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Projections of Precipitation Changes in Two Vulnerable Regions of São Paulo State, Brazil

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Abstract

Weather and climate extremes are part of the natural variability. However, the frequency and intensity of precipitation extremes have increased in the globe following the global warming. Extreme precipitation impacts such as landslides and flooding with implications to vulnerability and adaptation are discussed for two regions of the state of São Paulo: the Metropolitan Region of Campinas and the Metropolitan Region of the Baixada Santista, located in southeastern South America. Simulations and projections obtained from four integrations of the Regional Eta model are analyzed to investigate the model behavior during the period of 1961-1990 and the projections within the period of 2011-2100. Uncertainties are discussed based on the standard deviation among the model spread. The projections show precipitation increase in the Metropolitan Region of Campinas during DJF for the near and distant future, while there are more uncertainties in the other seasons. In the Metropolitan Region of Baixada Santista, the precipitation increase is projected to all seasons, except JJA, when there is higher uncertainty. Daily rainfall indices suggest an increase of precipitation during the rainy days, but a reduction in the number of rainy days in both locations. The projections show a reduction of light rains and an increase of heavy rains at both regions. The model identifies the South Atlantic Convergence Zone and frontal systems as precipitation patterns associated with extremes in the two locations. The results can be useful for adaptation actions, since the regions are highly populated and have high vulnerabilities.

Keywords

1. Introduction

World's fast-growing urban areas, especially in developing countries, will likely suffer from the consequences of climate change, a major issue facing human societies. The projected impacts of climate change are likely to require some adaptation, which in turn is based on future projections of whether adaptive capacity assets will be drawn upon in times of need [1]. Adaptive response, a component of vulnerability, is dependent on a range of variables that operate at diverse scales [1]; among them, the frequency and intensity of extreme events which are in connection to population vulnerability, may favor natural disasters.

Although part of the natural system, extreme weather and climate events can cause impacts and major disruptions in natural and human systems. The level of impacts depends on the intensity of the change and also upon the capacity of the social groupings to avoid and/or to overcome their negative effects. Therefore, aspects such as poor infrastructure facilities, inexistent or weak institutional mechanisms to cope with extremes of climate variability and change such as lack of financial resources as well as socio-spatial disparities, are potential contributors to more severe impacts of extreme weather and climate events. Because such extreme events can reduce the economic growth and development and obstruct competitiveness; their evaluation must be part of a more complex task of assessing extremes to provide knowledge and to inform societal risk relevant to adaptation [2]. Components of vulnerability include exposure, sensitivity risk and resilience [3]. Adaptation measures can contribute to reducing risks making a society less vulnerable and more resilient to extremes.

Precipitation extremes over São Paulo state have been discussed in several studies [4] [5] [6] [7] [8]. Studies on observed precipitation extremes over Southeastern Brazil, where the São Paulo state is located, are numerous [9] [10] [11], among others. Model simulations of extremes over South America, including São Paulo state were presented in [12] and [13]. Most of these studies have shown that rainfall extremes have been increasing during the last five decades, and future projections show the similar trend. Uncertainties in future of precipitation projections over South America were discussed in [14] [15] [16]. The main source of uncertainty has been identified as the differences in physical parameterizations among different models and also the possible role of urbanization, something that is not yet well represented in climate models.

In the present study, the analyses are focused on two metropolitan regions of São Paulo state using a regional model and future projections results to provide information that can be useful to adaptation measures in face of the vulnerabilities of the sites. The Metropolitan Region of Campinas (MRC) and the Metropolitan Region of Baixada Santista (MRBS) are dynamic economic centers with rich ecosystems, but also low environmental threshold[1], aggravated by the population increase and occupation of more risk-prone locations, such as hilly regions,

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[1]Natural systems can withstand disruption only up to a certain threshold (or "tipping point") beyond which ecological discontinuities with socially, economically and environmentally unacceptable and possibly irreversible consequences are likely to occur (Ecologic Institute and SERI, 2010).

which are affected by landslides or areas at risk of flooding. These actions led to relevant environmental changes during the last decades and made population more vulnerable to the impacts of extreme weather and climate.

São Paulo state is located in southeastern South America, in a region affected by the South Atlantic Convergence Zone (SACZ) [11] [17] [18] [19], a meteorological system that causes heavy and persistent precipitation. Heavy rainfall events over Southeastern Brazil have been associated with the SACZ and cold fronts [9]. In addition, these events can have the contribution of humidity flux from Amazonia, which is one of the sources of moisture to southeastern Brazil [20]. A review of large scale and synoptic systems influence on extreme precipitation over Southeastern Brazil is given in [21], where some cases during the first decade of 21st century were discussed. Positive precipitation trend identified in São Paulo city, the largest city in Brazil, during the wet season from 1933 to 2010, was attributed in part to natural climate variability and also to the urbanization effects [7]. Besides the heat island effect, the influence of sea breeze intensification due to warmer nights on the positive precipitation trend was suggested by [6].

The Eta Regional model has been used in operational weather forecasting at the Center for Weather Forecasting and Climate Studies/National Institute for Space Research (CPTEC/INPE). This model has also been used in climate simulations and projections of climate change [6] [22] [23] [24] [25]. These projections were obtained from the Eta model downscaling of the HadCM3 with four integrations using the A1B scenario, and HadGEM2-ES, MIROC5 and BESM from CMIP5, using the RCPs 4.5 and 8.5 scenarios for 1961-1990, 2010-2040, 2041-2070 and 2071-2100. Precipitation, temperature and atmospheric circulation climatology of the base period were validated against observations in [22]. The four members simulated the seasonal difference between DJF and JJA, representing the typical SACZ pattern over tropical and subtropical South America.

The model results and observed data information are presented in Section 2. In Section 3, the geographic and socio-economic features of the two metropolitan regions are informed. Section 4 indicates the precipitation changes projected by the model in the regions, the member spread and uncertainties. Extreme precipitation indices are shown in Section 5, and precipitation patterns simulated by the model in cases of extreme monthly precipitation are discussed in Section 6. Conclusions are shown in Section 7.

2. Data and Analyses

The observed precipitation data were obtained from the São Paulo state data set archive: http://www.sigrh.sp.gov.br/cgi-bin/bdhm.exe/plu. Simulation and projections were analyzed from results of the Regional Eta model, with 40 km horizontal resolution and 38 vertical levels. The lateral boundary conditions were provided by the HadCM3 coupled climate model [26] with the A1B scenario for the future projections. Four members of simulations and projections, based on

climate sensitivity were analyzed. Details of these integrations can be found in [22]. Maps of precipitation difference between two future periods (2011-2040) and (2070-2099) and the base period (1961-1990) are shown in percentages compared to the base period for the ensemble, ensemble plus and ensemble minus standard deviation among the members. Results from the four members were analyzed in the two locations, MRC and MRBS. Uncertainties are analyzed from the maps and considering members spread in the graphs.

Daily data from 1961 to 1990 (base period) and for three periods of the 21st century (2011-2040, 2041-2070 and 2071-2098) were used to calculate the precipitation indices shown in Table 1. The climatological monthly observed data and model results were used to obtain the annual cycle during the base period. Daily rain intensity was analyzed regarding class intervals of precipitation <1 mm to >51 mm. Monthly data was used to calculate the Standardized Precipitation Index (SPI). This index identifies extreme wet/dry (SPI ≥ 2.0/SPI ≤ −2.0), severe wet/dry (1.5 ≤ SPI < 2.0)/(−2 < SPI ≤ −1.5) and moderate wet/dry (1.0 ≤ SPI < 1.5)/(−1.5 < SPI ≤ −1.0) conditions. The anomalous precipitation patterns over South America associated with extreme wet monthly precipitation obtained from the 4 members in the 2 locations were analyzed in composites of precipitation anomalies for each season.

The vulnerability of each municipality is presented by means of the Social Vulnerability Index (SVI), developed by [27] which combines several variables of the 2010 Brazil census to indicate the vulnerability of each municipality. The SVI seeks to highlight the social inequality scenario in each metropolitan region, indicative of exclusion and social vulnerability, and was constructed using sixteen indicators grouped into three main dimensions: urban infrastructure, human capital and income and employment. Each dimension corresponds to a set of assets, resources or structures whose access, absence or failure indicate that the pattern of family life is low, suggesting, in extreme cases, the lack of access and non-compliance of social rights. Each variable has a relative weight, revealing their importance for the whole index.

The first dimension, the urban infrastructure vulnerability, reflects the conditions of access to basic sanitation and urban mobility and has three variables, each one with a weight in the index: percentage of people in households with inadequate water and sewage (0.3); percentage of population living in households without regular waste collection services (0.3); percentage of people living in households below poverty estimate and who spend more than one hour a day commuting (0.4). The second dimension, human capital, involves health and education

Table 1. Daily precipitation indices.

SDII	Mean Precipitation of rainy days >1 mm	mm/day
SDII_10	Mean Precipitation of days ≥10 mm	mm/day
R1	Number of rainy days	%
R10	Number of days with precipitation ≥10 mm	%

and has 8 indicators, each one weighted 0.125. The third and last dimension, income and employment, is composed of five indicators, each one weighted 0.2. The combination of the variables allows a unique value of exclusion and social vulnerability to the cities of the metropolitan regions. The SVI ranges between 0 and 1, the closer to 1, the greater the social vulnerability of a given municipality. Classes of social vulnerability are: 0 - 0.2 very low; 0.2 - 0.3 low; 0.3 - 0.4 medium; 0.4 - 0.5 high; and above 0.5 very high.

3. The Metropolitan Regions-Geographical and Socio-Economic Features

3.1. The Metropolitan Region of Campinas (MRC)

Created in 19 June 2000, the Metropolitan Region of Campinas (MRC, Figure 1(a)) has 20 municipalities (one aggregated to the region in 2015 only), spread over 3,791 km^2, with a population estimated in 3,094,181 inhabitants. The Gross Domestic Product (GDP) of the MRC is R$98.5 billion and its Human Development Index (HDI), 0.792 [27]. The MRC is a center for research and development of science, technology and innovation in Brazil, concentrating more than 50 branches of the 500 largest companies in the world and accounting for 10% of Brazilian industrial production in various sectors, such as automotive, textile, metallurgy, food, pharmaceutical, petrochemical, telecommunications and electronics. Agriculture (fruits, coffee and sugar-cane) and services are also important activities in this region. The International Airport of Viracopos, in Campinas, is one of the most important of the country, especially due to its role in cargo transport. The area has undergone rapid social, economic and environmental transformations and despite its economic vitality, as in many other fast-growing urban areas, the unplanned growth of the city has led to an increasing inability to house the growing population and to provide adequate infrastructure. Part of the population lives in areas at great risk to natural disasters, including those expected to worsen with climate change, like floods.

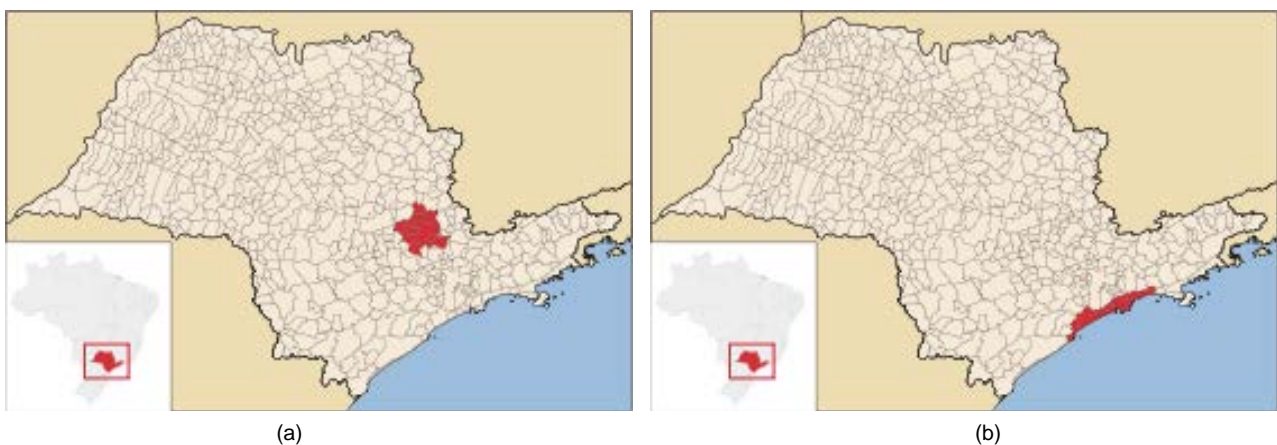Impacts produced by precipitation excess in Campinas, the main city of the

(a)   (b)

Figure 1. Locations of (a) Metropolitan Region of Campinas (MRC), (b) Metropolitan Region of Baixada Santista (MRBS) in relation to the state of São Paulo and Brazil (Source: Wikepedia).

region, have increased in number and types between 1958 and 2007 and have affected all social classes [28]. During the same period, changes in the distribution of extreme precipitation events were also verified, especially in the last two decades, with increase in the annual totals and in the frequency of daily events above 50 mm [29]. Notwithstanding, the increase of impacts triggered by precipitation shows that the severe impacts were associated not only with the magnitude of the rain totals, but also with the increased exposure of the population [30]. Precipitation totals are variable within the area (Table 2), higher totals occurring during spring and summer periods. In order to evaluate the weight of the largest amounts in the precipitation time series, the Concentration Index [31], which considers the contribution of the days of greatest rainfall to the entire series, was applied to the area, for a period spanning from 1958 to 2003 [32]. The authors verified that rainfall was quite concentrated, as a large proportion of the total precipitation during the entire period (70%) was registered on 25% of the days only. Death tolls due to weather events are on decrease after improvements on weather forecasting and preventive measures, but losses are still huge and many other challenges remain, like irregular occupation of risk-prone areas and lack of a responsive and efficient flood warning system. Although there are several individual studies related to these issues, there is a need to design and implement, in a coordinated way, a coherent and comprehensive understanding of the problems in the area.

3.2. The Metropolitan Region of Baixada Santista (MRBS)

The Metropolitan Region of Baixada Santista (MRBS), at the eastern edge of the Atlantic Ocean (Figure 1(b)), is the oldest settlement of Brazil, encompassing 9 municipalities spread in an area of 2421 km^2, being home of 1,664,136 inhabitants. The region presents rich ecosystems and extensive climatic and topographic diversity, but the rapid urban expansion rate of the area in the last decades promoted a comprehensive disturb in its ecological dynamics (only 7% of the original vegetation remain), as well as in the energy and water consumption. The Metropolitan Human Development Index (HDI) is 0.777 and the Gross Domestic Product (GDP) is R$47.3 billion [27]. The precipitation totals in the MRBS are high but variable spatially, as can be seen in Table 3. Concentration is more

Table 2. Average, maximum and minimum precipitation (1960-1999) to selected rain gauges within the MRC (Source: DAEE; CTH/USP; SIGRH, 2005).

Municipality	Alt. (m)	Lat. (S)	Lon. (W)	Avg. 1960-1999 (mm)	Annual Max. (mm)	Annual Min. (mm)
Holambra	600	23˚38'	47˚03'	1323.6	2,172.6 (1983)	878.9 (1968)
Pedreira	590	22˚45'	46˚56'	2456.2	2,456.2 (1983)	900.7 (1963)
Itatiba	780	23˚01'	45˚50'	2441.9	2,441.9 (1983)	587.7 (1978)
Americana	540	22˚42'	47˚17'	2017.8	2,017.8 (1983)	738.4 (1968)
Cosmópolis	560	22˚40'	47˚13'	1989.5	1,989.5 (1983)	770.6 (1968)
Campinas	600	22˚47'	47˚02'	2342.5	2,342.5 (1983)	885.7 (1963)

Table 3. Average, maximum and minimum precipitation (1960-1999) to selected rain gauges within the MRBS (Source: DAEE; CTH/USP; SIGRH, 2005).

Municipality	Alt. (m)	Lat. (S)	Lon. (W)	Avg. 1960-1999 (mm)	Annual Max. (mm)	Annual Min. (mm)
Bertioga	720	23˚45'	46˚08'	4657.4	7391.1 (1947)	1758.2 (2001)
Cubatão	5	23˚52'	46˚23'	2520.5	4138.6 (1947)	1754.8 (1963)
Guarujá	3	23˚57'	46˚11'	2306.4	5973.1 (1947)	1364.7 (1938)
Itanhaém	3	24˚11'	46˚48'	2132.4	3327.8 (1966)	358.1 (2000)
Mongaguá	20	24˚05'	46˚37'	2723.5	4129.2 (1995)	1422.5 (2002)
Santos	200	23˚53'	46˚13'	3375.6	5559.3 (1947)	1946.8 (2001)
São Vicente	10	23˚57'	46˚27'	2351.9	3176.1 (1973)	1425.5 (2001)

acute during summer, which coincides with an increase of tourism activities and thus, exposes more people to the risk of floods and landslides. Evaluating how concentrated was daily rainfall from 1958 to 2003, [32] found that few events registered very high rainfall amounts. Concentrated amounts of rainfall can largely impact the affected areas, causing flooding, erosion, landslide; in some situations high precipitation can be associated with storm surges, that bring major loss of property and life, reduce the economic growth and obstruct competitiveness.

In some sectors of the MRBS the high deforestation rate associated with the occupation of sites next to rivers or steeply slopes and the intense precipitation episodes have caused major natural disasters, as a large number of people live in areas at risk of mass movements and flooding. This occupational pattern and the pollution generated by the industrial complexes affected the vegetation, which originally protected the slopes and soils, leading to erosion landslides, mudslides and floods. Deforestation also reduced the water retention capacity of the soil, increased continental runoff and contributed to biodiversity losses.

The GDP of the MRBS corresponds to approximately US$21.9 billion and large-scale economic interests include the Port of Santos, the largest and more important of Latin America and the main logistic center of Brazil, as around a quarter of the products value traded in the country in the international market passes by this harbor. In addition, it is part of the largest system of road-rail transport and waterways (Tietê-Paraná) of the country and handles more than 90 million tons per year. The recent oil finds in the ultra-deep Pre-salt layer of Santos Basin is creating new demands for infrastructure, transport and communication, which might continue to exert strong pressure in this coastal sector (Governo do Estado de São Paulo, Secretaria de Desenvolvimento Metropolitano 2011).

3.3. Social Vulnerability in MRC and MRBS

Social vulnerability refers to the resilience of people when confronted by stresses, among them weather-related disasters. Inside the two metropolitan regions, dif-

ferences of infrastructure, security and availability of public spaces influence the welfare levels of individuals and families. In Table 4 and Figure 2, that present the SVI for the municipalities of the MRC, one can see that all cities present low to medium social vulnerability. Four of them, including Campinas—the seat of the MR, regional leader on economic development and home of 1,080,999 people present the highest values of SVI for the region. Campinas has experienced fast social, economic and environmental changes and presents deficiencies in the infrastructure. The urbanization rate is high and partially uncontrolled and uncoordinated, resulting in disperses clusters over space. Because people are more scattered, the costs of infrastructure and public services tend to be higher [33] and might pose additional problems in a situation of danger. Also in the MRBS all municipalities present low to medium social vulnerability (Table 5, Figure 3). However, five in nine present the highest values of SVI for the region. Santos, the center of the MRBS is the only city that has very low SVI. The differences among the cities of the MRBS expose the fact that although the Metropolitan Region should operate in a combined way to promote an equal and comprehensive development, important internal differences concerning vulnerability remain within the area.

Table 4. Social vulnerability index for each municipality of the MRC.

	Municipality	SVI (2010)
1	Americana	0.149
2	Artur Nogueira	0.260
3	Campinas	0.277
4	Cosmópolis	0.205
5	Engenheiro Coelho	0.284
6	Holambra	0.117
7	Hortolândia	0.308
8	Indaiatuba	0.154
9	Itatiba	0.178
10	Jaguariúna	0.198
11	Monte Mor	0.326
12	Nova Odessa	0.177
13	Paulínia	0.211
14	Pedreira	0.137
15	Santa Bárbara D'Oeste	0.174
16	Santo Antônio de Posse	0.216
17	Sumaré	0.244
18	Valinhos	0.179
19	Vinhedo	0.175
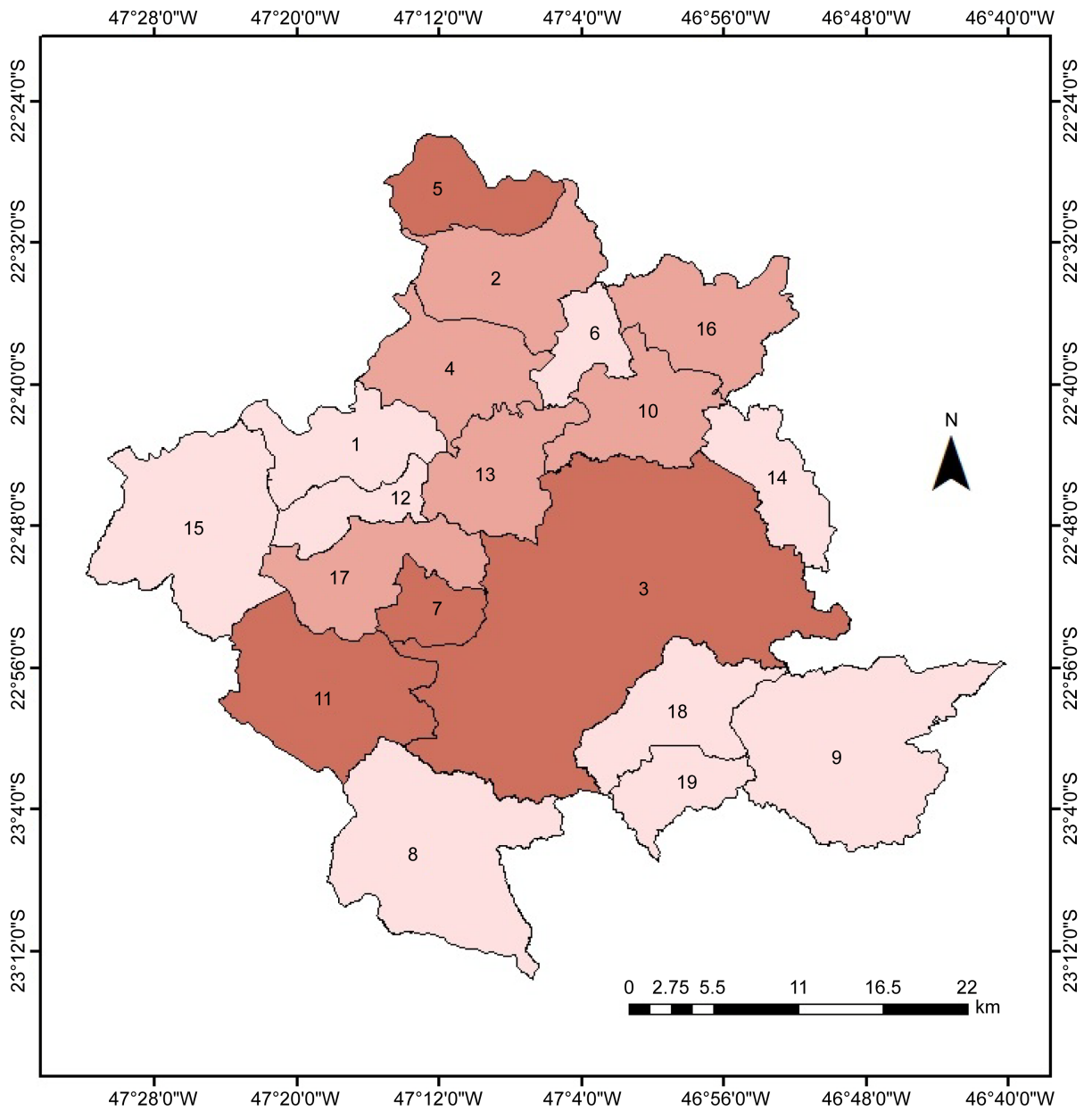
Figure 2. Social vulnerability index for the municipalities of MRC.

Legend:

- 0.117000 - 0.192000
- 0.192001 - 0.268000
- 0.268001 - 0.344000
- 0.344001 - 0.420000
- 0.420001 - 0.496000

1 - AMERICANA
2 - ARTUR NOGUEIRA
3 - CAMPINAS
4 - COSMÓPOLIS
5 - ENGENHEIRO COELHO
6 - HOLAMBRA
7 - HORTOLÂNDIA
8 - INDAIATUBA
9 - ITATIBA
10 - JAGUARIÚNA

11 - MONTE MOR
12 - NOVA ODESSA
13 - PAULÍNIA
14 - PEDREIRA
15 - SANTA BÁRBARA D'OESTE
16 - SANTO ANTÔNIO DE POSSE
17 - SUMARÉ
18 - VALINHOS
19 - VINHEDO

Table 5. Social vulnerability index for each municipality of the MRBS.

	Municipality	SVI (2000)	SVI (2010)
1	Bertioga	0.288	0.224
2	Cubatão	0.353	0.292
3	Guarujá	0.376	0.285
4	Itanhaém	0.359	0.250
5	Mongaguá	0.411	0.273
6	Peruíbe	0.372	0.245
7	Praia Grande	0.405	0.319
8	Santos	0.233	0.170
9	São Vicente	0.398	0.311

Reducing social vulnerability can decrease both human suffering and economic loss. As the two regions present high vulnerabilities regarding precipitation events leading to flooding and landslides, changes due to the global warming need to be assessed to improve adaptation actions. Therefore, in the next sections, future projections of precipitation are analyzed from model results, focusing in the two metropolitan regions.

4. Precipitation Changes Projected by the Regional Eta Model in the Metropolitan Region of Campinas (MRC) and Metropolitan Region of Baixada Santista (MRBS)

Results from the Eta-HadCM3 model simulations from the base period (1961-1990) and model projections for the future are discussed in this section. The annual cycle of observed and model ensemble precipitation in MRC and MRBS are shown in Figure 4. The annual cycles are reasonably well simulated, although with overestimated values in MRC and underestimated values in MRBS, where there is larger underestimation in the austral summer and autumn. The differences between the two annual cycles are likely related to the different precipitation regime between the two regions. In Figure 4, it is seen that at MRC, located relatively far from the ocean, the precipitation regime presents a seasonal contrast, with large amounts during summer, when a series of processes operate in the area bringing more moisture, and when there is development of the SACZ, while precipitation in winter, when the atmospheric circulation is different from summer, is primarily linked to the cold fronts. On the other hand, although MRBS is also affected by the SACZ, it presents lower inter- and intra seasonal variability and larger precipitation than MRC during the whole year as it is influenced by the humidity advection from the sea. In addition, the reduction from the summer to autumn and winter is gradual, while in MRC there is a greater reduction. The monthly differences between the future periods and the base period are indicated by the columns in Figure 4. There is a dominance of rainfall increase from late spring to early winter, in the three future periods, in
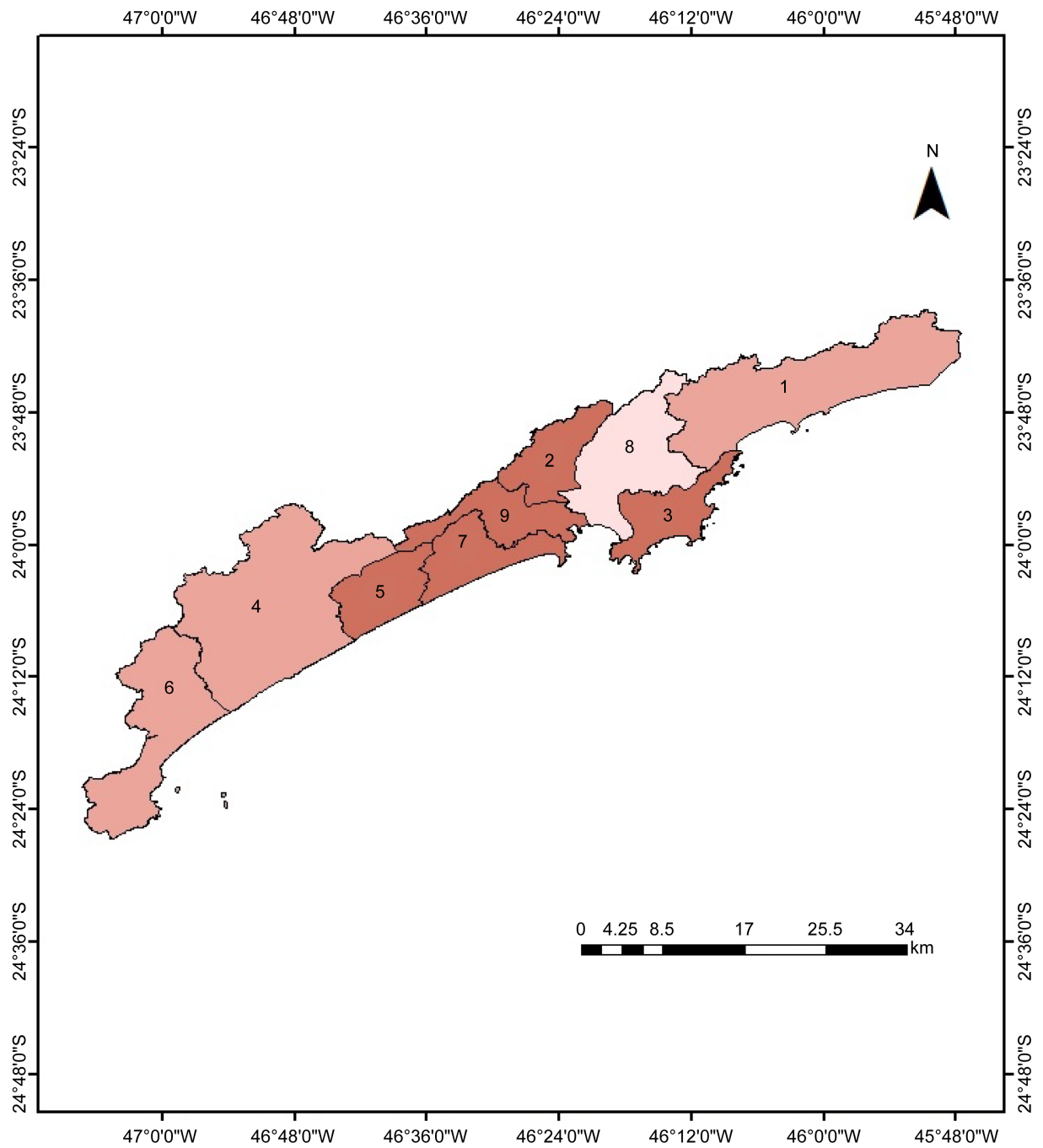
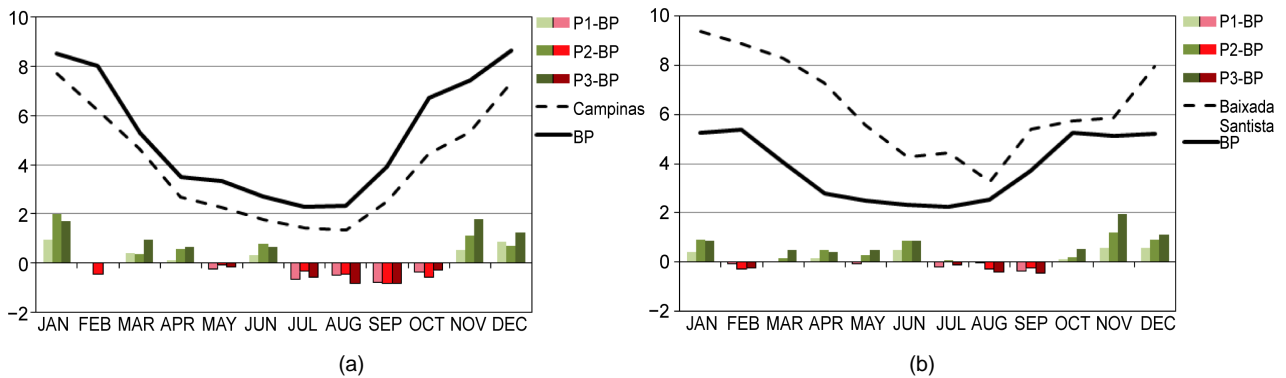**Figure 3.** Social vulnerability index for the municipalities of MRBS.

☐ 0.170000 - 0.192000	1 - BERTIOGA 6 - PERUÍBE
☐ 0.192001 - 0.268000	2 - CUBATO 7 - PRAIA GRANDE
☐ 0.268001 - 0.344000	3 - GUARUJÁ 8 - SANTOS
☐ 0.344001 - 0.420000	4 - ITANHAÉM 9 - SÃO VICENTE
☐ 0.420001 - 0.496000	5 - MONGAGUÁ

Figure 4. Annual cycle of precipitation. Model during Base Period (BP) of 1961-1990 (solid line). Observation during 1961-1990 (dashed line). Columns are the differences between future periods and base period. P1: (2011-2040) - (1961-1990), P2: (2041-2070) - (1961-1990), P3: (2070-2099) - (1961-1990). (a) MRC, (b) MRBS.

MRC. Reduced rainfall is projected from middle winter to middle spring. At MRBS small reductions are projected for August and September. From middle spring to early winter the projections show increased precipitation except in February and July, when there is a very small reduction. Then, in both locations, the rainy season is projected to be wetter and the dry season to be drier than in the base period.

Spatial changes in two future periods: near future (2011-2040) and distant future (2070-2099) compared to the base period (1961-1990) of MRC and MRBS are shown in **Figures 5-8**. The uncertainties are discussed in terms of the standard deviation among the members. The ensemble mean, ensemble mean plus or minus one standard deviation indicate large or small uncertainties and the members spread. In DJF (2011-2040) the ensemble mean indicates an increase of precipitation between 5% and 10% at MRC (**Figure 5(a)**). The increase interval is between 0% and 20%, from the ensemble minus to the ensemble plus. During DJF (2070-2099) the range of increase is between 10% to 20% in the ensemble and between 0% to 30% from the ensemble minus to the ensemble plus (**Figure 5(b)**). At MRBS the projections also show precipitation increase for the ensemble between 0% and 5% in the majority of municipalities (**Figure 5(c)**). Compared to the MRC, the uncertainty is larger at MRBS, since the ensemble minus standard deviation indicates a reduction between 0% and 5% and the ensemble plus standard deviation indicates an increase between 5% and 10% (**Figure 5(c)**). The uncertainty at MRBS is reduced during DJF (2070-2099) since the ensemble, ensemble minus and ensemble plus indicate increases between 0% and 20% (**Figure 5(d)**). **Figure 9** shows the spread among the four members of precipitation differences between three future periods and the base period. At MRC all members show increased precipitation in the future periods during DJF, indicating a convergence in the model response and then more confidence on the results (**Figure 9(a)**). At MRBS there is convergence among the members on precipitation increase during the last two future time slices (**Figure 9(b)**).

In MAM (**Figure 6(a)**), the uncertainties range from −10% to 20% at MRC during the period (2011-2040) and between −5% and 30% during (2070-2099),
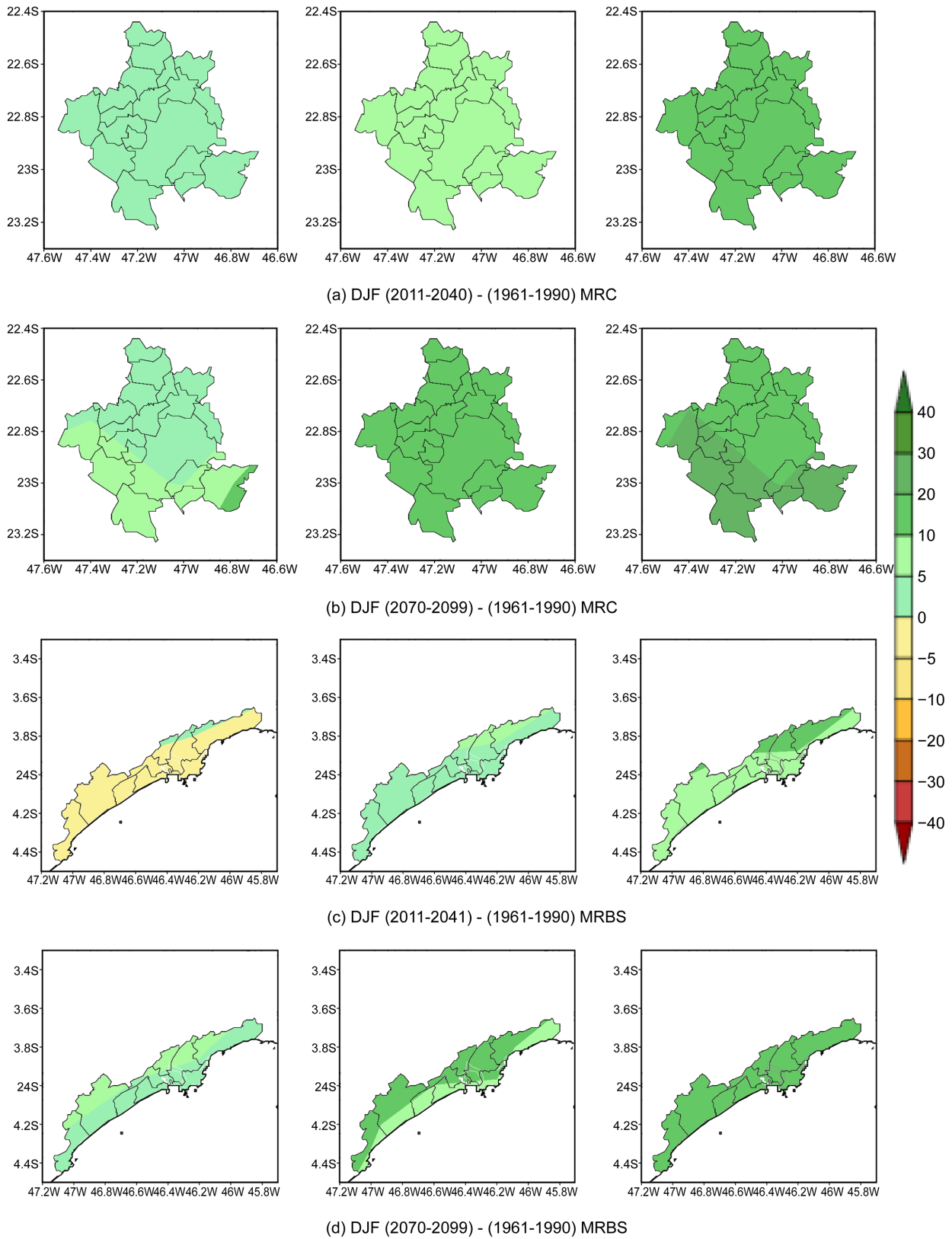
Figure 5. Difference of precipitation in DJF between future projections and the base period in % for the ensemble minus standard deviation among members (left panel), ensemble (middle panel) and ensemble plus standard deviation among members (right panel). (a) (2011-2040) - (1961-1990) at MRC, (b) (2070-2099) - (1961-1990) at MRC, (c) (2011-2040) - (1961-1990) at MRBS, (d) (2070-2099) - (1961-1990) at MRBS.
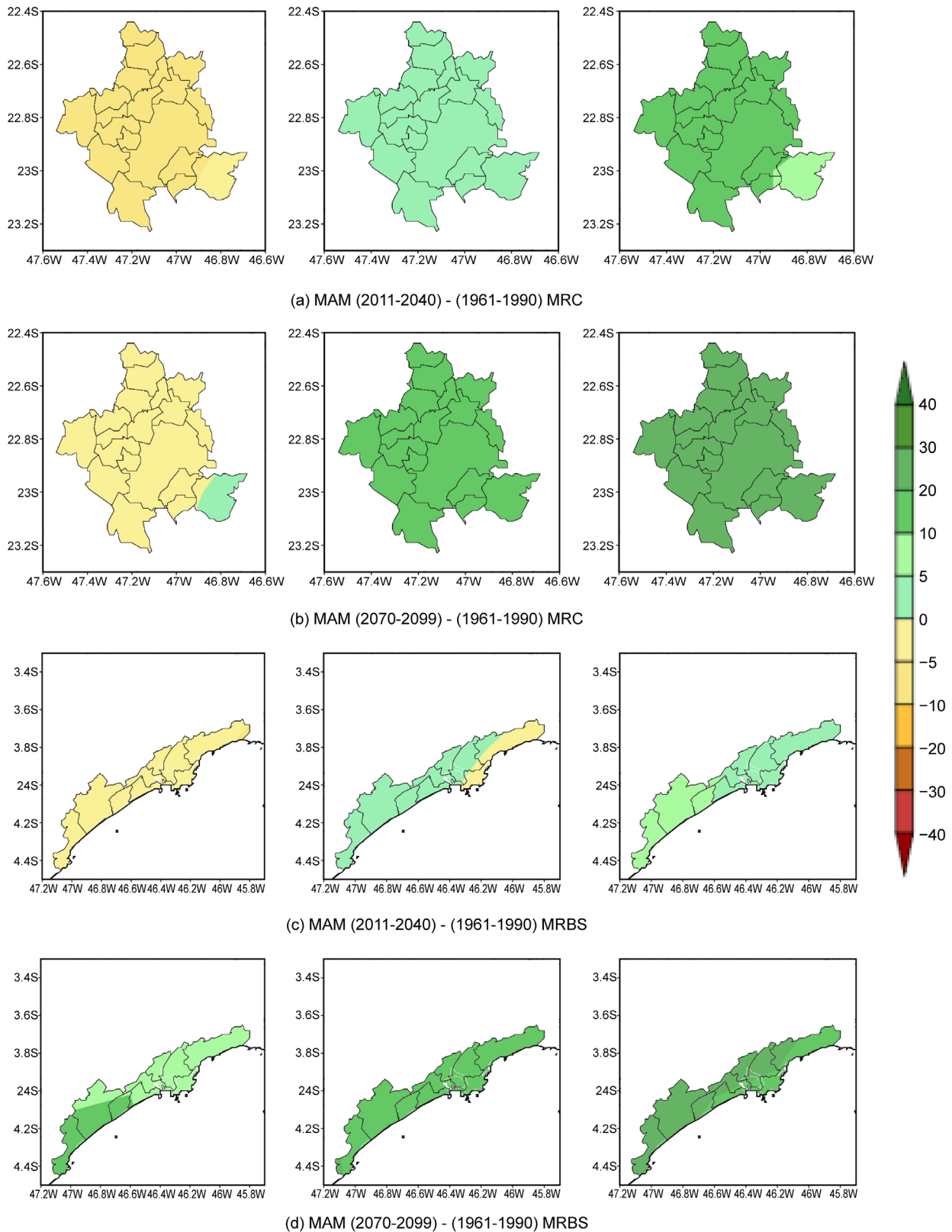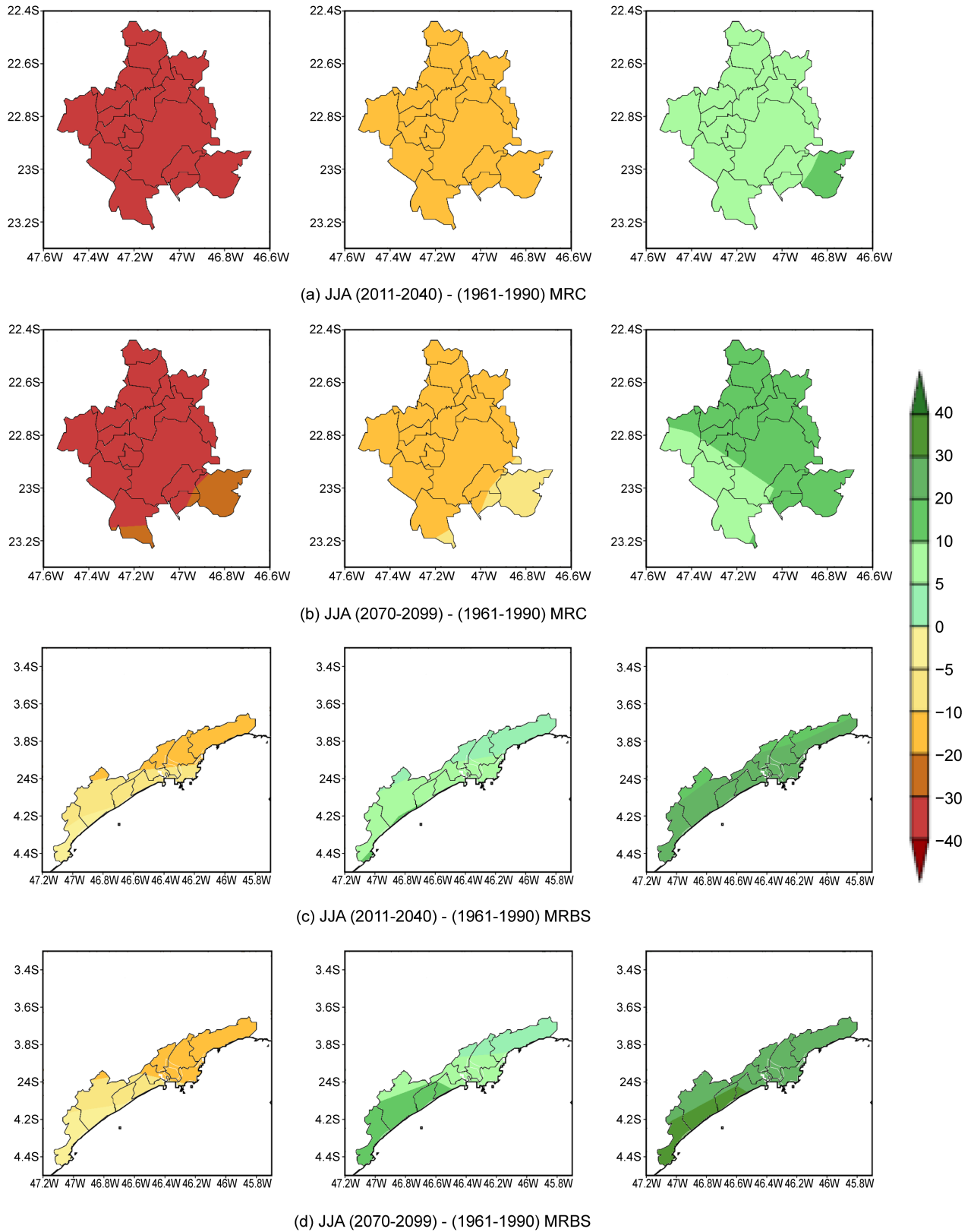
Figure 6. Difference of precipitation in MAM between future projections and the base period in % for the ensemble minus standard deviation among members (left panel), ensemble (middle panel) and ensemble plus standard deviation among members (right panel). (a) (2011-2040) - (1961-1990) at MRC, (b) (2070-2099) - (1961-1990) at MRC, (c) (2011-2040) - (1961-1990) at MRBS, (d) (2070-2099) - (1961-1990) at MRBS.
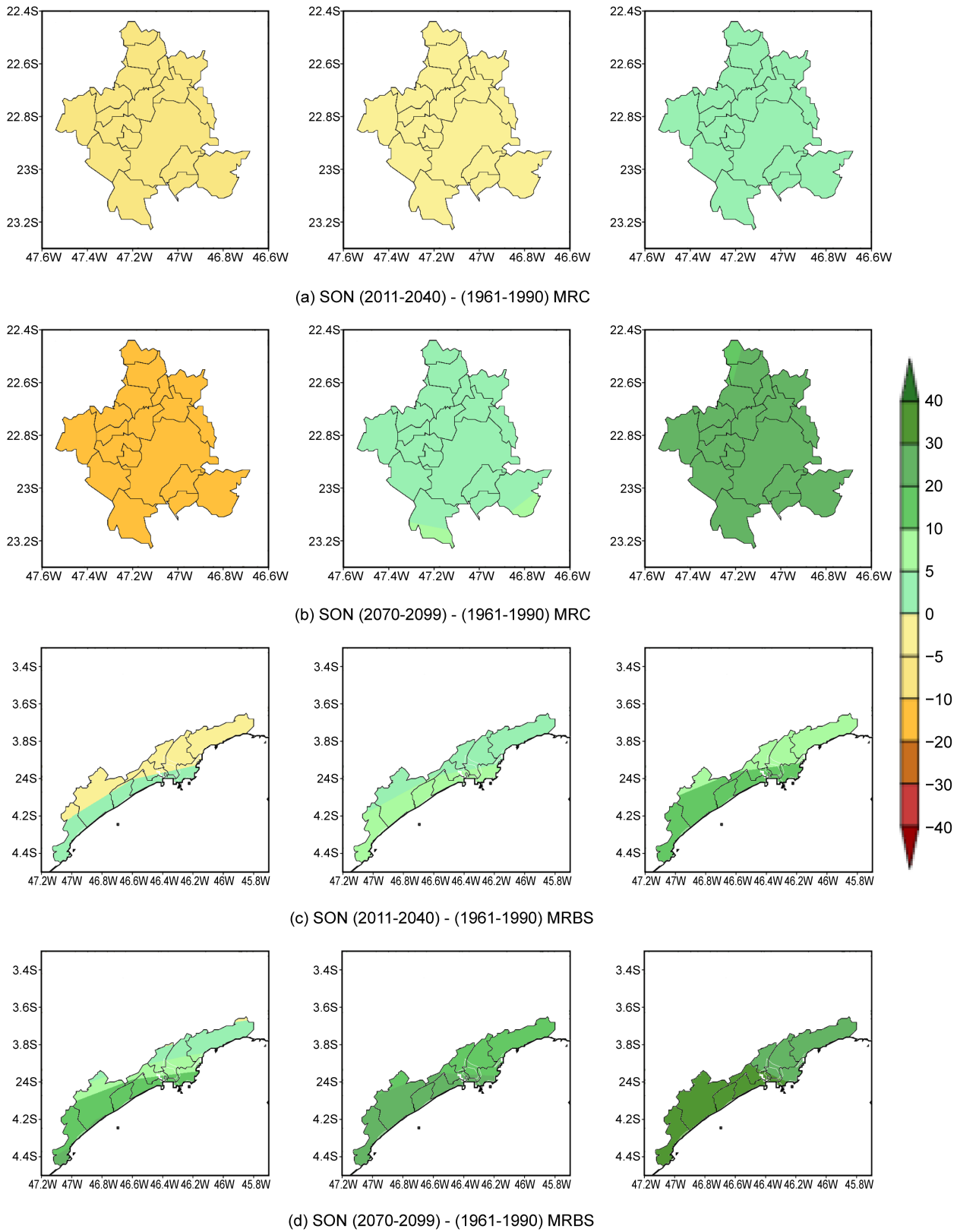
Figure 7. Difference of precipitation in JJA between future projections and the base period in % for the ensemble minus standard deviation among members (left panel), ensemble (middle panel) and ensemble plus standard deviation among members (right panel). (a) (2011-2040) - (1961-1990) at MRC, (b) (2070-2099) - (1961-1990) at MRC, (c) (2011-2040) - (1961-1990) at MRBS, (d) (2070-2099) - (1961-1990) at MRBS.
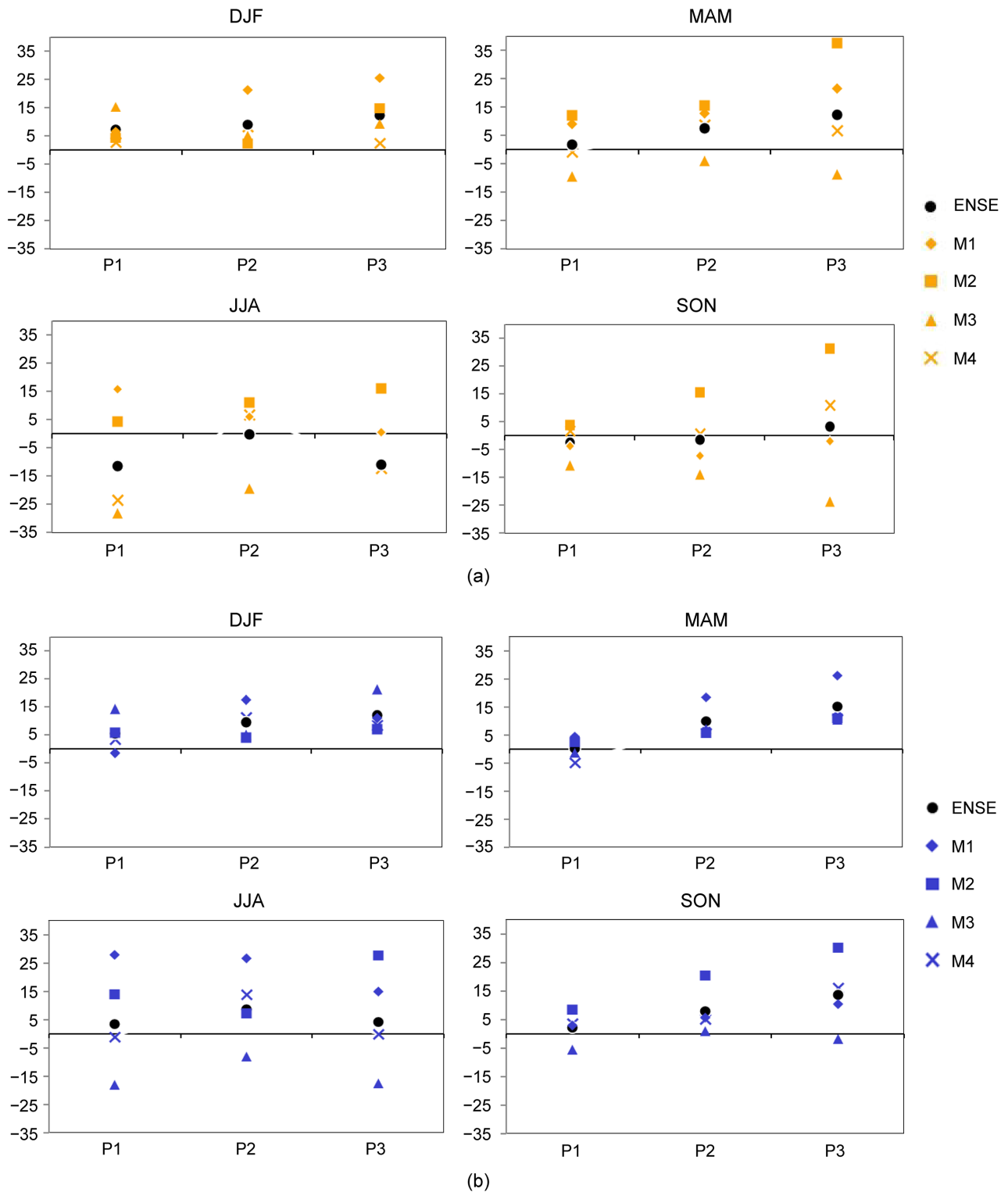
Figure 8. Difference of precipitation in SON between future projections and the base period in % for the ensemble minus standard deviation among members (left panel), ensemble (middle panel) and ensemble plus standard deviation among members (right panel). (a) (2011-2040) - (1961-1990) at MRC, (b) (2070-2099) - (1961-1990) at MRC, (c) (2011-2040) - (1961-1990) at MRBS, (d) (2070-2099) - (1961-1990) at MRBS.

Figure 9. Precipitation difference between future projections and base period. (a) MRC, (b) MRBS. P1: (2011-2040) - (1961-1990), P2: (2041-2070) - (1961-1990), P3: (2070-2099) - (1961-1990).

(**Figure 6(b)**). At MRBS the interval is between −5% to 10% (**Figure 6(c)**) during (2011-2040) and the uncertainties reduce during (2070-2099) as the changes show increase between 10% and 30% (**Figure 6(d)**). The spread in **Figure 9**

shows precipitation increase in the majority of members in both locations. JJA (2011-2040) and (2070-2099) present the larger uncertainties regarding the standard deviation among the members in both regions (Figure 7). The ensemble minus the standard deviation shows reduced precipitation in both locations and the ensemble plus the standard deviation shows increased precipitation. The interval ranges from −40% to 10% in MRC and from −20% to 30% in MRBS during (2011-2040). During (2070-2099) the intervals change from −40% to 20% in MRC and from −10% to 30% in MRBS. The uncertainties are also seen in the spread (Figure 9), although the ensemble shows reduction during two future periods in MRC and increase during three future periods in MRBS. In SON, MRC displays changes between −10% and 5% and MRBS changes between −5% and 20% during (2011-2040) (Figure 8(a), Figure 8(c)). The interval of changes increases in (2070-2099) from −20% to 30% in MRC and between 0% and 40% in MRBS (Figure 8(b), Figure 8(d)). Therefore the uncertainties in SON are larger in MRC than in MRBS, which is also seen in Figure 9 that shows precipitation increase in MRBS projected by the ensemble and the majority of members, while in MRC there is large spread among the members.

5. Precipitation Indices

The indices of Table 1 are shown in Figure 10(a) and Figure 10(b) for MRC and MRBS, respectively. SDII and SDII10 are well represented by the model, while R1 and R10 are overestimated in MRC. In this location, the projections show a gradual increase in the mean precipitation above 1mm (SDII) and 10 mm (SDII10) from the base period (1961-1990) to the last period of 21st century (2071-2098), with low spread among the members, represented by the minimum and maximum values. The number of rainy days (R1) reduces along the period, while there are small changes in the number of days with heavier precipitation (R10). The concurrent reduction of rainy days and precipitation increase, in the future, indicate more intense rains concentrated in a few days. In MRBS the model underestimates the four indices, but there is also an increase of SDII and SDII10 and reduction of R1.

The changes in the distributions of rain intensity are presented in Figure 11 (MRC) and Figure 12 (MRBS). In MRC there is an increase of days without rain in two future periods (2011-2040) and (2041-2070), but in (2071-2100) the uncertainty is high, since there are two members with opposite changes. There are less days with light rains in the three future periods, and the reduction is larger in the last period. The number of heavy rain increases, mainly in the last two periods (Figure 11(b)). In MRBS (Figure 12) the behavior of the days without rain is similar, with increase of dry days in the first two future periods and more uncertainty in the last. There is also a reduction of days with light rains and increase of heavy rains in the future projections. This result is consistent with other studies over South America that show an increase in the frequency of daily precipitation extremes in future periods [6] [24] [34].
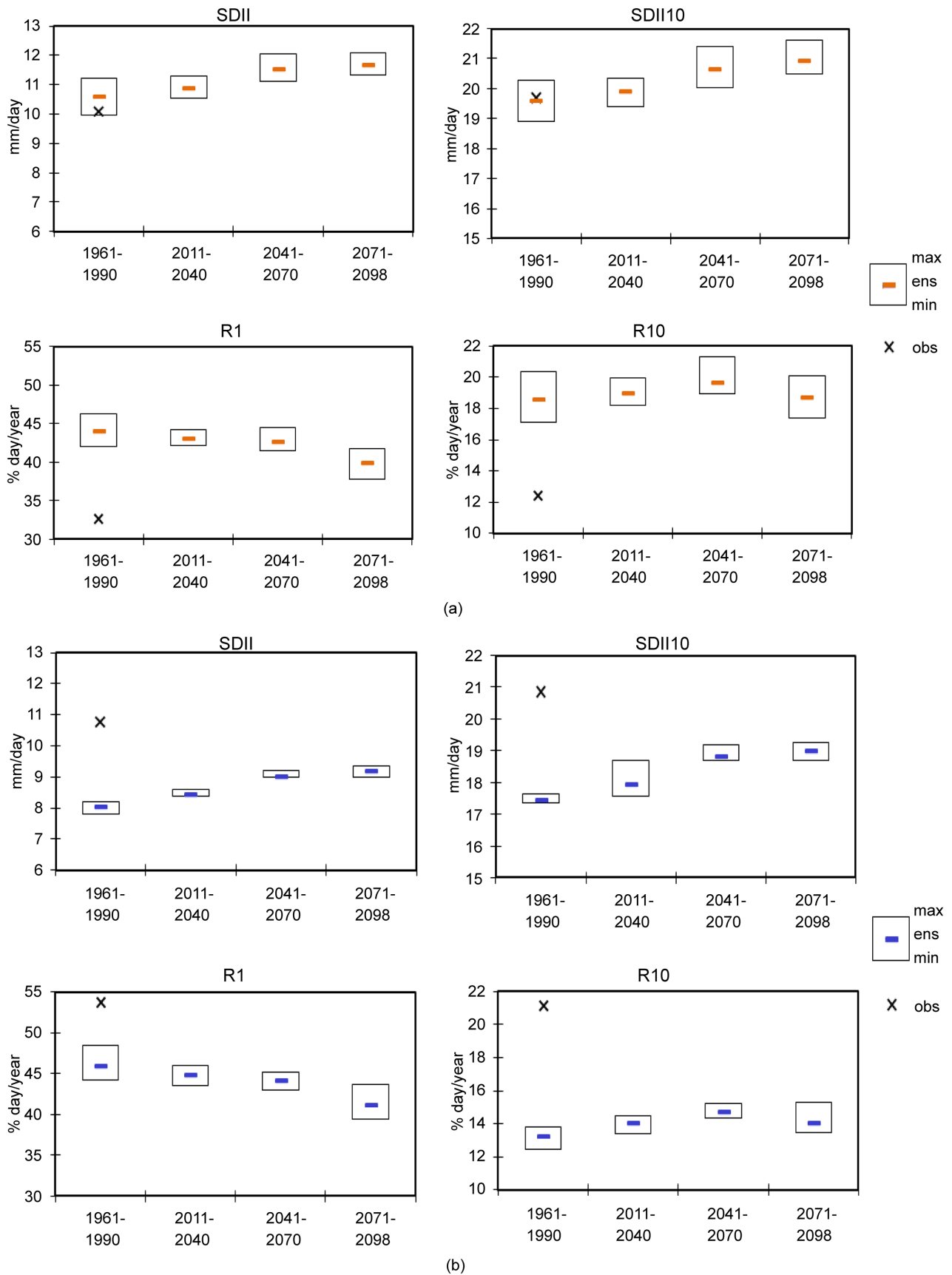
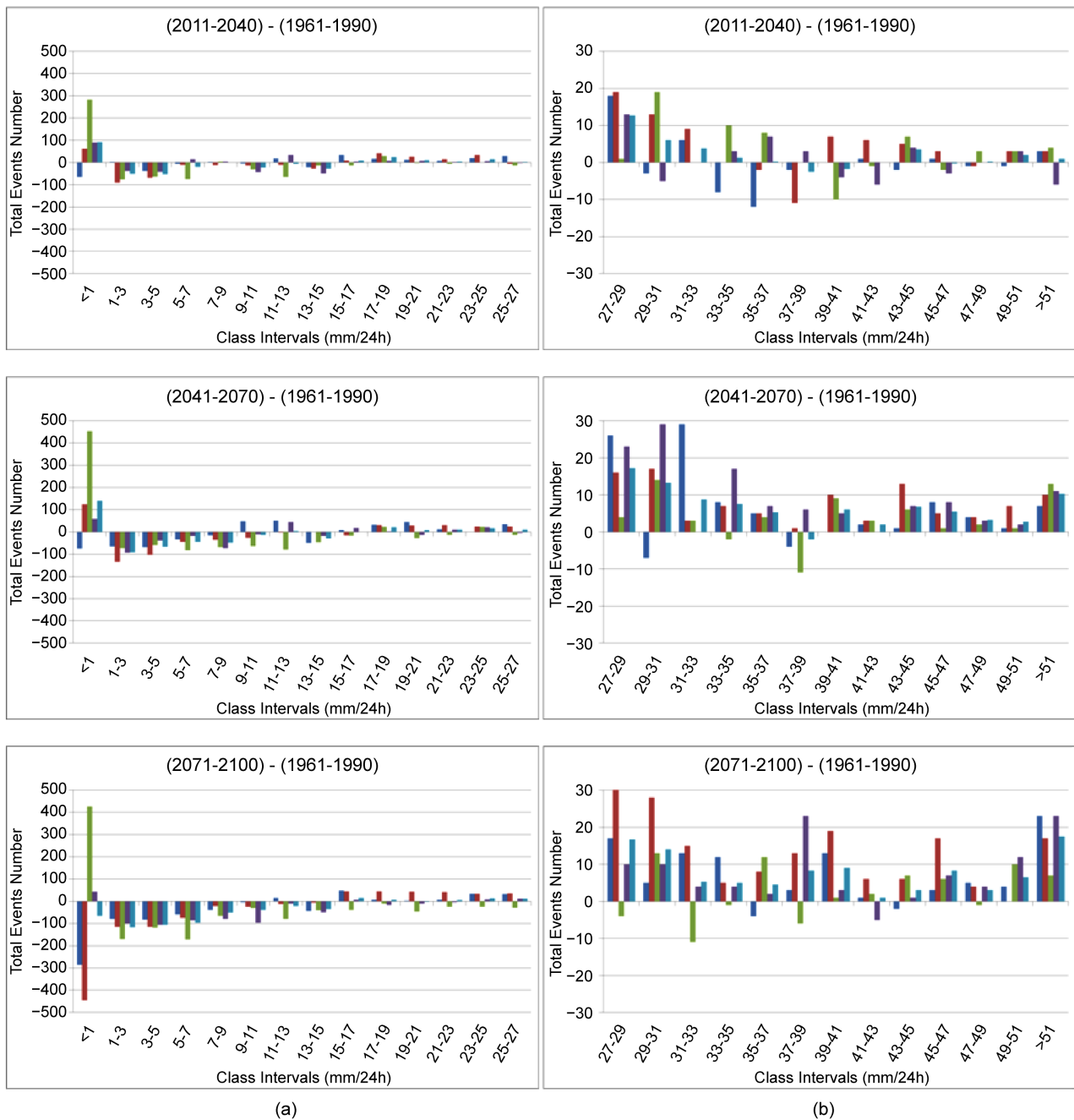**Figure 10.** Precipitation indices of SDII, SDII10, R1 and R10. (a) MRC, (b) MRBS.

Figure 11. Frequency distribution of precipitation events in MRC. (a) Precipitation <1 - 27 mm/day, (b) Precipitation between 27 and >51 mm/day.

6. Patterns of Extreme Monthly Precipitation

Besides the heavy daily precipitation, which can cause damages in the two metropolitan regions, as discussed in session 3, monthly extremes are also important to agriculture and water resources. These are calculated from the Standard Precipitation Index (SPI), which identifies extreme, severe and moderate monthly events. As the SPI is calculated from anomalies relative to the climatology of each period, the results do not show a systematic change in the frequency of extreme, severe and moderate cases from the base to the future periods.
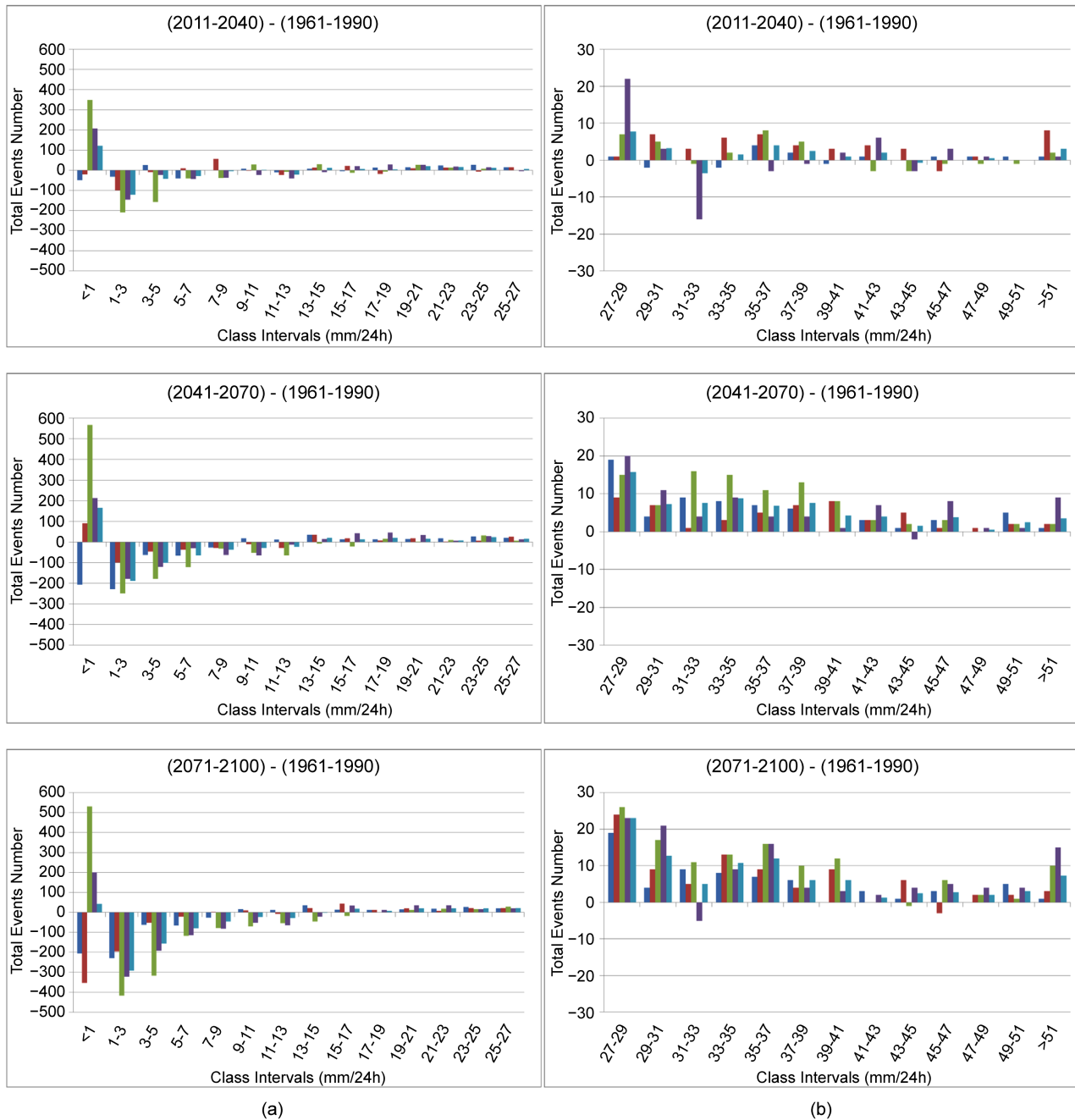
Figure 12. Frequency distribution of precipitation events in MRBS. (a) Precipitation <1 - 27 mm/day, (b) Precipitation between 27 and >51 mm/day.

In order to see what is the simulated precipitation pattern related to the extremes in the two locations, seasonal composites from extreme wet monthly events during the base period were analyzed. Composites for each region showed similar patterns; therefore we show the composites regarding the selected cases of precipitation extremes in both regions of MRC and MRBS (**Figure 13**). In DJF the pattern resembles the dipole associated with the SACZ variability [11] [18] [19] [35] and indicates, in this case, the weakness or southward displacement of the SACZ (**Figure 13(a)**). Previous studies show that this dipole is related to the
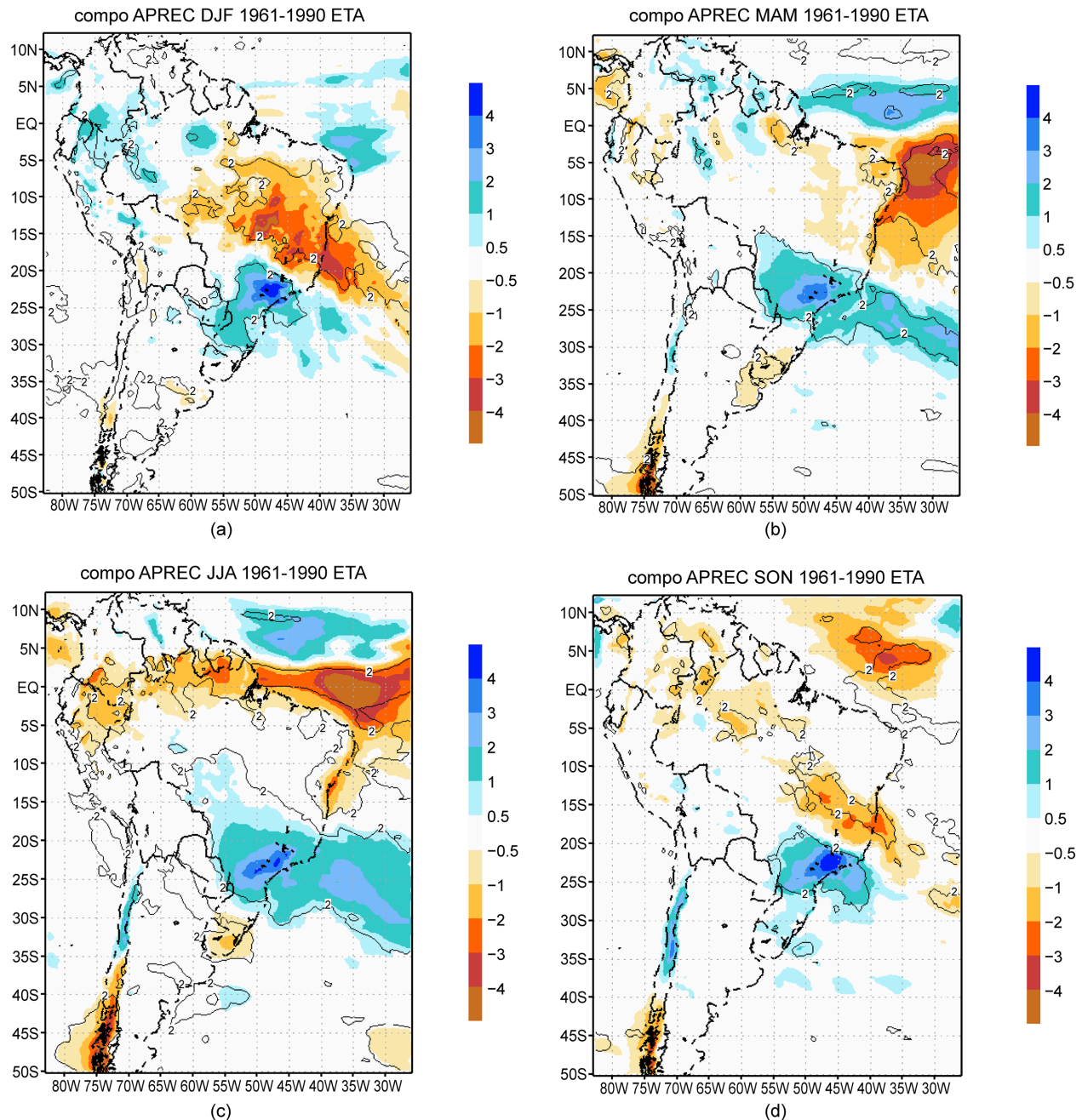
Figure 13. Composites of extreme wet monthly precipitation in MRC and MRBS in each season (mm/day) simulated by the Eta model during 1961-1990. The contour lines indicate regions with significance greater than 95%.

Pacific South America (PSA) wave-train pattern [10] [19] [35] and humidity flux from the Amazon region [36]. In MAM the pattern may show the influence of frequent or/and persistent frontal systems. Dry conditions to the north, mainly related to the ITCZ displaced northwards may indicate a large scale subsidence which traps the frontal systems over part of southeast and south regions (**Figure 13(b)**). In JJA the pattern indicates again the presence of frontal systems and dry conditions in the tropical region (**Figure 13(c)**). The precipitation dipole returns in SON, season that marks the beginning of the rainy season in the South Amer-

ica Monsoon region [37] [38] [39], although weaker than in DJF (**Figure 13(d)**).

It is also noted a precipitation dipole over Chile, which indicates the displacement of synoptic systems northward of the normal track. Therefore, the regional ETA model represents well the patterns associated with extreme monthly precipitation in the two regions of southeastern Brazil. It identifies the pattern of frontal systems, in MAM and JJA, and the influence of the SACZ in DJF and SON. The impact of these systems on observed extreme precipitation over Southeastern Brazil have been discussed in several studies, such as [9] [11] [22]. The ability of the ETA model in identifying seasonal patterns of extreme precipitation related to the influence of observed systems can increase the confidence on model results, reducing uncertainties, and also can be useful for seasonal predictions.

7. Conclusions

The two metropolitan regions (MRC and MRBS) are vulnerable in face of climate change. The model underestimates precipitation in MRBS, but represents well the annual precipitation cycle in MRC, although with overestimated values. In MRC, the projections in the near and distant future periods show precipitation increase during DJF, while there are more uncertainties in the other seasons. In MRBS, precipitation increase is projected during DJF, MAM and SON of the last period of the 21st century. The uncertainties are larger in JJA in both locations. The ensemble mean shows increased precipitation from late spring to middle summer and reduced precipitation from middle winter to early spring months, indicating drier conditions in the dry season and wetter conditions in the rainy season. The increase in the summer season and the decrease in the spring are consistent with [40] which discusses the delay in the South American Monsoon System due to drier conditions in this later season in future projections. In MRBS, the reduction from middle winter to early spring is very small, likely due to the location close to the sea. The projections show a precipitation increase during the rainy days and a reduction of the rainy days' number in both areas, indicating intensity increase in future projections.

The changes may impact the economy and may increase social problems due to floods and droughts in MRC and floods and landslides in MRBS. The vulnerabilities and the impacts of climate change need to be considered in adaptation actions in both regions. Even disregarding the effects of climate change, adaptation to the existing level of changes in both study areas is already critical. Due to the rapid transformation of these lively metropolitan regions, which place population at greater risk for natural disasters, including those expected to worsen with climate change, new challenges are posed, among them to understand and respond to the complex interactions between urban development and the climate system in view of building more resilient and adapted cities.

Acknowledgements

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