CLIMATE CHANGE ASSESSMENT FOR MINAS GERAIS – BRAZIL WITH EMPHASIS ON COFFEE AREAS

PART I – RECENT PAST (1960 – 2011)

Final draft

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1 Introduction

Minas Gerais is the largest coffee producing state in Brazil, accounting for more than a half of the country's coffee production. Weather related risks threaten the security of coffee growers and their families every year. Recent examples are the severe drought occurred in 2007 or the frequent frost damages at the southern region of the state. According to Camargo (2010), climatic variability, exacerbated in a climate change environment, is the main factor responsible for the oscillations and frustrations of the coffee bean yield in Brazil. Accurate assessment of changes in local climate related to coffee phenological stages is important to understand how climate change is affecting/will affect coffee production in the state and to address possible adaptation/mitigation measures against such effects.

The main objective of this study is to perform a detailed characterization of the spatio-temporal climate variability and a climate change risk assessment for Minas Gerais during the recent past decades as well as over the near future, with emphasis on the main coffee zones. It is also of interest to regionalize the coffee zones in Minas Gerais according to its present and future climate change characterization, in order to highlight the main areas of vulnerability to climate change. The study is divided in two main phases. Phase one analyzes the recent past climate (last five decades) in the state and is the subject of this report. The second phase will analyze climate projections for the rest of the 21st century in Minas Gerais from a high resolution regional climate model and its results will be presented in a second report.

The rest of this report is organised as follows. In Section 2 the coffee situation in Minas Gerais is briefly described, and the relationship between coffee and climate is reviewed. Methodological aspects of the study are summarized in section 3. The main results are presented and discussed in section 4. Concluding remarks and future work are stated in Section 5.

2 Coffee in Minas Gerais

Located in the Southeast region of Brazil, Minas Gerais is the fourth largest Brazilian state (after Amazonas, Pará and Mato Grosso), with a territorial area of 586,522 km^2 and 853 municipalities divided in 12 mesoregions[1] as presented in figure 1. The state is by far the largest coffee producing one in Brazil. The coffee harvest for the 2013/14 period was recently estimated in 25.49 million 60-kg bags (CONAB, 2013), which corresponds to 52.47% of the Brazilian coffee production or about 18% of the world coffee production. According to data from the Brazilian Institute of Geography and Statistics (IBGE), the area occupied by coffee in Minas Gerais have had some variations over the last two decades, as can be seen in Figure 2 and Table 1, with the inclusion of new areas at the north and north-west regions and a decrease at the north-east and central regions. However, coffee areas at the main coffee regions remained rather stable or with a little tendency to increase. Coffee production during this period was always spread over at least 70% of its 853 municipalities, covering all mesoregions (see Figure 2 and Table 1).

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[1] Mesoregions are subdivisions of Brazilian states, grouping together various municipalities in proximity and with common characteristics.

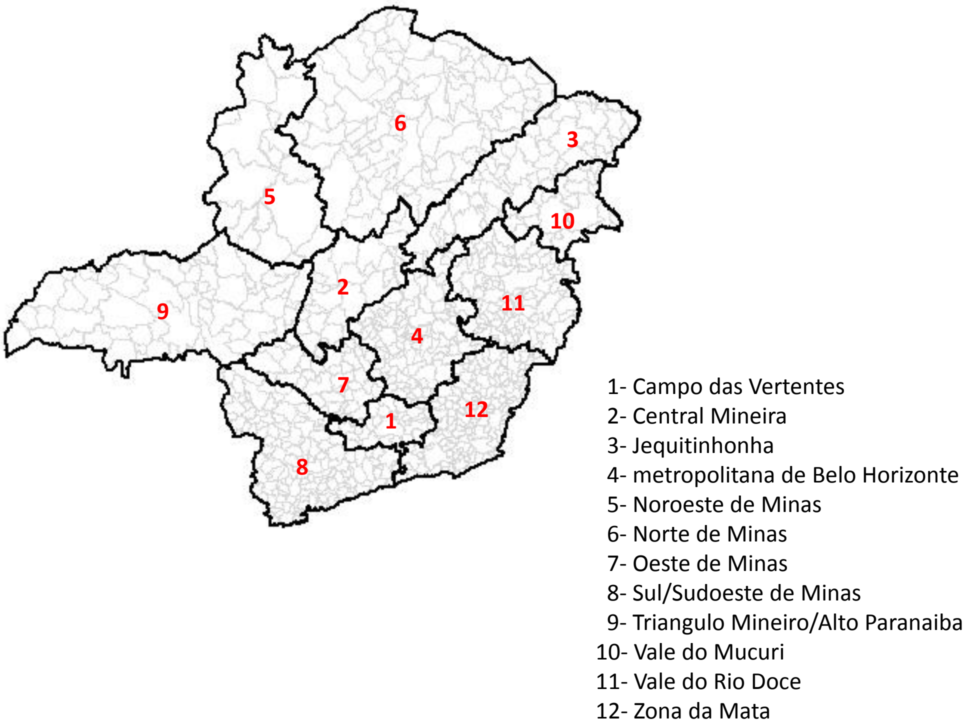

Figure 1: Mesoregions of Minas Gerais according to IBGE.

Table 1: Harvested coffee area (Ha) by mesoregion in Minas Gerais at 1990, 1995, 2000 and 2012, according to IBGE, and number of municipalities where these areas were located.

Mesoregion	1990	1995	2000	2005	2012
Noroeste de Minas	5,841	5,436	6,277	9,232	12,873
Norte de Minas	3,263	2,154	4,067	5,817	9,951
Jequitinhonha	29,152	26,193	35,149	34,845	23,763
Vale do Mucuri	17,141	18,152	17,503	13,287	6,889
Triângulo Mineiro/Alto Paranaiba	145,048	118,011	144,320	146,556	154,695
Central Mineira	3,855	3,718	2,040	359	780
Metropolitana de Belo Horizonte	7,370	6,796	4,494	3,861	2,386
Vale do Rio doce	76,316	66,664	84,358	91,759	78,379
Oeste de Minas	71,562	60,795	69,143	74,357	76,383
Sul/Sudoeste de Minas	404,836	326,701	414,309	442,917	433,932
Campos das Vertentes	23,300	19,197	23,955	25,668	26,507
Zona da Mata	175,467	179,198	187,503	194,650	205,669
Minas Gerais	963,151	833,015	993,118	1,043,308	1,032,207
N^o of municipalities	635	637	713	656	594

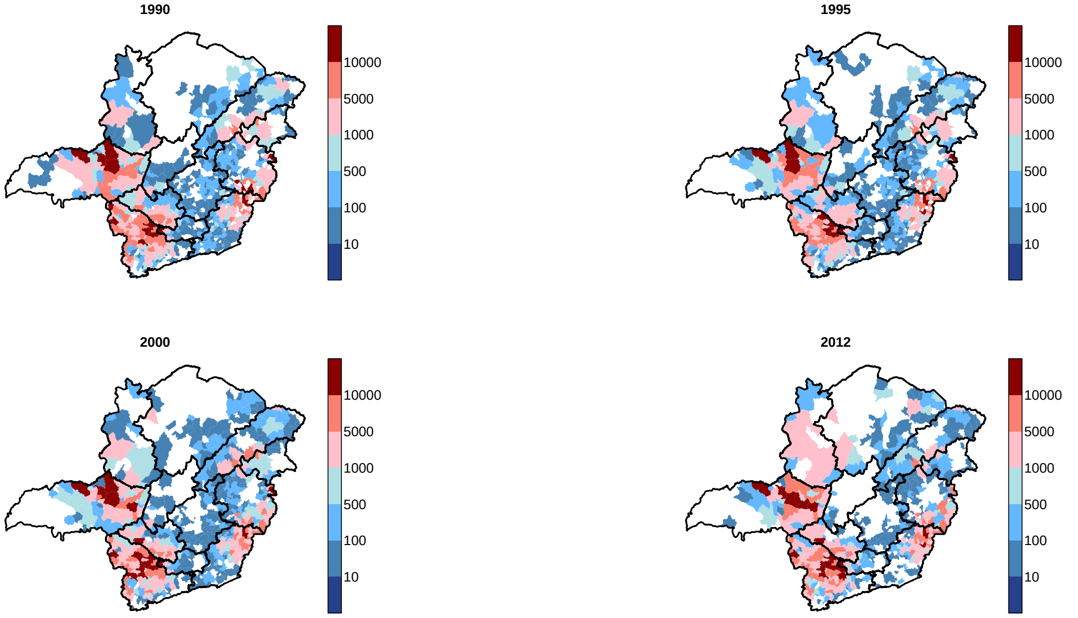

Figure 2: Municipalities of Minas Gerais with more than 10 Ha of green coffee harvested in 1990, 1995, 2000 and 2012 according to IBGE. The color scale is expressed in hectares. Black borders indicate the 12 mesoregions of the state.

2.1 Main coffee producing regions

According to Bernardes et al. (2012), 95% of the coffee producing areas in Minas Gerais in 2007 was located at altitudes between 500 and 1200 meters above sea level (m.a.s.l.). Sediyama et al. (2001) consider this range of altitude as optimal for coffee production in Minas Gerais due its favorable temperature conditions. Just 2.1% of coffee (about 19,500 Ha) was in areas below 500 m.a.s.l., being 85% of this areas located at the Vale do Rio Doce and Zona da Mata mesoregions. Coffee in these marginal areas is predominantly robusta type, which is known to be more tolerant to high temperatures. The remaining 2.9% of coffee areas (about 26,500 Ha) was above 1,200 m.a.s.l. and was mostly located at the mountainous Sul de Minas mesoregion. Coffee regions in Minas Gerais have, in general, well defined seasons, that is, a warm and rainy summer and a cold and dry winter, ideal climate conditions to produce high quality coffee.

According to IBGE, just 1.5% of the harvested area in the state in 2012 came from robusta type coffee. These areas are located at the North and North east regions of Minas Gerais, mainly at the Vale do Rio Doce mesoregion, which accounted for about 95% of all the robusta type coffee harvested in the state in that year, as shown in Figure 3.

In 1995 The Minas Gerais Institute of Agriculture (IMA) through ordinance No 165/95[2] delimited the four main coffee producing regions in the state, aiming to institute certificates of origin for these areas. The regions are briefly described as follows:

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[2] available at: `www.ima.mg.gov.br/portarias/doc_download/69-portaria-no-165`

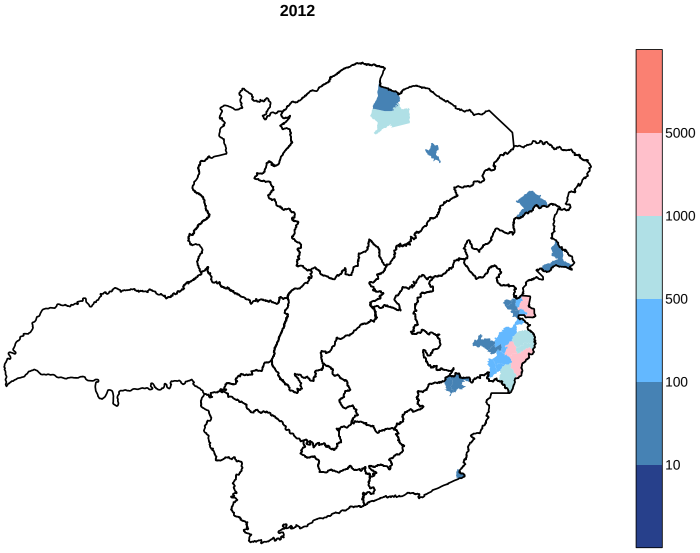

Figure 3: Municipalities of Minas Gerais with more than 10 Ha of green robusta type coffee harvested in 2012 according to IBGE. The color scale is expressed in hectares. Black borders indicate the 12 mesoregions of the state.

Cerrados de Minas region

Coffee in this region is produced in a particular type of savanna known as “Cerrado”, located in Brazil’s central high plains region, with altitudes ranging from 800 to 1,200 m.a.s.l., , with annual mean temperatures between 18 and 21^{o}C and annual rainfall averages varying between 1,000 and 1,200 mm. Climate is classified as humid (types B1 and B2 of Thornthwaite’s climatic classification, according to Carvalho et al., 2008). In Minas Gerais this area is limited by the parallels 16^o 37’ to 20^o 13’ latitude South and meridians 45^o 20’ to 49^o 48’ longitude West, including the *Triângulo Mineiro/Alto Paranaíba* and *Noroeste de Minas* mesoregions.

Coffee cultivation in this area just began in 1970s and it incorporated results of advanced agronomic researches tailored to produce coffee in this region. The area is characterized by big to medium size farms and it is more intensive in machinery use and irrigation systems than other regions of Minas Gerais, which leads to higher coffee yields.

Due to its well defined climate, the coffee flowering period in this region is very concentrated and the dry conditions and high luminosity during harvesting promotes a thorough and even drying of the coffee fruits, which translates into excellent coffee aroma and sweetness. Coffee of this region also was the first one in Brazil to get a certificate of origin.

Montanhas de Minas region

It is a coffee producing region characterized by a rugged topography and high altitude variations (ranging from 400 to 1,200 m.a.s.l). According to Cordeiro et al. (2010), 71% of coffee in this region is planted in sloped areas. The area is limited by the parallels 40^o 50’ to 43^o 36’ latitude South and meridians 18^o 35’ to 21^o 26’ longitude West, including the *Zona da Mata* and *Vale do Rio Doce* mesoregions as well as the east part of *Campos das Vertentes* mesoregion. Annual rainfall ranges between 1,000 and 1,700 mm and climate types vary from humid to dry sub-humid, with prevalence of types B1, B2, B3, C1 and C2 of Thornthwaite's classification (Carvalho et al., 2008). The vast majority of the area is characterized by small farms with lower degree of mechanization (mechanical harvesting is adopted by just 14% of coffee farms) when compared to the other coffee regions in the state. The coffee produced in this region is characterized by a moderate acidity and sweetness.

Nowadays coffee farms in this region are much less diversified than in the past. According to Cordeiro et al. (2010), coffee areas in this region currently occupy 56%, 57% and 75% of the total area of big, medium and small size coffee farms, respectively, which is unfavorable for biodiversity as much of these small farms are into environmental preservation areas.

Chapadas de Minas region

This is a small region of singular topography, limited by the parallels 17^o 05' to 18^o 09' latitude South and meridians 40^o 50' to 42^o 40' longitude West. It includes the *Vale do Mucuri* mesoregion and part of the *Jequitinhonha* and *Vale do Rio Doce* mesoregions. It is characterized by high plains and canyons crossed by rivers, with elevations around 1,100 m.a.s.l., and with annual rainfall averages that vary from 700 to 1,300 mm. The region is free of frost and climate is sub-humid to dry sub-humid (types C1 and C2 of Thornthwaite's classification according to Carvalho et al., 2008). Coffee is the main economic activity of small farmers in this region. Coffee produced in this region has consistent aroma and beverage characteristics as well as balanced body and acidity.

Sul de Minas region

This traditional mountainous *C. arabica* producing region is the largest one in the state. Most of the farms in this region are small to medium size[1]. The region is limited by the parallels 21^o 13' to 22^o 10' latitude South and meridians 44^o 20' to 47^o 20' longitude West, including the *Sul/Sudoeste de Minas* mesoregion and part of *Campo das Vertentes* and *Oeste de Minas* mesoregions. It is characterized by high altitudes, ranging from 700 to 1,400 m.a.s.l., with annual mean temperatures between 16.5 and 20^oC and annual rainfall averages varying between 1,200 and 1,500 mm. Climate is considered humid (predominantly types B2 and B3 of Thornthwaite's classification according to Carvalho et al., 2008). This region is notably cooler than the rest of the state, and some locations are subject to frost risk during the winter.

The semi-mechanized system is adopted by most of farms in this region, although full mechanization is possible in some areas. In fact, slopes greater than 20% are only present in 15% of the coffee area in this region (Bernardes et al., 2012). As in the *Montanhas de Minas* region, coffee farms here are nowadays less diversified when compared to past decades, being 47%, 43% and 48% of the total area of big, medium and small sizes coffee farms, respectively, currently occupied by coffee (Cordeiro et al., 2010). The types of coffee produced in this region have moderate body and sweetness, with medium to high concentrations of citric acid.

A new coffee producing region is also emerging at the northern region of Minas Gerais, in areas bathed by São Francisco river (mainly at municipalities of Pirapora and Ibiaí). The area is totally mechanizable and all coffee plantations are irrigated, a necessary condition given the high temperatures in the region. Cheap land and labor costs when compared to other coffee regions in the state are motivating the expansion of coffee areas in this region.

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[1] According to Cordeiro et al. (2010), small and medium size farms average 30 and 96 Ha, respectively, at Sul de Minas region, being roughly 45% of this area effectively occupied by coffee.

Based on data from the 2006 Brazilian Agricultural Census (IBGE, 2009), Tables 2 to 4 also detail the participation of each mesoregion of Minas Gerais in the coffee activity. It is noted that family farming in that year accounted for almost 80% of the coffee farms and it responded for 28% of total coffee production in the state. This participation becomes even more important in mountainous regions such as Zona da Mata (the third largest coffee region in the state), where 55% of coffee production comes from family farming. Currently the coffee varieties planted in Minas Gerais come predominantly from the species *C. arabica*. Actually less than 2% of the planted area in the state still remains with robusta type varieties (*C. canephora*). It is known that *C. arabica* is also more susceptible to climate variations and consequently it would be prone to be more affected by climate change.

Regarding irrigation, census results also stated that in 2006 less than 7% of the coffee area in Minas Gerais was cultivated under irrigation. These areas were mainly located at the Triangulo Mineiro and Noroeste de Minas mesoregions (Western of Minas Gerais), which accounted for 70% of the total coffee irrigated area, followed by Sul de Minas (7.6%), Jequitinhonha (7.0%), Vale do Rio Doce (6.6%) and the other regions (8.8%). The municipalities of Minas Gerais with irrigated coffee areas in 2006 are highlighted at Figure 4.

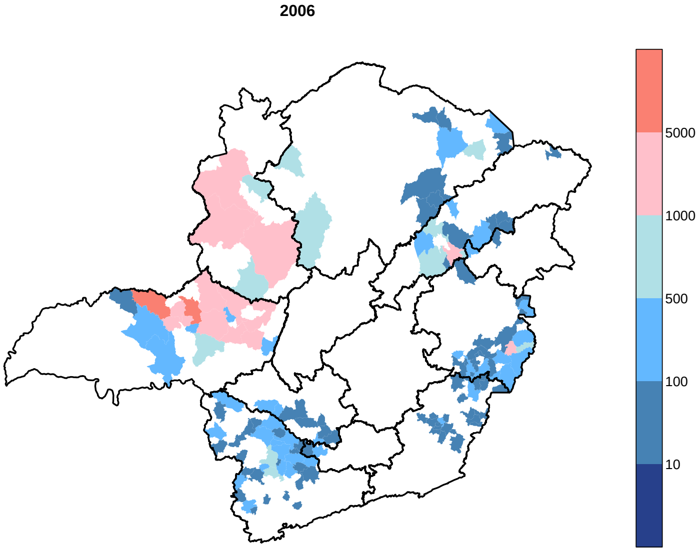


Figure 4: Municipalities of Minas Gerais with more than 10 Ha of irrigated coffee area in 2006 according to the 2006 Brazilian Agricultural Census. The color scale is expressed in hectares. Black borders indicate the 12 mesoregions of the state.

Table 2: Number of coffee farms by mesoregion in Minas Gerais according to the 2006 Brazilian Agricultural Census.

Mesoregion	C. arabica			C. canephora			total coffee		
	FF	NFF	Total	FF	NFF	Total	FF	NFF	Total
Noroeste de Minas	53	86	139	3	4	7	56	90	146
Norte de Minas	1,618	215	1,833	435	38	473	2,053	253	2,306
Jequitinhonha	4,196	488	4,684	690	45	735	4,886	533	5,419
Vale do Mucuri	2,306	106	2,412	433	20	453	2,739	126	2,865
Triângulo Mineiro/Alto Paranaíba	1,979	1,858	3,837	84	61	145	2,063	1,919	3,982
Central Mineira	30	21	51	14	5	19	44	26	70
Metropolitana de Belo Horizonte	771	162	933	248	19	267	1,019	181	1,200
Vale do Rio Doce	7,223	1,384	8,607	2,780	471	3,251	10,003	1,855	11,858
Oeste de Minas	2,927	1,389	4,316	269	54	323	3,196	1,443	4,639
Sul/Sudoeste de Minas	25,458	10,616	36,074	702	193	895	26,160	10,809	36,969
Campo das Vertentes	1,082	570	1,652	52	12	64	1,134	582	1,716
Zona da Mata	25,798	4,647	30,445	1012	167	1,179	26,810	4,814	31,624
Minas Gerais	73,441	21,542	94,983	6,722	1,089	7,811	80,163	22,631	102,794
Brazil	140,158	37,365	177,523	66,317	9,269	75,586	206,475	46,634	253,109

FF: family farming; *NFF:* não family farming; *Total:* FF + NFF.

Table 3: Area occupied with coffee (Hectares) by mesoregion in Minas Gerais according to the 2006 Brazilian Agricultural Census.

Mesoregion	C. arabica			C. canephora			total coffee		
	FF	NFF	Total	FF	NFF	Total	FF	NFF	Total
Noroeste de Minas	231	9,617	9,848	1	305	306	232	9,922	10,154
Norte de Minas	958	3,497	4,455	295	257	552	1,253	3,754	5,007
Jequitinhonha	7,576	15,915	23,491	929	839	1,768	8,505	16,754	25,259
Vale do Mucuri	3,678	2,005	5,683	635	334	969	4,313	2,339	6,652
Triângulo Mineiro/Alto Paranaíba	12,793	109,196	121,989	327	2,883	3,210	13,120	112,079	125,199
Central Mineira	31	270	301	28	32	60	59	302	361
Metropolitana de Belo Horizonte	406	1,474	1,880	141	86	227	547	1,560	2,107
Vale do Rio Doce	32,103	22,296	54,399	9,575	3,787	13,362	41,678	26,083	67,761
Oeste de Minas	11,675	48,486	60,161	961	1,176	2,137	12,636	49,662	62,298
Sul/Sudoeste de Minas	125,352	285,961	411,313	3,194	4,711	7,905	128,546	290,672	419,218
Campo das Vertentes	4,357	12,895	17,252	82	302	384	4,439	13,197	17,636
Zona da Mata	108,648	69,573	178,221	3,553	1,451	5,004	112,201	71,024	183,225
Minas Gerais	307,808	581,184	888,992	19,722	16,165	35,887	327,530	597,349	924,879
Brazil	578251	886,899	1,465,150	306,907	137,145	444,052	885,158	1,024,044	1,909,202

FF: family farming; *NFF:* não family farming; *Total:* FF + NFF.

Table 4: Coffee production (thousands of Tons) by mesoregion in Minas Gerais according to the 2006 Brazilian Agricultural Census.

Mesoregion	C. arabica			C. canephora			total coffee		
	FF	NFF	Total	FF	NFF	Total	FF	NFF	Total
Noroeste de Minas	0.41	17.76	18.17	0.0015	0.31	0.31	0.42	18.07	18.48
Norte de Minas	0.96	7.96	8.92	0.43	0.09	0.52	1.39	8.06	9.44
Jequitinhonha	7.49	16.89	24.38	1.17	0.59	1.76	8.66	17.49	26.14
Vale do Mucuri	2.40	2.01	4.41	0.44	0.24	0.68	2.83	2.25	5.09
Triângulo Mineiro/Alto Paranaíba	19.25	206.40	225.65	0.36	6.68	7.04	19.61	213.09	232.69
Central Mineira	0.05	0.69	0.74	0.047	0.13	0.17	0.097	0.82	0.91
Metropolitana de Belo Horizonte	0.52	1.77	2.29	0.24	0.078	0.32	0.77	1.84	2.61
Vale do Rio Doce	28.65	27.25	55.90	8.70	4.59	13.29	37.35	31.84	69.19
Oeste de Minas	13.01	68.73	81.74	2.03	1.75	3.78	15.04	70.48	85.52
Sul/Sudoeste de Minas	166.43	459.21	625.63	4.06	7.07	11.13	170.49	466.28	636.77
Campo das Vertentes	5.65	22.17	27.83	0.11	0.35	0.47	5.77	22.53	28.29
Zona da Mata	100.35	81.46	181.81	2.73	1.76	4.49	103.08	83.21	186.29
Minas Gerais	345.17	912.31	1,257.48	20.32	23.65	43.96	365.49	935.95	1,301.44
Brazil	622.75	1,326.94	1,949.70	276.50	195.29	471.78	899.25	1,522.23	2,421.48

FF: family farming; *NFF:* não family farming; *Total:* FF + NFF.

2.2 The coffee and climate relationship

Coffee green bean yield and beverage quality are strongly influenced by climatic variability (ex., variations in air temperature or in rainfall distribution), due to its direct interference on the different phenological stages of the coffee crop. The schematic representation of the phenological stages of arabica coffee under Brazilian conditions is shown in Figure 5. The two-years cycle of coffee starts with a vegetative period from September to August, that includes the formation of vegetative buds and its induction in floral buds, followed by a reproductive period in the second year.

Specifically for Minas Gerais, the main flowering period usually spans the period from early September to late November. It occurs after a water stress period during the preceding months (July-August), followed by an increase of the water potential inside the floral buds caused by rain or irrigation (Carr, 2001). According to Camargo and Camargo (2001), high temperatures during this phase, especially if associated with an intense water deficit, may cause abortion of flowers. The same author showed that the maturation of the reproductive buds in *C. arabica* under Brazilian conditions comes after the accumulation of about 350 mm of potential evapotranspiration, starting from the beginning of April or when the sum of degree days from the same period reaches 1,590 degree days, considering a base temperature of 10^oC.

Severe hydric stress during the expansion of fruits and bean formation phases, occurring from September to December and from January to March, respectively (Camargo and Camargo, 2001), may cause defective or underdeveloped fruits.

Ripening of fruits normally occurs between April and June. The time needed to complete this stage will depend on the weather conditions. Moderate water deficit at this phase benefits coffee quality. However, intense water deficit and high temperatures will accelerate ripening and will affect the fermentation process of fruits, leading to loss of beverage quality. On the other hand, with low temperatures the development of fruits is

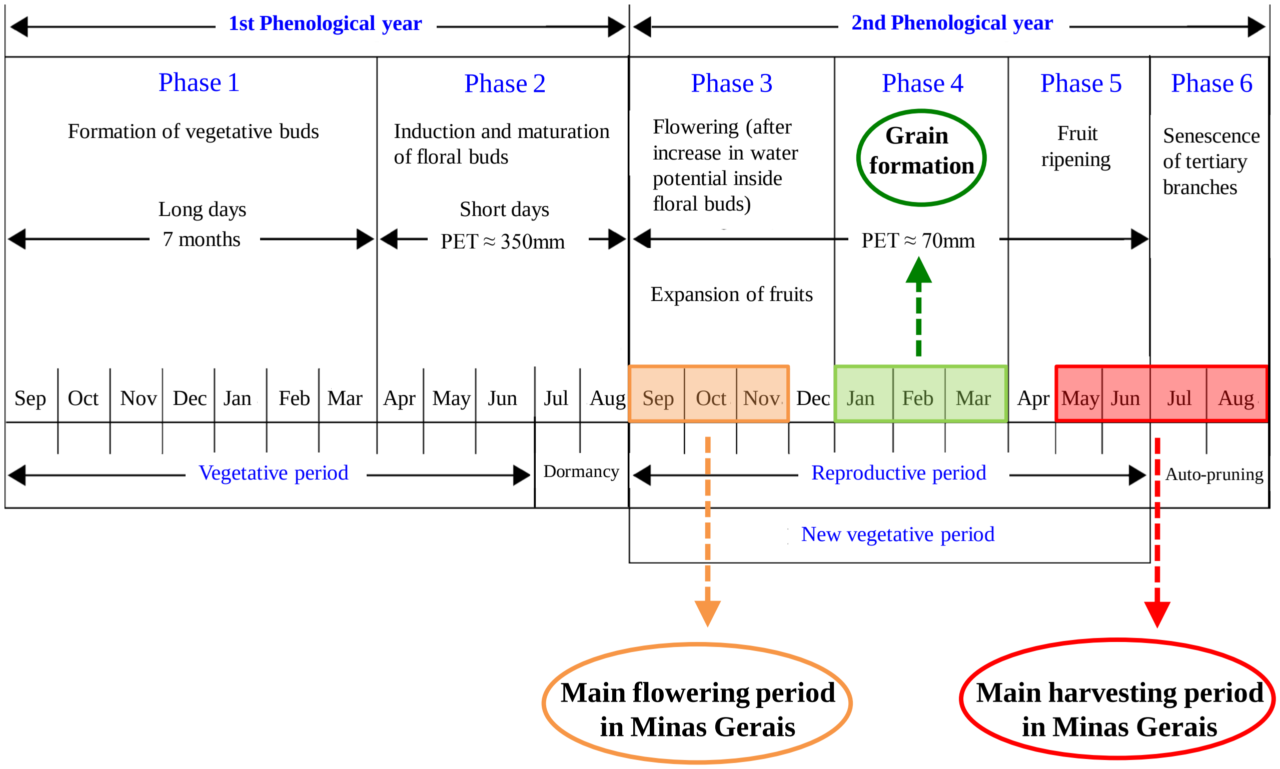


Figure 5: Schematization of the phenological phases of C. arabica under Brazilian conditions. Adapted from Camargo and Camargo (2001).

delayed, which can cause an overlapping of the ripening and flowering periods. Under this situation fruits of the past season are exposed to the rains that precedes the flowering of the new season, increasing the risk of attacks by microorganisms.

As all these phenological phases are strongly influenced by climate, the results of this study are focused on these key periods.

3 Methodology

3.1 Acquisition and pre-processing of historic weather data

Raw daily time series of precipitation (Prec), minimum temperature (Tmin) and maximum temperature (Tmax) for Minas Gerais and its near boundaries were obtained from the following climate data sources: National Institute of Meteorology (INMET), National Water Agency (ANA) and Center for Weather Forecasting and Climate Research (CPTEC/INPE). The original datasets included 140 stations recording temperature and over 1200 rain gauges, spanning the period from 1905 to 2011. However, most of the data at the first half of this period were missing or unreliable. Therefore, to guarantee the credibility of the trend analysis, the datasets were restricted to the period 1960-2011, considering only rainfall stations with at least 90% of their records actually observed. For minimum and maximum temperatures only stations with at least 70% of their data actually recorded were taken into account. These restrictions reduced the number of available stations to 68 and 264 in the case of temperature and precipitation, respectively, being 40 and 164 of them inside Minas Gerais and the rest on the boundary of the state. These boundary stations were selected to account for edge effects during mapping tasks. Figure 6 shows the location of the selected weather stations after the restriction.

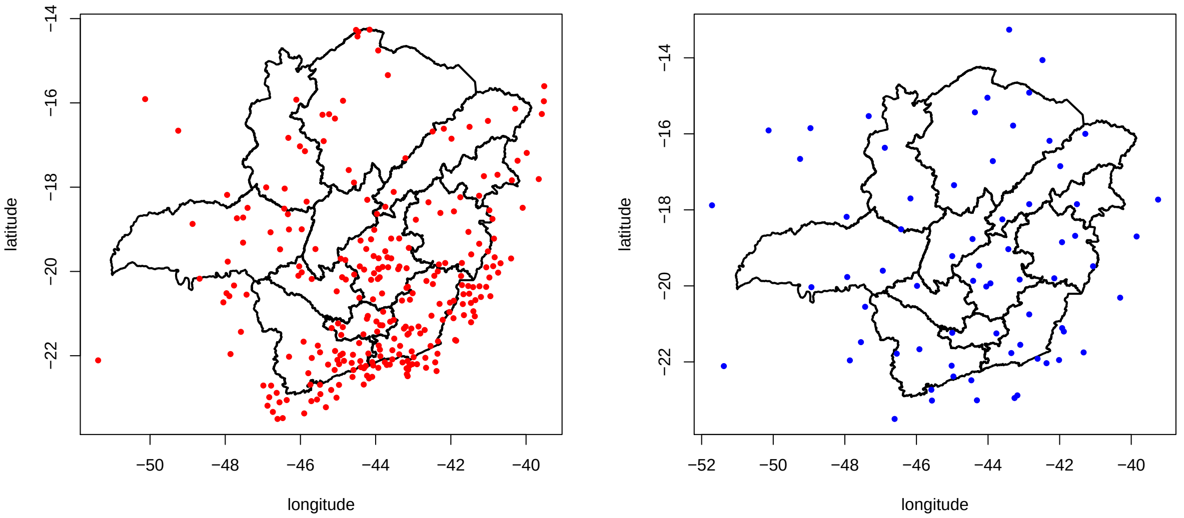
Firstly the raw datasets from different sources were unified and organized in a suitable format. Then they were quality checked and homogenized to finally construct the climate change indices and to estimate the climate trends. All the analyses where performed using the R statistical language (R Development Core Team, 2012).

The quality control procedure included the following activities:

- Screening to identify erroneous data (e.g. Tmin > Tmax, negative precipitation, etc.).
- Identification of temperature outliers using standard deviation thresholds. The variance of a station time series was calculated for each calendar day using the surrounding five days. All outliers greater than four standard deviations from the mean were further evaluated.
- Visual checks of the time series of daily maximum and minimum temperature, diurnal temperature range (Tmax minus Tmin), and precipitation to highlight outliers or unexpected changes in the seasonal cycle of the time series.
- Statistical gap-filling of missing temperature data through the Amelia multiple imputation method (Honaker and King, 2010). For each missing record $m = 20$ values where imputed and then averaged to fill-in the minimum and maximum temperature time series.
- In the case of precipitation, all the observations above 200 mm were checked to insure that high values were not due to accumulation over several days or due to digitization errors. Also, suspiciously long spells of the same value (for example, “0”) were evaluated.
- Homogeneity tests to detect significant breakpoints in the time series and to adjust the detected breaks when necessary. The RHtestsV3 R package (Wang and Yang, 2010) was used for this purpose. This package is capable of identifying multiple step changes at documented or undocumented change points in a time series, based on a two-phase regression model with a linear trend for the entire series (Wang, 2003, 2008; Wang et al., 2010).

3.2 The climate change detection indices

Often changes in extremes may have more impacts than changes in mean values. Furthermore, changes in extremes can be strong indicators of climate change (Aguilar et al., 2005). The joint World Meteorological Organization Commission on Climatology (CCl) and the Climate Variability and Prediction (CLIVAR) Expert Team on Climate Change Detection and Indices (ETCCDI) formulated a suite of 27 core climate extreme indices calculated from daily temperature and precipitation data (Peterson, 2005). As discussed in Skansi et al. (2013) and references therein, these extreme indices were defined with the aim of both monitoring changes in “moderate” extremes and for enhancing climate change detection studies given their high signal-to-noise ratio.



(a) rainfall

(b) temperature

Figure 6: Location of the selected stations in Minas Gerais and its near boundaries.

For this assessment 21 of the 27 core extreme indices defined by the ETCCDI will be considered (11 for temperature and 10 for precipitation), which are outlined as follows[3]:

Temperature indices:

- *SU32*, Number of very hot days: Annual count of days when daily maximum temperature (TX) $>$ 32^{o}C.
- *TR20* (number of tropical nights): Annual count of days when Tmin $>$ 20^{o}C.
- *TXx* (highest Tmax): Monthly maximum value of daily maximum temperature.
- *TNx* (highest Tmin): Monthly maximum value of daily minimum temperature.
- *TXn* (lowest Tmax): Monthly minimum value of daily maximum temperature.
- *TNn* (lowest Tmin): Monthly minimum value of daily minimum temperature.
- *TN10p* (cold nights): Percentage of days when Tmin $<$ 10th percentile.
- *TX10p* (cold days): Percentage of days when Tmax $<$ 10th percentile.
- *TN90p* (warm nights): Percentage of days when Tmin $>$ 90th percentile.
- *TX90p* (warm days): Percentage of days when Tmax $>$ 90th percentile.
- *DTR* (daily temperature range): Monthly mean difference between Tmax and Tmin.

Precipitation indices:

- *Rx1day*, Monthly maximum 1-day precipitation.

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[3] for a complete definition see `http://etccdi.pacificclimate.org/indices.shtml`

- *Rx5day*, Monthly maximum consecutive 5-day precipitation.
- *SDII* (simple precipitation intensity index): Let RR_{wj} be the daily precipitation amount on wet day w (RR $\geq$ 1mm) in year j. If W represents the number of wet days in j, then:

$$SDII_j = \frac{\sum_{w=1}^{W} RR_{wj}}{W}$$

- *R10mm*, Annual count of days when precipitation $\geq$ 10mm.
- *R50mm*, Annual count of days when precipitation $\geq$ 50mm.
- *CDD* (Maximum length of dry spell): maximum number of consecutive days with precipitation $<$ 1mm.
- *CWD* (Maximum length of wet spell): maximum number of consecutive days with precipitation $\geq$ 1mm.
- *R95P* (very wet days): Annual total precipitation when RR $>$ 95p: Let RR_{wj} be the daily precipitation amount on a wet day w (RR $\geq$ 1.0mm) in year j and let $RR_{wn}95$ be the 95th percentile of precipitation on wet days in the 1961-1990 period. If W represents the number of wet days in j, then:

$$R95p_j = \sum_{w=1}^{W} RR_{wj}, \quad \text{where} \quad RR_{wj} > RR_{wn}95$$

- *R99P* (extremely wet days): Annual total precipitation when RR $>$ 99p: Let RR_{wj} be the daily precipitation amount on a wet day w (RR $\geq$ 1.0mm) in year j and let $RR_{wn}99$ be the 99th percentile of precipitation on wet days in the 1961-1990 period. If W represents the number of wet days in j, then:

$$R99p_j = \sum_{w=1}^{W} RR_{wj}, \quad \text{where} \quad RR_{wj} > RR_{wn}99$$

- *PRCPTOT*, Annual total precipitation in wet days.

The RClimDex software (Zhang and Yang, 2010) was used to calculate the above indices on an annual basis for each station for the period 1960-2011. Percentile indices were calculated using the 1961-1990 base period.

Additionally, the number of sequences with at least 3 consecutive days when Tmax $> 32^o$C (*S3TX*) during the main coffee flowering period (September to November) was also calculated.

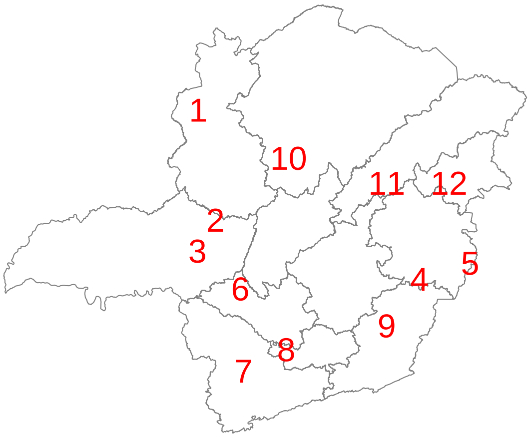
Linear trends in the climate indices and their 95% confidence intervals were estimated annually using a robust approach for trend estimation as described in Zhang et al. (2000). This is an adaptation of the Sen's slope estimator that takes into account serial correlation. It is also more robust to outliers and departures of normality of the distributions than the usual least squares method. Significance of the trends at the 0.05 level was determined using a nonparametric Mann-Kendall test to determine whether the slopes differed significantly from zero. Surface maps were generated from the data generated at the stations using a bilinear interpolation procedure.

4 Results

In this section the spatio-temporal variability of minimum temperature, maximum temperature and precipitation in Minas Gerais through the last five decades, as well as the regional trends in their derived climate change indices are presented and discussed. Results at the regional level are presented in the form of maps. Additionally, in order to locally analyze the behavior of trends in the climate change indices at the main coffee regions, nine stations at the municipalities with the highest coffee area in Minas Gerais (among the 40 stations available in the state) and three stations at municipalities that substantially increased/decreased its coffee area during the last 20 years (stations 10 to 12), were selected and their trends and significance were individually stated for the main climate change indices. The chosen stations are listed in Table 5 jointly with their location.

Table 5: Location of stations at municipalities with the highest coffee area among those with temperature stations available.

ID	municipality	1990 harvested area (Ha)	2012 harvested area (Ha)
1	Unaí	500	3281
2	Patos de Minas	4862	6308
3	Araxá	3384	2200
4	Caratinga	12192	8300
5	Aimores	1520	2017
6	Bambuí	2113	3320
7	Machado	13331	13357
8	Lavras	3857	4400
9	Viçosa	1500	2250
10	Pirapora	0	522
11	Itamarandiba	1206	500
12	Teófilo Otoni	1600	105



4.1 Temperature

4.1.1 Local and regional trends

An overwhelming majority of stations at all regions in Minas Gerais experienced significant warming over the 1960-2011 period, with warm extremes increasing and cold extremes decreasing, as can be seen in the Tables and Figures below.

The annual percentage of warm days (TX90p) is considered as most suited to determine whether maximum temperatures increased during the study period. Significant positive trends for this index were found in all selected stations, as shown in Table 6, suggesting that all the main coffee areas in Minas Gerais experienced significant warming from 1960 to 2011. However, there are differences in the magnitude of these trends. Stations at Zona da Mata in the eastern region (municipalities of Viçosa and Caratinga) had an average increase of 1.6% (± 1.3) per decade, whilst for stations at the north-west and western regions (Unaí and Araxá) this average increase was of 4.2% (± 1.15) per decade. The southern region of the state had an intermediate increase, with an average of 2.9% (± 1.3) per decade at stations in Bambui, Machado and Lavras. Significant negative trends in the annual percentage of cold days (TX10P) were consistent with the positive trends found for the TX90P index (Table 6), with average values of -0.65% (± 0.6), -1.5% (± 0.45) and -1% (± 0.5) per decade, respectively, for the same groups of stations mentioned above.

Significant positive trends were also found in all stations for the annual percentage of warm nights (TN90p), as shown in Table 6, being less accentuated in the southern region (1.7% ± 1 per decade in average at Bambuí, Machado and Lavras) and with intermediate values at Zona da Mata (2.8% ± 1.4 in average at Viçosa and Caratinga) and higher values at the north-east region (5.4 ± 2.2% in average at Aimores and Teófilo Otoni). On the other hand, there was a decreasing trend in the annual percentage of cold nights (TN10P) at all stations, although it was just significant in a half of them. Spatial coherence was evident for these four percentile-based indices, as can be seen in the trend maps of Figure 7.

The TXn and TXx indices also showed upward trends (Table 7), meaning a consistent change toward higher values of annual maximum daytime temperatures over most of the main coffee regions in Minas Gerais, being less accentuated at Zona da Mata region (Viçosa and Caratinga). Maximum values of nighttime temperatures as summarized by index TNx, also showed signals of moderate increase at Zona da Mata and Southern region of Minas Gerais and of higher values with significant positive trends in the other regions of the state, as shown in Table 7. Trend maps of Figure 8 confirm a moderate increase of maximum daytime and nighttime temperatures at the south-west and southern regions and a faster one in the rest of the state, particulary in the upper half.

Significant positive trends were also observed for the annual count of days with maximum temperature greater than 32^{o}C (SU32) as presented in Table 8. The largest increases were recorded at Unaí, Aimores, Pirapora and Teófilo Otoni (12.7 ± 7.1 days per decade on average), which are the stations at the lower altitudes (all of them below 500 m.a.s.l.). Stations at the southern region had a moderate increase (5.56 ± 2.9 days per decade in average at Bambui, Machado and Lavras), whilst the lowest increases in the number of very hot days were registered at Zona da Mata (2.35 ± 1.8 days per decade at Caratinga and Viçosa).

Similarly, an upward trend of higher magnitude for the annual number of tropical nights (TR20) was observed in stations located at the lowest altitudes (14.82 ± 11.2 days per decade). Trends in stations at Zona da Mata had intermediate values (5.45 ± 3.6 days per decade), whilst the southern region showed smaller and non-significant increases for this index (0.7 ± 0.65 days per decade at Machado and Lavras).

The number of sequences with three or more consecutive daily maximum temperature records greater than 32^{o}C during the September to November period (S3TX) mostly showed a non-significant or even a nonexistent trend, mainly at stations in Zona da Mata and Southern region. Exceptions were the stations at the eastern and western regions, which presented significant, yet moderate trends (0.53 ± 0.35 sequences per decade). Spatial coherence for these indices was also verified, as can be seen in Figure 9.

Table 6: Local trends (percentage of days per decade) for the percentile-based temperature indices TX10P (percentage of cold days), TX90P (percentage of warm days), TN10P (percentage of cold nights) and TN90P (percentage of warm nights) at the 12 selected stations during the period 1960-2011, using a robust linear trend estimate. 95% confidence intervals are stated in brackets. Values in bold indicate significance of the trend at the 0.05 level.

station	TX10P	TX90P	TN10P	TN90P
Unaí	**-1.4** (-1.9,-0.8)	**4.2** (3.2,5.2)	-0.8 (-1.7,0.2)	**1.8** (1,2.6)
Patos de Minas	**-1.6** (-2,-1.1)	**3** (2,4.1)	**-1.4** (-1.9,-0.8)	**3.4** (2.5,4.2)
Araxá	**-1.6** (-2,-1.1)	**4.2** (2.9,5.5)	**-1** (-2.4,0.1)	**6.5** (4.7,8.7)
Caratinga	-0.6 (-1.4,0)	**1.4** (0.1,2.6)	-0.1 (-1.1,1)	1.5 (-0.4,3.6)
Aimores	**-1** (-1.6,-0.3)	**3.3** (1.2,5)	-0.7 (-3,1.3)	**6.4** (4.9,8)
Bambuí	**-0.9** (-1.4,-0.2)	**2.5** (1.2,3.3)	1.1 (-0.2,2.1)	**1.9** (0.4,3.3)
Machado	**-1.1** (-1.6,-0.7)	**3.1** (1.2,5.1)	**-1** (-1.5,-0.3)	**1.7** (0.7,2.5)
Lavras	**-1.2** (-1.7,-0.7)	**3.1** (1.5,4.3)	**-0.9** (-1.4,-0.4)	**1.6** (0.7,2.4)
Viçosa	**-0.7** (-1.4,-0.1)	**1.8** (0.6,3.2)	**-2** (-2.8,-1.3)	**4.1** (3.4,4.9)
Pirapora	**-1.2** (-1.8,-0.4)	**2.3** (0.7,3.7)	**-2.6** (-3.1,-2)	**3.7** (2.4,5.1)
Itamarandiba	-0.5 (-1.2,0.1)	**1.1** (0.2,2)	**-1.1** (-1.9,-0.3)	**3** (1.7,4.3)
Teófilo Otoni	**-1.3** (-1.9,-0.7)	**2** (0.1,4)	**-1** (-2.2,-0.1)	**4.3** (0.7,7)

Table 7: Local trends (^{o}C per decade) for the monthly minimum/maximum temperature indices TNn (Monthly minimum of daily tmin), TNx (Monthly maximum of daily tmin), TXn (Monthly minimum of daily tmax) and TXx (Monthly maximum of daily tmax) at the 12 selected stations during the period 1960-2011, using a robust linear trend estimate. 95% confidence intervals are stated in brackets. Values in bold indicate significance of the trend at the 0.05 level.

station	TNn	TNx	TXn	TXx
Unaí	0.1 (-0.2,0.4)	**0.2** (0,0.3)	0.1 (-0.2,0.4)	**0.8** (0.6,1)
Patos de Minas	0.2 (-0.2,0.7)	**0.4** (0.2,0.5)	**0.4** (0.1,0.6)	**0.5** (0.2,0.7)
Araxá	**0.4** (0.1,0.9)	**0.4** (0.3,0.6)	**0.3** (0,0.7)	**0.4** (0.1,0.6)
Caratinga	-0.1 (-0.5,0.2)	0.01 (-0.1,0.1)	0.03 (-0.2,0.2)	0.2 (0,0.4)
Aimores	0 (-0.2,0.2)	**0.3** (0.1,0.5)	-0.01 (-0.2,0.2)	**0.4** (0.1,0.7)
Bambuí	-0.3 (-0.7,0)	**0.3** (0,0.6)	0.1 (-0.2,0.4)	**0.4** (0.1,0.7)
Machado	-0.1 (-0.4,0.3)	0 (-0.1,0.2)	**0.4** (0.1,0.7)	0.3 (0,0.6)
Lavras	0.2 (-0.1,0.6)	0.1 (0,0.2)	**0.4** (0,0.6)	**0.3** (0,0.5)
Viçosa	0.3 (0,0.6)	**0.3** (0.2,0.4)	-0.02 (-0.4,0.3)	0.3 (-0.1,0.6)
Pirapora	**0.5** (0.3,0.8)	**0.3** (0.1,0.6)	**0.3** (0.1,0.4)	**0.4** (0.2,0.7)
Itamarandiba	0.1 (-0.2,0.4)	**0.2** (0.1,0.4)	0 (-0.2,0.2)	**0.3** (0.1,0.6)
Teófilo Otoni	**0.5** (0.1,0.8)	0.2 (-0.1,0.5)	**0.3** (0,0.6)	**0.5** (0.2,0.8)

Table 8: Local trends for the temperature indices S3TX (number of sequences per decade), SU32, TR20 (number of days per decade) and DTR (^{o}C per decade) at the 12 selected stations during the period 1960-2011, using a robust linear trend estimate. 95% confidence intervals are stated in brackets. Values in bold indicate significance of the trend at the 0.05 level.

station	S3TX	SU32	TR20	DTR
Unaí	**0.4** (0,0.7)	**18.9** (13.7,23.7)	**9.1** (5,13.4)	**0.3** (0.1,0.4)
Patos de Minas	**0.5** (0.1,0.7)	**6** (3.7,8.5)	**1** (0.5,1.6)	**0.1** (0,0.2)
Araxá	0 (0,0.3)	**3.5** (2,5)	**3.2** (1.6,5.4)	**-0.1** (-0.3,0)
Caratinga	0 (0,0)	**2.9** (0.8,4.7)	5.8 (-0.3,10.7)	0.1 (-0.1,0.3)
Aimores	0.4 (-0.2,1)	**11.4** (1.8,20.2)	11.9 (-6.3,33.6)	-0.2 (-0.4,0.1)
Bambuí	0.2 (-0.1,0.6)	**7.2** (2.9,9.9)	**4.4** (0.8,8)	**0.2** (0,0.4)
Machado	0 (0,0.4)	**5.1** (1.6,8.2)	0.7 (0,1.2)	0.2 (0,0.3)
Lavras	0 (0,0.3)	**4.4** (1.9,6.2)	0.7 (0,1.5)	**0.2** (0.1,0.3)
Viçosa	0 (0,0)	**1.8** (0.2,3.6)	**5.1** (3.3,6.8)	**-0.1** (-0.3,0)
Pirapora	0 (-0.4,0.5)	**10.8** (4.1,18.3)	**18.5** (14.1,23.2)	**-0.1** (-0.3,0)
Itamarandiba	0 (0,0)	1.3 (0,2.8)	**0.9** (0.4,1.5)	-0.1 (-0.2,0.1)
Teófilo Otoni	**0.7** (0.2,1.1)	**9.7** (2.6,17.3)	**19.8** (3.2,35.8)	-0.1 (-0.3,0.2)

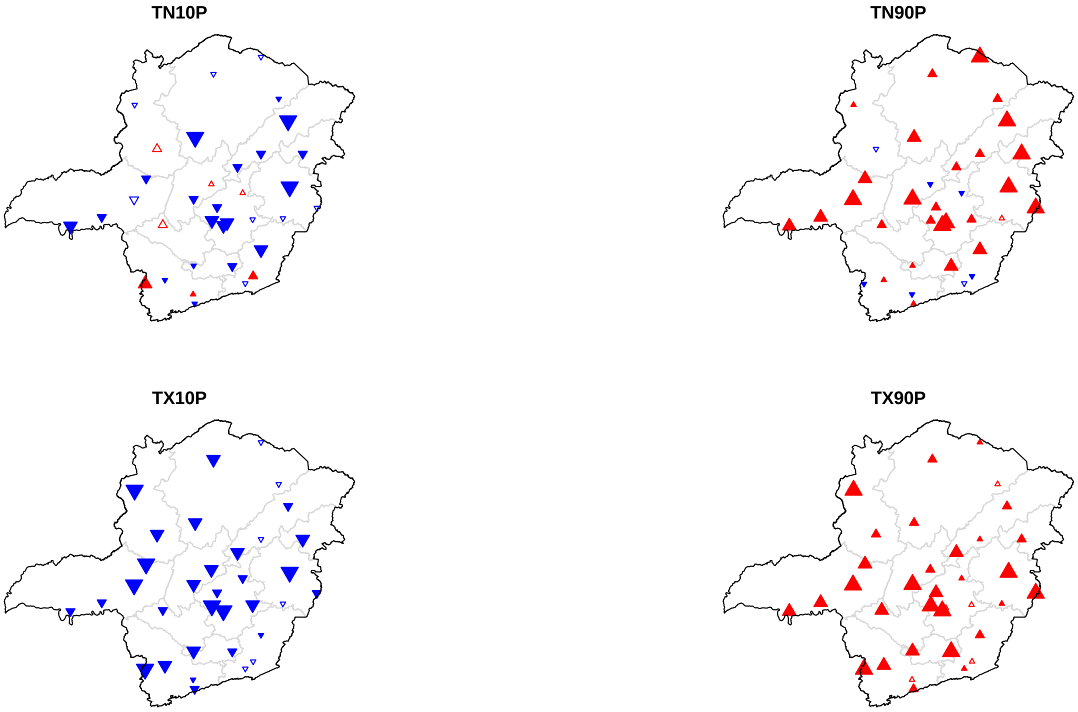


Figure 7: Trends of the percentile-based temperature indices TX10P (percentage of cold days), TX90P (percentage of warm days), TN10P (percentage of cold nights) and TN90P (percentage of warm nights) for 35 available stations in Minas Gerais. Red point-up/blue point-down triangles indicate positive/negative trends. Statistically significant trends at 0.05 level are represented by filled triangles. The size of the triangles is proportional to the magnitude of the trend.

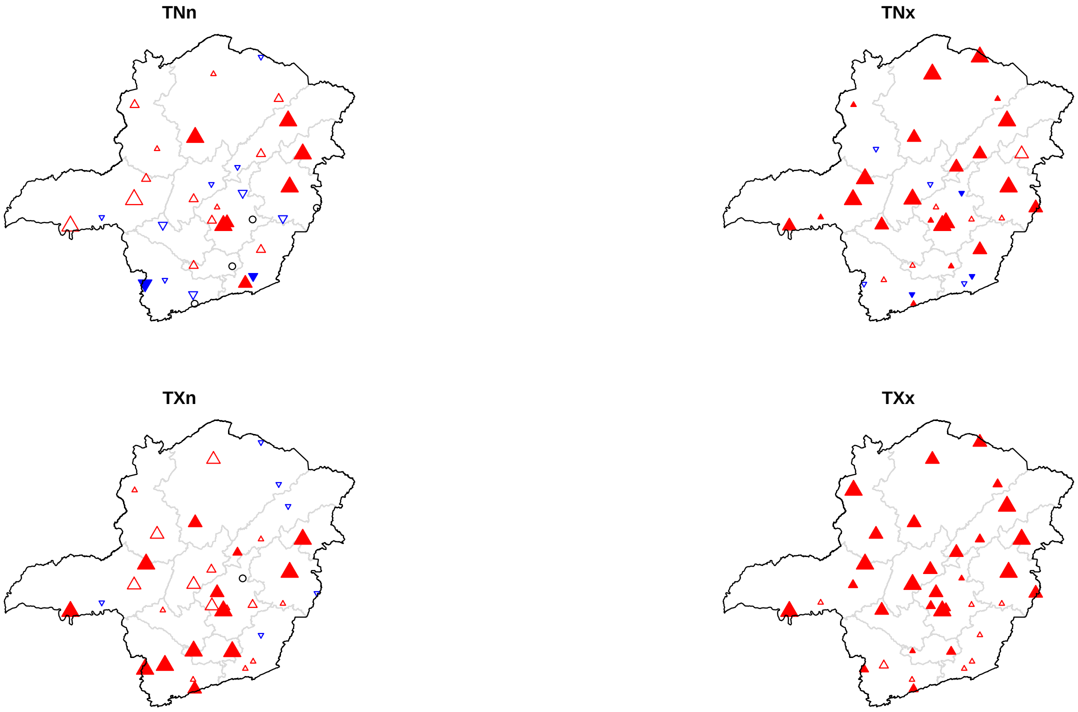


Figure 8: Trends of the annual minimum/maximum temperature indices TNn (Monthly minimum of daily tmin), TNx (Monthly maximum of daily tmin), TXn (Monthly minimum of daily tmax) and TXx (Monthly maximum of daily tmax) for 35 available stations in Minas Gerais. Red point-up/blue point-down triangles indicate positive/negative trends. Statistically significant trends at 0.05 level are represented by filled triangles. The size of the triangles is proportional to the magnitude of the trend. Empty black circles represent stations without detected trend.

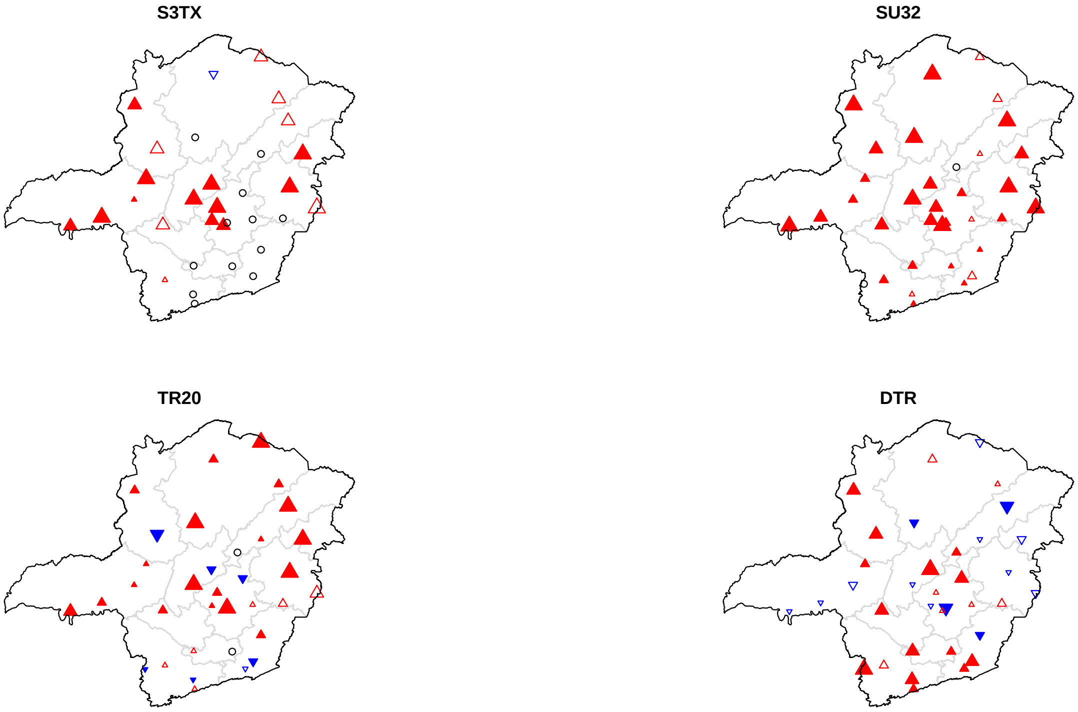


Figure 9: Trends of the S3TX, SU32, TR20 and DTR climate change indices for 35 available stations in Minas Gerais. Red point-up/blue point-down triangles indicate positive/negative trends. Statistically significant trends at 0.05 level are represented by filled triangles. The size of the triangles is proportional to the magnitude of the trend. Empty black circles represent stations without detected trend.

4.1.2 Spatio-temporal variability of minimum and maximum temperatures

Surface maps of mean maximum temperature in Minas Gerais averaged at the 1960-1985 and 1986-2011 periods are presented in Figure 10, separated by trimester. Differences between the two periods evidence a warming behavior in all regions of the state. It can also be noted that warming is happening in all seasons of the year, being more accentuated at the trimesters with higher temperatures. The increase of areas with very high temperatures at the upper half of the state became more intense from the eighties decade and have been growing since that time at each decade, as shown in Figure 11. Results found in the trend analysis of the climate change indices, such as moderate increases of maximum temperatures at Zona da Mata and southern region of Minas Gerais, are also visually confirmed here.

The mean maximum temperature anomaly (difference between the 1986-2011 and 1960-1985 periods) was positive in all regions of Minas Gerais, as shown in Figure 12. It also can be noted a strong SE-NW gradient in this anomaly during the July-November period, with the highest anomaly values (around 1^{o}C) during the September-November trimester at the "Noroeste de Minas" region. This gradient inverts during the December-May period, increasing in the SW-NE direction and with its highest values during the summer season (December to February).

A global picture of the change in minimum and maximum temperature at regional level is presented in the boxplots of Figure 13, which confirm the warming behavior in Minas Gerais as a whole at all trimesters of the year. A growing tendency in the time series of maximum and minimum temperature in the state was also reported by Minuzzi et al. (2010) for the period 1960-2004. Skansi et al. (2013) also found signals of warming in the south-east region of Brazil through the last 50 years.

There is an increase in the extent of areas experiencing the highest mean maximum temperatures (above 30 ^{o}C) by trimester in Minas Gerais, as shown in Figure 14. It predominantly occurs in the western, northern and north-east regions of the state, during the September to November trimester, although some areas of the eastern region are also experiencing such high temperatures during the summer season (December to February). The total count of very warm days ($>$ 34 ^{o}C), at stations in these areas also increased in the second period, as can be seen in Figure 15. However, the main coffee producing areas in Minas Gerais are not part of these very high temperatures zones at present.

Regional differences in the time when highest mean maximum temperatures occur through the year can also be verified looking at Figure 16, which indicates the September to November trimester as the warmest one at the north, north-east and western regions of Minas Gerais (group 1), whilst for the rest of the state (group 2) it occurs from December to February. Additionally, areas belonging to group 1, in general, experience higher temperatures than those of group 2, as shown in Figure 10. In fact, areas having mean maximum temperatures above 30 ^{o}C are predominantly located in this group (Figure 14). Therefore, it can be hypothesized that risk of heat stress during the coffee flowering period, causing flower abortion or a high incidence of star flowers, would be higher at coffee areas belonging to group 1.

The surface maps of mean minimum temperature by trimester, averaged at the 1960-1985 and 1986-2011 periods, also evidenced a warming trend, as can be seen in Figures 17 to 19. However, unlike maximum temperature, the increases in minimum temperatures were less accentuated during the warmest months (September to February). It was also verified that there was a decrease in the extent of areas with the lowest mean minimum temperatures (below 10 ^{o}C) for the colder trimesters (Figure 20). However, the main coffee producing regions, like "Sul de Minas", only experienced slight decreases, keeping these areas still under frost risk during the winter season.

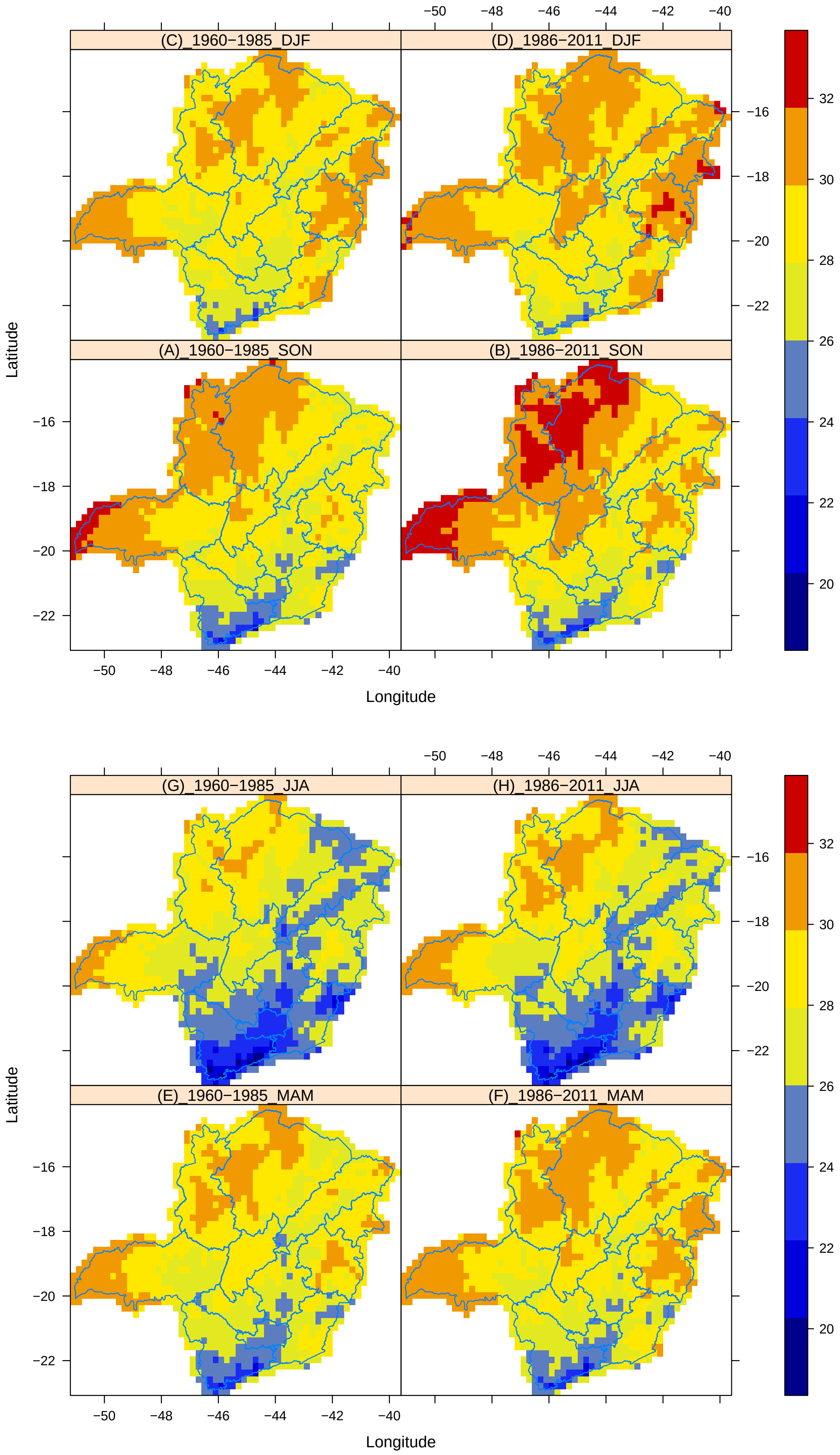


Figure 10: Surface maps of mean maximum temperature (^{o}C) by trimester averaged over the 1960-1985 and 1986-2011 periods (left and right columns, respectively).

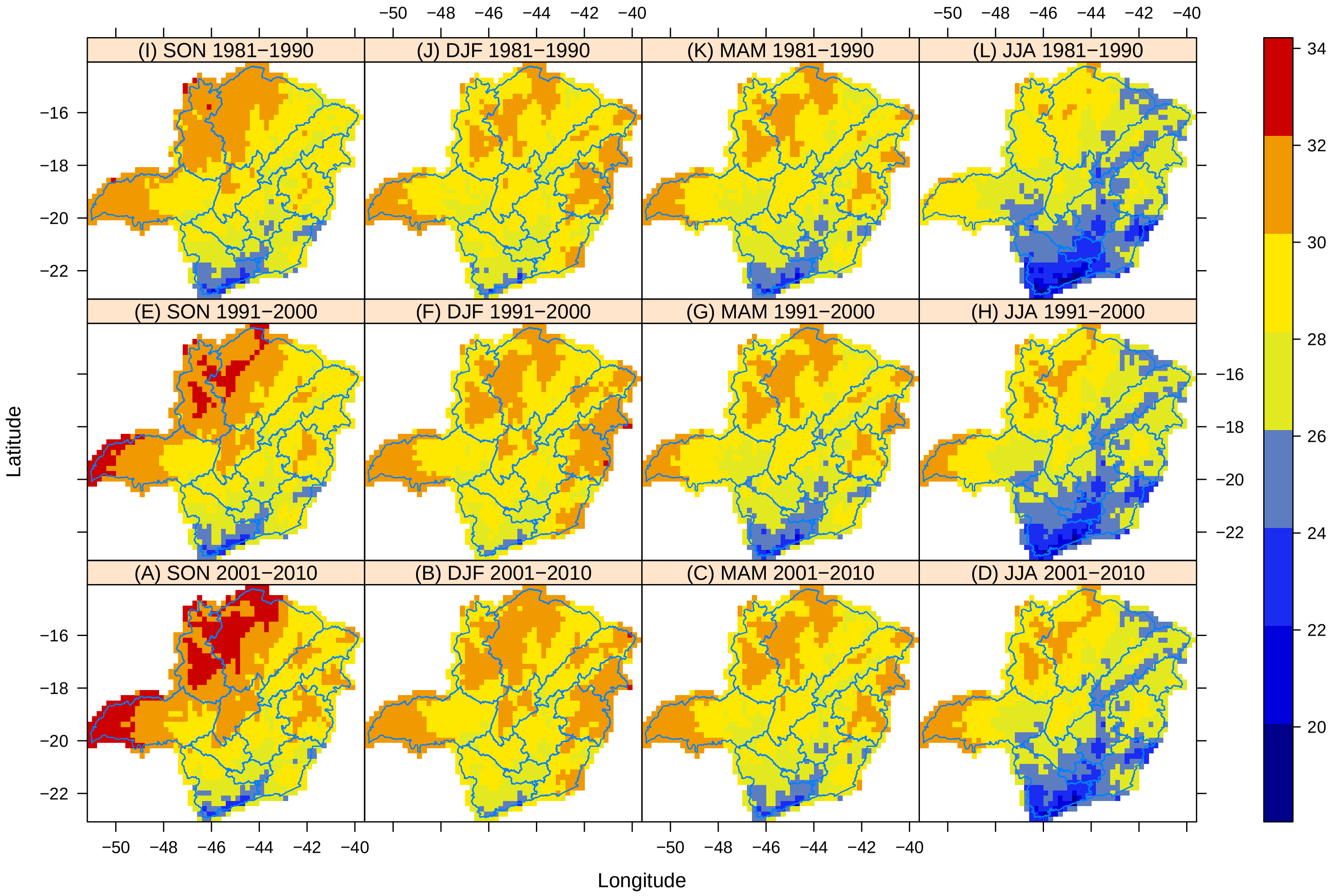


Figure 11: Surface maps of mean maximum temperature (°C) by trimester averaged over the 1981-1990, 1991-2000 and 2001-2010 decades.

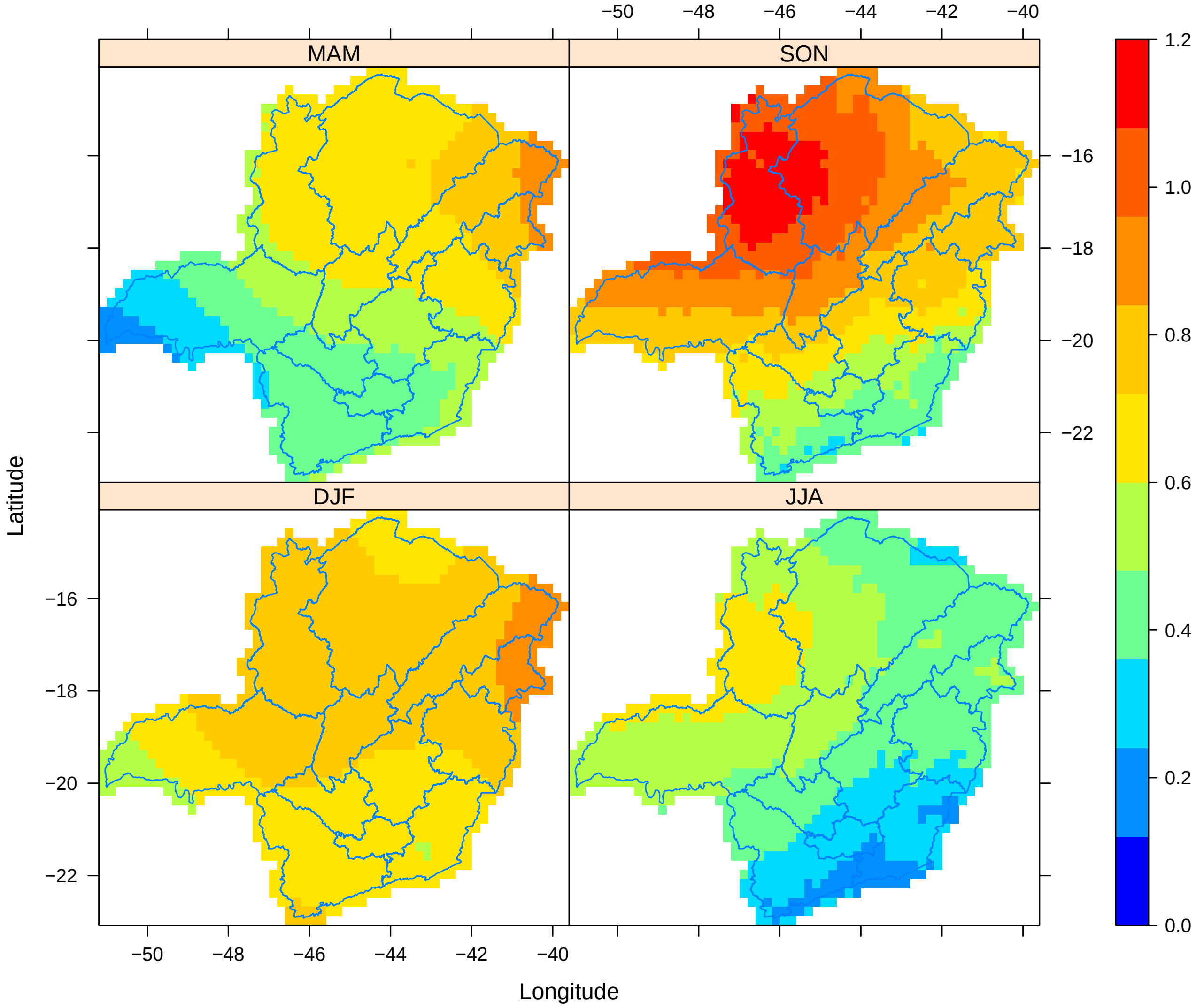
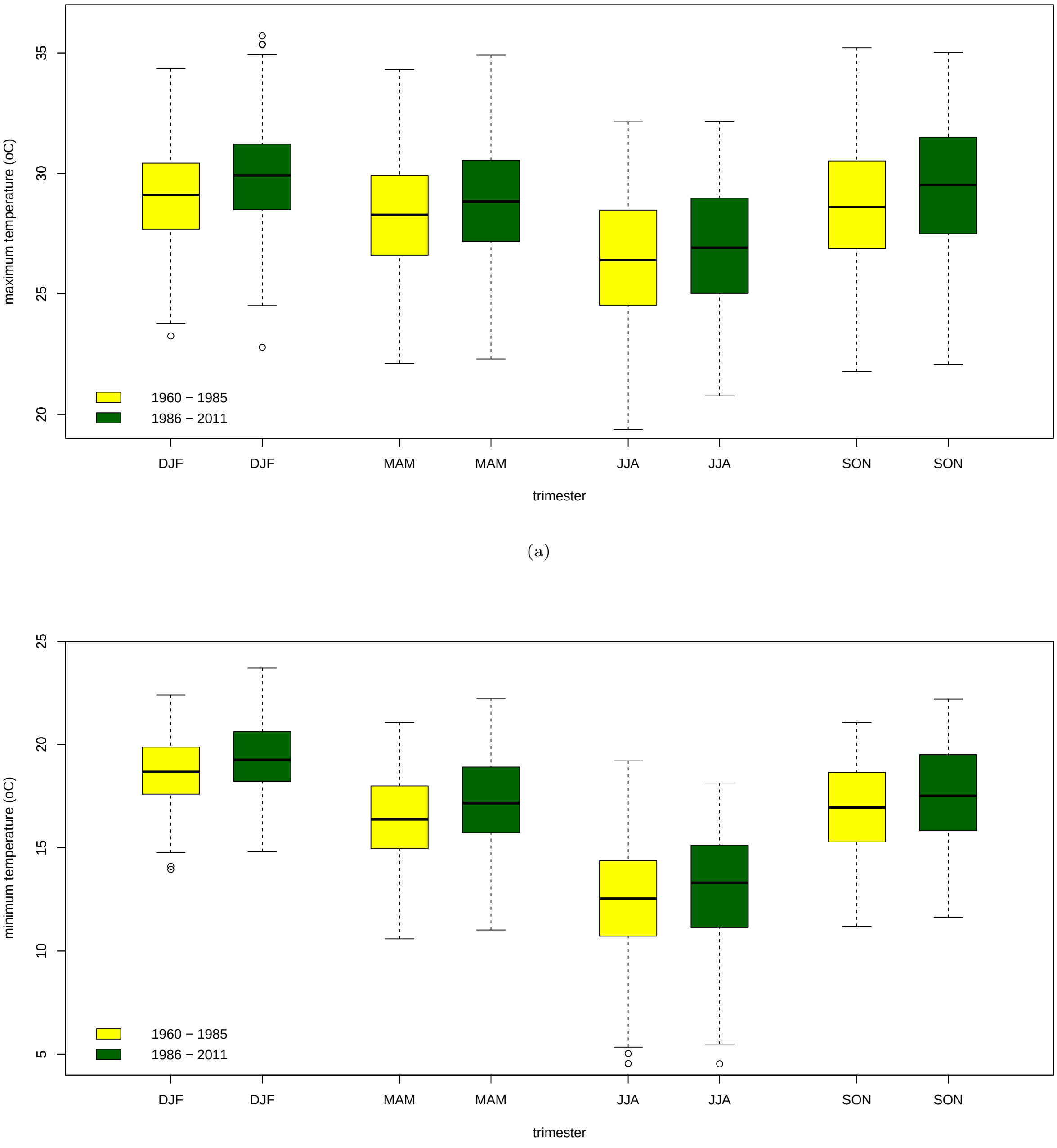


Figure 12: Mean maximum temperature anomaly (°C) by trimester in Minas Gerais (difference between the 1986-2011 and 1960-1985 periods).



(a)

(b)

Figure 13: Boxplots of the regional mean of maximum (a) and minimum (b) temperature by trimester (in ^{o}C), averaged over the 1960-1985 and 1986-2011 periods. The horizontal black line within the boxes represent the median value.

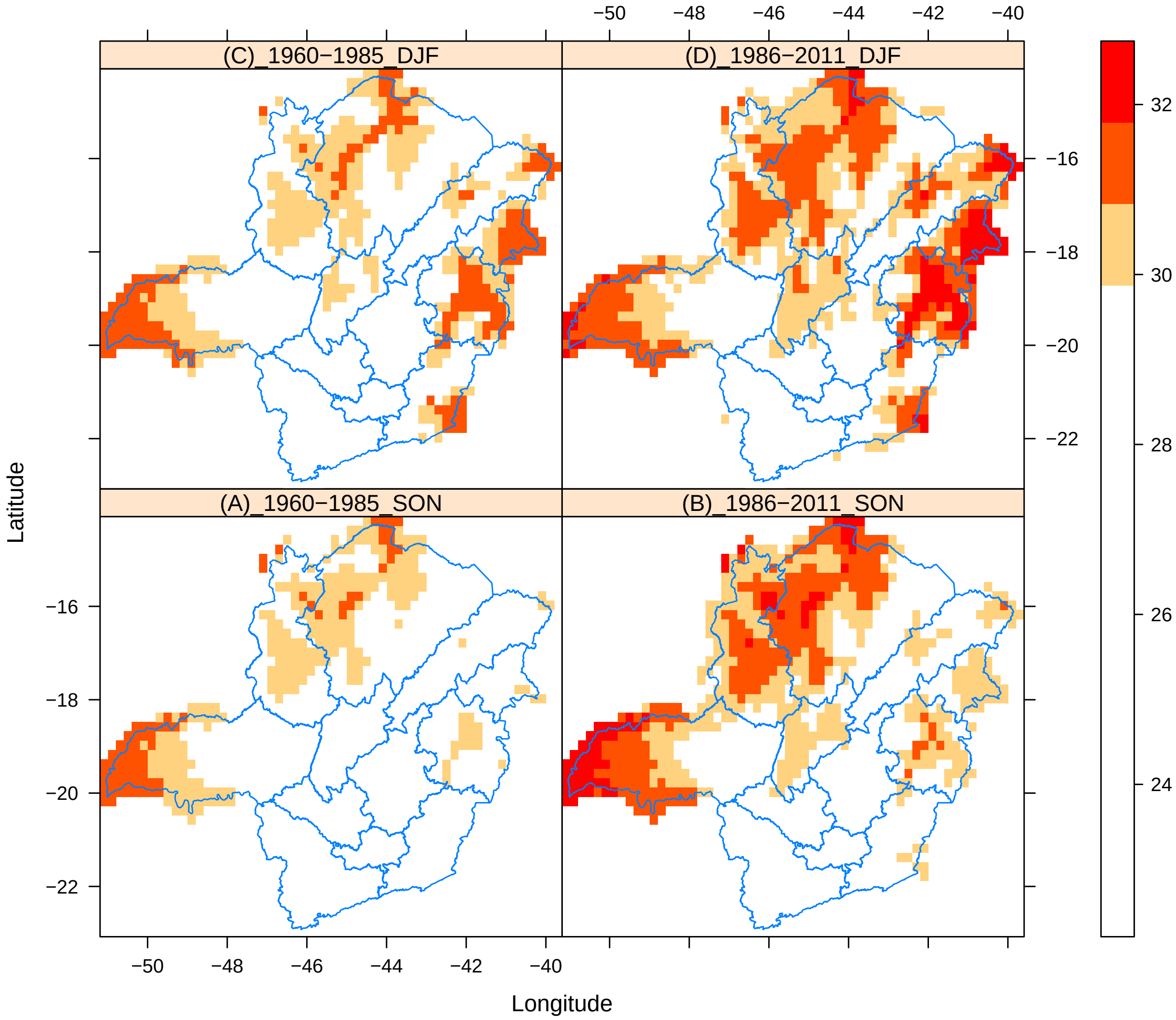


Figure 14: Regions with the highest mean maximum temperatures during the September to November and December to February trimesters, averaged over the 1960-1985 and 1986-2011 periods.

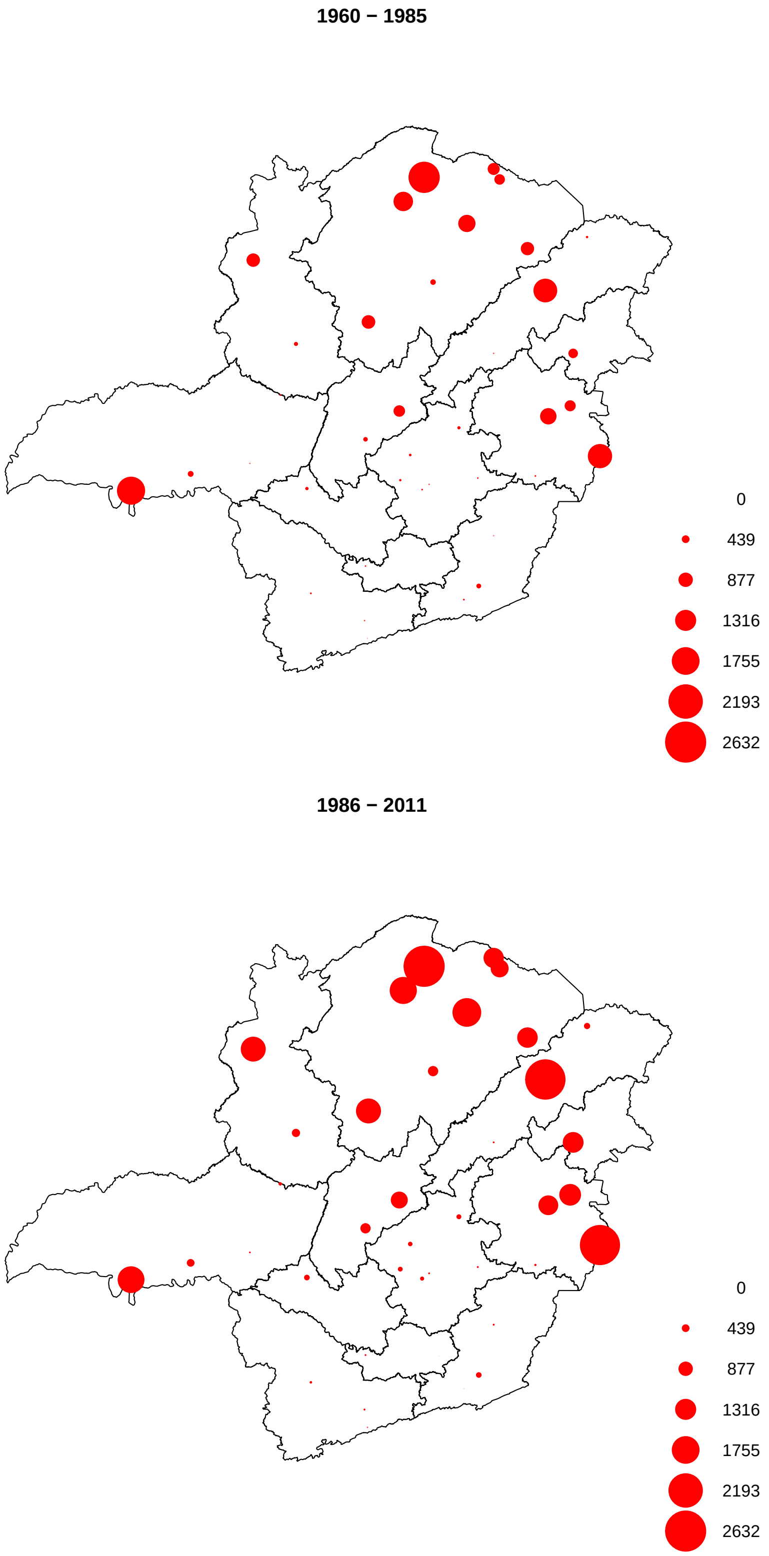


Figure 15: Total count of very warm days (above 34 ^{o}C) registered at the stations during the 1960-1985 and 1986-2011 periods. Dot sizes are proportional to the counts.

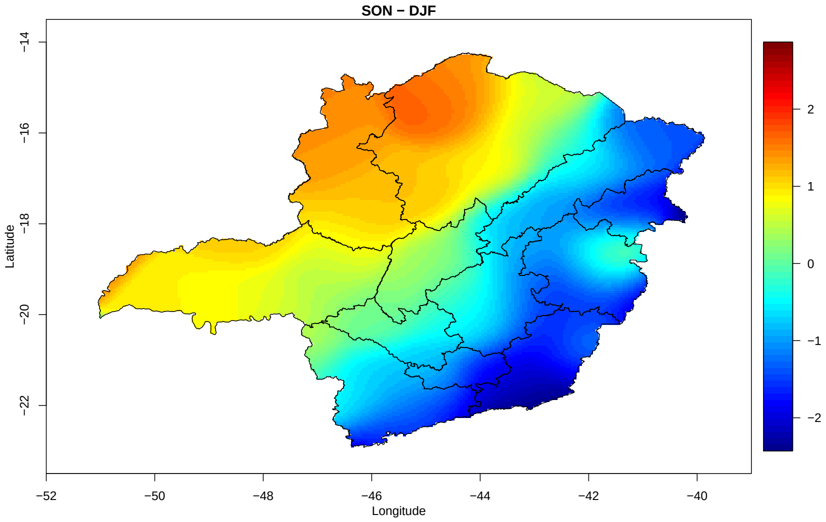


Figure 16: Difference (^{o}C) between the mean maximum temperature of the September to November and December to February trimesters in Minas Gerais, averaged over the 1971-2010 period.

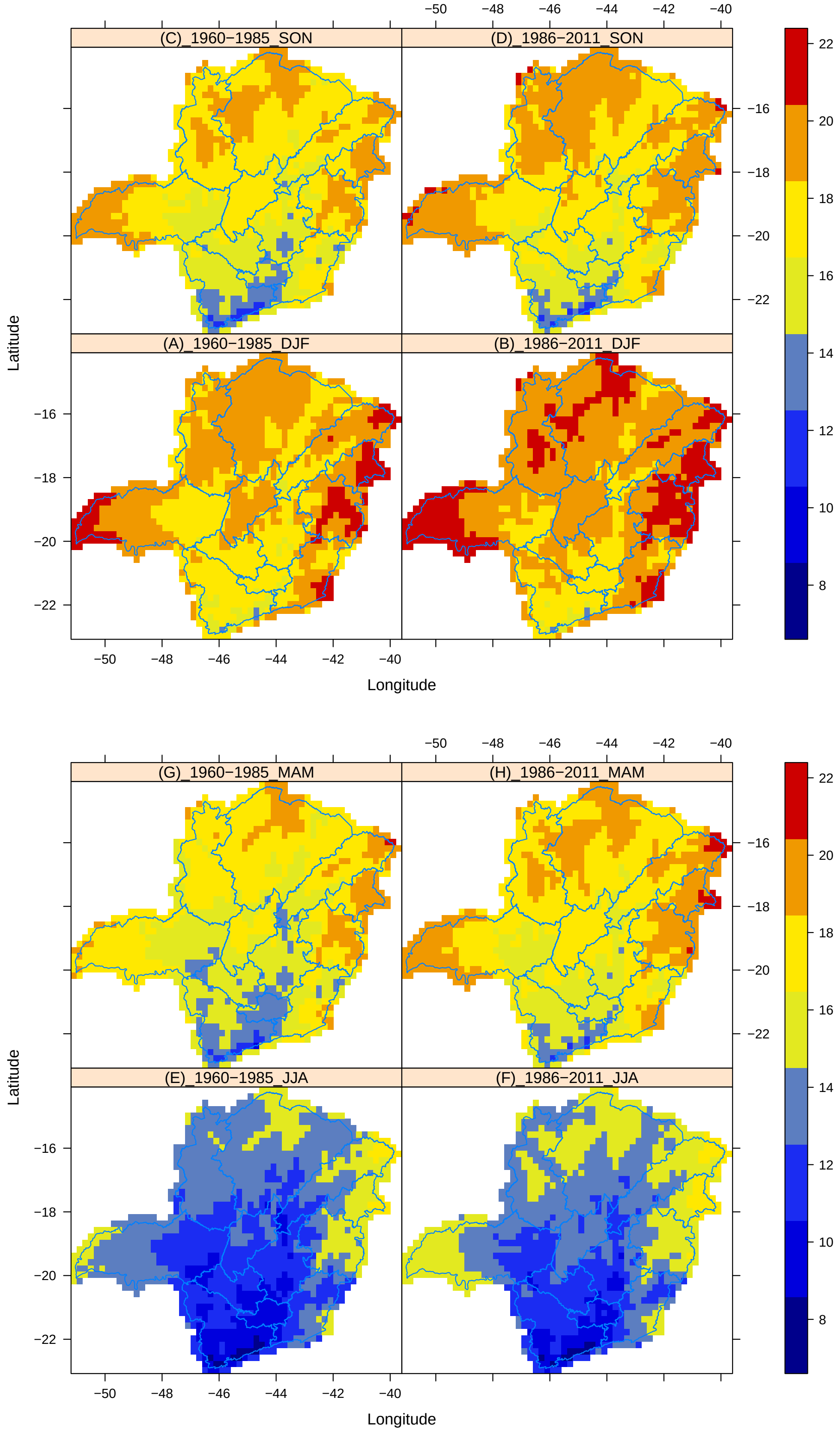


Figure 17: Surface maps of mean minimum temperature (^{o}C) for each season averaged over the 1960-1985 and 1986-2011 periods (left and right columns, respectively).

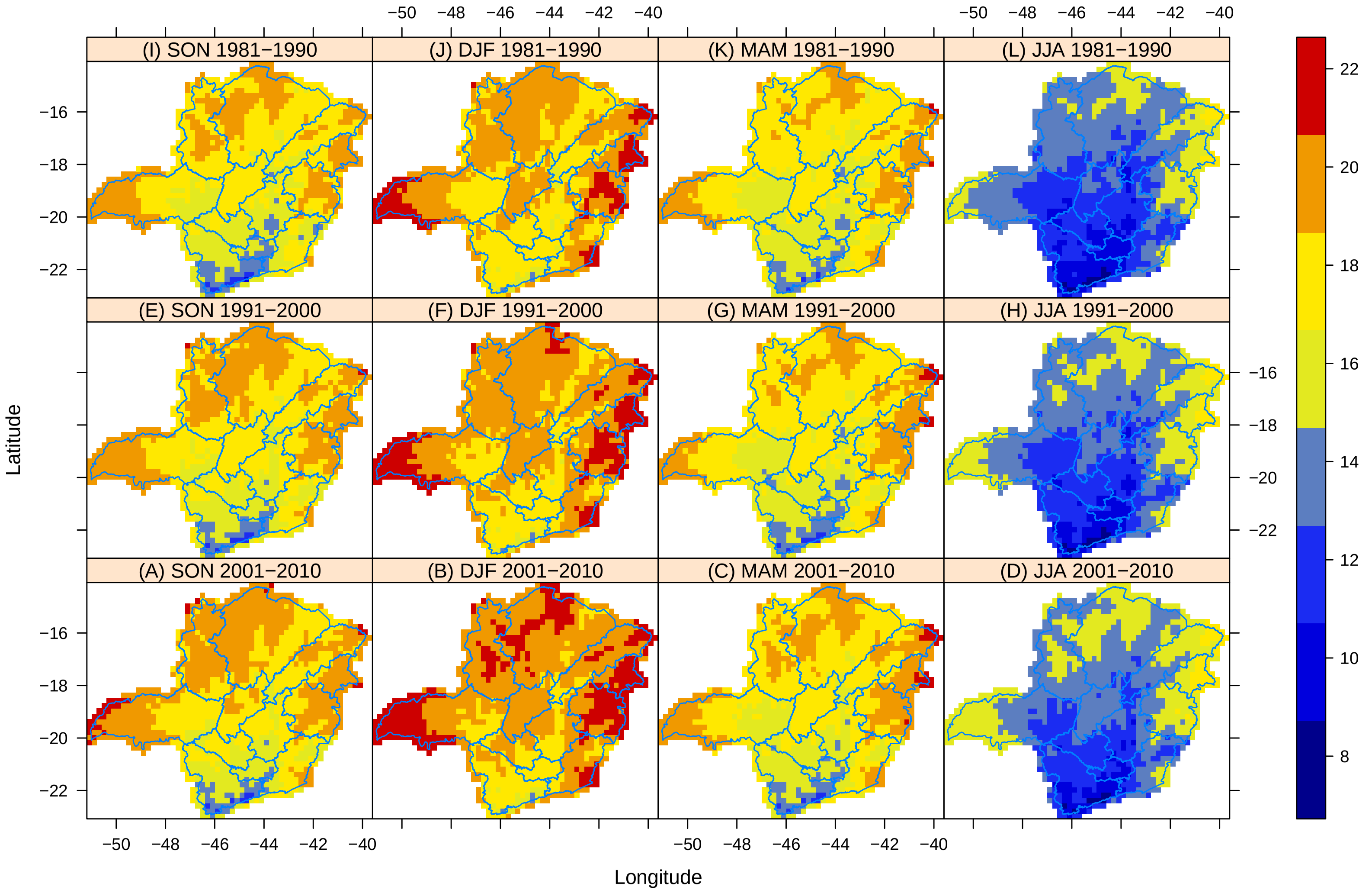


Figure 18: Surface maps of mean minimum temperature (^{o}C) by trimester averaged over the 1981-1990, 1991-2000 and 2001-2010 decades.

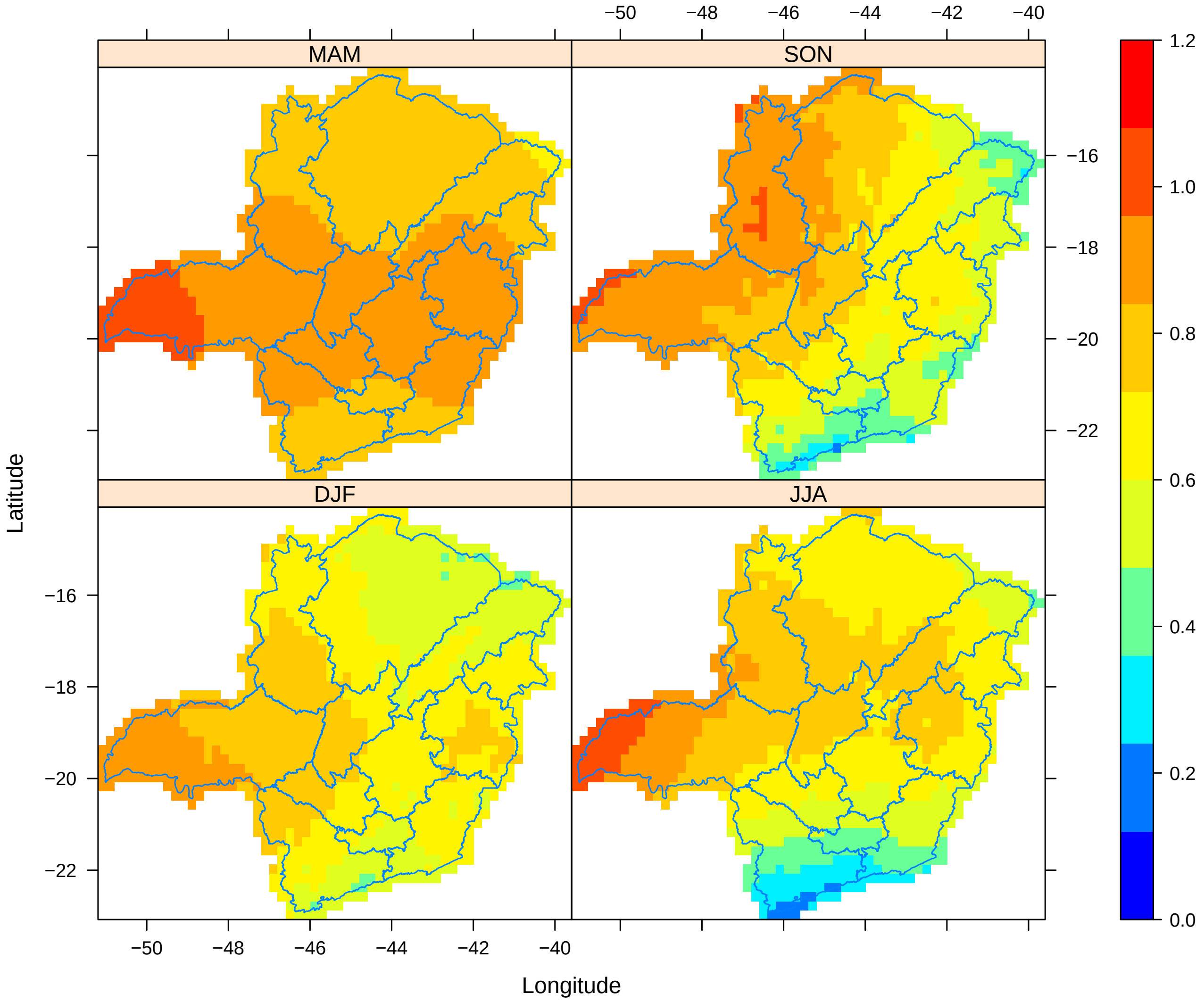


Figure 19: Mean minimum temperature anomaly (^{o}C) by trimester in Minas Gerais over 1960-1985 and 1986-2011 periods.

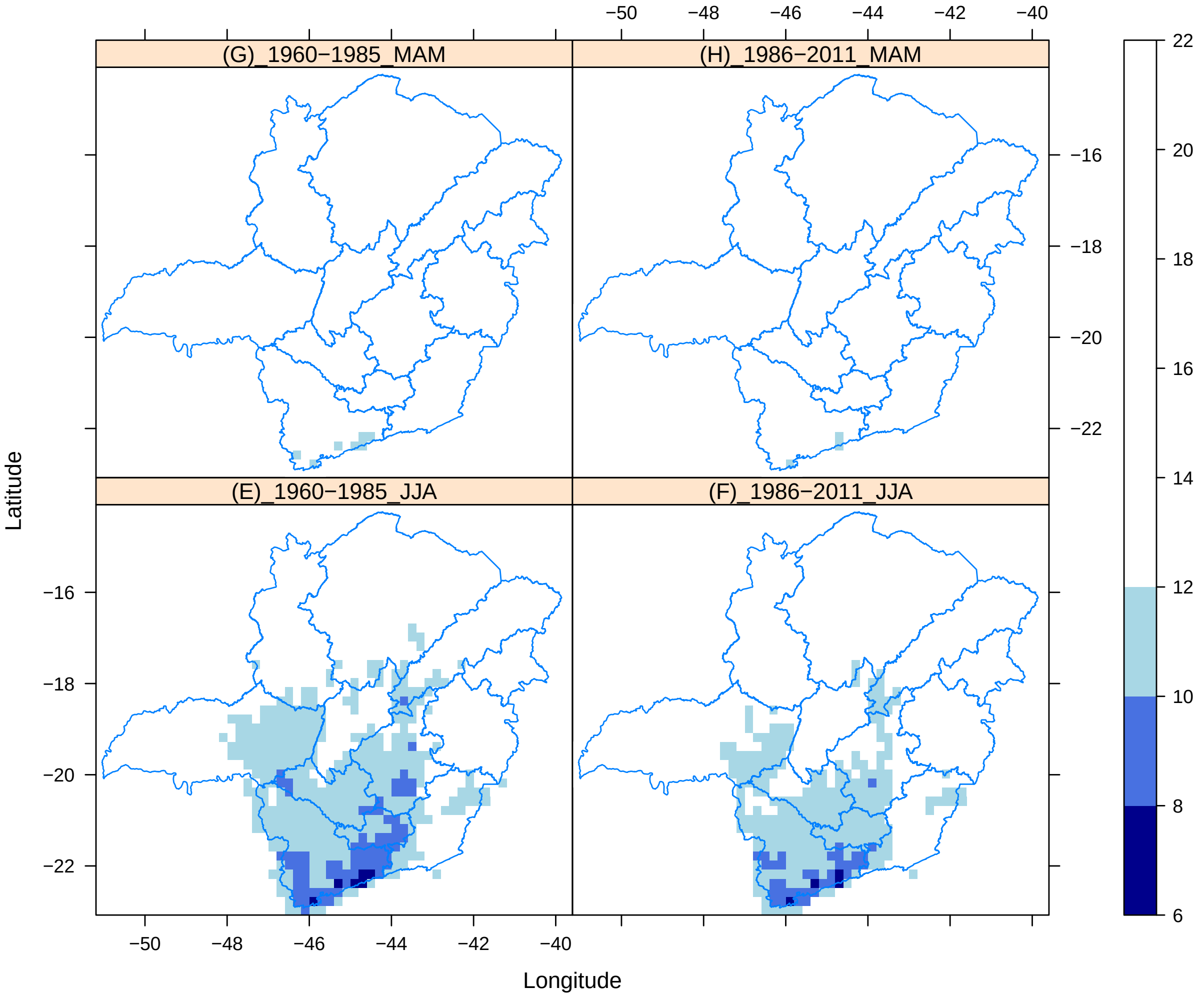


Figure 20: Regions with mean minimum temperature lower than 12^{o}C for the June to August trimester, averaged over the 1960-1985 and 1986-2011 periods.

4.2 Precipitation

4.2.1 Spatio-temporal variability of precipitation

Surface maps of the mean accumulated rainfall in Minas Gerais during the rainy season (October to March), averaged over the 1960-1985 and 1986-2011 periods, are presented in Figure 24. A strong NE-SW gradient can be seen, which becomes more extreme from 1960-1985 to 1986-2011. It is even stronger for the first trimester of the year, with the Southern and North-east regions of the state currently experiencing higher and lower levels of mean accumulated rainfall, respectively, compared to the 1960-1985 period. The October to December trimester is, at present, drier over most of the state, except the eastern region. On the other hand, the dry season (April to September) does not present significant changes in its levels of mean accumulated rainfall, as shown in Figure 25. The gradient of mean accumulated rainfall during the warm season is also as its anomaly (difference between the 1986-2011 and 1960-1985 periods), as shown in Figure 26. Minuzzi et al. (2007) had also pointed out higher levels of rainfall at the southern region of Minas Gerais from the middle of seventies and drier conditions over the rest of the state.

4.2.2 Dry spells

In order to study changes in the behaviour of dry spells[2] as well as in the water balance of Minas Gerais, the state was divided into four macro regions with different climatic characteristics as follows: macroregion 1 (MG1), which includes the southern region of Minas Gerais; macroregion 2 (MG2) formed by the Triângulo Mineiro and Noroeste de Minas regions; macroregion 3 (MG3) formed by Zona da Mata and the Metropolitan region of Belo Horizonte; and macroregion 4 (MG4) that includes all the other regions of the North and Northeast of Minas Gerais. This division is illustrated in Figure 42.

A general tendency of increase (from 1960-1985 to 1986-2011) in the number of dry spells classified as weak (5-9 days duration) was confirmed for all macro regions during the first three months of the year, as shown in Figures 27 to 30. The number of moderate dry spells (10-14 days duration) decreased in all months from December to March for macro region 1 and increased in February over macro regions 3 and 4, remaining relatively stable for the other months/macro regions. Also noted was an increase in the mean number of intense dry spells (> 14 days duration) for all macro regions in October and January and a decrease in February and March. The three types of dry spells decreased in December for all macro regions (except for the weak dry spells at macro region 4). Moderate and intense dry spells were more frequent during the first trimester of the year and are increasing so for macroregions 3 and 4.

In order to facilitate the visualization of these changes, contour maps of the number of weak (5-9 days), moderate (10-14 days) and intense (> 14 days) dry spells registered by month in Minas Gerais over the 1960-1985 and 1986-2011 periods are also presented in Figures 31 to 36).

The frequency of rainy days during the dry season is also represented in Figures 39 and 40. In general, there was not much variation in the total count of rainy days by month for the two periods (1960-1985 and 1986-2011), although an increase in the number of rainy days was detected in May and September for macro region 1 (Sul de Minas), where coffee harvest spans from May to October.

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[2] a dry spell is defined as the number of consecutive days without rainfall within the rainy season

4.2.3 Beginning and duration of the rainy period

The beginning of the rainy period in Minas Gerais was determined following the methodology in Minuzzi et al. (2006). The surface maps of Figure 37 illustrate the beginning of the rainy period in Minas Gerais averaged over the 1960-1985 and 1986-2011 periods. It can be seen that there is a strong S-N gradient, with the rains starting first at the southern region of the state, by the end of September, and last at the north, when the rainy season begins only by the end of October. Changes were also verified from 1960-1985 to 1986-2011, with the rainy period currently starting earlier and later at the south and north of Minas Gerais, respectively.

The mean duration of the rainy period is presented in the contour maps of Figure 38. It follows the same S-N gradient, with, greater duration in the south of Minas Gerais and shorter (up to 50 days less) in the north.

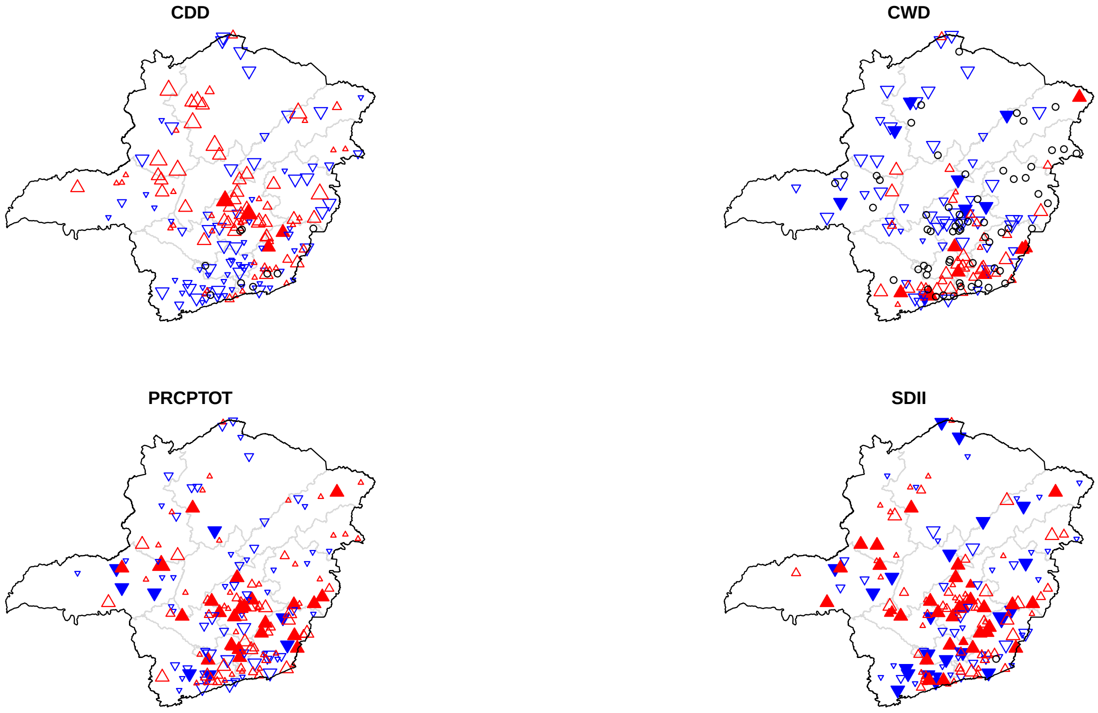


Figure 21: Trends of indices CDD, CWD, PRCPTOT and SDII for 163 rainfall stations available in Minas Gerais. Red point-up/blue point-down triangles indicate positive/negative trends. Statistically significant trends at 0.05 level are represented by filled triangles. The size of the triangles is proportional to the magnitude of the trend.

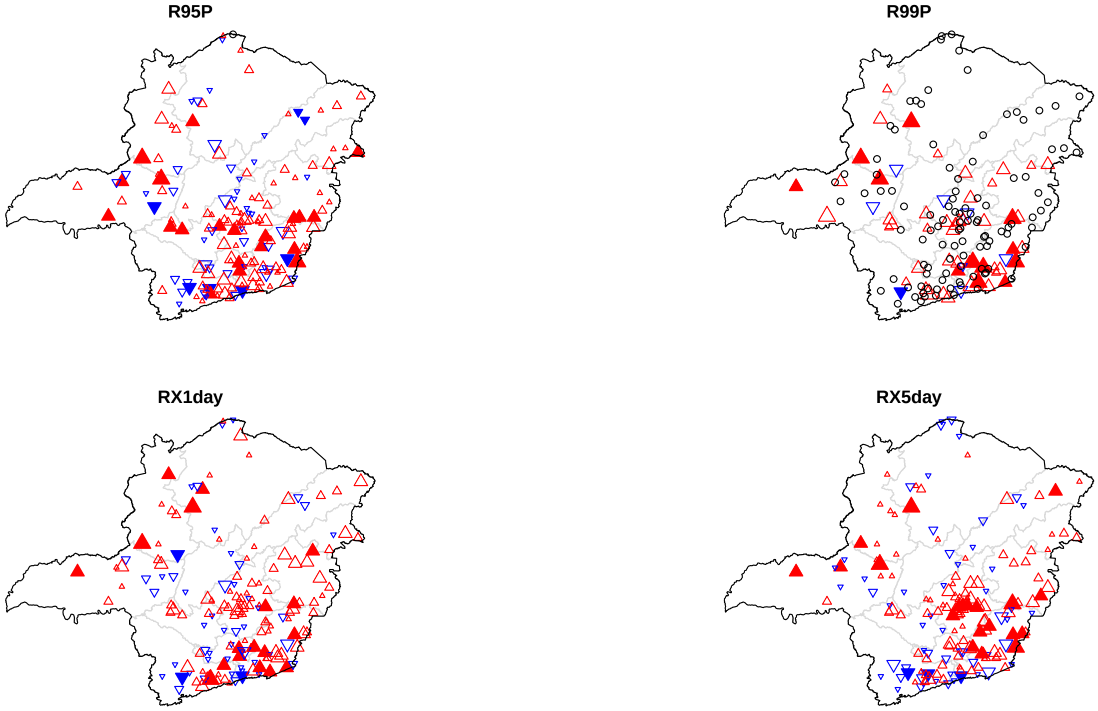


Figure 22: Trends of indices R95P, R99P, RX1day and RX5day for 163 rainfall stations available in Minas Gerais. Red point-up/blue point-down triangles indicate positive/negative trends. Statistically significant trends at 0.05 level are represented by filled triangles. The size of the triangles is proportional to the magnitude of the trend. Empty black circles represent stations without detected trend.

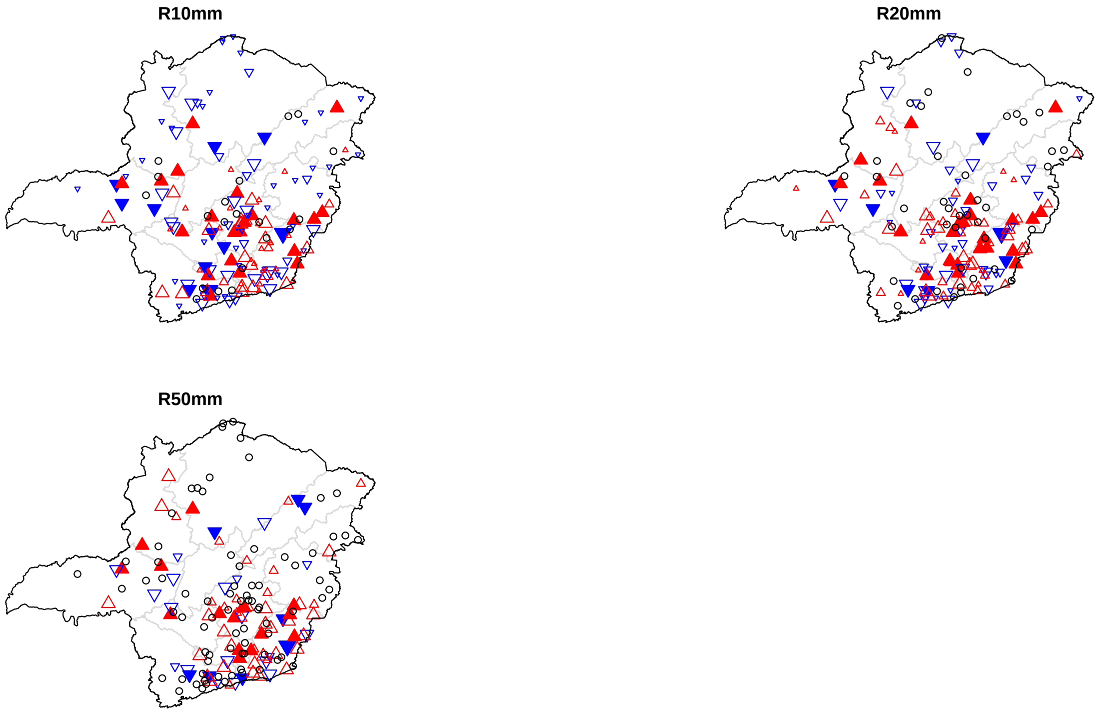


Figure 23: Trends of indices R10mm, R20mm and R50mm climate change indices for 163 rainfall stations available in Minas Gerais. Red point-up/blue point-down triangles indicate positive/negative trends. Statistically significant trends at 0.05 level are represented by filled triangles. The size of the triangles is proportional to the magnitude of the trend. Empty black circles represent stations without detected trend.

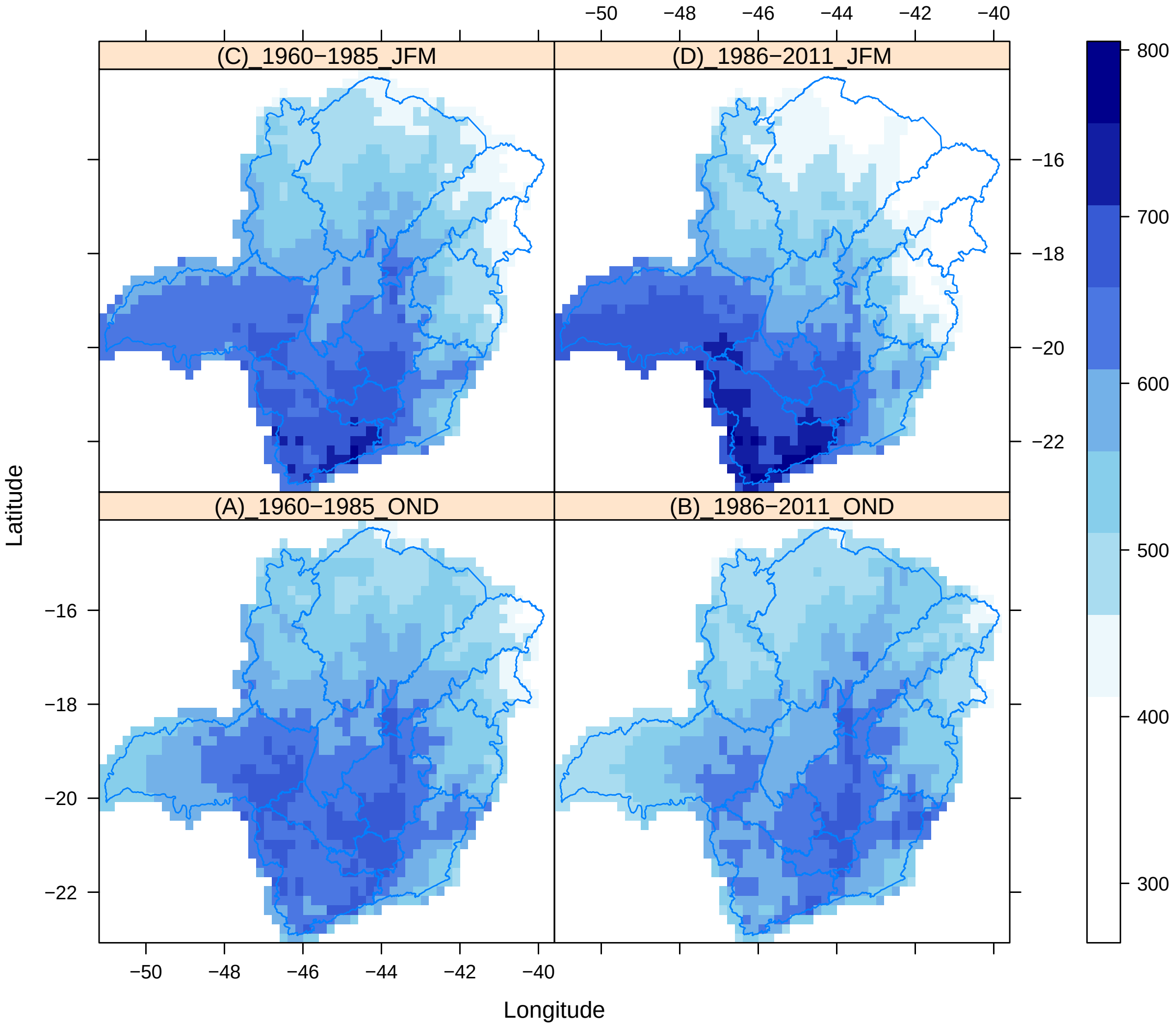


Figure 24: Mean accumulated precipitation (mm) by trimester in Minas Gerais during the rainy season (October to March) over 1960-1985 and 1986-2011 periods.

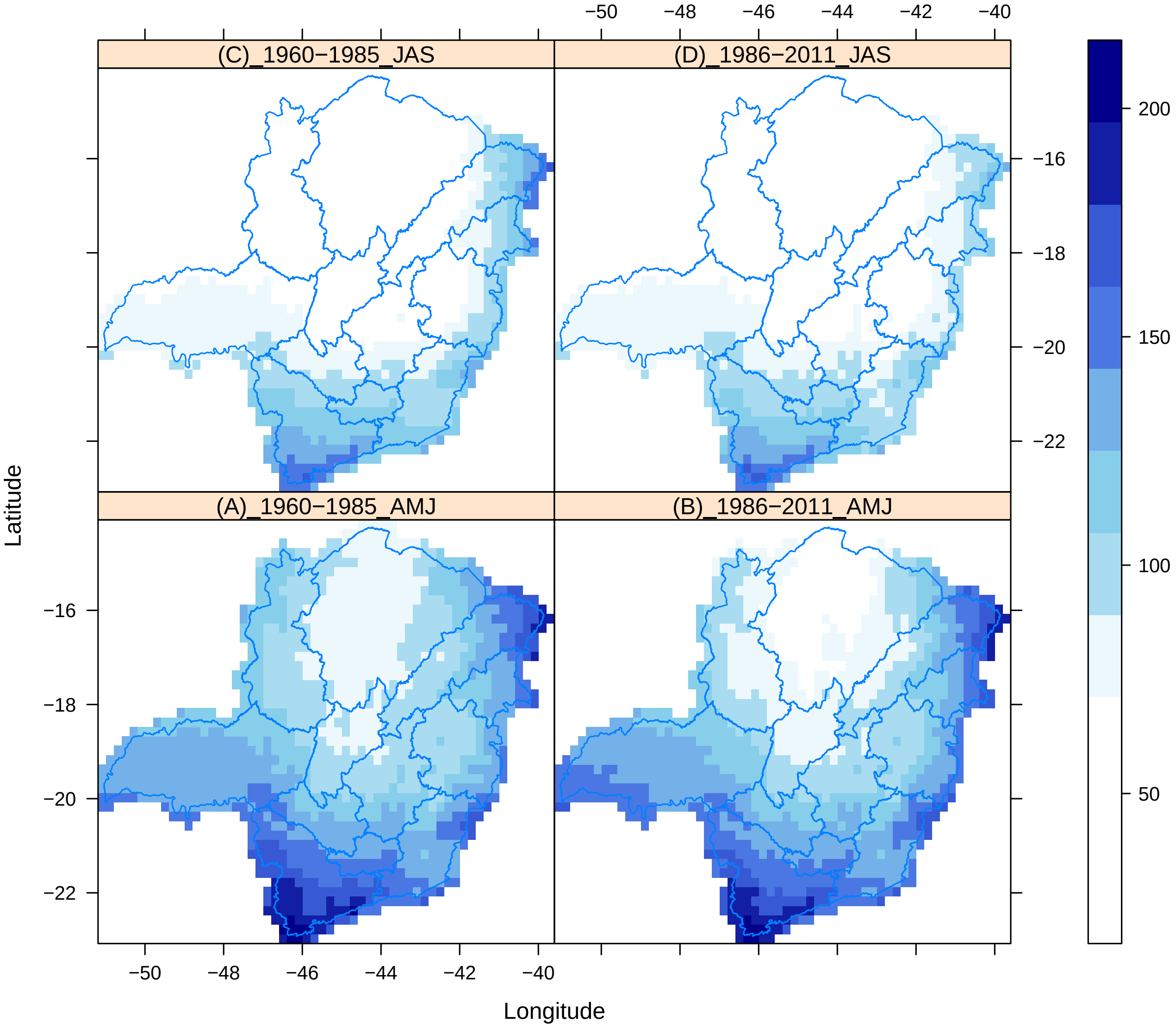


Figure 25: Mean accumulated precipitation (mm) by trimester in Minas Gerais during the dry season (April to September) over 1960-1985 and 1986-2011 periods.

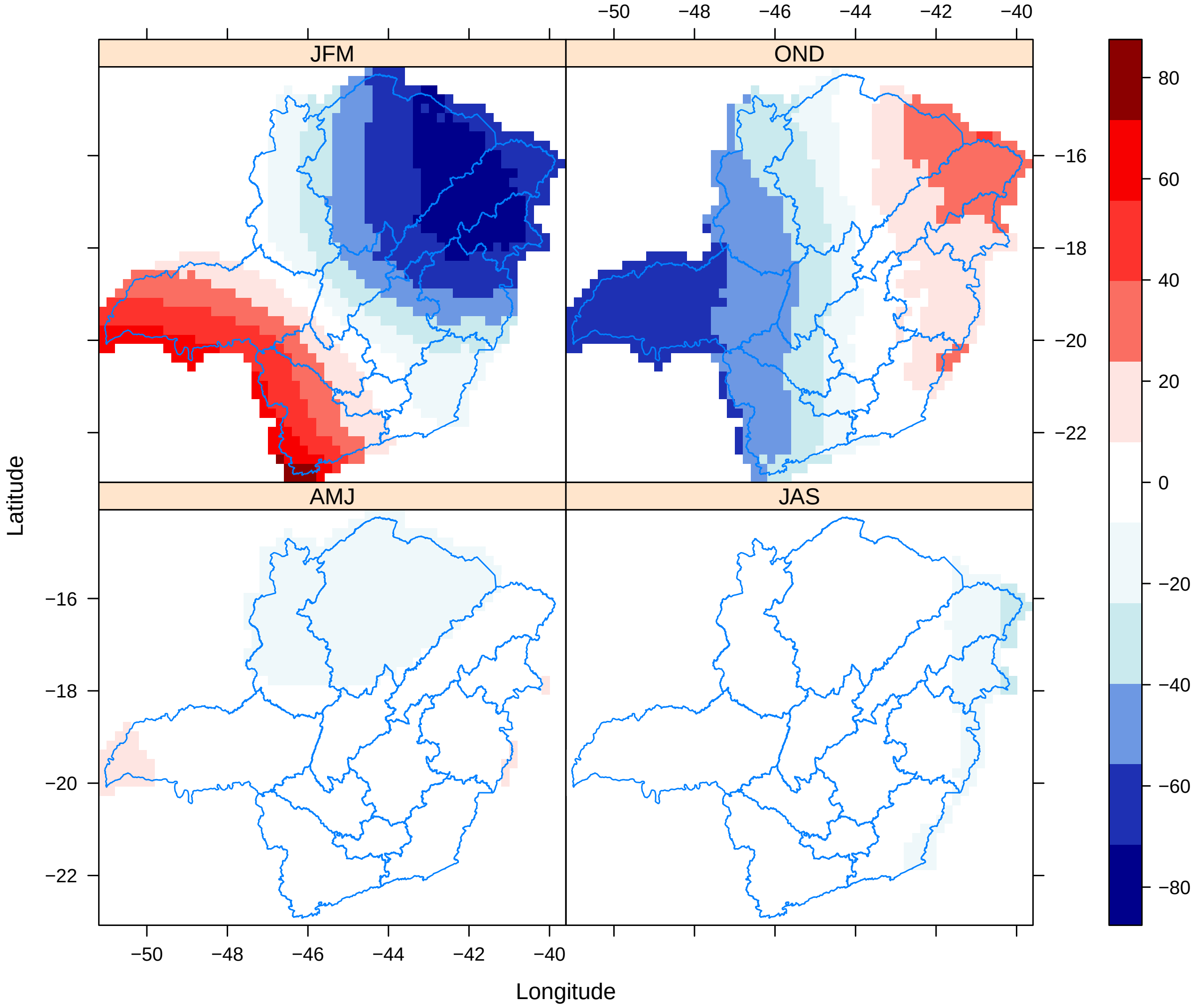


Figure 26: Mean accumulated precipitation anomaly (difference between the 1986-2011 and 1960-1985 periods) by trimester in Minas Gerais (expressed in mm).

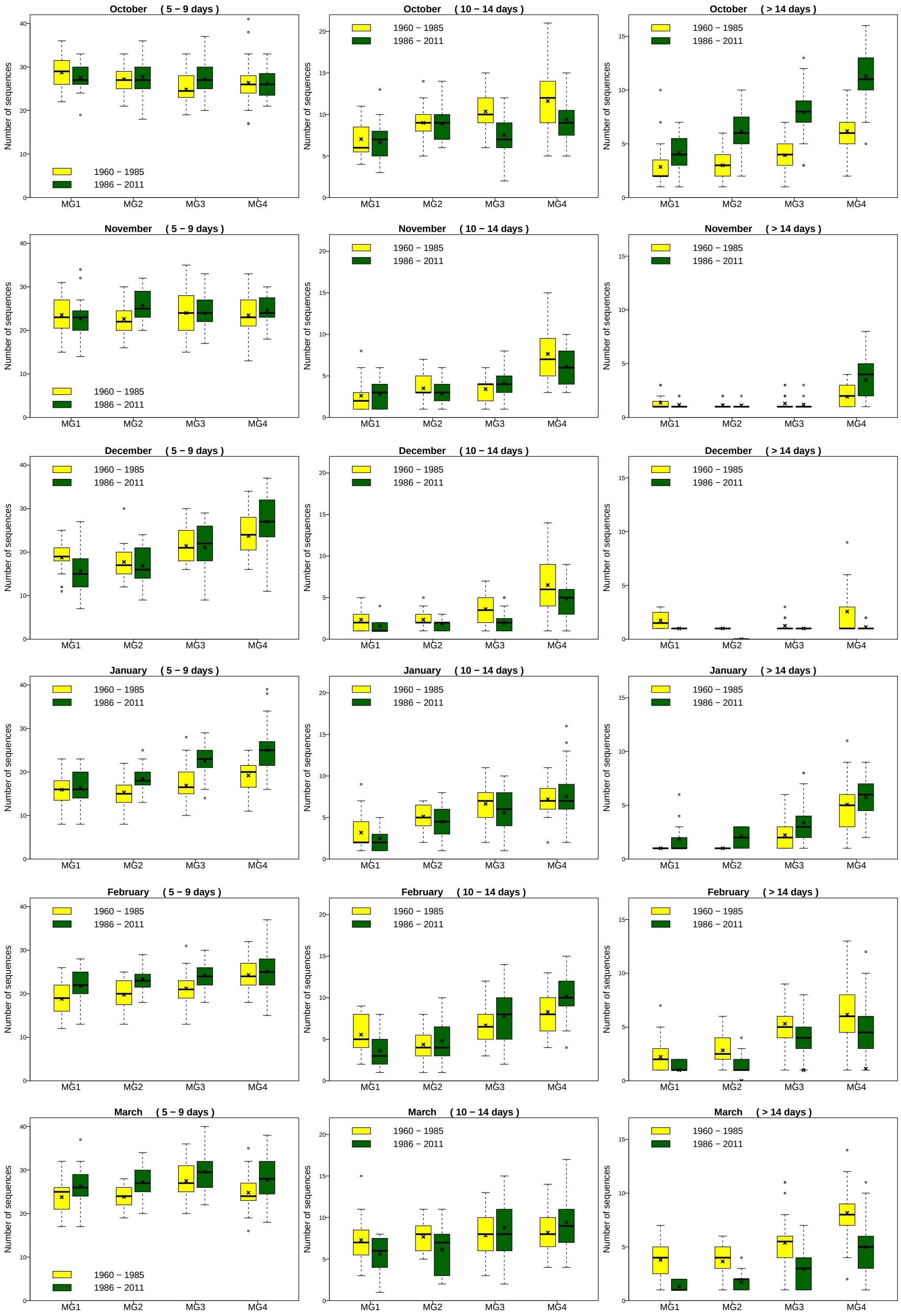


Figure 27: Boxplots of the number of weak (5-9 days), moderate (10-14 days) and intense (> 14 days) dry spells by month during the rainy season (October to March) in Minas Gerais, registered over the 1960-1985 and 1986-2011 periods.

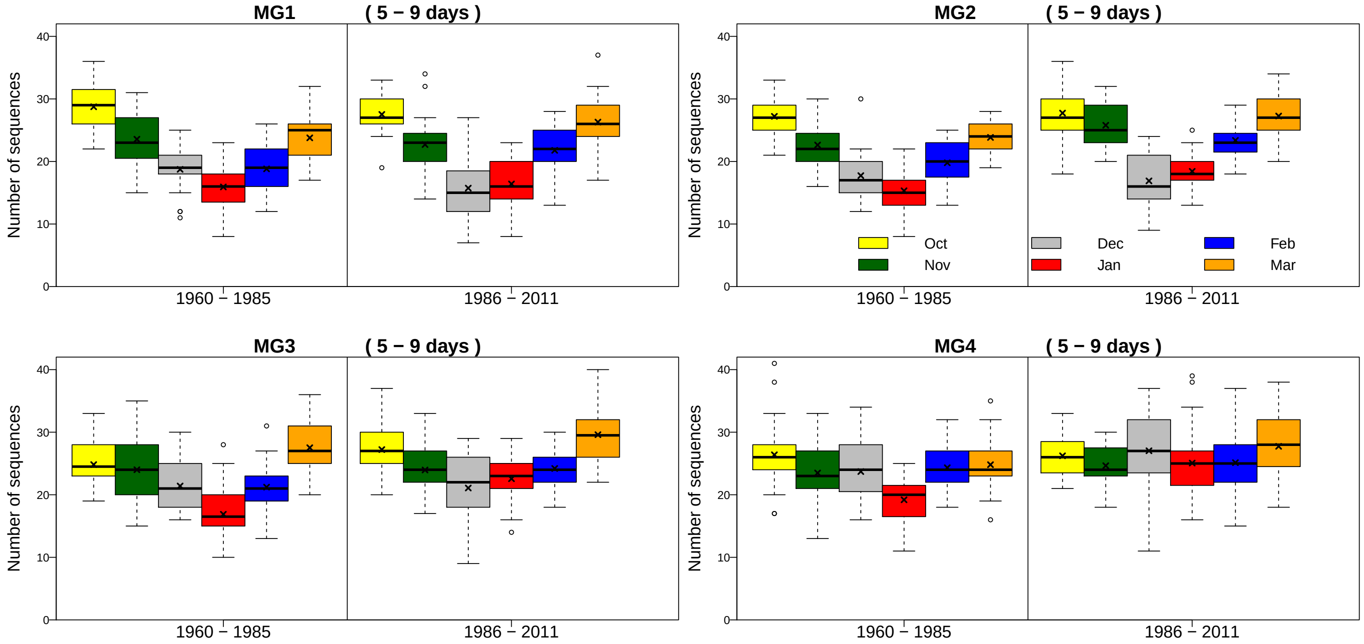


Figure 28: Boxplots of dry spells with duration between 5 and 9 days during the October to March period (rainy season) in Minas Gerais over the 1960-1985 and 1986-2011 periods.

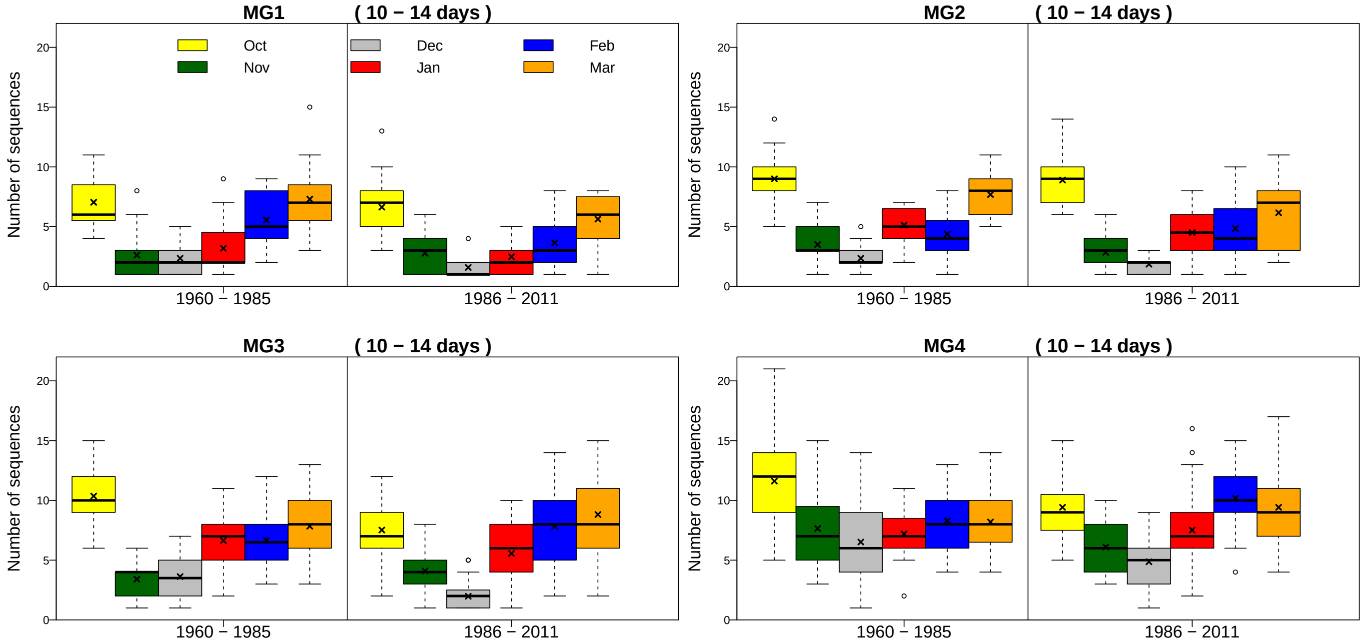


Figure 29: Boxplots of dry spells with duration between 10 and 14 days during the October to March period (rainy season) in Minas Gerais over the 1960-1985 and 1986-2011 periods.

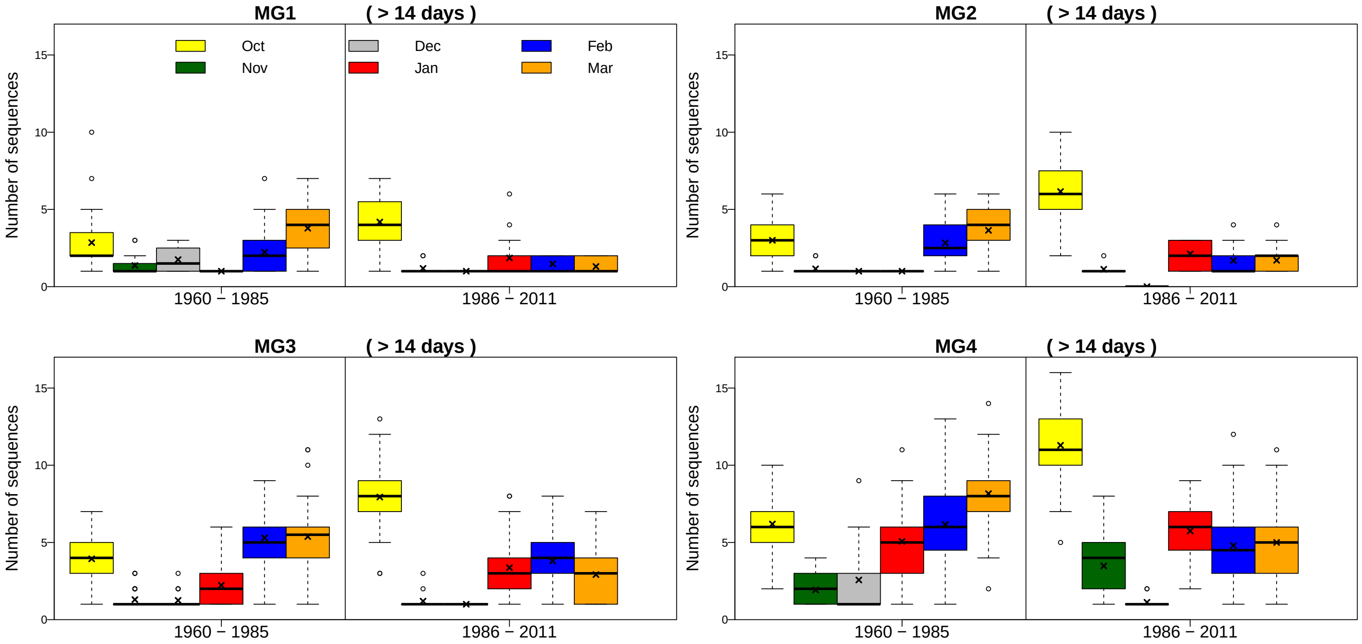


Figure 30: Boxplots of dry spells with duration greater than 14 days during the October to March period (rainy season) in Minas Gerais over the 1960-1985 and 1986-2011 periods.

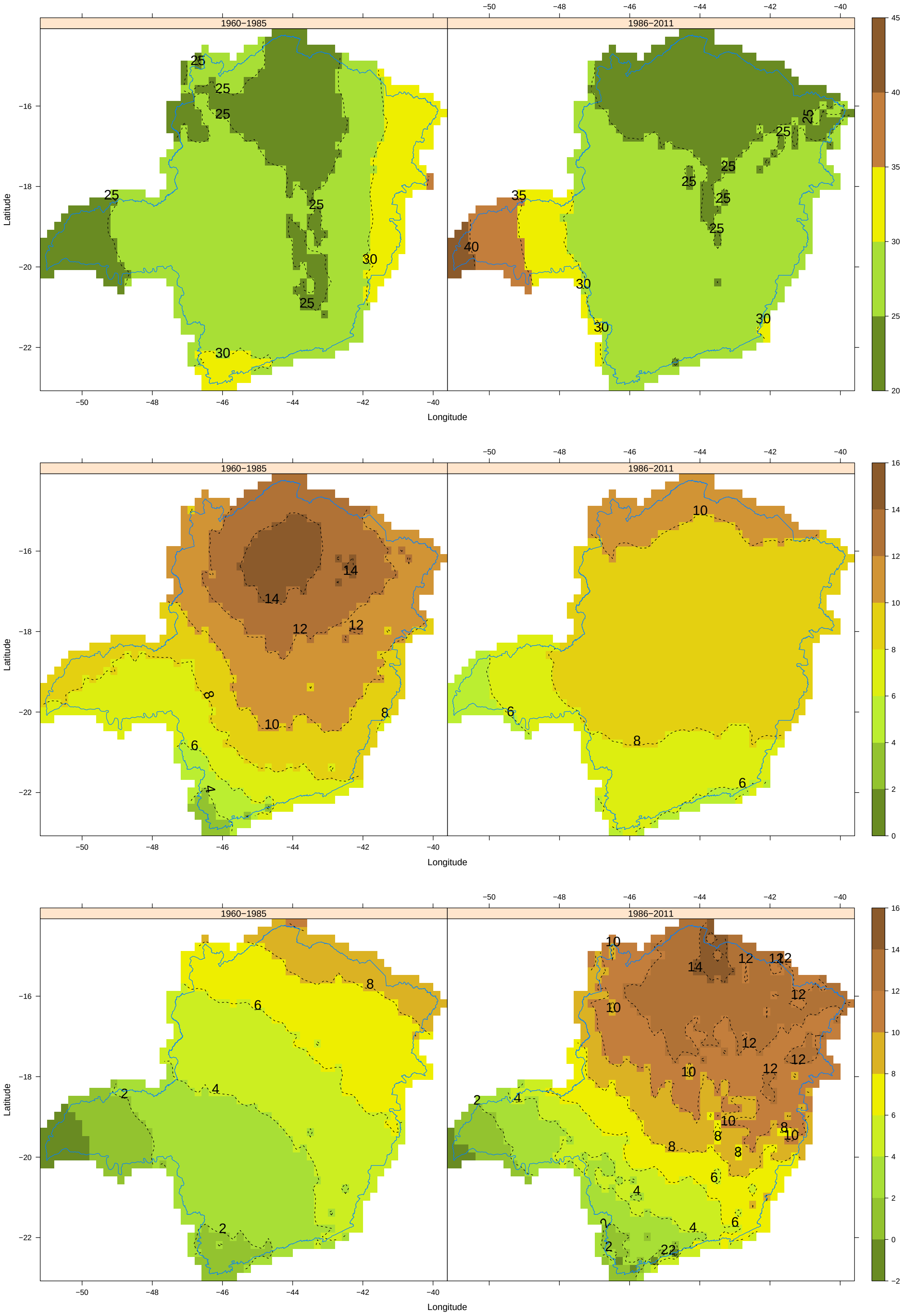


Figure 31: Contour maps of the number of weak (5-9 days), moderate (10-14 days) and intense (> 14 days) dry spells (top, middle and bottom maps, respectively), registered in October in Minas Gerais over the 1960-1985 and 1986-2011 periods.

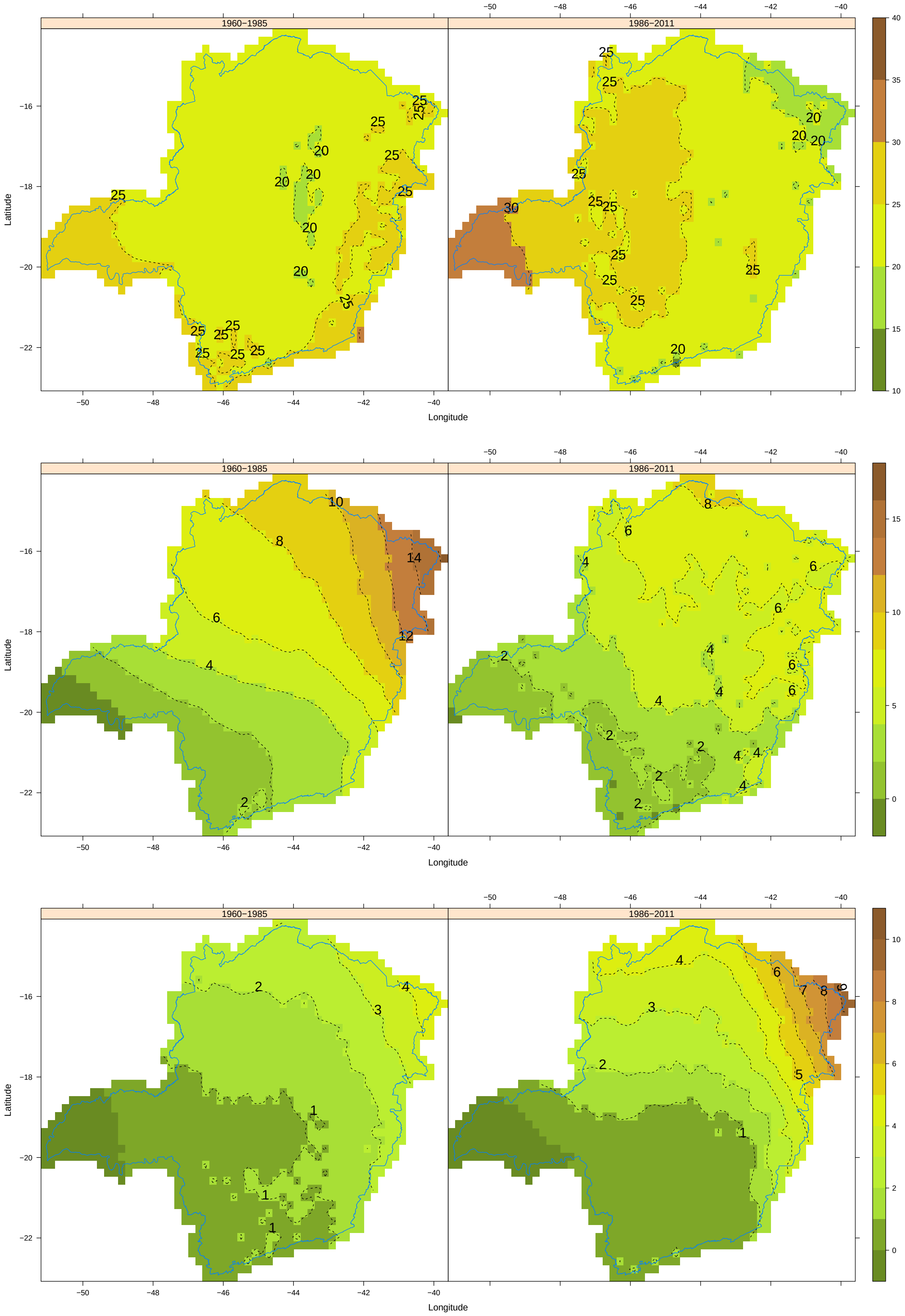


Figure 32: Contour maps of the number of weak (5-9 days), moderate (10-14 days) and intense (> 14 days) dry spells (top, middle and bottom maps, respectively), registered in November in Minas Gerais over the 1960-1985 and 1986-2011 periods.

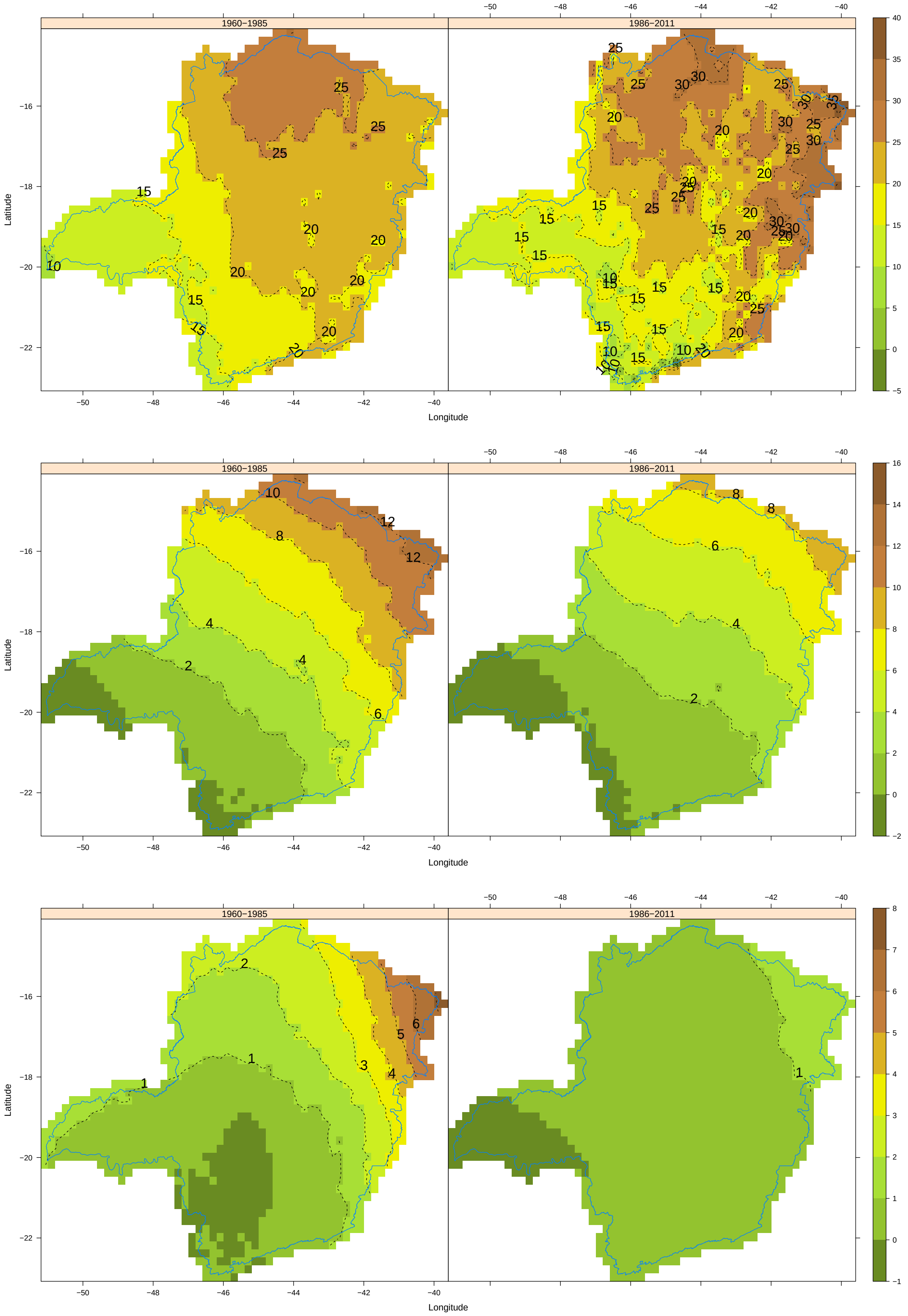


Figure 33: Contour maps of the number of weak (5-9 days), moderate (10-14 days) and intense (> 14 days) dry spells (top, middle and bottom maps, respectively), registered in December in Minas Gerais over the 1960-1985 and 1986-2011 periods.

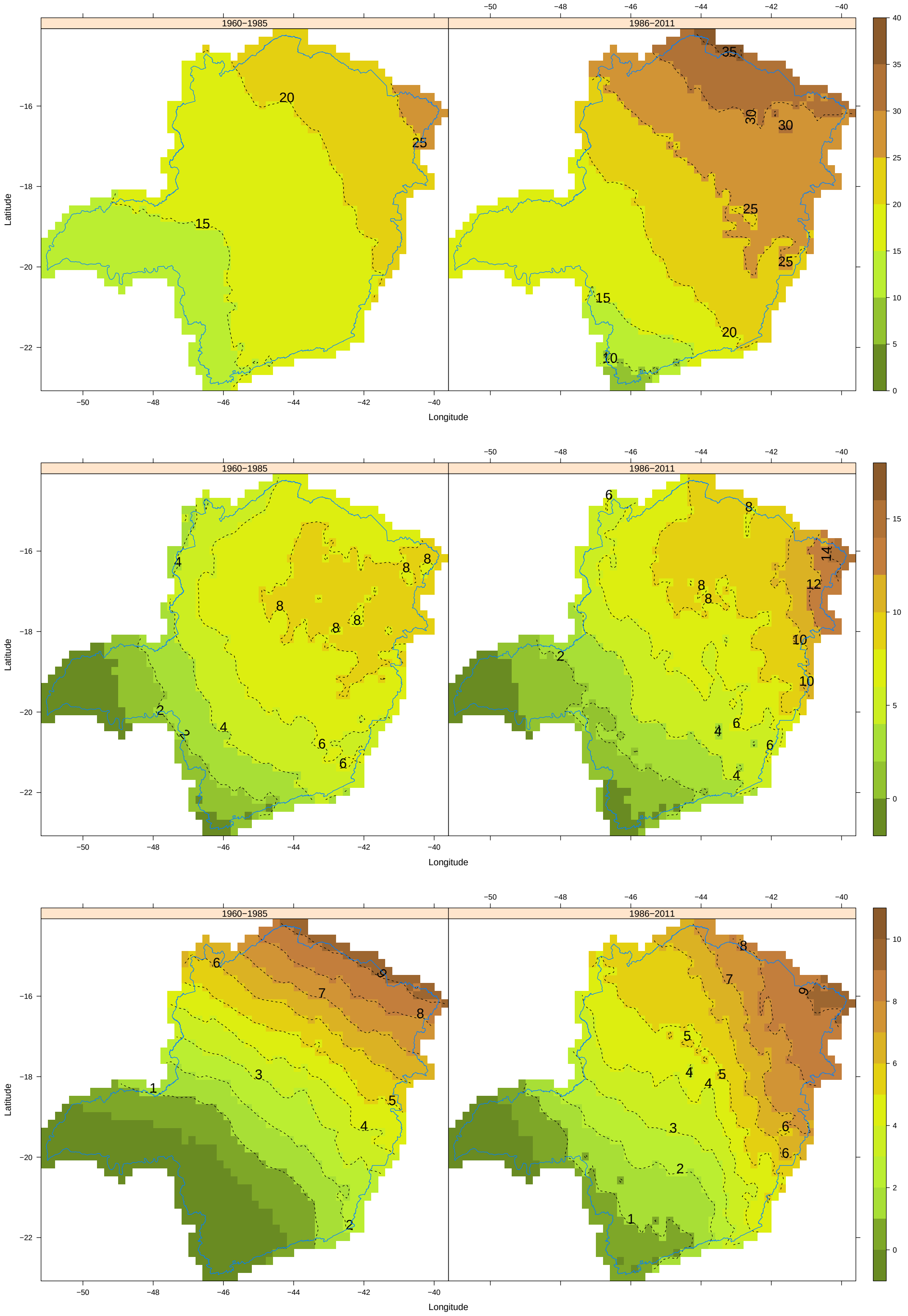


Figure 34: Contour maps of the number of weak (5-9 days), moderate (10-14 days) and intense (> 14 days) dry spells (top, middle and bottom maps, respectively), registered in January in Minas Gerais over the 1960-1985 and 1986-2011 periods.

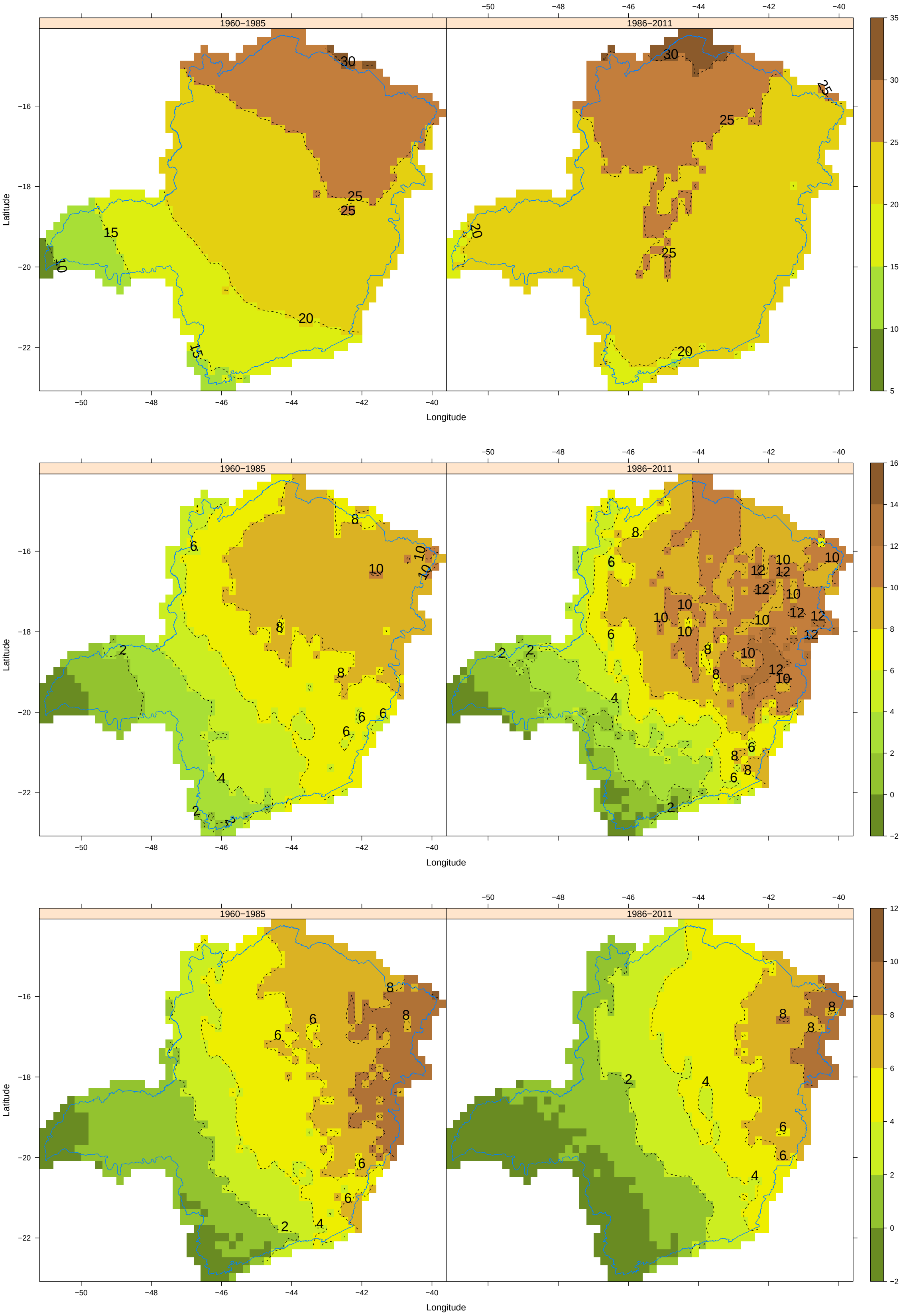


Figure 35: Contour maps of the number of weak (5-9 days), moderate (10-14 days) and intense (> 14 days) dry spells (top, middle and bottom maps, respectively), registered in February in Minas Gerais over the 1960-1985 and 1986-2011 periods.

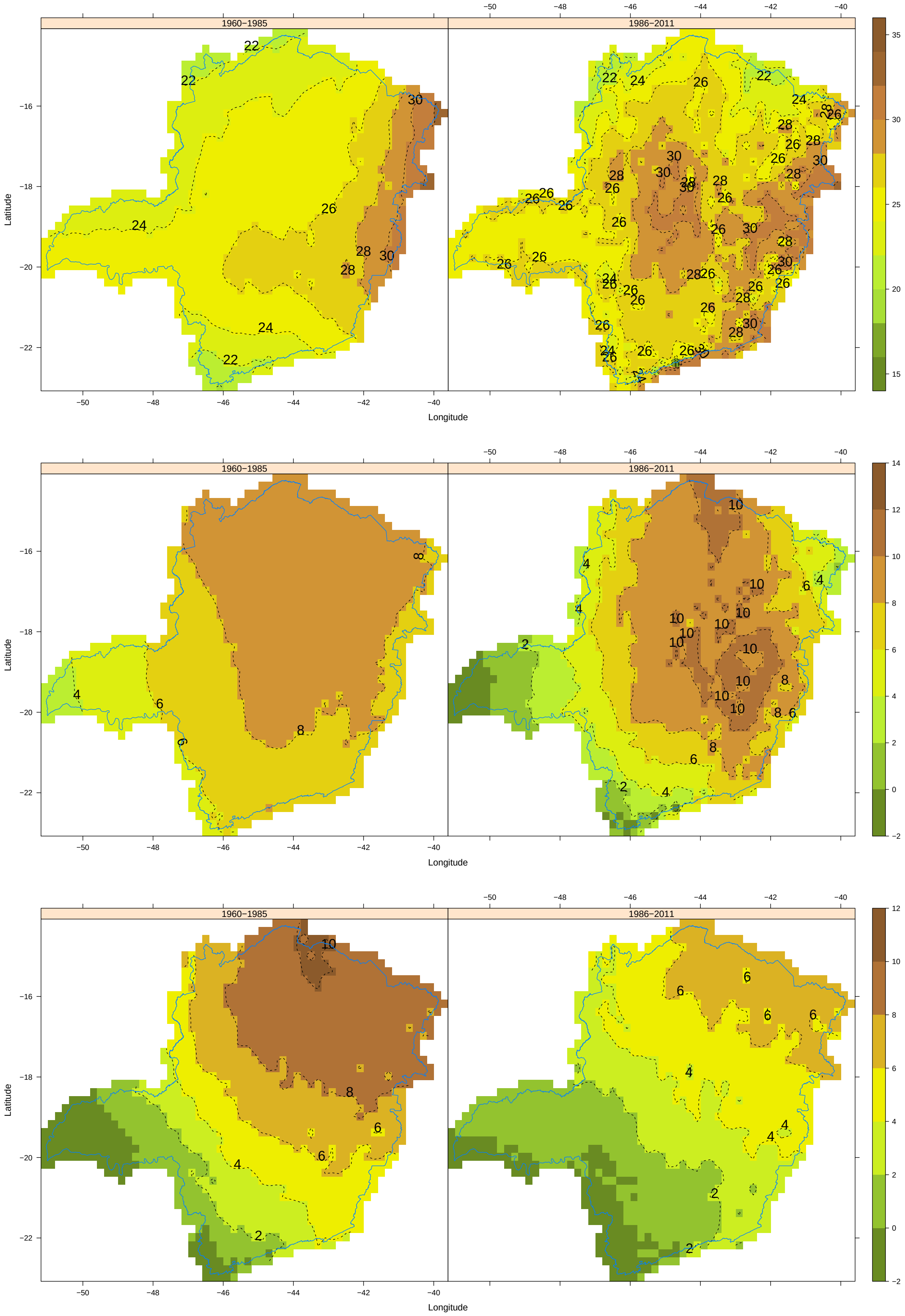


Figure 36: Contour maps of the number of weak (5-9 days), moderate (10-14 days) and intense (> 14 days) dry spells (top, middle and bottom maps, respectively), registered in March in Minas Gerais over the 1960-1985 and 1986-2011 periods.

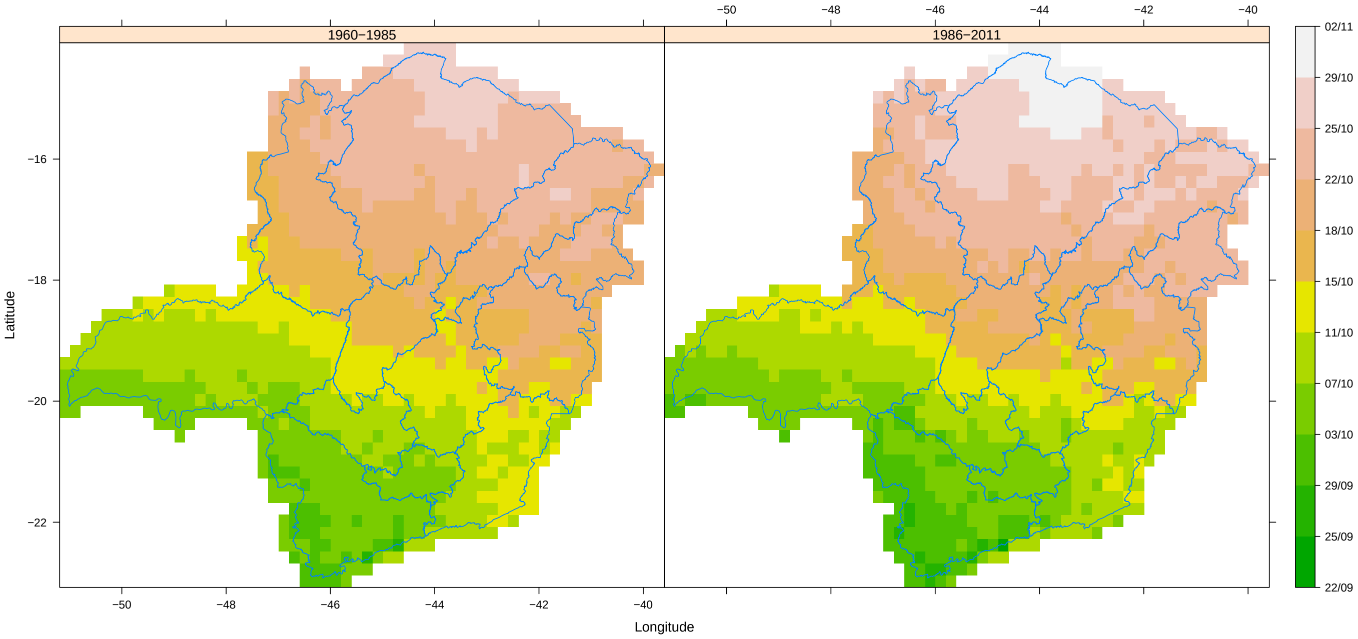


Figure 37: Surface maps of beginning of the rainy period in Minas Gerais averaged over the 1960-1985 and 1986-2011 periods.

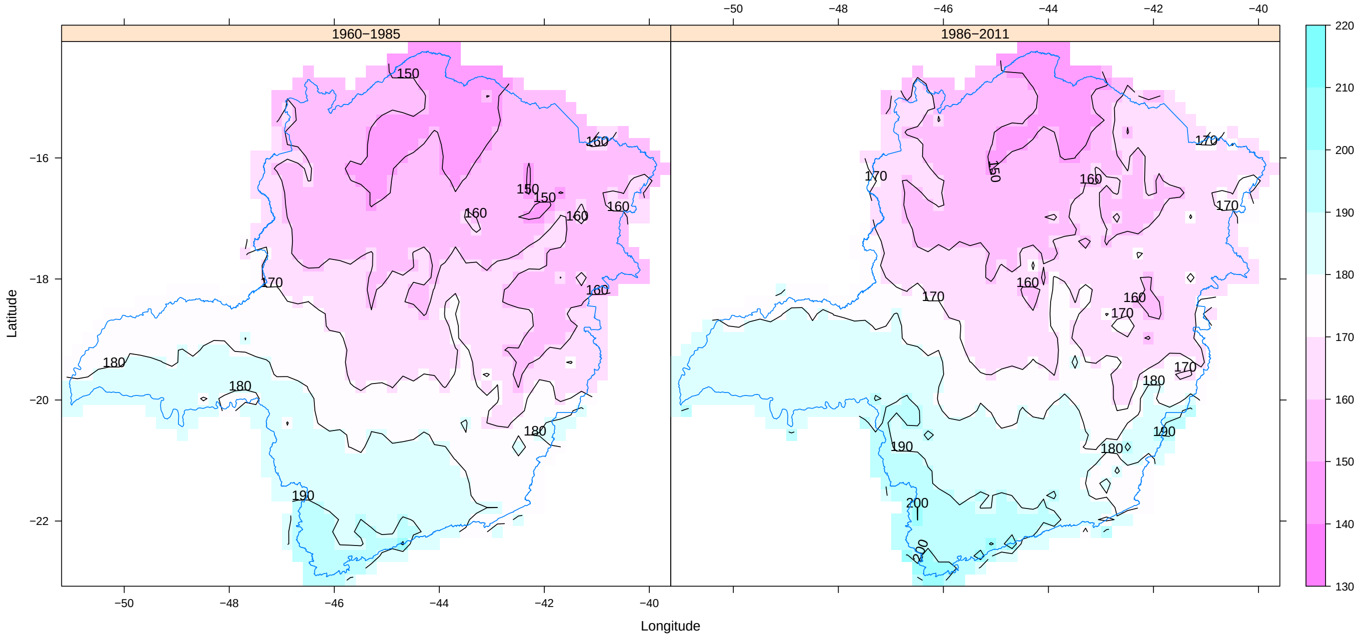


Figure 38: Contour maps of duration (days) of the rainy period in Minas Gerais averaged over the 1960-1985 and 1986-2011 periods.

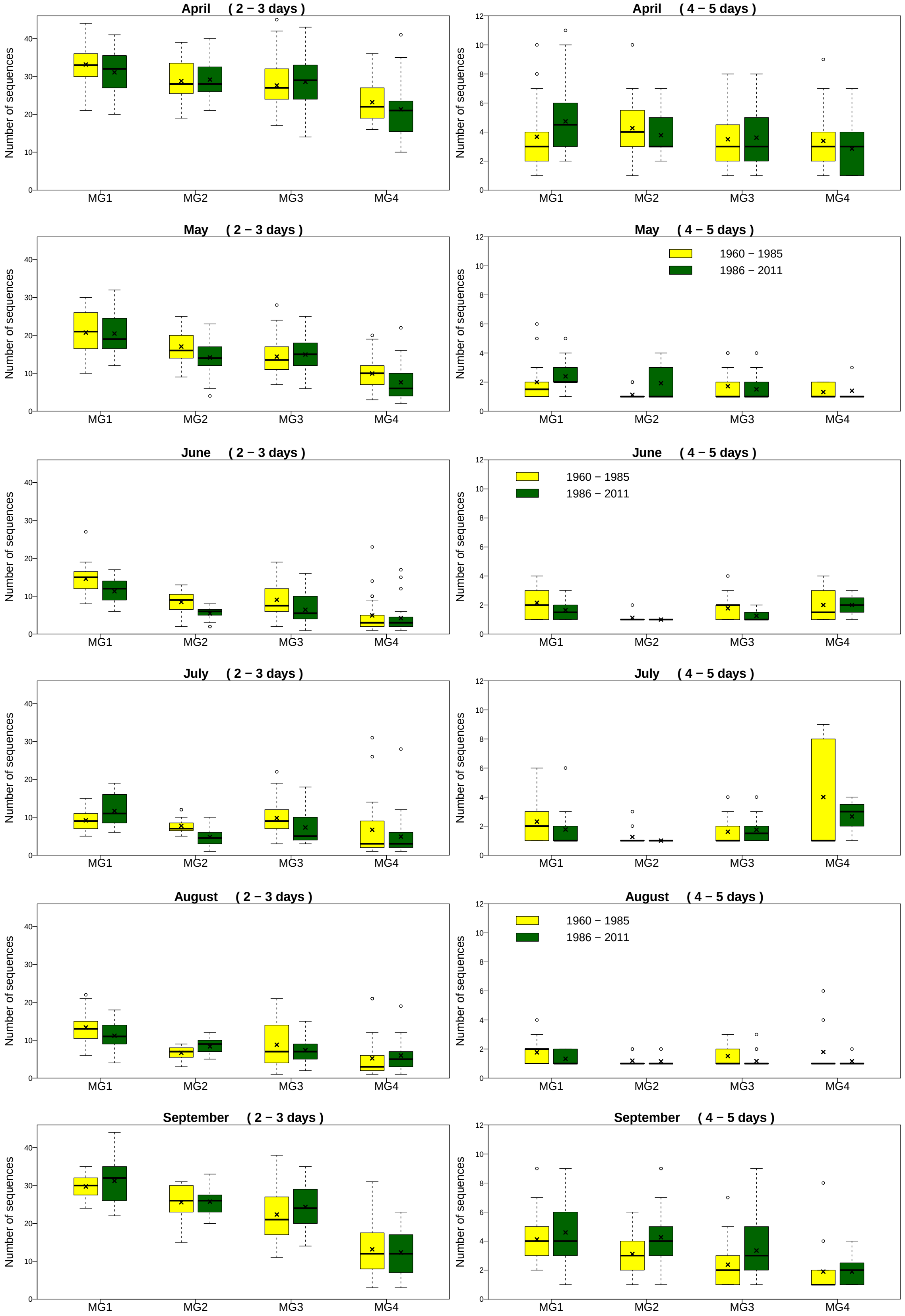


Figure 39: Boxplots of the number of wet spells by month during the dry season (April to September) in Minas Gerais, registered over the 1960-1985 and 1986-2011 periods.

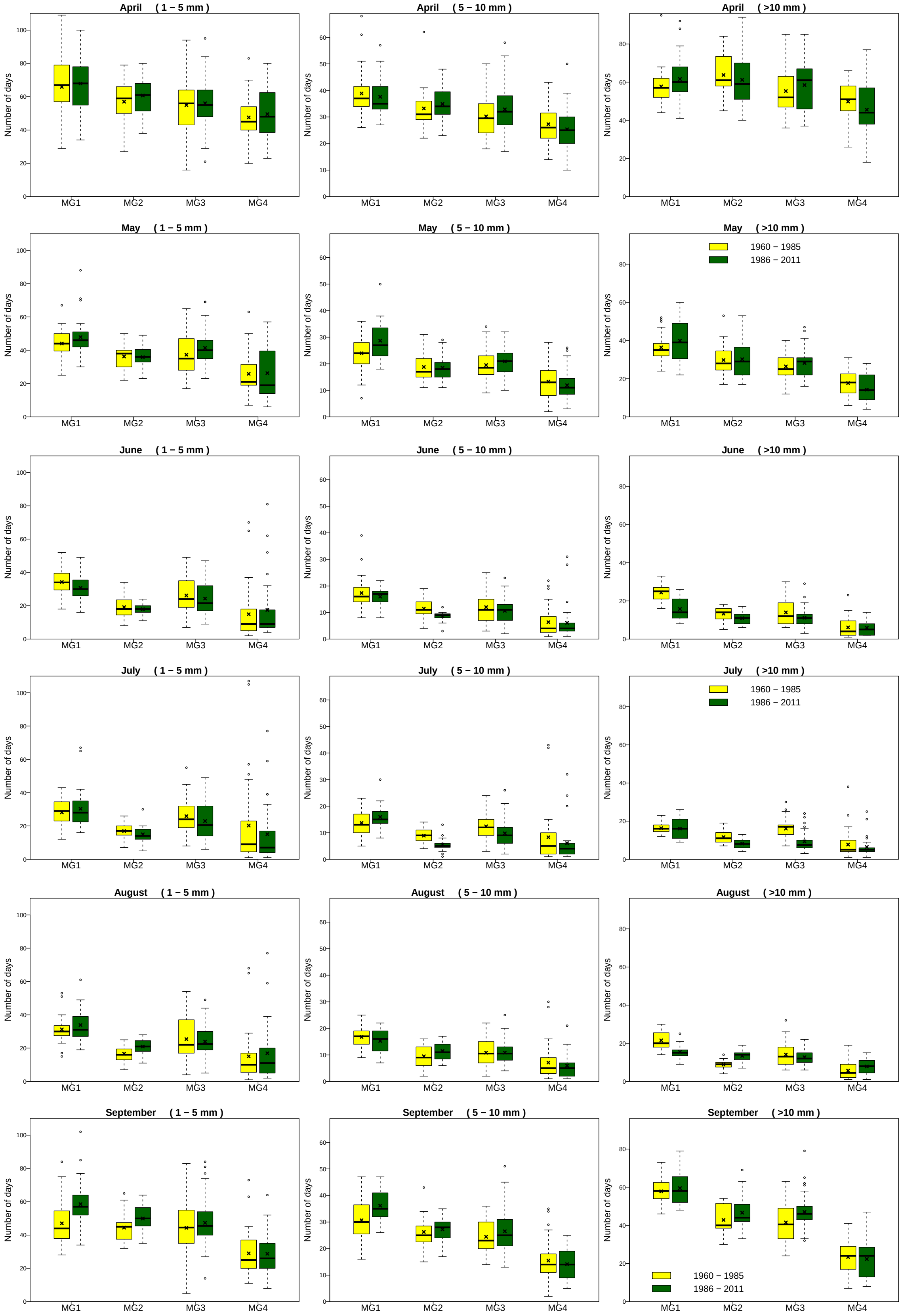


Figure 40: Boxplots of the number of wet days by month during the dry season (April to September) in Minas Gerais, registered over the 1960-1985 and 1986-2011 periods.

4.3 Water balance

The water balance in Minas Gerais over the 1960-1985 and 1986-2010 periods is summarized in Figure 41, with the state divided into the four macroregions described above. It was calculated following Thornthwaite's methodology (Thornthwaite, 1955), assuming an available water capacity (AWC) of 125 mm for all Minas Gerais. Some changes evidenced during the rainy season (October to March) were common to all macroregions, such as a decrease in the levels of available water for October, November and February and an increase in March, although the intensity of these changes varied according to the macroregion. For example, the decrease in October was more accentuated in macroregions 2 and 4, while in November it happened in macroregions 1 and 3. Macroregion 1, which includes the main coffee producing region in Minas Gerais (Sul de Minas), was the least affected by the decrease in available water. In fact, this macroregion evidenced an increase in its water surplus for the first trimester of the year from 1960-1985 to 1986-2011. There also was an increase in the water surplus in December for macroregions 3 and 4, which cover all the northern and eastern regions of the state (including Zona da Mata). However, the decrease in available water during January and February in these macroregions was greater than in the other ones.

Considering an AWC of 125 mm, Camargo (1977), cited by Pereira et al. (2008), suggested the following classification about coffee production suitability in terms of water supply:

Table 9: Coffee production suitability in terms of water supply.

Annual water deficit (mm)	Suitability
$DEF < 150$	suitable in terms of water supply, no irrigation needed
$150 \leq DEF < 200$	marginal suitability in terms of water supply, corrective irrigation will be needed sometimes
$DEF \geq 200$	unsuitable in terms of water supply, irrigation will be needed most of the time.

The results presented in Figures 42 and 43, following the above criteria, indicate that the slight increases in mean annual water deficit from 1960-1985 to 1986-2011 for the macroregions 1 and 3 (which include the main coffee producing regions at Sul de Minas and Zona da Mata), did not change their status of suitable coffee producing areas. On the other hand, coffee production in macroregions 2 and 4 (western and northern regions of the state) would be unsuitable (or very risky) at present without irrigation.

According to the surface map of mean annual water deficit anomalies (Figure 44), the mean annual water deficit increased over all regions of Minas Gerais, with the north and north-west regions having the higher increases from 1960-1985 to 1986-2011 (up to 160 mm less available water). In contrast, this increase was only moderate (up to 40 mm) for the main coffee producing regions.

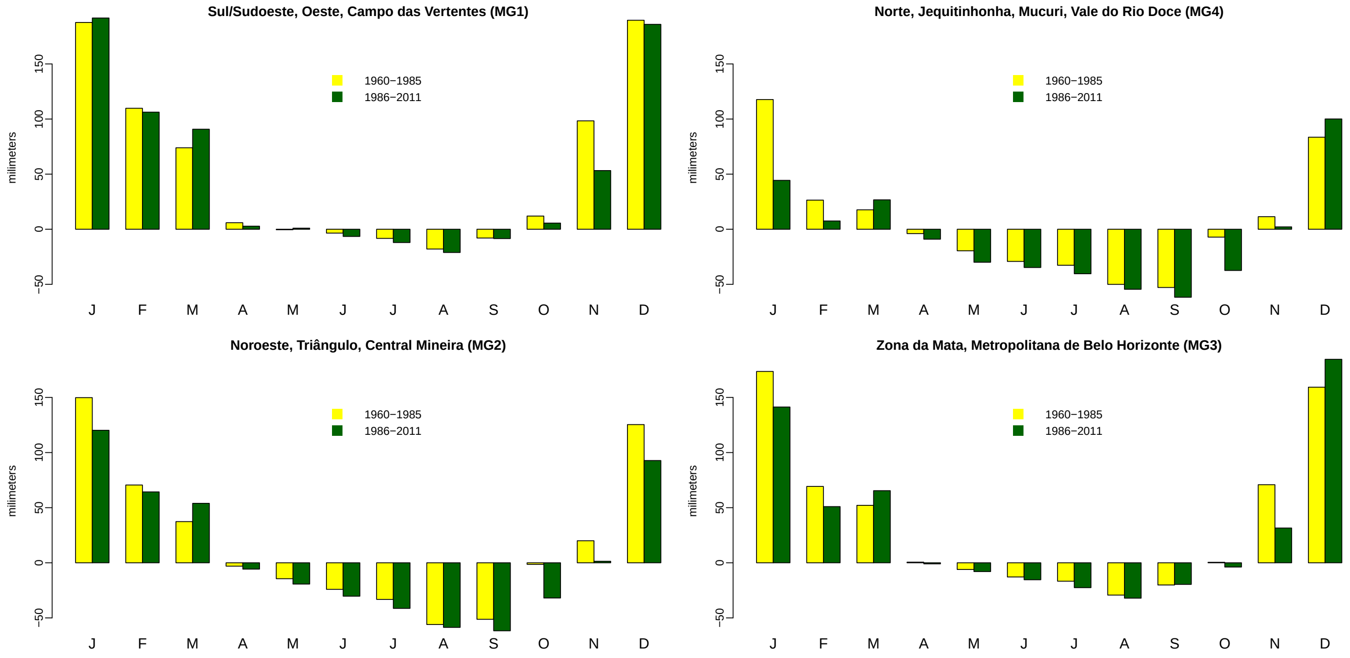


Figure 41: Water balance by macro region in Minas Gerais over 1960-1985 and 1986-2011 periods.

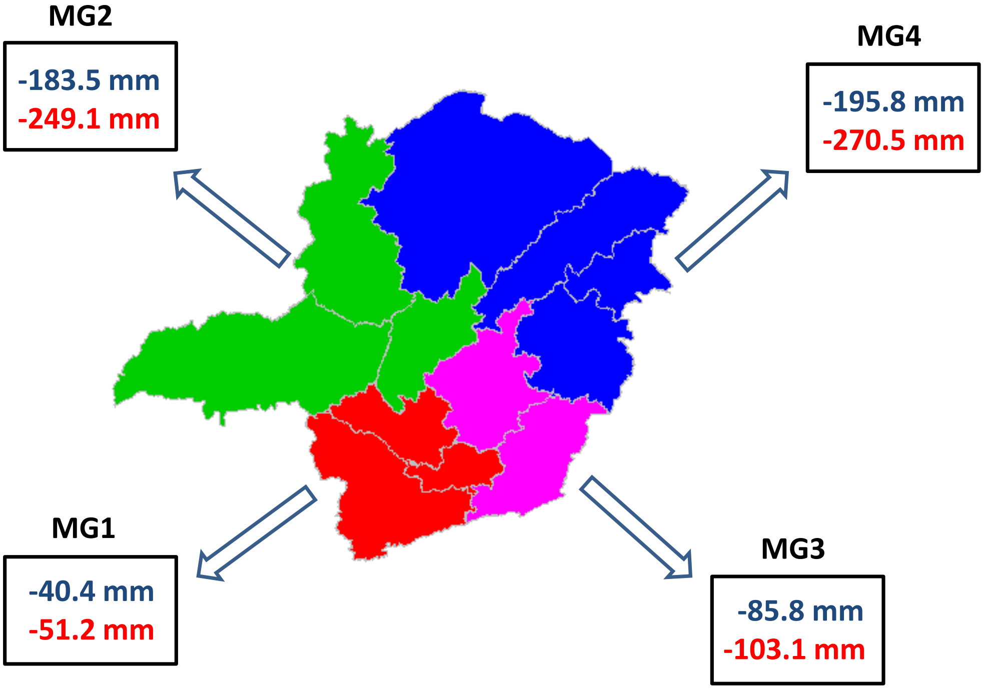


Figure 42: Mean annual water deficit in Minas Gerais by macroregion over 1960-1985 (values in blue) and 1986-2011 (values in red) periods.

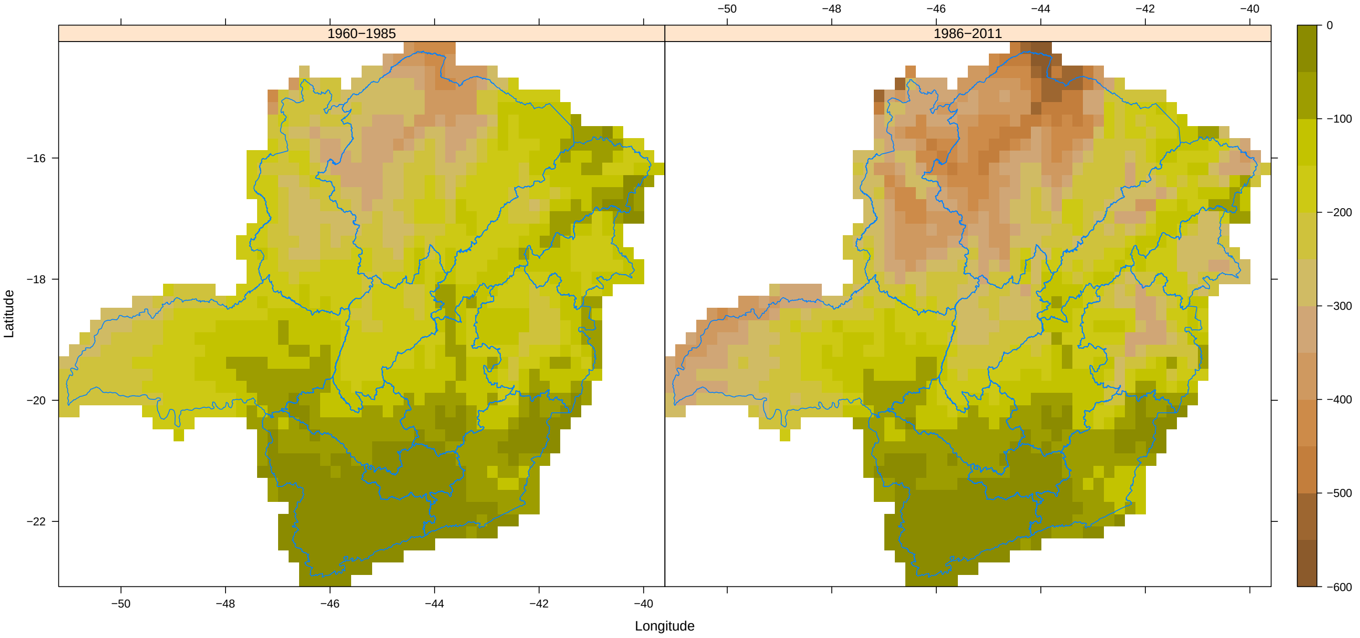


Figure 43: Surface map of mean annual water deficit (mm) in Minas Gerais over 1960-1985 and 1986-2011 periods.

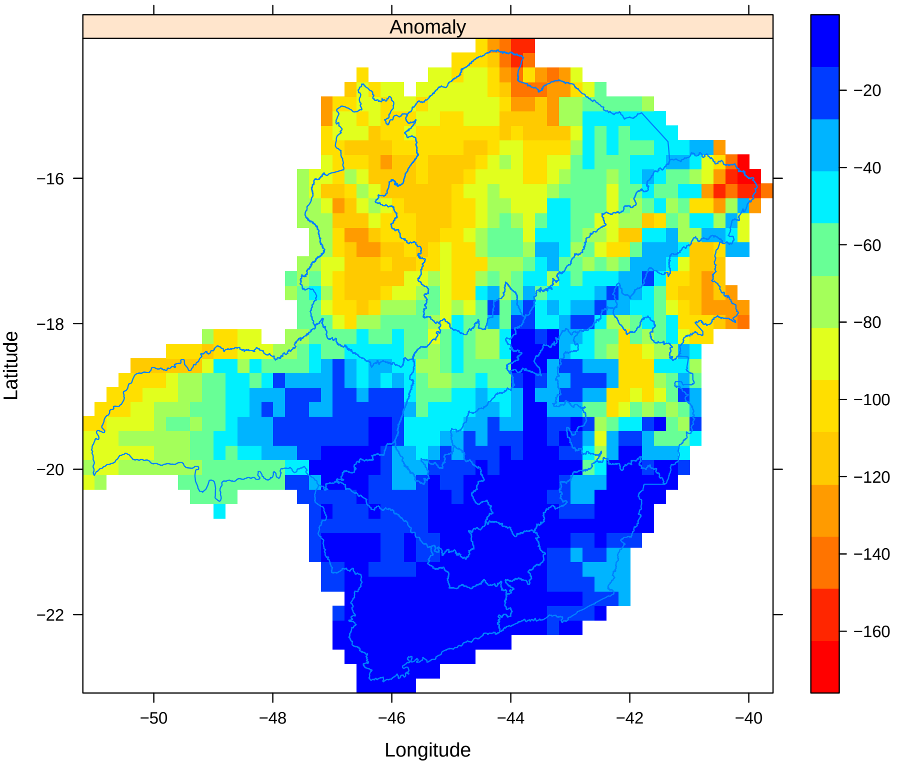


Figure 44: Mean annual water deficit anomalies (mm) in Minas Gerais (difference between the 1986-2011 and 1960-1985 periods).

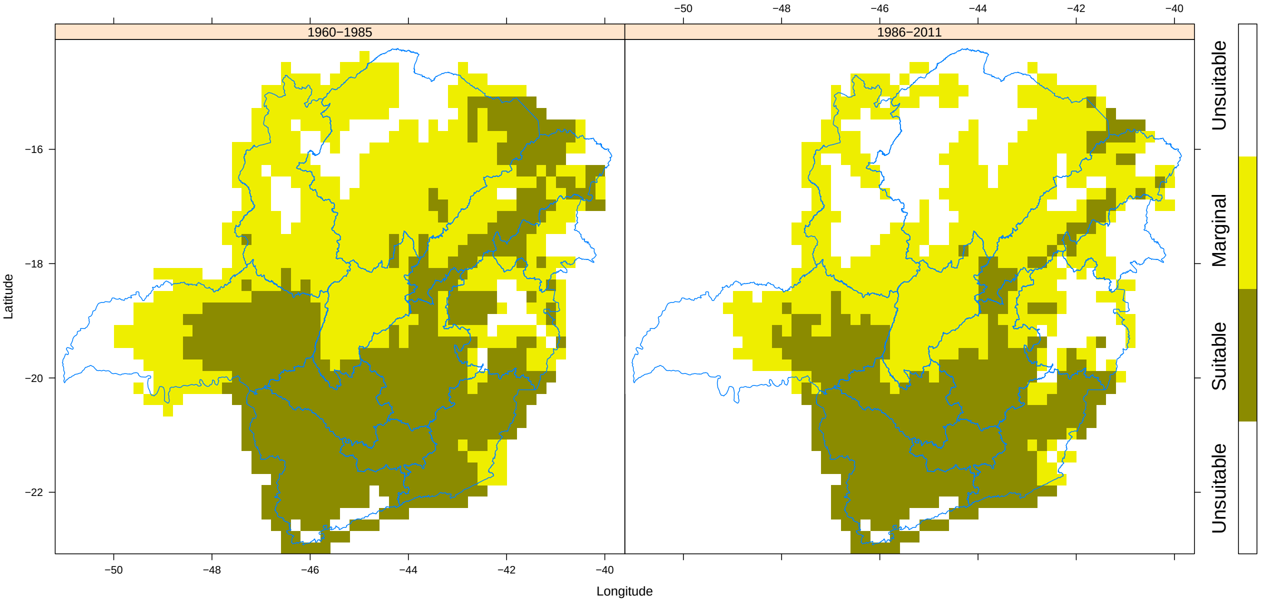


Figure 45: Suitability maps for C. arabica in Minas Gerais over 1960-1985 and 1986-2011 periods according to both, annual mean temperature and annual mean water deficit criteria. Suitable: $18 - 23$ ^oC and less than 150mm; marginal: $18 - 24$ ^oC and more than 150mm or $23 - 24$ ^oC and less than 150mm; unsuitable: less than 18^oC or more than 24^oC, and more than 150mm.

Mucuri/Jequitinhonha

Year	harvested coffee area (Ha)
1998	70170
2013	35863

Source: IBGE

Alto Jequitinhonha

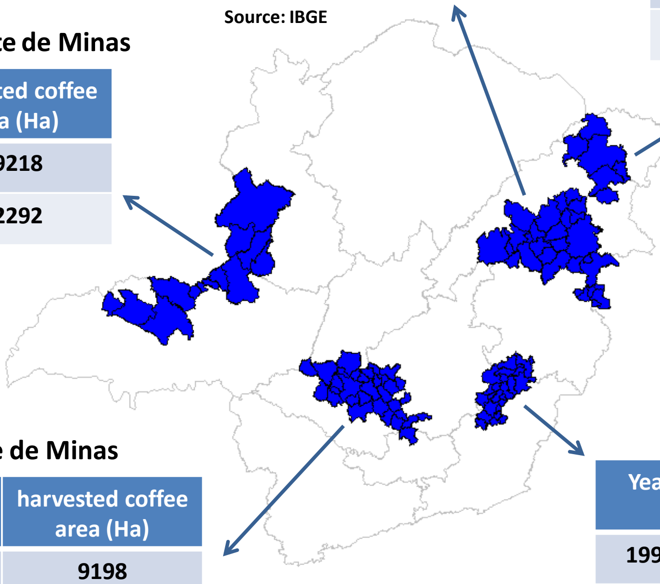
Year	harvested coffee area (Ha)
1997	2436
2013	332

Source: IBGE

Triangulo/Noroeste de Minas

Year	harvested coffee area (Ha)
1998	29218
2013	22292

Source: IBGE



Oeste de Minas

Year	harvested coffee area (Ha)
1997	9198
2013	2446

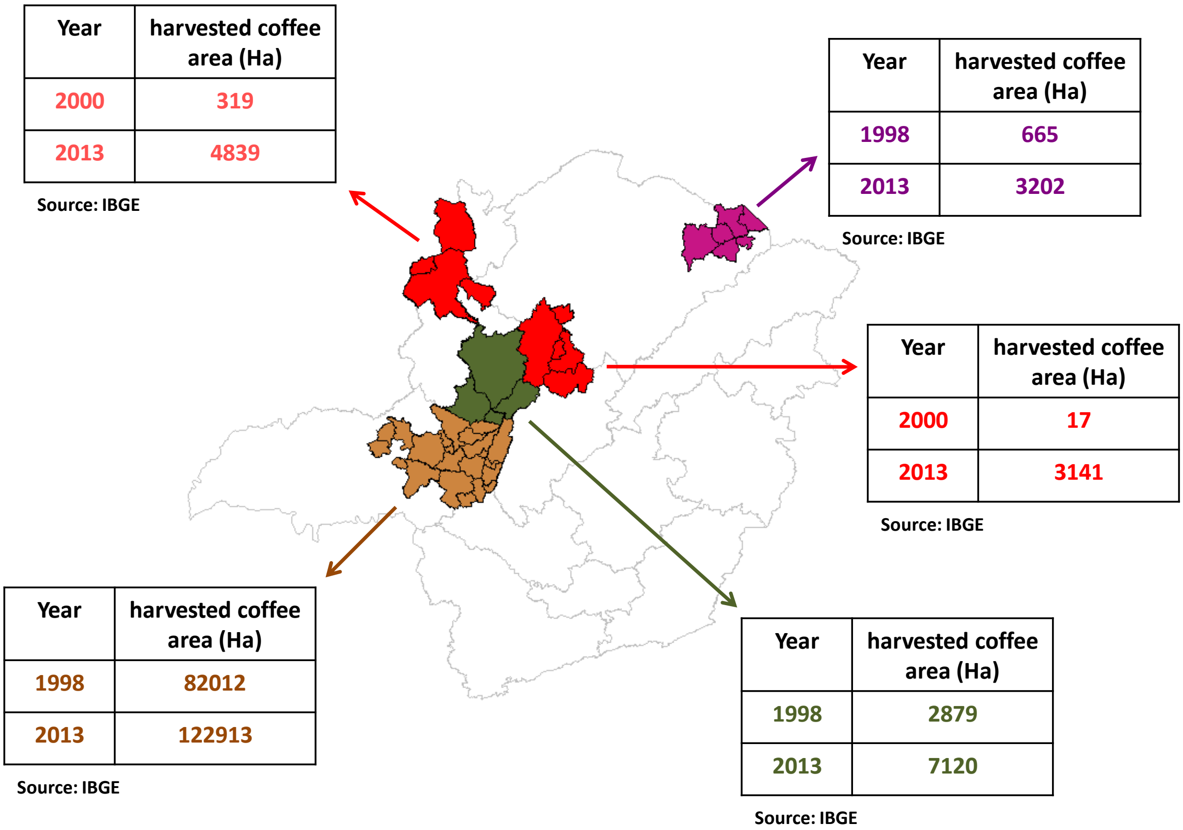
Source: IBGE

Zona da Mata

Year	harvested coffee area (Ha)
1998	19142
2013	11992

Source: IBGE

Figure 46: Regions of Minas Gerais with the largest reductions in coffee area during the last 15 years.



Year	harvested coffee area (Ha)
2000	319
2013	4839

Source: IBGE

Year	harvested coffee area (Ha)
1998	665
2013	3202

Source: IBGE

Year	harvested coffee area (Ha)
2000	17
2013	3141

Source: IBGE

Year	harvested coffee area (Ha)
1998	82012
2013	122913

Source: IBGE

Year	harvested coffee area (Ha)
1998	2879
2013	7120

Source: IBGE

Figure 47: Regions of Minas Gerais considered as marginal/unsuitable for C. arabica production where new coffee areas have been established in the last 15 years.

5 Concluding remarks

- The vast majority of stations over all regions of Minas Gerais experienced significant warming over the 1960-2011 period, with warm extremes increasing and cold extremes decreasing, and with the former being more accentuated than the latter.
- There are, however, differences in the magnitude of these temperature trends: stations in Zona da Mata had the lowest increases, while those in the north-west and western regions experienced the highest increases. Warming in the southern region of the state was moderate.
- The warming is happening in all seasons of the year, being more intense in spring and summer (SON and DJF trimesters).
- Differences were also verified in the distribution of the rainfall through the year, with increases in the accumulated precipitation during the JFM trimester in the Southern region and a decrease over all regions of Minas Gerais during the OND trimester (and as a consequence, warming is more intense during this period). On the other hand, the dry season (April to September) did not present significant changes in its levels of mean accumulated rainfall.
- The main coffee producing regions of Sul de Minas and Zona da Mata did not change their status of suitable coffee producing areas in terms of water supply even after their increases in mean annual water deficit from 1960-1985 to 1986-2011. On the other hand, irrigation is currently essential to produce coffee in most areas of the western and northern regions of the state.
- Moderate and intense dry spells in Minas Gerais are more frequent during the first trimester of the year, mainly in February, and its number is increasing more int the north, north-east and eastern regions of the state, although increases were also observed in the southern region in January and March.

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