

Köppen's climate classification map for Brazil

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Abstract

Köppen's climate classification remains the most widely used system by geographical and climatological societies across the world, with well recognized simple rules and climate symbol letters. In Brazil, climatology has been studied for more than 140 years, and among the many proposed methods Köppen's system remains as the most utilized. Considering Köppen's climate classification importance for Brazil (geography, biology, ecology, meteorology, hydrology, agronomy, forestry and environmental sciences), we developed a geographical information system to identify Köppen's climate types based on monthly temperature and rainfall data from 2,950 weather stations. Temperature maps were spatially described using multivariate equations that took into account the geographical coordinates and altitude; and the map resolution (100 m) was similar to the digital elevation model derived from Shuttle Radar Topography Mission. Patterns of rainfall were interpolated using kriging, with the same resolution of temperature maps. The final climate map obtained for Brazil (851,487,700 ha) has a high spatial resolution (1 ha) which allows to observe the climatic variations at the landscape level. The results are presented as maps, graphs, diagrams and tables, allowing users to interpret the occurrence of climate types in Brazil. The zones and climate types are referenced to the most important mountains, plateaus and depressions, geographical landmarks, rivers and watersheds and major cities across the country making the information accessible to all levels of users. The climate map not only showed that the A, B and C zones represent approximately 81%, 5% and 14% of the country but also allowed the identification of Köppen's climate types never reported before in Brazil.

Keywords: Köppen climate classification map for Brazil.

1 Introduction

130 years ago, Wladimir Köppen published his study about Earth's heat zones (KÖPPEN, 1884a; 1884b), and based on that, some years later, in 1899, he completed his first attempt for a regional climate classification of the Earth (KÖPPEN, 1900; KÖPPEN, 1901), which is considered by many scientists as the first quantitative climate type classification of the world (THORNTHWAITE, 1933; BHARUCHA and SHANBHAG, 1956; WILCOCK, 1968; SANDERSON, 1999; KOTTEK et al., 2006; SPAROVEK et al., 2007; RUBEL and KOTTEK, 2010).

Köppen climatic classification system is still widely used, and has been employed in a number of textbooks in climatology (ROHLI and VEGA, 2012), meteorology (VIANELLO and ALVES, 2013), geography (PETERSEN et al., 2012), bioclimatology (OMETTO, 1981), ecology (ADAMS, 2009), agrometeorology (PEREIRA et al., 2002), atlas (WREGE et al., 2011), and it has become part of

related teaching programs in many universities. Meanwhile, the use of Köppen's classification is not limited to teaching, because throughout the Köppen system history many researchers routinely used it for their own particular research purposes.

Nowadays many researchers have used the Köppen's climate classification as a basis for studies in agroclimatic zoning in Brazil (JURCA, 2005; ROLIM et al., 2007) and Mexico (MAES et al., 2009), in assisting the zonings of forestry species (ARAÚJO et al., 2012) and *Eucalyptus grandis* rust occurrence (SILVA et al., 2013), and also in climatic zoning of *Eucalyptus* plantations across Brazil (GONÇALVES et al., 2013). TORRES et al. (1997) used the climatic types to differentiate floristic groups in southeastern Brazil. In Australia and China, STERN et al. (2000) and BAKER et al. (2010), respectively, applied the Köppen-Trewartha system to define the climatic zoning of major vegetation groups and to assess the ecoregions with basis in climatic refuges. Other studies used the Köppen system in meteorology (GNANDESIKAN and STOUFFER, 2006) and hydrology (MCMAHON et al., 2007). Recently, significant contributions have been published to the climate change issue (FRAEDRICH et al.,

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2001; KALVOVA et al., 2003; WANG and OVERLAND, 2004; DIAZ and EISCHEID, 2007; RUBEL and KOTTEK, 2010) once the Köppen climatic types is a great opportunity to show didactically for both specialists and general public how the climate zones are changing. In geography relationships between the distribution of population and the main climates in the world has been addressed (STASZEWSKI, 1963; KUMMU and VARIS, 2011).

In Brazil, the climatology emerged in early 1870 when the Rio de Janeiro's Observatory hired the astronomer and meteorologist Emmanuel Liais who implemented the theoretical bases of atmospheric sciences in the country, and published in 1872 a treatise on the physical geography of Brazil (LIAIS, 1872). Over the same period, meteorological observations were being taken in the states of Ceará (THEOPHILO, 1883) and São Paulo (LOEFGREN, 1900). Henrique Morize compiled meteorological observations sparsely distributed in the states of Ceará, Pernambuco, Santa Catarina and Rio Grande do Sul, between 1872 and 1880, and produced the first study about the climate of Brazil (MORIZE, 1889). Later, Frederick Draenert expanded the study of Morize and published "The climate of Brazil" (DRAENERT, 1896). Both researchers adopted a more climatological than meteorological approach. Afterwards, Morize adopted the concepts of Köppen and proposed his second climatic classification of Brazil based on 106 weather stations (MORIZE, 1922). Meanwhile, MATTOS (1905) did an important study on the climate regionalization in São Paulo state emphasizing the influence of latitude, altitude and distance from the sea as climatic factors. During the same decade arose the study of climatic classification of Brazil for purposes of adaptation, hygiene and public health by PEIXOTO (1907). Thereafter, Delgado de Carvalho proposed the "climatography" of Brazil in his books (CARVALHO, 1916; 1917), which not only produced the most complete work on the Brazilian climatology of that time but also introduced an eminently geographic analysis. SEREBRENICK (1940, 1941) conducted a critical review of the proposed Brazilian climate classifications and differentiate the geographical and the meteorological types.

Even though all these Brazilian studies were contemporary to the Köppen's work, none of them achieved such recognition among the Brazilian scientific community. RUBEL and KOTTEK (2011) showed a total of 193 bibliographic citations in just five years since his study of global climate mapping (KOTTEK et al., 2006). Considering the usefulness of Köppen's system and its wide use and application in Brazil and the development of high resolution geographical information system and geostatistical tools, the Köppen's climate classification of Brazil can be improved to allow deeper natural science insights (KOTTEK et al., 2006; PEEL et al., 2007; SPAROVEK et al., 2007). Thus, the objective of this study is to produce 1 ha-resolution map of the Köppen's climate classification for Brazil to be used for basic and applied applications related with climatic studies.

2 Material and methods

We chose to base our map key criteria in the latest version of Köppen climate classification (KÖPPEN, 1936), as done recently by KOTTEK et al. (2006), PEEL et al. (2007) and RUBEL and KOTTEK (2010), in order to allow reproducibility of the maps.

The Köppen climate types are symbolized by two or three characters, where the first indicates the climate zone and is defined by temperature and rainfall, the second considers the rainfall distribution and the third is the seasonal temperature variation. The climate zones, descriptions, symbols and the full key criteria for climate classification are presented in Table 1.

For standardizing the seasonal average and total calculations for temperature and rainfall, the summer was considered as the six warmest months in the southern hemisphere (from October to March) and the winter as the six coldest months in the southern hemisphere (from April to September). As Brazil has a small portion of its territory in the Northern Hemisphere, for this area the summer and winter criteria was considered the opposite (PEEL et al., 2007). We built a realistic spatially distributed model for the following continuous variables: latitude, longitude, altitude, temperature and rainfall. A Geographic Information System (GIS) was used as a work platform in which the entire spatial database was compiled, managed and processed. The complete Köppen's climate classification system algorithm was programmed in GIS using geoprocessing procedures (THEOBALD, 2007; ALLEN, 2011). A simplified format of the model implemented in GIS are presented in Fig. 1.

The proposed model is enclosed and complete, i.e., it is impossible to find a location with more than one type of climate. So, for the entire Brazil, 852 million 1 ha-pixels where analyzed using Table 1 criterias and the final map was elaborated with a color code according to the type of climate (RGB colors pattern suggested by PEEL et al., 2007).

To estimate the meteorological information for each pixel, a large database of climatological data from several Brazilian and global sources were used. A total of 2,950 weather stations were processed and used as sources of rainfall data (Fig. 2). These rainfall stations have adequate temporal data series (> 25 years between 1950 and 1990). The same period was considered for mean monthly temperature data, from 2,400 weather stations, which were organized and analyzed by ALVARES et al. (2013). Both rainfall and temperature databases were obtained from the following sources: Brazilian National Institute of Meteorology (INMET) (BRAZIL, 1992); Brazilian National Department of Works Against the Droughts (DNOCS); and Food and Agriculture Organization of the United Nations (FAO/ONU) (FAO, 2001). The weather stations density in the Brazilian territory used in this study is higher than used by SPAROVEK et al. (2007) for Brazil and for the world by KOTTEK et al. (2006) and PEEL et al. (2007).

Table 1: Temperature and rainfall criteria for the complete Köppen's climate classification.

Temperature		Rainfall		Climate		Symbol	
T_{COLD}	T_{HOT}	T_{ANN}	R_M	R_{ANN}			
$\geq 18\text{ }^\circ\text{C}$			$R_{DRY} \geq 60\text{ mm}$ $R_{DRY} < 60\text{ mm}$	$\geq 25 (100 - R_{DRY})$ $< 25 (100 - R_{SDRY})$ $< 25 (100 - R_{WDRY})$ $\geq 5 * R_{THRESHOLD\&}$ $< 10 * R_{THRESHOLD}$ $< 5 * R_{THRESHOLD}$	(A) Tropical	(f) without dry season (m) monsoon (s) with dry summer (w) with dry winter (h) low latitude and altitude (k) mid-latitude and high altitude (b) with hot summer (a) with hot summer (b) with temperate summer (c) with short and cool summer (a) and hot summer (b) and temperate summer (c) and short and cool summer (a) and hot (b) and temperate (c) and short and cool summer (a) with hot summer (b) with temperate summer (c) with short and cool summer (d) with very cold winter (a) with hot summer (b) and temperate summer (c) and short and cool summer (d) and very cold winter (a) and hot (b) and temperate (c) and short and cool summer (d) and very cold winter	Af Am As Aw BSh BSk BWh BWk Cfa Cfb Cfc Cwa Cwb Cwc Csa Csb Csc Dfa Dfb Dfc Dfd Dwa Dwb Dwc Dwd Dsa Dsb Dsc Dsd ET EF
$\geq -3\text{ }^\circ\text{C} < \& < 18\text{ }^\circ\text{C}$	≥ 22	$\geq 18\text{ }^\circ\text{C}$ $< 18\text{ }^\circ\text{C}$ $\geq 18\text{ }^\circ\text{C}$ $< 18\text{ }^\circ\text{C}$	$R_{DRY} > 40\text{ mm}$		(B) Dry	(S) Semi-arid (W) Arid	
$\geq -38\text{ }^\circ\text{C} & < 18\text{ }^\circ\text{C}$	$< 22\text{ }^\circ\text{C} \& T_{M10} \geq 4$				(C) Humid subtropical	(f) Oceanic climate, without dry season	
$\geq -3\text{ }^\circ\text{C} < \& < 18\text{ }^\circ\text{C}$	$< 22\text{ }^\circ\text{C} \& 1 \leq T_{M10} < 4$		$R_{DRY} < 40\text{ mm}$ $R_{SWET} \geq 10 * R_{WDRY}$		(w) With dry winter	(w) With dry winter	
$\geq -38\text{ }^\circ\text{C} & < 18\text{ }^\circ\text{C}$	$< 22\text{ }^\circ\text{C} \& T_{M10} \geq 4$				(s) With dry summer		
$\geq -3\text{ }^\circ\text{C} < \& < 18\text{ }^\circ\text{C}$	$< 22\text{ }^\circ\text{C} \& 1 \leq T_{M10} < 4$		$R_{DRY} < 40\text{ mm}$ $R_{SWET} \geq 3 * R_{SDRY}$ $R_{SWET} < 10 * R_{WDRY}$ $R_{DRY} > 40\text{ mm}$		(D) Temperate continental	(f) Without dry season	
$\geq -38\text{ }^\circ\text{C} & < 18\text{ }^\circ\text{C}$	$< 22\text{ }^\circ\text{C} \& T_{M10} \geq 4$				(w) With dry winter		
$\geq -38\text{ }^\circ\text{C} & < -3\text{ }^\circ\text{C}$	$< 22\text{ }^\circ\text{C} \& 1 \leq T_{M10} < 4$				(s) With dry summer		
$< -38\text{ }^\circ\text{C} \& < -3\text{ }^\circ\text{C}$	$\geq 22\text{ }^\circ\text{C}$		$R_{DRY} < 40\text{ mm}$ $R_{SWET} \geq 10 * R_{WDRY}$		(E) Polar	(s) With dry summer	
$\geq -38\text{ }^\circ\text{C} \& < -3\text{ }^\circ\text{C}$	$\geq 22\text{ }^\circ\text{C} \& T_{M10} \geq 4$						
$< -38\text{ }^\circ\text{C} \& < -3\text{ }^\circ\text{C}$	$< 22\text{ }^\circ\text{C} \& 1 \leq T_{M10} < 4$		$R_{DRY} < 40\text{ mm}$ $R_{WWET} \geq 3 * R_{SDRY}$ $R_{SWET} < 10 * R_{WDRY}$				
$< -38\text{ }^\circ\text{C} \& < -3\text{ }^\circ\text{C}$	$< 22\text{ }^\circ\text{C} \& 1 \leq T_{M10} < 4$						
$< -38\text{ }^\circ\text{C} \& < -3\text{ }^\circ\text{C}$	$< 10 \& \geq 0\text{ }^\circ\text{C}$ $< 0\text{ }^\circ\text{C}$						

T_{COLD} = Temperature of the coldest month; T_{HOT} = Temperature of the hottest month; T_{ANN} = Annual mean temperature; R_M = Monthly Rainfall; R_{ANN} = Annual Rainfall; R_{DRY} = Rainfall of the driest month; R_{SDRY} = Rainfall of the driest month in summer; R_{WDRY} = Rainfall in the driest month in winter; R_{SWET} = Rainfall of the wettest month in summer; R_{WWET} = Rainfall in the wettest month in winter; T_{M10} = number of months where the temperature is above $10\text{ }^\circ\text{C}$; $R_{THRESHOLD}$ = varies according to equation 1; For the southern hemisphere summer is defined as the warmer six month period (ONDJFM) and winter is defined as the cooler six month period (AMJJAS). For the northern hemisphere summer is defined as the warmer six month period (AMJJAS) and winter is defined as the coolest six month period (ONDJFM).

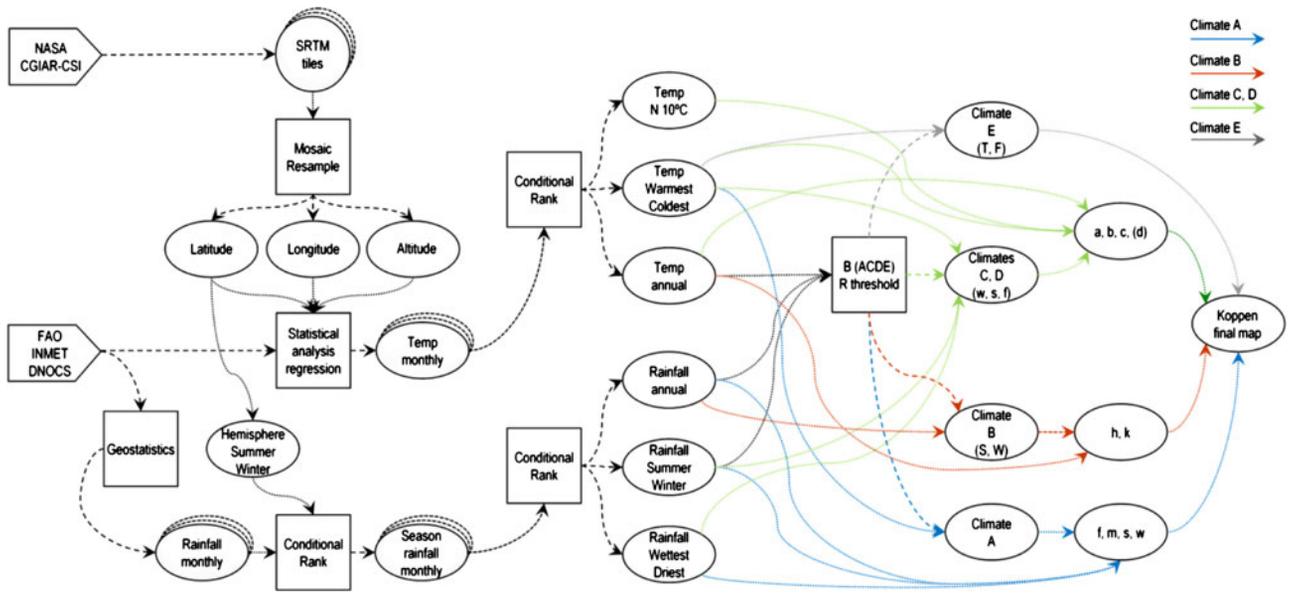


Figure 1: Flowchart of the modeling process for the Köppen climate classification. NASA / CGIAR-CSI = National Aeronautics and Space Administration / Consultative Group on International Agricultural Research - Consortium for Spatial Information; SRTM = Shuttle Radar Topography Mission; FAO = Food and Agriculture Organization; INMET = Brazilian National Institute of Meteorology; DNOCS = Brazilian National Department of Works Against the Droughts.

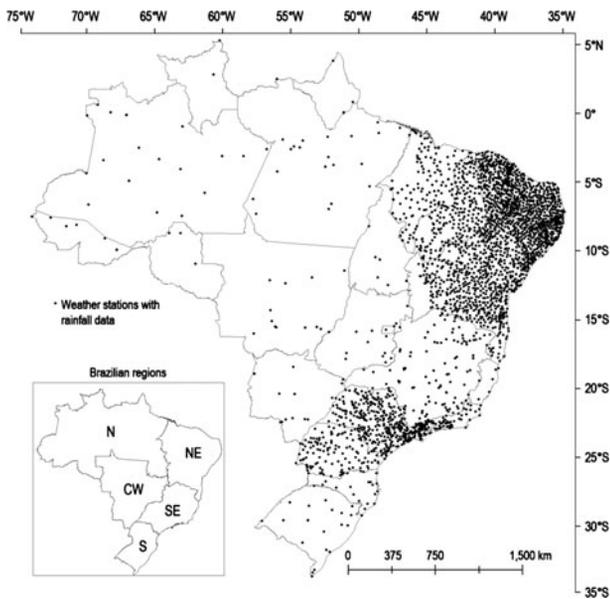


Figure 2: Location of the Brazilian weather stations with rainfall data used in this study.

Monthly rainfall data was analyzed according to geostatistical procedures. Normality hypothesis was tested according to the W test at 5% (SHAPIRO and WILK, 1965). Using the geostatistical software GS + v.9 (ROBERTSON, 2008) the omnidirectional experimental semivariograms for the monthly rainfall data was prepared whereas only 10 lag classes of equal interval in a geometric field of 50% range fitting set (latitude and longitude). The experimental semivariograms were tested by adjusting them to the theoretical spherical, exponential,

Gaussian and linear models, since they usually covered the general dispersion of environmental spatial events (BURROUGH and MCDONNELL, 1998). The best fits were based on the smallest reduced sums of squares (RSS) and on the highest determination coefficient (R^2) (ROBERTSON, 2008). Furthermore, the quality of theoretical models was certified by cross-validation and also by the spatial dependence index (SDI). In cross-validation analysis each measured point in the spatial domain is individually removed from the domain and its value estimated, then the point is replaced and the next point is removed and estimated, and so on (ROBERTSON, 2008). SDI was used as recommended by ALVARES et al. (2011), as a measure of the structural variance effect on total variance (sill) of the sample. SDI comprises the following classification: weak for $SDI < 25\%$; moderate for SDI between 25% and 75%; and strong for $SDI > 75\%$. Through these structural parameters of the theoretical semivariograms extracted from experimental semivariograms, rainfall maps were composed with the geographic information system. A punctual ordinary kriging estimator was used for geostatistical interpolation. With these procedures, the maps had a spatial resolution of 100 m, or 1 hectare per pixel.

Monthly temperature maps were developed by applying the multivariate equations adjusted by ALVARES et al. (2013). These authors adjusted monthly models for Brazil with precision and accuracy for maximum, minimum and mean monthly air temperature. These equations estimate air temperature based on the independent variables such as altitude, latitude and longitude. We adopted the current fourth version (JARVIS et al., 2008) of digital elevation model (DEM) from the Shuttle Radar

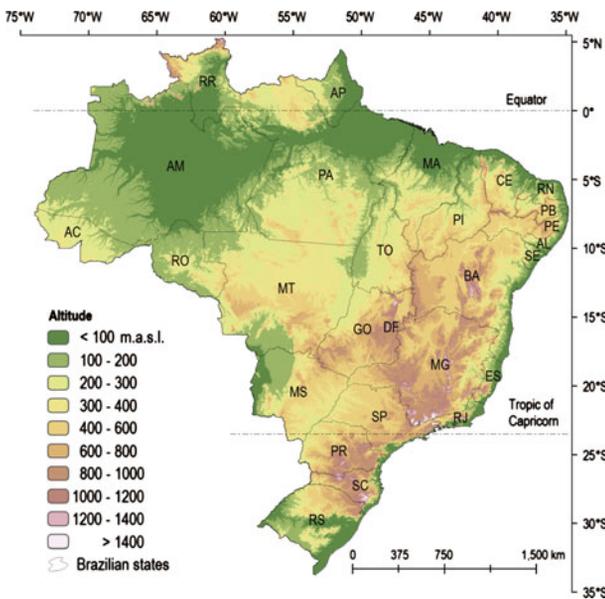


Figure 3: Digital elevation model of Brazil.

Topography Mission (SRTM) (FARR and KOBRICK, 2000) as the source of those independent variables. DEM data available on <http://srtm.csi.cgiar.org>, were organized into tiles with a spatial resolution of 90 m. Fourty-nine tiles were downloaded and into the GIS the DEM mosaic for Brazil was composed. The DEM was then resampled to a spatial resolution of 100 m (Fig. 3). Latitude and longitude layers were obtained in decimal degrees using the central coordinates of each pixel of the DEM (THEOBALD, 2007). Next, using map algebra (BURROUGH and MCDONNELL, 1998) and geoprocessing techniques (THEOBALD, 2007) all temperature models were programmed and run in GIS. The annual mean temperature map is shown in Fig. 4, and as reported by ALVARES et al. (2013), the predictor equation had an excellent performance ($R^2 = 0.93$, RMSE = 0.80 °C and DW statistic test = 2.01).

In order to illustrate the monthly distribution of precipitation and mean temperature in each of the Brazilian climatic types in high-resolution maps, 12 thermopluviograms were established, similar to those presented by KÖPPEN (1936). Every climate type was represented by its typical locality described above.

Two climate diagrams were prepared: i) annual rainfall *versus* mean annual temperature and ii) annual rainfall *versus* rainfall of the driest month. These climate diagrams graphically displays the key criteria for definitions of climatic types (Table 1). The models presented by KÖPPEN (1936) were adapted to plot points related to Brazilian well known municipalities using their shapefile perimeter (IBGE, 2007). Each municipality has the same color of the respective climatic types in the map. Two diagrams were also plotted for the typical localities of each climate type in Brazil.

To better present the climate variability in Brazil, a latitudinal climatic profile from northern (Oiapoque) to

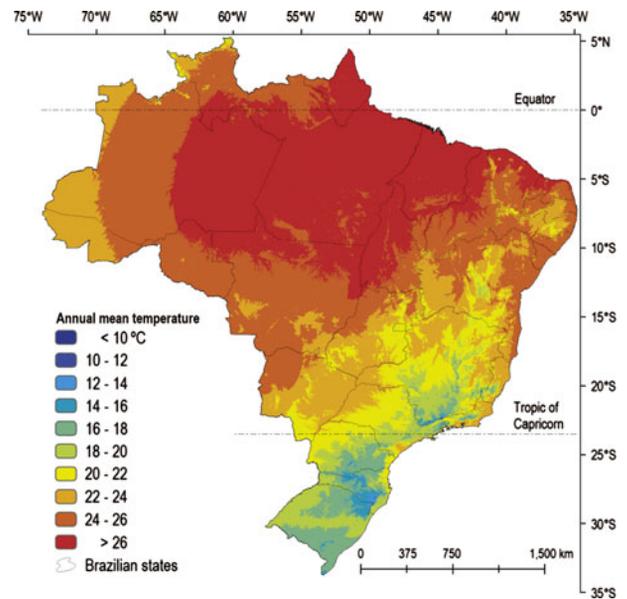


Figure 4: Annual mean air temperature map for Brazil (modified from ALVARES et al., 2013).

southern extremes (Chuí) was created to express the latitudinal range of climate in the country. This 4,200 km transect varies more than 37° in latitude, from 4°21'27"N at Cape Orange (Oiapoque in Amapá state) to 33°38'55"S at Chuí Stream (Chuí in Rio Grande do Sul state). This transect is almost a straight N-S line. Climatic types and states divisions were associated with the top and bottom x-axis, respectively. Thus the climatic profile comes to be a didactic illustration and shows when there is a change in the climate type and, at the same time, is possible to see variations in temperature, rainfall and altitude in different Brazilian states where the transect crosses.

3 Results and discussion

Rainfall in Brazil

Monthly rainfall data from 2,950 weather stations were analyzed according to the concepts of the regionalized variables theory (MATHERON, 1971) and all the geostatistical adjustments were considered to be of good quality (Table 2). For all months, an asymmetric distribution was found which required data transformation, since p-values were close to zero by normality test (SHAPIRO and WILK, 1965). Among the theoretical models tested, the spherical model was the best one to describe the experimental semivariograms (Table 2). The estimated residues were low and a high coefficient of determination, above 0.97, and a strong SDI for all months was obtained (Table 2).

Nugget effect was very low in all months except September, meaning that this month has components of variability which are not detected by semivariograms

Table 2: Models, parameters and quality of experimental semivariograms adjusted to monthly rainfall in Brazil.

Month	Model	Vo ¹	Vo + V ²	Ro ³	V/(Vo + V)	SDI ⁴	⁵ R ²	R.S.S. ⁶	⁷ r
		mm ²		degree	%			mm ²	
January	Spherical	0.039	0.842	24.51	95	strong	0.99	2.8 10 ⁻³	0.89
February	Spherical	0.057	0.370	11.89	85	strong	0.99	5.8 10 ⁻⁴	0.85
March	Spherical	0.041	0.311	11.57	87	strong	0.99	4.6 10 ⁻⁴	0.83
April	Spherical	0.080	0.542	16.68	85	strong	0.99	3.5 10 ⁻⁴	0.84
May	Spherical	0.063	1.661	10.56	96	strong	0.99	2.2 10 ⁻²	0.87
June	Spherical	0.010	3.425	11.78	100	strong	0.99	2.7 10 ⁻²	0.85
July	Spherical	0.010	3.576	9.54	100	strong	0.99	6.6 10 ⁻²	0.85
August	Spherical	0.001	2.922	6.90	100	strong	0.99	1.1 10 ⁻¹	0.83
September	Spherical	0.193	1.705	6.49	89	strong	0.99	3.2 10 ⁻²	0.86
October	Spherical	0.080	3.170	18.69	97	strong	0.99	5.2 10 ⁻²	0.90
November	Spherical	0.001	3.012	16.44	100	strong	0.97	2.5 10 ⁻¹	0.90
December	Spherical	0.001	2.011	26.68	100	strong	0.97	4.1 10 ⁻²	0.89

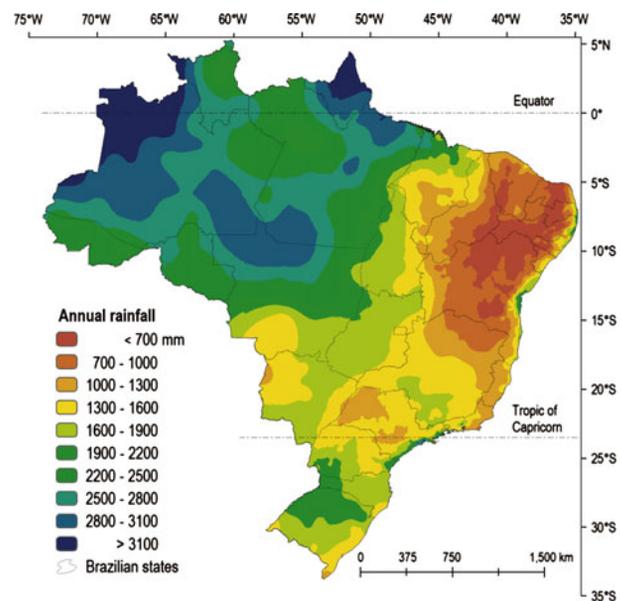
¹Vo = nugget;²Vo + V = Sill (V = structural variance);³Ro = range;⁴SDI = spatial dependence index;⁵R² = model adjustment determination coefficient;⁶R.S.S. = Residue Sum of Squares;⁷r = crossed validation correlation coefficient.

(Table 2). If the sill and range were plotted (not presented), a seasonal pattern could be identified, being that in the autumn and winter months (May, Jun, Jul and Aug), Brazil has a high data variance (Vo + V) and low range (Ro) of spatial dependence. Summer months (wettest) has higher range, showing that the zone of influence of samples is higher. This pattern occurs because in Brazil there is a high spatial variability in rainfall in autumn-winter (mainly dry period) in relation to spring-summer (mainly wet period) (GRIMM, 2009a).

The map shows that the annual rainfall of Brazil (Fig. 5) has spatial variability similar to the climatological normal map presented by meteorological service in Brazil: INMET (www.inmet.gov.br). Annual rainfall ranged from 387 to 4,003 mm, very similar to what was found in other studies (GOLFARI et al., 1978; NIMER, 1989; GRIMM, 2009b; MARENGO and NOBRE, 2009; ALVES, 2009; NUNES et al., 2009). The annual rainfall above 2,500 mm was mapped mainly in northern Brazil, as well as in the central coast of the state of São Paulo where annual rainfall achieves more than 3,000 mm on average, promoted by the orographic effect caused by Serra do Mar mountains (CONTI and FURLAN, 2011). Moreover, annual rainfall less than 700 mm occurs in Borborema Plateau, Paraíba Agreste (semi-arid region), São Francisco River Valley and northern Bahia, the driest regions of the country, also named as *Sertão* (Backwoods).

A-Climate zone

Three zones and 12 types of climates were classified throughout Brazil (Fig. 6 and Table 3). Tropical climate, A zone, was the one with the largest area, representing 81.4% of the Brazilian territory, occurring in all regions

**Figure 5:** Total annual rainfall in Brazil.

of the country, except in the states of Rio Grande do Sul and Santa Catarina and great part of Paraná in the Southern region. The main reason for this climate to be present in a large part of the country is because in these areas there are no limiting factors regarding altitude, rainfall and temperature to impose other climatic zones.

The climate Af was found in 22.6% of the Brazilian territory (Table 3). It covers 82.3% of Amazonas state, except for its southern end, and small portions of the highlands in the far north at the border with Venezuela. SCHMIDT (1942) used climatological normals from 1901 to 1931 to present a climate map for the Amazon

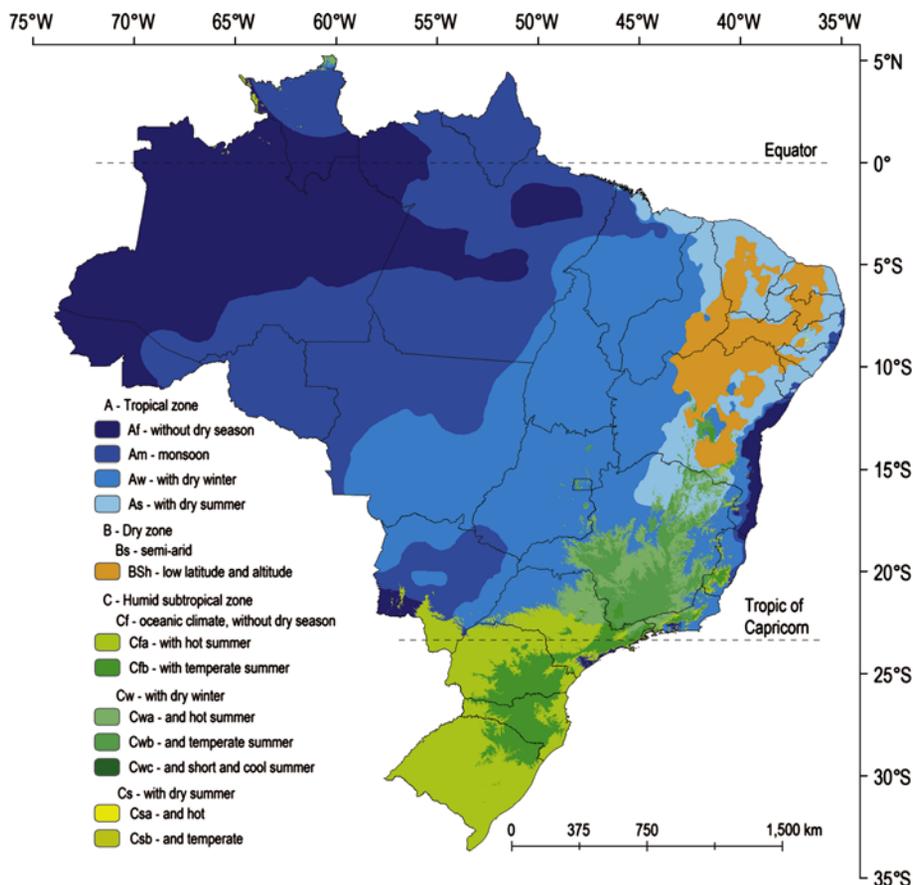


Figure 6: Climate classification for Brazil, according to the KÖPPEN (1936) criteria.

region where the Af climate occurs a little higher than in the map presented in this study (Fig. 6) located along the equatorial line. The climate Af also occurs in the southern part of the Roraima state (38.8%), covering the Depressions and Pediplains of Negro River Basin and limits the northern region of the state where the rainfall seasonality begins. More than 28% of the area in the Pará state have Af climate occurring primarily in three regions: i) in the Plains and Tablelands of lower Amazon River to the far north, at the border with Guyana, where the annual rainfall is between 1,900 and 2,400 mm; ii) in the central and eastern region of the state with annual rainfall between 2,200 to 2,700 mm; iii) Marajó Island, south of the capital Belém, and in the Tocantins River alluvial fan where annual rainfall is between 3,000 and 4,000 mm. Others studies also found Af climate in the region of Belém (BERNARDES, 1951; VIEIRA, 1960; GALVÃO, 1966; MARTORANO et al., 1993; KOTTEK et al., 2006; SPAROVEK et al., 2007; PEEL et al., 2007). In the east-central Amazon, and all over the Pará State, the climate Af shows mean annual temperature greater than 26 °C (Fig. 7), as was the case of Manaus (03°05'S; 60°01'W; 30 m), the Amazonas state capital, which was chosen as the location representative of climate Af (Fig. 8 and 9). Manaus has a mean annual temperature of 26.7 °C with few seasonal variation between 25.9 to 27.7 °C, annual rainfall of 2,420 mm and the dri-

est month in August when monthly rainfall is about 80 mm (Fig. 8 and 9). This is a type of climate in which the seasons do not succeed clearly (ZARUR, 1943).

In the state of Bahia, the Af climate was identified over the coast on a narrow strip on the Marine Plains and Coastal Tablelands. However, in this region, the climate is not like the Amazonian equatorial climate, but rather a climate type of transition between south of this area, with a summer rainy season (Aw) and north of it, with a winter rainy season (As) (BERNARDES, 1951). In Rio de Janeiro state, Af climate appears in a very small area (2.1% of its territory) including the state capital, Rio de Janeiro, and Niterói, which was also identified by SETZER (1946), BERNARDES (1951) and SOUTO MAIOR (1954), and goes to the southern coast, in the lowlands, up to 150 m, facing the Atlantic Ocean.

In southwestern Mato Grosso do Sul in Southern Pantanal (Brazilian Tropical Plains and Wetlands) (ROSS, 2011), Af climate was also identified being one of the most southern places with its occurrence always at altitudes lower than 400 m and annual rainfall between 1,400 and 1,800 mm. Af was also mapped in almost all São Paulo state coast, on the Marine Plains (IBGE, 2006), with less than 150 m of altitude from Ubatuba until Ilha Comprida (24°53'S), the location with the highest latitude where Af occurs in South America (Fig. 7), similarly mapped by SETZER (1946,

Table 3: Proportion of occurrence of each type of Köppen's climate in the Brazilian states.

State	km ²	Af	Am	Aw	As	BSh	Cfa	Cfb	Cwa	Cwb	Cwc	Csa	Csb
%													
Acre – AC	152,581	70.5	29.5	-	-	-	-	-	-	-	-	-	-
Alagoas – AL	27,768	0.4	11.7	1.8	71.2	14.9	-	-	-	-	-	*	-
Amapá – AP	142,815	-	100.0	-	-	-	-	-	-	-	-	-	-
Amazonas – AM	1,570,746	82.3	17.6	-	-	-	*	-	-	-	-	-	-
Bahia – BA	564,693	9.0	2.0	34.0	17.6	33.3	0.6	0.8	0.9	1.7	-	-	-
Ceará – CE	148,826	-	-	*	62.3	37.7	-	-	-	-	-	-	-
Distrito Federal – DF	5,802	-	-	67.9	-	-	-	-	22.1	10.0	-	-	-
Espírito Santo – ES	46,078	2.9	14.3	53.3	-	-	14.9	10.4	0.8	3.3	*	-	-
Goiás – GO	340,087	-	4.1	94.0	-	-	-	-	1.5	0.3	-	-	-
Maranhão – MA	331,983	-	14.3	75.4	10.3	-	-	-	-	-	-	-	-
Mato Grosso – MT	903,358	-	47.2	52.8	-	-	-	-	-	-	-	-	-
Mato Grosso do Sul – MS	357,125	6.6	45.6	36.6	-	-	11.2	-	-	-	-	-	-
Minas Gerais – MG	586,528	-	*	34.9	12.3	-	0.5	0.7	25.5	26.0	*	-	-
Pará – PA	1,247,690	28.4	66.6	4.9	*	-	-	-	-	-	-	-	-
Paraíba – PB	56,44	-	1.2	0.8	57.1	40.7	-	-	*	0.1	-	-	-
Paraná – PR	199,315	*	0.4	0.8	-	-	61.7	37.0	-	-	-	-	-
Pernambuco – PE	98,312	-	4.9	0.1	32.7	61.4	*	-	0.3	0.3	-	0.3	*
Piauí – PI	251,529	-	-	60.7	19.8	19.6	-	-	-	-	-	-	-
Rio de Janeiro – RJ	43,696	2.1	5.3	44.1	-	-	14.3	9.4	17.9	6.9	*	-	-
Rio Grande do Norte – RN	52,797	-	-	*	38.8	61.2	-	-	-	-	-	-	-
Rio Grande do Sul – RS	281,749	-	-	-	-	-	86.7	13.3	-	-	-	-	-
Rondônia – RO	237,576	-	100.0	-	-	-	-	-	-	-	-	-	-
Roraima – RR	224,299	38.8	55.2	2.7	-	-	1.6	-	1.7	-	-	-	-
Santa Catarina – SC	95,346	-	-	-	-	-	40.1	59.9	-	-	-	-	-
São Paulo – SP	248,209	1.9	0.5	30.8	-	-	33.4	12.6	17.4	3.4	*	-	-
Sergipe – SE	21,91	-	12.8	-	73.7	13.5	-	-	-	-	-	-	-
Tocantins – TO	277,621	-	-	100.0	-	-	-	-	-	-	-	-	-
Brasil	8,514,877	22.6	27.5	25.8	5.5	4.9	6.5	2.6	2.5	2.1	*	*	*

Official Territorial Area (IBGE): Resolution No. 05, October 10, 2002. <http://www.ibge.gov.br/home/geociencias/areaterritorial/principal.shtm>, * < 0.01% of occurrence

1966), BERNARDES (1951), SPAROVEK et al. (2007) and ROLIM et al. (2007).

Am climate was found in 27.5% of Brazilian territory, the most representative climate of the country (Table 3). It was found covering entire states like Amapá and Rondônia. In the Roraima state, Am climate is limited in the south by the Af climate and goes up covering the Boa Vista Depression and the southern part of Roraima Tablelands to the border with Venezuela and Guyana always in areas with altitude below 1,200 m and until 4°48'N (Fig. 7). In this short transect from north to the south, annual rainfall decreases from 2,500 to 1,700 mm (Fig. 10). Other climate maps also classified this region as Am (SCHMIDT, 1942; BERNARDES 1951; VIEIRA, 1960; GALVÃO, 1966; KOTTEK et al., 2006; PEEL et al., 2007). Am climate presents annual rainfall above 3,300 mm in the north-central Amapá, and located a little further south is Macapá (00°01'S; 51°04'W; 12 m), the Amapá's capital, which presents annual rainfall of 2,850 mm with monsoon period between February and May, when the monthly rainfall is around 400 mm (Fig. 8). Macapá is one of the wettest Brazilian localities and also the warmest with impressive mean annual temperature of 27.6 °C, varying seasonally between 25.8 to 29 °C (Fig. 8 and 9).

Under strong north-south gradient of amount and distribution of rainfall the Am climate is present in the Mato Grosso state, from its north, with approximately 3,000 mm year⁻¹, to southwest, where the annual rainfall is around 2,000 mm and the dry winter begins (Fig. 10). A large area of Am climate was mapped in western Mato Grosso do Sul, in the lower Pantanal, where annual rainfall is between 1,300 and 1,600 mm and in the central region of the state, in the Dourados Plateau, where rainfall is slightly higher, ranging from 1,600 to 1,900 mm year⁻¹.

On the coast of northeastern Brazil, Am climate occurs in the Coastal Tablelands, from João Pessoa (capital of Paraíba state) and going down to the coast of Pernambuco, where it advances a little further inland (60 km). From this point, Am climate goes to the coast of Alagoas state, south of Maceió, the capital of Alagoas state. The region between Pernambuco and Alagoas states also is classified as Am climate by GUERRA (1955). In the state of Bahia, the humid northeastern coast, where the Am climate crosses the coastal region, there is a very narrow strip of just a few kilometers, immediately after the seaside Af climate.

Right below, in Espírito Santo state, the Am climate with annual rainfall between 1,200 and

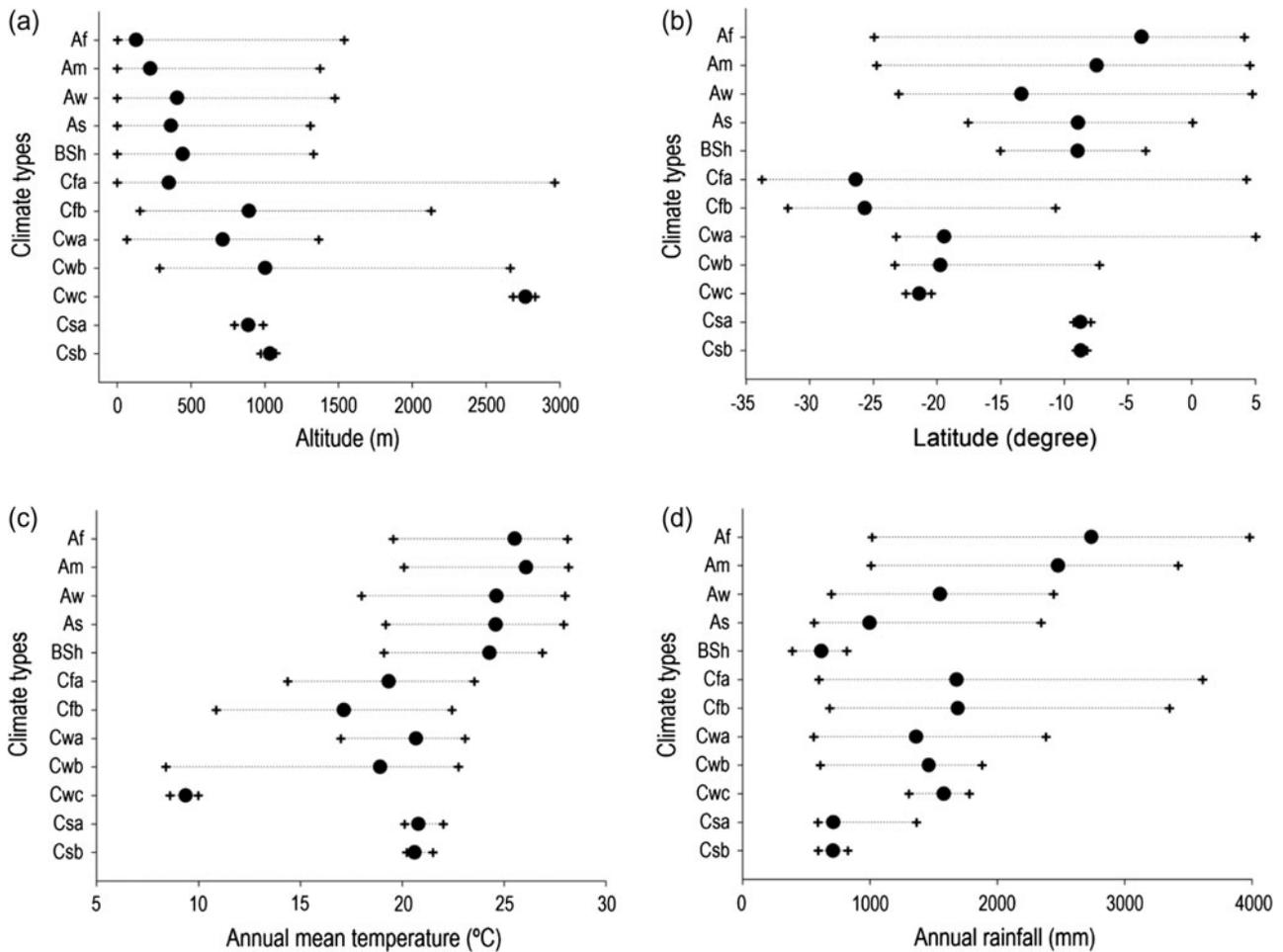


Figure 7: Relationship between Köppen's climate types, altitude, latitude, annual mean temperature and annual rainfall in Brazil. Circle = mean value; plus sign = extremes minimum and maximum

1,300 mm year⁻¹, covers the Coastal Tablelands region where rainfall seasonality starts to become more evident. Am climate also was identified in Rio de Janeiro state, across the edge of Guanabara Bay, verified by SOUTO MAIOR (1954). Am climate occurs in small areas along the coast of São Paulo state, always close to the Af climate, which was also observed by ROLIM et al. (2007), and advances to lowlands (altitude < 150 m) in the Jacupiranga River Valleys (until 24°42'S).

Aw climate covers a wide area in Brazil (25.8% of its territory) (Table 3). It was observed mainly in central Brazil in an extension of more than 2,300 km from the northern Maranhão (03°21'S) to the south of Mato Grosso do Sul (22°50'S) (Fig. 6 and 7). The northern limit of the Aw climate in Brazil is located in an isolated point in Roraima Highlands (05°05'N, Fig. 7) on the border with Guyana.

In the large area of central Brazil, Aw climate is markedly seasonal. It is the only type of climate in the state of Tocantins which has a strong longitudinal gradient (east-west) of annual rainfall from 1,300 to 1,900 mm (Fig. 5) and an opposite gradient (west-east) in the rainfall seasonality. Right in the middle of these two gradients of

rainfall distribution lies Palmas (10°10'S; 48°20'W; 250 m), Tocantins' capital, chosen as the typical locality of Aw climate type (Fig. 8 and 6). In "Handbuch" version (KÖPPEN, 1936), Cuiabá (capital of Mato Grosso state) was chosen as a typical location of Aw climate. Palmas has markedly seasonal climate, with rainfall in December, January and February with more than 250 mm per month, and a dry winter from May to September with a very dry weather between June and August.

Aw climate was also observed in almost all state of Goiás where rainfall is between 1,600 to 1,900 mm year⁻¹, skirting the landscapes with altitudes of 1,200 m and therefore having annual mean temperature between 19 to 20 °C. In the state of Mato Grosso, the Aw climate comes from the south with annual rainfall of 1,400 mm (Pantanal region) and goes through the central part of the state, Parecis Plateau, where annual rainfall totals range from 1,800 to 2,300 mm thus being the wettest Aw climate locations in Brazil (Fig. 7).

Aw climate was identified in a wide range of strong west to east humidity gradient coming from the west of the Piauí, Bahia, Minas Gerais and São Paulo states. In Piauí and Bahia states, Aw occurs along the landscapes

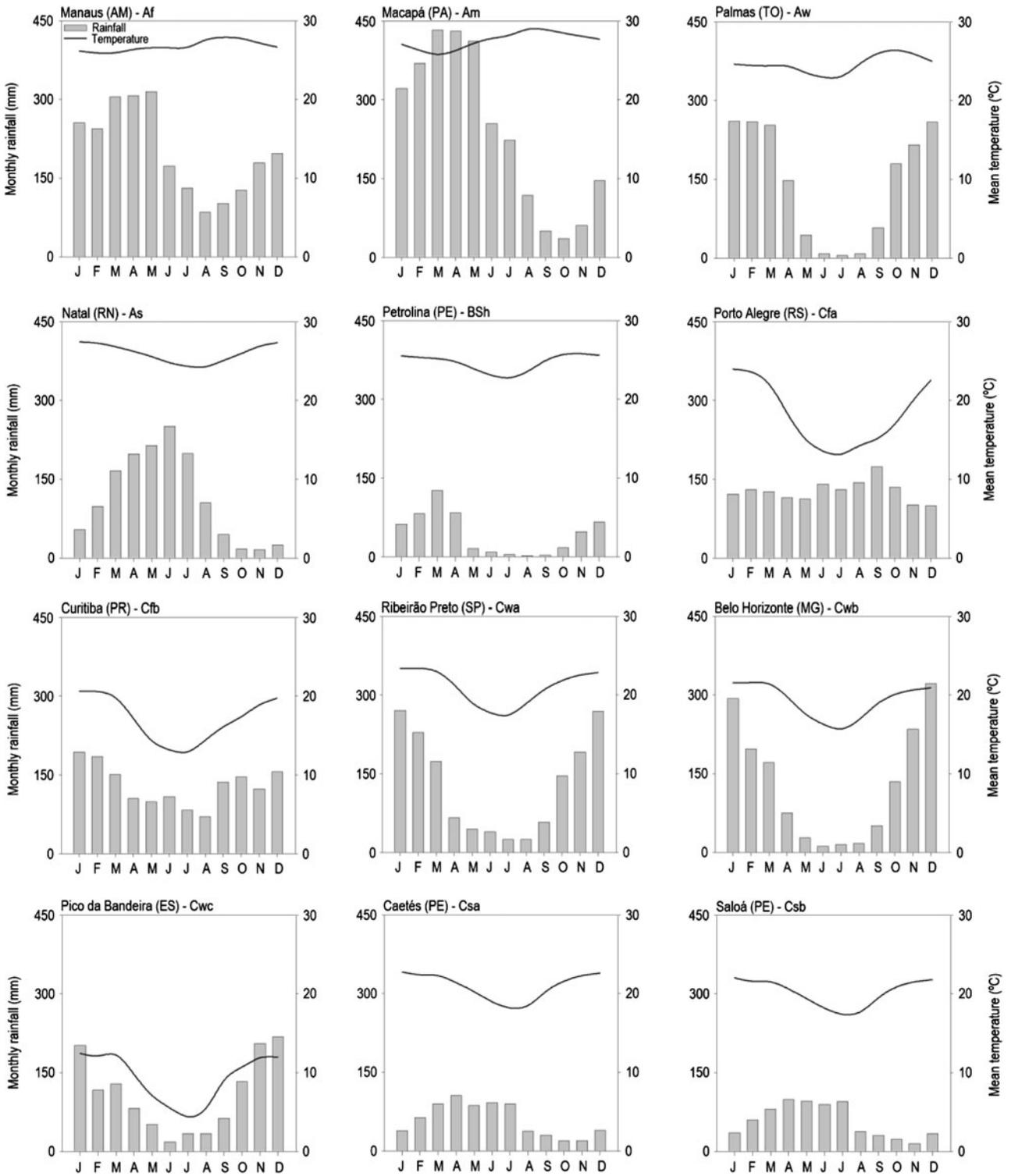


Figure 8: Monthly temperature and rainfall for Brazilian locations representing each type of Köppen's climate.

with annual rainfall between 800 mm (longitude 42°W), which is the driest region of the Aw climate in Brazil to 1,400 mm (46°W) (Fig. 6 and 7). Considering the same gradient, Aw climate occurs in the northwestern Minas Gerais (between 44°W to 47.50°W) covering lowlands, depressions and plateaus of São Francisco River Basin, limited by altitudes of 750–800 m. The climatic maps pre-

sented by [BERNARDES \(1951\)](#) and [VIEIRA \(1960\)](#) showed Aw with similar distribution in this region. Moreover, [SÁ JUNIOR et al. \(2012\)](#), using data from Worldclim ([HIJMAN et al., 2005](#)), found the Aw climate in a region much higher at altitudes greater than 1,000 m.

Northern Espírito Santo has Aw mapped in the Coastal Plains until the perimeter with the Minas Gerais

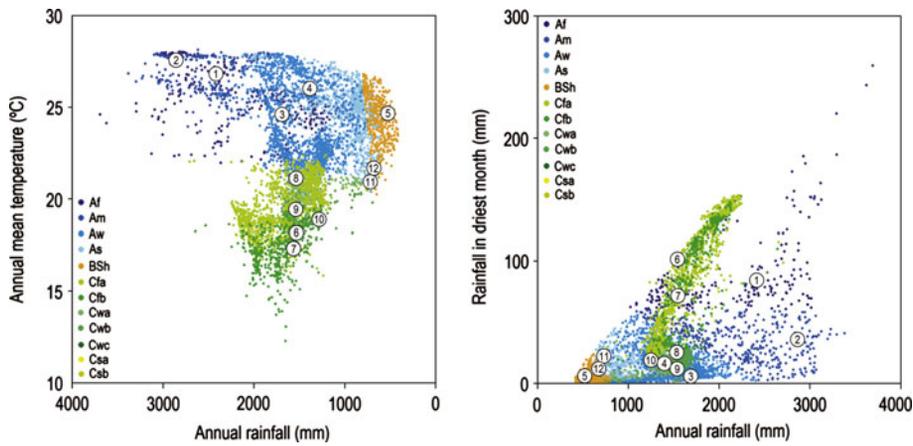


Figure 9: Climatic diagram of all Brazilian municipalities with emphasis on regions with each type of Köppen's climate. The following locations were chosen to represent each type of Köppen's climate found in Brazil: 1 = Manaus; 2 = Macapá; 3 = Palmas; 4 = Natal; 5 = Petrolina; 6 = Porto Alegre; 7 = Curitiba; 8 = Ribeirão Preto; 9 = Belo Horizonte; 10 = Ibitirama (Pico da Bandeira); 11 = Caetés; 12 = Saloá.

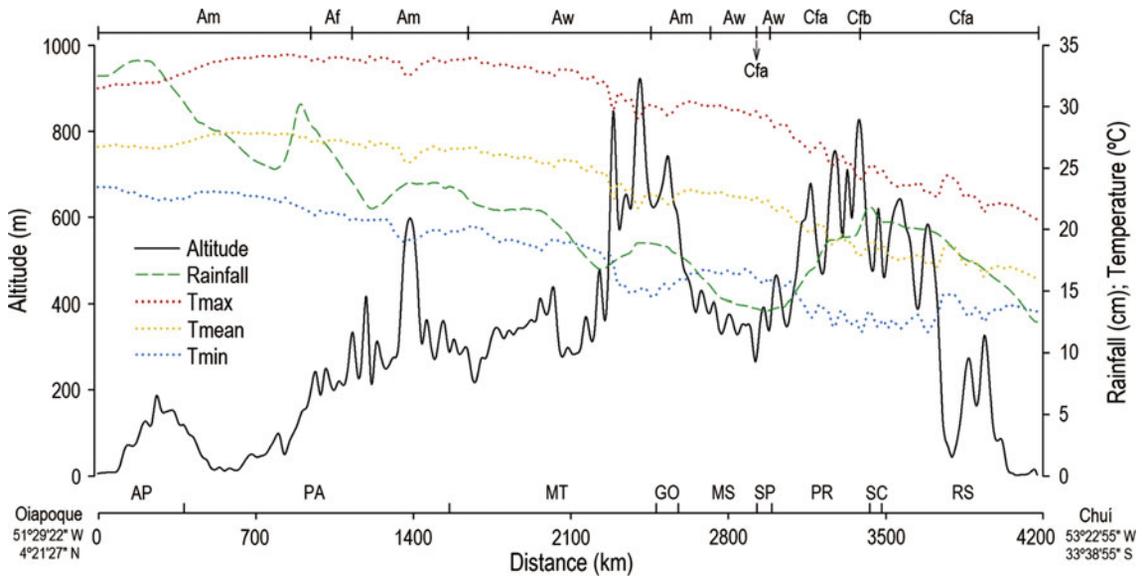


Figure 10: Climatic profile (altitude, rainfall and temperature) in a 4,200 km latitudinal gradient in Brazil, from Oiapoque (RR) to Chui (RS), including the states of Amapá (AP), Pará (PA), Mato Grosso (MT), Goiás (GO), Mato Grosso do Sul (MS), São Paulo (SP), Paraná (PR), Santa Catarina (SC), and Rio Grande do Sul (RS).

in altitude not higher than 500 m and annual rainfall between 1,000 to 1,400 mm. The southern coast of Espírito Santo, drier than the northern, with 1,100 mm year⁻¹, Aw climate occurs throughout the coastal region skirting the valleys and plateaus at altitudes lower than 400-450 m, because above this elevation the annual mean temperature is below 18 °C. Under the same conditions, Aw climate enters in Rio de Janeiro state and spreads all over the north and northwest coastline at altitudes not exceeding 250-300 m. Even in Rio de Janeiro (Lakes Region), Aw climate extends to Arraial Cape (23°S), a location with annual rainfall less than 1,000 mm. This locality is the most southern occurrence of Aw climate in Brazil

(Fig. 7). Aw climate was also identified between Parana and Mato Grosso do Sul states, exactly limited to the same latitude (23°S) of Arraial Cape, both being almost 1,200 km distant.

Western São Paulo state has an annual rainfall between 1,100-1,300 mm (Fig. 5), and Aw climate goes through the Western Plateau at landscapes below 400-450 m, because from the Paranapanema and Tiete Lower River begins subtropical climate by modifications imposed by altitude (TREWARTHA, 1943). SETZER (1946) showed that Aw climate covered a small part of the western São Paulo state, which was changed in his subsequent publication (SETZER, 1966) and thus comes

closest to our high spatial resolution climate map. [ROLIM et al. \(2007\)](#) showed that Aw covers almost the whole western São Paulo.

Tropical climate, which has winter rainfall (As), covers only 5.5% of the Brazilian territory ([Table 3](#)). In a general view, As climate occurs from 45°W including both Maranhão (01°18'S) and Mina Gerais (17°30'S) states, distant in more than 1,600 km ([Fig. 6](#)). As climate reaches a maximum of 600 km from the Atlantic Coast and occurs mainly in northeastern Brazil between Aw and BSh climates.

Ceará state has 62.3% of the As climate covering mainly in the Araripe Plateau, which was also observed by [BERNARDES \(1951\)](#) and [VIEIRA \(1960\)](#). As climate has been mapped into the strip that defines the *Agreste* region (Semi-arid), between Rio Grande do Norte and Bahia states. Analyzing the use of Köppen climate for Brazil, based on the Trewartha's world map ([TREWARTHA, 1937](#)), [ZARUR \(1943\)](#) concluded that "the Brazilian coastal region is characterized by forests of the super-humid regions, however there are numerous points disagreeing with this generalization, due to the complex configuration of local relief. In this region lies the curious As climate".

From Rio Grande do Norte to the Sergipe, As climate is coastal, where it presents a strong rainfall gradient (east to west), from 1,500 to 700 mm. [SCHMIDT \(1942\)](#), [BERNARDES \(1951\)](#), [SENRA \(1954\)](#), [GUERRA \(1955\)](#), [VIEIRA \(1960\)](#) and [KOTTEK et al. \(2006\)](#) also classified as As climate, the coastal strip along these two states, though the mapping of [BERNARDES \(1951\)](#), [GUERRA \(1955\)](#) and [VIEIRA \(1960\)](#) had identified a small region of Aw climate on the Pernambuco Coast, details consistent with the high resolution map of this study. Within this coastal strip lies Natal (05°47'S; 35°12'W; 35 m), capital of Rio Grande do Norte, that was selected to represent the location with a typical As climate ([Fig. 8](#) and [9](#)), which presents the rainy season concentrated between May and July and the intense dry season in the spring (September to December).

Curiously, it was unexpected its occurrence, As climate is observed in the north of Minas Gerais (12.3% of the state), especially in the Espinhaço Range (Montes Claros region), and in the lowlands of São Francisco River. In this region, As is mapped at altitudes lower than 950 m, depending on the latitude: the further north the highest altitude to be a subtropical climate. It is unexpected the classification of As climate in this Brazilian region, since previous studies have found it only in the low latitudes in northeastern Brazil ([BERNARDES, 1951](#); [SENRA, 1954](#); [GUERRA, 1955](#); [SPAROVEK et al., 2007](#); [PEEL et al., 2007](#)). Elsewhere, in north of Minas Gerais As climate is found in a scalloped landscape between Cwb and Cwa, which is a complex region due to the regional topography, limited to the maximum altitude of 700-800 m. Thus, the high-resolution climate map of this study is able to define in detail the depth of the valleys of several river basins that occur in this region.

B-Climate zone

Semi-arid climate (B zone) is notably the typical climate of northeastern Brazil, occurring basically in landscapes where annual rainfall drops on average to less than 800 mm ([Fig. 5](#) and [6](#)). It is about an enclave of scarce rainfall in the Brazilian tropical region. BSh climate was the only one of B zone found in Brazil, confirming studies of [BERNARDES \(1951\)](#), [SENRA \(1954\)](#), [GUERRA \(1955\)](#), [VIEIRA \(1960\)](#), [GALVÃO \(1966\)](#), [KOTTEK et al. \(2006\)](#), but otherwise [PEEL et al. \(2007\)](#) were the only authors to indicate the occurrence of BWk climate in Brazil.

BSh is a hinterland climate, but in Rio Grande do Norte state, it is found covering around 150 km of coastline ([Fig. 6](#)). This coastal belt has an annual rainfall lower than 650 mm and thus it can be inferred that it is the driest and warmest coast region of Brazil, since mean annual temperature is slightly higher than 26.5 °C ([Fig. 4](#), [7](#) and [9](#)). About this, [AB'SÁBER \(1977\)](#) also classified as semi-arid (*Caatinga's* morphoclimatic domain) such extensive coastal area of northeastern Brazil. Paraíba has the BSh climate extending throughout the Borborema Plateau, where in the Paraíba river valley, the annual rainfall is around 400 mm, considered one of the driest sites of Brazil ([Fig. 7](#)), consistent with the results obtained by [GUERRA \(1955\)](#).

BSh climate is quite representative in the Pernambuco state, covering 61.4% of the territory ([Table 3](#)), occurring along the depressions and plains of São Francisco River, and almost everywhere in the hinterland region, where the annual rainfall is less than 500 mm. Petrolina (09°23'S; 40°30'W; 380 m) is a good example of the BSh climate ([Fig. 8](#) and [9](#)), where it may be observed a dry period of nine months and rainfall concentrated from February to April is noted. In the state of Ceará, the BSh climate was identified in regions with an annual rainfall less than 700 mm while occurring within 70 km from the coast. Similar BSh climate in the Ceará state was also found by [BERNARDES \(1951\)](#), [SENRA \(1994\)](#) and [GUERRA \(1955\)](#).

In Alagoas and Sergipe states, BSh climate covers only the depressions of São Francisco river, where the annual rainfall exceeds 900 mm and tends to increase toward the Atlantic coast. According to the climate data, Paulo Afonso, Bahia (8°55'S; 38°47'W) is the driest region of Brazil, where annual rainfall is lower than 400 mm ([Fig. 7](#)). The region near to Raso da Catarina Ecological Station is also known as one of the driest region in Brazil ([RODRIGUES, 1992](#); [CHESF, 2001](#); [CONTI and FURLAN, 2011](#)), exactly where [PEEL et al. \(2007\)](#) presented the occurrence of BWk climate.

The southernmost point with BSh climate was found in the municipality of Piripá, southern Bahia, (latitude of 15°S), in the edges of the Vitória da Conquista Tablelands, less than 20 km from the border with Minas Gerais state ([Fig. 6](#)). Based on this, it is clear that there is no BSh climate in the Minas Gerais state, which was also

observed by SCHMIDT (1942), BERNARDES (1951), SENRA (1954), VIEIRA (1960), ANTUNES (1980), KOTTEK et al. (2006) and PEEL et al. (2007), but not by SPAROVEK et al. (2007) and SÁ JUNIOR et al. (2012) that showed small BSh areas in the north of the Minas Gerais state.

C-Climate zone

Subtropical climate, classified in the C zone, covers 13.7% of the Brazilian territory (Table 3), which is mainly in the southern region, in their plateaus and mountains. The Köppen's key criteria worked well for Brazil since was noted that below and above the Tropic of Capricorn there is a dominance of subtropical and tropical climates, respectively (Fig. 6).

Cfa climate covers 6.5% of the Brazilian territory, mainly in the southern states. This climate occurs in a continuous area from the southwestern São Paulo to southern Rio Grande do Sul (Fig. 6 and 10).

In the maps reported in the literature in a state level as in MOTA (1951) and KUINCHTNER and BURIOL (2001), in a national level as BERNARDES (1951) and VIEIRA (1960), and in a global level as in KOTTEK et al. (2006), the shift line between Cfa and Cfb climates is not as far west as in the map presented in this study. Porto Alegre (30°02'S; 51°14'W; 30 m), the capital of Rio Grande do Sul, was selected as a typical location with a Cfa climate (Fig. 8 and 9), presenting monthly rainfall well distributed, between 100 and 170 mm. In the northern coastal region of Rio Grande do Sul, Cfa was identified at altitudes lower than 500 m. Central-northern Rio Grande do Sul state, the Cfa covers landscapes with altitudes below 550 m. Further west, this limit changes to 600 m, and a little more northwest, therefore further from the ocean, the altitude limit between Cfa and Cfb climates rises to 650 m.

Santa Catarina presents Cfa climate in its western region, always at altitudes below 700 m. To the east of this region Cfa climate covers the valleys of Uruguay river at elevations below 650 m. Cfa climate is also observed across the Santa Catarina coast, in the altitudes up to 500 and 600 m. In Paraná state, Cfa climate is present everywhere in the west and at the coastline, as also observed by CAVIGLIONE et al. (2000). In the western Paraná, Cfa is observed in the Iguazu river valley, always below altitudes between 750 and 800 m.

In all Paraná coastal belt Cfa climate was identified from the Marine Plains to find (at west) Serra do Mar mountain ranges, which was similar to that presented by BERNARDES (1951), VIEIRA (1960), GALVÃO (1966) and CAVIGLIONE et al. (2000). In this region, the Cfa climate was mapped in the escarpment with altitudes lower than 650 m in the north coast, and until the 600 m in the south.

Cfa is a typical climate in southwestern São Paulo (below 21°30'S) and in the Peripheral Depression (below 22°30'S). In these two zones, the Cfa climate covers a

wide range of altitudes: between 450 and 750 m in the northern boundary (borders between Aw, Cwa and Cfb climates) and between 400 and 700 m in the southern limit (borders with Cfb climate). It is also observed in the Paraíba do Sul river plains, similar to what was found by ROLIM et al. (2007). Cfa climate covers a strip along the entire Coastal Plain, whenever between Af or Am and Cfb climates. Rio de Janeiro has Cfa climate in a narrow range, between Am and Cfb, in the Serra of Mar mountains, which correlates to the findings of BERNARDES (1952), and more northerly between Am and Cwa.

The present climate map also shows Cfa climate in the plateaus in the south of Mato Grosso do Sul state, as previously reported by BERNARDES (1951), VIEIRA (1960), KOTTEK et al. (2006), SPAROVEK et al. (2007), and PEEL et al. (2007). Curiously, this type of climate was also observed in the Pantanal's uplands, above 900 m of altitude, region classified as remnant mountains of upper Paraguay river (ROSS, 2011).

In the following Brazilian states, Cfa climate is unusually observed, since it was not previously reported. In Minas Gerais, the Cfa climate is present on the tops of plateaus, with altitudes between 550 and 800 m and further north, between 650 and 850 m. In Vitória da Conquista Plateau (15°S), in the Bahia state, Cfa climate has a higher proportion in the altitudes between 750 and 900 m, and where annual rainfall is around 700 to 800 mm (Fig. 7). Another region where Cfa climate occurs is in the Brazilian northern hemisphere, between Amazonas and Roraima states. Although it is an equatorial region, the interaction between altitude and latitude allows the occurrence of such climate type. The highest point in Brazil, the Neblina Peak (2,993 m), in the state of Amazonas, has a Cfa climate, with an annual mean temperature between 16 and 18 °C (Fig. 7).

Cfb climate is observed in only 2.6% of Brazilian territory (Table 3). The main occurrence of this climate is from southern Minas Gerais (Mantiqueira Mountain) and part of Rio de Janeiro and Espírito Santo to Rio Grande do Sul state (Araucárias Plateaus). Cfb covers the southern regions at maximum distance of 500 km from the Atlantic Ocean, located 300 km in the São Paulo state and only 100 km in Rio de Janeiro and Espírito Santo states (Fig. 6). The continentally effect is remarkable, since further north, more close to the coast is the Cfb climate.

Cfb climate occupies all remaining territory of Rio Grande do Sul and Santa Catarina states where the altitude (or temperature, $T_{HOT} < 22$ °C) limits Cfa. This is also true for Paraná state since the areas with tropical climates, Am and Aw, present in the state are considerably small in the extreme north. Rio Grande do Sul state has the Cfb climate from the eastern border of the Parana river basin to the Araucária Plateaus. BERNARDES (1951), MOTA (1951), VIEIRA (1960), KUINCHTNER and BURIOL (2001) likewise indicated in their maps the occurrence of the Cfb climate in these regions, although the maps of BERNARDES (1961) and KUINCHTNER and

BURIOL (2001) were more similar to the map presented in this study. The Cfb climate covers the coldest regions of Brazil, as Urupema, Urubici and São Joaquim, in the state of Santa Catarina, where there are peaks with altitudes exceeding 1,800 m.

Curitiba (25°26'S; 49°16'W; 930 m), the capital of Paraná state, is a typical location with this type of climate, with annual mean temperature of 17 °C (20.5 °C in January and 13 °C in July) and annual rainfall of 1,550 mm, slightly concentrated in the summer months, and having as the driest months July and August (Fig. 8 and 9).

Cfb climate crosses the São Paulo state, from Paranaíacaba Mountain to the south of Minas Gerais and west of Rio de Janeiro, throughout the Serra do Mar Mountains. In this region, Cfb climate has annual rainfall exceeding 3,300 mm (Fig. 7). On the São Paulo coast, Cfb climate occurs at altitudes above 700 m, and between 700 m and 130 m was classified as the Cfa climate and from this point to the sea level Aw, or Af, climate were mapped. Similar occurrences of Cfb climate for the São Paulo state were also reported by BERNARDES (1951) and SETZER (1966).

The Cfb climate is in 9.4% of the Rio de Janeiro state in the Orgãos Mountain National Park at altitudes above 2,100 m and with annual mean temperature lower than 12 °C. It occurs in the southern Espírito Santo at lower latitudes as Jacobina Mountains (up to 10°S), which is the northernmost point in Brazil with this climate type (Fig. 7). Cfb climate in the highlands of Diamantina Plateau is not a novelty and confirms the mapping obtained by VIEIRA (1960).

Cwa is a typical climate of southeastern Brazil and covers only 2.5% of the national territory (Fig. 6). Taubaté municipality (23°10'S), in São Paulo state, is the southernmost occurrence of Cwa climate (Fig. 7), in agreement with maps presented by BERNARDES (1951) and SETZER (1966). São Paulo has 17.4% of its territory classified as Cwa, especially in the Peripheral Depression and also in part of Western Plateau. In this region lies Ribeirão Preto (21°11'S; 47°49'W; 550 m), which was selected as a typical representation of Cwa climate, since it has an annual mean temperature of 21 °C, January being the warmest (23.5 °C) and July the coldest month (17.5 °C) (Fig. 8 and 9).

Approximately 25.5% of the Minas Gerais state territory is classified as Cwa climate, whenever observed in landscapes between Aw/As and Cwb climates. Southern Minas Gerais has Cwa climate covering altitude between 800 and 850 m in Furnas Lake region, and up to 900 m in the Grande river valley. A large part of the Triângulo Mineiro is characterized as subtropical climate (Cwa), which confirms the maps obtained by SCHMIDT (1942), BERNARDES (1951), MONTEIRO (1951), GALVÃO (1966) and SPAROVEK et al. (2007). As explained in Aw climate section, SÁ JUNIOR et al. (2012) classifies the Cwa climate at altitudes higher than those of our high resolution climate map, and thus the occurrence of either Cwa or Cwb is more restricted, i.e. in their maps of

Minas Gerais is more tropical than the one presented in present study. Cwa climate is also observed in Espinhaço Mountain in altitudes between 500 and 800 m.

Few uplands of northeastern Brazil are classified as Cwa climate, like in Borborema Plateau, between Paraíba and Pernambuco states, at altitudes between 900 and 1,000 m, where the annual rainfall is less than 700 mm, and thus is the driest region with this climate type (Fig. 7).

In the Brazilian Central Plateau (Goiás state), Cwa climate is found in landscapes above Aw and below Cwb. In the south of Goiás state, altitude in the areas with Cwa climate ranges from 900 to 1,000 m and in the northern region they range from 1,000 to 1,100 m of altitude, showing latitude effects, because of the increase in annual mean temperature from south to north. In these upland regions of Goiás state, MONTEIRO (1951), BERNARDES (1951) and VIEIRA (1960) also demonstrated in their climatic maps the occurrence of Cwa climate, which was innovative because they were the first ones to show that. The northernmost point of the Cwa climate in Brazil was found in landscapes with altitude of 900 m and an annual mean temperature of 16 to 17 °C (Fig. 7).

Cwb climate is observed in only 2.1% of the Brazilian territory (Table 3) and similarly to Cwa, Cwb is a typical climate of southeastern Brazil (Fig. 6). Cwb occurs of central-southern Minas Gerais (26%), and the limit of this climate coincides with the administrative borders of this state with São Paulo and Rio de Janeiro. Thus, in Minas Gerais, Cwb climate occupies the whole region of Mantiqueira (22°S, > 850 m), Canastra (20°15'S, > 900 m) and the Espinhaço (18°50'S, > 950 m) Mountains. The Minas Gerais capital, Belo Horizonte (19°55'S; 43°56'W; 855 m), was selected as a typical location with a Cwb climate in Brazil (Fig. 8), to show the evident climatic seasonality in this region, where winter is cold and dry and summer is hot and humid. Regarding Curitiba (Cfa), Belo Horizonte is a bit warmer, with annual mean temperature of 19.3 °C, with a minimum of 15.5 °C in July and a maximum of 21.5 °C in January.

Many regions of Bahia are classified as Cwb climate. Cwb is mapped in the south-central region where the altitudes are greater than 1,000 m throughout Espinhaço Mountain. Diamantina Plateau also presents Cwb climate, in altitudes above 1,100 m where the annual rainfall is lower than 700 mm, and thus it is the driest Cwb location in Brazil (Fig. 7). On the some landscapes of high altitude in the Borborema Plateau (Pernambuco and Paraíba states), in the hillslopes of altitude above 1,000 m, is the most northerly of the Cwb climate occurrence in Brazil (7°49'S, Fig. 7).

In the Goiás state, the Cwb climate is always found in the landscapes above Cwa. Cwb is also observed in northern Goiás, at altitudes above 1,300 m (14°S).

São Paulo has Cwb climate covering the Basaltic Cuestas in the municipalities of Itirapina (22°22'S, > 800 m), Analândia (Cuscuzeiro Mountain), Batatais (20°55'S, > 850 m) and Franca (20°10'S, > 900 m). In the upper

Paraíba do Sul river, Cwb is found at altitudes above 700 m. In the Rio de Janeiro state, Cwb climate follows the boundary of the Minas Gerais state in the Serra do Mar Mountain where the altitude is higher than 650 m, as also proved by the map obtained by BERNARDES (1951).

This is the first study that found Cwc climate in Brazil. Only three sites are classified in Brazil fulfilling the Cwc climate criteria. All of them are located in extremely high points in southeastern Brazil, near the coast, less than 120 km from the Atlantic Ocean. The most northern site is located in the region between Minas Gerais and Espírito Santo states, along the Caparaó Mountain. Bandeira Peak (20°26'S; 41°47'W; 2890 m) was chosen as the geographical landmark to show its rainfall and temperature monthly distribution (Fig. 8). Cwc climate has autumn and winter (May to September) with dry and cold conditions and monthly rainfall lower than 50 mm and monthly mean temperature of 4.5 °C in July. The annual mean temperature is 9.4 °C and the annual rainfall is approximately 1,300 mm (Fig. 9). The Cwc climate was also observed in other high peaks, between Minas Gerais and Rio de Janeiro states.

The Cs climate (subtropical with dry summer) is observed only in Borborema Plateau, in the Pernambuco and Alagoas states (Table 3), in small areas surrounded by As and BSh climates. Csa climate is observed at a specific altitude, between 800 and 1,000 m (Fig. 7). Above this range of altitude, the climate is classified as Csb (Humid subtropical with dry and temperate summer). The occurrence of Csb climate in Brazil is unprecedented since no other study showed its occurrence in the Brazilian territory. Csa is present in a higher altitude in the Caetés region (Pernambuco state), and thus this location was selected as representative of the Csa climate in Brazil (08°45'S; 36°40'W; 950 m). In Caetés, the rainfall reaches 710 mm per year, but concentrated in the autumn, from April to June, and in the early winter (July), with no more than 100 mm per month (Fig. 8). The annual average temperature in Csa climate in Brazil is 20.9 °C with maximum in January (22.7 °C) and minimum in August (18.1 °C). The Csa climate was also reported in some areas of Borborema Plateau by BERNARDES (1951), GUERRA (1955) and SPAROVEK et al. (2007).

In the southern state of Pernambuco, the Csb climate is observed in the Saloá region (09°01'S; 36°47'W; 1050 m), a location with annual rainfall of 690 mm and seasonal distribution similar to Caetés (Fig. 8 and 9), which is expected since they are very close in the Borborema Plateau. The difference between Cs climates is due to the altitude in the region of its occurrence, which reduce the annual mean temperature.

4 Conclusions

The high resolution Köppen's climate map developed in this study improved and highlighted the different climates found across Brazil landscape when compared with any

previous published maps. It also represents the first approach in the literature to develop a Köppen climate map in a hectare scale for Brazil (851,487,700 ha).

At this fine scale the three climate types of Brazil (A, 81.4%; B, 4.9% and C, 13.7%) were described with the following subtypes; Af, Am, Aw, As, Bsh, Cfa, Cfb, Cwa, Cwb, Cwc, Csa, Csb. These zones and climate types identified in the high resolution climate map provided both a deeper climate insight at the regional and local levels and the identification of climatic types never before reported in the Brazilian landscape. Considering the increasing fragmentation of natural landscapes and agricultural and urban uses, the hectare scale for planning seems to be the ideal approach for future development of many applications.

Considering that the new climatological normal for Brazil will be published just after 2020, this climate map will remain accurate for the next decade. This high resolution map will be made available for public download in order to facilitate its potential use on basic and applied agricultural, forest and other natural sciences climatologic researches.

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