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Climate change assessment for Minas Gerais – Brazil with emphasis on coffee areas
Part II – Climate Projections (2011 – 2070)

Final draft

Author:

Ramiro Ruiz Cárdenas
Federal University of Minas Gerais
Belo Horizonte – Brazil
email: ramiro@est.ufmg.br

Produced for the Initiative for Coffee & Climate

March 2015

Main contact: Stine Albrecht, E.D.E. Consulting
Coffee & Climate
c/o E.D.E. Consulting (affiliate of Hanns R. Neumann Stiftung)
Am Sandtorpark 4 • Coffee Plaza
20457 Hamburg • Germany
Email: stine.albrecht@hrnstiftung.org

Contact, Coffee & Climate Brazil: Máximo G. Ochoa
Associação Hanns R. Neumann Stiftung do Brasil
Av. Ananias Luiz de Avelar, 315 Centro
Santo Antônio do Amparo, Minas Gerais, Brazil
Email: max.ochoa@hrnstiftung.org
Tel:+ 55 35 38631186

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c/o E.D.E. consulting (affiliate of Hanns R. Neumann Stiftung) • Am Sandtorpark 4 • Coffee Plaza • 20457 Hamburg • Germany

1 Introduction

Located in the Southeast region of Brazil, Minas Gerais is by far its largest coffee producing state. The coffee harvest for the 2014/15 period was estimated in 23.34 million 60-kg bags (CONAB, 2015), which corresponds to 50.11% 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, with the inclusion of new areas in the north and north-west regions and a decrease in the north-east and central regions. However, coffee areas at the main coffee producing regions (Triângulo Mineiro, Sul de Minas and Zona da Mata) remained rather stable or with a little tendency to increase. Coffee production in the state during this period was always spread over at least 70% of its 853 municipalities, covering all mesoregions[1] (see Ruiz-Cárdenas, 2013, for a detailed characterization of the main coffee producing regions in Minas Gerais).

Weather related risks threaten the security of coffee growers and their families every year. Recent examples are the severe drought occurred in 2014 or the frequent damages by frost and hail events 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 was 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 both, the main coffee zones and the key periods of the year linked to the main phenological phases of coffee plant. It was 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 was divided in two main phases. Phase one analyzed the recent past climate in the state and it was the subject of a first report (Ruiz-Cárdenas, 2013). The present report summarizes the results of the second phase of the study, which analyzed climate projections up to 2070 in Minas Gerais from a high resolution regional climate model.

The rest of this report is organised as follows. Section 2 summarizes methodological aspects of the study. The main results are presented and discussed in section 3. Concluding remarks and future work are stated in Section 4.

1.1 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 plant. The schematic representation of the phenological stages of arabica coffee under Brazilian conditions is shown in Figure 1. 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.

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

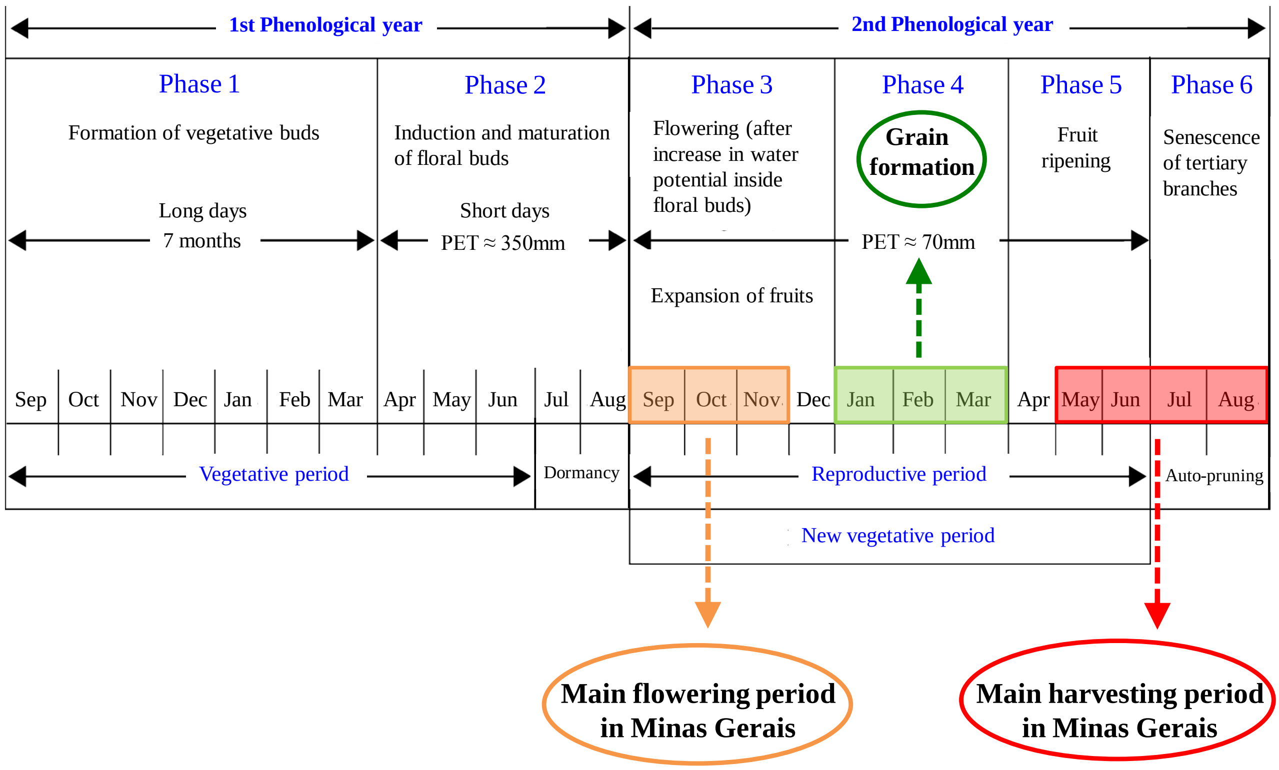


Figure 1: Schematization of the phenological phases of C. arabica under Brazilian conditions. Adapted from Camargo and Camargo (2001).

Specifically for Minas Gerais, the main flowering period usually spans 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), very high temperatures during this phase, especially if associated with an intense water deficit, may cause abortion of flowers.

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.

The main harvesting period spans from May to August. The time needed to complete ripening of fruits will depend on the weather conditions. Moderate water deficit during this phase benefits coffee quality. However, intense water deficit and high temperatures will accelerate ripening and will affect the fermentation processes inside fruits, leading to loss of beverage quality. On the other hand, with low temperatures the development of fruits is 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.

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

2 Methodology

2.1 The climate model

Developing climate change scenarios at regional scale can be considered as a first step for the understanding of climate impacts under global warming conditions, directed to the provision of information to be used for vulnerability assessments, and for the design of measures and strategies for climate change adaptation (Marengo et al., 2012). Global Climate Models (GCMs) are the main tools for studying long-term climate variability and change. However, these models have rather coarse resolution, which poses limitations to the explicit simulation of mesoscale processes as well as to the representation of land surface characteristics. Increases in spatial resolution can be achieved by downscaling techniques, for example nesting high resolution Regional Climate Models (RCMs) in GCMs conditions; or through statistical downscaling of GCM simulations (Chou et al., 2012). Particularly, climate change projections derived from RCMs are acknowledged as useful for impact studies because of the subcontinental nature of the patterns involved. Due to its limited domain, RCMs allow a more detailed representation of the structure of weather systems as well as the explicit simulation of mesoscale processes. However, it is worth to note that the climate generated from a regional model is strongly dependent upon the lateral boundary conditions (Chou et al., 2012).

Climate projections over Minas Gerais were evaluated using a modified version of the Eta-CPTEC regional Model driven by the UK Met Office Hadley Centre HadCM3 global model, hereinafter refered as the Eta-HadCM3 nested model (see details below). A previous version of the Eta-HadCM3 model, with 40km horizontal resolution and nested with four members of the driving model, had been used by Marengo et al. (2012) to analyse future changes in temperature, atmospheric circulation and aspects of the hydrological cycle over South America and over the time slices 2011-2040, 2041-2070 and 2071-2100 relative to the baseline climatology of 1961-1990. In this work runs were performed over South America with a 20km horizontal resolution and with changes in the CO_2 concentration up to the year 2100, consistent with the driving model. Projections were generated at the Brazilian Center for Weather Forecasts and Climate Studies (CPTEC) for the "present day" (1961-1990) and for the future (2010-2100) for the IPCC SRES A1B scenario (IPCC, 2000). The regional and driving models used are briefly described as follows.

The HadCM3 global model

The lateral boundary conditions used to drive the Eta-CPTEC regional model were supplied by the UK Met Office Hadley Centre coupled climate model version 3 - HadCM3 (Collins et al., 2001; Gordon et al., 2000). The atmospheric component of the model has 19 levels with a horizontal resolution of 2.5 degrees of latitude by 3.75 degrees of longitude, which produces a global grid of 96 x 73 grid cells. This is equivalent to a surface resolution of about 417 km x 278 km at the Equator, reducing to 295 km x 278 km at 45 degrees of latitude.

HadCM3 has been used extensively for climate prediction and climate sensitivity studies. It also was one of the major models used in the IPCC Third and Fourth Assessments, and also contributed to the Fifth Assessment. Its good simulation of current climate without using flux adjustments[1] was a major advance at the time it was developed and it still ranks highly compared to other models in this respect (Reichler and Kim, 2008).

[1] artificial adjustments applied to climate model simulations to prevent them drifting into unrealistic climate states

The Eta-CPTEC regional model

Since 1996, the Eta Model (Mesinger et al., 1988) has been operationally used to investigate the predictability of weather at different time scales - seasonal, monthly and weekly over South America (Chou et al., 2005). Comparison of the Eta-CPTEC seasonal forecasts with the CPTEC GCM and observed climatologies showed that dynamical downscaling through the regional model provides considerable improvement and additional useful information over the driver model (Marengo et al., 2012). The Eta-CPTEC regional model (configured with 40-km horizontal resolution and 38 layers in the vertical) has shown to reproduce "present climate" (the 1961-1990 period) reasonably well when forced by HadCM3 (Chou et al., 2012). Outputs from this model were also useful driving an hydrology model to assess future changes in the hydrology of an important river basin in southeast Brazil (Viola et al., 2014).

Some modifications were made to Eta-CPTEC to be adapted for climate change runs. A detailed description of the Eta-CPTEC configuration, including those modifications, can be found in Marengo et al. (2012) and references therein.

Bias correction

When compared to observations, the regional simulations exhibit systematic errors which might be related to the physics of the RCMs (e.g., convective schemes, land surface characterization) and the lateral boundary conditions, as well as possible biases inherited from the driving model. Therefore, a statistical bias correction technique was applied to the climate change simulations from the Eta-HadCM3 model. Modeled and observed daily values of mean, minimum and maximum temperature and total monthly precipitation were used to construct transfer functions for the period 1961-1990, which were then applied to correct model outputs at the 2011-2040 and 2041-2070 periods using a quantile mapping approach as described in (Boé et al., 2007). The *R* package "qmap" (Gudmundsson, 2014) was used in this process.

3 Results

This section presents and discusses projected spatio-temporal variability maps of minimum temperature, maximum temperature and precipitation, at regional level, in Minas Gerais, for the 2011-2040 and 2041-2070 periods, as derived from the Eta-HadCM3-20km model runs, under a A1B scenario. Climate anomalies for these periods (with respect to the 1961-1990 base climatology) are also presented. Additionally, regions in the state are clustered according to the intensity of changes in future climate. Finally, projected suitability maps for *C. arabica* and *C. canephora* in Minas Gerais are constructed. All maps were generated using the *R* statistical language (R Development Core Team, 2014).

3.1 Projected temperatures

3.1.1 Maximum temperature

Projected surface maps of mean maximum temperature in Minas Gerais by trimester, averaged at the 2011-2040 and 2041-2070 periods, are presented in Figures 2 and 3. Maps for the 1961-1990 period, simulated from the same climate model, are also included as a reference. The warming behavior is evident in all regions of the state and for all seasons of the year, being more accentuated at the trimesters with higher temperatures. Areas with very high temperatures are projected to increase more dramatically in the north and western regions of the state, when compared to the increases projected at "Zona da Mata" and "Sul de Minas" (main coffee producing mesoregions in the south and southeast). In fact, the mean maximum temperature anomalies (with respect to the 1961-1990 climatology) for the two projected periods, presented in Figure 4, shows a strong SE-NW gradient during the September to November period (main coffee flowering period), with the highest anomaly values (up to 4.5^{o}C in 2070) at "Triângulo Mineiro", "Norte de Minas" and "Noroeste de Minas" mesoregions. For the December to February period, the warming gradient grows mainly in the north-east direction, with its highest values found at "Norte de Minas" and "Jequitinhonha" mesoregions. All changes are more intense after 2040.

The clustering of mesoregions in Minas Gerais, according to their mean maximum temperatures during the SON trimester in the two projected periods, and considering only pixels at altitudes between 600 and 1,200 m.a.s.l.[2], is presented in Figure 5. The cluster with higher mean maximum temperatures is, at the same time, the one with more intense projected increases for this variable, having positive anomalies of 1.7^{o}C in average in the 2011-2040 period, which rises to 3.5^{o}C in 2041-2070. It is formed by mesoregions of the north and western parts of the state. On the other hand, projected increases in the cluster of lower mean maximum temperatures, formed by "Sul de Minas", "Campo das Vertentes" and "Zona de Mata" mesoregions, in the southern part of the state, were of 1^{o}C and 2^{o}C in the two projected periods, respectively. A third cluster formed mainly by the eastern mesoregions ("Jequitinhonha", "Vale do Mucuri" and "Vale do Rio Doce"), as well as "Oeste de Minas" and "Belo Horizonte", presented intermediate increases in the mean SON maximum temperatures, averaging 1.2^{o}C and 2.6^{o}C in 2011-2040 and 2041-2070 periods, respectively.

These results are in line with the warming behavior found in a previous analysis of observational data in Minas Gerais during last five decades (Ruiz-Cárdenas, 2013), which pointed out a more intense warming trend in the north and eastern regions of the state during the warm season.

3.1.2 Minimum temperature

Similarly, Figures 6 and 7 present the projected surface maps of mean minimum temperature in Minas Gerais by trimester, averaged at the 2011-2040 and 2041-2070 periods. A warming behavior is also projected for this variable in all regions of the state and for all seasons of the year. Quartely mean minimum temperature anomalies for the two projected periods during the cold season (March to August) is presented in Figure 8. It shows a clear W-E gradient, with the highest anomaly values (up to 4^{o}C in 2070) at "Triângulo Mineiro" mesoregion. As with maximum temperatures, changes are more intense after 2040.

The clustering of the mesoregions in Minas Gerais, according to their mean minimum temperatures, during the coldest trimester (July to August), for the two projected periods, is presented in Figure 9. Unlike maximum temperatures, in this case all the three formed clusters project similar average increases in their mean minimum temperatures, with positive anomalies ranging from 1.7 to 1.8^{o}C in average for the 2011-2040 period and from 2.5 to 2.7^{o}C for the 2041-2070 period.

It is worth to note that with an average increase of more than 2^{o}C in the minimum temperature of the coldest trimester in the southern part of the state, the risk of frost in this region is expected to be reduced in the future, mainly after 2040.

[2]According to Bernardes et al. (2012), above 90% of the coffee producing areas in Minas Gerais in 2007 was located at altitudes between 600 and 1200 meters above sea level (m.a.s.l.).

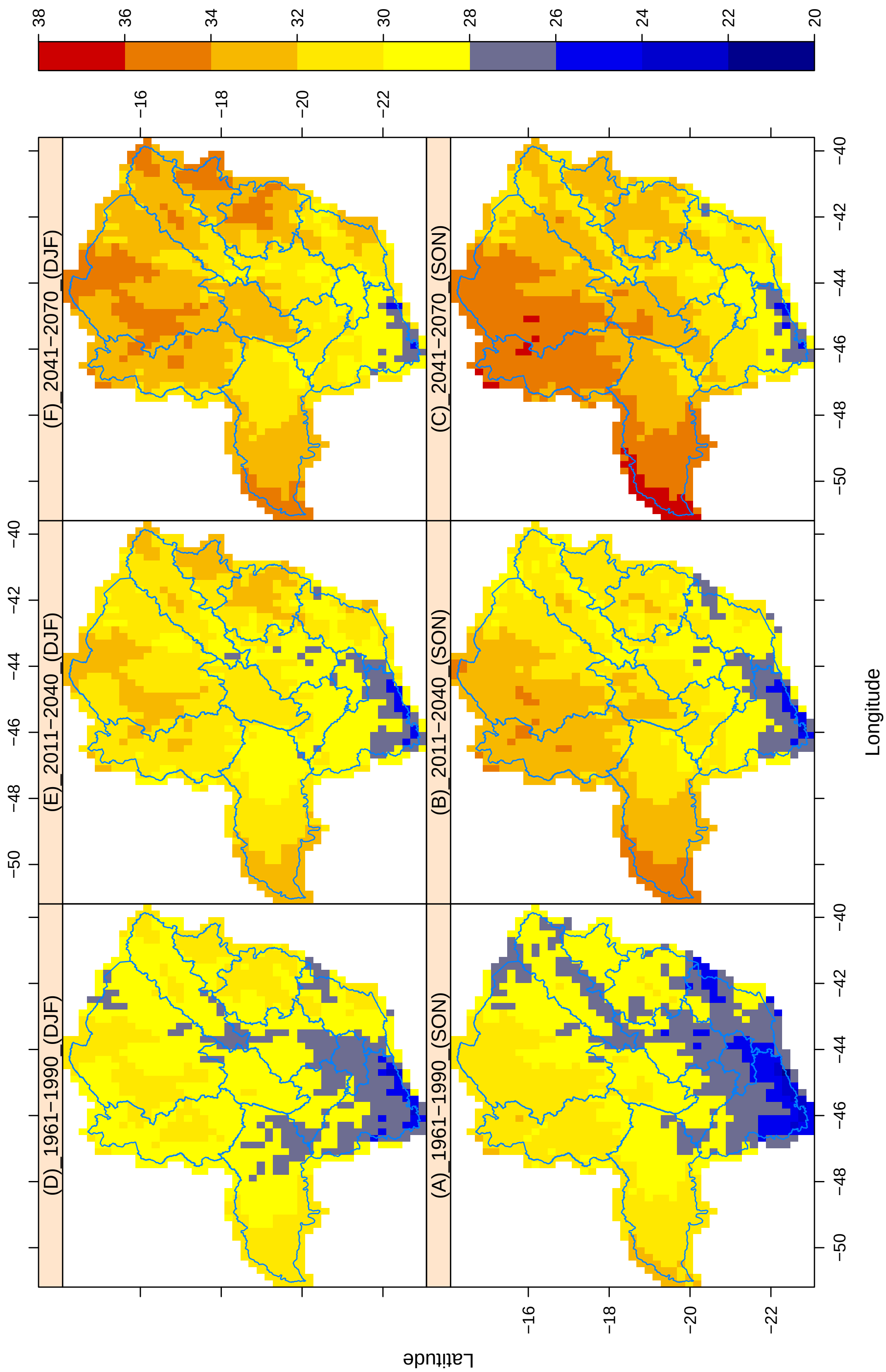


Figure 2: Eta-HadCM3-20km climate projections for mean maximum temperature (°C) during the warmest trimesters in Minas Gerais.

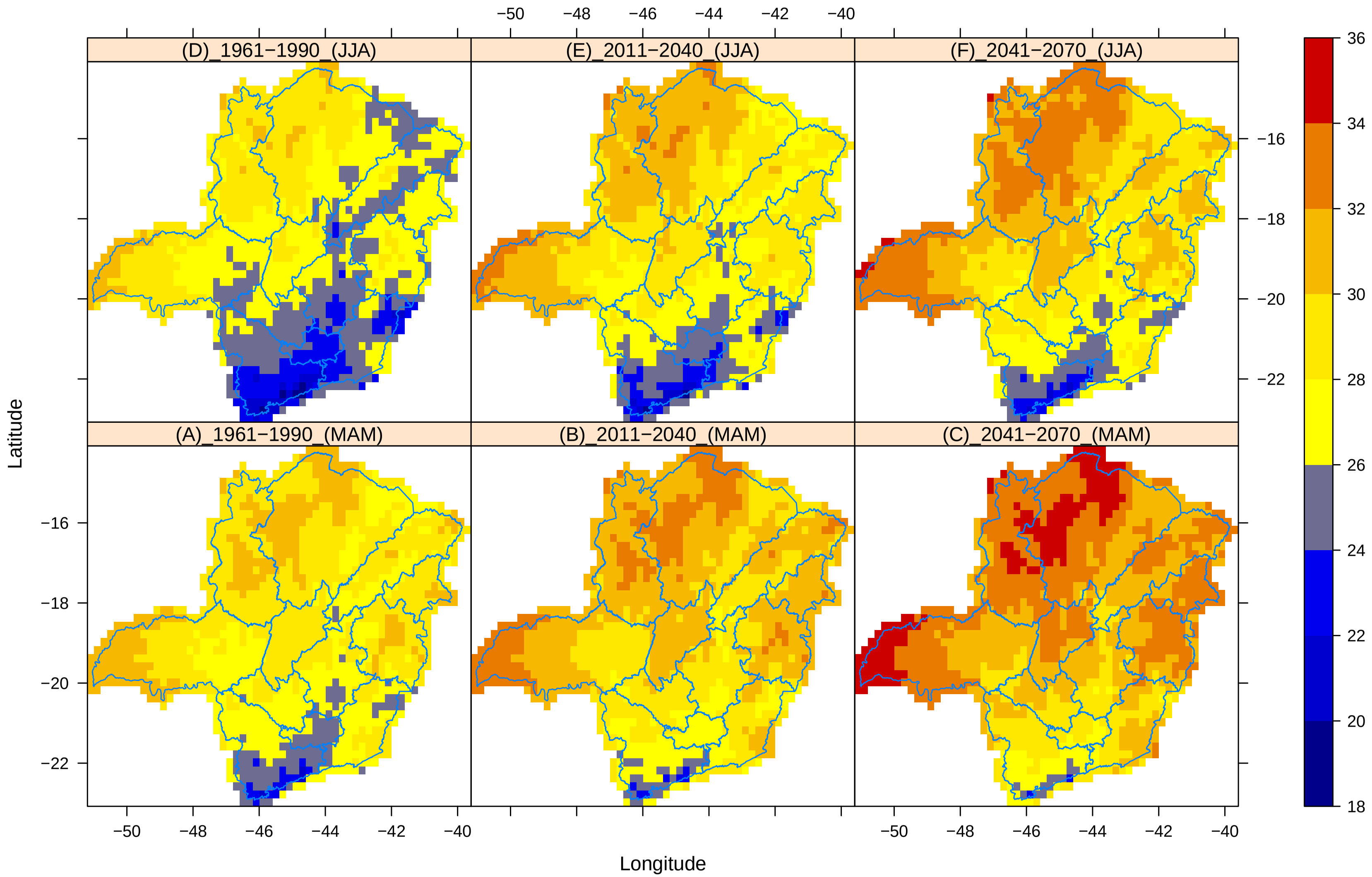


Figure 3: Eta-HadCM3-20km climate projections for mean maximum temperature (^{o}C) during the coldest trimesters in Minas Gerais.

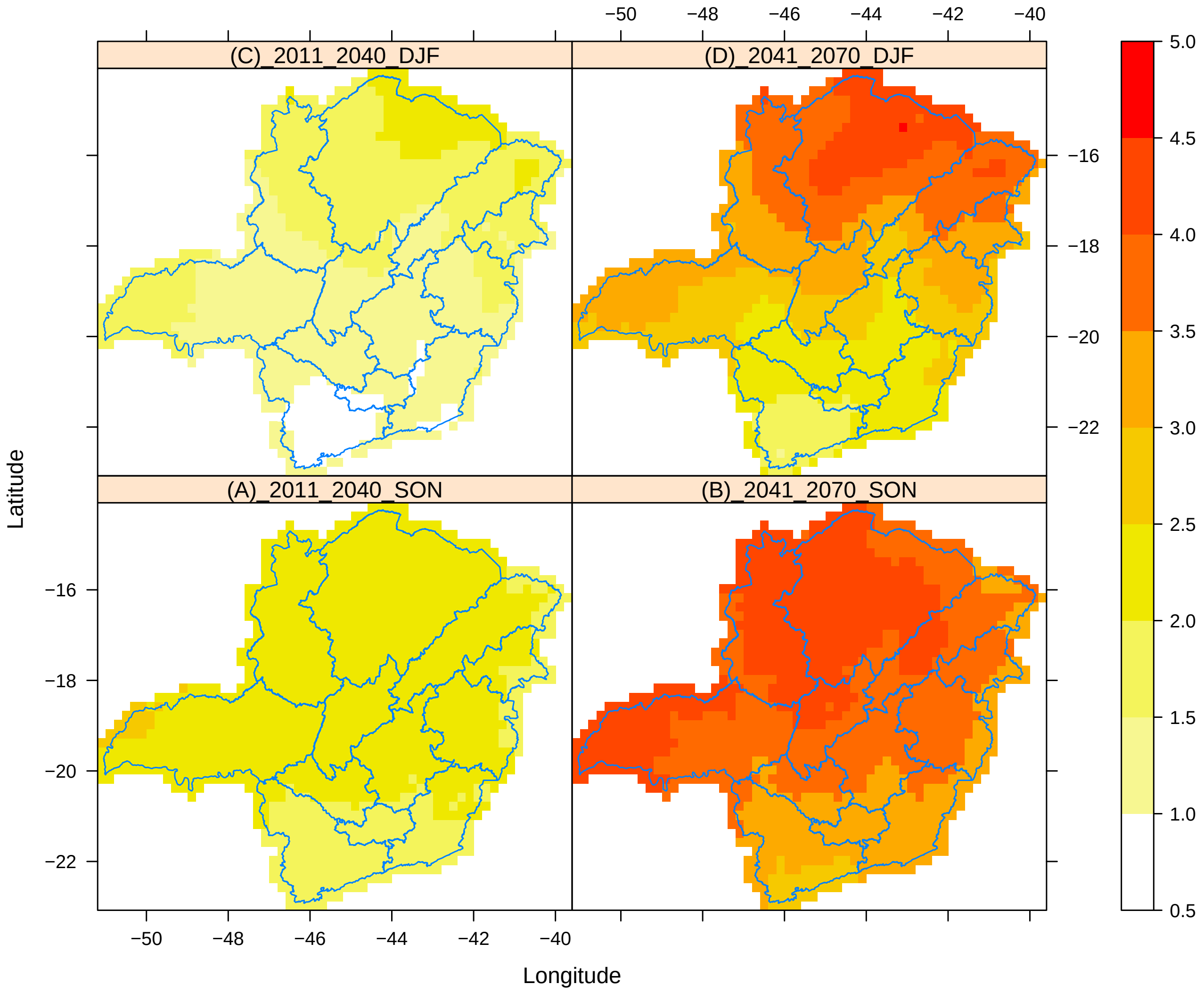
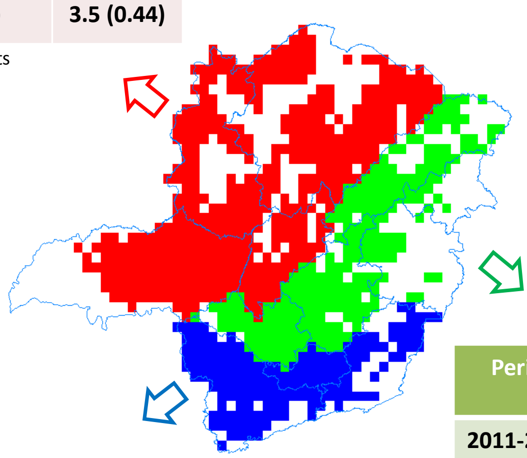


Figure 4: Eta-HadCM3-20km climate anomalies by trimester (with respect to 1961-1990 climatology) for mean maximum temperature (^{o}C) during the warm season in Minas Gerais.

Period	Maximum temperature [°C]	Anomaly [°C]
2011-2040	31.5 (1.27)	1.7 (0.25)
2041-2070	33.3 (1.35)	3.5 (0.44)

Standard deviation values in brackets



Period	Maximum temperature [°C]	Anomaly [°C]
2011-2040	30.5 (1.44)	1.2 (0.15)
2041-2070	32.0 (1.54)	2.6 (0.32)

Standard deviation values in brackets

Period	Maximum temperature [°C]	Anomaly [°C]
2011-2040	28.4 (1.35)	1.0 (0.10)
2041-2070	29.8 (1.44)	2.0 (0.20)

Standard deviation values in brackets

Figure 5: Eta-HadCM3-20km mean maximum temperature projections and their anomalies (with respect to the 1961-1990 climatology) clustered by region in Minas Gerais during the SON trimester. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

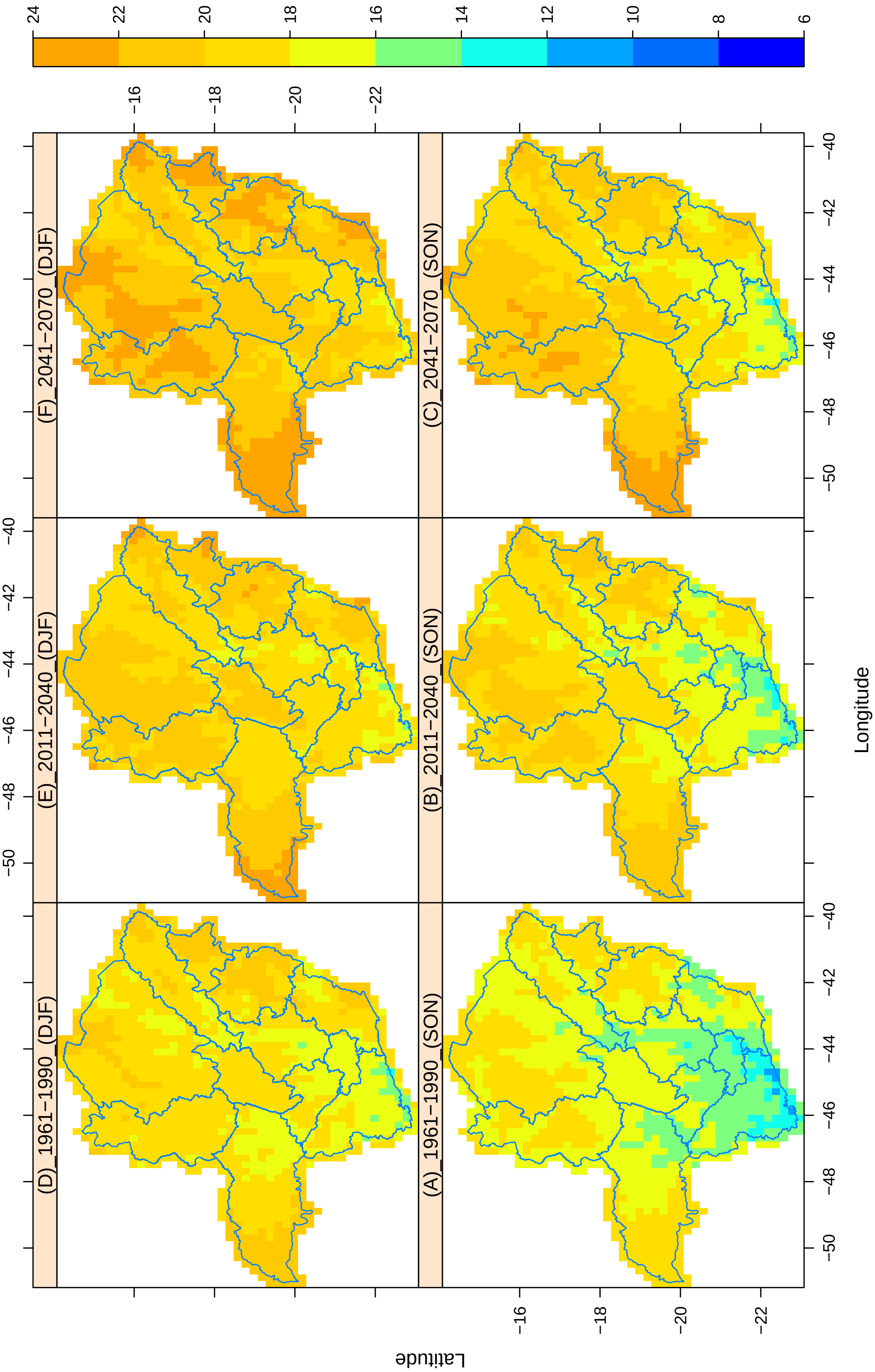


Figure 6: Eta-HadCM3-20km climate projections for mean minimum temperature (°C) during the warmest trimesters in Minas Gerais.

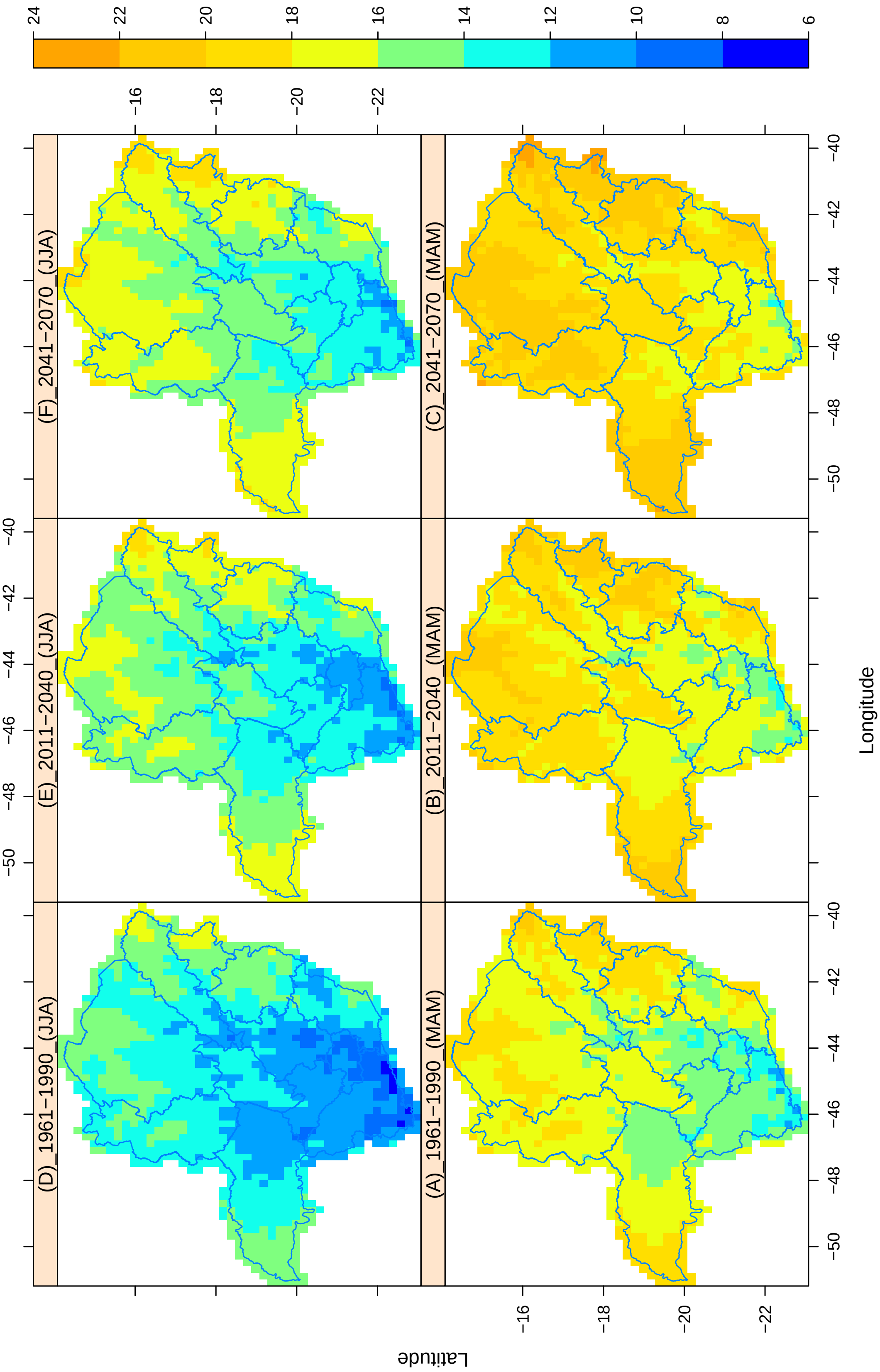


Figure 7: Eta-HadCM3-20km climate projections for mean minimum temperature (°C) during the coldest trimesters in Minas Gerais.

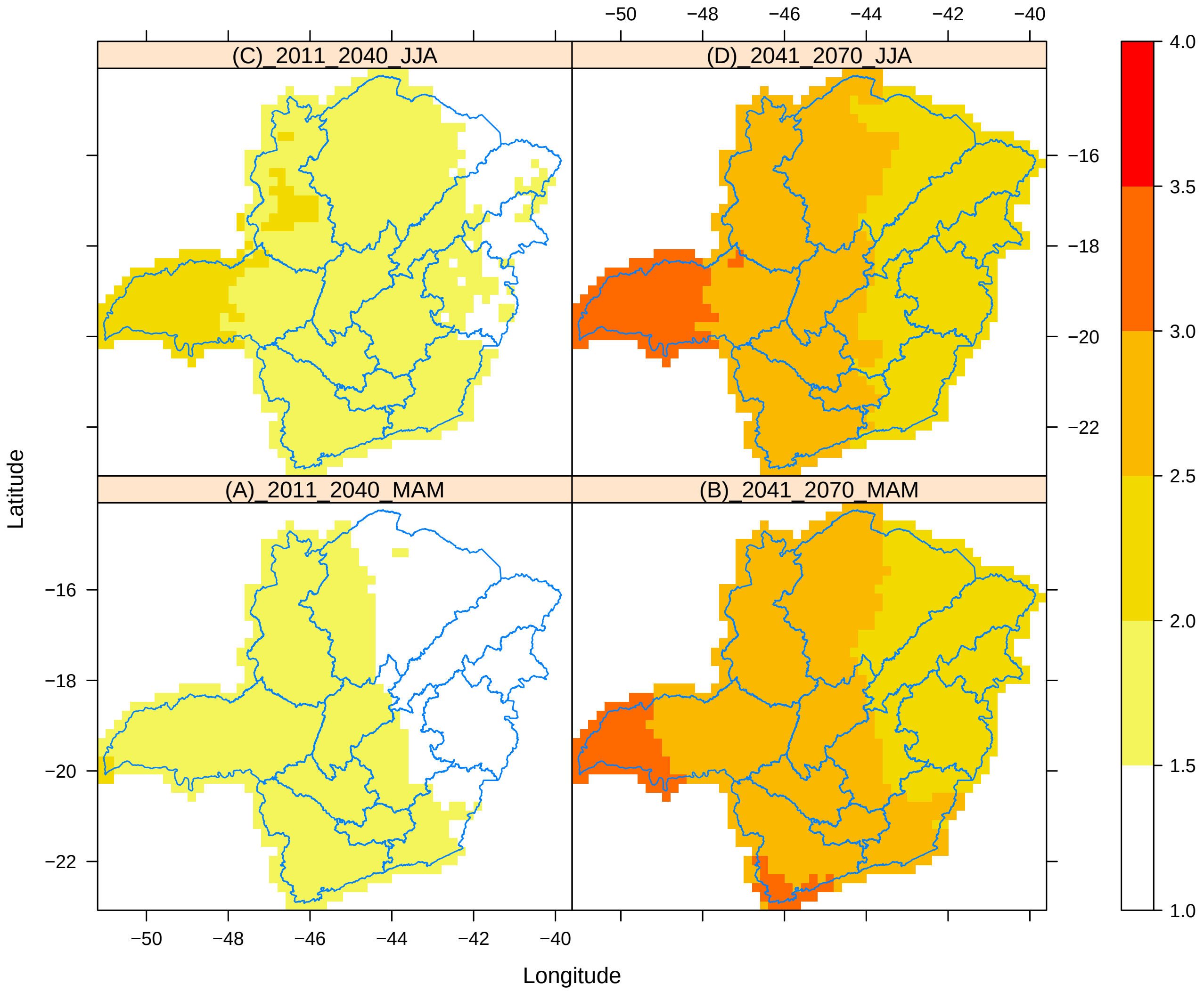
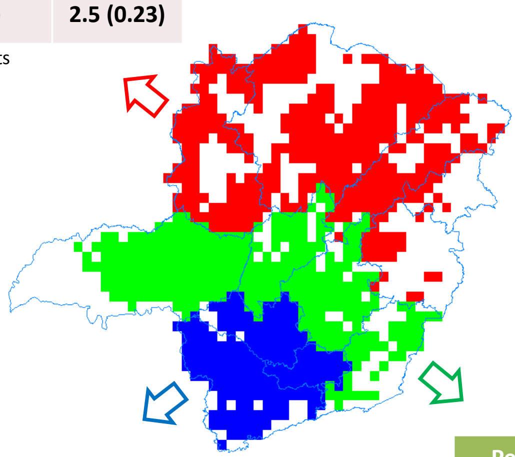


Figure 8: Eta-HadCM3-20km climate anomalies (with respect to 1961-1990 climatology) for mean minimum temperature (^{o}C) during the cold season in Minas Gerais.

Period	Minimum temperature [°C]	Anomaly [°C]
2011-2040	14.9 (0.87)	1.7 (0.18)
2041-2070	15.8 (0.88)	2.5 (0.23)

Standard deviation values in brackets



Period	Minimum temperature [°C]	Anomaly [°C]
2011-2040	12.2 (0.80)	1.7 (0.05)
2041-2070	13.0 (0.80)	2.6 (0.07)

Standard deviation values in brackets

Period	Minimum temperature [°C]	Anomaly [°C]
2011-2040	13.6 (0.94)	1.8 (0.17)
2041-2070	14.4 (0.98)	2.7 (0.26)

Standard deviation values in brackets

Figure 9: Eta-HadCM3-20km mean minimum temperature projections and their anomalies (with respect to the 1961-1990 climatology) clustered by region in Minas Gerais during the JJA trimester. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

3.2 Projected Precipitation

Quarterly surface maps of the accumulated precipitation in Minas Gerais, averaged for the 2011-2040 and 2041-2070 periods, are presented in Figures 10 and 11. A strong NE-SW gradient can be seen in all trimesters, which becomes more extreme as projected time horizon increases. It is even stronger for the first trimester of the year. Precipitation anomalies for the two projected periods during the rainy season (October to March), presented in Figure 12, clearly highlight this gradient, with positive anomalies in southern Minas Gerais, mainly during the JFM trimester (grain formation period), and strong negative anomalies in the north, being more accentuated during the OND trimester. For the May to August period (main harvesting period), there are no important projected changes in precipitation amounts (Figure 13). As in the case of warming, all projected changes in precipitation are more intense after 2040.

The clustering of mesoregions in Minas Gerais, according to their mean accumulated precipitation by trimester during the rainy season, in the two projected periods, considering only pixels at altitudes between 600 and 1,200 m.a.s.l., is presented in Figures 14 and 15. Projected drier conditions are much more intense in the cluster formed by the mesoregions in the north part of the state, where the amount of total precipitation in all the trimesters is already lower than in other parts of Minas Gerais. In this cluster mean projected decreases in the accumulated precipitation during the first trimester of the year are of 8.2% and 24.3% for the 2011-2040 and 2041-2070 periods, respectively (when compared to the 1961-1990 climatology). The mean projected decreases in this cluster for the OND trimester are even higher (17% and 34%, respectively). On the other hand, model projections in the southern part of the state, which clusters the mesoregions with the highest accumulated precipitation during the rainy trimesters, suggest a wetter condition, with increases averaging 13.2% and 18.4%, for the 2011-2040 and 2041-2070 periods, respectively, during the JFM trimester, and with a stabilization in the precipitation amount accumulated during the OND trimester, where just slight mean increases are projected (1.3% and 3.3%, in the two projected periods, respectively). A third cluster between these two contrasting regions is characterized by intermediate levels of mean accumulated precipitation. Climate projections followed this behavior.

The harvesting period (May to August), is the driest one in Minas Gerais. Clustering results based on the mean accumulated precipitation during this period (Figure 16) pointed out that in most parts of the state, including the north, eastern and western regions, average projected anomalies will just be slightly negatives (less than 20mm up to the 2041-2070 period). In the southern region, positive anomalies of about 30mm are projected for the 2011-2040 period, with no apparent changes for the 2041-2070 period. However, is not expected that these small changes will have significant effects on coffee harvesting activities.

Clustering results based on the annual rainfall also followed the general tendency seen by trimester in Minas Gerais (see Figure 17), that is, more rainfall projected in the south, with average annual increases of 6.8% and 9.7%, respectively for the 2011-2040 and 2041-2070 periods, and a strong decrease in the already drier north part of the state, averaging 13.3% and 26.9% less rainfall for the two projected periods.

These differences in projected precipitation by region also agree with results based on observed data reported by Ruiz-Cárdenas (2013). They found that total precipitation amount in southern Minas Gerais during the JFM trimester is nowadyas higher, whilst regions in the north became much more drier during all wet season and variations during the dry season were small in all regions of the state. This wet-get-wetter and dry-get-drier response in the south and north parts of the state, respectively, could be physically explained by the named "rich get richer mechanism" (Chou et al., 2009), which states that under global warming, water vapour in the atmosphere increases, resulting in enhanced precipitation over wet (ascending) regions and reduced precipitation over dry (descending) regions. Such changes have been reported in observations and model simulations for several regions around the world, including the south-east of Brazil (ex., Chou et al., 2013; Greve et al., 2014).

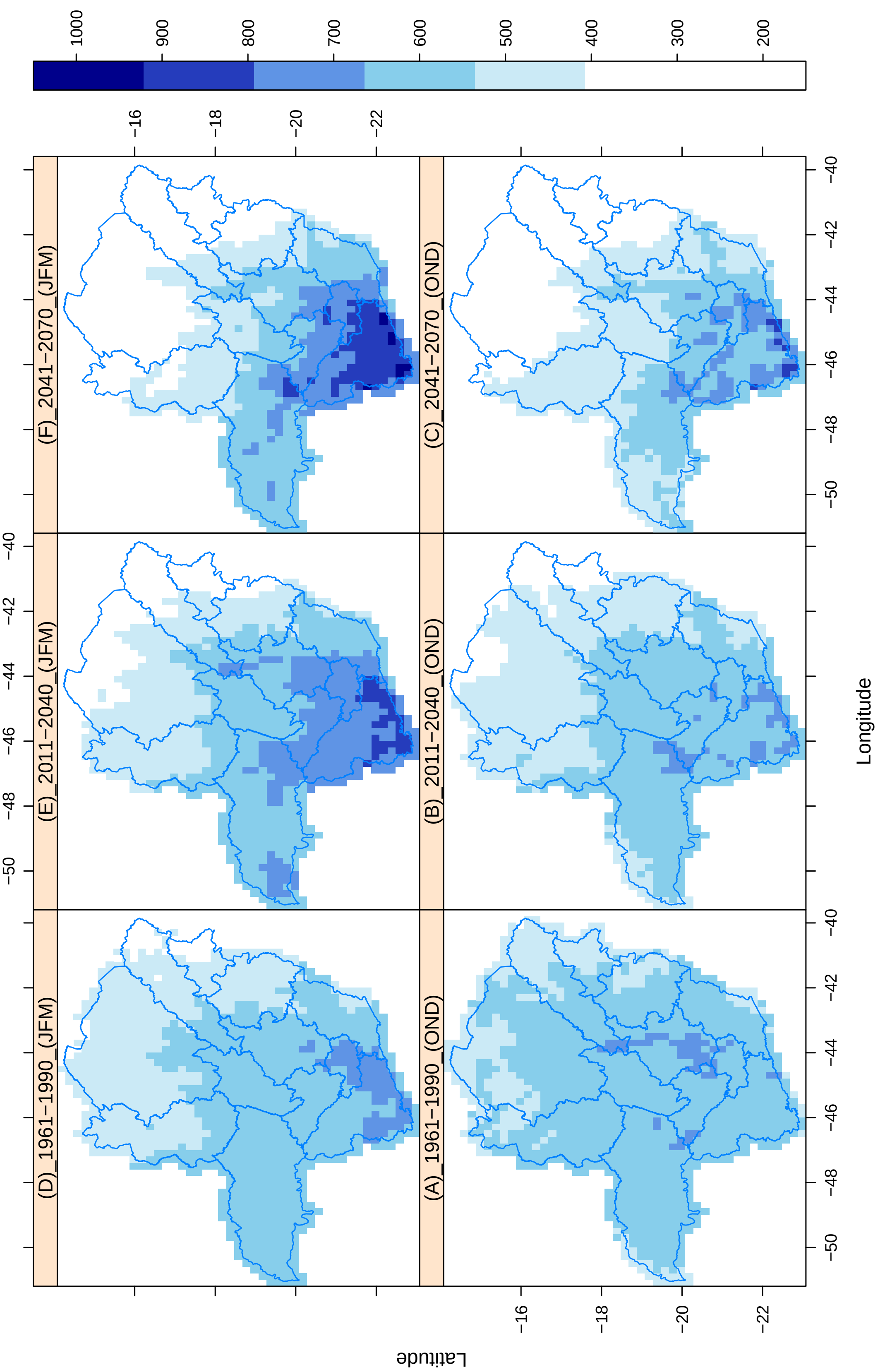


Figure 10: Eta-HadCM3-20km climate projections for accumulated precipitation (mm) during the wet season in Minas Gerais.

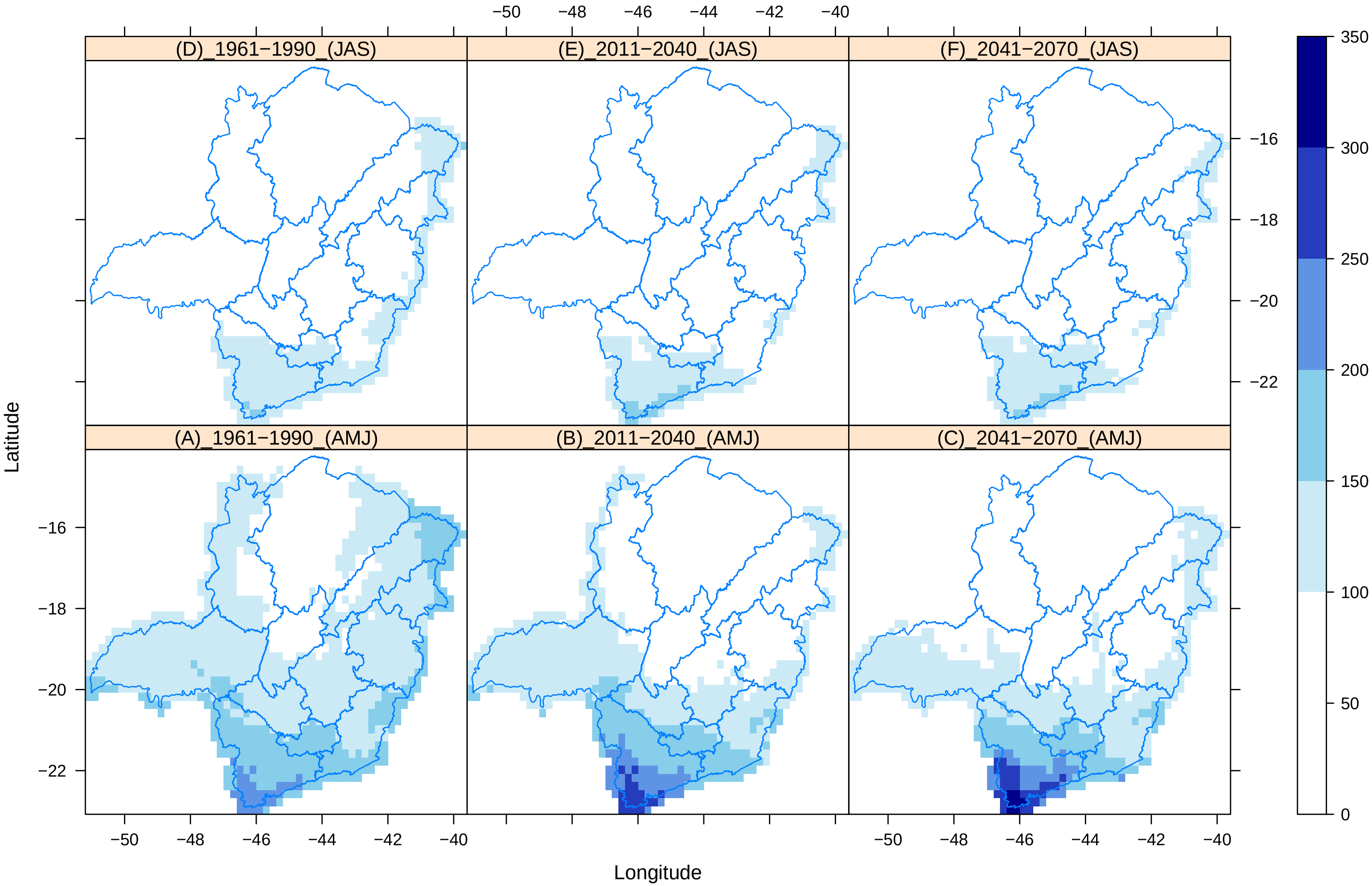


Figure 11: Eta-HadCM3-20km climate projections for accumulated precipitation (mm) during the dry season in Minas Gerais.

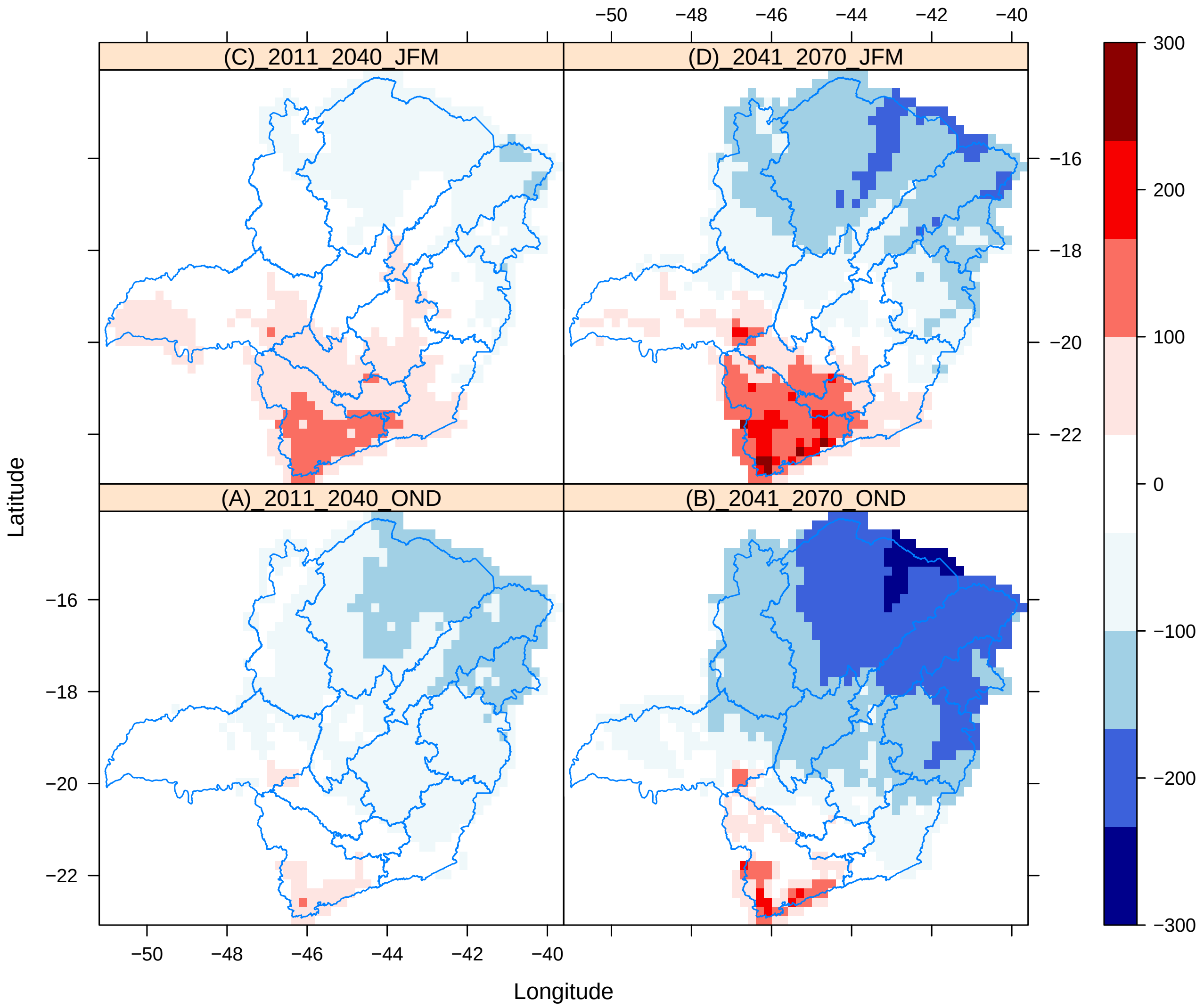


Figure 12: Mean Eta-HadCM3-20km rainfall anomalies (mm) for the 2011-2040 and 2041-2070 periods, with respect to 1961-1990 climatology, during the rainy season (October to March) in Minas Gerais.

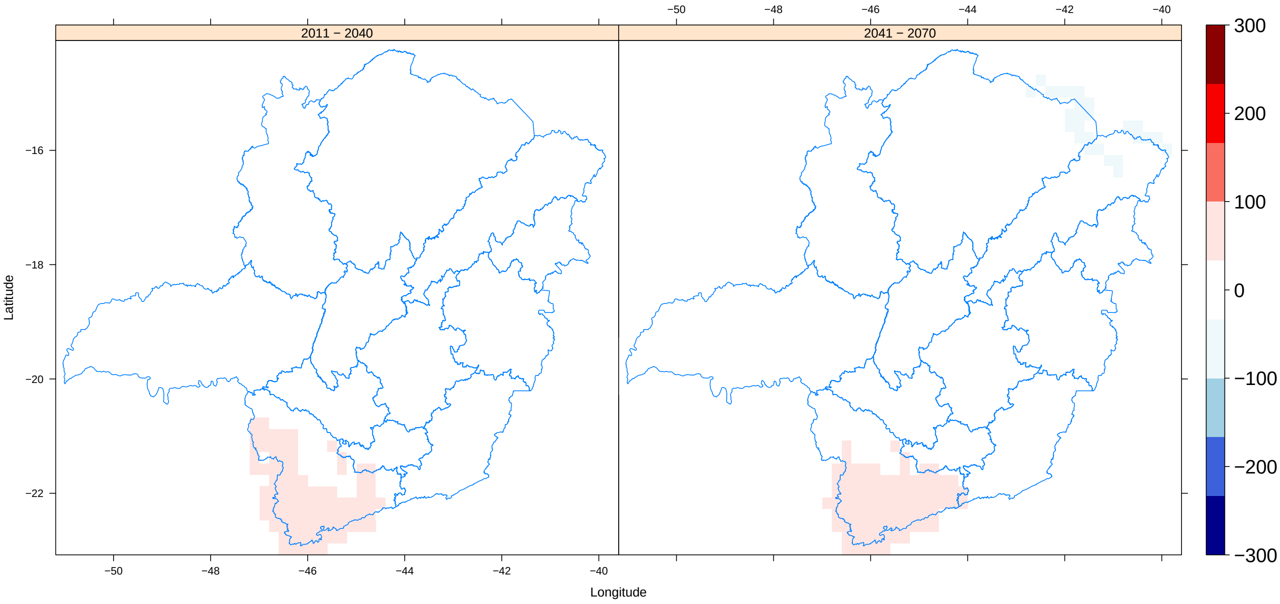
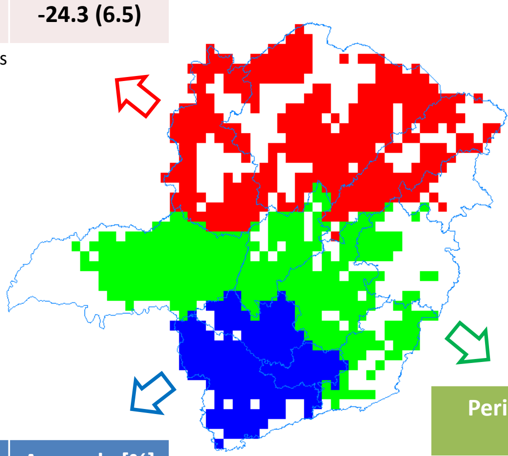


Figure 13: Mean Eta-HadCM3-20km rainfall anomalies (mm) for the 2011-2040 and 2041-2070 periods, with respect to 1961-1990 climatology, during coffee harvesting period (May to August) in Minas Gerais.

Period	Accumulated rainfall [mm]	Anomaly [%]
2011-2040	464.9 (75.5)	-8.2 (6.3)
2041-2070	383.2 (73.1)	-24.3 (6.5)

Standard deviation values in brackets



Period	Accumulated rainfall [mm]	Anomaly [%]
2011-2040	626.8 (54.1)	4.0 (4.9)
2041-2070	588.5 (79.4)	-2.4 (9.0)

Standard deviation values in brackets

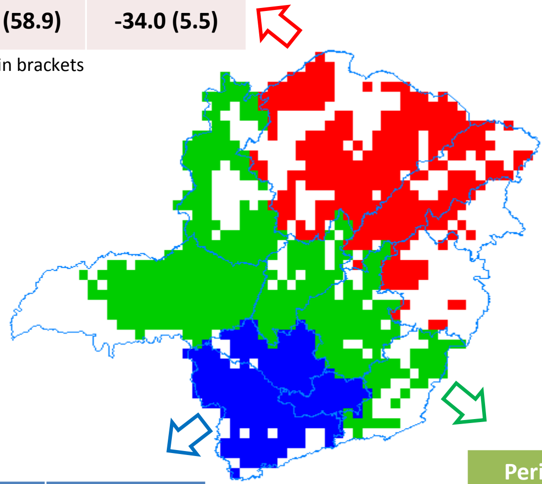
Period	Accumulated rainfall [mm]	Anomaly [%]
2011-2040	736.9 (46.3)	13.2 (4.1)
2041-2070	770.6 (69.4)	18.4 (7.9)

Standard deviation values in brackets

Figure 14: Eta-HadCM3-20km mean accumulated precipitation projections and their anomalies (with respect to the 1961-1990 climatology) clustered by region in Minas Gerais during the JFM trimester. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

Period	Accumulated rainfall [mm]	Anomaly [%]
2011-2040	471.7 (54.3)	-17.3 (4.5)
2041-2070	376.4 (58.9)	-34.0 (5.5)

Standard deviation values in brackets



Period	Accumulated rainfall [mm]	Anomaly [%]
2011-2040	638.5 (24.9)	1.3 (4.4)
2041-2070	651.6 (51.3)	3.3 (8.5)

Standard deviation values in brackets

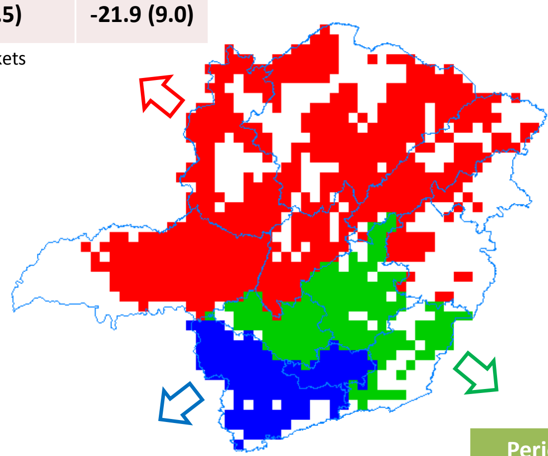
Period	Accumulated rainfall [mm]	Anomaly [%]
2011-2040	576.7 (41.0)	-6.0 (3.6)
2041-2070	525.1 (66.6)	-14.4 (7.6)

Standard deviation values in brackets

Figure 15: Eta-HadCM3-20km mean accumulated precipitation projections and their anomalies (with respect to the 1961-1990 climatology) clustered by region in Minas Gerais during the OND trimester. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

Period	Accumulated rainfall [mm]	Anomaly [%]
2011-2040	66.0 (26.4)	-10.1 (7.1)
2041-2070	57.3 (23.5)	-21.9 (9.0)

Standard deviation values in brackets



Period	Accumulated rainfall [mm]	Anomaly [%]
2011-2040	167.0 (33.6)	24.3 (10.2)
2041-2070	167.3 (40.1)	24.4 (14.9)

Standard deviation values in brackets

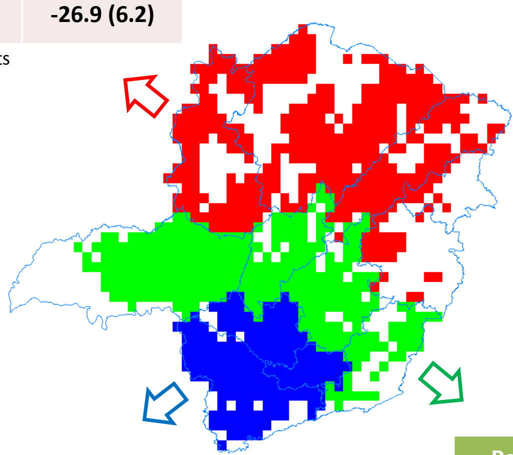
Period	Accumulated rainfall [mm]	Anomaly [%]
2011-2040	95.3 (27.1)	3.3 (7.6)
2041-2070	89.5 (28.6)	-3.0 (9.7)

Standard deviation values in brackets

Figure 16: Eta-HadCM3-20km mean accumulated precipitation projections and their anomalies (with respect to the 1961-1990 climatology) clustered by region in Minas Gerais during the harvesting period (May to August). Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

Period	Accumulated rainfall [mm]	Anomaly [%]
2011-2040	1081 (129.1)	-13.3 (5.7)
2041-2070	911 (133.9)	-26.9 (6.2)

Standard deviation values in brackets



Period	Accumulated rainfall [mm]	Anomaly [%]
2011-2040	1651 (117.3)	6.8 (4.6)
2041-2070	1695 (173.9)	9.7 (8.1)

Standard deviation values in brackets

Period	Accumulated rainfall [mm]	Anomaly [%]
2011-2040	1399 (99.4)	-2.7 (3.6)
2041-2070	1318 (151.5)	-8.3 (7.1)

Standard deviation values in brackets

Figure 17: Eta-HadCM3-20km annual rainfall projections and their anomalies (with respect to the 1961-1990 climatology) clustered by region in Minas Gerais. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

3.3 Projected coffee zoning for Minas Gerais

Projected suitability maps for *C. arabica* and *C. canephora* in Minas Gerais were derived following the two main criteria adopted in agricultural zoning studies in Brazil, they are, annual mean temperature and mean annual water deficit. These criteria have been used in previous zoning studies of arabica coffee in Minas Gerais (ex., Sediyama et al., 2001; Assad et al., 2004).

Considering an annual water deficit of 125 mm, Pereira et al. (2008) suggested the following classification about coffee production suitability in terms of water supply:

Table 1: Suitability conditions for coffee production in terms of water supply.

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

Suitable ranges of annual mean temperature for arabica and robusta coffee were also suggested by Pereira et al. (2008) and Camargo (2010) as follows:

Table 2: Suitability conditions for *C. arabica* and *C. canephora* according to the annual mean temperature criterion.

Classification	Annual mean temperature (^oC)	
	C. arabica	*C. canephora*
unsuitable	$<$ 17	$<$ 20
marginal	17 - 18	20 - 22
suitable	18 - 23	22 - 26
marginal	23 - 24	26 - 27
unsuitable	$>$ 24	$>$ 27

Mapping results are firstly presented for each criteria separately, followed by coffee suitability maps that combine both criteria.

The projected surface maps for annual mean temperature in Minas Gerais averaged at the 2011-2040 and 2041-2070 periods, as well as for their anomalies (related to the 1961-1990 climatology) are presented in Figures 18 and 19. Clustering of mesoregions according to this variable is also shown in Figure 20. As in the case of quarterly minimum/maximum temperatures shown above, warming of annual mean temperatures is projected to be more intense in the north and eastern regions of the state, averaging increases of 1.7^{o}C and 3^{o}C for the two projected periods, respectively, in the cluster formed by these regions. Projected warming in the other regions would reach 1.5 and 2.5 in average for the same two periods. However, the cluster formed by "Sul de Minas" "Campo das Vertentes" and "Zona da Mata" mesoregions, would still be considered a suitable area for arabica production in terms of annual mean temperature ($< 23^oC$), even after this warming. On the other hand, warming experienced during the first projected period (2011-2040) would be enough to let the north and eastern regions with the status of unsuitable regions, with the situation being worst in the 2041-2070 period (Figure 21). Regarding C. canephora, it can be seen a projected trend of inversion in the areas considered as suitable/unsuitable for production of robusta coffee in Minas Gerais, in terms of annual mean temperature (Figure 22), with current suitable areas in the north and north-west regions of the state becoming unsuitable in the 2041-2070 period, at the same time that suitable areas for C. canephora are projected to increase in regions of southern Minas Gerais that are currently classified as suitable for arabica production.

The projected water balance in Minas Gerais was calculated following Thornthwaite's methodology (Thornthwaite, 1955), assuming an available water capacity of 125 mm for all regions of the state. Figure 23 presents projection maps for the water deficit (defined as the difference between precipitation and potential evapotranspiration), which were derived from the water balance, and yearly averaged for the 2011-2040 and 2041-2070 periods. Projected anomalies and regional clustering for this variable are also shown in Figures 24 and 25. The main coffee producing region in Minas Gerais, which includes the mesoregions at the southern part of the state and "Zona da Mata", was the least affected by the projected decrease in available water. In this region the mean annual water deficit is expected to keep below the suitability threshold of 150mm, even in 2070. For the rest of the state projections suggest that water requirements for coffee production could only be supplied by irrigation. This situation is even more critical in the north and north-east regions.

The combination of the above criteria (annual mean temperature and annual mean water deficit) yielded the projected coffee sutability maps for *C. arabica* and *C. canephora* in Minas Gerais for the 2011-2040 and 2041-2070 periods presented in Figures 26 and 27. It can be seen that coffee zoning is largely dominated by mean temperature restrictions, assuming that irrigation would be available in regions with more than 150mm of mean annual water deficit, as is currently the case of virtually all coffee areas in the north and western Minas Gerais. According to these results, the current main arabica coffee production areas in Minas Gerais, at Triângulo Mineiro, Sul de Minas, Campo das Vertentes, Oeste de Minas and Zona da Mata mesoregions, would keep their status of suitable coffee producing areas up to 2040. For the 2041-2070 period, projected suitability for arabica production becomes more restricted but it still covers a significant part of these areas.

Outputs from the Eta-HadCM3-20km model allowed a detailed analysis of the projected climate behavior in Minas Gerais at the regional level, without relying on downscaling techniques (usually used to improve resolution of coarser climate models), which could generate additional uncertainty to model projections. To the best of our knowledge, the 20-km resolution used in this study is the highest one used in long term runs of a climate model considered in future coffee zoning studies for Minas Gerais. An early work by Assad et al. (2004), based on results of the Third IPCC assessment report, simulated the effect of increases of 1^oC, 3.5^oC and 5.8^oC in current annual mean temperatures and a constant increase of 15% in precipitation levels, to derive projected coffee suitability maps for Minas Gerais. There was no a climate model involved in this study. Instead, their work was based on high resolution interpolation of the parameters of interest. Projected suitability for *C. arabica* and *C. canephora* cultivation in Brazil for 2080, under a A2 scenario was also assessed by Alves et al. (2013, Figs 7 and 12), based on the downscaling of global model CCMA (Flato et al., 2000) to a high resolution grid. These previous studies also presented results for Brazil or for Minas Gerais as a whole. Our study, besides performing coffee zoning using a regional model with the best available resolution, also details projected climate behavior for the different regions of the state, with focus on specific periods of the year that are important for coffee from a phenological point of view.

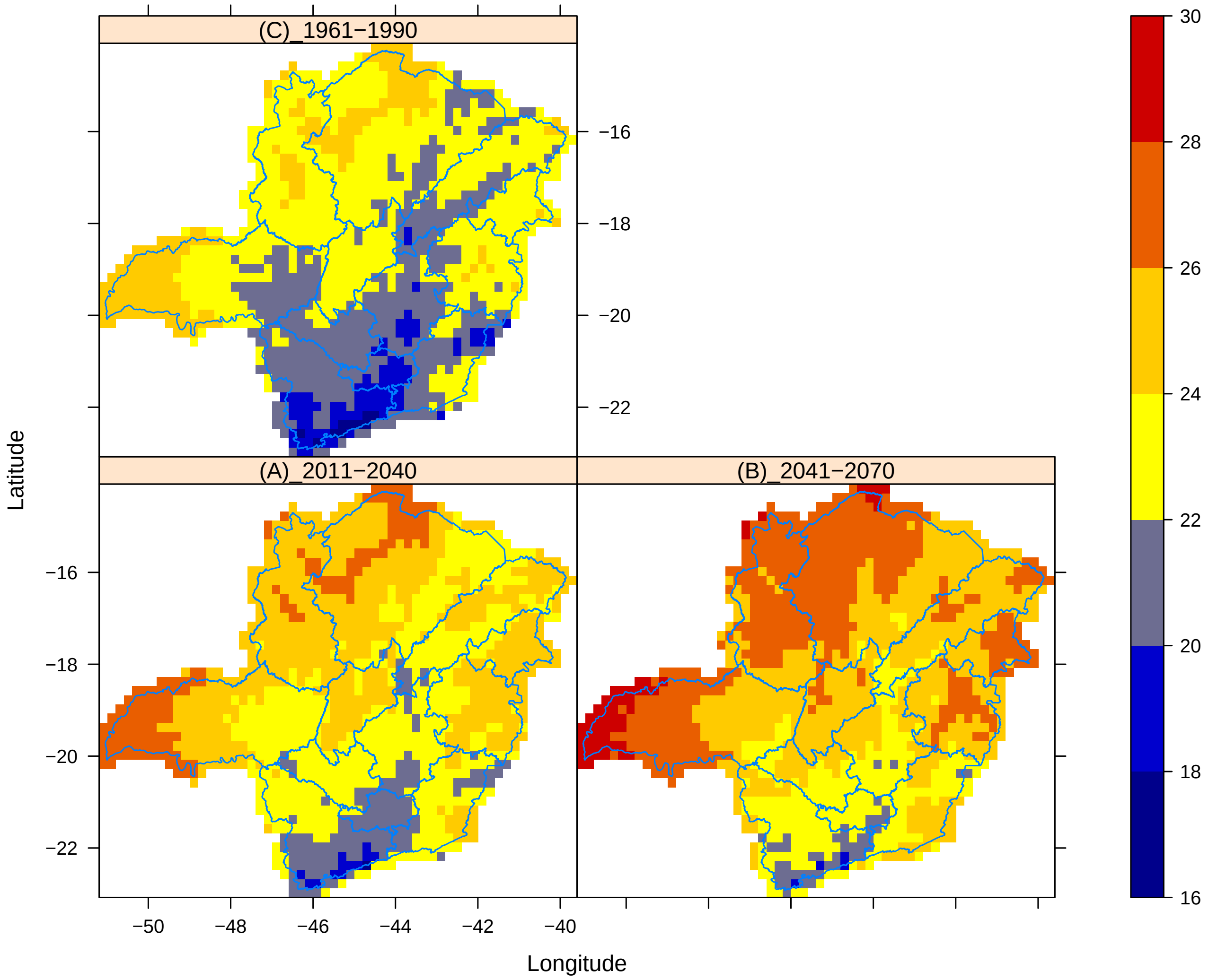


Figure 18: Eta-HadCM3-20km climate projections for annual mean temperature (^oC) in Minas Gerais.

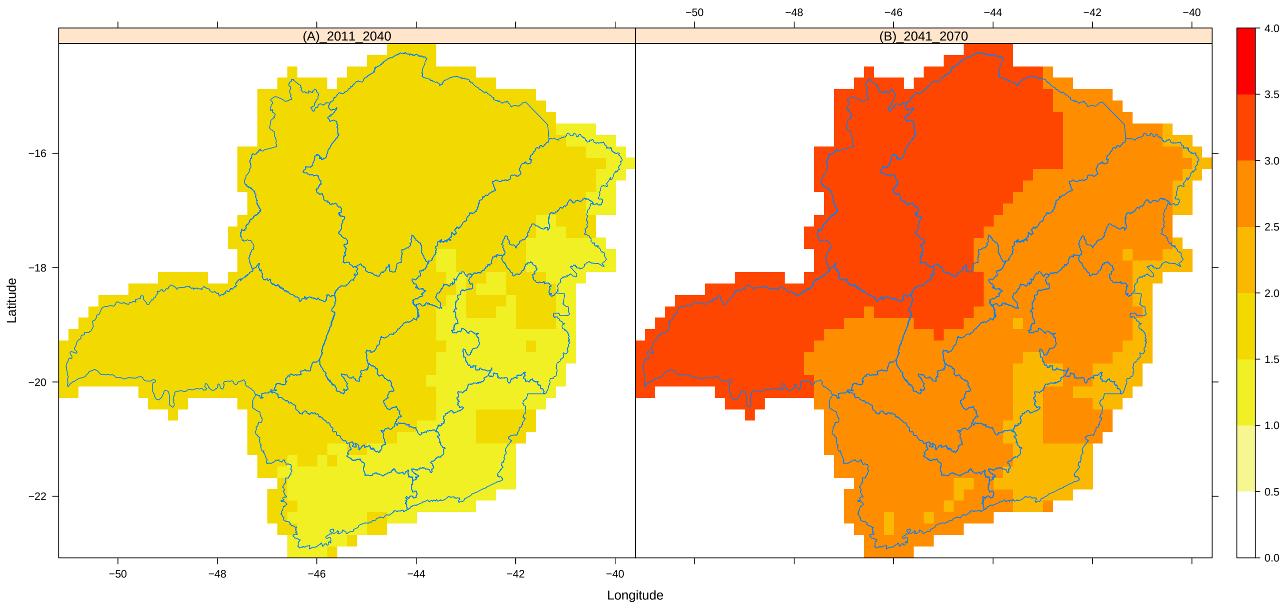
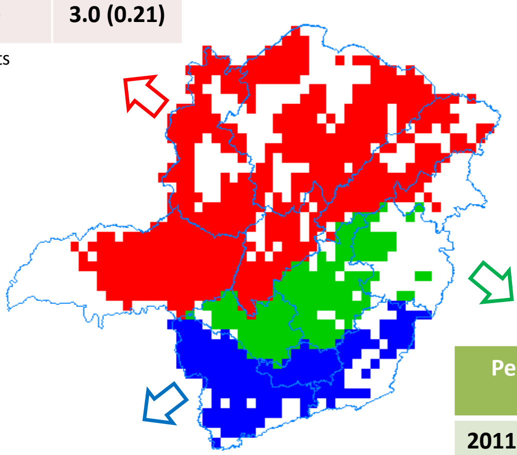


Figure 19: Eta-HadCM3-20km climate anomalies (with respect to 1961-1990 climatology) for annual mean temperature (^oC) in Minas Gerais.

Period	Annual mean temperature [ºC]	Anomaly [ºC]
2011-2040	**24.2 (0.88)**	**1.7 (0.11)**
2041-2070	**25.5 (0.96)**	**3.0 (0.21)**

Standard deviation values in brackets



Period	Annual mean temperature [ºC]	Anomaly [ºC]
2011-2040	**22.8 (0.71)**	**1.5 (0.05)**
2041-2070	**23.9 (0.75)**	**2.6 (0.11)**

Standard deviation values in brackets

Period	Annual mean temperature [ºC]	Anomaly [ºC]
2011-2040	**21.9 (0.91)**	**1.5 (0.05)**
2041-2070	**22.9 (0.93)**	**2.5 (0.09)**

Standard deviation values in brackets

Figure 20: Eta-HadCM3-20km annual mean temperature projections and their anomalies (with respect to the 1961-1990 climatology) clustered by region in Minas Gerais. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

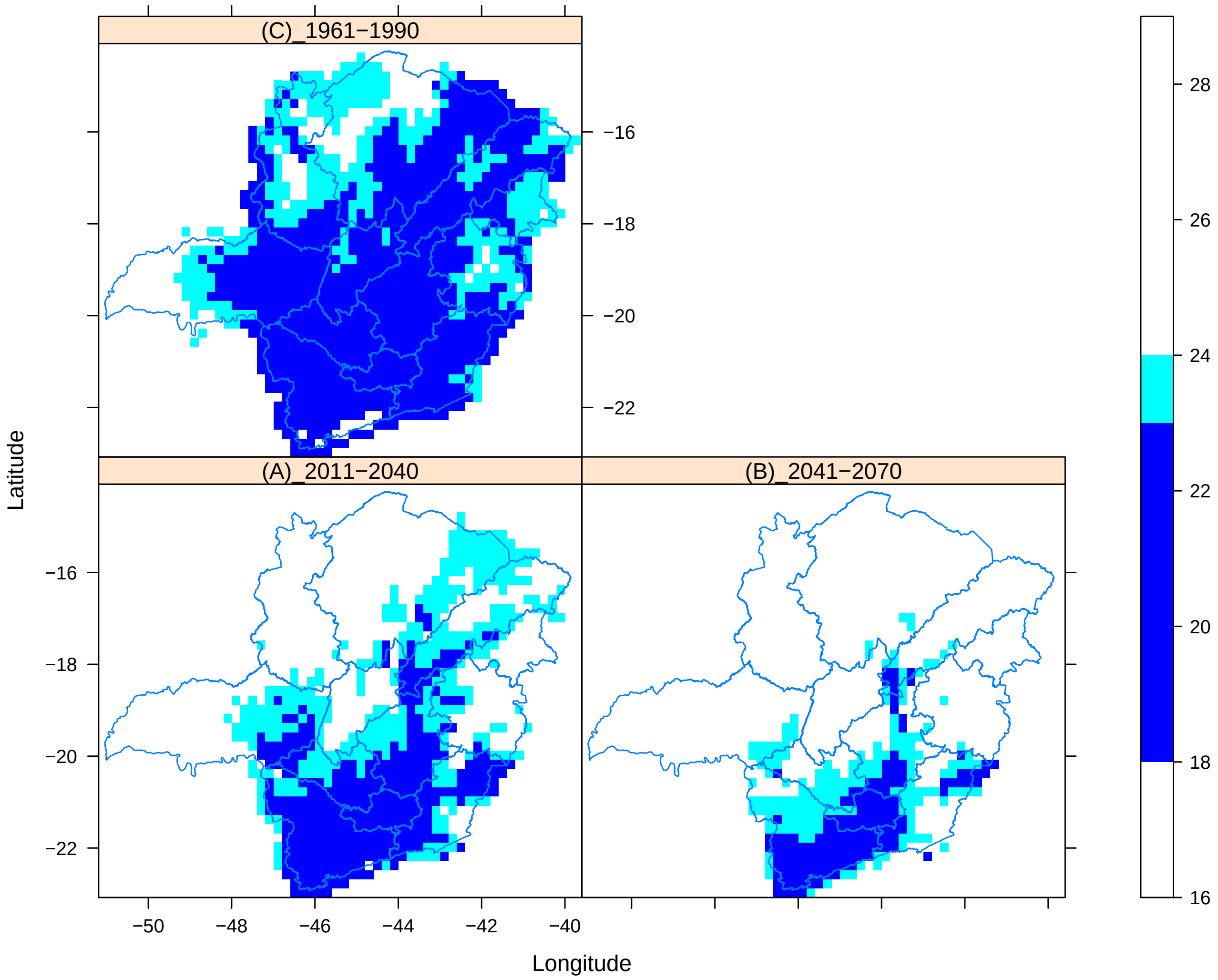


Figure 21: Suitability map for C. arabica production in Minas Gerais according to Eta-HadCM3-20km annual mean temperature projections (^oC). Suitable: 18 – 23 ^oC; marginal: 23 – 24 ^oC; unsuitable: less than 18^oC or more than 24^oC.

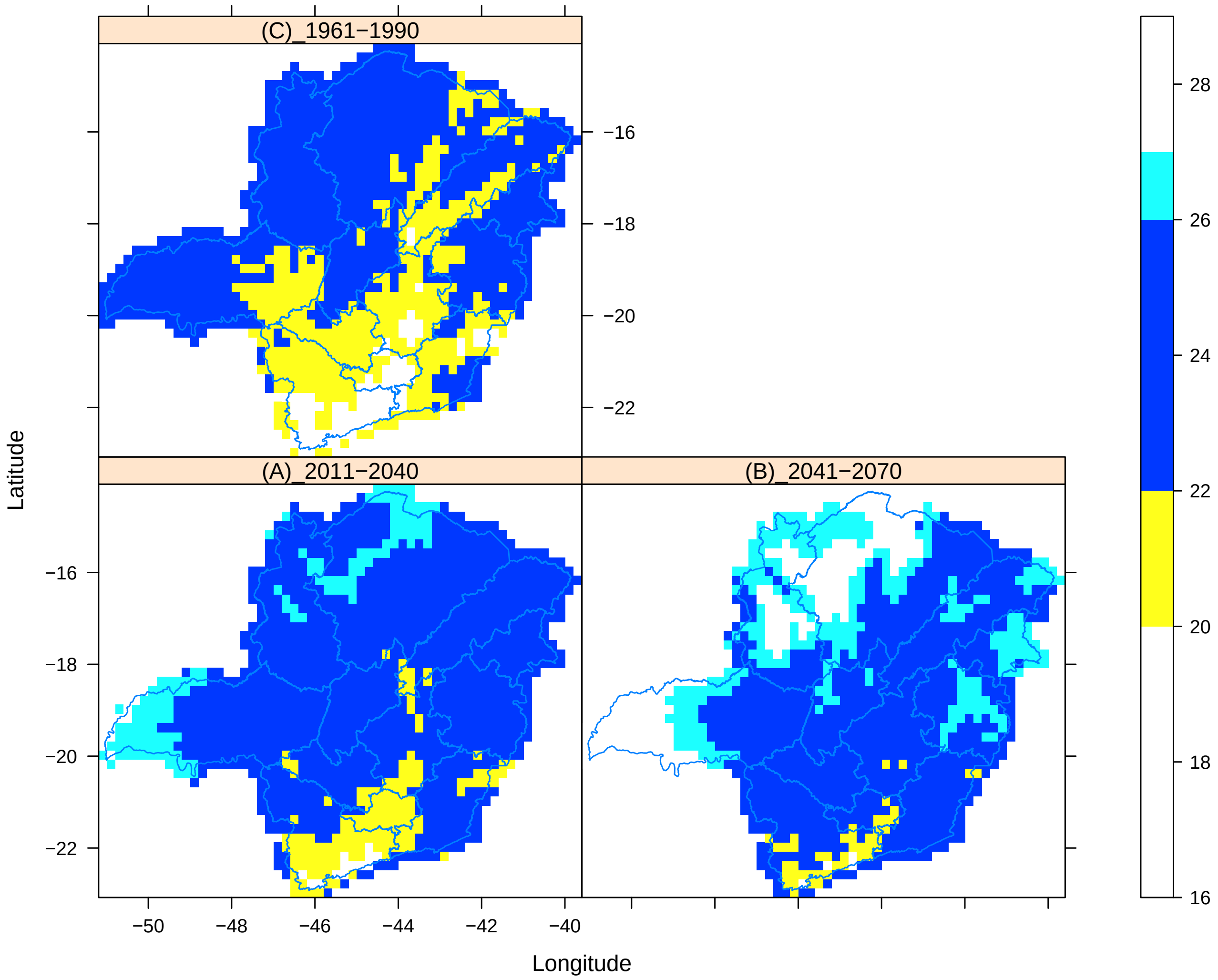


Figure 22: Suitability map for C. canephora production in Minas Gerais according to Eta-HadCM3-20km annual mean temperature projections (^{o}C). Suitable: $22 - 26\ ^{o}C$; marginal: $20 - 22\ ^{o}C$ or $26 - 27\ ^{o}C$; unsuitable: less than $20^{o}C$ or more than $27^{o}C$.

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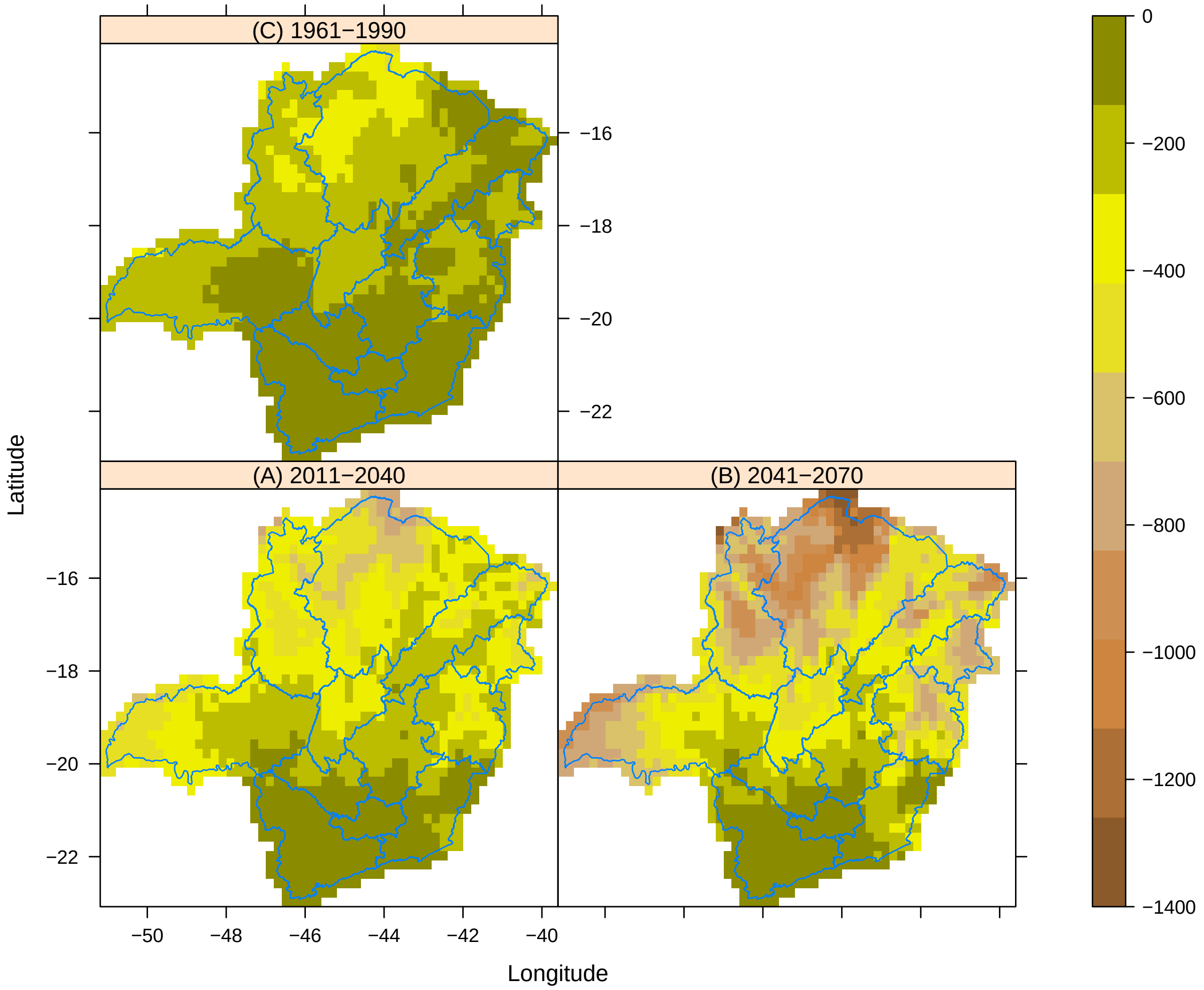


Figure 23: Eta-HadCM3-20km climate projections for mean annual water deficit (AWD) in Minas Gerais, expressed in mm, averaged at the 2011-2040 and 2041-2070 periods. Dark green pixels indicate areas with less than 150mm of projected AWD. Results based on model runs for the 1961-1990 climatology are included as a reference.

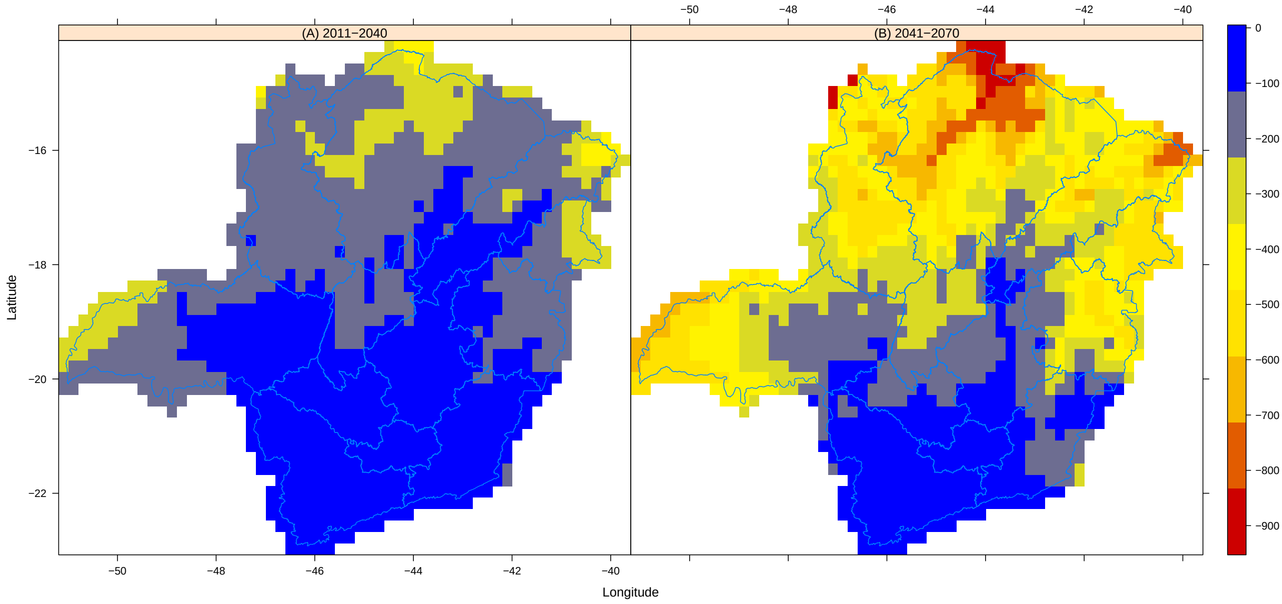
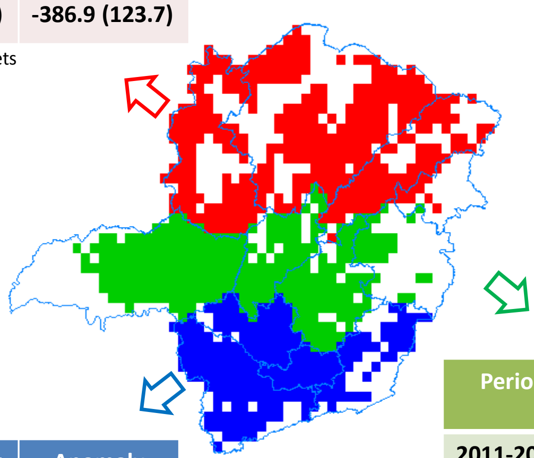


Figure 24: Eta-HadCM3-20km anomalies for the annual mean water deficit in Minas Gerais, expressed in mm, averaged at the 2011-2040 and 2041-2070 periods (with respect to the 1961-1990 climatology).

Period	Annual water deficit [mm]	Anomaly [mm]
2011-2040	-332.9 (96.9)	-153.5 (45.1)
2041-2070	-566.3 (173.2)	-386.9 (123.7)

Standard deviation values in brackets



Period	Annual water deficit [mm]	Anomaly [mm]
2011-2040	-217.6 (66.8)	-93.6 (29.4)
2041-2070	-317.8 (112.0)	-193.8 (76.4)

Standard deviation values in brackets

Period	Annual water deficit [mm]	Anomaly [mm]
2011-2040	-69.5 (50.9)	-27.5 (22.9)
2041-2070	-103.8 (74.2)	-61.8 (45.7)

Standard deviation values in brackets

Figure 25: Eta-HadCM3-20km mean annual water deficit projections and their anomalies (with respect to the 1961-1990 climatology) clustered by region in Minas Gerais. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

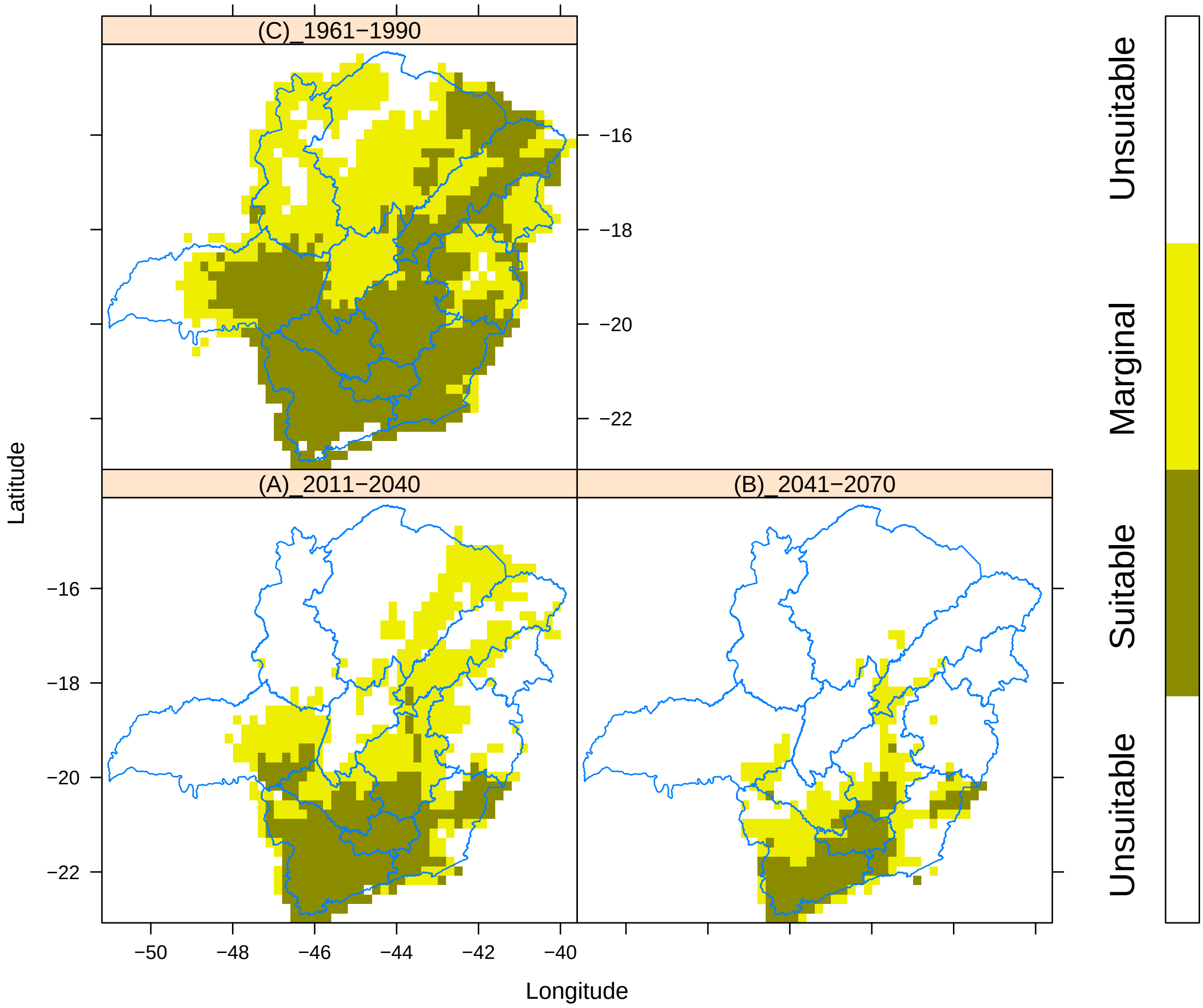


Figure 26: Projected suitability maps for C. arabica in Minas Gerais according to both, annual mean temperature and annual mean water deficit criteria from the Eta-HadCM3-20km model run under a SRES A1B scenario. Suitable: 18 – 23 ^oC and less than 150mm; marginal: 18 – 24 ^oC and more than 150mm or 23 – 24 ^oC and less than 150mm; unsuitable: less than 18^oC or more than 24^oC, and more than 150mm.

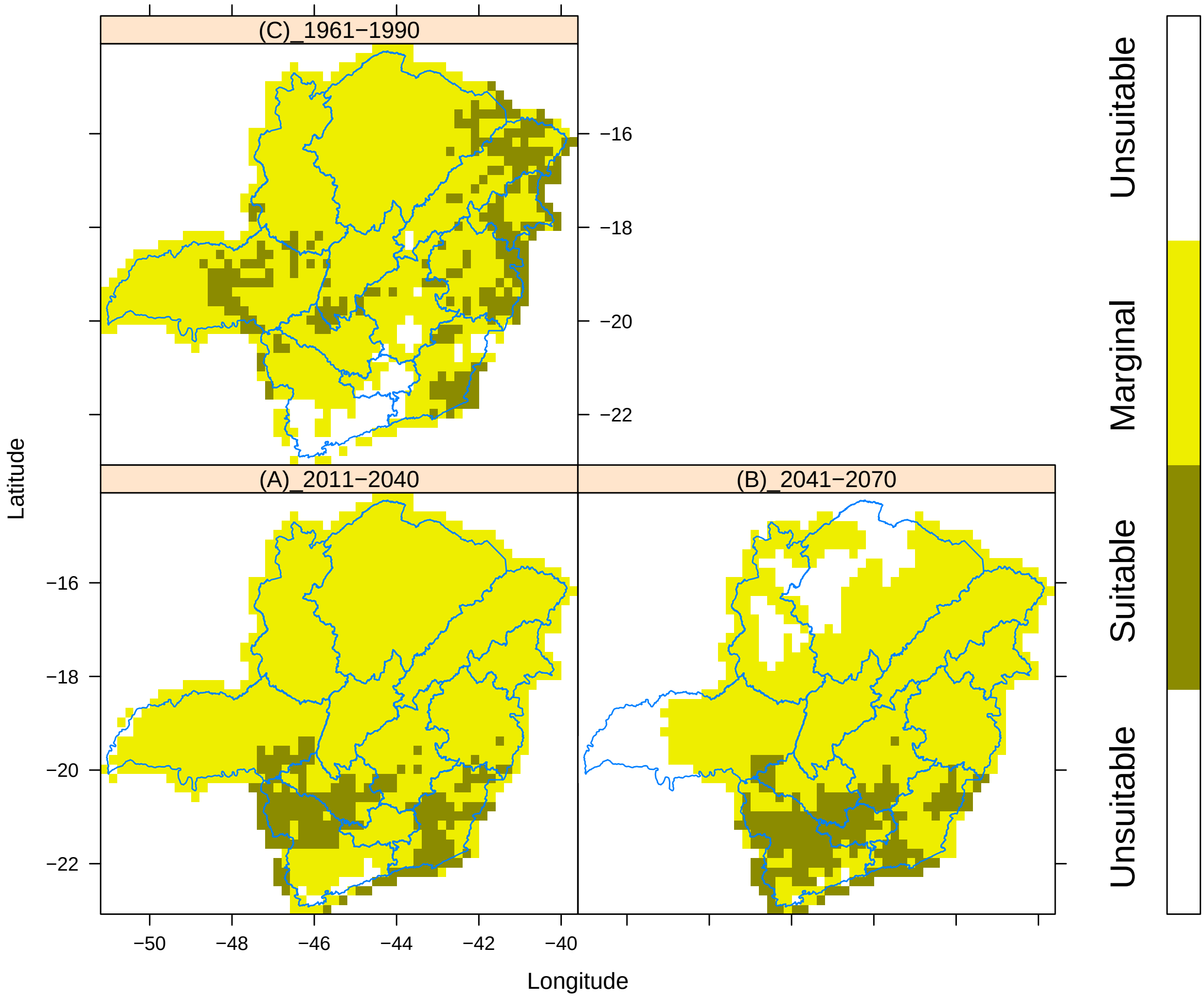


Figure 27: Projected suitability maps for C. canephora in Minas Gerais according to both, annual mean temperature and annual mean water deficit criteria from the Eta-HadCM3-20km model run under a SRES A1B scenario. Suitable: 22 – 26 ^oC and less than 150mm; marginal: 20 – 27 ^oC and more than 150mm, or 20 – 22 ^oC and less than 150mm, or 26 – 27 ^oC and less than 150mm; unsuitable: less than 20^oC or more than 27^oC, and more than 150mm.

4 Final remarks

Outputs from the Eta-HadCM3-20km model used in this study allowed a detailed analysis of the projected climate behavior in Minas Gerais at the regional level for the 2011-2040 and 2041-2070 periods, with focus on specific periods of the year that are important for coffee from a phenological point of view. Climate anomalies were also quantified and clustered according to the intensity of future changes by region. Finally, projected suitability maps for *C. arabica* and *C. canephora* in Minas Gerais were constructed.

Warming is projected for all regions of Minas Gerais and for all seasons of the year. Changes in maximum temperatures will be more accentuated during the warm season (September to February). Particularly, areas with very high temperatures are projected to increase dramatically in the north and western regions of the state during the main coffee flowering period (September to November), with expected consequences such as more frequent problems of abortion of flowers due to heat stress. Due to a projected average increase of more than 2^{o}C in the minimum temperature of the coldest trimester (July to August) in southern Minas Gerais, the risk of frost in this region is expected to be reduced in the future, mainly after 2040.

Regarding precipitation, the projected wet-get-wetter and dry-get-drier response in the south and north parts of the state, respectively, agrees with previous results based on historical observed data (Ruiz-Cárdenas, 2013). Positive rainfall anomalies are projected in southern Minas Gerais during the grain formation period (January to March). In contrast, drier conditions are expected in the north during all rainy season (October to March), affecting the normal development of fruits. All changes are more intense after 2040.

Although the projected mean annual water deficit is expected to keep below the suitability threshold of 150mm in coffee areas of southern Minas Gerais and "Zona da Mata", the need for irrigation in the rest of the state, due to intense water deficit, represents a challenge.

It is worth to note that the projected coffee zoning results found here (Figures 26 and 27) apply in a scenario where no measures were taken to respond to the effect of climate change and following the current conditions for coffee cultivation in the state. However, several actions are plausible to attenuate these effects, such as the use of new varieties with enhanced tolerance to heat and water stress, shade trees, mulching, among others.

It is necessary to study in deep the implications that the projected changes in climate found in this study would have on the coffee areas of Minas Gerais, particulary in topics like increase/decrease in levels of pests and diseases, effects on the quality of produced coffee, among others. This will be the subject of a future study.

One limitation of the present study is the use of a single run of the climate model and the consideration of only one future scenario (A1B). However, projected results were in agreement with observed trends in local climate, verified through the last five decades, which add some level of confidence to the climate projections used here.

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A Appendix

Tables 3 to 9 detail Eta-HadCM3-20km model projections and its anomalies for all the variables analysed, summarized by each of the 12 mesoregions in Minas Gerais, as defined in Figure 28.

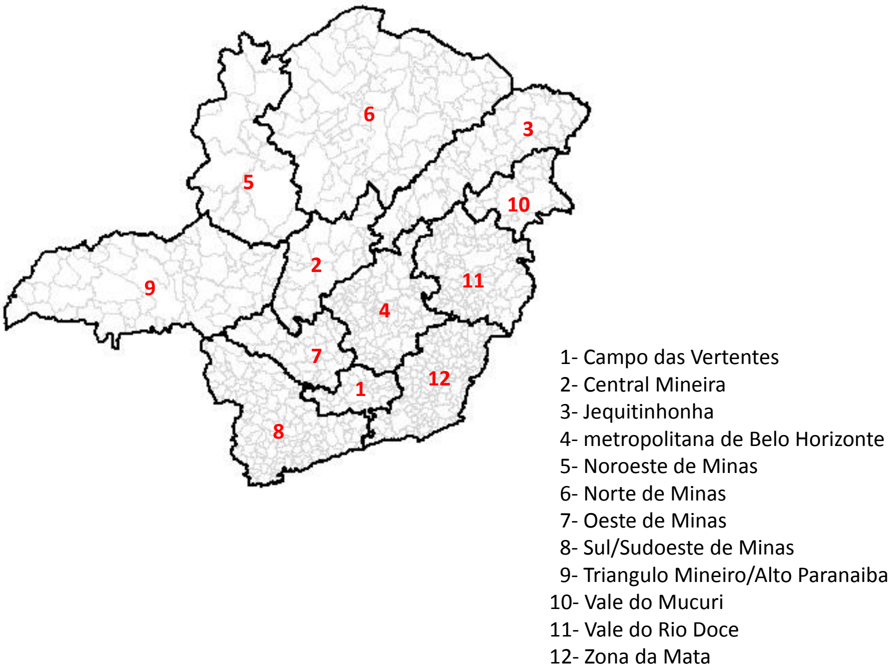

Figure 28: Mesoregions of Minas Gerais according to IBGE.

Table 3: Eta-HadCM3-20km precipitation anomalies (mm) by trimester for 2011–2040 and 2041–2070 periods (with respect to the 1961–1990 model climatology) in each mesoregion of Minas Gerais. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

Mesoregion	2011 – 2040								2041 – 2070							
	JFM		AMJ		JAS		OND		JFM		AMJ		JAS		OND	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
Noroeste de Minas	-19.4	15.0	-20.1	4.7	-15.1	4.3	-39.7	10.0	-93.4	15.8	-30.3	5.8	-6.2	4.1	-122.4	11.8
Norte de Minas	-52.3	26.8	-30.1	10.3	-13.8	4.0	-99.9	25.2	-138.2	26.7	-29.1	8.3	-7.4	5.4	-199.7	29.1
Jequitinhonha	-43.2	44.2	-41.4	14.7	-11.1	4.0	-103.6	25.2	-125.0	38.2	-38.5	11.4	-10.4	4.9	-195.2	29.8
Vale do Mucuri	-51.9	16.0	-40.4	6.4	-6.2	3.5	-112.8	10.5	-131.7	18.3	-39.1	1.7	-6.1	5.8	-193.2	11.2
Vale do Rio Doce	-6.6	29.2	-24.0	7.5	-14.5	3.7	-71.6	15.9	-79.6	33.5	-27.6	7.0	-15.3	3.6	-151.4	20.8
Central Mineira	20.4	16.2	-18.2	4.9	-13.9	1.8	-38.8	10.1	-39.8	35.8	-20.2	3.8	-9.1	1.8	-114.7	21.5
Metropolitana de Belo Horizonte	34.7	24.9	-17.8	4.5	-15.6	1.9	-54.4	11.5	-15.6	44.4	-16.3	5.2	-12.0	5.3	-96.9	31.2
Triangulo Mineiro	24.5	25.7	-15.6	9.3	-11.0	2.0	-21.1	27.1	5.2	54.9	-35.1	9.0	-4.2	2.8	-52.2	52.3
Zona da Mata	26.7	45.4	-9.4	14.9	-11.7	6.9	-45.9	23.5	3.3	57.0	-12.0	11.0	-14.2	7.3	-69.9	44.1
Oeste de Minas	59.6	19.8	-0.4	9.1	-10.7	3.0	-13.0	22.8	74.2	47.8	-12.1	10.1	-3.9	4.0	-24.7	44.8
Sul/Sudoeste de Minas	99.8	22.1	26.0	12.9	-1.2	5.9	23.7	21.2	146.6	36.2	23.4	27.3	-1.9	5.5	48.6	46.4
Campo das Vertentes	87.1	13.7	8.3	9.2	-6.0	3.9	-8.1	19.7	110.4	38.8	9.0	9.9	0.4	3.5	9.0	26.1

sd: standard deviation.

Table 4: Eta-HadCM3-20km mean climate projections for accumulated rainfall (mm) during the harvesting period (May to August) and mean rainfall anomalies for 2011–2040 and 2041–2070 periods (with respect to the 1961–1990 model climatology) in each mesoregion of Minas Gerais. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

Mesoregion	accumulated rainfall (mm)						rainfall anomaly (mm)			
	1961 – 1990		2011 – 2040		2041 – 2070		2011 – 2040		2041 – 2070	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
Noroeste de Minas	68.4	10.4	62.7	11.0	50.8	8.9	-5.7	4.7	-17.6	5.8
Norte de Minas	54.9	17.6	44.7	14.9	39.6	11.3	-10.2	4.9	-15.3	7.5
Jequitinhonha	94.5	38.9	83.9	36.3	73.5	36.0	-10.7	4.2	-20.8	6.9
Vale do Mucuri	103.1	13.7	96.5	13.4	85.2	13.3	-6.6	3.8	-17.9	2.9
Triangulo Mineiro	95.2	10.5	91.6	13.4	79.6	11.3	-3.6	4.5	-15.6	5.9
Central Mineira	57.8	11.1	50.4	12.5	46.2	12.4	-7.4	2.2	-11.5	2.3
Metropolitana de Belo Horizonte	74.7	13.8	74.2	17.3	68.4	18.7	-0.5	4.0	-6.3	5.6
Vale do Rio Doce	77.7	17.8	73.1	15.4	63.2	15.9	-4.6	4.1	-14.4	3.5
Oeste de Minas	95.1	11.3	101.4	17.3	95.0	18.6	6.3	6.4	-0.1	8.7
Zona da Mata	119.0	15.8	124.4	18.1	119.1	22.1	5.4	8.9	0.1	11.8
Sul/Sudoeste de Minas	139.4	21.1	175.5	33.1	175.5	41.7	36.2	13.1	36.1	21.5
Campo das Vertentes	118.1	7.9	138.8	14.1	140.1	15.3	20.7	7.3	22.0	8.1

sd: standard deviation.

Table 5: Eta-HadCM3-20km mean climate projections for annual rainfall (mm) and annual rainfall anomalies for 2011–2040 and 2041–2070 periods (with respect to the 1961–1990 model climatology) in each mesoregion of Minas Gerais. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

Mesoregion	annual rainfall (mm)						anomaly (mm)			
	1961 – 1990		2011 – 2040		2041 – 2070		2011 – 2040		2041 – 2070	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
Noroeste de Minas	1271	65.1	1176	76.5	1018	83.5	-94.3	20.0	-252.3	25.6
Norte de Minas	1216	68.8	1020	103.5	842	101.1	-196.0	55.9	-374.5	57.4
Jequitinhonha	1260	85.4	1060	150.7	890	146.0	-199.3	80.0	-369.1	74.1
Vale do Mucuri	1234	43.4	1023	46.3	864	31.6	-211.3	27.6	-370.1	25.5
Central Mineira	1360	42.9	1309	61.5	1176	90.2	-50.4	24.6	-183.8	57.0
Vale do Rio Doce	1337	49.5	1220	84.7	1063	94.5	-116.7	50.8	-274.0	58.6
Triangulo Mineiro	1453	46.6	1430	92.0	1367	143.7	-23.2	54.9	-86.3	109.8
Metropolitana de Belo Horizonte	1453	67.8	1400	89.6	1313	140.0	-53.1	34.7	-140.8	79.8
Zona da Mata	1466	54.5	1426	107.8	1373	138.5	-40.3	76.5	-92.8	108.1
Oeste de Minas	1493	46.9	1529	83.4	1527	142.0	35.6	49.4	33.5	101.8
Sul/Sudoeste de Minas	1564	51.1	1712	94.5	1780	142.1	148.2	53.2	216.8	101.5
Campo das Vertentes	1580	34.7	1661	57.6	1709	88.6	81.2	41.3	128.8	71.5

sd: standard deviation.

Table 6: Eta-HadCM3-20km mean climate projections for annual mean temperature (^oC) and annual mean temperature anomalies for 2011–2040 and 2041–2070 periods (with respect to the 1961–1990 model climatology) in each mesoregion of Minas Gerais. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

Mesoregion	annual mean temperature (^oC)						anomaly (^oC)			
	1961 – 1990		2011 – 2040		2041 – 2070		2011 – 2040		2041 – 2070	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
Noroeste de Minas	23.1	0.5	24.9	0.5	26.3	0.6	1.8	0.03	3.2	0.10
Norte de Minas	22.6	0.8	24.4	0.8	25.8	0.9	1.7	0.10	3.1	0.20
Jequitinhonha	21.9	0.7	23.4	0.7	24.6	0.7	1.5	0.05	2.7	0.11
Vale do Mucuri	22.2	0.5	23.7	0.4	24.9	0.4	1.5	0.05	2.6	0.07
Triangulo Mineiro	22.2	0.9	24.0	1.0	25.3	1.0	1.7	0.07	3.0	0.13
Central Mineira	22.3	0.5	24.0	0.6	25.3	0.6	1.7	0.06	3.0	0.11
Vale do Rio Doce	21.8	0.4	23.3	0.5	24.5	0.5	1.5	0.03	2.6	0.08
Metropolitana de Belo Horizonte	21.1	0.7	22.7	0.8	23.8	0.8	1.5	0.08	2.6	0.14
Oeste de Minas	21.2	0.6	22.8	0.7	23.9	0.7	1.6	0.03	2.7	0.07
Zona da Mata	20.8	0.7	22.3	0.7	23.3	0.7	1.5	0.05	2.5	0.08
Sul/Sudoeste de Minas	20.4	1.0	21.9	1.0	23.0	1.0	1.5	0.05	2.6	0.09
Campo das Vertentes	19.9	0.5	21.4	0.5	22.5	0.5	1.5	0.03	2.5	0.04

sd: standard deviation.

Table 7: Eta-HadCM3-20km mean climate projections for annual water deficit (mm) and annual water deficit anomalies for 2011–2040 and 2041–2070 periods (with respect to the 1961–1990 model climatology) in each mesoregion of Minas Gerais. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

Mesoregion	annual deficit (mm)						deficit anomaly (mm)			
	1961 – 1990		2011 – 2040		2041 – 2070		2011 – 2040		2041 – 2070	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
Noroeste de Minas	-203.2	35.4	-358.0	60.4	-597.2	121.2	-154.8	27.0	-393.9	87.8
Norte de Minas	-198.6	59.6	-363.8	99.5	-616.9	182.7	-165.2	47.1	-418.3	129.9
Jequitinhonha	-109.5	41.2	-236.9	55.7	-419.6	119.5	-127.3	48.9	-310.1	117.7
Vale do Mucuri	-105.5	13.8	-223.2	31.1	-414.6	61.4	-117.7	26.6	-309.0	58.1
Triangulo Mineiro	-123.7	35.2	-223.1	66.4	-339.9	113.9	-99.4	31.9	-216.2	79.6
Central Mineira	-162.0	26.7	-275.1	46.0	-392.2	75.1	-113.1	19.9	-230.2	49.7
Vale do Rio Doce	-114.8	26.1	-200.8	34.0	-312.3	77.4	-86.0	16.5	-197.6	62.4
Metropolitana de Belo Horizonte	-98.0	33.6	-169.1	50.3	-223.1	75.0	-71.1	17.4	-125.1	42.0
Oeste de Minas	-69.6	24.7	-115.5	44.1	-167.6	68.0	-46.0	20.5	-98.1	44.5
Zona da Mata	-41.4	19.1	-82.4	35.1	-122.8	52.8	-41.0	19.4	-81.4	35.1
Sul/Sudoeste de Minas	-28.3	22.8	-40.7	35.9	-68.3	59.8	-12.4	13.4	-40.0	37.5
Campo das Vertentes	-27.8	9.4	-43.7	17.1	-58.9	22.3	-15.9	8.6	-31.1	13.2

sd: standard deviation.

Table 8: Eta-HadCM3-20km mean climate projections for mean maximum temperature (^{o}C) during the September–November trimester and mean maximum temperature anomalies for 2011–2040 and 2041–2070 periods (with respect to the 1961–1990 model climatology) in each mesoregion of Minas Gerais. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

Mesoregion	mean maximum temperature (^{o}C)						mean maximum temperature (^{o}C)			
	1961 – 1990		2011 – 2040		2041 – 2070		2011 – 2040		2041 – 2070	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
Noroeste de Minas	30.4	0.54	32.7	0.53	34.5	0.58	2.3	0.05	4.1	0.08
Norte de Minas	29.5	1.12	31.7	1.17	33.5	1.24	2.2	0.08	4.1	0.16
Jequitinhonha	27.9	0.64	30.0	0.67	31.7	0.78	2.1	0.10	3.8	0.24
Vale do Mucuri	28.0	0.39	30.1	0.37	31.7	0.38	2.1	0.05	3.7	0.07
Triangulo Mineiro	29.3	0.88	31.6	0.96	33.2	1.01	2.3	0.09	3.9	0.15
Central Mineira	29.4	0.63	31.7	0.67	33.3	0.68	2.3	0.07	3.9	0.10
Vale do Rio Doce	28.0	0.45	30.0	0.46	31.7	0.53	2.1	0.04	3.8	0.12
Metropolitana de Belo Horizonte	27.7	0.84	29.8	0.91	31.3	0.99	2.1	0.09	3.6	0.18
Oeste de Minas	28.1	0.78	30.1	0.84	31.6	0.88	2.1	0.09	3.5	0.13
Zona da Mata	26.6	0.80	28.5	0.83	29.9	0.85	2.0	0.10	3.3	0.14
Sul/Sudoeste de Minas	26.7	1.39	28.5	1.49	29.9	1.59	1.8	0.12	3.2	0.22
Campo das Vertentes	26.2	0.62	28.0	0.63	29.4	0.66	1.9	0.05	3.2	0.07

sd: standard deviation.

Table 9: Eta-HadCM3-20km mean climate projections for mean minimum temperature (^{o}C) during the June–August trimester and mean minimum temperature anomalies for 2011–2040 and 2041–2070 periods (with respect to the 1961–1990 model climatology) in each mesoregion of Minas Gerais. Only pixels at altitudes between 600 and 1,200 m.a.s.l. were considered.

Mesoregion	mean minimum temperature (^{o}C)						mean minimum temperature (^{o}C)			
	1961 – 1990		2011 – 2040		2041 – 2070		2011 – 2040		2041 – 2070	
	mean	sd	mean	sd	mean	sd	mean	sd	mean	sd
Noroeste de Minas	13.0	0.64	14.9	0.67	15.8	0.65	1.9	0.06	2.8	0.07
Norte de Minas	13.3	0.77	14.9	0.77	15.8	0.78	1.6	0.13	2.5	0.16
Jequitinhonha	13.4	1.32	14.9	1.28	15.7	1.28	1.5	0.06	2.3	0.07
Vale do Mucuri	13.9	0.69	15.4	0.67	16.2	0.66	1.5	0.03	2.3	0.05
Central Mineira	12.1	0.51	13.9	0.53	14.7	0.53	1.8	0.06	2.7	0.07
Vale do Rio Doce	12.8	0.66	14.3	0.64	15.1	0.65	1.5	0.04	2.3	0.04
Triangulo Mineiro	11.9	0.95	13.8	1.02	14.8	1.07	2.0	0.09	2.9	0.15
Metropolitana de Belo Horizonte	11.3	0.78	12.9	0.77	13.8	0.75	1.6	0.06	2.4	0.11
Zona da Mata	11.8	0.80	13.3	0.78	14.1	0.77	1.6	0.04	2.4	0.06
Oeste de Minas	10.9	0.60	12.6	0.62	13.5	0.61	1.7	0.04	2.6	0.04
Sul/Sudoeste de Minas	10.3	0.82	12.0	0.85	12.9	0.85	1.7	0.05	2.6	0.07
Campo das Vertentes	10.0	0.47	11.7	0.46	12.6	0.45	1.7	0.03	2.5	0.05

sd: standard deviation.