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Short Communication

Computer assisted Koeppen climate classification: a case study for Brazil

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Abstract:

Koeppen's climate classification, developed one century ago, is still used as a reference for large-scale climate mapping and useful for climatologic research (climate shift, climate model testing, and ecological research). This paper describes a software that was developed to allow non-assisted Koeppen climate classification based on a simple database (monthly mean temperatures and rainfall) as input. The software follows, as strictly as possible, the original concepts suggested by Koeppen, but does not include climates that cannot be defined by simple input parameters. Combined with GIS tools, the software was used to produce the first comprehensive climate map of Brazil using a large database. The map showed 21 Climate Equations in three climate zones (A = tropical moist; B = dry; C = moist with mild winter). This map was compared with an existing climate map of Brazil (FAO/SDRN). The two maps showed good agreement only in the less detailed information (climate zone and type). The complete Climate Equations were not comparable in relation to spatial distribution and class coincidence. Improvements were made for Koeppen's climate classification, avoiding computational or database errors, and it increased the details for climate classification of Brazil. Copyright © 2006 Royal Meteorological Society

KEY WORDS climate classification; Koeppen; Brazil; GIS

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INTRODUCTION

Wladimir Koeppen developed the first quantitative climate classification in 1900. Koeppen's system was based on the principle that plants integrate several climate elements. Koeppen fitted isolines of temperature and precipitation data to the five vegetation groups identified by the French botanist De Candolle, which were based on the late Greek climate zones: (1) ***A***, the plants of the torrid zone; (2) ***C***, plants of the temperate zone; (3) ***D*** and ***E***, frigid zone (no plants); (4) ***B***, for plants of the dry zone. Koeppen added sequential letters (1) to account for moisture (rainfall), (2) for a better description of maximum and minimum temperatures, (3) for the seasonal distribution of rainfall (Sanderson, 1999), and (4) for special features such as fog incidence. From its first publication until now, the concepts outlined in the last revised version of Koeppen's work 'Grundriss der Klimakunde' (Koeppen, 1931) have not significantly changed. Improvements were suggested by Trewartha (1980), Rudloff (1981), Guetter and Kutzbach (1990), and Stern *et al*. (2000) in order to adapt Koeppen's system for specific purposes or localities, but without changing the original concepts of classification. Even with the more recent classification, developed by the North American climatologist Thornthwaite (Thornthwaite, 1948) on the basis of potential evapotranspiration and precipitation, Koeppen's classification of world climates is the most widely used. Regional climate assessments and climate maps in atlases are based on Koeppen's system (FAO/SDRN, 1997). Koeppen's system is useful for climate research, as shown by Fraedrich *et al*. (2001) for continental climate shifts, seasonal variation of climate boundaries in the USA (Suckling and Mitchell, 2000), and comparative pedological research (Bockheim, 2005). Also, Koeppen's classified climates describe different surface-energy balances (Kraus and Alkhalaf, 1995) and are used in model testing and calibration, as shown by Nonomura *et al*. (2003) for vegetation cover in Africa, and by Kalvova *et al*. (2003) in general circulation models. Most criticisms of Koeppen's system are related to the rigid boundary criteria (Stern *et al*., 2000) that, in some cases, include diverse natural landscape features in the same climate class, as a result there is a strong internal variability of important climate elements (Triantafyllou and Tsonis, 1994).

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Computer assisted database tools and Geographic Information System (GIS) interpolation may improve the quality and accuracy of regional thematic maps of Koeppen's climate classification. This study describes a software developed for climate classification according to the original concepts of 'Grundriss der Klimakunde' (Koeppen, 1931), which allows non-assisted data processing. The software is applied using data from a large number of climate stations, and a comprehensive climate map of Brazil is obtained.

MATERIALS AND METHODS

The software

The climate classification software was developed in Microsoft Visual Basic. It reads standardized text format input files of monthly mean values of rainfall and temperature. Other input variables are the location (latitude and longitude in decimal degrees) and the identification of the climate station. These variables allow the establishment of the initial and final dates of the four seasons (summer, fall, winter, and spring) and also report the station identification and location in the output file. Seasonal periods are defined according to the meteorological criteria, i.e. for the Northern Hemisphere: meteorological spring (1 March–31 May), summer (1 June – 31 August), fall (1 September–30 November), and winter (1 December–28 February). The same dates were used for the Southern Hemisphere, but the seasons were reversed.

Climate zone, -type, and -subdivision or the Climate Equation ('Klimaformel', *q.v.* Koeppen (1931) page 127) are defined according to the criteria summarized in Table I and Figures 1, 2, and 3. In order to keep the input data file simple, some climate types and subdivisions suggested by Koeppen (1931) are not automatically processed by the software. The inclusion of some climate types would increase the amount and complexity of information needed in the input file (e.g. subtype n is defined according to the frequency of fog incidence). For other subtypes, the definitions of Koeppen (1931) do not allow a quantitative assessment of the climate type using monthly mean values (e.g. x' describes a climate type with '*rare, but strong rainfall in all seasons*'). To avoid the need for more input parameters or subjective interpretation, the following climate types are not processed by the software: s'' = equal to s′, but with a bi-modal rain season with a slight wet period in between; w'' = equal to w′, but with a bi-modal rain season with a slight wet period in between; t' = hottest period is postponed from summer to fall because of ocean influence 'Kap-Verdescher Wärmegang' (*q.v.* Koeppen (1931) page 45); t'' = coldest temperatures during the summer, usually associated with rainfall 'sudanischer Wärmegang – ebenda', (*q.v.* Koeppen (1931) page 45 and 128); n, n', n'', n''' = associated with fog incidence;

Table I. Climate zones, types, and subdivisions of Koeppen's climate classification, and classification criteria. Climate types and subdivisions in italics are not classified in the software

Zone	Criteria	Type	Subdivisions (criteria)
A	$T_{min} \geq 18\,^\circ C$ (Figure 2)	Af	s′ (analogous s with $P_{max,aut} > P_{max,win}$)
		Aw	w′ (analogous w with $P_{max,aut} > P_{max,sum}$)
		Am	s'', w''
		As	t', t''
B	Annual rainfall criteria (Figure 1)	BS	h ($T_{med} \geq 18\,^\circ C$)′
		BW	k ($T_{med} < 18\,^\circ C$; $T_{max} \geq 18\,^\circ C$)
			k′ ($T_{max} < 18\,^\circ C$)
			s, w (dry summer, dry winter, according to criteria Figure 3)
			n, n', n'', n''
C	$-3\,^\circ C < T_{min} < 18\,^\circ C$ (Figure 3)	Cs	a ($T_{max} \geq 22\,^\circ C$)
		Cw	b ($T_{max} < 22\,^\circ C$; 4 to 11 months with $T \geq 10\,^\circ C$)
		Cf	l ($T_{max} < 22\,^\circ C$; all months with $T \geq 10\,^\circ C$)
		Cx	g (warmest month before solstice and before wettest month)
		Cx′	i (only for Cw and Cf: $T_{max} - T_{min} \leq 5$)
D	$T_{min} \leq -3\,^\circ C$ and $T_{max} \geq 10\,^\circ C$ (Figure 3)	Dw	a ($T_{max} \geq 22\,^\circ C$)
		Df	b ($T_{max} < 22\,^\circ C$; 4 to 11 months with $T \geq 10\,^\circ C$)
		Dx	c ($T_{min} > -38\,^\circ C$; 1 to 4 months with $T \geq 10\,^\circ C$)
			d ($T_{min} \leq -38\,^\circ C$
E	$T_{max} < 10\,^\circ C$	ET	i ($T_{max} - T_{min} \leq 5$)
		EF ($T_{max} < 0\,^\circ C$)	

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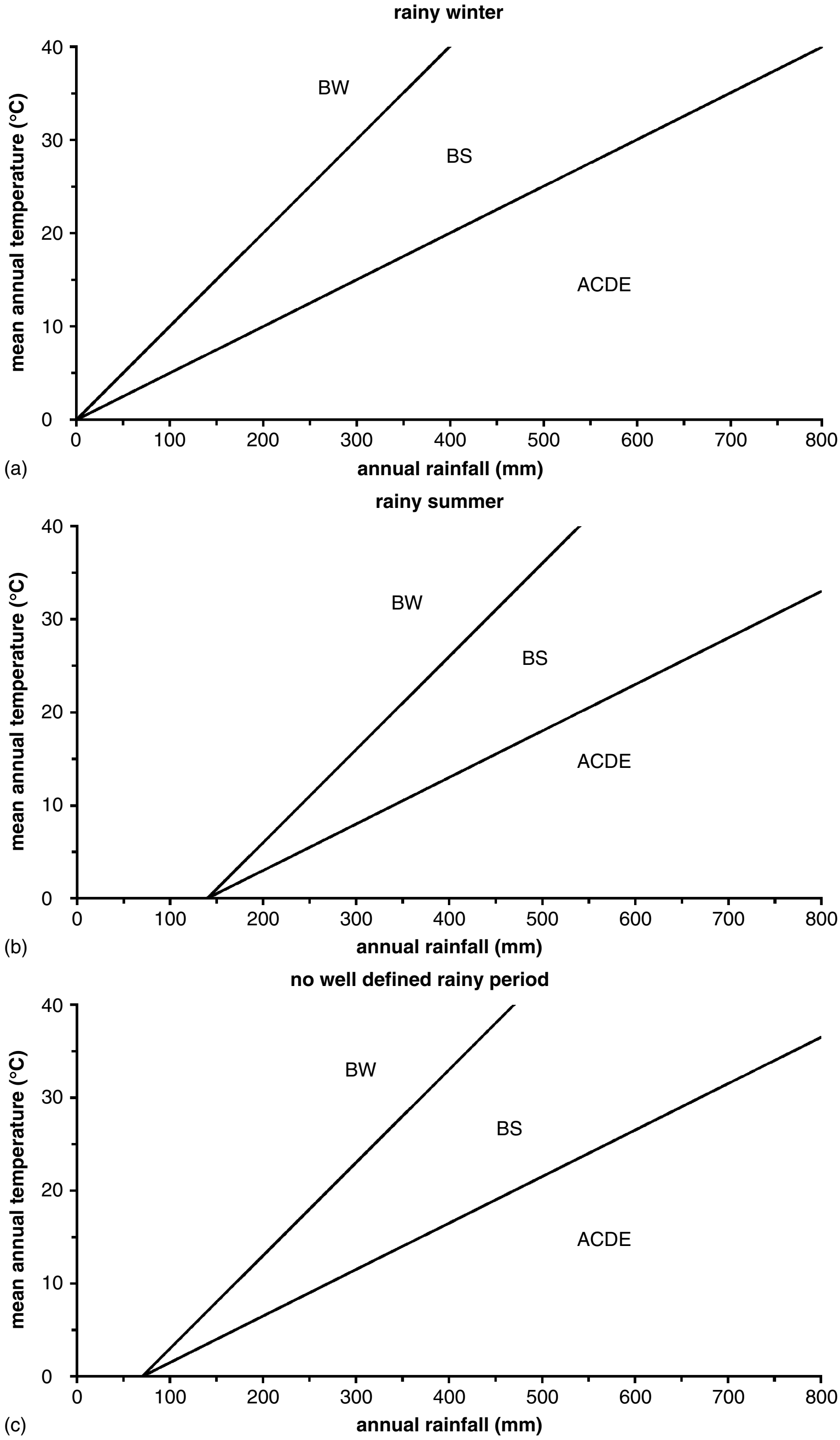

Figure 1. Division between dry (B) and wet (A,) (C), (D), (E) climates, and subdivision in BW and BS as related to mean annual temperature and annual rainfall, for the cases of (a) rainy winter, (b) a rainy summer, and (c) no well defined rainy period (adapted from Koeppen, 1931, page 129)

x = maximum rain at the beginning of summer and cool temperatures in late summer; x' = rare, but strong rainfall in all seasons.

The software output consists of a file report with identification and location of the stations and the complete climatic classification (Climate Equation), down to the lowest possible level (zone, type, subdivision) that can be achieved using the original description reported in Koeppen (1931).

Case study application: a new climate map for Brazil

Data from a total of 1342 climate stations, covering continental Brazil and the South American neighboring

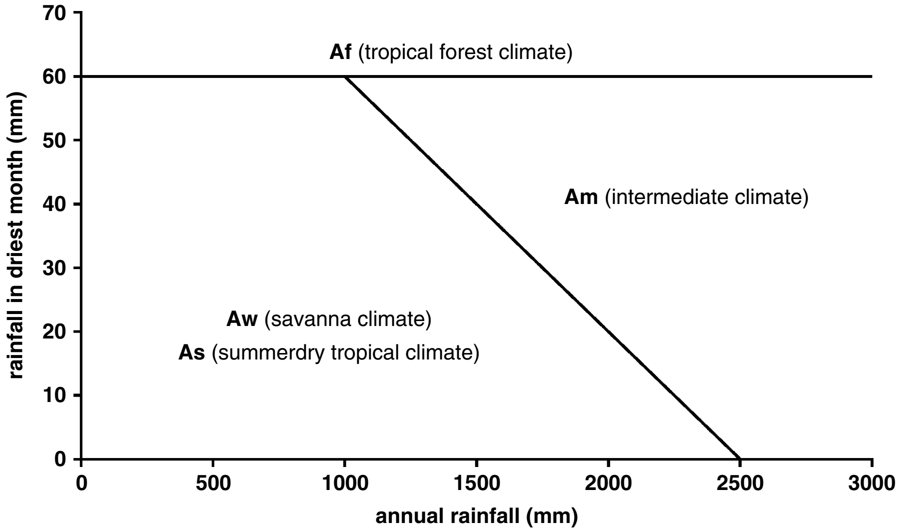

Figure 2. Subdivision of A climates as related to annual rainfall and rainfall in the driest month (adapted from Koeppen, 1931, page 131). Subdivision between Aw and As is made according to figure 3

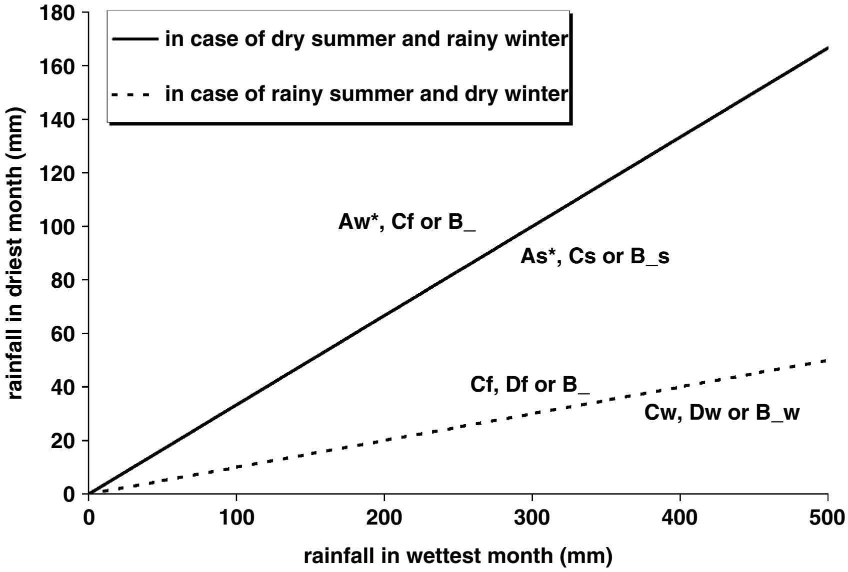

Figure 3. Subdivision of climates as related to rainfall in the wettest and driest months for climates with dry summers and dry winters. * In the case of A climates, this subdivision is only used if not previously classified as Af or Am

countries, containing monthly values of mean temperature and rainfall were used as input data for climate classification. The sources of these data were the Food and Agriculture Organization of the United Nations (FaoClim), the Brazilian Institute for Meteorology (Inmet), and the Integrated Centre for Agro-climatic Information of the State of São Paulo, Brazil (CIIAGRO). Inmet (Brazil) and CIIAGRO (State of São Paulo) are responsible for most climate stations in the respective areas, and a much used source of data for local climate research. The length of time of the time series and the procedures for collecting and processing data vary for each station. Stations with records for periods less than 15 years, duplicated coordinates or very close locations, outliers, stations with missing values, and unusual seasonal variation were excluded. In addition, after interpolation by Voroni polygons, small polygons with sharp boundaries (e.g. a small A climate polygon surrounded by B climate) were checked for local variations in altitude or natural vegetation that could explain the abrupt change. The locations of the climate stations are presented in Figure 4(b). Voronoi polygons, with the assigned Climate Equations, were calculated for interpolation (Figure 4(c)). The climate map resulting from automatic processing and GIS interpolation was compared with an earlier climate map that includes Brazil (FAO/SDRN, 1997) by merging the two sources and calculating the weighted Kappa coefficient for the coincident classes. The Kappa coefficient represents the agreement obtained after removing the proportion of agreement that could be expected to occur by chance (Foody, 1992). Also, the non-coincident climates were quantified and described.

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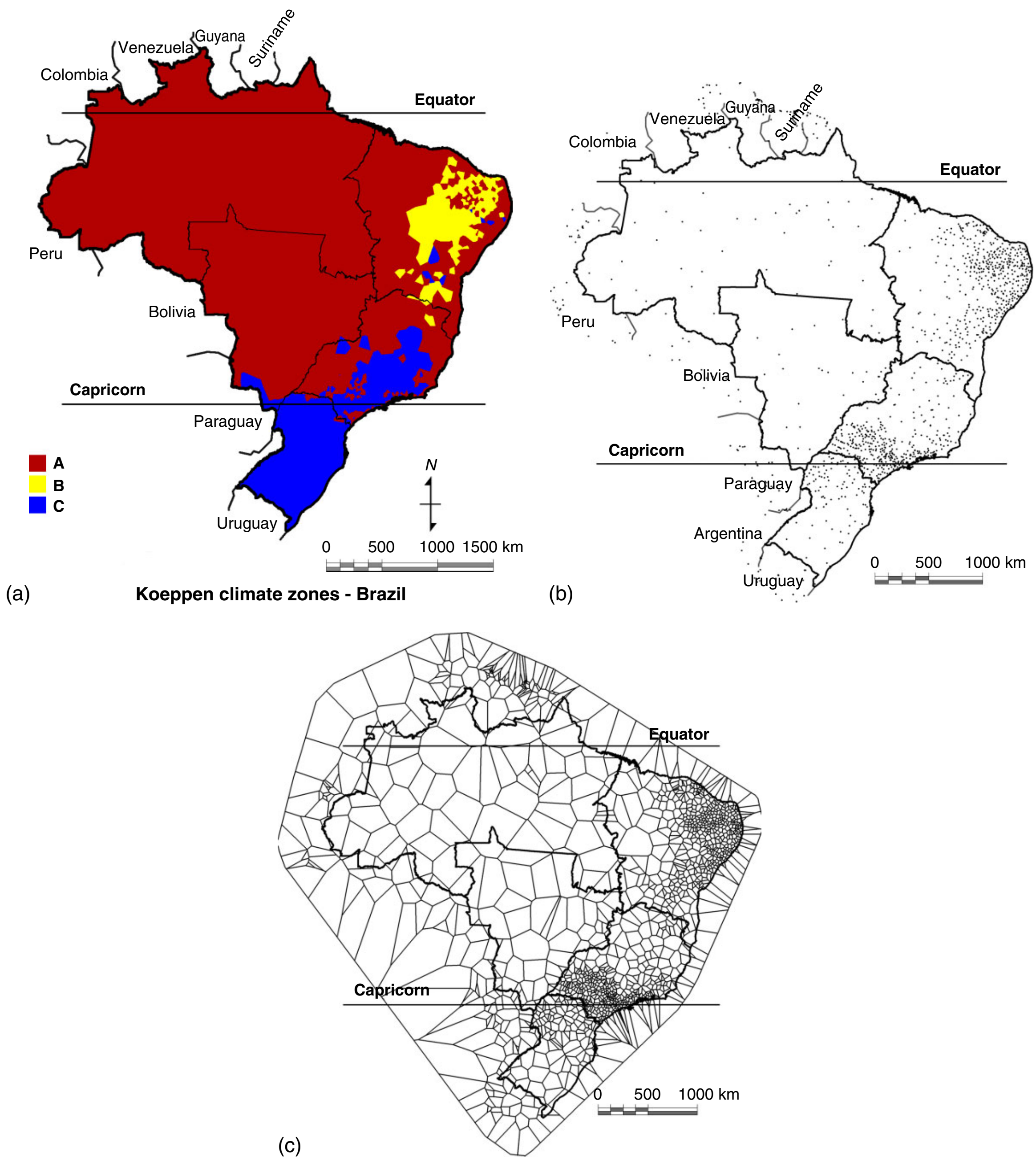

Figure 4. Geographical map of Brazil (a) with Koeppen climate zones, (b) with dots indicating climate station locations, (c) showing Voronoi polygons calculated for climate type interpolation. This figure is available in colour online at www.interscience.wiley.com/ijoc

The Geographic Information System TNTmips version 6.8, of Microimages and statistic calculations on SAS, was used for analytical procedures.

RESULTS AND DISCUSSION

Interpolation procedure

The station distribution in the database was non-uniform. Brazilian northeast coastal areas, where drier areas prevail, and some parts of the south and southeast, especially the state of São Paulo, show a higher density of stations. The lower coverage of the remaining areas is due to the absence of climate stations (north) or the difficulty in accessing climate information collected at the state level (Central and South Brazil). The frequency distribution of the Voronoi polygons area is presented in Figure 5. In 50% of the stations, Voronoi polygons covered less than 2000 km^2 and in 10% of the cases their area was greater than 36 000 km^2. The low coverage of stations in large parts of Brazil probably did not affect the climate zones, which formed large uniform polygons in these areas (Figure 4(c)). The climate types, and subdivisions, described by the suffixes of the zones, were more variable. The low coverage of stations in the north, and in some northeast parts of Brazil may reduce the accuracy of the interpolation in these regions (Figure 6(a)). This is not expected in the south, where the Cf climate type (moist with mild winter and humid) prevails.

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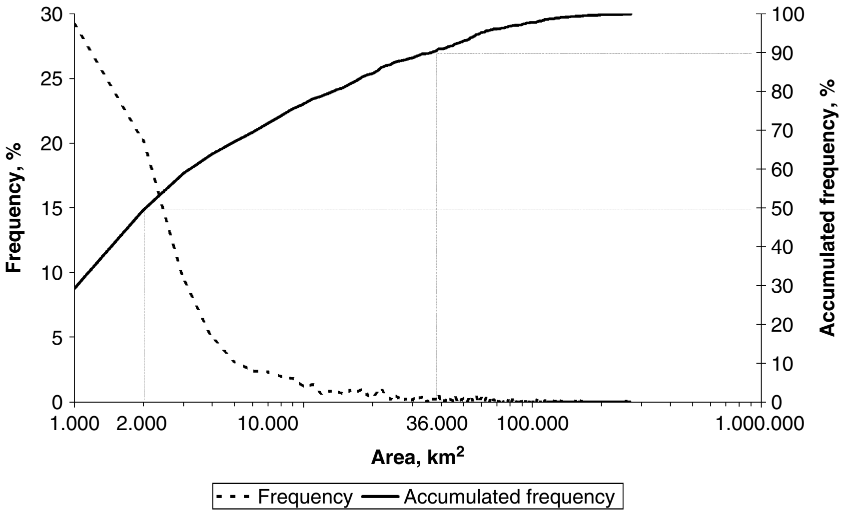

Figure 5. Area frequency distribution and accumulated frequency of the Voronoi polygons used for climate interpolation

Table II. Complete Climate Equation description of Brazilian climates (according to Koeppen, 1931)

Zone			Type			Subdivision					
Zone	Description	%	Type	Description	%	Level 1		%	Level 2	Description	%
A	Tropical moist	83.65	Af	Wet	14.14						
			Am	Monsoon (short Dry season)	28.46						
			As	Dry summer	0.35						
			As′	Wet spring	1.13						
			Aw	Dry winter (savanna)	29.62						
			Aw′	Wet spring (savanna)	9.95						
B	Dry	5.00	BS	Semiarid	4.77	BSh			BSh	Hot	0.74
							Hot	4.77	BShs	Very dry summer	0.23
									BShw	Very dry winter	3.80
			BW	Arid	0.23	BWh	Hot	0.23	BWhw	Very dry winter	0.23
C	Moist with Mild winter	11.36	Cf	Humid	8.44	Cfa	Hot	5.75	Cfa	Hot	5.72
									Cfai	Low temperature range	0.03
						Cfb	Cool	0.01			
						Cfl	Mild	2.68	Cfl	Mild	2.52
									Cfli	Low temperature range	0.16
			Cs	Dry summer (Mediterranean)	0.04	Csa	Hot	0.04	Csa	Hot	0.02
									Csai	Low temperature range	0.02
			Cw	Dry winter	2.87	Cwa	Hot	1.65		Hot	
						Cwb	Cool	0.00		Cool	
						Cwl	Mild	1.22	Cwl	Mild	1.13
									Cwli	Low temperature range	0.08

The resulting climates

Brazil is a tropical country, but extends well into the temperate zone. Owing to its continental dimensions, very diverse climates occur. These climates are influenced by Brazil's geographical configuration, significant coastal length, geomorphology, and territorial air-mass dynamics. The Amazon Basin has a typically hot, tropical climate because of the Equatorial air masses. The Brazilian Highlands, which include roughly half the total area, are subtropical. The climate of the narrow coastal lowland area ranges from tropical in the north to temperate in the south. The upland plains of the south have a temperate climate.

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Table III. Climate zones contingency table and weighted Kappa coefficient

		FAO–SDRN (1997)			Line total
		A	B	C	
			%		
Koeppen zones	**A**	**76.61**	0.34	6.73	83.69
	B	3.70	**1.12**	0.21	5.03
	C	0.79	0.01	**10.49**	11.29
Column total		81.10	1.47	17.43	100

Weighted Kappa coefficient = 0.64.

Table IV. Coincident climate types contingency table and weighted Kappa coefficient

		FAO/SDRN (1997)						Row total
		Af	Am	Aw	BS	Cf	Cw	
		% in relation to the total area[a]						
Koeppen types	Af	**9.92**	1.16	2.95	0	0.10	<0.01	14.13
	Am	5.56	**6.78**	15.60	0	0.43	<0.01	28.39
	Aw	0.65	29.92	**2.62**	0.34	1.64	4.16	39.71
	BS	0.10	3.35	0.12	**1.03**	0.18	0	4.80
	Cf	0	0.21	0.03	0.01	**7.48**	0.50	8.36
	Cw	0	0.47	0.05	0	0.36	**1.92**	2.89
Total columns		16.22	43.46	21.41	1.47	10.18	6.59	

[a] Classes not available in FAO/SDRN (1997): As with (1.45%), BW (0.23%), Cs (0.04%) – Total not available = 1.72%.
[a] Classes not available in this paper: C (0.07%), Ca (0.54%), Cb (0.03%) – Total not available = 0.65%.
Weighted Kappa coefficient of coincident types = 0.36.

Table V. Coincident Climate Equation contingency table and weighted Kappa coefficient

		FAO/SDRN (1997)								Row total
		Af	Am	Aw	BSh	Cfa	Cfb	Cwa	Cwb	
		% in relation to the total area[a]								
Koeppen Climate Equation	Af	**0.29**	0.04	0.37	0	0.02	0.04	<0.01	0	14.13
	Am	0.09	**0.85**	1.55	0	0.40	0.03	0	<0.01	28.39
	Aw	0.38	9.53	**0.40**	0.04	1.40	0.17	3.49	0.36	29.78
	BSh	0	0.22	0	**0.33**	0	0	0	0	0.74
	Cfa	0	0.13	<0.01	0	**4.63**	0.42	0.10	0.22	5.62
	Cfb	0	0	0	0	0	**0.00**	0	0.01	0.01
	Cwa	0	0.37	0.03	0	0.10	0.07	**0.81**	0.20	1.66
	Cwb	0	0	0	0	<0.01	<0.01	0	**0**	<0.01
Total columns		0.86	12.68	2.55	1.47	7.87	2.20	4.97	1.30	

[a] Classes not available in FAO–SDRN (1997): As with (0.34%), As' (1.11%), Aw' (9.93%), BShs (0.23%), BShw (3.82%), BWhw (0.23%), Cfai (0.03%), Cfl (2.54%), Cfli (0.16%), Csa (0.02%), Csai (0.02%), Cwl (1.14%), Cwli (0.08%) – Total not available = 19.70%.
[a] Classes not available in this paper: Afi with (15.36%), Ami (30.78%), Awi (18.86%), C (0.07%), Ca (0.54%), Cb (0.03%), Cf (0.11%), Cw (0.32%) – Total not available = 66.05%
Weighted Kappa coefficient of coincident types = 0.29.

The relative area of Koeppen climate zones is shown in Table II. Climate classification for Brazil resulted in 21 Climate Equations. The tropical moist climate, zone A, predominates, occupying 84% of the Brazilian territory. The tropical moist climate with a dry winter (savanna, Aw) and a short dry season (monsoon, Am), with 30% and 28%, respectively, prevails in zone A. The dry climate (zone B) occurs in only 5% of Brazil. In this zone, the semiarid class (BS) is predominant (4.8%), which is divided into several other sub-classes. The most representative sub-class, with 3.8%, is a semiarid, hot, and very dry winter climate (BShw). The arid

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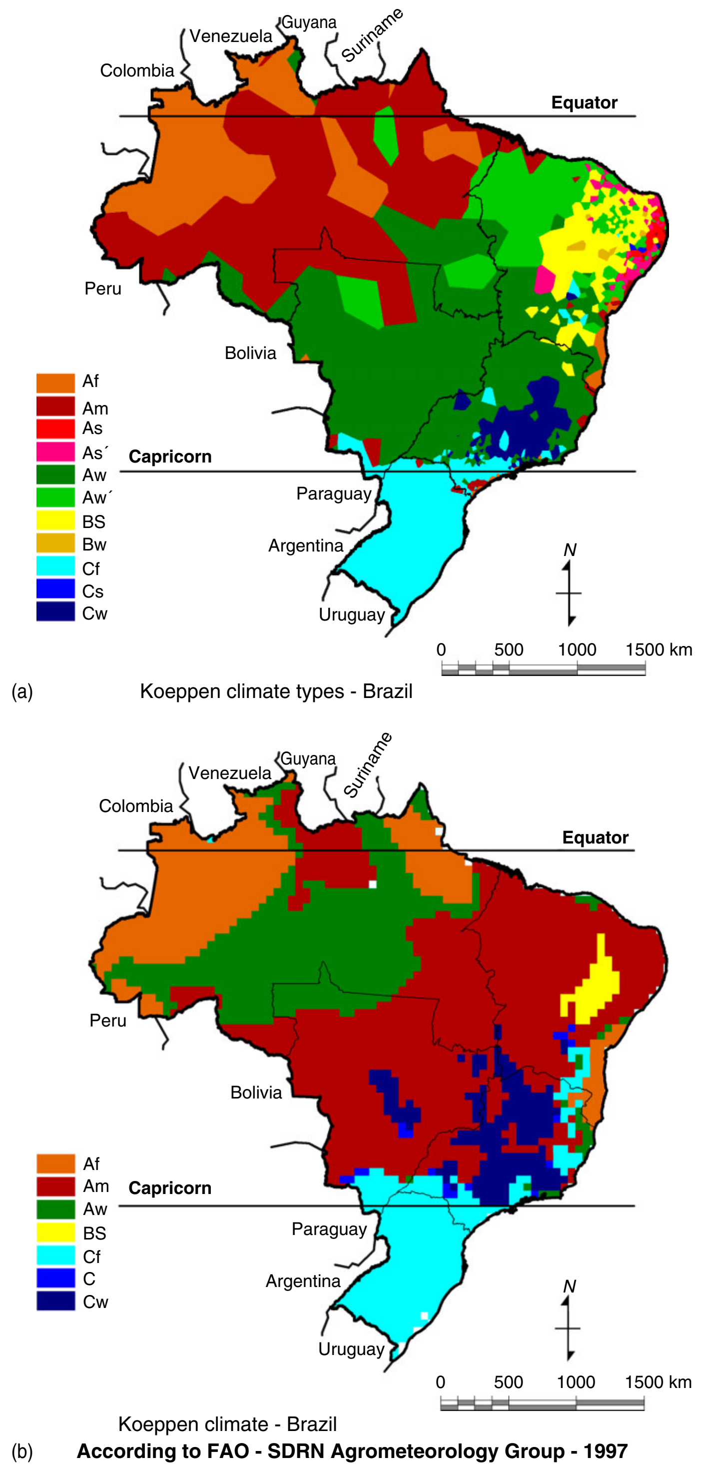

Figure 6. Koeppen climate types for Brazil (a) according to this paper, (b) according to FAO/SDRN (1997). This figure is available in colour online at www.interscience.wiley.com/ijoc

climate (BW) occupies 0.23% of the territory and is also concentrated in the arid, hot, and very dry winter type climate (BWhw). Both, semiarid and arid climates are concentrated in the northeast part of Brazil (Figure 6). The C zone (moist with mild winter) covers 11% of Brazil, with the predominance of the moist class (Cf, with 8%). In this class, the hot sub-class (Cfa) is predominant in 6% of the area. The second most important class in zone C, representing 3% of the total area, is Cw, which is moist with a mild and dry winter. Zone C is concentrated in South and Southeast Brazil.

The old and the new climate map of Brazil

The comparison with the FAO/SDRN (1997) climate type map is shown in Figure 6(a) in map format and in Table III (climate zones), Table IV (climate types), and Table V (Climate Equations) in tabular form (contingency table and weighted Kappa coefficient). Considering the climate classification of this study as reference, the overall agreement at climate zone level (first letter of the Climate Equation) can be considered as good. The Kappa coefficient of 0.64 indicates a high nonrandom effect of agreement, and the contingency table (Table III) shows minor exclusion errors in zones A (tropical moist) and B (dry) and inclusion in C (moist with mild winter). Major discrepancies occurred between B (new map) and A (FAO map), and A (new map) and C (FAO map).

At the climate type level (first and second letter of the Climate Equation), the agreement of the coincident classes decreased, reducing Kappa coefficient to 0.36. FAO/SDRN (1997) did not include important climate types like BW (dry and arid) and As (tropical moist and dry summer), which may be restrictive for annual or perennial crops. The climate types Ca and Cb occurred in FAO/SDRN (1997) but were not found in this study. By convention, Climate Equations based on Koeppen's classification present the zone as the first letter followed by the moisture regime and, if applicable, a thermal condition. For zone C (moist with mild winter), types Cf (humid), Cs (dry summer), and Cw (dry winter) were found, followed by the thermal condition (e.g. Ca accounts for the condition $T_{max} \geq 22\,°C$ and C?b accounts for the condition $T_{max} < 22\,°C$ and 4 to 11 months with $T \geq 10\,°C$). The Climate Equations Ca or Cb that appear in FAO/SDRN (1997) do not contain information about moisture regime, limiting their descriptive capability. Missing values in databases or processing problems may explain the incomplete Climate Equations in FAO/SDRN (1997).

At the climate type level, major discrepancies occurred between Aw (tropical moist, dry winter, savanna-like) and Am (tropical moist, short dry season, monsoon) types. Large Aw (new map) areas were mapped as Am in FAO/SDRN (1997) (Figure 6(a), Table IV). The criteria to distinguish between Am and Aw types are clearly defined in Koeppen's classification and shown in Figure 2. According to the FAO/SDRN (1997) map, the Brazilian Central West region, where savannas prevail, is dominated by monsoon climate type (Am). Large parts of the north region, where savannas are rare and tropical forests prevail, are covered by the savanna climate type (Aw). Additionally, the Cw (moist with mild climate and dry winter) region in FAO/SDRN (1997) expands over Aw regions. In FAO/SDRN (1997), the northeast region shows a small proportion of BS (semiarid) type when compared with the map presented in this study (Figures 6(a) and (b)). The arid and semiarid region of Brazil is usually considered to have a greater extension than shown in FAO/SDRN (1997) and also a large climatic variability (Juarez and Liu, 2001). The sudden change from the BS to the Am type (tropical moist and short dry season) in the FAO/SDRN map, without a gradual transition from a dry to a moist condition, as shown in Figure 6(b), seems unlikely.

When considering the entire Climate Equations (Table V), the coincident classes and the agreements are very low. Scale effects and computational differences resulted in non-comparable information at this level. The two sources of information cannot be considered as comparable for applications in which spatial precision of the entire Climate Equation is needed.

The large number of climate stations considered in this study, interpolations using Voronoi polygons, and the aid of computational tools for automatic climate classification resulted in a more detailed and precise Koeppen climate map of Brazil.

CONCLUSIONS

The adopted computational tools resulted in a consistent climate map for Brazil, following the definitions described in Koeppen's original work (Koeppen, 1931).

The suggested procedures avoid computational errors or subjective decisions, and this increases the comparability of studies that consider Koeppen's climate classifications.

The resulting climate map of Brazil shows improvements in relation to the earlier FAO/SDRN map. It indicates a greater extension of Brazil's arid and semiarid region (B climates), a smaller extension of C climates in favor of A climates, and reclassification of many Am areas to Aw and vice-versa. Also, unlikely transitions are, in some cases, eliminated.

ACCESS TO SOFTWARE AND DATABASES

The software (codes and executable version) and the databases (GIS files and climate classification for Brazil at the municipal level) are available for research purposes. For request, please contact the corresponding author by e-mail.

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