{model,present,case} \quad (1)$$
$$FED_{model,scenario,case} = ED_{OBS,case} + \Delta E_{model,scenario,case} \quad (2)$$

where:

$ED_{OBS,case}$ is the estimated energy demand when BES is driven by the observational dataset, for a given intervention (MJ/m^2);

$ED_{model,scenario,case}$ is the estimated energy demand when BES is driven by a particular RCM, following a specific climate change scenario, and for a given intervention (MJ/m^2);

$ED_{model,present,case}$ is the estimated energy demand when BES is driven by a particular RCM, under present climate conditions, and for a given intervention (MJ/m^2);

$\Delta E_{model,scenario,case}$ is the intrinsic estimated change in the energy demand when climate warms, according to specific model-scenario combination, and for a given intervention (MJ/m^2). This is a bias-corrected result, where the mean systematic error of such RCM has been removed.

Equation (2) indicates that, for each case of intervention, the *energy delta* $\Delta E_{model,scenario,case}$ was added to the estimated energy demand based on observations, being the result the estimated future energy demand, following a specific climate change scenario and according to given models' projections.

In addition, for each driving model, the percentage savings (S) of the RI and RWI cases in respect of BC were calculated for each scenario:

$$S_{model,scenario,intervention} = 100.(FED_{model,scenario,BC} - FED_{model,scenario,intervention})/FED_{model,scenario,BC} \quad (3)$$

3. RESULTS

3.1. Present climate

Figure 5 shows the results of the present climate experiments. They are clustered by interventions and account for the integrated energy demand under mean climate conditions.

It is evident that the original design (BC) presents the worst performance for all forcing sets. The original roof is particularly deficient, with 14% of the total ceiling made of concrete without any insulation. Therefore, upgrading the roof's complete insulation (RI) results in approximately 50% less consumption for three out of five forcing sets (i.e., RCA, REMO and RegCM). An additional 13% of savings is obtained if the complete envelope is upgraded (RWI). RI savings ascend to 75% when forcing with WRF, and to 88% when conducting with observations. Except for WRF, RCMs overestimate nighttime temperature (not shown), which could explain the lower consumption saving that the rest of models show for RI. Lower minimum temperatures (OBS and WRF) enhance heat losses during nighttime, the house's temperature drops and, therefore, less cooling energy is needed. On the other hand, the RWI intervention makes almost no difference for the observational set, while it produces a small increase in the cooling energy when forcing with WRF. A possible hypothesis to explain this is that WRF's diurnal cycle presents the highest amplitude (not shown), so increasing the envelope's insulation restricts heat losses during nighttime. Such increase in the cooling energy seems to be an isolated case for this study. However, it shows that it is crucial to analyze the temperature diurnal cycle of the city of interest since it plays a defining role on the impact of design strategies. These findings suggest that buildings placed in cities with elevated summer temperatures and high thermal amplitude could considerably benefit from just an efficient roof during summer.

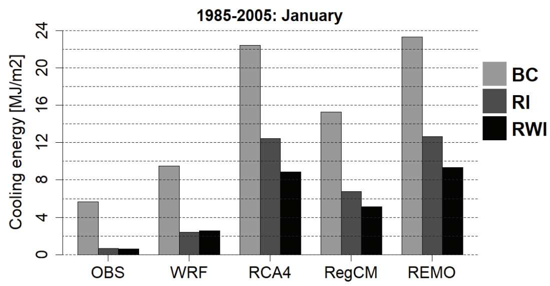

Figure 5: Integrated energy demand needed to maintain the temperature below 26 °C in January for the BC (light grey), RI (dark grey) and RWI (black) cases under present climate conditions (1985-2005), when conducting with each forcing set. Units are in MJ/m^2.

Moreover, the cooling energy demand is overestimated when conducting BES with all RCMs. This is a direct consequence of the models' warm bias during daytime hours (Section 2.1.) that shows the importance of removing systematic errors when projecting future energy demand estimations.

3.2. Future climate

Figure 6 shows the projected energy demand change for all the house prototypes during January, with bars showing the reference energy demand under mean observed climate conditions (as in Fig. 5).

Analogue to present climate results, all experiments simulate the original design (BC) as the least efficient (highest FED projection). It also

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becomes evident that the RWI is the best option for all scenarios, which highlights the importance of adequately insulating the house's envelope to ensure comfort conditions.

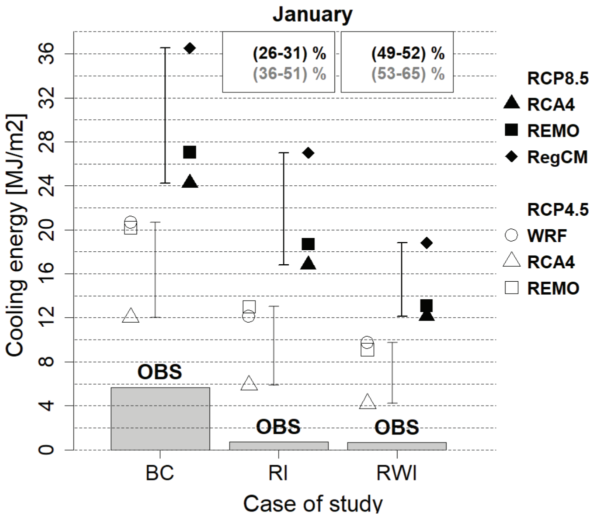

Figure 6: Energy demand estimations to maintain temperature below 26 °C in January. Light grey bars represent the present energy demand when driven by observations for base case (BC), roof intervention (RI) and roof-wall intervention (RWI). Points illustrate the estimated future energy demand under RCP4.5 (empty) and RCP8.5 (filled) emissions' scenarios, according to each RCM. Vertical segments define the uncertainty range for each intervention-scenario. Values in parentheses show the percentage savings range of each intervention in respect of the BC prototype under the RCP4.5 (grey) and RCP8.5 (black) scenarios. Such ranges are determined by calculating the percentage savings for each RCM-scenario driving experiment. Units are MJ/m^2.

For each intervention, values in parentheses show the percentage savings span of the RI and RWI cases in respect of the BC prototype under a given scenario (S, Equation 3). Such ranges are defined by calculating S for the BES experiments when driving by the individual RCMs. The RI case produces the major impact on savings for all experiments. Analogously to present climate conditions (Fig. 5), insulating the complete envelope (RWI) contributes to a lesser extent once the roof is suitable. These prototypes still require cooling energy for acclimatization, so more ambitious strategies are needed. However, the proposed interventions produce substantial decreases in the energy consumption. For the most adverse energy demand projection (RegCM, RCP8.5), RI results in savings of 26%, while RWI, of 49%. Whereas for the most auspicious projection (RCA4, RCP.4.5), RI results in savings of 51% and RWI, in savings of 65%. This shows that **the lower the projected emissions, the more percentage savings are simulated by the same intervention**. Such result is reinforced when comparing FED projections when conducting with RCA4 and REMO (RCMs available for both scenarios). Both models simulate bigger percentage savings under the RCP4.5 scenario (values not shown). Although January shows the greatest inter-scenario gap for temperature (Fig. 2), its values do not differ much between both scenarios. However, FED estimations substantially differ between scenarios, as their uncertainty range stretch from RCP4.5 to RCP8.5: going from around 12-21, 6-13 and 4-10 MJ/m^2 for the BC, RI and RWI cases to 24-37, 17-27 and 12-19 MJ/m^2, respectively. **Interventions' uncertainty ranges widen as the GHG emissions increase, becoming more difficult to evaluate the impact of proposed strategies**. However, **uncertainties are reduced when the house's efficiency enhances** and experiments begin to converge.

4. CONCLUSION

The Built Environment and its energy demand are projected to keep growing [5], so migrating towards low energy and zero-carbon new buildings, and improving the efficiency of already existing building stocks is essential. Building Energy Simulation (BES) is a powerful tool that allows analyzing a house's performance and its response to climate. Therefore, a key component of BES is its forcing weather file. To assess climate change impacts, future weather files must be based on climate models' projections, which have high levels of uncertainty associated to their reproduction of the climate system and the estimation of GHG emissions. Thus, a methodology to create weather files based on high frequency outputs from climate models was proposed in this work. Such approach maintains temporal coherence and consistent climate variability, and allows to evaluate BES results and their uncertainties. The generated weather files were used as BES forcings to evaluate design improvements and estimate future energy demand projections for a social dwelling in Rosario city (Argentina). Three cases were evaluated for present climate conditions and under climate change projections from the RCP4.5 and RCP8.5 emissions scenarios: the original prototype (BC), a roof-intervened case (RI, insulation in roofs was increased) and a roof-wall-intervened case (RWI, the envelope's insulation was increased).

For present conditions, it was found that the RWI proposal (which encloses the RI one) is the most efficient one. However, the RI intervention produces the major percentage savings in respect of the BC case. The main reason for this is that the original design's roof is inefficient and our results remark the importance of an adequate roof to reach comfort conditions, since it limits heat transfer due to incident solar radiation. In addition, the cooling energy demand was overestimated when conducting BES with climate models, a direct consequence of the warm bias such models show during daytime hours.

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Such systematic errors were removed when projecting future energy demand estimations.

Analogously to the present period results, although the RWI prototype is the most efficient under all climate change projections, the RI one produces the major impacts. Savings are about 44% (RCP 4.5) and 29% (RCP 8.5) for the RI case; and about 59% (RCP 4.5) and 51% (RCP 8.5) for the RWI one. The experiments depict a greater percentage impact of the same intervention as GHG emissions decreases, which highlights the advantages of cutting off emissions. However, these interventions are not enough to turn off acclimatization systems, so more ambitious strategies are required. For instance, cross-natural ventilation and its efficiency under climate change projections is an essential resource during warm months to be studied in future work. It is clear, though, that analyzing local climate variations makes the most of the planning stage.

As the building's efficiency enhances, experiments converge and the inter-model span narrows. This occurs likely because the house's thermal behaviour becomes less sensitive to climate variations. On the other hand, as GHG emissions increases, so does the experiments' uncertainty range and evaluating climate change impacts becomes more difficult. The use of additional RCMs would help coping with this, at the expense of a higher computational demand. However, our findings highlight the advantage of working with the greatest variety of RCMs as possible since it provides a more robust approach to evaluate impact studies.

We discourage the use of a models' ensemble mean as unique forcing to BES experiments because valuable information regarding the uncertainty generated by each model's outputs is lost. This specially happens during cold months, when the models' temperature span widens. However, such approach is currently under study, as well as analyzing whether our results maintain throughout the whole year.

This research analyses mean cooling energy demand projections under climate change scenarios. Further studies are being pursued in order to evaluate energy consumption peaks projections due changes in the frequency of occurrence and in the characteristics of extreme events (e.g., heat waves).

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