International Journal of Climatology   RMetS

RESEARCH ARTICLE

Climate change evidence in Brazil from Köppen's climate annual types frequency

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This article proposes to use the Köppen classification to evidence climate change in Brazil. To do so, the average monthly temperature and precipitation data were computed for a set of 208 stations, representative of the climatic diversity of Brazil for the period from 1964 to 2015. The originality of our approach is not only to look at the shift between the averages of two references periods but also to observe how each year can be classified using Köppen's classification; thus, we defined "annual climate types" (ACT) and established the frequency of ACTs for each station and each period of 26 years: 1964–1989 and 1990–2015. The statistical and cartographic treatment of this information makes it possible to define the limits of the climates of Brazil and look at its evolution showing the diversity of regional situations in Brazil. The results show that 35 stations (17%) changed from the average Köppen's type, with significant regression of wet tropical types (Af and Am) and temperate types (C). On the other hand, the tropical (Aw), arid and semi-arid (B) types progress between the two periods showing significant modifications of the climatic limits in Brazil: extension of aridity in the northeast of Brazil and increasing extinction of tropical types upon temperate climates in the south of the country and upon rainy types in the south of the Amazon. These results are consistent with other studies and illustrate the potential for climate change and variability monitoring using a simple classification method.

KEYWORDS
annual climate type, Brazil, climate change, Köppen

1 | INTRODUCTION

Among the classifications of climates, the one of W.P. Köppen (1901), is the most famous and the most used in the world. It was developed in 1900 from the world maps of vegetation available at the time, the author seeking to match climate data with the boundaries of large biomes areas. It is often considered as the first attempt to a quantitative climate classification (Thornthwaite, 1933; Trewartha, 1937; Sanderson, 1999). Starting from a simple combination of monthly average temperature and precipitation data, it is applicable quickly and everywhere. Several authors (Hantel, 1989; Essenwanger, 2001) have proposed adaptations of the thresholds and limits proposed by W. Köppen and, more recently, many studies have used this approach to illustrate

the current and future evolution of climate (Suckling and Mitchell, 2000; Kottek *et al.*, 2006; Rubel and Kottek, 2010; Chen and Chen, 2013) over periods of 10–30 years.

In Brazil, one has to wait for the second Morize classification (1922) to see the use of the Köppen method (Sant'Anna Neto, 2013). Subsequently, its use was not confined to climatology; thus, it has been used both for the definition of agro-climatic regions (Rolim *et al.*, 2007) and for the mapping of large forest (Araujo *et al.*, 2012) or floristic divisions (Torres *et al.*, 1997). More recently, SáJunior *et al.* (2012) and then Alvares *et al.* (2013) used this classification for a detailed mapping of the climatic regions of Minas Gerais and Brazil: from the data of nearly 3,000 stations for the period 1950–1990, the use of GIS, various interpolation methods and a Digital Terrain Model with a spatial

resolution of 100 m, allowed a fine approach of the distribution of climates. In all of these studies, however, the approach has remained based on the use of averaged data over a period, without taking into account interannual climate variability.

Using the thresholds and limits proposed by Köppen and his successors, several authors have also tried to correct the static aspect of this classification by applying it not on climatic averages but for each year. The term "annual climate type" (ACT) was thus used to define the ambient climate of a given year (Brisse *et al.*, 1982). In that sense, the classification of W. Köppen has already been applied by some authors to define these ACT in the northwest of Argentina (Planchon and Rosier, 2005) or in France (Quénol *et al.*, 2008; Eveno *et al.*, 2016). More recently, ACTs based on the Köppen classification have been used to show the diversity of regional situations in Brazil (Dubreuil *et al.*, 2017). This approach made it possible to propose a new cartographic synthesis of the climates of Brazil by distinguishing the strong nuclei, that is all the stations belonging most frequently to a given type, and the transition areas, corresponding to the stations which, depending on the year, different ACT could be observed. However, this study only examined the frequency of ACT for a single period as a whole without taking into account the differences that may result from the climatic changes observed during the last decades. The purpose of this paper is to analyse how the frequency of ACT has evolved over time by comparing two sub-periods of equal duration (1965–1989 and 1990–2015), inspired by the study of the climate change according to Köppen's classification from Rubel and Kottek (2010). The aim is to show the potential of this method for illustrating how climate change is occurring in Brazil, and compare with results of several studies (Nobre and Borma, 2009; Magrin *et al.*, 2014; Almeida *et al.*, 2016; Marengo *et al.*, 2017) that have recently shown the major trends and issues.

2 | DATA AND METHODS

2.1 | Database used

For this study, monthly average temperature and precipitation data were used for all years covering the period from 1964 to 2015, that is, 52 full years. All of the data used were acquired from the database of the Banco de Dados Meteorológicos para Ensino e Pesquisa (BMDP) of the Instituto Nacional de Meteorologia (INMET, 2017) of Brazil, available online. Missing data were obtained (also online) from the Hydrology Department (Hidroweb) of Agência Nacional de Águas (ANA, 2017) in Brazil: these data mainly concern precipitation and allowed to fill most of the gaps using neighbouring stations of the same municipality.

Nearly 350 series were collected but several series had to be eliminated because of too large gaps or major discontinuities detected following statistical homogeneity tests of series breaks (see details in Delahaye *et al.*, 2015 and Dubreuil *et al.*, 2017). Afterwards, 208 stations were selected with a deliberate choice to favour a homogeneous coverage of the Brazilian territory in order to compensate for the under-representation of data in the west and north of the country, where the density of available stations is significantly low. Nevertheless, the density of stations remains lower in the north, notably the State of Amazonas with 23 stations for 1,571 million km^2, than in the south–east or the south: 13 stations for 282,000 km^2 in the state of Rio Grande do Sul, for example (see Figure A1 for localization of Brazilian States in Appendix A). The distribution of the stations by altitude classes of the country is also satisfactory with a slight overrepresentation of the stations located at less than 50 m above sea level, which is linked to the large number of coastal stations in the east of the country, historically the oldest populated area (Dubreuil *et al.*, 2017).

The database thus constituted represents nearly 250,000 monthly data, making it possible to establish nearly 10,500 ACT for the entire Brazilian territory. On the other hand, the large number of gaps before 1964 (especially in the north) prevents the comparison of two periods of 30 years. Also, for the 208 stations representative of Brazil's climatic diversity, we compared the frequencies of the ACT between the two sub-periods 1964–1989 and 1990–2015, that is, 26 years each. Over these two periods, the Köppen classification has been applied to the averages as well as to each individual year (ACT).

2.2 | Adaptation of the Köppen classification

The thresholds of the ACT are the same as those proposed in the Geiger's adaptation of Köppen classification (Geiger, 1961) and are based on temperature and precipitation data for each month and year (Table 1). The classical approach distinguishes climates according to their thermal regimes (A, C, D, E and subtypes a, b, c, d, h and d) and rainfall (BW, BS and sub types f, m, s and w).

The BW type corresponds to stations for which the annual precipitation (in mm) is less than $10 \times$ annual temperature + 100 and the BS type to stations for which the annual precipitation (in mm) is less than $20 \times$ annual temperature + 200.

For the rainfall patterns of climates A, the type "f" (no dry month) is defined when the least watered month receives at least 60 mm. The type "w" corresponds to the years during which the precipitation of the driest winter month is between 60 mm and [100 − (accumulated annual precipitation)/25]. The "s" type (summer dry season) is assigned to the years when the least-watered summer month receives less than one third of the precipitation of the wettest winter month. The "m" ("monsoon") type applies to years with the driest winter month precipitation less than 60 mm and less than [100 − (accumulated annual precipitation)/25].

TABLE 1 Synthesis of the Köppen classification

		Rainfall				
		Throughout the year	Summer maximum	Winter maximum	Insufficient all year round	
Thermal regimes	$T- > 18$ °C	**Af** $P- > 60$ mm	**Aw** $60 < Pw- < (100-P)/25$	**As** $Ps- < Pw \pm 3$	BW $P < 10*T_m + 100$	BS $P < 20*T_m + 200$
			Am $Pw- < 60$ and $<100-(P/25)$		**BWh**: $T_m > 18°$ **BWk**: $T_m < 18°$	**BSh**: $T_m > 18°$ BSk: $T_m < 18°$
	$T+ > 10$ °C $-3 < T- < 18$ °C	Cf Not "w" and not "s"	Cw $Pw- < 10Ps+$	Cs $Psm < 2Tsm$		
		Cfa: $T+ > 22$ °C **Cfb**: $T+ < 22$ °C	**Cwa**: $T+ > 22$ °C **Cwb**: $T+ < 22$ °C	**Csa**: $T+ > 22$ °C **Csb**: $T+ < 22$ °C		
	$T+ > 10$ °C $T- < -3$ °C	Df	Dw	Ds		
	$0 < T+ < 10$ °C			ET		
	$T+ < 0$ °C			EF		

Note. In bold, the types corresponding to ACT observed in Brazil. $T+$, average temperature of the hottest month; $T-$, mean temperature of the coldest month; T_m, annual average temperature; T_{sm}, mean temperature of each summer month; P, accumulated annual precipitation; $P-$, least watered month; $Pw-$, driest winter month; $Pw+$, wettest winter month; $Ps-$, driest summer month; $Ps+$, wettest summer month; Psm, mean rainfall of each summer month.
Major climate types of Köppen: **Af**, warm climate without dry season; **Am**, warm monsoon climate; **As**, warm climate with winter rain; **Aw**, hot climate with summer rain; **BWh**, arid and hot climate; **BSh**, semi-arid and hot climate; **Cfa**, temperate climate without dry season and hot summer; **Cfb**, temperate climate without dry season and cool summer; **Cwa**, temperate climate with hot and humid summer; **Cwb**, temperate climate with cool and wet summer; **Csa**, temperate climate with dry and hot summer; **Csb**, temperate climate with dry and cool summer. Note that D types (not detailed here) are unknown in Brazil.

For C climates, the type "s" has been adapted using the Gaussen (1952) dry month thresholds: it is defined when at least one of the three summer months receives less rain (in millimetres) than twice the average of this month's temperatures. This change was made to better take into account the summer drought which is not only a rainfall matter (as suggested by the Köppen–Geiger threshold) but a balance between evaporation (here temperature) and rainfall. This is particularly critical to define the summer dry season in subtropical regions and this is why the Gaussen threshold have been chosen by many studies in the world (Walter, 1984) especially in the Mediterranean Basin (Blondel *et al.*, 2010), in Africa (Houérou, 2009), France (Eveno *et al.*, 2016) or South America (Planchon and Rosier, 2005). For "w" types, these are the years when the least watered month of winter receives less than one tenth of the precipitation of the wettest summer month. Finally, the type "f" is assigned to years that are neither "s" nor "w". Concerning the subtypes "a" and "b," which apply either to the Cs, Cw or Cf types, they are used to differentiate climates with hot summers (average temperature of the hottest month greater than 22 °C for the type "a") and those with cool summers (mean temperature of the hottest month below 22 °C for type "b").

2.3 | The frequencies of the ACTs

In this study, we used the same methodology as various authors (Planchon and Rosier, 2005; Quénol *et al.*, 2008; Eveno *et al.*, 2016; Dubreuil *et al.*, 2017), that is, we apply the method of Köppen not only on averages calculated over a long period but for each year taken individually: thus we assigned an "ACT" for each year (Brisse *et al.*, 1982); this approach is also similar than the annual climatic limits made by Trewartha for the United States (Trewartha, 1966). In a second step, an approach in terms of frequency allowed to specify for each station the proportion of ACT over a given period. It is thus possible to clearly distinguish (Figure 1) stations where the ACTs are often the same (Brasilia, Belem, Porto Velho) and others where it varies greatly from 1 year to another (Cruzeta, Londrina); in that sense, this methodology allows describing not only climate change, but also climate variability (Suckling and Mitchell, 2000; Chen and Chen, 2013).

The stations for which the most frequent ACT corresponds to the average climate type of Köppen are the majority, as is the case for 169 of them, that is, almost 76% of the stations! For 13 of them (6.3%) the climate of Köppen represents even 100% of ACT, every time the type Aw (Dubreuil *et al.*, 2017). However, for a significant number of stations (24%, almost a quarter), the most frequent ACT does not correspond to the average Köppen climate. As already shown in France (Eveno *et al.*, 2016), the calculation of averages over long periods can therefore present a type of climate of Köppen sometimes different from that which is actually observed each year. One can understand here the interest to look in more detail the frequencies of the ACT (and not only the Köppen's average) and their evolution in time.

3 | RESULTS

3.1 | Changes in average types

A first series of results concerns the average Köppen types calculated for each of the two periods (Figure 2). The two maps show the predominance of the tropical alternating rainy season (Aw), representing about 46% of the stations for the two periods: it forms a compact area centred on the
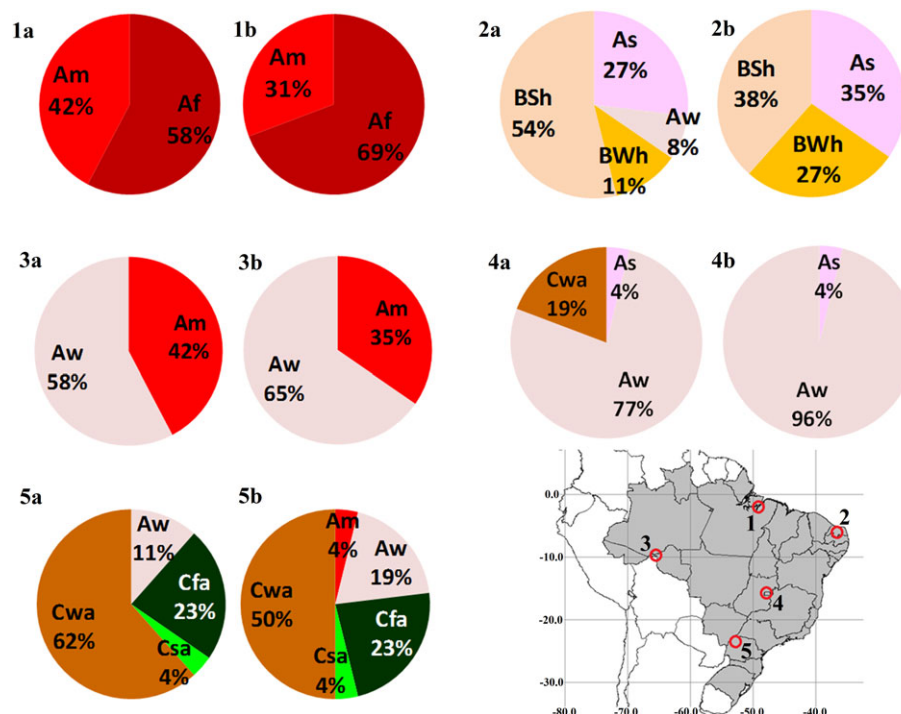
FIGURE 1 Example of frequencies of ACT for Belém (1), Cruzeta (2), Porto Velho (3), Brasília (4) and Londrina (5) for the periods 1964–1989 (a) and 1990–2015 (b): see the text and Table 1 for the meanings of the ACT [Colour figure can be viewed at wileyonlinelibrary.com]

cerrados (Brazilian savannas) of the interior of Brazil (Nimer, 1989). If one had to retain a typical "Brazilian" climate, it would probably be this one!

The Af and Am types (tropical humid and monsoon) are the second highest observed types with nearly 15% of the stations. The Am type is found in the south and east of the Amazon as well as on the eastern coast and punctually in the south. The Af type corresponds to the hot and rainy during the whole year climates of western

Amazonia, the Amazon's mouth region, but also, as for the Am type, some of the stations on the eastern and southeastern coast, at the extreme southern limit of tropical climates. The last type A climate concerns the northeastern coastline, famous for its dry summer season, As (Hastenrath, 2012), and observed in only less than 4% of the stations.

Inland, from Ceará to the north of Minas Gerais (Figure A1 in Appendix A), the semi-arid BSh type also concerns about
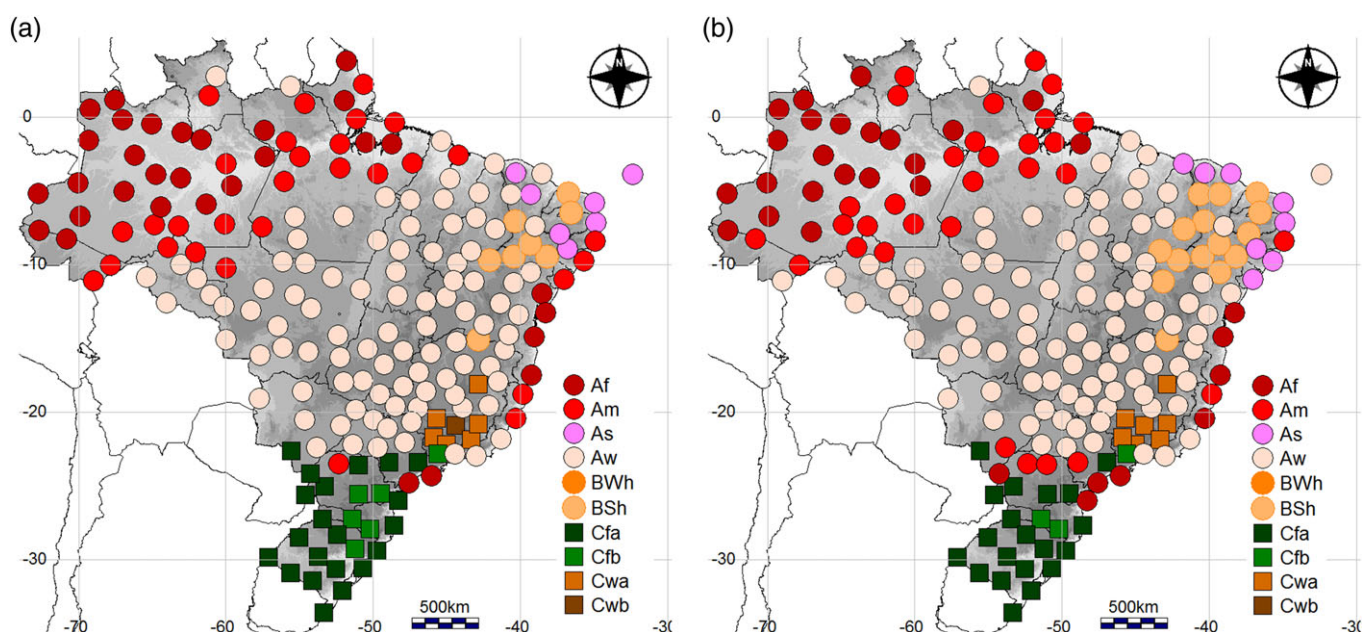

FIGURE 2 Average Köppen types in Brazil calculated for the periods 1964–1989 (a) and 1990–2015 (b): see the text and Table 1 for the meaning of the types [Colour figure can be viewed at wileyonlinelibrary.com]

10 stations. None of the selected stations correspond to the BWh type, the least rainy stations (Petrolina-PE and Paulo Afonso-BA) each receiving around 500 mm annually. The most significant change between the two periods concerns this semi-arid warm type (BSh) whose number of stations concerned doubles between the two periods increasing from 8 to 15 stations, that is, reaching more than 7% of cases in the second period.

In southern Brazil, type C climates represent only about 30 stations, almost as many as the Am type, recalling that most of Brazil is in the tropics. Wet types (Cf) represent a higher percentage (12%) than winter dry season types (Cw) with 3% of stations. The most represented type is the Cfa type, from Rio Grande do Sul to São Paulo state. At higher altitude, especially in Santa Catarina or Campos do Jordão in São Paulo State, it gives way to the cool and rainy type Cfb (three to six stations). Cwa climate type include some stations in the southern interior of Minas Gerais, with only one high station (Barbacena) representing the Cwb type for the first period. No stations, even the most southerly ones, have been classified as Csa or Csb types, showing that, on average, these regions remain relatively rainy during the summer (Monteiro, 1968; Mendonça and Danni-Oliveira, 2007).

Table 2 and Figure 3 show the types of changes that occurred between the two periods. It can be noted that 35 stations (17%) have changed of average type but often with an equilibrated balance when the analysis is made for the whole Brazilian territory. For example, 10 stations have passed in type Am while 9 have left, 3 have passed in type Cfa but as many went out. The main evolutions concern the BSh type (+7 positive balance) which concerns the interior of northeast Brazil and, in the south, the Cwb/Cfb pair (which lose four stations without winning any). In both cases, these trends reflect changes described by other studies, namely: (a) the decrease in rainfall in northeastern Brazil (Lacerda et al., 2015; Marengo et al., 2017) and (b) the rise in temperatures observed everywhere but which is particularly marked in the regions of transition climates in the south of Brazil (Marengo and Camargo, 2008): this is thus the case for the station of Londrina (Figure 1) which passed from the Cfa type to Am type, that is, from warm temperate to tropical. But the evolution can also concern fresh temperate types of altitude stations (Cfb) evolving in warm temperate (Cfa) like Curitiba in Paraná.

3.2 | Frequency changes of ACT

In this part, we are looking at the evolution in frequency of all the ACTs for all the stations between the two periods. The maps in Figure 4 show for each of the 208 stations the frequency distribution of the ACT for the two periods. The most striking point is the Aw-type hegemony in central and west-central Brazil, especially in the recent period when a higher number of stations had recorded this only one ACT. Table 3 also summarizes for the whole Brazil the distribution of ACT and their evolution: we can thus refine the interannual variability by station and look at certain infrequent annual types (Csb and BWh) which are not expressed in terms of average climates. The Csa type is also original because it represents in the south of the country a frequent ACT (about 3% of all) but which disappears systematically on average for the benefit of the Cfa type! This table confirms the trend of tropical heat extension towards southern Brazil with a decrease in the frequency of all C types; only the Cfa type escapes the rule but the increase of this ACT is mainly due to the decrease of cool climates (Cfb); the lower frequency of Csa types associated with increased rainfall in southern Brazil observed by many authors (Teixeira and Satyamurty, 2011; Ávila et al., 2016; Ely and Dubreuil, 2017) can also explain it.

The other evolution confirmed by Table 3 is the extension of the "dry and hot" ACT BSh and BWh. The arid ACT saw their frequency triple between the two periods, which confirms the strong downward trend of precipitation in northeastern Brazil: the years of "desert" climate have thus multiplied over the past two decades. However, contrary to what one could expect from Table 1, the ACT tropical alternating rainy season (As or Aw) did not see their frequency decrease, on the contrary! It is necessary to seek the explanation further with the decrease of the frequency of the humid tropical ACT (Af and especially Am). To understand these trends, it is necessary to look in more detail at the frequency distribution of these ACT across the country.

TABLE 2 Number of stations having changed from the average Köppen type between 1964–1989 and 1990–2015

Evolution of average types between 1964–1989 and 1990–2015	Af	Am	As	Aw	BSh	Cfa	Cwa	Total
Af		**6**		1				−7
Am	3		2	4				−9
As				1	2			−3
Aw		2	2		5			−9
BSh								0
Cfa	1	2						−3
Cfb						3		−3
Cwb							1	−1
Total	+4	+10	+4	+6	+7	+3	+1	35

Note. Each cell in the table gives the category change between the first (online) and the second period (in column); for example, six stations (in bold font) have changed from Af type to Am type.
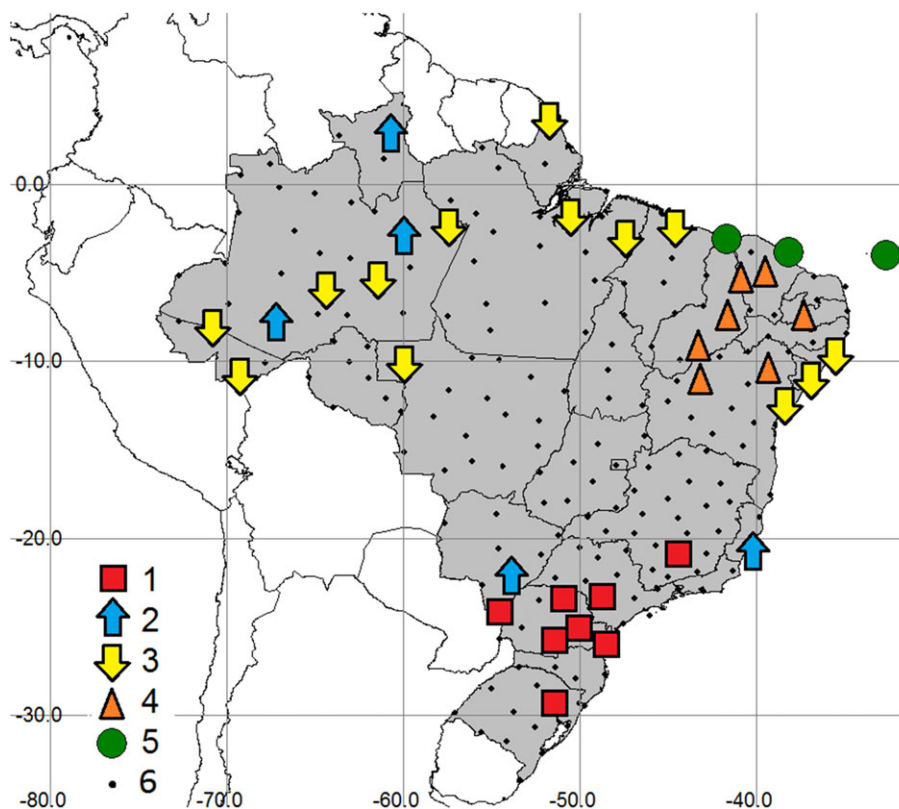
FIGURE 3 Map synthesis of stations having changed of Köppen mean types in Brazil between 1964–1989 and 1990–2015. (1) Change towards a warmer climate type; (2) change towards a wetter climate; (3) change towards a drier climate; (4) change towards a more arid climate; (5) other type of change; (6) without change [Colour figure can be viewed at wileyonlinelibrary.com]

For each ACT, maps of frequency distribution from data from the 208 stations and for each of the two periods studied were constructed. The chosen cartographic interpolation method is based on the inverse of the squared distance and no geographical factor (altitude, distance to the sea, etc.) is therefore used, the density of the network making it difficult to such fine approach. Two modes of representation are shown here: the evolution of the frequency of each ACT

between the two periods, calculated by a simple difference between the two maps (Figure 5); the juxtaposition of the frequencies of the two periods for the three major ACT families (Figure 6).

In Figure 5, the evolution of ACT Af appears overall negligible with essentially an increase (decrease) in its frequency in the east (west) of the State of Amazonas. The Am type shows a more interesting evolution with a clear increase
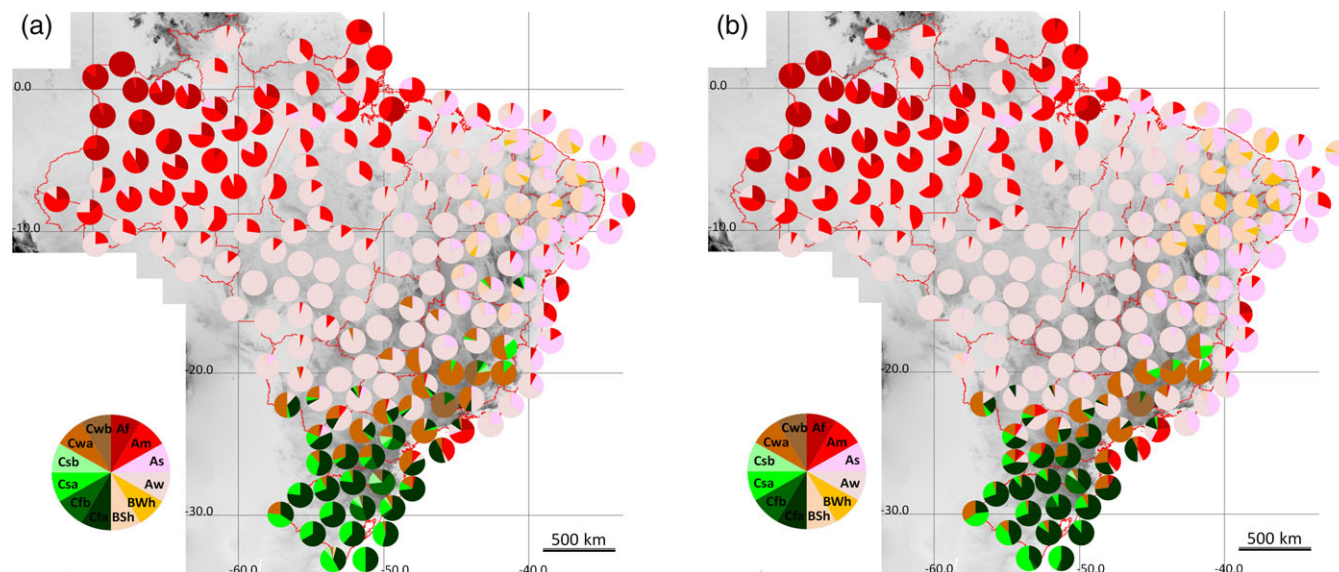

FIGURE 4 Frequency of ACT per station for the periods 1964–1989 (a) and 1990–2015 (b) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Evolution of the frequency (in %) of all Köppen ACT in Brazil between 1964–1989 and 1990–2015

	Af	Am	As	Aw	BWh	BSh	Cfa	Cfb	Csa	Csb	Cwa	Cwb
1964–1989	6.2	14.2	11.4	43.7	0.4	5.3	6.7	1.0	3.3	0.3	6.6	0.9
1990–2015	6.0	13.2	11.8	45.1	1.3	6.2	7.0	0.6	2.6	0.1	5.4	0.6
Evolution	−0.2	−1.0	0.4	1.4	0.9	0.9	0.3	−0.4	−0.6	−0.2	−1.2	−0.2

in the north and the centre of the Amazonian region (Roraima, Amapá, Amazonas and western Pará) and a very sensitive decrease in the south and east of the Amazon: south of Amazonas, north of Mato Grosso, east of Pará: this evolution is essentially made to the detriment or benefit of the Aw type, giving a clear impression of a shift of the monsoon regime towards the north. The Aw type, the one with the greatest growth, extends not only to the south of the Amazon but also to the south of Brazil in western Minas Gerais, São Paulo and Mato Grosso do Sul. This extension is mainly a result of the decrease of C types, confirming the progression of the tropical/temperate limit towards the south (Magrin et al., 2008). The Aw type, however, decreases eastwards, particularly in Bahia and northern Minas Gerais, where the frequencies of types As and especially B rise. Thus, in the northeast of Brazil, the most spectacular evolution concerns the increasing frequency of B types from Ceará to Bahia, confirming the aridification of the region during the recent period. In the western part of the region, this aridification seems to be more a process of intensification than a spatial extension because the boundary between the BS and As types does not move westward and remains positioned on the state of Piauí. The last remarkable evolution concerns the decrease of the frequency of temperate and cool summer types (Csb, Cwb and Cfb) which are everywhere in retreat between the two periods, confirming that the warming trend also affects the south of Brazil. The extension of the Cfa and Cwa types from Paraná to Rio Grande do Sul therefore corresponds especially to the rise in altitude of the a/b limit in the high areas of southern Brazil. The stronger progression of Cf type compared to the other two (Cw and Cs) can be explained by a climate that became generally wetter in all seasons, especially for the east of Parana, Santa Catarina and north and east of Rio Grande do Sul.

The maps in Figure 6 provide a synthetic measure of the shifts of the regional frequency of the main ACT large classes (A, B, C) by representing their respective percentages for each period. These maps confirm that humid tropical climates (cumulating Af and Am) have declined sharply in the western central part of the country and the southern Amazon, confirming the decrease in precipitation observed in this region by various authors (Marengo, 2005; Dubreuil et al., 2012; Fu et al., 2013; Debortoli et al., 2015; Almeida et al., 2016; Arvor et al., 2017; Khanna et al., 2017): in Porto Velho, for example (Figure 1-3) the Am type represented only a third of the ACT observed during the recent period. In the northeast of Brazil, the extension of the frequencies of "B" types confirms the increasing aridity of the interior of the Bahia to the coastline of Ceará (Lacerda et al., 2015; Marengo et al., 2017). Finally, in the south and southeast, the frequencies of ACT "C" have strongly decreased from the interior of Minas Gerais to Paraná via the State of São Paulo where the increase in temperatures is well documented (Vincent et al., 2005; Marengo and Camargo, 2008; Rosso et al., 2015; Fante et al., 2017). Thus, in Londrina (Figure 1-5), the "A" types increased from 11 to 23% between the two periods; temperate "C" ACT have also no more been observed in the state of Goiás and the federal capital in the recent period (Figure 1-4).

4 | CONCLUSION

This study shows that only 35 Brazilian stations out of 208 (17%) changed Köppen's average type between 1965–1989 and 1990–2015. Most of the observed changes reflect either an increase in temperatures (transition of types C to A or b to a), or a decrease in precipitation (transition of types f and m to w or from A to B); the other types of change are more marginal and none of them reflect a cooling trend, confirming the trend of global warming observed in Brazil by many authors. But the absence of any change in average Köppen type does not mean an absence of climate change, simply that the station remains in the same range of values, between the thresholds of the classification. This is why the use of the ACT frequency proposed by this study allows a much detailed analysis of the current climate changes in Brazil.

Thus, our ACT study shows more profoundly a significant regression of Af and Am types (equatorial and monsoon climate) in the north and the temperate types "C" and cool summer (b) in the south. On the other hand, the tropical (Aw), arid and semi-arid (B) types increased between the two periods showing (a) intensification of the "tropicality" of climate in vast areas of the Brazilian territory and (b) significant shifts and modifications of the climatic limits in Brazil: aridification of the climate in the northeast of the country (including for stations that were already classified as arid), decrease of the frequency of the hyper-humid years in the south of the Amazon, rising in latitude and altitude of the tropical domain at the expense of the temperate regions in the south of Brazil. Climate change therefore manifests itself when the distribution of ACT shows different configurations in terms of frequency between the two periods. The method thus integrates the variability of the climate system: taking into account the inter-annual variability, the study of the
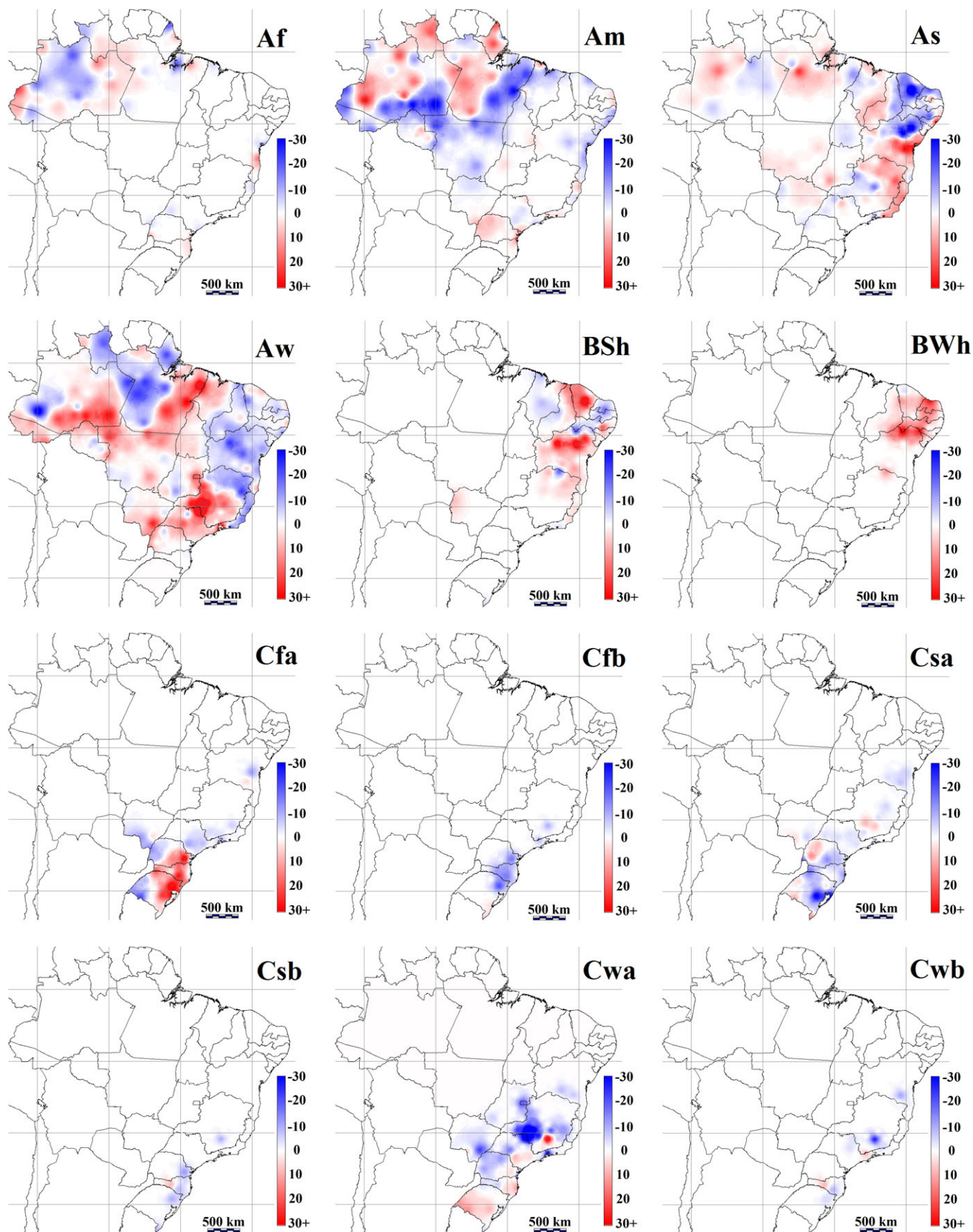
FIGURE 5 Frequency evolution of ACT (in percentage) in Brazil between the periods 1964–1989 and 1990–2015 [Colour figure can be viewed at wileyonlinelibrary.com]
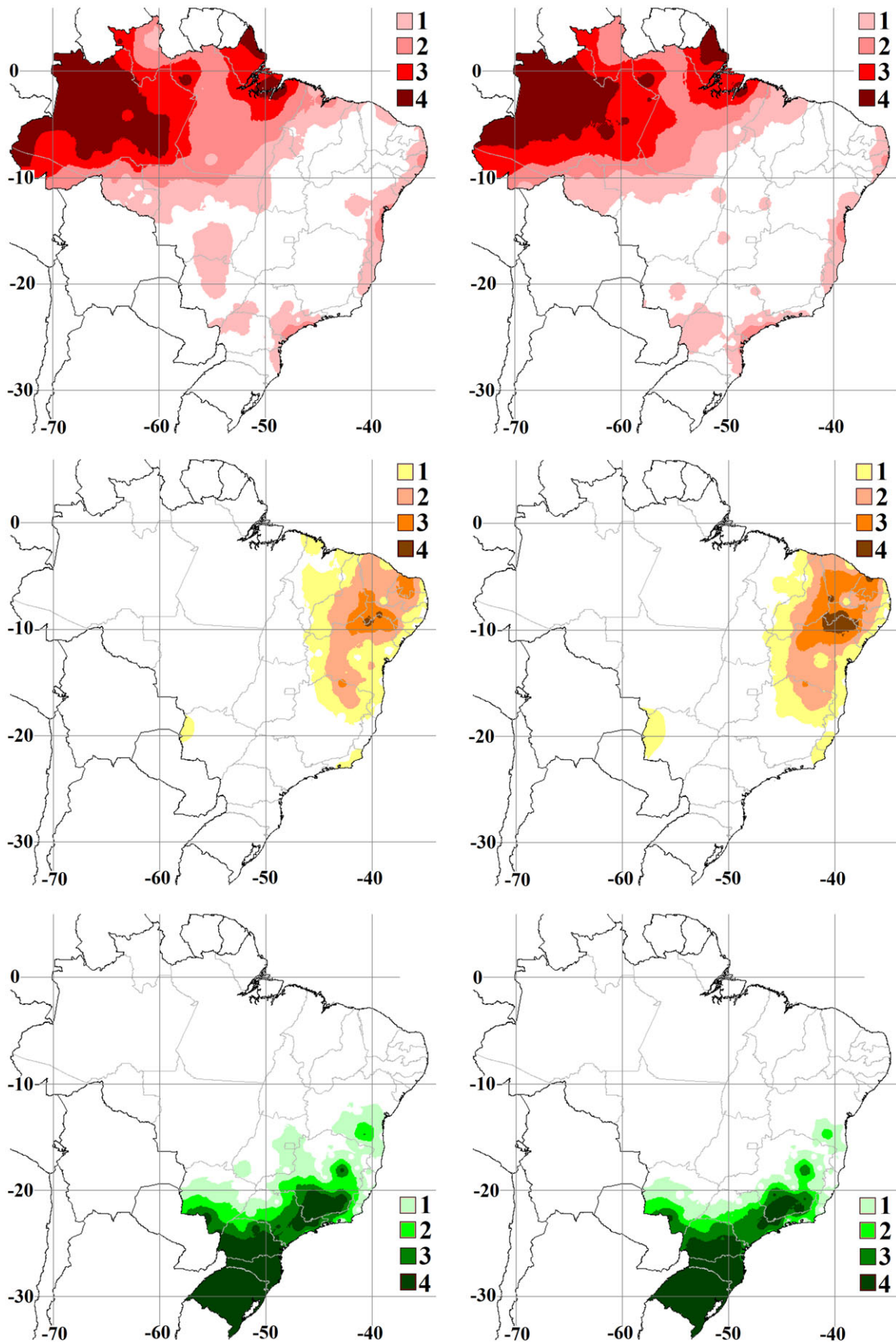
FIGURE 6 Frequency of main ACT Köppen types in Brazil calculated for the periods 1964–1989 (left) and 1990–2015 (right). Frequency of accumulated ACT Af and Am (top). Frequencies of accumulated ACT BWh and BSh (middle). Frequencies of all accumulated ACT "C" (bottom). Legend: 1 = from one to 4 (20%) observed ACT; 2 = from 5 to 13 (50%) observed ACT; 3 = from 14 to 21 (80%) observed ACT; 4 = more than 21 (80%) observed ACT [Colour figure can be viewed at wileyonlinelibrary.com]

evolution of the frequencies of the ACT thus makes it possible to grasp more finely the climatic changes that occurred in Brazil. Such a method could therefore easily be used for the characterization of the future climate by applying it to data from model projections.

Author contributions

V. Dubreuil and J. L. Sant'Anna Neto initiated the project and designed the research. O. Planchon and V. Dubreuil developed the methodology. V. Dubreuil and K. Fante collected the database and made the statistical tests. V. Dubreuil made the maps and spatial analysis and drafted the manuscript. All authors wrote and contributed ideas to the manuscript.

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APPENDIX A: List of Brazilian states

List and abbreviations of the names of Brazilian states used in the text (Figure A1):
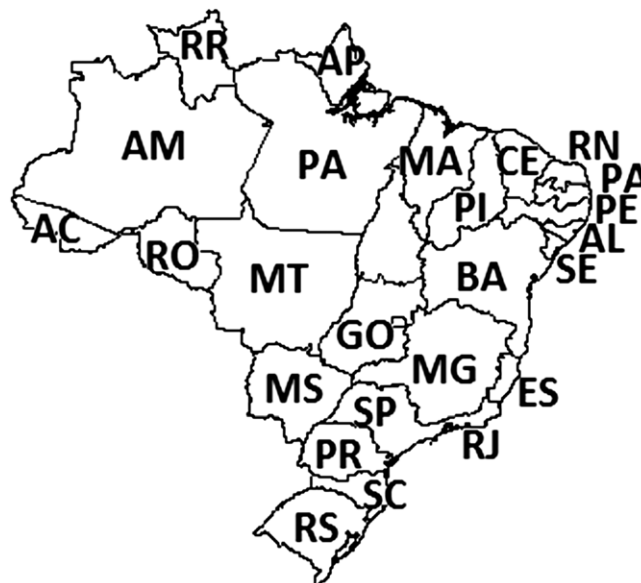

FIGURE A1   Localization of Brazilian States

Abbreviations	States
AC	Acre
AL	Alagoas
AM	Amazonas
AP	Amapá
BA	Bahia
CE	Ceará
ES	Espírito Santo
GO	Goiás
MA	Maranhão
MG	Minas Gerais
MS	Mato Grosso do Sul
MT	Mato Grosso
PA	Pará
PB	Paraíba
PE	Pernambouc
PI	Piauí
PR	Paraná
RJ	Rio de Janeiro
RN	Rio Grande do Norte
RO	Rondônia
RR	Roraima
RS	Rio Grande do Sul
SC	Santa Catarina
SE	Sergipe
SP	São Paulo
TO	Tocantins

Graphical abstract

Climate change evidence in Brazil from Köppen's climate annual types frequency

V. Dubreuil, K. P. Fante, O. Planchon, and J. L. Sant'Anna Neto
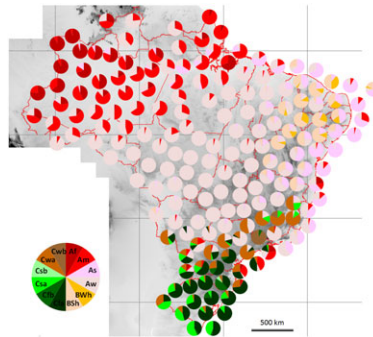
The Köppen's classification is very often used in climatology. However, almost all the works use it on average data over periods of 20 or 30 years, thus erasing the inter-annual variability of climate. The originality of our study is to use this classification on an annual scale to calculate frequencies of "types of annual climate" for two periods and to compare them. The study focuses on Brazil, which presents two additional interests: such a frequency approach has never been realized there to study climate change; the diversity of climates and changes observed in this country makes it possible to test the robustness of the method on different climates (from equatorial to semi-arid and temperate types). In the figure, frequency of TCA per station for the period 1990–2015.