INVESTIGATION OF GROUND TEMPERATURES FOR THE IMPLEMENTATION OF GEOTHERMAL SYSTEMS IN HISTORICAL AND FUTURE PERIODS

INVESTIGAÇÃO DAS TEMPERATURAS DO SOLO PARA A IMPLEMENTAÇÃO DE SISTEMAS GEOTÉRMICOS EM PERÍODOS HISTÓRICOS E FUTUROS

INVESTIGACIÓN DE LAS TEMPERATURAS DEL SUELO PARA LA IMPLEMENTACIÓN DE SISTEMAS GEOTÉRMICOS EN PERÍODOS HISTÓRICOS Y FUTUROS

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ABSTRACT
This study investigated variations in ground temperatures in four cities in Mato Grosso, considering the emission scenario SSP5-8.5 from the Sixth IPCC Assessment Report. Using computational simulations and historical and future climatic data, the research revealed significant changes in average ground temperatures. In Alta Floresta, simulations indicated a notable increase, especially in the months of April, May, and June, contrasting with estimates based on the EPW climatic file. Alto Taquari showed a distinct response, while Campo Verde and Sinop exhibited significant temperature increases until 2080. The research highlights the importance of considering specific soil characteristics for accurate projections, providing crucial insights for climate change adaptation strategies. There is an emphasis on the need to implement passive cooling strategies in buildings, especially in hot regions, to adapt to future conditions.

KEYWORDS
Climate change, Ground temperature, Computational simulations, SSP5-8.5 scenario, Environmental adaptation

RESUMO
Este estudo investigou variações nas temperaturas do solo em quatro cidades de Mato Grosso, considerando o cenário de emissão SSP5-8.5 do Sexto Relatório de Avaliação do IPCC. Utilizando simulações computacionais e dados climáticos históricos e futuros, a pesquisa revelou mudanças significativas nas temperaturas médias do solo. Em Alta Floresta, as simulações indicaram um aumento notável, especialmente nos meses de abril, maio e junho, contrastando com as estimativas baseadas no arquivo climático EPW. Alto Taquari mostrou uma resposta distinta, enquanto Campo Verde e Sinop exibiram aumentos significativos de temperatura até 2080. A pesquisa destaca a importância de considerar características específicas do solo para projeções precisas, fornecendo insights cruciais para estratégias de adaptação às mudanças climáticas. Há ênfase na necessidade de implementar estratégias de resfriamento passivo em edifícios, especialmente em regiões quentes, para se adaptar às condições futuras.

http://dx.doi.org/10.29183/2447-3073.MIX2024.v10.n3.153-161
ISSN: 2447-0899 (IMPRESSA) | 2447-3073 (ONLINE)

PALAVRAS-CHAVE
*Mudanças Climáticas, Temperatura do Solo, Simulação Computacional,
Cenário de Emissões SSP5-8.5, Adaptação Ambiental*

RESUMEN
Este estudio investigó variaciones en las temperaturas del suelo en cuatro ciudades de Mato Grosso, considerando el escenario de emisión SSP5-8.5 del Sexto Informe de Evaluación del IPCC. Utilizando simulaciones computacionales y datos climáticos históricos y futuros, la investigación reveló cambios significativos en las temperaturas medias del suelo. En Alta Floresta, las simulaciones indicaron un aumento notable, especialmente en los meses de abril, mayo y junio, en contraste con las estimaciones basadas en el archivo climático EPW. Alto Taquari mostró una respuesta distinta, mientras que Campo Verde y Sinop exhibieron aumentos significativos de temperatura hasta 2080. La investigación destaca la importancia de considerar características específicas del suelo para proyecciones precisas, proporcionando información crucial para estrategias de adaptación al cambio climático. Se hace hincapié en la necesidad de implementar estrategias de enfriamiento pasivo en edificios, especialmente en regiones cálidas, para adaptarse a las condiciones futuras.

PALABRAS CLAVE
*Cambio Climático, Temperatura del Suelo, Simulación Computacional,
Escenario de Emisiones SSP5-8.5, Adaptación Ambiental*

1. INTRODUCTION

Climate change is considered a potential risk of vulnerability for building occupants in the 21st century. Air temperatures are rising, and extreme events are becoming more frequent. Consequently, the demand for artificial cooling in residential buildings could increase by up to 750%, and in commercial buildings by 275% by 2050 (SANTAMOURIS, 2016).

In 2022, the Intergovernmental Panel on Climate Change (IPCC) released its Sixth Assessment Report (AR6), presenting emission scenarios known as Shared Socioeconomic Pathways (SSPs), categorized into five illustrative scenarios: sustainability (SSP1-1.9), intermediate scenario (SSP1-2.6), regional rivalry (SSP2-4.5), inequality (SSP3-7.0), and high use of fossil fuels (SSP5-8.5). The projected warming by 2100 ranges from 1.0°C to 1.8°C for SSP1-1.9 and from 3.3°C to 5.7°C for SSP5-8.5 (IPCC, 2022).

In this context, building performance simulations emerge as a crucial analytical tool, especially when considering predictions of future climate changes to adapt buildings to new conditions. The dynamic interaction between building systems and the external climate in the face of climate change is notably complex, involving a wide range of variables and parameters, making the use of computational simulation techniques an efficient approach (KUTTY, et al. 2024).

During simulations, the incorporation of various independent variables is essential. These include the thermophysical parameters of the building and the conditions of the deployment region. Emphasis is placed on considering soil temperature, particularly for ground-level structures with direct contact between the floor and the soil. This complex variable represents dynamic heat exchanges through conduction between indoor spaces and the adjacent soil (NUNES, et. al, 2019)

In recent years, the direct use of geothermal energy has globally expanded its installed capacity (POIEL, WOJTKOWIAK, BUERNACKA, 2001). The primary application of ground geothermal energy is in building conditioning. This has generated interest and the need to develop or enhance predictive models capable of estimating variations in soil temperature at shallower depths.

Therefore, the aim of this research is to investigate variations in soil temperature for geothermal systems, considering the SSP5-8.5 emission scenario from the IPCC's Sixth Assessment Report, both in the historical period and projections for 2050 and 2080. These variations will be obtained through computational simulation and compared with temperatures provided by historical and future climatic files.

2. METHODOLOGY

2.1 Characterization of the study regions

For the investigation, five cities located in the state of Mato Grosso, in the Central-West region of Brazil, were selected. The cities chosen for the study were Alto Taquari, Campo Verde, Paranatinga, Sinop, and Alta Floresta. Table 1 provides the description of these cities.

City	Long.	Lat.	Alt.	Biome*
Alta Floresta	17°49.0'	53°16.9'	289m	AM
Alto Taquari	9°51.9'	56°6.3'	877m	CE
Campo Verde	15°31.9'	55°7.9'	751m	CE
Paranatinga	14°25.0'	54°1.9'	476m	CE
Sinop	11°58.9'	55°34.0'	373m	CE

*Legend: Amazon Rainforest (AM), Cerrado (CE), and Pantanal (PA) Biomes

Table 1: Description of the study regions.

Most of the state is represented by the Aw climate type (tropical with summer rainfall), covering approximately 90% of its territory, while approximately 10% is classified as the Am climate type (tropical with monsoon climate). This climatic classification is commonly found in various regions worldwide, located between the Tropics of Cancer and Capricorn, and it is the second most prevalent climate type, covering about 11.5% of the Earth's land area (PEEL, FINLAYSON, McMAHON. 2007). Additionally, the representative biomes of the state are the Amazon Rainforest, Cerrado, and Pantanal.

2.2 Development of Future Climate Scenarios

The Morphing method has been employed to mathematically transform the current climate into future climates, considering scenarios of climate change (BELCHER, HACKER, POWELL, 2015). The Future Weather Generator tool utilizes the Morphing methodology to make climate projections, illustrating monthly changes in climatic variables. This tool is based on the GCM model EC-Earth3, which is part of the CMIP6 project and serves as the foundation for the Intergovernmental Panel on Climate Change's Sixth Assessment Report (AR6) (IPCC, 2022).

The tool utilizes a base climatic period for the projections from 1985 to 2014 and generates future climatic files for 2050 (period 2036-2065) and 2080 (period 2066-2095) for emission scenarios SSP2-4.5, SSP3-7.0, and SSP5-8.5. It presents the results as future climatic files in the EPW format, widely used in thermal and energy performance simulations of buildings and cities.

Additionally, the tool was developed in the Java programming language, and its source code is freely available under the Creative Commons Attribution 4.0 Share-Alike license (RODRIGUES, FERNANDES, CARVALHO. 2023). To make its use more accessible for simulators and designers, the authors created a graphical interface that allows the insertion of historical climatic files and, consequently, the generation of future climatic scenarios.

In this research, the SSP5-8.5 scenario, labeled as "pessimistic" by the AR6 (IPCC, 2022), was chosen for the projections of 2050 and 2080. The base climatic files for the cities consist of the Solar and Wind Energy Resource Assessment (SWERA) due to its better alignment with the historical period used as the basis for the projections, as indicated in the tool's documentation.

2.3 Obtaining Soil Temperature for Geothermal Systems: A Perspective on Climatic Files and Computational Simulation in Historical and Future Periods

The acquisition of soil temperature involved two processes, namely: i) through historical and future climatic files, and ii) through computational simulation. In the header of EPW-type climatic files, it is possible to obtain soil temperatures at depths of 0.50 meters, 2.0 meters, and 4.0 meters. Therefore, this research utilized soil temperatures at a depth of 2.0 meters provided by these files for the historical period and future projections for 2050 and 2080.

Subsequently, the auxiliary program "CalcSoilSurfTemp" in the EnergyPlus software version 9.1 was employed. This program is dedicated to calculating three essential parameters for integrating tubes in geothermal systems based on buildings. These parameters encompass the annual average temperature of the soil surface, the amplitude of the soil surface temperature, and the constant phase of the soil surface temperature.

The CalcSoilSurfTemp program estimates these parameters considering a multitude of factors. These factors include convective heat transfer between air and soil, absorption of solar radiation by the soil, emission of long-wave radiation from the soil, and the loss of latent heat resulting from the evaporation of moisture present on the soil surface (KUSUDA, ACHENBACH, 1965). The soil type adopted in this analysis was classified as "Heavy and saturated," while the soil surface type was categorized as "Bare and wet."

Based on the results obtained, it became feasible to calculate the monthly soil temperature. This calculation was performed using the method developed by Kusuda and Achenbach (KUSUDA, ACHENBACH, 1965), with Equation [1] serving as a guiding reference.

$$T_{z,t} = T_m - A_s \exp[-z(\pi / 365\alpha_s)^{1/2}] \cos\{[2\pi/365 [t - t_o - z/2 (365/\pi\alpha_s)^{1/2}]\} \quad (1)$$

Where:
$T_{z,t}$ – Soil Condition;
T_m - Average Surface Soil Temperature (ºC);
A_s - Amplitude of Surface Soil Temperature (ºC);
t_o - Phase Constant of Soil Temperature
α_s - Thermal Diffusivity of Soil

For the execution of this procedure, specific values were adopted for soil properties. The thermal diffusivity of the soil was set at 0.80 W/m·K, while the soil density was established at 2,240 kg/m³. Additionally, the specific heat of the soil was determined to be 15,165 J/(kg·K). These properties play a crucial role in calculating thermal variations. Furthermore, the tubes were positioned at a depth of 2 meters in the soil.

This choice of depth is relevant for determining the influence of deeper thermal conditions on geothermal system simulations. This procedure was carried out for both the historical period and future scenarios.

3. RESULTS AND DISCUSSION

3.1 Alta Floresta

The annual average soil temperature obtained through simulation for the historical period is 34.8°C, whereas in the EPW climatic file, it is 24.2°C, resulting in a difference of 10.6°C. However, with the impact of climate change, the annual average soil temperatures increase by +2.2°C and +4.8°C in simulations and by +3.1°C and +6.3°C in the EPW file for the years 2050 and 2080, respectively.

It can be observed that the temperatures obtained through simulation exceed 28.0°C in all months, reaching values higher than 34.0°C in April, May, and June during the historical period (Figure 1-A). In contrast, temperatures obtained from the EPW climatic file do not exceed 25.0°C in any month during the same period (Figure 1-B). With the impacts of climate change, monthly average temperatures increase, surpassing 31.0°C in 2050 and 33.0°C in 2080 in computational simulations (Figure 1-A), and above 23.0°C in 2050 and 25.0°C in 2080 in the climatic file (Figure 1-B).

The discrepancies in soil temperatures obtained through simulation and from the EPW file arise from the consideration, in the simulation, of specific soil characteristics such as thermal diffusivity, density, and specific heat. In the climatic file, it is often an estimate based on air temperature.

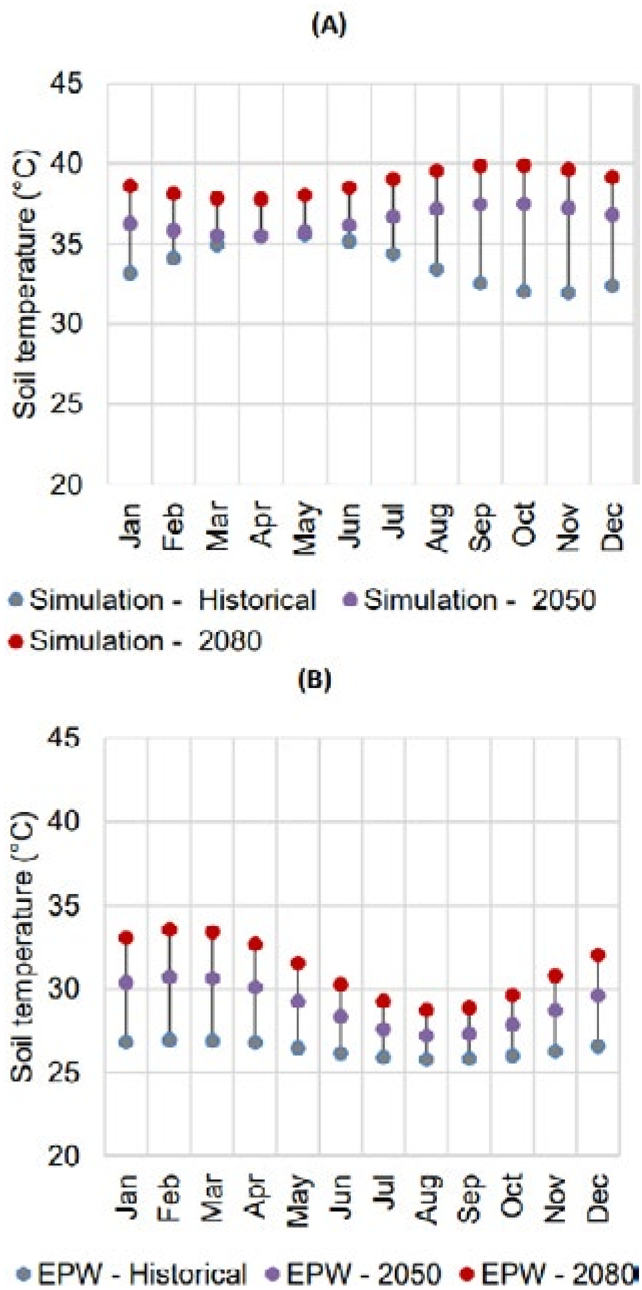


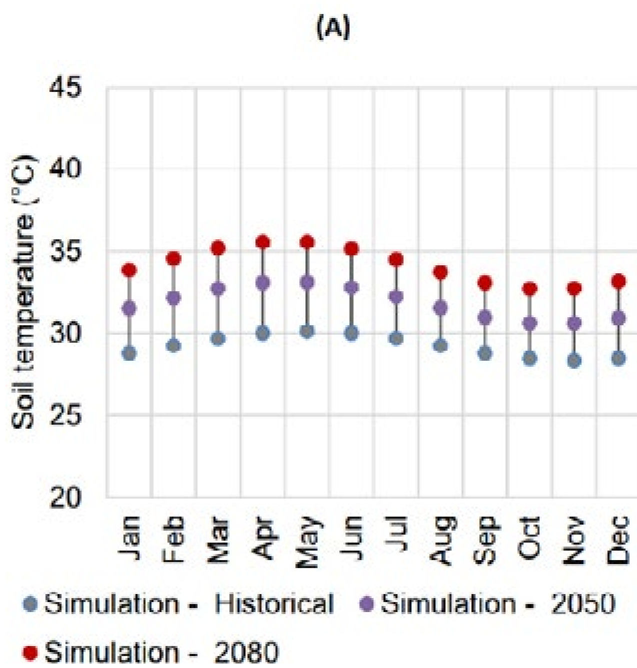
Figure 1: Monthly Average Soil Temperature during the Historical Period and Future Scenarios in Alta Floresta

3.2 Alto Taquari

In Alto Taquari, during the historical period, the annual average soil temperature obtained through simulation is 30.1°C, while in the EPW file, it is 24.5°C. In 2050 and 2080, simulated temperatures increase to 33.1°C and 35.6°C, respectively, while those obtained from the EPW rise to 27.8°C and 30.5°C, showing an increase of approximately +3.0°C in 2050 and +5.5°C in 2080 in both datasets.

It is observed that simulated temperatures during the historical period exceed 30.0°C only in the months of April, May, and June, while in other months, they remain around 29.0°C (Figure 2-A). Temperatures recorded by the EPW exceed 24.0°C only in the months of December, January, and February; in other months, temperatures do not exceed 23.5°C during the historical period (Figure 2-B). It is worth noting that in the months of July and August, the soil temperature obtained by the EPW during the historical period is around 20.5°C.

In the period of 2050 and 2080, monthly average temperatures increase, reaching values above 30.6°C and 32.8°C in all months in the simulated files (Figure 2-A), while in the EPW, temperatures are above 23.1°C and 24.5°C, respectively (Figure 2-B).



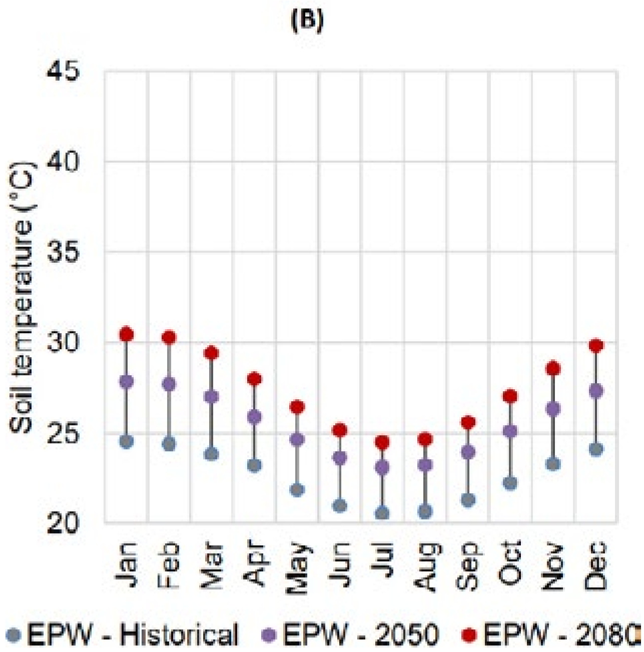


Figure 2: Monthly Average Soil Temperature during the Historical Period and Future Scenarios in Alto Taquari

3.3 Campo Verde

In Campo Verde, the monthly average soil temperature during the historical period is 30.1°C, while computational simulations and EPW data record values of 25.3°C. In 2050, simulations indicate a significant increase, raising the soil temperature by +4.5°C, reaching 34.6°C. For the year 2080, an even greater increase is predicted, reaching +6.9°C and resulting in an average temperature of 37.1°C. In the same temporal context, temperatures estimated by the EPW also show increases of +3.1°C and 6.1°C in 2050 and 2080, respectively, rising to 28.3°C and 31.4°C.

The monthly average soil temperatures in Campo Verde, during the historical period, obtained through computational simulation, exceed 28.3°C, reaching values of 30.0°C in the months of April, May, and June (Figure 3-A). In contrast, soil temperatures obtained by the EPW remain around 24.0°C throughout all months of the year (Figure 3-B).

With the impact of climate change, there is an increase in temperatures, especially in the simulations. In 2050, simulated temperatures become higher than 31.0°C, particularly in the months of April, May, and June, with soil temperatures above 34.0°C. For 2080, the monthly average temperatures reach an average of 35.0°C (Figure 3-A). Meanwhile, soil temperatures estimated by the EPW remain below 30.0°C in both future climate scenarios. Only in 2080 do they exceed the 30.0°C mark in the months of February, March, and April (Figure 3-B).

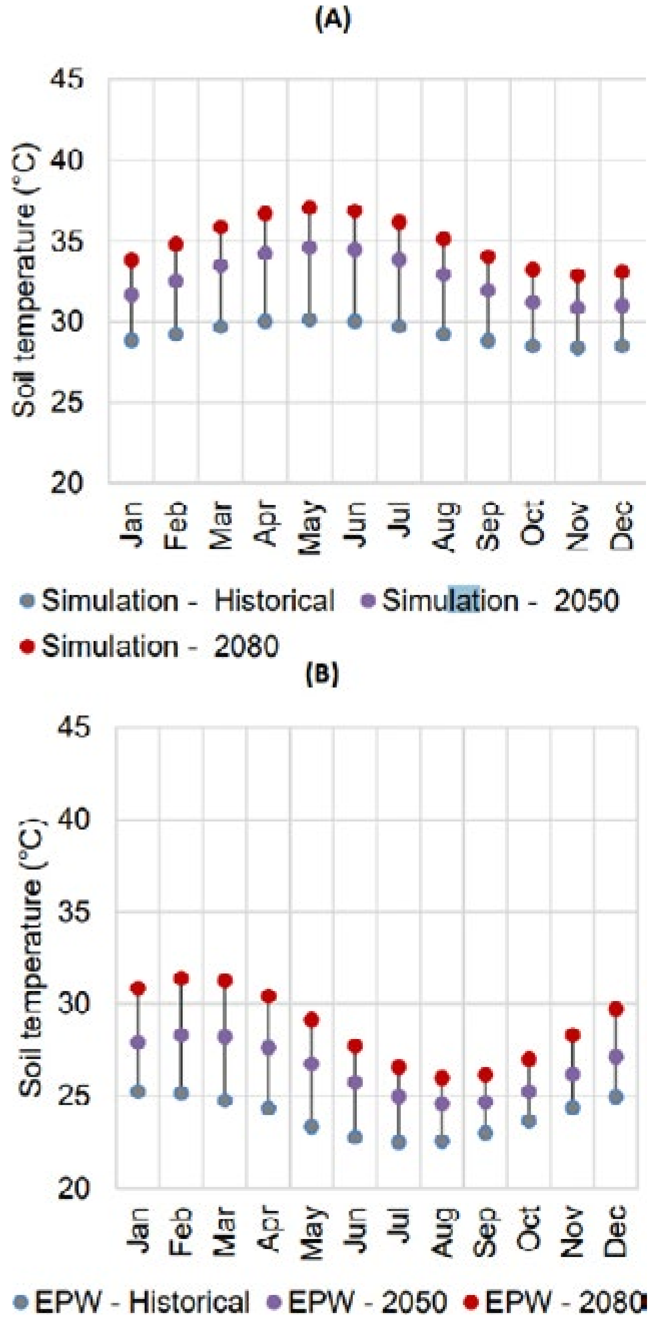


Figure 3: Monthly Average Soil Temperature during the Historical Period and Future Scenarios in Campo Verde

3.4 Sinop

Finally, in Sinop, the average annual soil temperatures are 34.8°C and 24.2°C in the historical period for simulation files and EPW, respectively. However, due to the impacts of climate change, these temperatures rise to 37.0°C and 27.2°C in 2050 and to 39.6°C and 30.4°C in 2080, representing an increase of +4.8°C and +6.3°C, respectively, compared to the historical period.

The average monthly temperatures in Sinop, during the historical period, stand out for their elevation compared to other cities. The temperatures obtained through computer simulation exceed 31.0°C from February to August, while in other months, they remain around 28.5°C (Figure 4-A). In contrast, temperatures obtained through EPW do not exceed 24.0°C (Figure 4-B).

In future climate scenarios, these temperatures experience a significant increase, surpassing 32.0°C in all months of the year in simulations and exceeding 25.0°C in EPW in 2050. In 2080, soil temperatures reach high levels, recording values of 39.6°C in April for simulations, while EPW estimates indicate temperatures around 30.3°C for the same month.

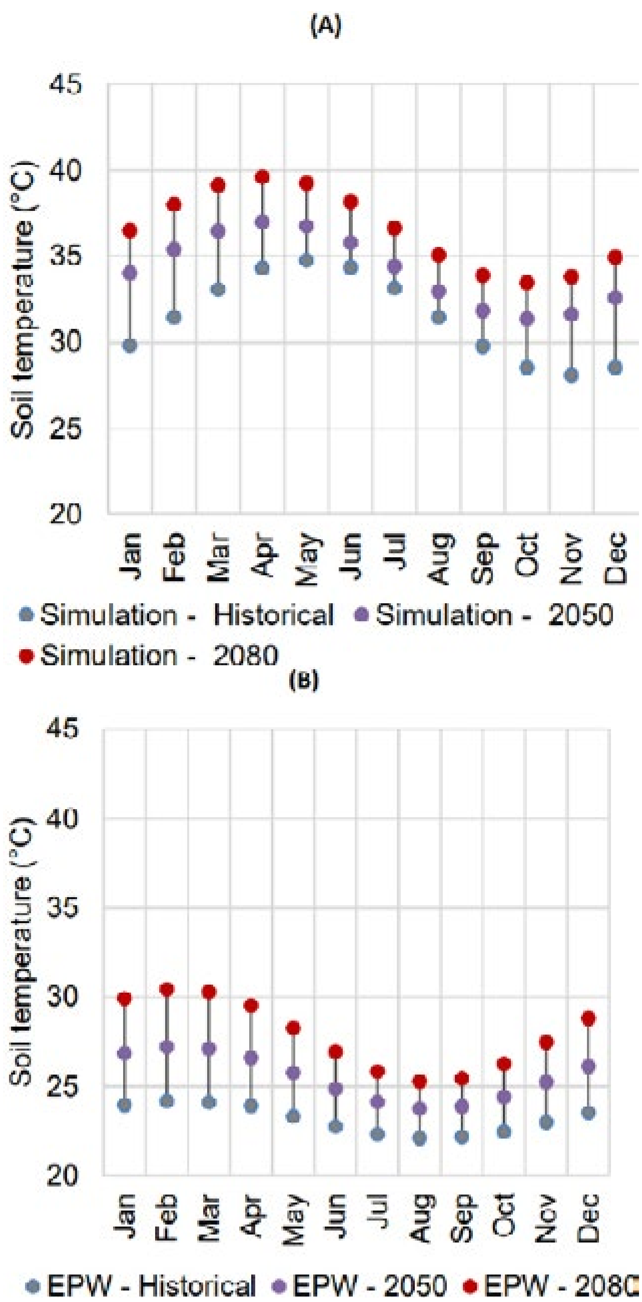


Figure 4: Monthly Average Soil Temperature during the Historical Period and Future Scenarios in Sinop

4. CONCLUSION

The study of climate projections in different regions (Alta Floresta, Alto Taquari, Campo Verde, and Sinop) reveals significant changes in average soil temperatures over time, considering historical and future scenarios. Computational simulations, which take into account specific soil characteristics such as thermal diffusivity, density, and specific heat, provide results that contrast with estimates based on EPW climate files, often grounded in air temperature.

In Alta Floresta, a notable disparity was observed between simulated temperatures and those from EPW, highlighting the influence of soil characteristics on projections. The projected increase in average annual temperatures, especially in the months of April, May, and June, underscores the sensitivity of this region to climate change, presenting a challenging scenario for environmental management and agricultural activities.

Alto Taquari, on the other hand, shows a distinct but equally relevant response to climate change. Simulations indicate an increase in average annual temperatures, while EPW shows a more moderate behavior. Seasonal variations in soil temperatures emphasize the importance of considering specific soil data for more accurate predictions.

Campo Verde presents a similar scenario, with projections of a significant increase in soil temperatures until 2080. Computational simulations predict values exceeding 34.0°C, especially in the months of April, May, and June, highlighting the need for adaptive strategies to address environmental changes. Finally, in Sinop, projections indicate a substantial increase in average annual temperatures, especially in simulations. The contrast between simulated temperatures and EPW estimates suggests the importance of more detailed approaches in regional climate modeling.

In summary, the results of this study highlight the importance of considering specific soil characteristics when assessing climate projections. This more detailed approach is crucial for a precise understanding of the impacts of climate change in different regions, providing valuable insights for planning and implementing adaptation strategies. Despite these projected increases, it is crucial to emphasize the importance of implementing passive cooling strategies in buildings. This is particularly relevant in hot regions, serving as a means to adapt structures to the evolving future conditions.

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ACKNOWLEDGMENTS

We would like to express our gratitude to FAPEMAT for granting research scholarships under notice No. 010/2022 Research with Medium Level of Maturity in Engineering. Title: Geothermal Energy Applied to the Cooling of Agricultural Buildings in the Context of Sustainable Development in the State of Mato Grosso.

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HOW TO CITE THIS ARTICLE:

CALLEJAS, Ivan Julio Apolonio; DA GUARDA, Emeli Lalesca Aparecida; DURANTE, Luciane Cleonice; ARÊDES, Fernanda Marques Botelho; ROSSETI, Karyna de Andrade Carvalho. Investigation of ground temperatures for the implementation of geothermal systems in historical and future periods. **MIX Sustentável**, v. 10, n. 3, p. 153-161, 2024. ISSN 2447-3073. Disponível em: <http://www.nexos.ufsc.br/index.php/mixsustentavel>. Acesso em: _/_/_.doi: <https://doi.org/10.29183/2447-3073.MIX2024.v10.n3.153-161>.

SUBMETIDO EM: 19/02/2024
ACEITO EM: 20/06/2024
PUBLICADO EM: 12/08/2024
EDITORES RESPONSÁVEIS: Lisiane Ilha Librelotto e Paulo Cesar Machado Ferroli

Record of authorship contribution:
CRediT Taxonomy (http://credit.niso.org/)

ELAG: conceptualization, formal analysis, investigation, methodology, visualization, writing - original draft, writing - review & editing, and data curation.

IJAC: conceptualization, formal analysis, investigation, methodology, visualization, writing - original draft, writing - review & editing, data curation, resources and supervision.

LCD: conceptualization, formal analysis, investigation, methodology, visualization, writing - original draft, writing - review & editing, data curation, resources and supervision.

FMBA: conceptualization, formal analysis, investigation, methodology, visualization, writing - original draft, writing - review & editing and data curation.

KACR: project administration, funding acquisition, resources, writing - review & editing, conceptualization and supervision.

Conflict declaration: nothing has been declared.