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Recent climate change variations in the state of Rio de Janeiro in southeastern Brazil, as determined by the geothermal method

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Abstract Summary

The impact of recent climate variations on the shallow crust was investigated in the state of Rio de Janeiro, southeastern Brazil, using geothermal method and data from 42 groundwater wells (up to 300 meters deep) in different geological and urban contexts. Building on previous analyses (Aguiar et al. 2024), this study integrates mountainous, coastal, and metropolitan regions, combining thermophysical parameters with climate modelling.
Direct modelling of residual temperature revealed an average warming of 2.7°C in recent decades, with greater magnitudes observed in urban areas (up to 6.9°C) and an average disturbance age of 40 years. This value summarizes the recent average warming in the state, taking into account regions affected by human activities. The automated Python-based methodology ensured the accuracy and reproducibility of the results when interpreting thermophysycall maps, provinding a tool for monitoring recent climate variations.

Introduction

Recent climate changes have impact the heat balance of the shallow crust, generating detectable signals in geothermal profiles. Previous studies in the south-central region of Rio de Janeiro (Aguiar et al., 2024) have identified a warming trend of 2–3.5°C over the past three decades. This trend has been attributed to variations in vegetation cover, human activities and the thermophysical conditions of the rocks and tectonic compartments. However, the limited spatial coverage of the data (24 wells) has restricted local-scale analysis. This study extends the analysis to 42 wells, covering the whole of the state of Rio de Janeiro, including mountainous, coastal, and urban areas. The aim is to quantify recent climate variations using the geothermal method and correlate them with thermophysical parameters (geothermal gradient, thermal conductivity and heat flow), as well as geological and anthropogenic factors. The potential of these methods for climate monitoring will also be evaluated.

Method and/or Theory

The geothermal parameters were obtained from temperature profiles in 42 wells distributed throughout the Rio de Janeiro state at depths ranging from 50 to 270 meters. The geothermal gradient (Γ) was calculated using linear regression and the least squares method in intervals that were considered to be undisturbed by surface influences (CVL method). For highly disturbed profiles, the bottom-hole temperature was considered to be more stable and was used alongside the average surface temperature over the last 50 years (CBT method).

The thermal conductivity (λ) of the wells was determined using the weighted average of the thermal conductivities of the different lithological types, weighted by their relative thicknesses (e):

$$\lambda_{pond} = \frac{\sum_{i=1}^{n} e_i \lambda_i}{\sum_{i=1}^{n} e_i} \quad (1)$$

where λ_i are the reference values for each lithotype, as published by Guimarães et al., (2022). This weighting of the average thermal conductivity value helps to minimize the effects of lateral heat dispersion variation in the rock and pressure. The variation in lateral heat dispersion in the rock and heat flow (q), as measured at the surface, was then calculated as follows:

$$q = \Gamma \times \lambda \tag{2}$$

The climate signal of recent thermal variations is calculated by subtracting the mean geothermal gradient value from the temperature measurements taken at depth (the geothermal profile), which generates the residual temperatures (T_R):

$$T_R(z) = T_z - \left[T_0 + \frac{(\Gamma \times z)}{1000}\right] \tag{3}$$

These "residues" were modelled using an analytical solution to the heat conduction equation for linear surface climate variations. This equation is based on the model proposed by Lanchenbrunch & Marshall (1986) and has been adapted to account for linear thermal disturbances over time:

$$T_{(z,t)} = T_0 \left[\left(1 + 2\left(\frac{z^2}{4kt}\right)\right) erfc\left(\frac{z}{\sqrt{4kt}}\right) - \left(\frac{2}{\sqrt{\pi}}\right)\left(\left(\frac{z}{\sqrt{4kt}}\right) exp\, exp\, \left(\frac{-z^2}{4kt}\right)\right)\right] \tag{4}$$

T_0 corresponds to the temperature measured at the surface, k to the thermal diffusivity of the medium and t to the duration of the climate variation. To automate the calculations of this methodology, a Python code was developed to processed the temperature profiles of the 42 wells. The program executed four steps:

1. Calculate the geothermal gradient using either the *CBT* or *CVL* methods.
2. Climate signal modeling, with automatic adjustment of the T_0 and t parameters to minimize the mean square error (*MSE*) between the observed data and the model.
3. Validation and output of the results. This involves automatically generating the values of T_0, t and *MSE*. The latter serves as a metric of the reliability of the adjustment (values below 0.1 indicate a better fit of the model).
4. Modelling with time set to 10, 30 and 50 years, in order to obtain the T_0 at the respective ages of change.

Finally, thematic thermophysical maps were generated at a regional level using the Oasis Montaj/Sequeent software. Kigrid/variogram interpolation was used, which relies on the random distribution of the data and considers the thermophysical parameters, as well as the magnitude and age of the climate variations.

Results

Grouping the thermophysical and climatic data by tectonic compartments (Heilbron et al. 2008) revealed significant patterns in the distribution of thermophysical parameters and recent climatic variations in the state of Rio de Janeiro. The average of these parameters was calculated for each tectonic-sedimentary group.

a. Geothermal gradient: values ranged from 8.8°C/km in the Paraíba do Sul terrain to 44.6°C/km in the Rio Negro magmatic arc, which is associated with high-conductivity rocks and granitic intrusions. The overall average was 18.8°C/km.
b. Thermal conductivity: the ranged varies from 2 W/m·K (Cenozoic cover) to 4.9 W/m·K (western terrain – Upper domain), with an average across the state of 2.9 W/m·K. Sedimentary deposits exhibited lower values (2.4 W/m·K), while crystalline rocks demonstrated greater heat conduction efficiency (3.1 W/m·K).

c. Heat flow: the flux ranged from 21.1 to 133.8 mW/m², with an overall average of 53.7 mW/m². Generally, values below 50 mW/m² were observed in the Paraíba do Sul terrain and regions with sedimentary cover.
d. Climate variations: the magnitude of warming ranged from 0.12 to 10°C (with the maximum being an anomaly associated with direct industrial activities in land use), averaging 2.7°C. The age of the variations averaged 45 years, indicating recent events.
e. Validation by *MSE*: the average *MSE* was 0.075, with most wells presenting an *MSE* of less than 0.1, which validates the robustness of the model.

As can be seen in Figure 1, there is a direct proportional relationship between the distribution of thermal conductivity, geothermal gradient and heat flow values. Where the geothermal gradient is greater, the heat flow is also greater. This is evident from the distribution of the weighted average thermal conductivity.

The highest heat flow observed in the central regions of the state are possibly associated with land that conducts heat poorly, holding it for longer within a certain range, or with land use itself. Deforestation, for example, exposes the soil directly to solar radiation; consequently, the thermal signals of the solar energy that reaches the surface are found in the current geothermal field of the layers adjacent to the surface.

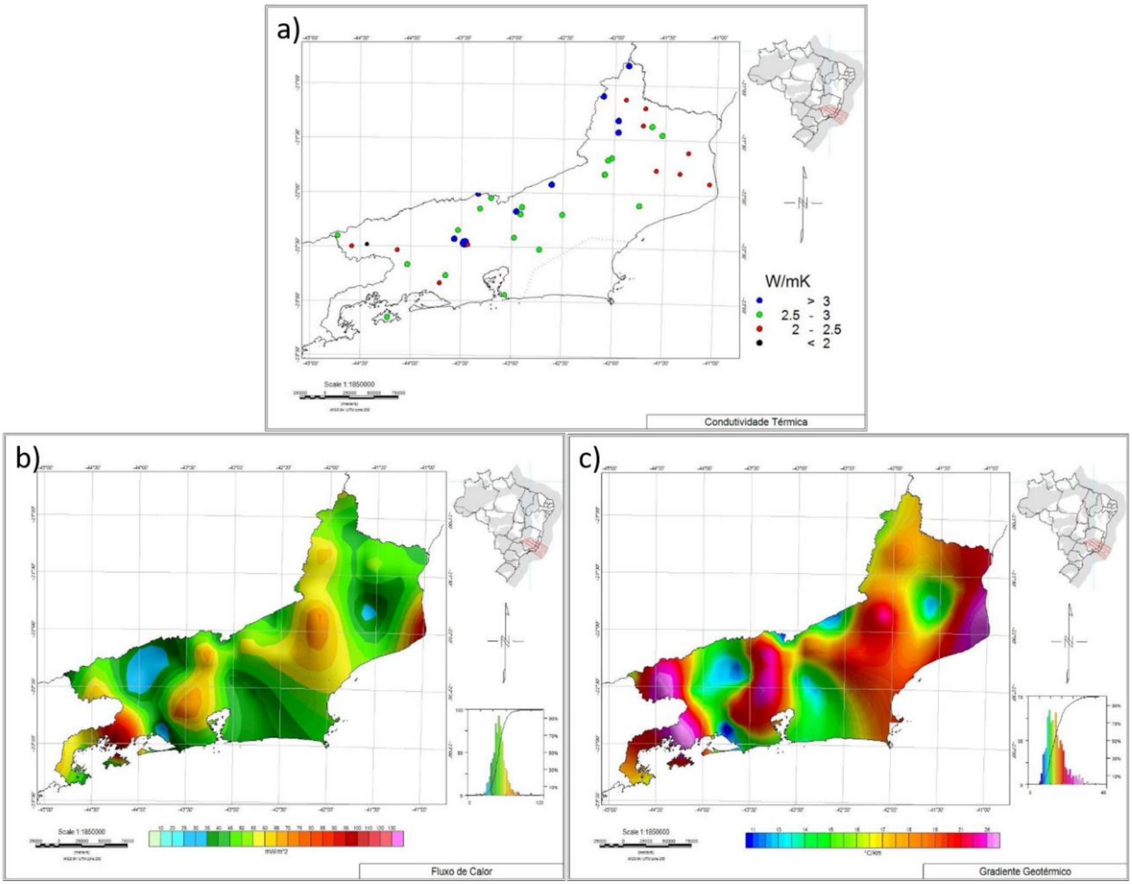

Figure 1: Maps showing the distribution of thermophysical parameters: (a) Thermal conductivity, (b) Heat flow and (c) Geothermal gradient.

Figure 2 shows how the magnitude and duration of climate change evolve. The model was adjusted to determine the ages and to enable comparison of the thermal disturbances on the surface.

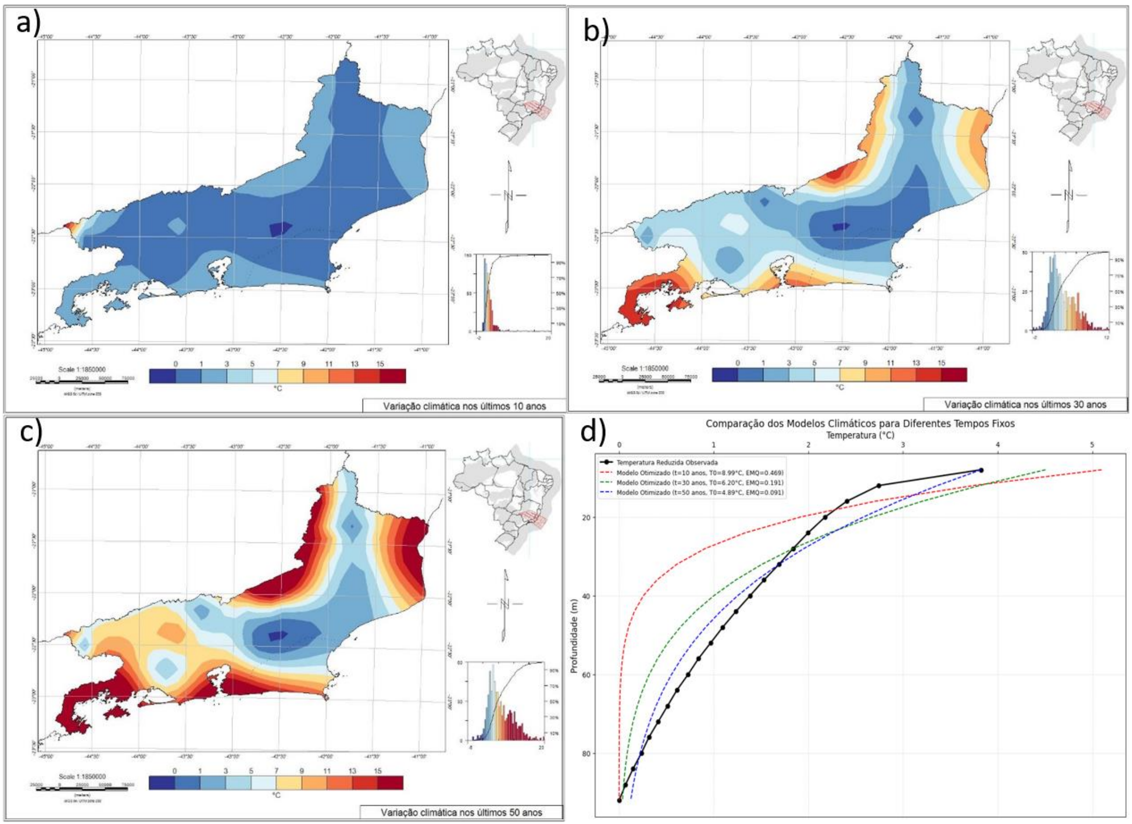

Figure 2: Linear projections of temperature increases in relation to the ages of change: (a) 10 yaers; (b) 30 years and (c) 50 years. (d) Graph showing the statistical validation of the change simulation.

Conclusions

Using geothermal profiles measured in shallow groundwater wells distributed throughout the state of Rio de Janeiro, it was possible to quantify recent climate variations and characterize thermophysical parameters on a regional scale. Increased sampling from the first study of the south-central region of the state enable geological-geothermal patterns to be identified, such as crystalline rocks having the highest thermophysical parameters and sedimentary areas being associated with lower values. Climate modelling revealed an average warming of 2.9°C over the past 4-5 decades, with more pronounced magnitudes and shorter durations in more urban areas.

MSE validation (average of 0.075) confirmed the robustness of the analytical model and the Python code developed to automated calculations and process large volumes of data with precision. Data interpolation enable the creation of thermophysical maps at state level for assessing critical warming areas in relation to geological and anthropological factors, such as deforestation and urbanization.

The classification of the state as having low to medium enthalpy (Gomes and Hamza, 2008; Aguiar et al. 2025) indecates its low potential for geothermal energy exploration. It is therefore concluded that any significant recent climate variations are anthropogenic, as the state does not have a geothermal system with high thermal energy, i.e. the shallow crustal variation is low and is mainly influenced by recent atmospheric changes. Ultimately, it is concluded that the geothermal method is a functional, albeit supplementary tool for climate monitoring.

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