Climate Change Impacts On Evapotranspiration in Brazil: a Multi-model Assessment

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Research Article

Keywords: evapotranspiration projections, Turc method, Abtew method, CMIP5

Posted Date: January 17th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1236485/v1

Version of Record: A version of this preprint was published at Theoretical and Applied Climatology on April 6th, 2024. See the published version at https://doi.org/10.1007/s00704-024-04942-6.

Abstract

A large part of Brazil is highly vulnerable to climate changes projected for the end of the 21st century. Analyzing these vulnerabilities is particularly important for agriculture, since the country is one of the largest agricultural commodity producers in the world. Changes in the reference evapotranspiration (ET_o) can impact crops and make cultivation unfeasible. However, studies on ET_o patterns under climate change scenarios for Brazil have been restricted to regional scales and use too few climate models or too simplified water balance models for their analysis. This can lead to uncertainties in assessing the impacts of climate change on ET_o. Therefore, this study seeks to analyze ET_o patterns in Brazil towards the end of the 21st century using two methods that are better at estimating regional ET_o, i.e., the *Turc* and *Abtew* methods, under two radiative forcing scenarios (RCPs 4.5 and 8.5). Daily data on near surface air temperature (mean and maximum), global solar radiation, and near surface relative humidity from six General Circulation Models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) were used to analyze the simulations and projections for climate change. The performance of climate simulations is heterogeneous among the GCMs, with overestimations (~ 2.5 mm day^{-1}) in some models, and underestimations (~ 1.5 mm day^{-1}) in others. In general, climate change projections indicate increases of up to 1 mm day^{-1} in ET_o, mainly in the North, Northeast, and Center-West regions of Brazil. Both estimation methods showed similar spatial patterns, however the *Turc* method projected lower intensity changes compared to the *Abtew* method.

Highlights

• The *Turc* method showed the best performance in estimating ET_o, resulting in more reliable climate simulation and projections.

• There was divergence between climate models when simulating solar radiation and relative humidity.

• Climate models projected an increase in temperature (mean and maximum), and a reduction in relative humidity towards the end of the 21st century.

• The projected ET_o showed similar patterns between the *Turc* and *Abtew* methods.

• Increases from 0.4 to 1 mm day^{-1} are projected for ET_o in the North, Northeast, and Center-West of Brazil, and from 0.2 to 0.4 mm day^{-1} in the South of Brazil.

1 Introduction

Extreme weather and climate event changes have been recorded and projected for different regions of South America (Natividade et al. 2017; Avila-Diaz et al. 2020a,b; Cerón et al. 2021; Regoto et al. 2021. Generally, warmer climates are projected for all of Brazil by the end of the 21st century, possibly increasing by 5°C in the south of the Amazon, in the Center-West, and the western part of Minas Gerais state (Torres and Marengo 2014; IPCC 2021). Furthermore, models project heterogeneous rainfall trends in the form of reduced rainfall at lower latitudes and increased rainfall at higher latitudes (IPCC, 2013, 2021; Llopart et al. 2020), making much of Brazil vulnerable to climate change (Torres et al. 2012; Darela et al. 2016; Silva et al. 2019; Lapola et al. 2020; Torres et al. 2021).

Since Brazil is one of the largest agricultural commodity producers in the world, it requires efficient irrigation systems to properly manage water resources and ensure sustainable commercial production (Jerszurki et al. 2019; Monteiro et al. 2021). Studies on climate change impacts and vulnerabilities have been increasingly targeted towards different socioeconomic sectors (Guimarães et al. 2016; Lyra et al. 2017), especially the agricultural sector, which is highly dependent on climate conditions (Santos et al. 2017; Porfirio et al. 2018).

The reference evapotranspiration (ET_o) is the main agrometeorological variable used by irrigation projects, and also considered in the assessment of agricultural impacts through indicators of drought, and agricultural crop and forestry growth and yield (Fan et al. 2016; Dewes et al. 2017; Jerszurki et al. 2019; Monteiro et al. 2021). Plants dissipate heat into the atmosphere via ET_o to keep their plant tissue temperatures at appropriate levels for their metabolisms (Devi and Reddy 2018; Abreu et al. 2022). The higher temperatures and irregular precipitation patterns that are projected for Brazil (IPCC, 2013, 2021) are expected to affect ET_o (Valipour et al. 2017; Wang et al. 2018), since increases in air temperature tend to increase evapotranspiration, and because precipitation controls the amount of soil water available. Plants lose water to the atmosphere at higher rates with increased evapotranspiration (Santos et al. 2017), and this can impact certain crops and make cultivating them unfeasible if water availability is not adequate (Ramirez-Cabral et al. 2017; Tavares et al. 2018; Elli et al. 2020). It can also reduce crop productivity and quality (Heinemann et al. 2017; Tironi et al. 2017; Fraga et al. 2019).

Authors like Wang et al. (2007) and Zhang et al. (2015) reported opposite trends in the so-called 'evaporation paradox', where increases in air temperature reduced evapotranspiration. Given the 'evaporation paradox', global increases in air temperature may not result in increased evapotranspiration (Liu et al. 2018), if there are combined influences from variations (increases/decreases) in other metrological variables like wind speed, relative humidity, and precipitation (Fan et al. 2016). Since there are uncertainties as to the aforementioned trends, the contribution of these evapotranspiration-altering meteorological variables needs to be studied and analyzed individually (Zhang et al. 2015; Liu et al. 2018; Monteiro et al. 2021), to better understand evapotranspiration patterns under climate change scenarios (Gondim et al. 2018; Moses and Hambira 2018).

Although the ET_o variable is sensitive to projected climate changes (Dewes et al. 2017; Valipour et al. 2017; Liu et al. 2018; Jerszurki et al. 2019; Llopart et al. 2020), it is not directly available in climate model databases, e.g., those belonging to the Coupled Model Intercomparison Project (CMIP), given its nature and complexity, making it difficult to study under climate change scenarios (Valipour et al. 2017). Therefore, from ET_o estimation methods that best represent current climate conditions (Monteiro et al. 2021), it is necessary to verify the spatiotemporal ET_o patterns under future climate conditions.

Furthermore, there are few studies on projected evapotranspiration changes for Brazil, and the ones that do exist are limited in that i) they are restricted to a single regional (or local) scale (Lyra et al. 2017; Gondim et al. 2018; Santos et al. 2019; Sousa et al. 2019); and/or ii) they use too few climate models (Pan et al. 2015; Guimarães et al. 2016; Jerszurki et al. 2019) or too simplified water balance models (Llopart et al. 2020) in their analyses. Therefore, these studies may contain inconsistencies in assessing climate change impacts on ET_o and do not represent all of Brazil.

This study seeks to contribute to scientific literature, relative to studies that have already been carried out, by analyzing the influence of climate projections to the end of the 21st century (2071-2100) on daily evapotranspiration in Brazil using six climate models under two radiative forcing scenarios based and using two methods that best estimate ET_o.

2 Materials And Methods

2.1 Methods for estimating the reference evapotranspiration

According to Monteiro et al. (2021), the *Turc* (Valipour et al. 2017) and *Abtew* (Abtew, 1996) methods are the most appropriate for estimating ET_o for Brazil under current climatic conditions. Therefore, these two methods will be used in this study to analyze the ET_o under future climate scenarios.

The ET_o in the *Turc* (*Tu*) and *Abtew* (*Ab*) methods is calculated, respectively, using equations 1 and 2:

$$ET_o = \left(0.3107R_s + 0.65\right)\frac{Ta_t}{T+15}$$

1

$$ET_o = \frac{0.01786R_sT_{max}}{\lambda}$$

2

Where ET_o is the reference evapotranspiration (mm day^{-1}); R_s is global solar radiation (MJ m^{-2} day^{-1});T is the mean daily near surface air temperature (°C); T_{max} is the maximum daily near surface air temperature (°C); and λ is the latent heat for vaporization (2.4418 MJ kg^{-1}). Furthermore, in Equation 1, $a_t = 1$ when near surface relative air humidity $(RH) \geq 50\%$ or $a_t = 1 + \frac{50-RH}{70}$ when RH < 50%.

2.2 Analysis of the performance of ET_o estimation methods using data from climate models

The performance analysis for the ET_o values calculated from data from six General Circulation Models (GCMs) from 1980-2005 was performed by comparing the ET_o calculated from the observed data spatialized to grid points (GWD), provided by Xavier et al. (2016) (https://utexas.app.box.com/v/Xavier-etal-IJOC-DATA), using the *Tu* and *Ab* methods. The data provided by Xavier et al. (2016) have horizontal resolution equal to 0.25° latitude/longitude covering all of Brazil.

The six GCMs used in this study (specified in Table 1) belong to the Coupled Model Intercomparison Project Phase 5 (CMIP5), from the World Climate Research Program, made available via the Earth System Grid data portal (https://esgf-data.dkrz. from/search/cmip5-dkrz/). The GCMs have horizontal resolution ranging from 1.1° to 2.8° latitude/longitude, which were later interpolated to the 0.25° grid to compare with GWD (Table 1).

Table 1
List of the CMIP5 models used in this study, with approximate horizontal resolutions, and the institutions from which data were obtained

Models	**Spatial Resolution**	**Institute**
CanESM2	2.8° x 2.8°	Canadian Centre for Climate Modelling and Analysis, Canada
CNRM-CM5	1.4° x 1.4°	*Centre National de Recherches Météorologiques, Météo-France*, France
HadGEM2-CC	1.3° x 1.9°	Met Office Hadley Centre, U.K.
IPSL-CM5A-MR	1.3° x 2.5°	*Institut Pierre-Simon Laplace*, France
MIROC-ESM	2.8° x 2.8°	AORI, NIES, JASMETC, Japan
MRI-CGCM3	1.1° x 1.1°	Meteorological Research Institute, Japan

This subset of CMIP5 models (Table 1) was chosen given the availability of daily data, given that the necessary input variables for the *Tu* and *Ab* methods (Equations 1 and 2) were contained in their databases, and since they are widely used in literature.

Validation was performed on a seasonal and annual scales for each GCM and considering the average from the six models (ensemble mean). Statistical bias was used to quantify how well the GCMs simulate ET_o, as per:

$$bias = \frac{\sum_{i=1}^{nd} (E_i - O_i)}{nd}$$

3

Where E_i are the ET_o values obtained from the GCMs data; O_i are the observed ET_o values obtained from gridded weather dataset provided by Xavier et al. (2016); and nd is the number of daily observations (from 1980 to 2005). The bias was calculated considering *Tu* and *Ab* methods.

2.3 Projected changes to the reference evapotranspiration

The projections were based on seasonal and annual analysis on the six GCMs and the ensemble mean, using the *Tu* and *Ab* methods and two radiative forcing scenarios, called Representative Concentration Pathways (RCPs) (4.5 and 8.5), projected to the end of the 21st century (2071-2100). RCPs 4.5 and 8.5 represent intermediate radiative forcing scenarios (4.5 W m^{-2}) and more intense radiative forcing scenarios (8.5 W m^{-2}) and correspond to equivalent CO2 concentrations at 650 and 1370 ppm, respectively (Moss et al. 2010; Van Vuuren et al. 2011).

Projected future climate changes were calculated by taking the difference between the climatological average for future period (2071-2100) from the climatological average from the historical period (1980-2005), considering the two analyzed RCPs, and the different ET_o estimation methods (*Tu* and *Ab*).

3 Results And Discussion

3.1 Climate models performance

The performance of GCMs in simulating ET_o show under/overestimations that varied according to region and model (Figures 1 and 2). By contrast, the results using the *Tu* method (Figure 1) and the *Ab* method (Figure 2) were quite similar. The ensemble mean of GCMs smoothened the individual biases of the models, but still showed overestimations for some locations throughout the year, mainly in the North of Brazil (Figures 1 and 2).

There was divergence in ET_o estimation among the GCMs when using *Tu* (Figure 1) and *Ab* (Figure 2) methods, different from results from Llopart et al. (2020) when using a combination of 2 global and 8 regional models for South America. The CanESM2, CNRM-CM5, IPSL-CM5A-MR and MIROC-ESM models showed overestimations (up to 2.5 mm day^{-1}) in both methods, mainly in the North of Brazil, and in parts of the Center-West. The HadGEM2-CC and MRI-CGCM3 models showed underestimations (up to 1.5 mm day^{-1}) in the Southern and Northeastern regions of Brazil, respectively. In general, both methods showed the same under/overestimates per region and per model. The only difference was that under/overestimates were more intense in the *Ab* method (Figure 2) than in the *Tu* method (Figure 1).

When individually analyzing model performance in simulating the variables that are used to calculate ET_o, we identified that the temperature patterns (mean and maximum) were similar among the GCMs, except for CanESM2, which had overestimations up to 5°C for the northern region of Brazil during the austral spring (Supplementary Material 1 and 2). For *RH* (SM. 3), the CanESM2, CNRM-CM5 and IPSL-CM5A-MR models gave underestimates above 10%, mainly in the North, and overestimates from the Northeast to South of Brazil. The HadGEM2-CC, MIROC-ESM and MRI-CGCM3 models showed an opposite trend for under/overestimated, i.e., the models could not adequately simulate *RH*, showing discrepancies among the GCMs with respect to the data. The GCMs patterns diverged from each other mainly in the R_s simulations (SM. 4), with most overestimates (greater than 3 MJ m^{-2} day^{-1}) for all of Brazil throughout the year. In general, the MRI-CGCM3 better represented the climate variables (in magnitude and spatial pattern), and consequently better represented ET_o estimates (Figures 1 and 2). This result is different from Guimarães et al. (2016) performed for the Northeast of Brazil, where the HadGEM2-CC climate model performed the best for ET_o (correlation = 0.6 to 0.8) of all the GCMs studied.

3.2 Climate changes on ET_o

Figures 3 to 6 show the seasonal and annual climate changes projected for ET_o using the *Tu* and *Ab* methods under different radiative forcing scenarios for the end of the 21st century (2071-2100) for all of Brazil. In general, climate change projections for ET_o relative to RCP 4.5 (Figures 3 and 5) show similar spatial patterns with lower intensity compared to RCP 8.5 (Figures 4 and 6). Additionally, the projected climate changes for ET_o show similar spatial patterns and magnitudes between the different estimation methods. The *Tu* method gave lower intensity results compared to the Ab method.

Both methods project a general increase (0.6 to 1 mm day^{-1}) for ET_o, mainly in the North, Northeast, and Center-West of Brazil for the CanESM2, HadGEM2-CC and MIROC-ESM models. The CNRM-CM5 and MRI-CGCM3 models showed less intense increases (0.2 to 0.4 mm day^{-1}) for all of Brazil. The IPSL-CM5A-MR model had the smallest projected increases (0 to 0.2 mm day^{-1}), mainly using the *Tu* method. Almost all of Brazil will be affected by increases greater than or equal to 1 mm day^{-1} in the ET_o rate under greater radiative forcing scenarios (Figures 4 and 6). The climate projections by the ensemble mean for the six GCMs using the different estimation methods (*Tu* and *Ab*) showed a tendency for increased ET_o for all of Brazil, but the magnitude of this increase was smoother, mainly in the North, Northeast, and Center-West of Brazil (Figures 3-6). These results corroborate the results of Cardoso and Justino (2014), who calculated ET_o using the Penman-Monteith method for a regional climate model coupled with a potential vegetation model, and Llopart et al. (2020), who considered a simplified water balance with regional climate models. Both authors obtained an increase of up to 3 mm day^{-1} for the Northern region of Brazil. However, our results differ from Andrade et al. (2020), who used soil water assessment tools and regional climate models and obtained a reduction of 0.36 mm day^{-1} for a part of Northeastern Brazil.

The climate change projections for T, T_{max}, RH and R_s for RCP 4.5 show similar spatial patterns, but with lower intensities than RCP 8.5. For brevity's sake, the supplementary material shows projections for only these variables for scenario RCP 8.5 (SM. 5-8). The GCMs show good agreement among each other for T (SM. 5) and T_{max} (SM. 6) projections, with increases towards the end of the 21st century up to 6°C for RCP 8.5. The most intense temperature changes (from 4 to 6°C) were projected in the CanESM2, HadGEM2-CC, IPSL-CM5A-MR and MIROC-ESM models, mainly for the North and Center-West regions of Brazil. The CNRM-CM5 and MRI-CGCM3 models projected less intense increases (from 2 to 3°C) for southern Brazil.

RH projections showed variable spatial patterns and magnitudes among the GCMs for all of Brazil (SM. 7). Nonetheless, generally these tended to decrease by 6% (RCP 4.5) to 10% (RCP 8.5) towards the end of the 21st century. This *RH* reduction can be explained by decreased precipitation across most of Brazil

(Llopart et al. 2020; Sousa et al. 2019). In the South of Brazil, where precipitation increases are projected, there was no significant projection for increased/reduced *RH*. In the CanESM2, CNRM-CM5, HadGEM2-CC and MIROC-ESM models, the greatest *RH* reduction (~ 10%) occurred in the North and Center-West of Brazil projected throughout the year, and in the Northeast of Brazil during JJA and SON in the MRI-CGCM3 model. By contrast, the IPSL-CM5A-MR model did not show significant trends towards increased or decreased *RH* towards the end of the 21st century.

The R_s projections were different among the six GCMs (SM. 8). The CanESM2, HadGEM2-CC, MIROC-ESM and MRI-CGCM3 models projected increased R_s at around 3 MJ m^{-2} day^{-1}, mainly in the North and Northeast of Brazil. The CNRM-CM5 model did not show any significant increase (or reduction) for the end of the 21st century. The IPSL-CM5A-MR model, on the other hand, showed a reduction at 1.5 MJ m^{-2} day^{-1} in the extreme North of Brazil, and inland in the Northeast. This pattern was also observed by Cardoso and Justino (2014), who explained these divergences as changes in surface albedo and in the heterogeneity of precipitation projections from the individual regional climate models.

In general, the results converge to the spatial and temporal patterns expected in the signal change (increase), since the projected increases in air temperature and reductions in relative humidity should lead to increased ET_o (Lemos Filho et al. 2010; Santos et al. 2017; Jerszurki et al. 2019). With respect to spatial and temporal patterns, results released by the IPCC (2013, 2021), Torres and Marengo (2014) and Torres et al. (2021) proved that increases in temperature will be more intense in the North, Northeast and Center-West of Brazil, and there will be different precipitation pattern changes, which will be negative (positive) in the Northeast (South). This indicates greater ET_o increases in the North, Northeast, and Center-West of Brazil, and possibly lesser increases in the South of Brazil, as demonstrated using both methods (Figures 3-6).

Some authors (e.g., Fan et al. 2016; Gao et al. 2017; Lin et al. 2018) emphasize that impacts to evapotranspiration arise from interactions between climatic factors and local conditions, e.g., type of vegetation cover, and the impacts of human activities. Such factors increase uncertainties with respect to the contribution that each variable, both above and below ground (Ruosteenoja et al. 2018; Monteiro et al. 2021), will have on evapotranspiration processes in future climate conditions. New analyses should be performed with recent state-of-the art GCMs (CMIP6), that have been evaluated in the IPCC Sixth Assessment Report (IPCC AR6), using different socioeconomic pathways (Eyring et al. 2016). Moreover, future studies could take into account additional important meteorological variables for impact evaluations, like soil moisture.

4 Final Considerations

This study analyzed the reference evapotranspiration at the end of the 21st century, using two ET_o estimation methods (*Tu* and *Ab*), two radiative forcing scenarios (RCPs 4.5 and 8.5), and six climate models from the CMIP5 (CanESM2; CNRM-CM5; HadGEM2-CC; IPSL-CM5A-MR; MIROC-ESM; MRI-

CGCM3). The analyses were carried out with the ensemble mean and individually to analyze the response of each model, despite MRI-CGCM3 being slightly superior in simulating ET_o for historical period.

The six climate models showed different simulations for global solar radiation and relative humidity (largest discrepancy), except for mean and maximum air temperature input variables. Additionally, the models showed some divergence for ET_o simulations using the *Tu* and *Ab* methods, with overestimates (up to 2.5 mm day^{-1}) in some climate models, and underestimates (up to 1.5 mm day^{-1}) in others. Therefore, since the *Tu* method was slightly superior to the *Ab* method when comparing to the observed data, the *Turc* method was more reliable in estimating ET_o for future climate chance scenarios.

Despite the divergences in the climate models for some input variables used to calculate ET_o, climate projections indicated similar patterns for the analyzed climate models, and for the two ET_o estimation methods used, with projected increases (1 mm day^{-1}) mainly in the North, Northeast, and Center-West of Brazil. The results were more intense when using the *Ab* method.

The assessment of the impacts of climate change on evapotranspiration performed by this study can be useful in outlining adaptation measures to cope with damages caused by changes to various sectors of the economy, e.g., agriculture, forestry, and hydroelectric generation in Brazil. Additionally, future studies seeking to verify climate change evapotranspiration trends should also consider both above and below ground variables, as well as they should be performed with recent state-of-the art GCMs (CMIP6), that have been evaluated in the IPCC Sixth Assessment Report (IPCC AR6), using different socioeconomic pathways.

Declarations

Funding: Partial financial support was received from Minas Gerais Research Support Foundation (FAPEMIG) to the projects APQ-01392-13 and APQ-01258-17, and for granting scholarships to the 1st author (FAPEMIG process number ID-13748 - 5.304/15), and from Coordination for the Improvement of Higher Education Personnel (CAPES, process numbers 1780316 and 88882.430051/2019-01) for granting scholarships to the 1st and 4th authors.

Conflicts of interest/Competing interests: The authors have no relevant financial or non-financial interests to disclose.

Ethics approval/declarations: Not applicable.

Availability of data and material: The data used in the article will be fully available, in order to contribute to transparency. If was necessary, all data used to support the findings of this study are available from the corresponding author upon reasonable request.

Code availability: Not applicable.

Credit authorship contribution statement:

Monteiro, A. F. M.: Conceptualization, Design of methodology, Data acquisition, Data analysis, Writing and editing, Data curation, Software. **Torres, R. R.:** Conceptualization, Design of methodology, Data analysis, Writing, review and editing, Supervision, Project administration, Founding acquisition. **Martins, F. B.:** Conceptualization, Design of methodology, Data analysis, Writing, review and editing. **Marrafon, V. H. de. A.:** Data analysis, Data curation, Software.

Acknowledgments

The authors would like to thank the Minas Gerais Research Support Foundation (FAPEMIG) for financially supporting projects APQ-01392-13 and APQ-01258-17, and for granting scholarships to the 1st author (FAPEMIG process number ID-13748 - 5.304/15), and to also thank the Coordination for the Improvement of Higher Education Personnel (CAPES, process numbers 1780316 and 88882.430051/2019-01), for granting scholarships to the 1st and 4th authors. The authors also thank PhD. Alexandre Cândido Xavier for making available the observed spatialized data on the Brazilian territory, and the Natural Resources Institute of Universidade Federal de Itajubá for providing subsidies to experiments and publication of this article.

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Figures

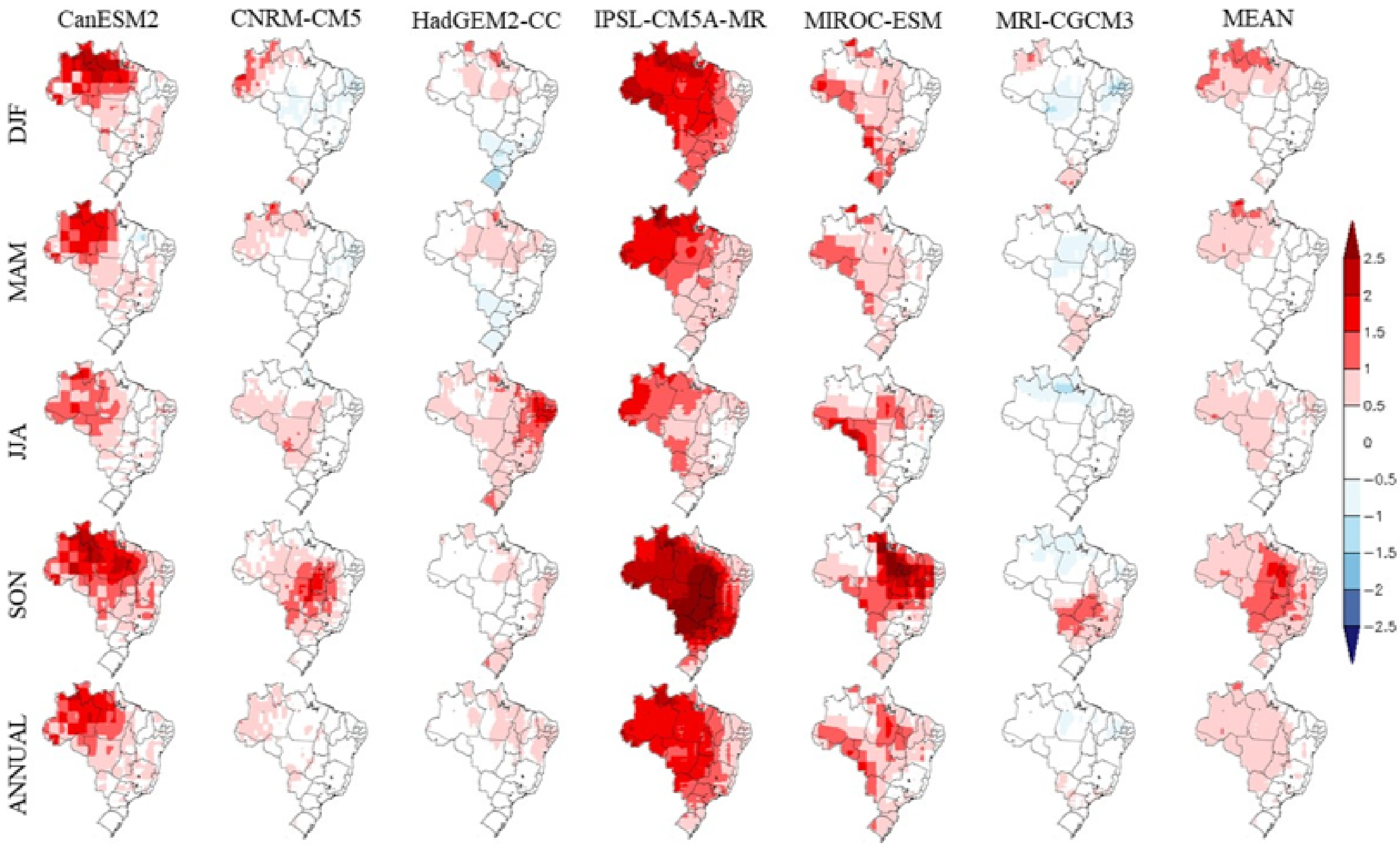

Figure 1

Seasonal and annual spatial pattern (1980-2005) for the reference evapotranspiration (ET_o) bias of each model, and the ensemble mean, using the *Tu* method. DJF, MAM, JJA and SON refer to summer, autumn, winter, and austral spring, respectively. Units are in millimeters per day.

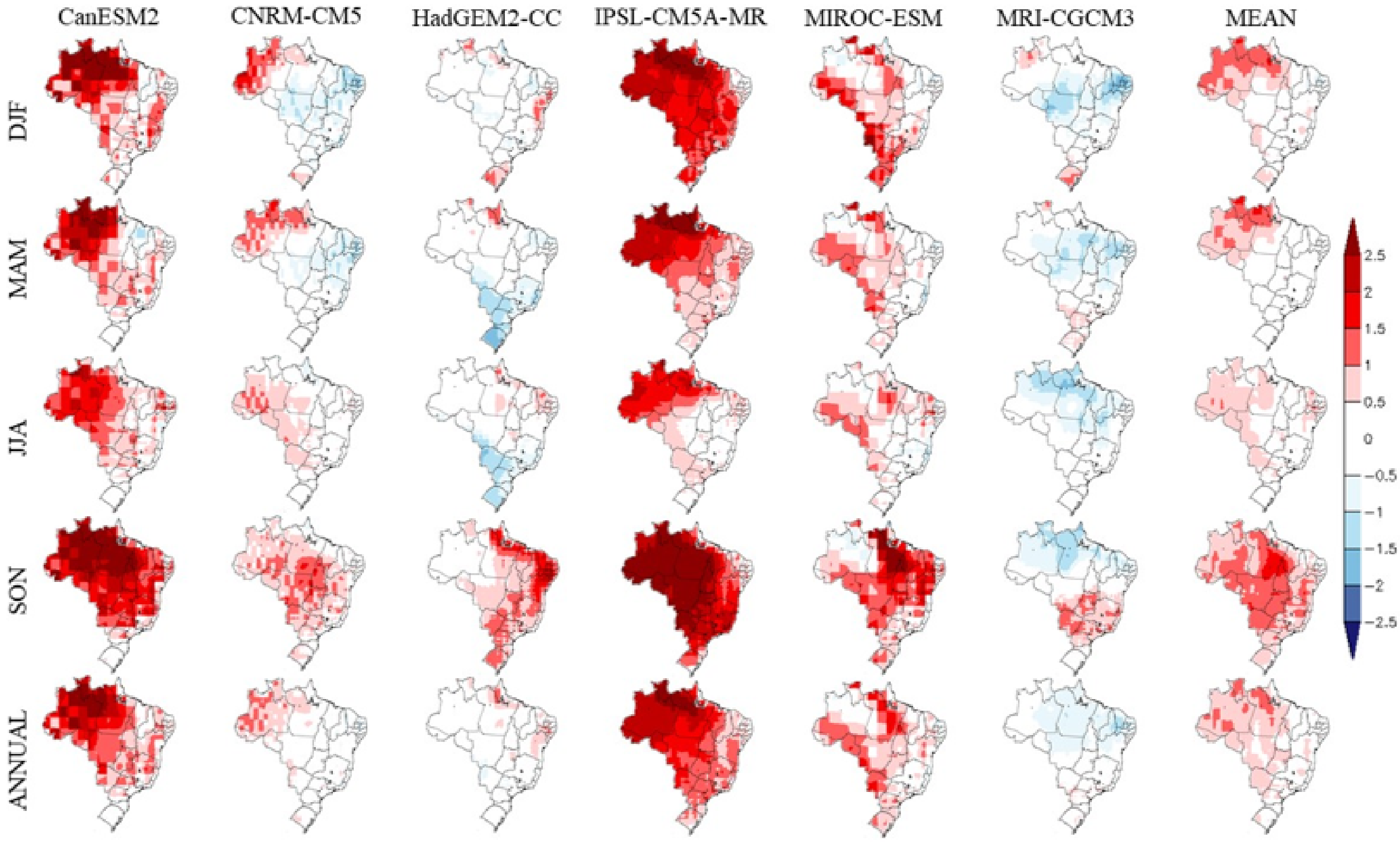

Figure 2

Seasonal and annual spatial pattern (1980-2005) for the reference evapotranspiration (ET_o) bias of each model, and the ensemble mean, using the *Ab* method. DJF, MAM, JJA and SON refer to summer, autumn, winter, and austral spring, respectively. Units are in millimeters per day.

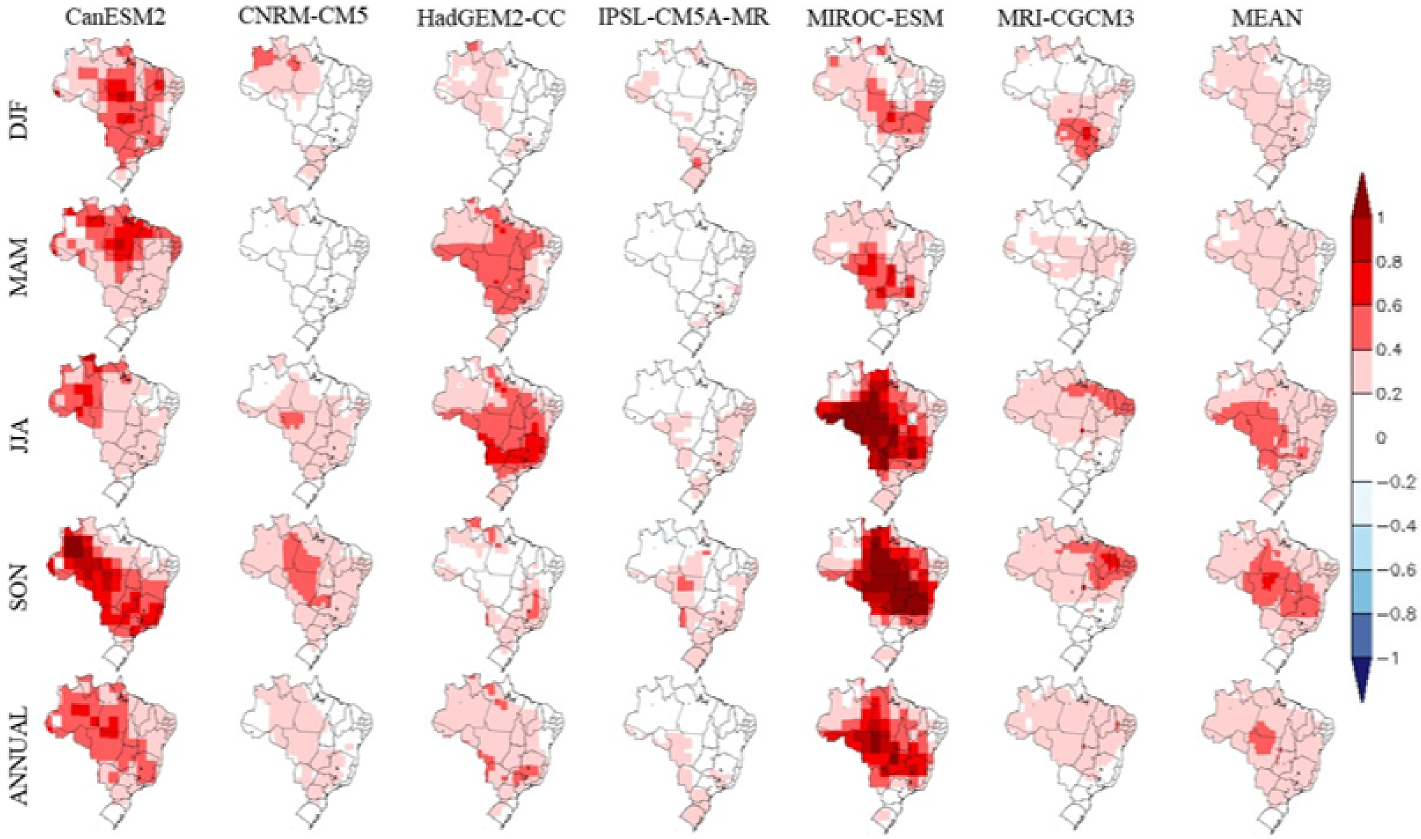

Figure 3

Seasonal and annual projected climate change in the reference evapotranspiration using the *Tu* method for the late 21st century (2071-2100) for RCP 4.5. DJF, MAM, JJA and SON refer to summer, autumn, winter, and austral spring, respectively. Units are in millimeters per day.

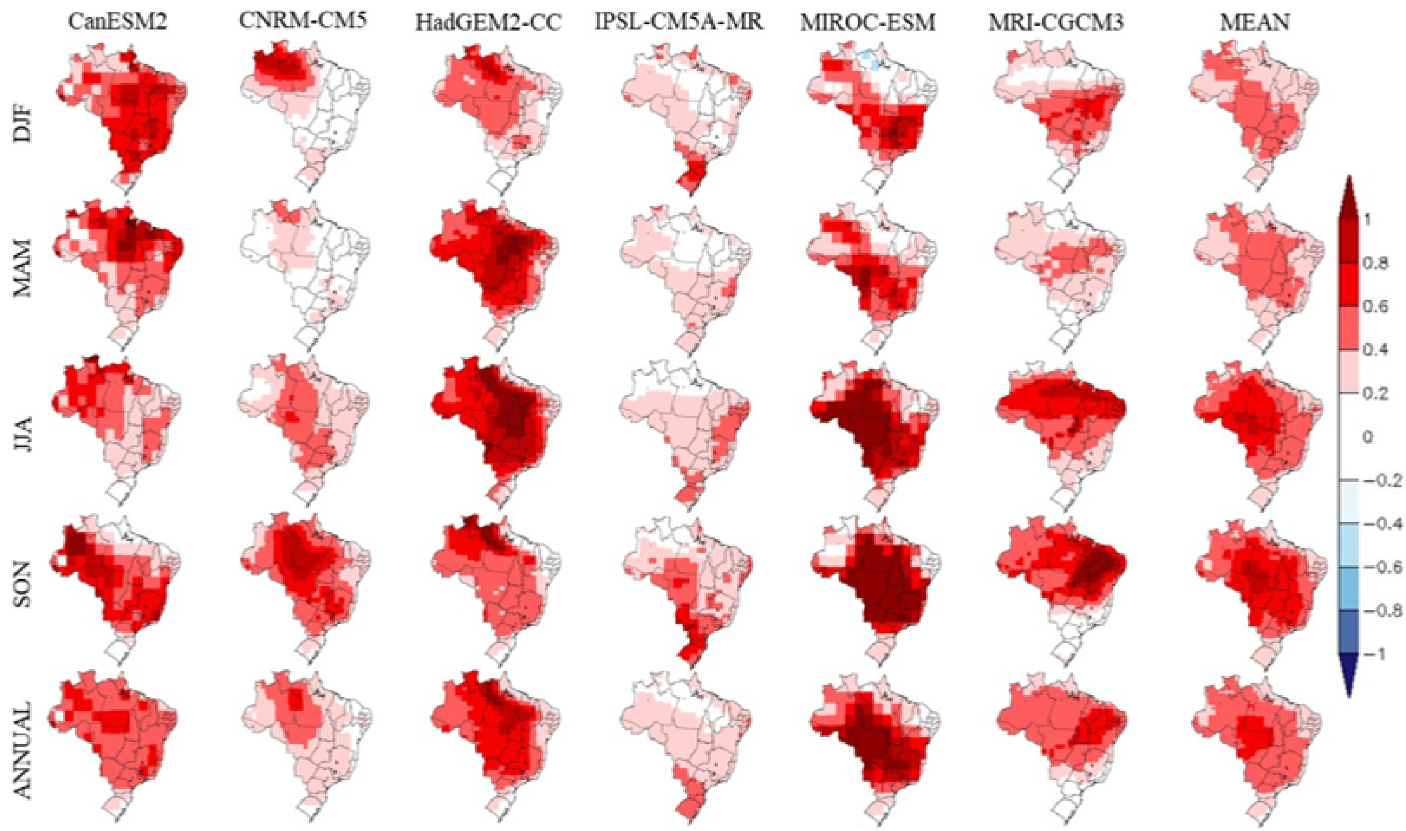

Figure 4

Seasonal and annual projected climate change in the reference evapotranspiration using the *Tu* method for the late 21st century (2071-2100) for RCP 8.5. DJF, MAM, JJA and SON refer to summer, autumn, winter, and austral spring, respectively. Units are in millimeters per day

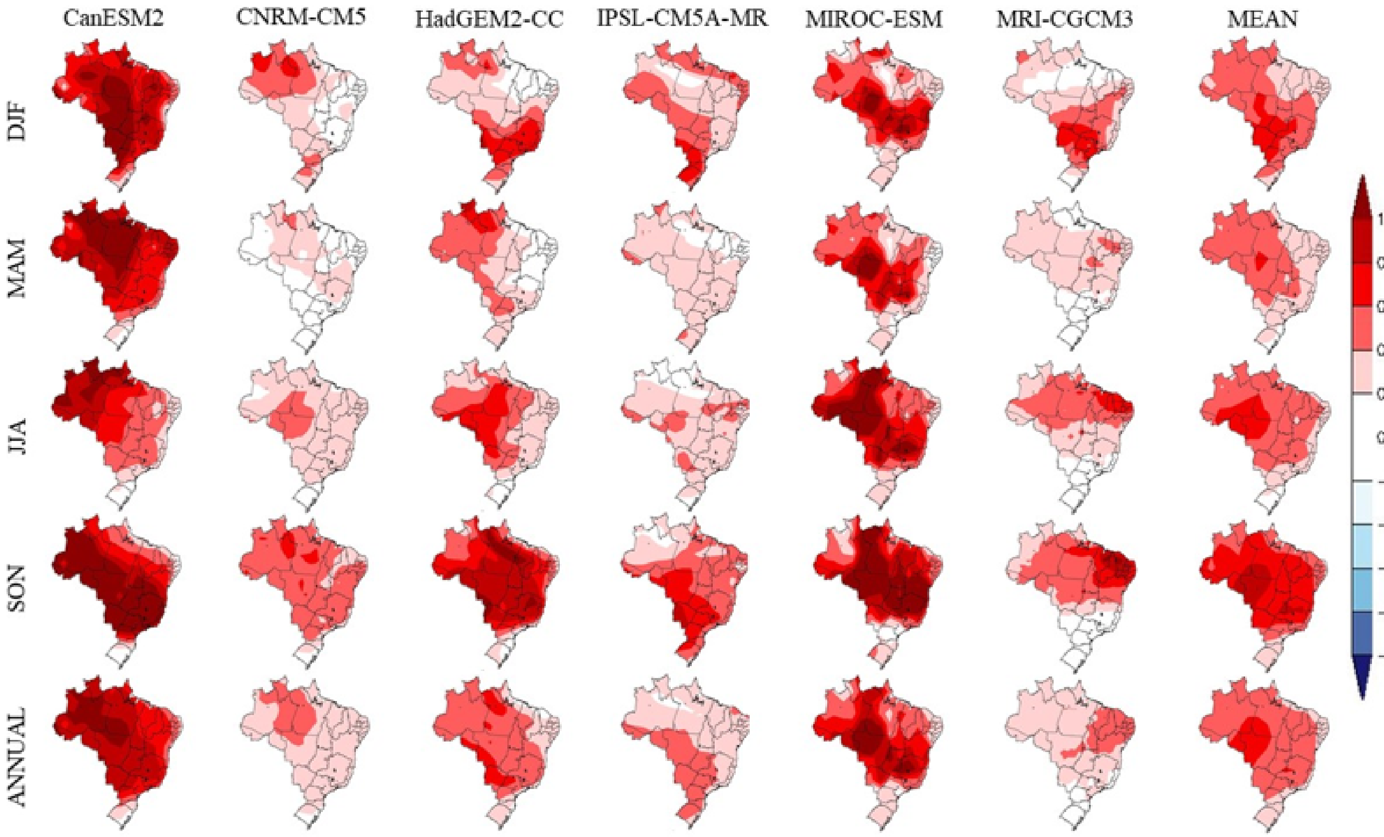

Figure 5

Seasonal and annual projected climate change in the reference evapotranspiration using the *Ab* method for the late 21st century (2071-2100) for RCP 4.5. DJF, MAM, JJA and SON refer to summer, autumn, winter, and austral spring, respectively. Units are in millimeters per day

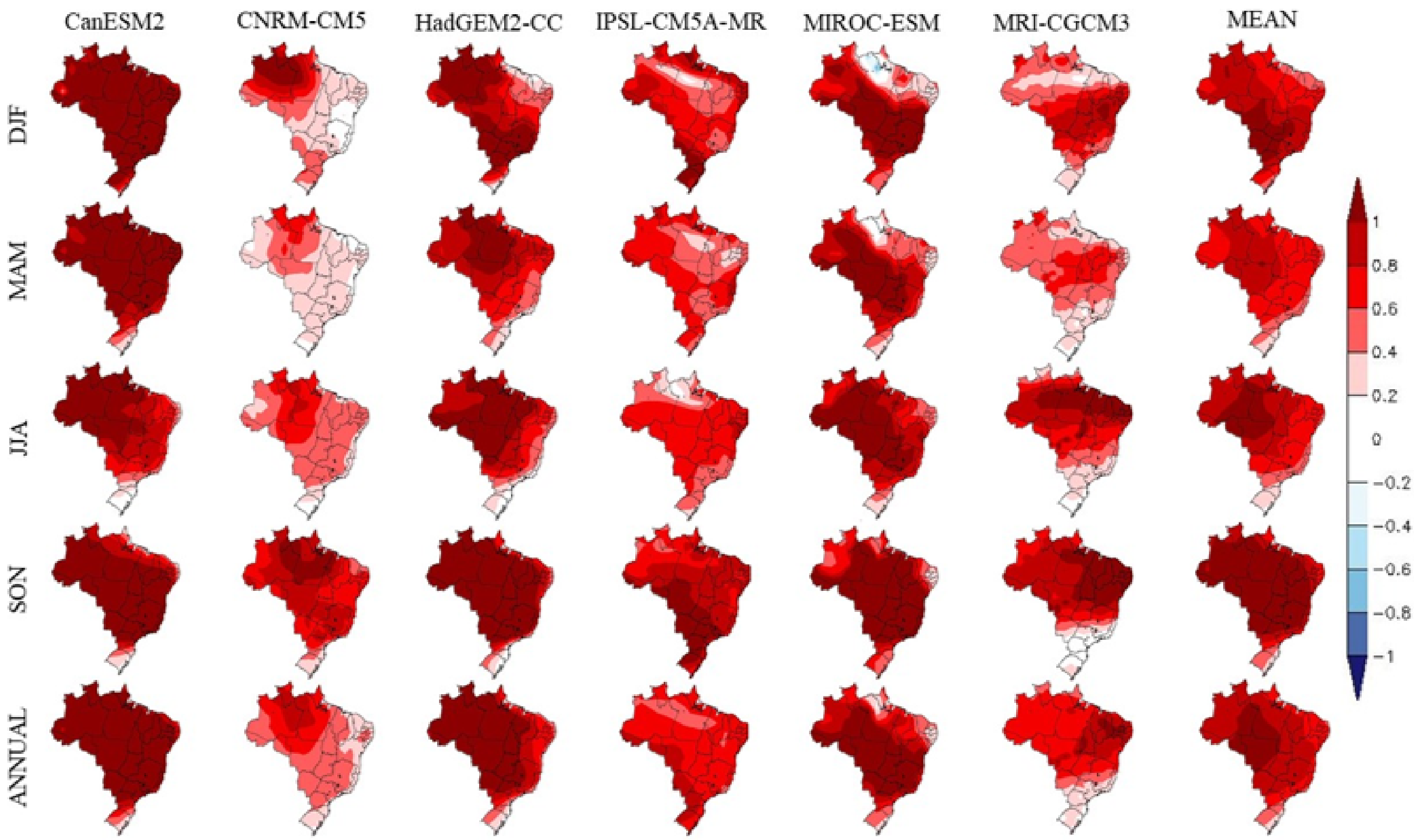

Figure 6

Seasonal and annual projected climate change in the reference evapotranspiration using the *Ab* method for the late 21st century (2071-2100) for RCP 8.5. DJF, MAM, JJA and SON refer to summer, autumn, winter, and austral spring, respectively. Units are in millimeters per day

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