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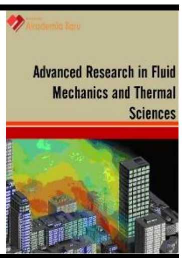

Methodology Allying Standard Penetration Test and Era-Interim Data Set for Numerical Simulations of Earth-Air Heat Exchangers

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ABSTRACT

Earth-Air Heat Exchangers (EAHE) are devices installed on buildings to reduce electrical energy consumption with air conditioner systems. They consist of buried ducts where the air is blown and induces heat exchange with the surrounding soil. Computational modeling plays an important role in the study of EAHE. However, there is no well-defined methodology for the determination of soil characteristics and air and soil surface temperature boundary conditions for performing numerical simulations. Aiming to fill this gap, the main goal here is to develop a consistent and universal methodology to numerically simulate EAHE installations submitted to realistic soil and temperature conditions. It is proposed to combine the Standard Penetration Test (SPT) information and the Era-Interim reanalysis temperature data. In order to validate this methodology, the results obtained by a computational model based on the Finite Volume Method (FVM) were compared with experimental *in-situ* data reaching a mean error of 0.03 °C, a root mean squared error of 0.93 °C, a mean absolute percentage error of 4.20%, and a Pearson correlation coefficient of 0.98. The validation indicated that the proposed methodology could be adequately adopted for EAHE numerical simulations, allowing a reliable adoption of the soil characteristics assignment from SPT reports and the prescription as boundary conditions of inlet air temperature and soil surface temperature from ERA/Interim data.

1. Introduction

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Specially, due to global warming, different technologies have been developed, aiming to improve the buildings' thermal condition. To do so, the thermal comfort in the building needs to be achieved and maintained. For instance, during hot seasons, the temperature inside the built environment must be decreased and, from that, preserved, being the air conditioner devices normally used for this purpose. However, not everyone can acquire an air conditioner and afford the high electricity consumption costs resulting from their use [1]. Therefore, it is possible to employ economical technologies to promote the thermal condition improvement of buildings.

In this sense, one can quote the thermal insulation technology for cooling and temperature control of built environments [1]. Morsy *et al.,* [2] used the Design-Builder software to analyze the energy consumption and the indoor thermal comfort of an educational building at Cairo, Egypt, where the thickness influence of eight types of thermal insulation materials was tested. The results indicated that to reduce the energy consumption and to improve the thermal comfort, the recommended strategy is the employment of insulation layers with different thicknesses for each floor instead of the adoption of a unique thickness value. Besides, regarding the thermal insulation materials, the expanded polystyrene and the vermiculite cement presented better performance, respectively, for the reduction of energy consumption and improvement of thermal comfort. Din *et al.,* [1] also studied thermal insulation materials, but with a sustainable focus, i.e., they analyzed the applicability of recycled solid waste for the thermal insulation in residential buildings. Experiments were performed with seventeen recycle materials, classified into two categories: the materials that can absorb heat and the materials that can reflect heat. Among all investigated materials, the oil palm leave is recommended to be used in the wall and roof insulation; and the recycled textile is indicated for insulation of underground floor.

Another economic and sustainable technology that can be adopted is the Earth-Air Heat Exchanger (EAHE). The EAHE can be used to improve the thermal condition of the buildings, allowing significant savings in electricity consumption; since it is installed in association or replacing the air conditioning system. This device is composed of one or more buried ducts, into which the ambient air is forced to flow, being the scope of the current work. The EAHE operation principle is based on heat exchanger between flowing air inside the ducts and the surrounding soil outside the ducts, promoting an increase or a decrease of air temperature that exits the device, respectively, in cold or hot seasons. This heat exchange is only possible because of the surface layers of soil store the incident solar radiation as thermal energy, allowing the harnessing of this renewable energy source by the EAHE [3].

The EAHE performance is affected by geographical and climate conditions, thermo-physical soil properties, constructive parameters, and operational conditions [4]. Analytical [5-8], experimental [9-11], and numerical [12-14] approaches can be employed to investigate these aspects. More details about these approaches can be found in the literature review about EAHE [15-18].

Dealing specifically with the numerical approach, the Computational Fluid Dynamic (CFD) is usually employed to reproduce the EAHE operating principle to evaluate the influence of constructive and operational parameters in its performance. For instance, Misra *et al.,* [19] used a validated FVM computational model developed in Fluent software to study the effect over a horizontal EAHE installed in Ajmer, India, of soil thermal conductivity, usage time, diameter of the ducts, and air flow velocity. Among its main findings, one can quote that soils with higher values of thermal conductivity decrease the influence of duct diameter in EAHE thermal performance; and higher airflow velocities decrease the EAHE thermal potential. In Ahmed *et al.,* [20], a parametric study of a horizontal EAHE installed in the city of Rockhampton, Australia, was numerically carried out during the summer season using a validated FVM model developed in Fluent software. It was inferred that its ideal parameters are: duct with a length of 60 m, a diameter of 0.062 m and thickness of 0.003 m, through which the air flows with 1.5 m/s and being installed in a depth of 8 m, conducting to a temperature reduction of 4.11 °C. Belatrache *et al.,* [21] developed and validated a MATLAB code for horizontal EAHE simulations performed in the region of Adrar, Algerian Sahara. The parametric performed study led to the following conclusions: a duct length of 25 m promotes the thermal equilibrium between the airflow and the surrounding soil; the maximum decrease of air temperature is reached with an installation depth of 5 m, and cooling energy saving of 246.82 kWh was achieved. In its turn, Zhengxuan *et al.,* [22] developed and validated a computational model for vertical EAHE simulations in the MATLAB/Simulink software, which realized a parametric analysis with obtaining the following recommendations for the city of Changsha, in China. According to them, stainless steel is the most indicated as duct material, and smaller duct diameters improve the thermal capacity while larger duct diameters are adequate to enhance the EAHE coefficient of performance (COP). The simple increase of the EAHE installation depth it is not an effective strategy to improve the outlet air temperature and soil types with higher thermal conductivity (e.g., sandy soil) are adequate for EAHE performance.

Therefore, numerical simulations play an essential role in defining ideal parameters for an EAHE that will be installed in a specific region. In this sense, the EAHE computational modeling should be carried out considering climate conditions and soil characteristics realistically, thus ensuring reliable results. Regarding the climate conditions, information about external ambient air and soil surface temperatures variation is necessary. For the soil characteristics, it is needed to know the geotechnical constitution of its superficial layers as well as its thermo-physical properties. However, in the majority of the EAHE researches, as exemplified with the above works of Misra *et al.,* [19], Ahmed *et al.,* [20], Belatrache *et al.,* [21], and Zhengxuan *et al.,* [22], these data were experimentally obtained.

Given the exposed, from the literature review [15-18] and to the best of the authors' knowledge there is no a universal and well-defined methodology which provides information about the temperature variation of air and soil surface, as well as to the geotechnical characteristics and thermo-physical properties of soil, gathering a data set to be used as input of EAHE computational models. Therefore, the main goal of the present work is to purpose a methodology that fills this gap regarding EAHE numerical simulations without the need to promote new experiments.

So, the present work purposes a methodology for the numerical simulation of EAHE that defines: i) the soil stratification from existing Standard Penetration Test (SPT) reports, with its thermo-physical properties defined by literature; and ii) the air and the soil surface temperature variations from the data provided by ERA-Interim. Accordingly, to show the applicability of this methodology for EAHE researches, several analyses were performed. Firstly, the temperature data for the air from ERA-Interim and the temperature data for the soil surface available in ERA-Interim/Land were validated by comparison with *in-situ* data presented in Vaz *et al.,* [9] for the city of Viamão in the state of Rio Grande do Sul (RS) - Brazil. In sequence, the annual heat diffusion in Viamão soil for different depths was evaluated comparing ERA-Interim/Land data, numerical results (obtained by a two-dimensional, 2D, CFD model), and the *in-situ* data of Vaz *et al.,* [9]. After employing a three-dimensional, 3D, CFD model, the numerical simulation of an EAHE installed in Viamão was performed applying the proposed methodology, aiming to compare the EAHE outlet temperature results with those obtained by *in-situ* experimental measurements of Vaz *et al.,* [9]. Finally, using the 2D CFD model and the proposed methodology, the numerical results for temperature variation in different depths for five cities of the state of RS (Ibirubá, Novo Hamburgo, Eldorado do Sul, São José do Norte, and the Rio Grande) it was compared with correspondent data of ERA-Interim/Land.

Regarding specifically the usage of ERA-Interim data as input to engineering researches, it is possible, among others, to quote: Zikra *et al.,* [23] that studied temporal variation in significant wave height to support energy assessment in Indonesia Sea; Campaniço *et al.,* [24] which developed a methodology to evaluate the buildings cooling demand savings by means the use of ventilation passive cooling systems in the Iberian Peninsula; Solanki *et al.,* [25] where estimation was carried out about the available potential of offshore solar energy along the coast of India; and Ruhnau *et al.,* [26] which investigated the heat demand and heat pump efficiency for energy system modeling in 16 countries of Europe. However, despite these different applications found in literature, the ERA-Interim data have not been used yet in EAHE applications. The unique exception is the work of Hermes *et al.,* [27], where the proposed methodology was already adopted for the numerical study of an EAHE in Rio Grande City. However, in Hermes *et al.,* [27], no validation of this methodology was showed. For this reason, in the present work the validation of the proposed methodology is performed together with its complete explanation and with a more comprehensive analysis, justifying the scientific contribution of the article.

2. Methodology

2.1 Standard Penetration Test (SPT)

As indicated in Wesley [28] and Wazoh and Mallo [29], the Standard Penetration Test (SPT) was developed in 1927, and it is an in-situ dynamic trial used to obtain data about subsurface soils, being nowadays the most employed test for geotechnical investigation purposes. The SPT allows determining the shear strength of soils following the number of the blows (NSPT) for a 750 mm free fall of a 65 kg hammer, which is needed for the sampler penetrating 450 mm into the analyzed soil. Usually, the blows necessary for the first 150 mm of penetration are not considered due to fall-in and hole contamination, being adopted only the required blows number for the last 300 mm of sampler penetration. Therefore, NSPT is related to the soil resistance to penetration, being a standard measure that can also be used to the definition of other soil properties, for instance: relative density, shear strength, and bearing capacities. During the SPT progress, data about soil samples and groundwater are also acquired.

2.2 ERA-Interim and ERA-Interim/LAND

The ERA-Interim [30], in agreement with Dee *et al.,* [31] and Nogueira [32], is a global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), which employs 4D variational data assimilation from satellite and *in-situ* observations. Its data are available from 1 January 1979 to 31 August 2019 with a spatial resolution of approximately 80 km horizontally and 60 vertical levels, while the temporal resolution is of 3-hourly. ERA-Interim provides a realistic representation of the hydrological cycle and atmospheric circulation on the Earth. Among the several available data by Era-Interim, the air temperature variation can be obtained.

The ERA-Interim/Land [33], as stated by Balsamo *et al.,* [34,35], is a global land-surface reanalysis data set provided by ECMWF, describing the evolution of soil temperature, among other parameters, from 1979 to 2010. These data have a time-frequency of 3-hourly for a horizontal resolution around 80 km. It is generated by a simulation with the latest ECMWF land surface model driven by meteorological forcing from the ERA-Interim [30] atmospheric reanalysis and precipitation adjustments based on monthly Global Precipitation Climatology Project (GPCP, [36]).

2.3 Study Areas

Six cities of the state of Rio Grande do Sul, in southern Brazil, are considered in this work, as shown in Figure 1 and as indicated in Table 1.

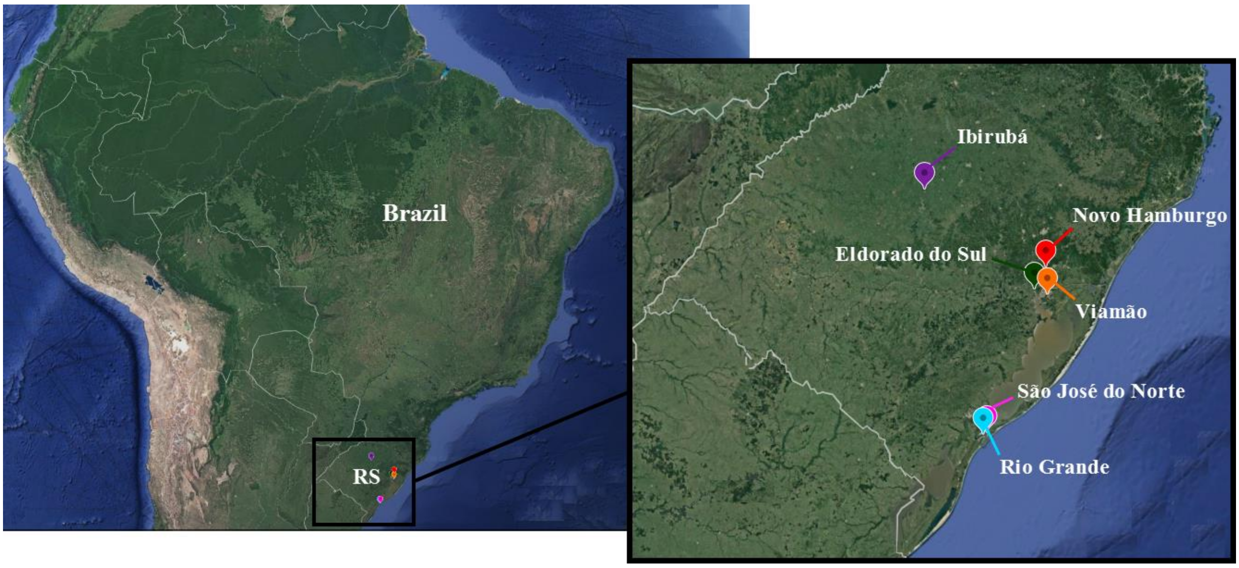

Fig. 1. Identification of the study areas

Table 1
Name and geographical coordinates of the study areas

City	Geographical Coordinates	
	South (*S*)	West (*W*)
Ibirubá	28°37'57.7''	53°06'10.6"
Novo Hamburgo	29°43'30.5"	51°08'56.9"
Eldorado do Sul	30°03'36.5"	51°30'59.6"
Viamão	30°04'51.0"	51°01'24.0''
São José do Norte	32°02'10.8''	52°02'17.0''
Rio Grande	32º04'27.6''	52º10'1.9''

Based on the SPT report of these six localities, it was possible to identify the soil stratification in each case. Figure 2(a) to 2(f) depict the soil layers for Ibirubá, Novo Hamburgo, Eldorado do Sul, Viamão, São José do Norte, and the Rio Grande, respectively. As these SPT reports presented only information about the soil type and water table level, the thermo-physical properties of different soil types were adopted in agreement with Oke [37]. Therefore, density (ρ), specific heat (c_p), and thermal conductivity (κ) for soils of Figure 2 are indicated in Table 2.

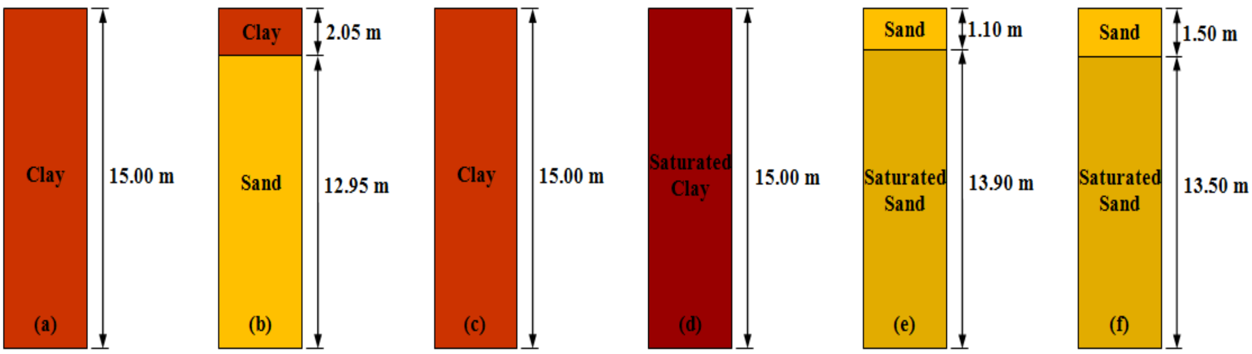

Fig. 2. Soil stratification of: (a) Ibirubá; (b) Novo Hamburgo; (c) Eldorado do Sul; (d) Viamão; (e) São José do Norte; and (f) Rio Grande

Table 2
Thermo-physical properties of soil types of study areas [37]

Soil Type	ρ (kg/m³)	c_p [J/(kg.K)]	κ [W/(m.K)]
Sand	1600	800	0.30
Saturated Sand	2000	1480	2.20
Clay	1600	890	0.25
Saturated Clay	2000	1550	1.58

However, the properties of Viamão soil (Figure 2(d)) were experimentally defined in Vaz *et al.,* [3]: ρ = 1800 kg/m^3; c_p = 1780 J/(kg·K); κ = 2.1 W/(m·K). In its turn, the thermo-physical properties of air in Viamão were also obtained in Vaz *et al.,* [3] as: ρ = 1.16 kg/m^3; c_p = 1010 J/(kg·K); κ = 0.0242 W/(m·K); and absolute viscosity of ν = 7.7894×10^{-5} kg/(m·s). These values were adopted for all studied regions since it is well known that there are no significant variations for its air properties.

Moreover, the annual temperature variations of air (from ERA-Interim) and the annual temperature variation of soil surface (from ERA-Interim/Land) were obtained following the geographic coordinates of each city (see Table 1). The annual temperature variation of soil in each studied city was also obtained in the ERA-Interim/Land for the following depths: 0.5 m, 1.0 m, 2.0 m, and 3.0 m, aiming to compare the numerical results. Specifically, for the city of Viamão, the depth of 0.3 m was also considered.

2.4 Computational Modeling

Two CFD models were used in this work. Both are based on the Finite Volume Method (FVM), which were developed in ANSYS Fluent software. One of these computational models is used to numerically simulate the heat diffusion occurred only in the soil due to the incidence of solar radiation. Hence, only the energy conservation equation is numerically solved in this 2D model. The computational domain is a rectangular slice of soil (with the length of l = 25.77 m and height of h = 15 m), where the soil surface temperature variation is imposed as a boundary condition of prescribed temperature in the top edge; while the other edges are considered as thermally insulated. The soil thermo-physical properties (see Table 2) are also set for each soil layer according to the soil stratification (see Figure 2). This model was presented and validated in Brum *et al.,* [12,38]; therefore, it is not shown in this work for the sake of brevity.

The other computational model is addressed to the numerical simulation of the EAHE operating principle. It is a 3D model in which the time-averaged conservation equations of mass, momentum, and energy were solved in association with the equations of the k-□ turbulence model for simulation of turbulent airflow in the buried ducts. Moreover, the heat diffusion equation is solved to obtain the thermal field in the soil. The computational domain is composed by a parallelepiped volume (representing the soil, with the length of l = 25.77 m, the height of h = 15 m, and width of w = 5 m) in which it is inserted a horizontal cylindrical perforation (representing the EAHE duct, with a diameter of d = 110 mm and length of l = 25.77 m; installed in a depth of 1.6 m). On the superior surface of the domain, the annual temperature variation of the soil surface is imposed as a boundary condition, while the other surfaces of parallelepiped are defined as thermally insulated. Besides, at the duct inlet, the airflow velocity and the external ambient air annual temperature variation are imposed as boundary conditions. The thermo-physical properties of soil (see Table 2 and Figure 2) and air (see section 2.3) are also set in the computational model. As this model was presented, verified, and validated in Brum *et al.,* [12,39] and Rodrigues *et al.,* [13], it is not shown here for brevity.

To represent the computational domain of these models, Figure 3 depicts the 2D model (Figure 3(a)) and the 3D model (Figure 3(b)) for the numerical simulations performed for the city of Viamão (see Figure 2(d)). One can note in both images the superior brown line/surface of the domain in which the annual soil surface temperature variation is imposed as prescribed temperature, and the external black lines/surfaces of domain indicate a thermal insulation boundary condition. Besides, specifically to the 3D model (Figure 3(b)), it is possible to observe the air inlet surface (in red color) where the annual air temperature variation and the air flow velocity (of 3.3 m/s) are imposed, respectively, as prescribed temperature and prescribed velocity. Finally, at the end of the EAHE duct, the outlet air surface (in blue color) can be viewed, where atmospheric pressure is imposed as a boundary condition.

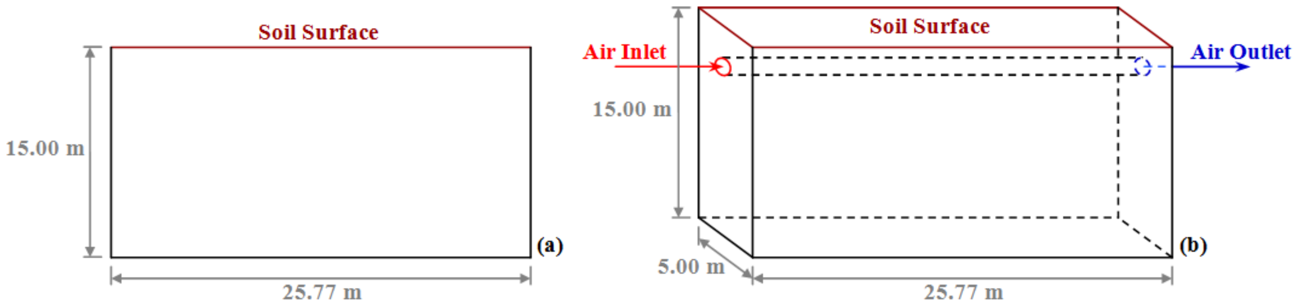

Fig. 3. Computational domain of the Viamão City: (a) 2D model of soil; and (b) 3D model of EAHE installation

Regarding the spatial discretization, the soil was meshed with computational cells of size 3*d* for triangular and tetrahedral shapes, respectively, for the 2D and 3D models, while the duct was meshed with tetrahedral computational cells with the size of *d*/3. These spatial discretizations were based on the mesh convergence test carried out in Rodrigues *et al.,* [13]. Besides, the temporal discretization was 3600 s for the 3D model and 1800 s for the 2D model [13,38]. All simulations were performed for a total time of 2 years (63,072,000 s), however only the second one was considered a result. This procedure is adopted since the initial condition for the entire computational domain is always defined as the average soil temperature. So, the first simulation year is used to guarantee an adequate soil temperature distribution.

2.5 Statistical Analysis

Several comparisons were carried out aiming to evaluate the proposed methodology (allying ERA-Interim temperature data and SPT reports, for EAHE numerical simulations), and to prove its applicability. Statistical measures were adopted based on previous studies with similar analyses [40-44]. Therefore, in agreement with Wilks [45], the adopted statistical indicators are

i) Mean Error (ME): also known as *BIAS,* is the simplest error measure, indicating the estimator tendency to overestimate or underestimate the data in relation to the reference. This tendency is also called systematic error, being possible to assume positive or negative values. A null ME value indicates a perfect fit between estimator and reference, which is almost impossible in a practical situation. The ME is defined as

$$\mathrm{ME} = BIAS = \frac{1}{n}\sum_{i=1}^{n}\left(T_i^{Est} - T_i^{Ref}\right) \quad (1)$$

where: T_i^{Est} is the estimated temperature data; T_i^{Ref} is the temperature data used as reference; and *n* is the total number of data.

ii) Root Mean Squared Error (RMSE): is a widely used measure of the differences between estimated values and the reference data. The RMSE is always a non-negative value, and a value equal to zero indicates a perfect agreement; however, a null RMSE value is rarely reached in practice. Thus, RMSE is given by

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(T_i^{Est} - T_i^{Ref}\right)^2} \tag{2}$$

iii) Mean Absolute Percentage Error (MAPE): is a measure that expresses the accuracy of the error as a percentage, indicating how much the estimated values are erroneous in relation to the reference data. A null value of MAPE indicates no error between estimated values and reference data. The MAPE is given as

$$\text{MAPE} = \frac{100}{n}\sum_{i=1}^{n}\left|\frac{T_i^{Ref} - T_i^{Est}}{T_i^{Ref}}\right| \tag{3}$$

iv) Pearson Correlation Coefficient (r): is a statistical indicator that measures the linear correlation between two variables. Its values range is -1 ≤ r ≤ 1; if r = -1 there is a perfect negative linear correlation, if r = 0, there is no linear correlation, and if r = 1, there is a perfect positive linear between variables. The r indicator is obtained as

$$r = \frac{n\sum_{i=1}^{n}\left(T_i^{Est}\cdot T_i^{Ref}\right) - \left(\sum_{i=1}^{n} T_i^{Est}\right)\cdot\left(\sum_{i=1}^{n} T_i^{Ref}\right)}{\sqrt{n\sum_{i=1}^{n}\left(T_i^{Est}\right)^2\left(T_i^{Est}\right)^2}\cdot\sqrt{n\sum_{i=1}^{n}\left(T_i^{Ref}\right)^2\left(T_i^{Ref}\right)^2}} \tag{4}$$

It is worth mentioning that in some comparisons, the reference data were those of Vaz *et al.,* [9], while in other analyses, the ERA-Interim/Land data were adopted as reference.

3. Results and Discussion
3.1 Validation of ERA-Interim Temperatures

As earlier stated, at first validation of ERA-Interim temperature data for the city of Viamão (during the year of 2007) was provided, confronting them with *in-situ* data presented by Vaz *et al.,* [9]. Figure 4 is concerned with air temperature variation, and Figure 5 is related to soil surface temperature variation.

The results of Figure 4 and 5 show qualitatively a good agreement of ERA-Interim data with *in-situ* data. Qualitatively, it is possible to notice the similarity in the thermal behavior of air and soil surface. In order to perform a quantitative analysis, the time interval of the existing gaps in the *in-situ* data (see Figure 4 and 5) were discarded for the statistical measures calculations of Table 3.

Based on Table 3, ME indicates that the ERA-Interim data overestimate the experimental data, due to its positive values. The magnitude of this overestimation can be considered low for the air temperature and acceptable for the soil surface temperature. The values of RMSE and MAPE are also acceptable, while Pearson's r indicates a robust linear correlation between data.

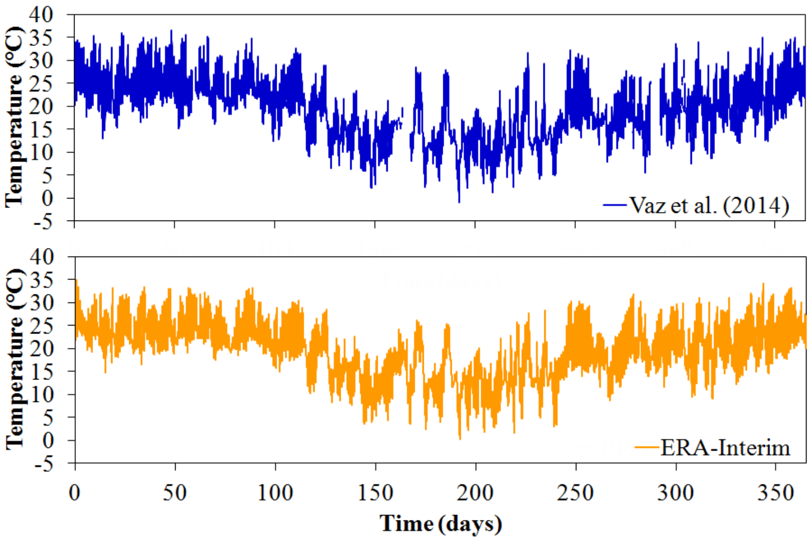

Fig. 4. Variation of air temperature in 2007 in the city of Viamão

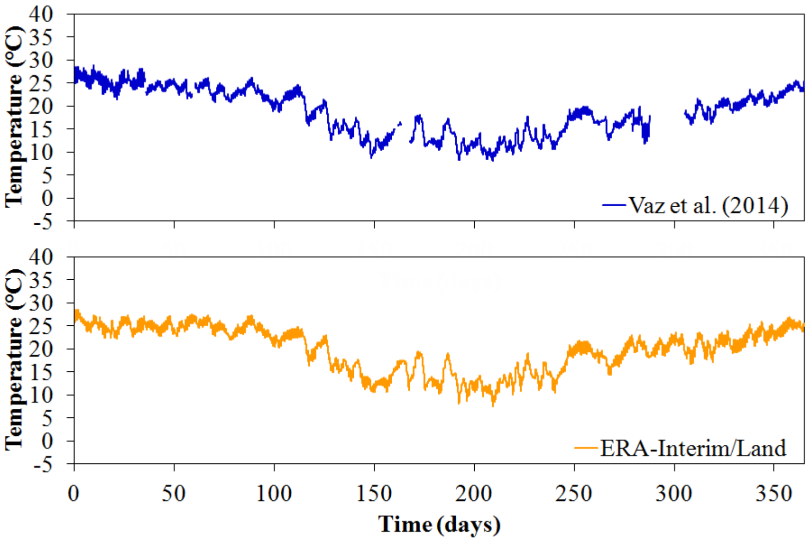

Fig. 5. Variation of soil surface temperature in 2007 in the city of Viamão

Based on the statistical measures of Table 3 and taking into account the technical difficulties and the high cost for the acquisition of experimental *in-situ* data, one can affirm that the data from ERA-Interim can be adequately employed for engineering applications purposes.

Table 3
Statistical analysis between ERA-Interim/Land data and *in-situ* data of Vaz *et al.,* [9] in Viamão

Indicator	Air Temperature	Soil Surface Temperature
ME (°C)	0.33	1.22
RMSE (°C)	2.32	1.63
MAPE (%)	9.66	7.00
r	0.94	0.98

3.2 Comparison of the Annual Heat Diffusion Estimated by Different Approaches in Viamão

Considering the satisfactory results provided by the validation of air and soil temperature from ERA-Interim and ERA-Interim/Land, respectively, it was analyzed here the annual heat diffusion in the city of Viamão by four cases: Case 1 consists of the experimental *in-situ* data of Vaz *et al.,* [9], being adopted as the reference; Case 2 represents the ERA-Interim/Land data; Case 3 is a 2D numerical simulation (see Figure 3(a)) where the temperature boundary condition at the soil surface and the soil thermo-physical properties were based in Vaz *et al.,* [9]; and Case 4 is a 2D numerical simulation (see Figure 3(a)) with the proposed methodology, in which the temperature boundary condition of the soil surface was imposed from ERA-Interim/Land and thermo-physical properties were defined from the work of Oke [37]. The annual temperature variation was analyzed for the year of 2007, for depths of 0.3 m, 0.5 m, 1.0 m, 2.0 m, and 3.0 m. These results can be viewed in Figure 6.

One can note in Figure 6(a) and 6(b) a good agreement among the four cases. However, from Figure 6(c) it is possible to observe a quite difference of ERA-Interim/Land data (Case 2) in relation to the Case 1 (adopted as reference), as well as to the Cases 3 and 4; this trend is intensified with the increase of the soil depth (Figure 6(d) and 6(e)). In other words, the deviation with the depth is more intense for Case 2 than for cases 3 and 4, showing that the modeling of the soil with the heat diffusion equation is adequate for estimation of thermal field in different depths of the soil domain.

Table 4 shows the statistical measures of Cases 2, 3, and 4 related to Case 1, indicating a good general agreement among the cases.

From Table 4, Case 2 presented negative ME for all depths, except for the depth of 1 m, indicating a general underestimation of the temperature values. The opposite is found for Cases 3 and 4, indicating a general overestimation of temperatures. One can also observe that the RMSE values range between 0.62°C and 2.31°C for all cases and depths. Most of the values are within the 1°C - 2°C interval, indicating the expected error for the proposed methods. Case 4 presented lower RMSE values when compared to Case 2 and Case 3, for all depths, whereas Case 3 presented lower RMSE values than Case 2 for most depths. The largest RMSE was observed in the depth of 3 m for Case 2 and 2 m for Cases 3 and 4. Besides, the MAPE values are between 2.23% and 10.55%, being the lowest average MAPE of 5.08% reached by the proposed methodology (Case 4). Finally, the excellent *r* values observed for all cases and depths indicate that they can represent the temporal variability of temperatures.

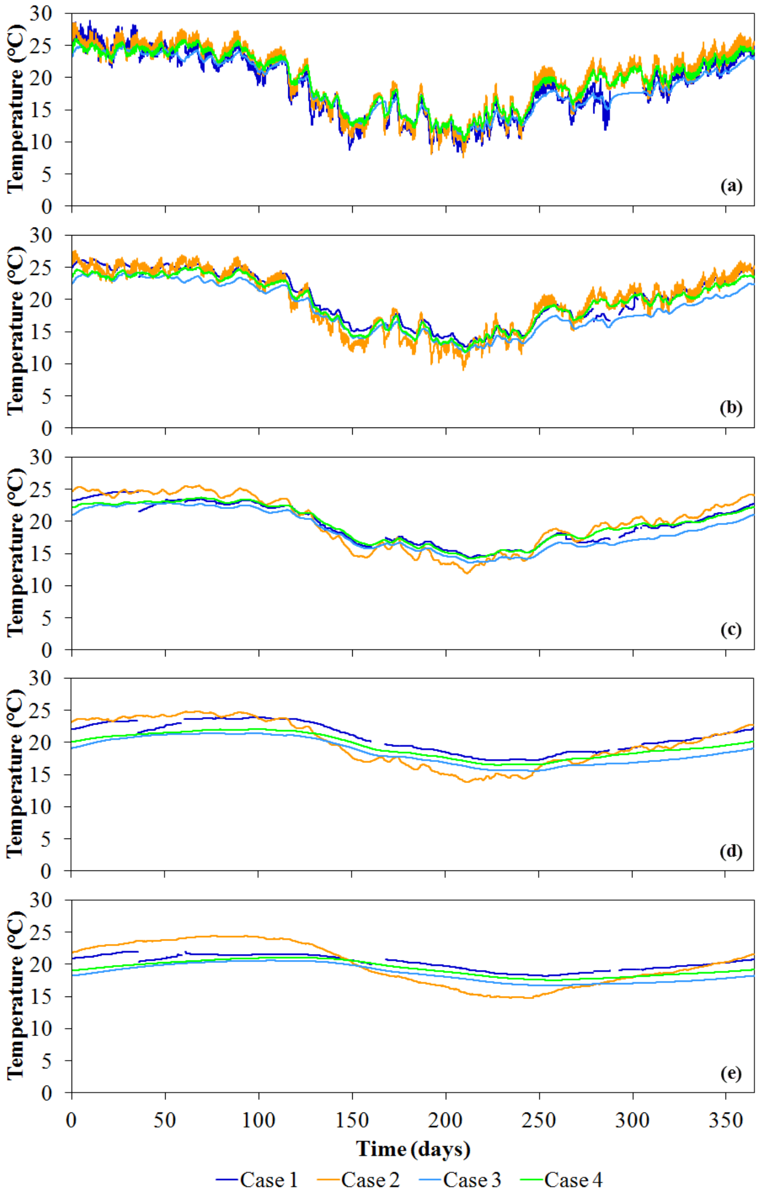

Fig. 6. Variation of Viamão soil temperature in 2007 for depths of: (a) 0.3 m; (b) 0.5 m; (c); 1.0 m; (d) 2.0 m; and (e) 3.0 m

Table 4
Statistical analysis comparing simulated temperatures (Case 2, Case 3 and Case 4) against *in-situ* data for the soil of Viamão (Case 1)

Indicator	Case	Depth of 0.3 m	Depth of 0.5 m	Depth of 1.0 m	Depth of 2.0 m	Depth of 3.0 m
ME (°C)	2	-0.25	-0.29	0.32	-0.84	-0.26
	3	1.52	1.57	0.99	2.20	1.65
	4	0.45	0.53	0.01	1.35	-0.93
RMSE (°C)	2	1.91	1.46	1.38	1.82	2.31
	3	1.63	1.66	1.14	2.26	1.76
	4	1.26	0.95	0.62	1.44	1.05
MAPE (%)	2	7.81	6.31	6.41	7.29	10.13
	3	6.52	7.78	5.29	10.55	8.23
	4	8.37	3.86	2.23	6.33	4.60
r	2	0.93	0.95	0.97	0.94	0.93
	3	0.99	0.99	0.98	0.97	0.90
	4	0.96	0.98	0.85	0.99	0.91

3.3 Application of the 3D CFD Model to Simulate EAHE in Viamão

After that, using the EAHE computational model (3D model - see Figure 3(b)), three cases were numerically simulated: Case 1 is considered the reference case, since its temperature boundary conditions for inlet air and soil surface, as well as the thermo-physical properties of soil, were defined by the *in-situ* data of Vaz *et al.,* [9]; Case 2 employs as inlet air and soil surface boundary conditions the data from ERA-Interim associated with the *in-situ* soil properties of Vaz *et al.,* [9]; and Case 3 was simulated with the proposed methodology, i.e., temperature boundary conditions from ERA-Interim allied with soil properties from Oke [37]. The results of these numerical simulations are presented in Figure 7, where the outlet average daily temperatures of EAHE were plotted to allow its better visualization.

It is possible to view in Figure 7 an excellent agreement among the three simulated cases. More specifically, the concordance between Cases 2 and 3 is such that it is challenging to distinguish both in several parts of the curve. Therefore, the use of soil thermo-physical properties available in the literature, respecting the soil stratification defined by the SPT report of the study region, can be accurately adopted. This assumption is valid since there is no relevant difference when compared with the EAHE computational modeling, which used *in-situ* thermo-physical soil properties. The statistical measures of Table 5 ratify this finding.

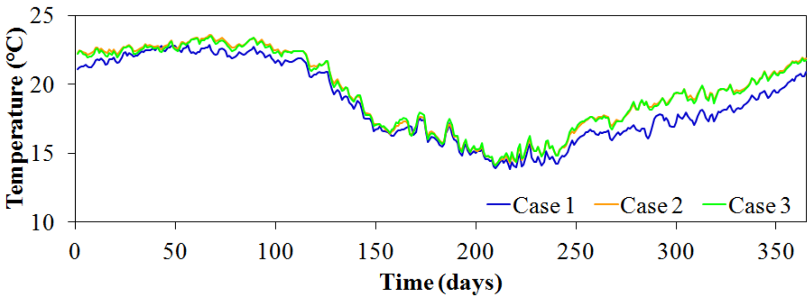

Fig. 7. Variation of EAHE outlet temperature in 2007 in the city of Viamão

The statistical measures in Table 5 indicate that both Cases 2 and 3 provide reliable results. The small ME values show that the temperatures can be considered not biased, i.e., the errors are nearly random, without precise under or overestimation. The excellent *r* values show both cases' capability to represent the temporal variability of temperatures, whereas the RMSE indicates an error smaller than 1°C can be expected. In its turn, the MAPE values are around 4% when compared with the results obtained from *in-situ* reference data, being an excellent accuracy.

As earlier mentioned, the difference of only 0.16% between MAPE values of Cases 2 and 3 allows to state that it is possible to adopt the SPT reports information associated with thermo-physical properties values from literature as a reliable way to define the soil characteristics for numerical simulations of EAHE devices. Therefore, the results of Figure 7 and Table 5 validate and evidence the applicability of the proposed methodology to the numerical study of EAHE.

Table 5
Statistical analysis for the EAHE simulations in the city of Viamão during the year of 2007

Indicator	Case 2 vs. Case 1	Case 3 vs. Case 1
ME (°C)	0.04	0.03
RMSE (°C)	0.98	0.93
MAPE (%)	4.36	4.20
r	0.98	0.98

3.4 Numerical Simulation of Soil Temperature Variation for Five Cities in the Rio Grande Do Sul, Brazil

Finally, it was performed numerical simulations employing the 2D soil computational model (see Figure 3(a)) imposing as boundary condition the 2015 and 2016 annual variation of temperature in soil surface obtained from ERA-Interim/Land data; and considering the soil stratification (see Figure 2) from SPT reports with the respective thermo-physical properties of each soil layer (see Table 2).

Numerical probes in depths of 0.5 m, 1.0 m, 2.0 m, and 3.0 m were used to monitor the temperature variation during the simulations, aiming to compare it with the ERA-Interim/Land data. Figure 8 to 12 show these results for the cities of Ibirubá, Novo Hamburgo, Eldorado do Sul, São José do Norte, and Rio Grande (see Figure 1), respectively; as well as Table 6 to 10 presented the statistical indicators calculated considering as reference the ERA-Interim/Land data.

From Figure 8 to 12, one can note that the seasonal cycle of the temperature is reproduced in both ERA-Interim/Land data and the numerical results. However, this oscillation is much smoother for larger depths in the numerical results, when compared to ERA-Interim/Land. Higher frequency oscillations of temperature are also smoothed in the numerical results.

Moreover, Figure 8 to 12 confirmed the trend previously observed: for greater soil depths, the numerically obtained results are not so concordant with the data from the ERA-Interim/Land. Regarding the statistical measures, this tendency is proved by increasing the indicators values with increasing soil depth (Table 6 to 10). Possibly this fact is related to the way that the ERA-Interim/Land takes into account the soil properties in the soil temperatures reanalysis. However, it is important to remember that the numerical results generated with the proposed methodology have a better thermal behavior agreement with the experimental *in-situ* data of Vaz *et al.,* [9] for both small and large depths (see Figure 6).

Besides, one can infer in Table 6 to 10 that the numerical results always underestimate the temperature values concerning the ERA-Interim/Land data adopted as a reference, since the ME indicator was negative for all analyzed situations. In a general way, it was also observed an increase in RMSE values for soil deeper, indicating a worsening in the data agreement. It is still possible to notice that the minimum MAPE value of 6.17% and the maximum MAPE value of 22.85%, among all analyzed cities and depths were obtained for the city of Rio Grande. It is also highlighted that for all studied cases, the results of the 2015 year always presented lower MAPE values than the results of the 2016 year, inferring that the better accuracy has been achieved for the 2015 year. Concerning *r* indicator, for the depth of 0.5 m, there is a robust linear correlation, while for the depth of 3.0 m, there is no linear correlation in several cases.

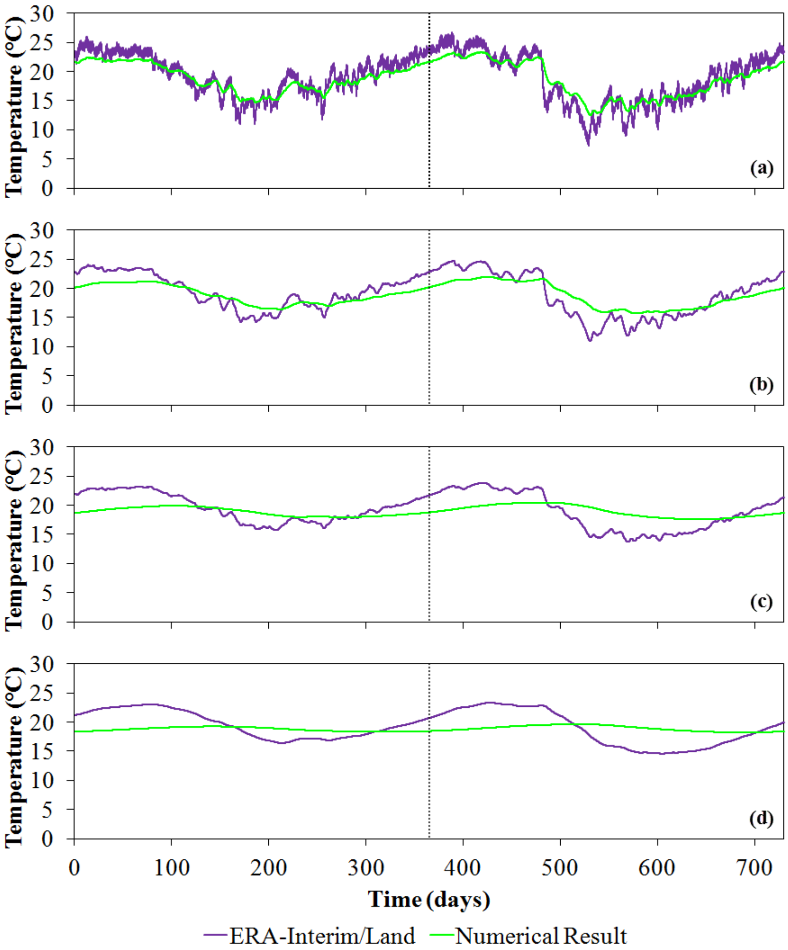

Fig. 8. Variation of soil temperature in 2015 and 2016 in the city of Ibirubá, for depths of: (a) 0.5 m; (b); 1.0 m; (c) 2.0 m; and (d) 3.0 m

Table 6
Statistical analysis between numerical results and ERA-Interim/Land data for city of Ibirubá

Indicator	Depth of 0.5 m		Depth of 1.0 m		Depth of 2.0 m		Depth of 3.0 m	
	2015	2016	2015	2016	2015	2016	2015	2016
ME (°C)	-0.60	-0.62	-0.67	-0.60	-0.82	-0.55	-0.94	-0.52
RMSE (°C)	1.52	1.97	1.75	2.31	2.18	2.88	2.41	3.13
MAPE (%)	6.42	9.30	7.56	11.01	8.94	14.27	9.98	15.48
r	0.94	0.94	0.90	0.89	0.64	0.64	0.23	0.29

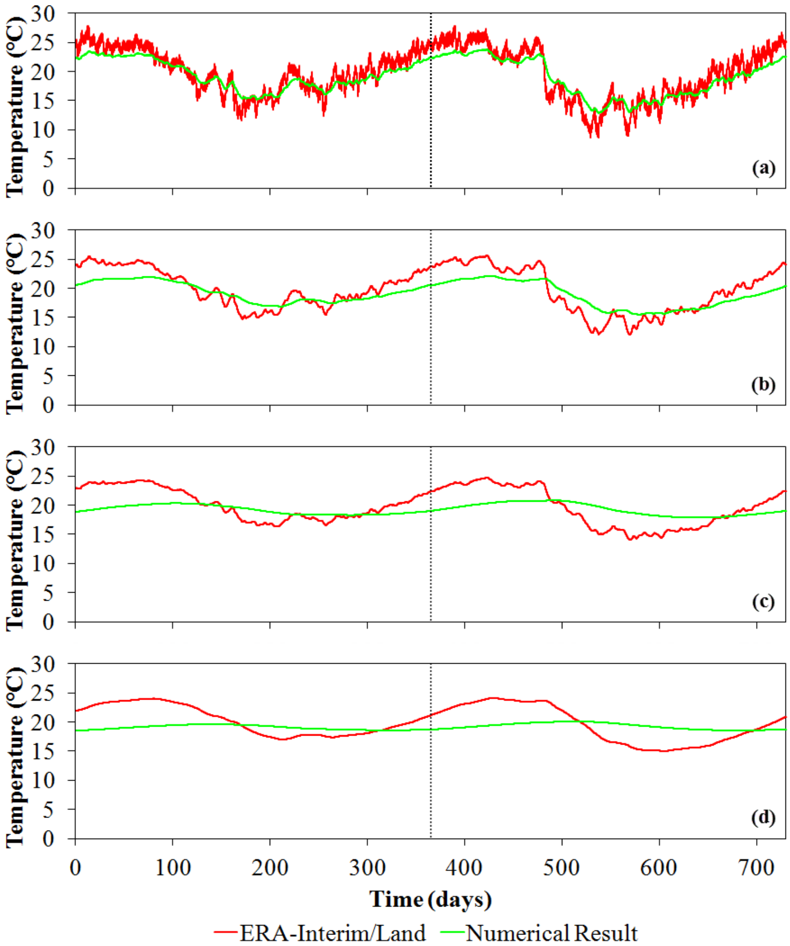

Fig. 9. Variation of soil temperature in 2015 and 2016 in the city of Novo Hamburgo, for depths of: (a) 0.5 m; (b); 1.0 m; (c) 2.0 m; and (d) 3.0 m

Table 7
Statistical analysis between numerical results and ERA-Interim/Land data for city of Novo Hamburgo

Indicator	Depth of 0.5 m		Depth of 1.0 m		Depth of 2.0 m		Depth of 3.0 m	
	2015	2016	2015	2016	2015	2016	2015	2016
ME (°C)	-0.71	-0.64	-0.84	-0.67	-1.11	-0.75	-1.31	-0.81
RMSE (°C)	1.64	1.97	1.97	2.39	2.48	3.02	2.72	3.23
MAPE (%)	6.71	8.98	7.91	10.89	9.33	13.99	10.35	14.93
r	0.94	0.95	0.90	0.90	0.62	0.64	0.27	0.36

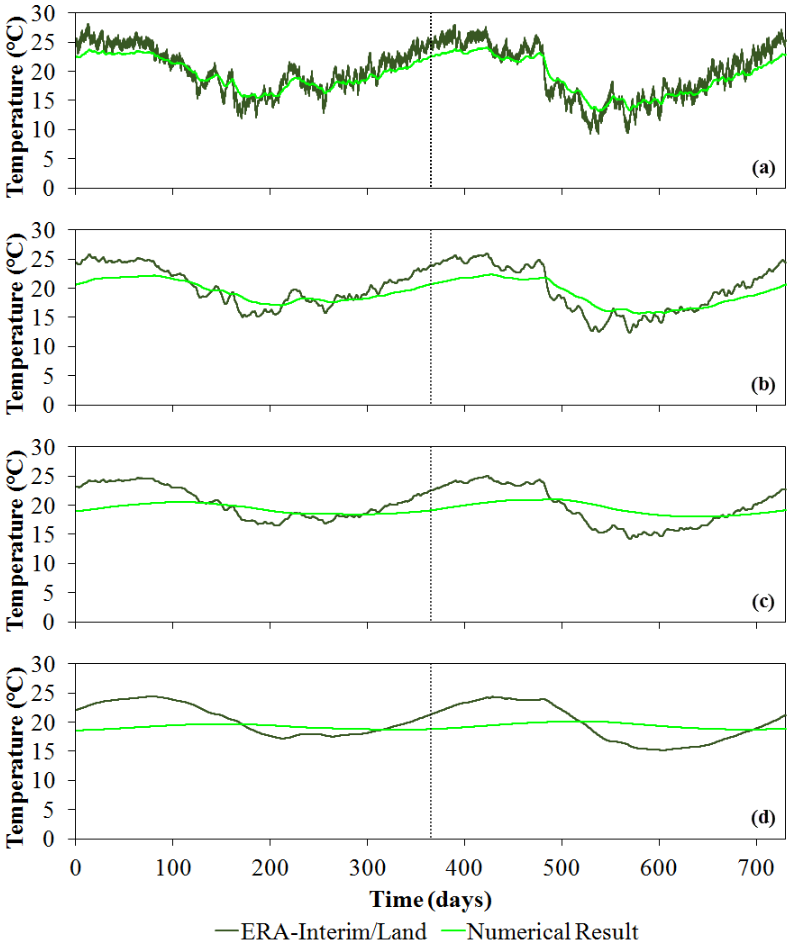

Fig. 10. Variation of soil temperature in 2015 and 2016 in the city of Eldorado do Sul, for depths of: (a) 0.5 m; (b); 1.0 m; (c) 2.0 m; and (d) 3.0 m

Table 8
Statistical analysis between numerical results and ERA-Interim/Land data for city of Eldorado do Sul

Indicator	Depth of 0.5 m		Depth of 1.0 m		Depth of 2.0 m		Depth of 3.0 m	
	2015	2016	2015	2016	2015	2016	2015	2016
ME (°C)	-0.73	-0.67	-0.88	-0.71	-1.18	-0.81	-1.44	-0.90
RMSE (°C)	1.65	1.95	2.01	2.43	2.60	3.08	2.92	3.35
MAPE (%)	6.38	8.68	8.07	10.93	9.58	14.02	10.86	15.21
r	0.94	0.95	0.89	0.90	0.60	0.62	0.11	0.22

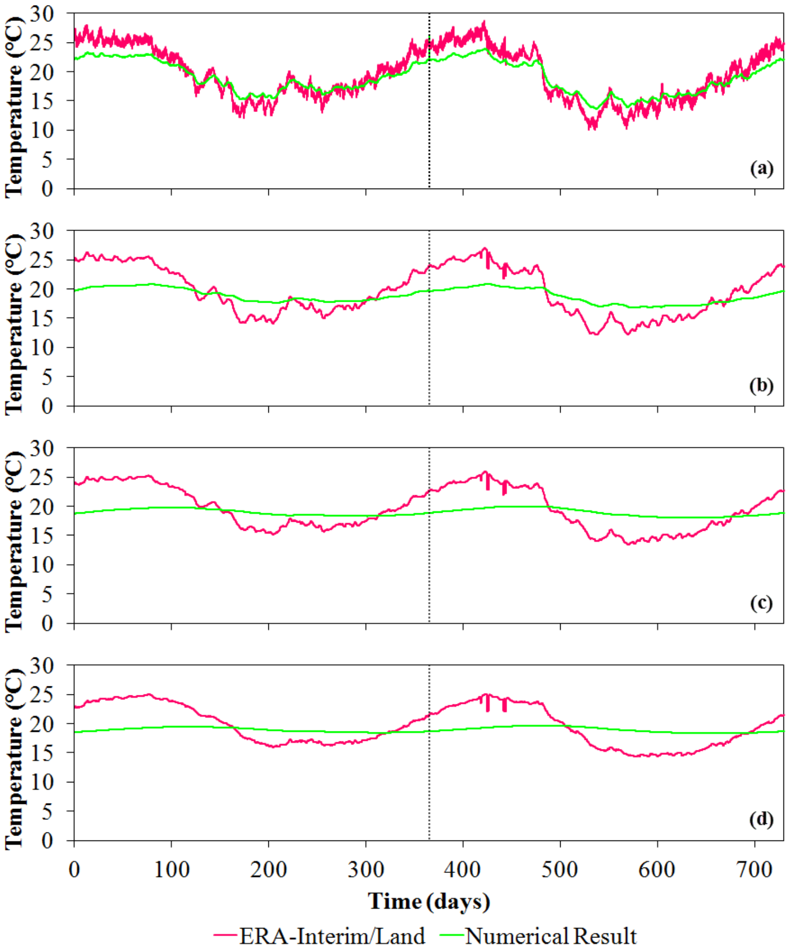

Fig. 11. Variation of soil temperature in 2015 and 2016 in the city of São José do Norte, for depths of: (a) 0.5 m; (b); 1.0 m; (c) 2.0 m; and (d) 3.0 m

Table 9
Statistical analysis between numerical results and ERA-Interim/Land data for city of São José do Norte

Indicator	Depth of 0.5 m		Depth of 1.0 m		Depth of 2.0 m		Depth of 3.0 m	
	2015	2016	2015	2016	2015	2016	2015	2016
ME (°C)	-0.68	-0.47	-0.94	-0.51	-1.11	-0.52	-1.21	-0.52
RMSE (°C)	1.82	1.97	2.92	3.27	3.20	3.51	3.21	3.40
MAPE (%)	7.23	9.13	11.73	15.72	12.78	16.98	12.81	16.31
r	0.98	0.98	0.93	0.93	0.70	0.71	0.55	0.59

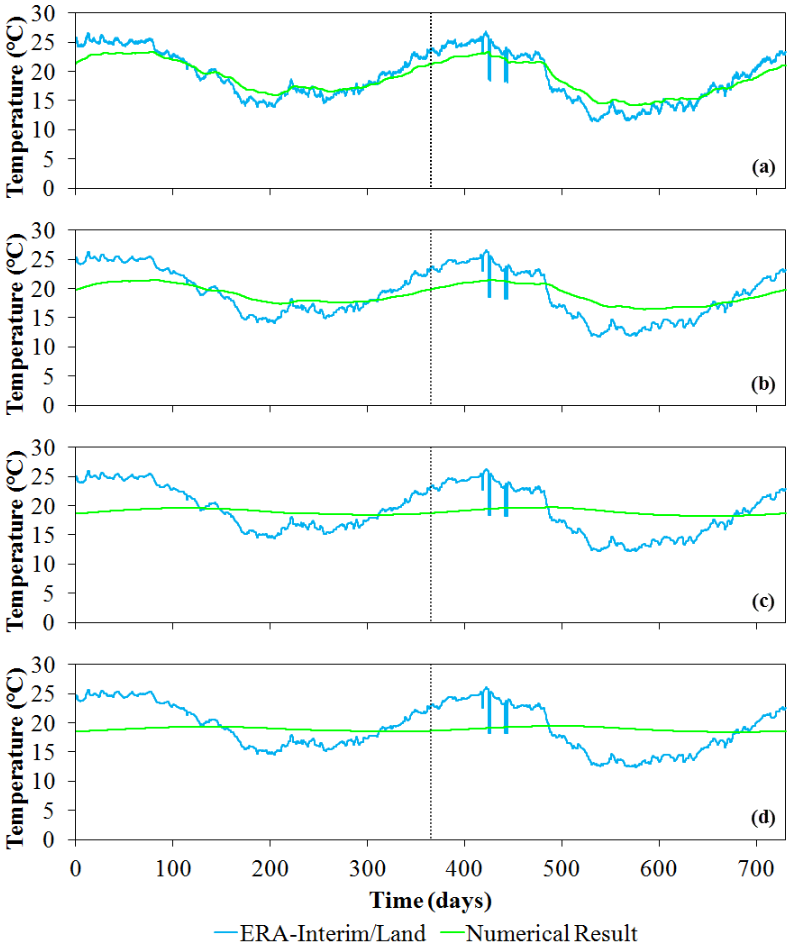

Fig. 12. Variation of soil temperature in 2015 and 2016 in the city of Rio Grande, for depths of: (a) 0.5 m; (b); 1.0 m; (c) 2.0 m; and (d) 3.0 m

Table 10
Statistical analysis between numerical results and ERA-Interim/Land data for city of Rio Grande

Indicator	Depth of 0.5 m		Depth of 1.0 m		Depth of 2.0 m		Depth of 3.0 m	
	2015	2016	2015	2016	2015	2016	2015	2016
ME (°C)	-0.35	-0.06	-0.62	-0.10	-0.92	-0.05	-1.01	-0.04
RMSE (°C)	1.51	1.81	2.57	5.42	3.58	5.71	3.66	5.75
MAPE (%)	6.17	9.23	10.74	16.57	15.04	22.71	15.38	22.85
r	0.97	0.96	0.90	0.31	0.39	0.04	0.05	0.00

4. Final Considerations

The proposed methodology - allying the soil stratification from SPT reports, the soil thermo-physical properties from literature, the prescribed air temperature variation from ERA-Interim, and the prescribed soil surface temperature variation from ERA-Interim/Land - it was validated and considered adequate to numerical simulations related to Earth-Air Heat Exchanger (EAHE) purposes. The following aspects can be highlighted inferring the applicability of this methodology

i. The employment of SPT reports already performed for the interest region since this is a test widely carried out when buildings are built;

ii. The adoption of soil thermo-physical properties from literature did not require additional experimental tests since an accuracy difference of only 0.16% was identified between EAHE simulations performed with *in-situ* and literature values;
iii. The ERA-Interim data for air temperature were validated when compared with *in-situ* data of Vaz *et al.,* [9] with an accuracy of 90.34%, allowing its imposition as a boundary condition in the EAHE inlet;
iv. The ERA-Interim/Land data for soil surface temperature were validated with *in-situ* data of Vaz *et al.,* [9] with an accuracy of 93.00%, allowing its imposition as a boundary condition in the soil surface;
v. The ERA-Interim/Land data present a crescent deviation trend from *in-situ* data of Vaz *et al.,* [9] as the soil depth increases, e.g., the accuracy of 93.69% at a depth of 0.5 m whereas at a depth of 3.0 m the accuracy is of 89.87%;
vi. The numerical results for the soil heat diffusion are in good agreement with *in-situ* data of Vaz *et al.,* [9], reaching an average accuracy of 94.92%;
vii. The difference in the estimation of the thermal field in different soil depths identified between ERA-Interim/Land data and the numerical results in Viamão City was also observed for the other analyzed cities, varying its accuracy between 93.83% and 77.15%;
viii. The EAHE numerical results obtained with the proposed methodology are in excellent agreement with those obtained by numerical simulations with *in-situ* data of Vaz *et al.,* [9], achieving an accuracy of 95.80%;

Therefore, the proposed methodology was validated and can be universally used to investigate the EAHE performance in any location of the World, being a need for the desired region an existing SPT report and the temperature data from ERA-Interim reanalysis.

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