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DATA FUSION STRATEGY FOR MAPPING ENVIRONMENT AND CLIMATE VARIABLES OF BRAZIL

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ABSTRACT

The study aims at utilizes the machine learning methods in cartography with a case study of climate and environmental mapping of Brazil. Rapid advances in machine learning applied to Earth observations have resulted in the application of scripting and programming languages for cartographic visualization and modelling. This research applies the Generic Mapping Tools (GMT) scripting toolset for advanced environmental mapping of Brazil. The data includes TerraClimate dataset of 2020. The GMT is an advanced cartographic tools that operates mapping from the console using scripts. Selected codes of the used scripts are presented in the research for technical explanation of the workflow. The results show correlation among the parameters and demonstrate climate and environmental trends notable for different biomes of Brazil: Amazônia, Caatinga, Cerrado, Pampa and Pantanal. The study presents 10 new maps made using GMT. Based on the obtained results, the increase of precipitation is notable in the Amazônia, along with the highest temperatures in the northern Brazil (Negro river basin) which corresponds to the increase in soil moisture and runoff. The evapotranspiration is higher in the southern regions than those in the north. On the contrast, the Caatinga region shows the minimal values of evapotranspiration, soil moisture and runoff. The main advantage of scripting cartography, demonstrated in this research, consists in automated data processing which pushes climate studies towards a data-driven research. Automated mapping technically facilitates the workflow due to the fast and smooth handling of various formats and types of data. The results contribute to the environmental analysis of climate in Brazil that has applications in agricultural and food studies and shows technical use of GMT.

Key words: Brazil. Environment. Geography. Cartography. Machine Learning. Sustainable Development.

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1 Introduction

For environmental assessment, variables in the geospatial datasets are accommodated through thematic mapping using GIS and Remote Sensing (RS) methods [1-7]. Normally, climate variables include such parameters as temperature, soil moisture, evapotranspiration, precipitation, and vapor pressure deficit. Varied by different GIS approaches, normally cartographic visualization and methods of mapping are used in different environmental applications and tasks for data fusion and visualization.

At the same time, GIS differ in terms of functionality and approaches to handle spatial data using either conventional Graphical User Interface (GUI) or advanced machine learning applications of scripting or OBIA [8–12]. However, the traditional GIS (such as ArcGIS, SAGA GIS, QGIS, ILWIS GIS) is not the exclusive method in which datasets can be integrated, assessed and visualized and used for environmental analysis [13–15].

Machine learning methods based on automatization in data processing recently achieved much attention in geospatial domains, including climate and environmental studies [16-17]. The machine based data processing includes such approaches as scripting cartographic tools (e.g. Generic Mapping Tools (GMT) of GRASS GIS) [18-19], deep learning algorithms [20-21], programming languages (e.g. Python or R) [22-23] and advanced statistical data analysis [24-25].

However, the application of scripting cartographic toolset GMT have not so far been sufficiently presented in the environmental and climate mapping of Brazil. At the same time, GMT presents the advanced tools for thematic mapping and visualizing data as map series [26-27]. Specifically, the GMT operates mapping by scripting from the console. This facilitates mapping compared to the traditional GUI-based GIS approach. The GMT makes mapping fast, accurate and fine, which is achieved through the machine based data processing.

Using scripting and machine learning approaches in mapping enables to effectively visualize descriptive geographic datasets with coordinates and variables in multiple physical properties, to perform fusion of the multi-source data (e.g. netCDF, TIFF, txt, gmt), to technically integrate and overlay raster and vector layers and to visualize conceptual elements of the environmental landscapes. In such a way, scripting cartography presents a deep link between the technical data processing and geographical phenomena depicted on the maps.

Here this study reports on the use of the advanced cartographic machine learning method of GMT scripting for studying climate variability and its environmental effects of several biomes of Brazil observed using TerraClimate dataset: https://climate.northwestknowledge.net/TERRACLIMATE/index_directDownloads.php

TerraClimate is a project of the open source gridded data collection covering the Earth. It consists of environmental, meteorological and hydrological variables as time series, starting from 1958 until now. The data are downloadable on a monthly basis with high geospatial resolution, global coverage, and time repeatability of observations, which makes TerraClimate a valuable source for environmental and meteorological research. The climate grids are derived from the WorldClim project with metadata for the time-series analysis. The advantages of the TerraClimate datasets can be summarized as follows:

First, datasets of TerraClimate are free and open access, available for everyone to download for analysis, study, research or mapping.

1. Second, TerraClimate presents regular monthly climate reports which enable to perform statistical analysis of the data, e.g., model climate change fluctuation.
2. Third, TerraClimate includes hydrological variables for the ecological and environmental mapping and analysis of surface hydrological processes, such as runoff, actual evapotranspiration, soil parameters (for example, soil moisture), and climatic water deficit.
3. Forth, TerraClimate presents integration of spatial high-resolution climate data with high temporal repeatability starting from 1958 up to now. It enables to perform time series analysis.

A series of climate model has been presented using TerraClimate data visualized from the NetCDF formal to determine the correlation between variables (temperature, precipitation, soil moisture, runoff, Palmer Drought Severity Index (PDSI) and vapor pressure deficit). These datasets were used to demonstrate the connectivity between the environment and climate that led to the formation of various landscapes and biomes in Brazil. This study concludes by considering the implications of the presented maps and advanced cartographic visualization for a better understanding of the factors controlling the environmental patterns in Brazil: Amazônia, Caatinga, Cerrado, Pampa and Pantanal. The paper also discusses the role that climate variation plays in the formation of the ecological landscapes in South America.

2 Experimental and Methodological Part

This study uses the GMT to present a new series of maps demonstrating that the spread of such climate variables as temperature, soil moisture, precipitation and surface runoff well illustrates a correlation among these data showing the environmental variability in the important biomes of Brazil: Amazônia, Caatinga, Cerrado, Pampa and Pantanal [28].

For the visualization and mapping, data selection for climate and environmental parameters was determined for the year 2020. The TerraClimate dataset for climate mapping (Fig. 2–10), and a GEBCO high-resolution dataset (Figure 1) have been used for mapping to investigate the variations in the environmental, climate and elevation parameters over Brazil. The data were visualized in a spatial coverage of the whole country. Various cartographic color palettes were applied to better approximate the climate characteristics within the data extend for each of the maps.

Different regions of Brazil (Amazônia, Caatinga, Cerrado, Pampa and Pantanal) have been visualized using the TerraClimate and GEBCO datasets in order to demonstrate gradual changes in environmental and climate parameters according to the climate situation in 2020. The cartographic techniques used for all maps are described in Section 2.3 (Machine learning in cartography) which includes the most important codes of GMT. In order to enable comparison of maps, the TerraClimate and GEBCO data were visualized in the identical projection (Mercator) and spatial extent (Brazil), for instance, Fig. 2 and Fig 3 showing climate parameters on precipitation and temperature of Brazil for the year 2020.

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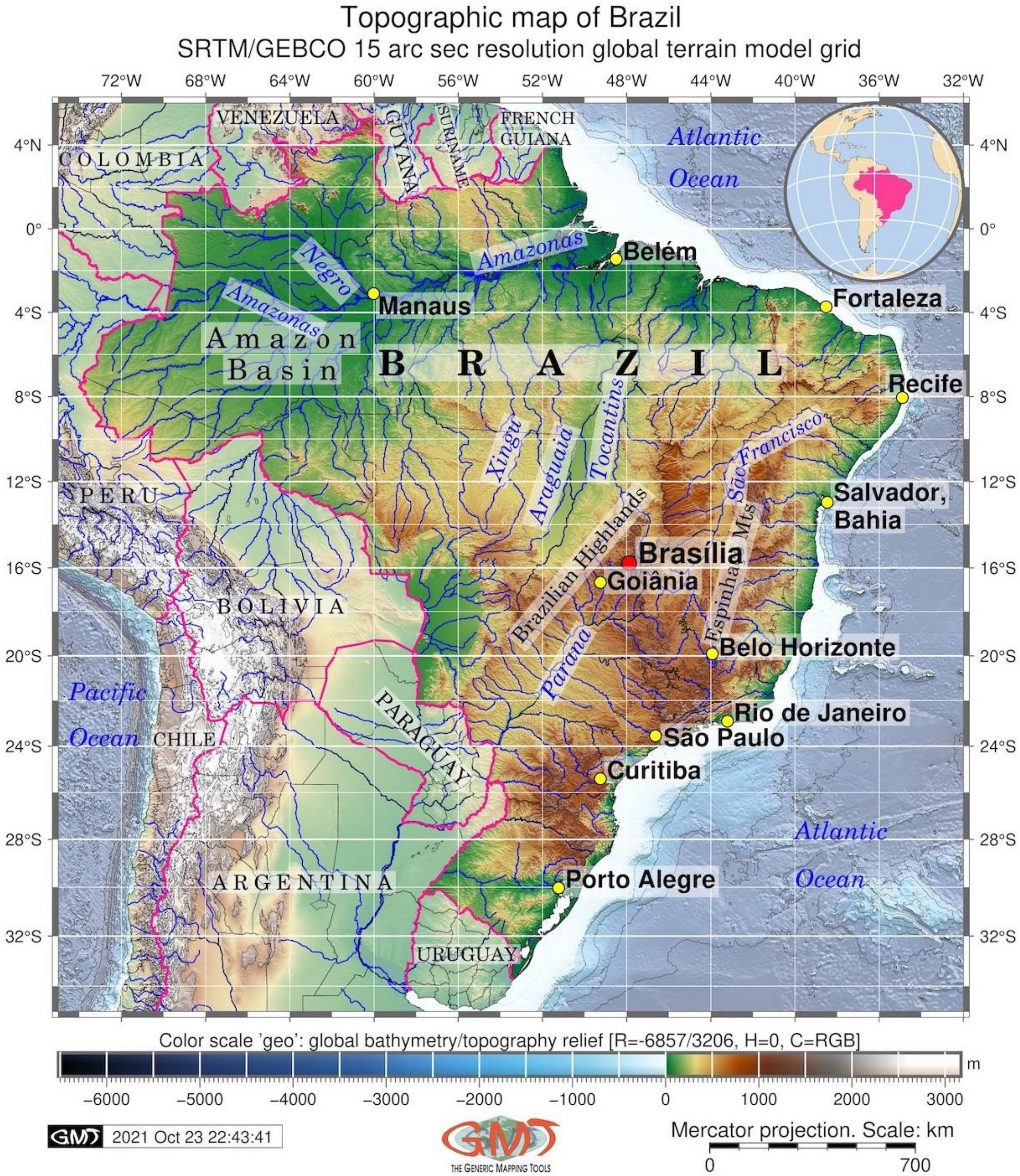

Figure 1 – Topographic map of Brazil. Mapping: GMT. Source: author.

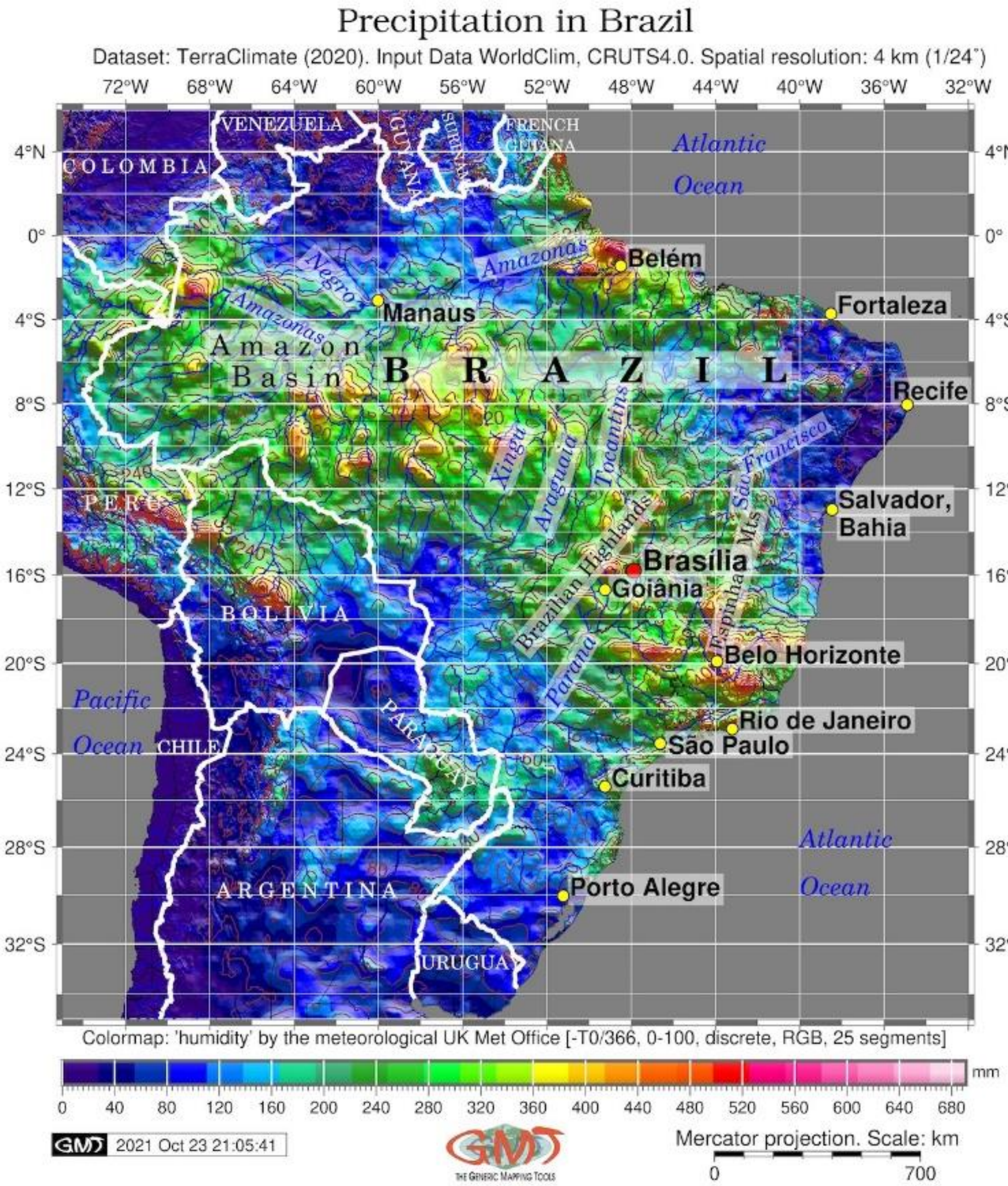

Figure 2 – Precipitation map of Brazil. Mapping: GMT. Source: author.

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2.1 Study area

Brazil covers 47% of the South America which makes it the most significant country of the continent [29]. The exact geographical extent of the country is between 33°44'32"S to 5°16'20 N latitude, and between 73 59'32" W to 34°47'30" E longitude (Figure 1). Brazil has boundaries with all South American countries except for Chile and Ecuador [30]. The most important biomes of Brazil include Amazônia, Caatinga, Cerrado, Pampa and Pantanal. They have different climate and environmental setting, as briefly discussed below.

The Amazônia biome is formed by the Amazon, the 2nd longest river in the world and the largest one in Brazil [31]. The Amazon largely affects the environmental and climate setting of the country as observed in multiple remote sensing based studies [32-34]. Being the most influencing and significant hydrological network in the country, the Amazon is an important source of hydro-energy [35-36]. It stretches for about 6,840 km forming a dense, complex hydrological network of connected tributary rivers. The Amazon creates a habitat for thousands of unique jungle species and endangered rain forest plants including endemics of the Amazônia National Park, which makes it a precious region for biodiversity [37].

The Caatinga, located in the NE of Brazil, is presented by thorn xeric shrubland and seasonally dry forests, with rich and diversified biota in over the 2000 species [38], formed under the impact of dry climate and specific soils [39-40].

Cerrado, the vast tropical savanna ecoregion, is located in the central-western Brazil [41]. It includes massive grasslands covering ca. 25% of its surface, classified among the most threatened regions in South America [42-43] and reported for their environmental vulnerability [44]. The distribution of pastures in cerrado correlates with local climate setting where the higher scattered tree density is generally observed in regions with lower and concentrated rainfalls [45]. The geographical distribution of the cerrado generally corresponds to the Brazilian Highlands.

The Pampa presents a plain region in the southernmost of Brazil notable for temperate climate and evenly distributed precipitation pattern ranging from ca. 600 to 1,200 mm. The Pampa biome presents a grassland with high species richness and important role in food production in South America [46].

The Pantanal is the world's largest tropical wetland area and the flooded grasslands situated in the center of the Upper Paraguay River Basin, with area os 360,000 km^2 [47].

Such distinct geographical physical features of Brazil are presented in physiographic divisions with diverse biomes. Among them, the Pantanal, Pampa and Caatinga are the least studied in terms of ecological restoration, and Amazônia is the most studied region [48]. The diversity and uniqueness of the Brazilian environmental patterns are largely influenced by climate variations that deserve special studies and monitoring supported by the advanced cartographic outputs, as attempted in this study.

2.2 Data

Data mining, data integration and data fusion as new methods of environmental modelling with application to Brazil are presented in the existing literature [49-50]. Remote sensing grids, climate observations and geospatial coordinated data are considered as information sources in this study. Specifically, data used in this study are acquired from the open source TerraClimate project [51] which is received through the remote sensing Earth observations and climate modelling.

The application and actuality of the open data for environmental studies is explained by the following factors:

- free access of climate information which includes the metadata, descriptions and explanations of the TerraClimate project;
- transparent and reliable sampling of GMT techniques which provide a suite of maps based on the datasets that may be used to characterize climate changes at regional scales between various regions of Brazil.
- compatible formats of the raster grids presented as netCDF format that can be converted into acceptable graphical formats, e.g. TIFF or JPG;
- standardized individual sampling techniques of TerraClimate enables highlighting correlation between different data that results in a series of compatible maps and comparative visualized data.

In order to strike a correlation between the observed range change in environmental and climate datasets and topographic model with elevation changes in various regions of Brazil (Amazônia, Caatinga, Cerrado, Pampa and Pantanal), this study presented a series of compatible maps with identical projection and spatial extent covering Brazil using a scripting machine learning methods in GMT, as explained below.

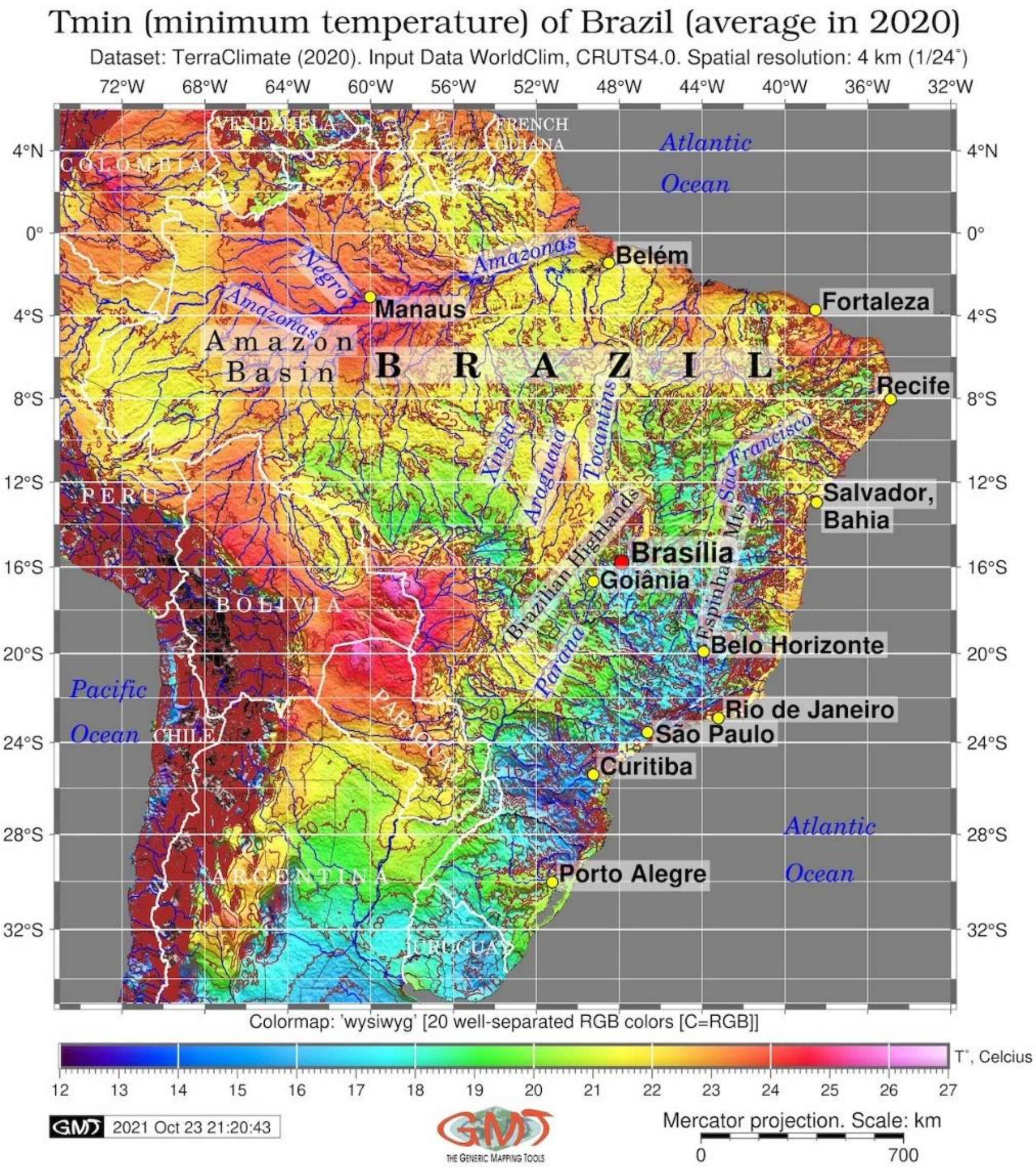

Figure 3 – Minimal temperature in Brazil. Mapping: GMT. Source: author.

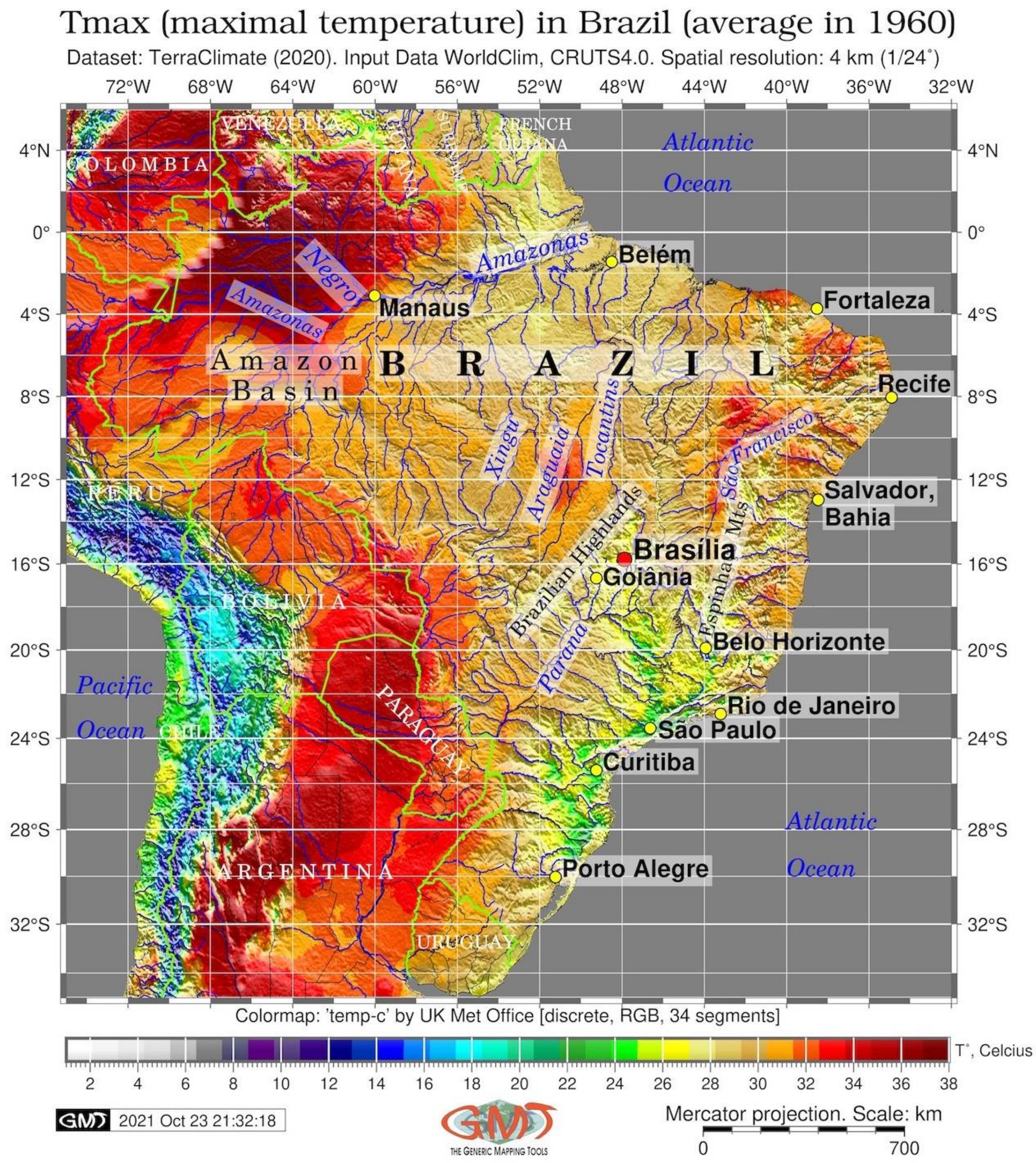

Figure 4 – Maximal temperature in Brazil. Mapping: GMT. Source: author.

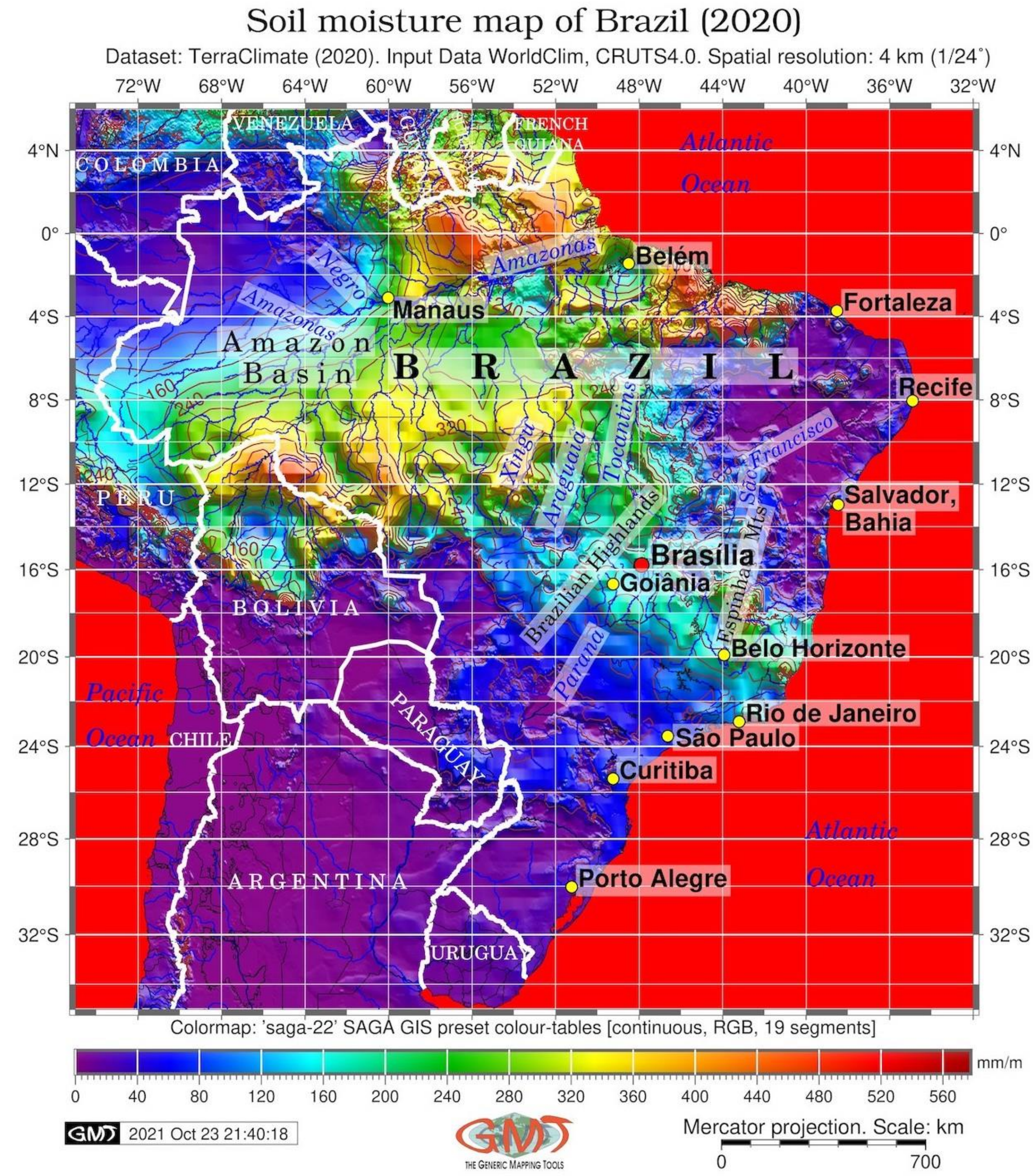

Figure 5 – Soil moisture map in Brazil. Mapping: GMT. Source: author.

2.3 Machine learning in cartography

With the rapid advances of methods of machine learning such as scripting and programming languages, their applications in cartography have recently developed in Earth and environmental sciences and now become an important approach of data processing, visualization and analysis [52-54].

By combining the knowledge on environmental and climate variations in the Brazil and a high-performance cartographic modelling by GMT using available techniques [55-57], a series of thematic maps has been established so as to visualize and analyse the variability of climate variables by the biomes in Brazil (including the min/max temperature, precipitation, runoff, PDSI, VPD and topography) and describe the specific trends and correlation of the climate variability in a cartographic and quantitative way. The data visualization and modeling methods used in this study included a variety of GMT modules used for stepwise plotting of layers using the following examples of snippets of codes:

1. Extracting a subset for the study area: ‘gmt grdcut TerraClimate_tmax_2020.nc -R285/328/-35/6 -Gbr_tmax.nc’ (Here: map of maximal temperature). In this code a sequence of 'flags', with controlling parameters executed the module. For example, in the '-R' parameter of this expression, module ‘grdcut’ subsets the region from the whole original NetCDF file (TerraClimate_tmax_2020.nc) using the defined coordinates. In this case, ‘-R285/328/-35/6’ means selecting the study from 75°W to 32°W (the system of 0° to 360°, that is 285 corresponds to the 75°W and 328 – to the 35°W) and from 35°S to 6°S.
2. Generating color palette: 'gmt makecpt -Cprecip3_16lev -V -T0/192 > pauline.cpt'. In this code, GMT computed the color palette using range defined in '-T' flag, that is, from 0 to 192. The original color palette (precip3_16lev) was extended according to the real data range which was inspected by GDAL (using 'gdalinfo').
3. Making background image: ‘gmt grdimage br_aet.nc -Cpauline.cpt -R285/328/-35/6 -JM6i -I+a15+ne0.75 -Xc -P -K > $ps’. The resulting image based on clipped data was then visualized as a background using the 'grdimage' module. The Mercator projections was used for all 10 maps by the "-JM6i" flag, where ‘6i’ means a physical printing extent of the map set up as 6 inches. The flag ‘-I+a15+ne0.75’ signifies the illumination added on the image as intensities of the output file in the (-1,+1) range and affects the ambient light.
4. Adding cities by the pstext module: ' gmt pstext -R -J -N -O -K -F+f10p,0,white+jLB+a-0 >> $ps << EOF 313.67 -23.85 São Paulo EOF'. In this code, the flags '-R -J -N -O -K ' mean continue plotting the image and overlay of the previous code; -R and -J mean continue using the same spatial extent and defined projection; -N means not clipping the image at the map boundary. The flag ‘-F+f10p,0,white+jLB+a-0’ defines the appearance of the text: its font (e.g., type ‘0’ signifies ‘Helvetica’), size (here 10 pixels, f10p) color, location (here location ‘left bottom’) and rotation of the text. The text itself is written between the EOF expression, which is a standard Linux-defined ‘end of file’ definition for a compiler, which gives an indication that the file it was reading has ended.
5. Finding statistical information from GDAL: 'gdalinfo -stats br_runoff.nc' (Here: runoff in Brazil for 2020).
6. Similar logic in the GMT language syntax has been used for plotting all the presented maps demonstrating the successful example of the machine learning applications in modern cartography. The machine learning approach in cartography provides important technical scripting support for mapping gridded raster datasets by automated visualizing that ensures precise and refined visualization in a fast and accurate way.

3 Results and discussions

3.1 Precipitation and temperature

To ascertain the comparative analysis of the distribution of background general climate variables, such as temperature and precipitation, in recent period in Brazil, data for 2020 were collected from the TerraClimate source and mapped accordingly (Figures 2, 3 and 4). Mapping climate variables is important for estimation and modelling of climate change which has been considered as one of the greatest future challenges for world environment including food [58-59].

The maximal values of precipitation in 2020 were identified in the central and south-eastern coastal areas reaching up to 600 mm (bright pink colors in Figure 2), and selected spot in the Amazônia within the small areas (360-500 mm, yellow to orange colors), while regions adjacent to the northern neighbor countries (Venezuela, Guyana, Suriname) show lesser values (40-120 mm, blue-colored areas).

Annual temperatures in 2020 vary by biomes of Brazil with the minimal values noted in the southern coastal region (between Curitiba and Porto Alegre, at around 12-14°C) and selected areas in the Espinhaço Mountains, Figure 3. Accordingly, the maximal values detected in Pantanal and central Amazonia (over 32°C), Figure 4.

3.2 Soil moisture and runoff

The results on soil moisture and runoff show correlated values visualized in maps of Figures 5 and 6, accordingly. The data well indicate the increase in soil moisture to the north of Amazon river up to 520 mm/m (bright red colors, Figure 5) and moderate local increase in soil moisture in the SE regions of Brazil (Espinhaço Mountains, Brazilia and the Goiás State).

More specifically, soil moisture map contains a sharp increased bend on the border with the north Bolivia and in the northern Brazil downstream of Manaus (as shown in Fig. 5) with the values reaching their maximum in soil moisture. Another region with notable increased soil moisture is located between the Belem and São Luís, Maranhão, which is caused by the dominating forested plain crossed by numerous rivers in the eastern part of the tropical rain forests of Amazônia.

Correspondingly, the runoff values in this region as well as in the central Amazônia have increased values (up to 350 mm, red colors in Figure 6), which is consistent in proportions with the soil moisture values observed in Figure 5. The lowest values of the soil moisture and runoff can be seen in around Caatinga (NE of Brazil) which well corresponds to the dry environmental setting in the area. In general, the change regions in the runoff as shown in the map in Figure 6 represent hydrological model that fits to changes in the precipitation map (Figure 2) and soil moisture (Figure 5), accordingly.

3.3. Evapotranspiration

Evapotranspiration is generally higher in the southern regions than those in the north (Figures 7 and 8). The average values based on TerraClimate dataset in the central Amazon basin is 55-108 mm/year (Figure 7) withs a clearly visible increase of values in the Caatinga and Cerrado (108-162).

The values of the potential evapotranspiration are comparable with those of the actual evapotranspiration (Figure 8) by the comparative analysis of the two maps, with slightly increasing values southwards of Brazil and the lowest values of AET in Caatinga (NE of Brazil, values range 12 to 65, blue colors in Figure 8). A representative model in the changes of evapotranspiration fits to the PDSI (Figure 10) and temperature maps (Figures 3 and 4). Previous studies on evapotranspiration in Brazil also shown the role of these variables for environmental monitoring [60-61].

3.4 Vapor Pressure Deficit and Palmer Drought Severity Index

The values of Vapor Pressure Deficit (VPD) in Brazil range between the 0.6-1.0 (beige colors in Figures 9). Meanwhile, certain increase in the Caatinga region can be seen within the values from 1.4 to 1.8. The Pantanal shows the slight increase in VPD values rising from 1.6 to 2.0. The VPD shows the difference between maximal possible and actual real values of the air pressure showing the effects of plants transpiration.

Because VPD corresponds to the plant transpiration rates, it is also an excellent environmental indicator for plant production and agriculture. The PDSI is more pronounced in the dry regions compared to the Amazonia rainforests (Figure 10). The values of VPD are the highest in Caatinga where they reach 1.8. This results in a good correspondence between the changes in climate and hydrological parameters, and topographic elevations. These variables well correlate with the distribution of major biomes of Brazil and show a balance with the trends of the parameters: precipitation, soil moisture, VPD, PDSI, evapotranspiration, temperature range, and runoff.

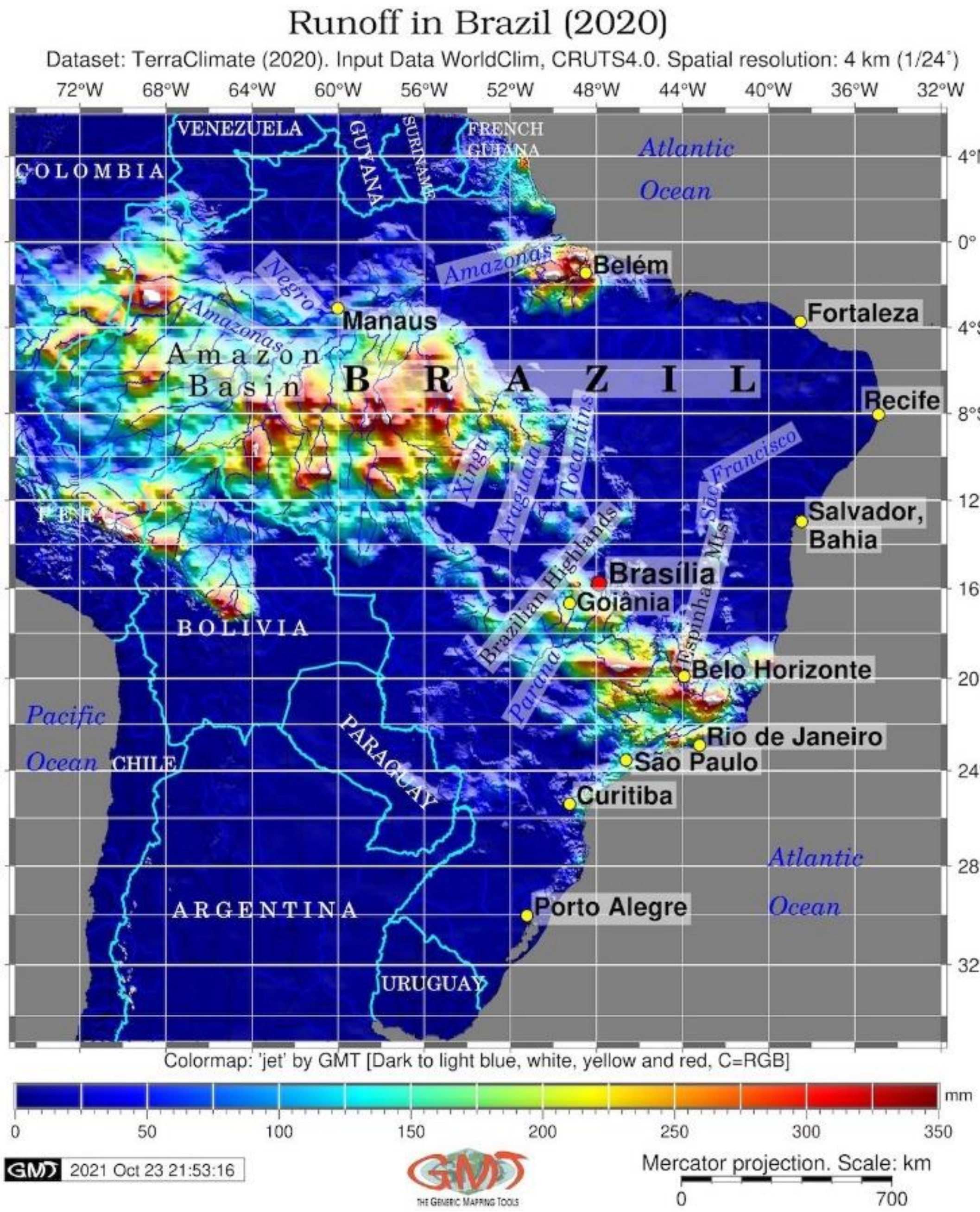

Figure 6 – Runoff in Brazil. Mapping: GMT. Source: author.

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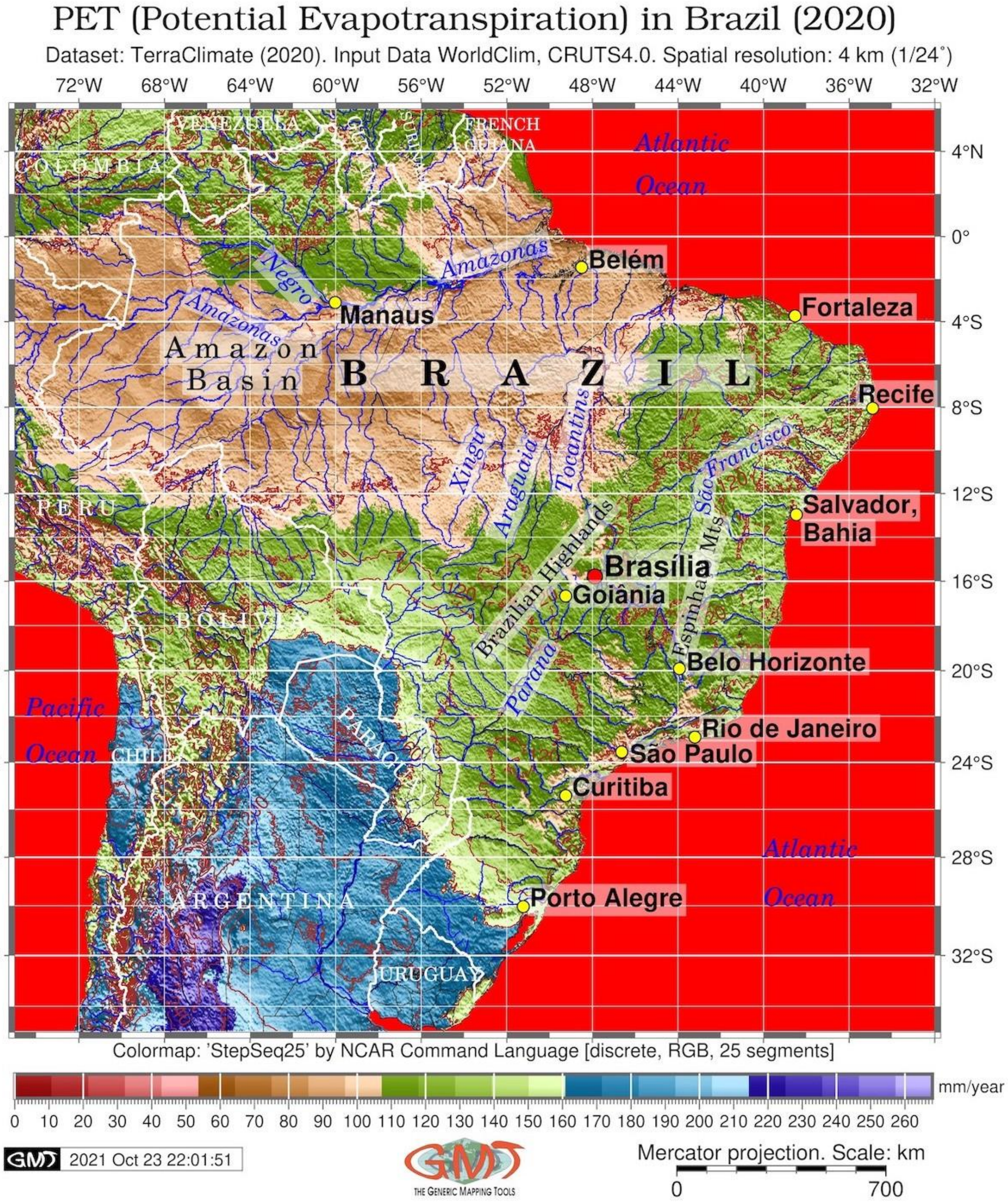

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Figure 7 – Potential evapotranspiration (PET). Mapping: GMT. Source: author.

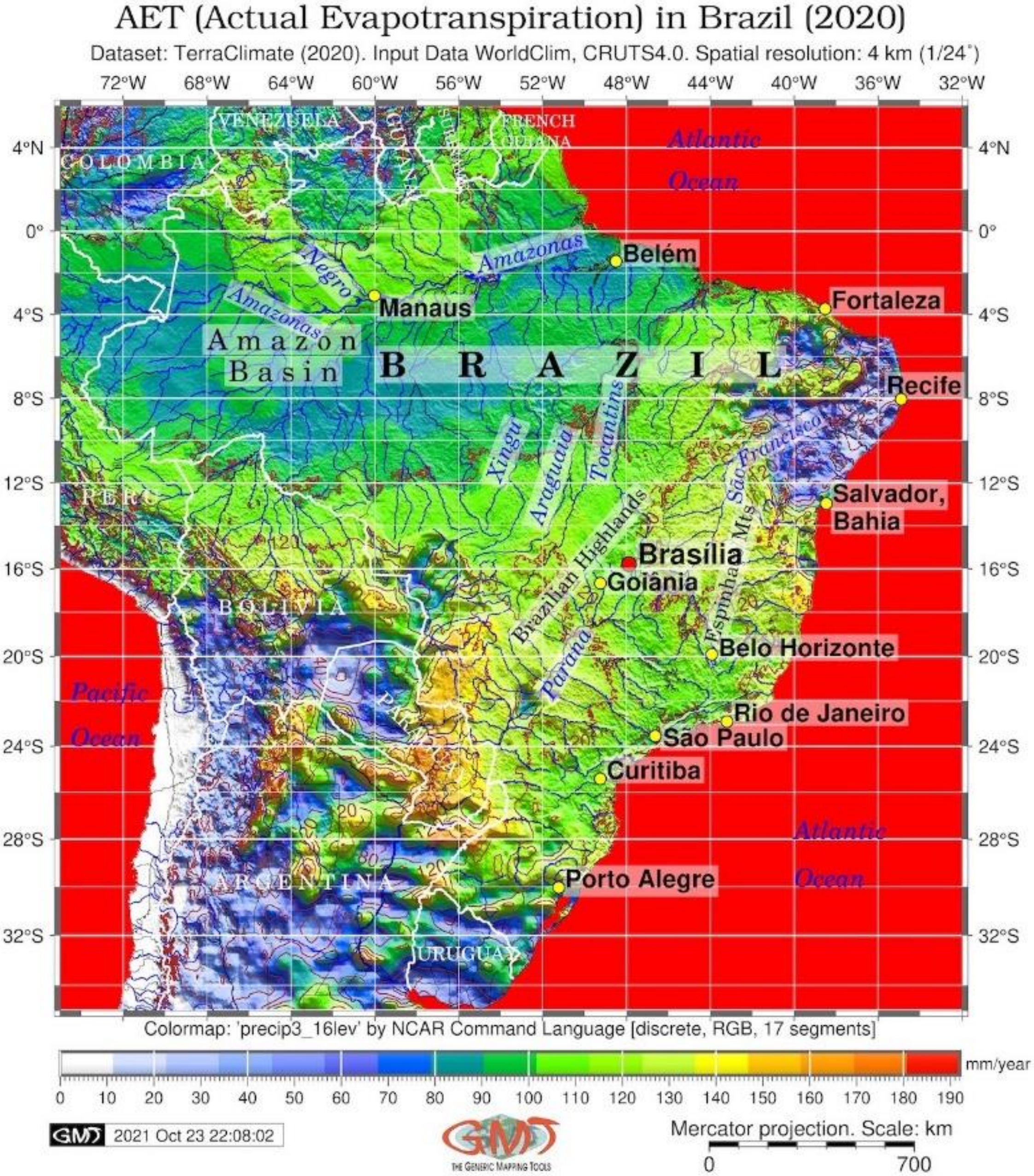

Figure 8 – Actual evapotranspiration (AET). Mapping: GMT. Source: author

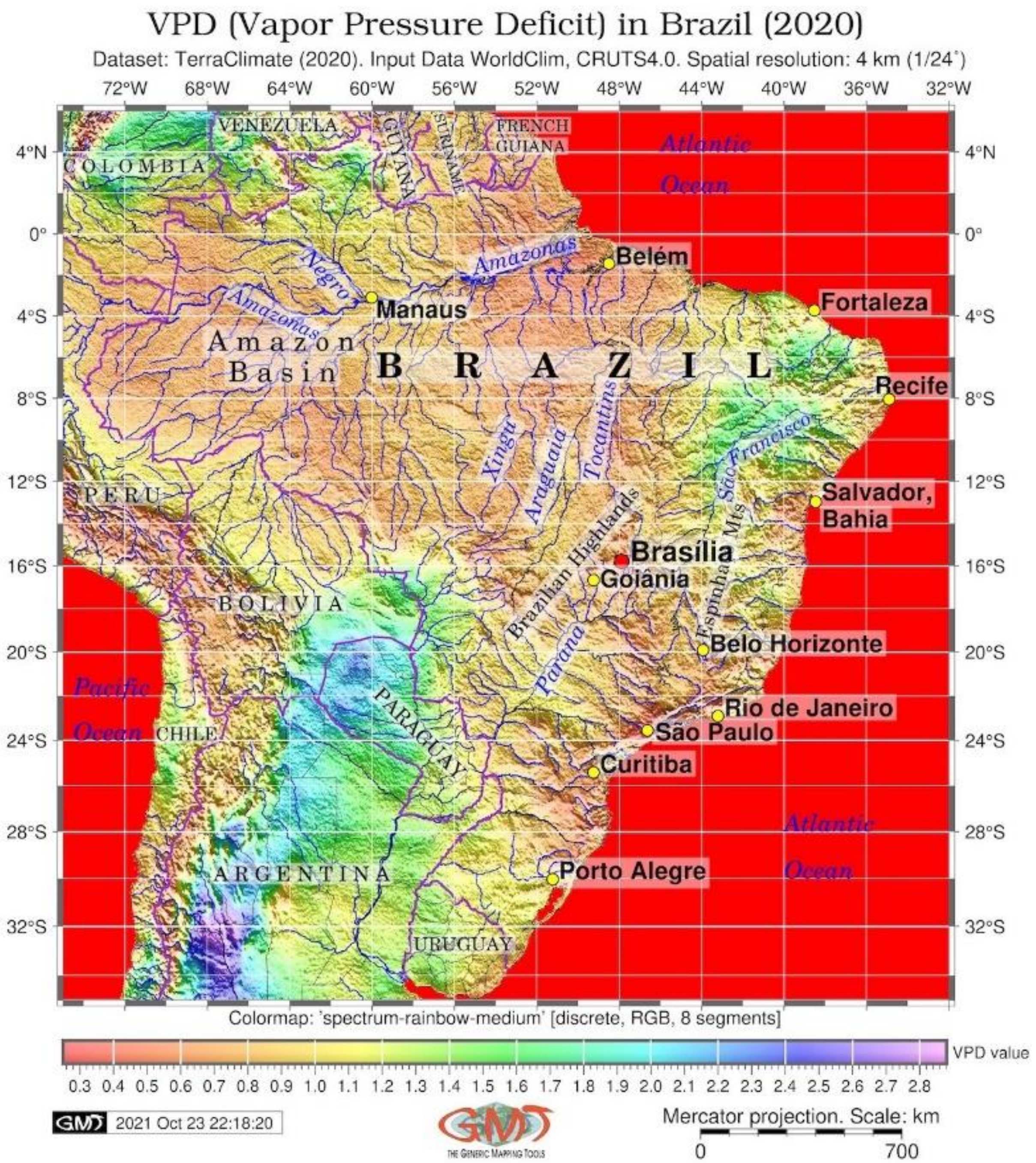

Figure 9 – VPD in Brazil (2020). Mapping: GMT. Source: author

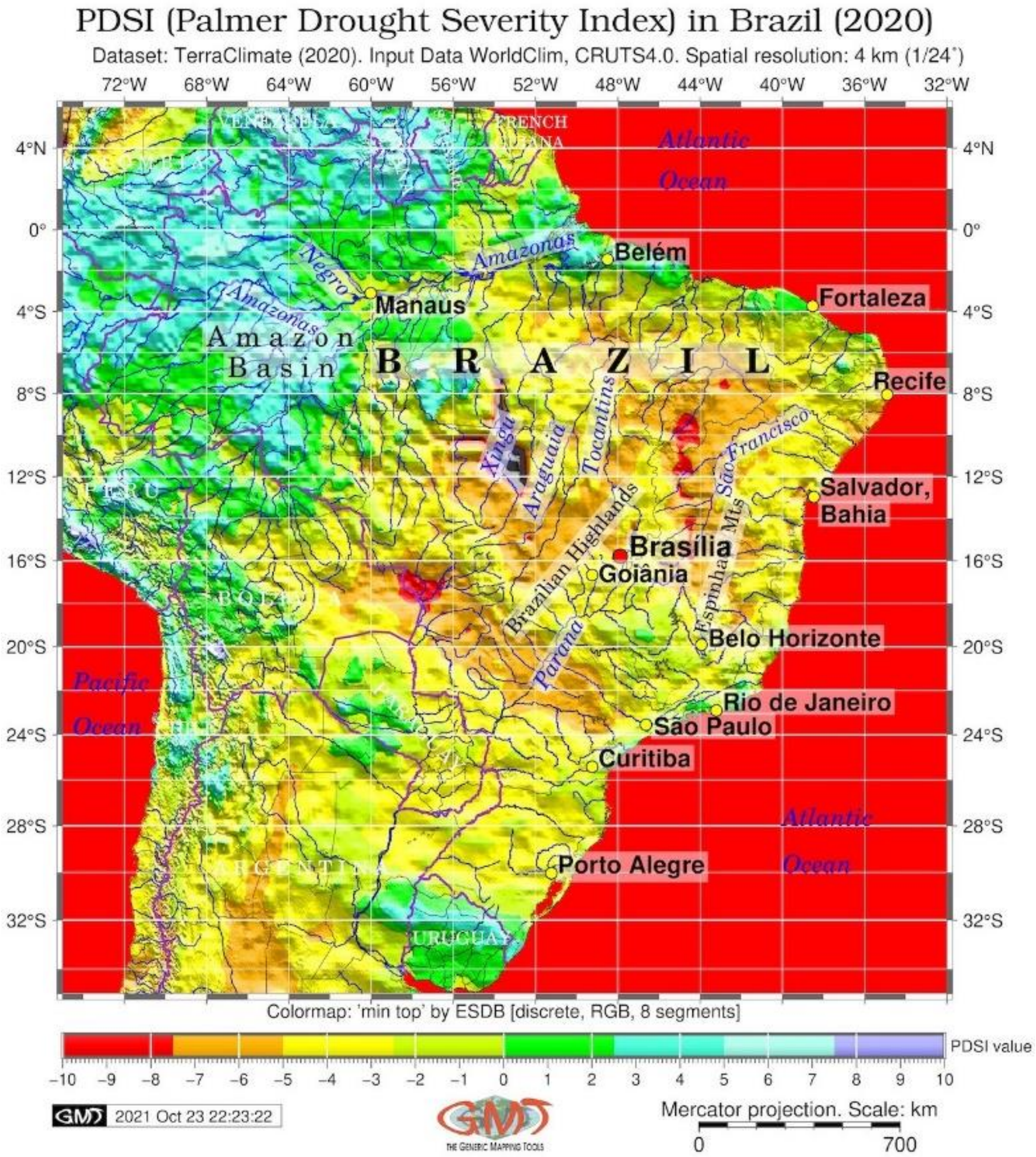

Figure 10 – PDSI in Brazil (2020). Mapping: GMT. Source: author

4 Conclusion

The demonstrated interplay among the climate and environmental factors serves climate modelling showing variations in surface temperature, precipitation, soil moisture and runoff and supports the existing studies on climate and environmental changes in Brazil. In turn, this corresponds to the distribution of PDSI and VPD over Brazil. Confirmation of topography−climate interactions over Brazil was provided by the series of plotted thematic maps using GMT scripting toolset. Spatial distribution of the climate and environmental parameters and their topographic locations have all been mapped using various color palettes aimed at highlighting general trends in changes over the main regions of Brazil.

Both datasets (obtained from GEBCO and TerraClimate, correspondingly) were visualized in the identical spatial scales and projection for compatibility reasons. The maps show complex trends in the environmental, climate and hydrological parameters in Brazil and clearly visible variations in climate variables across major biomes of the country: Amazônia, Caatinga, Cerrado, Pampa and Pantanal. Specifically, the maps show that the precipitation increases more in the rainforests of Amazon, which is followed by the Pantanal region on the border with Bolivia showing on average soil moisture increase with a clear decline of moisture south- and eastwards (Caatinga region). In regions showing the cerrado (savanna) biomes, which is the biologically richest savanna in the world, demonstrates the climate characteristics of the semi-humid tropical climate.

The importance of the climate change can be illustrated by its effects on land use and cover types which in turn causes degradation of soils and landscapes. As a result, such processes may negatively affect the food production. In view of this, this study contributes to the environmental analysis of Brazil and continues existing reports on climate modelling and monitoring maintaining policies on hazard mitigation and environmental protection [62–73]. The presented series of ten new maps made using scripting machine learning approach of GMT aims to illustrate the v ariability of the environmental setting in Brazil at regional scale.

Variation in trends and heterogeneities of the climate parameters may have various reasons (e.g., geologic origin or tectonic control, anthropogenic or topographic effects) which results in climate and environmental change. These parameters should be visualized to show correlations in environmental and climate trends. Due to the limited possibilities of traditional GIS, a systematic mapping of thematic maps might be tedious and time-consuming work. Therefore, plotting a series of thematic maps requires advanced cartographic techniques for mapping rapidly yet effectively. These challenges necessitated application of the advanced technique of GMT which presents the machine learning approach for comprehensive mapping of climate parameters in Brazil based on all available data.

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ESTRATÉGIA DE FUSÃO DE DADOS PARA MAPEAMENTO DE VARIÁVEIS AMBIENTAIS E CLIMÁTICAS DO BRASIL

RESUMO: O estudo visa utilizar os métodos de machine learning em cartografia com um estudo de caso de mapeamento climático e ambiental do Brasil. Avanços rápidos no aprendizado de máquina aplicado às observações da Terra resultaram na aplicação de linguagens de script e programação para visualização e modelagem cartográfica. Esta pesquisa aplica o conjunto de ferramentas de script GMT para mapeamento ambiental avançado do Brasil. Os dados incluem o conjunto de dados TerraClimate de 2020. O GMT é uma ferramenta cartográfica avançada que opera o mapeamento a partir do console por meio de scripts. Trechos selecionados de códigos usados são apresentados na pesquisa para explicação técnica do fluxo de trabalho. Os resultados mostram correlação entre os parâmetros e demonstram tendências climáticas e ambientais notáveis para diferentes biomas do Brasil: Amazônia, Caatinga, Cerrado, Pampa e Pantanal. O estudo apresenta 10 novos mapas feitos em GMT. Com base nos resultados obtidos, o aumento da precipitação é notável na Amazônia, juntamente com as maiores temperaturas no norte do Brasil (bacia do rio Negro) que correspondem ao aumento da umidade do solo e do escoamento superficial. A evapotranspiração é geralmente maior nas regiões do sul do que nas do norte. Em contrapartida, a região da Caatinga apresenta os valores mínimos de evapotranspiração, umidade do solo e escoamento superficial. A principal vantagem da cartografia de scripts, demonstrada nesta pesquisa, consiste no processamento automatizado de dados que impulsiona os estudos ambientais a serem baseados em dados. O mapeamento automatizado facilita tecnicamente o fluxo de trabalho devido ao manuseio rápido e suave de vários formatos e tipos de dados. Os resultados contribuem para a análise ambiental do clima no Brasil que tem aplicações em estudos agrícolas e de alimentos e mostra o uso técnico de GMT.

Palavras-chave: Brasil. Meio Ambiente. Geografia. Cartografia. Aprendizado de máquina. Desenvolvimento sustentável.

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