Vol. ■■
doi: 10.3354/cr01324

CLIMATE RESEARCH
Clim Res

Published ■■

C 1324 31 Jul 2015 CE: VK TS: LJ PP: CF Marengo JA, Alves LM, Torres RR

Contribution to the Theme Section 'Xxxxx'

Regional climate change scenarios in the Brazilian Pantanal watershed

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ABSTRACT: In the Brazilian Pantanal, hydrometeorological conditions exhibit a large interannual variability. This variability includes the seasonality of floods and droughts which can be related to land surface processes and to El Niño/La Niña. Based on regional climate change projections derived from the Eta-HadGEM2 ES models with 20 km latitude−longitude resolution for the RCP8.5 for 2071−2100, it is expected that there will be an annual mean warming of up to or above 5−7°C and a 30% reduction in rainfall by the end of the 21st century. As a consequence of higher temperatures and reduced rainfall, an increased water deficit would be expected, particularly in the central and eastern parts of the basin during spring and summer, which could affect the pulse of the Paraguay River. While the changes projected by the Eta-HadGEM2 ES are consistent with the changes produced by the CMIP5 models for the same scenario and time slice, we can affirm that changes in the hydrology of the Pantanal are uncertain, because in a comparison of CMIP5 and Eta-HadGEM2 ES model projections, some show increases in rainfall and in the discharges of the Paraguay Basin, while others show reductions.

KEY WORDS: Climate change · Pantanal · Hydrology · River levels · Rainfall

1. INTRODUCTION

The Pantanal region in South America, one of world's largest wetlands, is located in a large floodplain in the center of the upper Paraguay River basin. The basin has an area of around 360 000 km^2, of which the Pantanal occupies about 140 000 km^2, comprising one of world's largest wetlands. During the summer rainy season (November–March), the rivers overflow their banks and flood the adjacent lowlands, inundating as much as 70% of the floodplain by July and forming shallow lakes and innumerable swamps and marshes and leaving island-like areas of higher ground. Large sectors of the Pantanal floodplain are submerged from 4 to 8 mo each year by water depths ranging from a few cm to more than 2 m. During the drier winter season (April–September), the rivers withdraw to their banks, but the lowlands are only partially drained. The water leaves via the Paraguay River and eventually into the Paraná River, leaving behind grasslands that support grazing animals.

Human activities in the region such as navigation, cattle ranching, and farming, are strongly regulated by this hydrologic regime. For instance, the available land for cattle ranching and farming is dependent on the extent of the inundation during each wet season. Several human activities, such as agriculture, cattle ranching, dam building, and other changes in hydraulic conditions, are threatening the Pantanal's ecological balance (Tucci & Clarke 1998, Hamilton 1999, 2002, Da Silva & Girard 2004).

The strategic ecological and economic importance of the Pantanal region has motivated the development of international and interdisciplinary projects.

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Two of the most important are the CLARIS LPB (Boulanger et al. 2011) and SINERGIA (Girard et al. 2014), which are dedicated to the investigation of impacts of natural climate variability and anthropogenic changes in the La Plata basin, and to the discussion of strategies for adaptation to these changes.

The Pantanal functions as a large reservoir that stores water from the surrounding plateaus during the rainy season and then delivers it slowly to the lower sections of the Paraguay River, delaying for almost 6 mo the maximum flows to the Parana River, thereby minimizing downstream flooding. As a result, any significant change in the rainfall pattern is likely to have major impacts on the local ecology and socioeconomic relations. The peak flood season for the lower Paraná River basin is 2 to 3 mo earlier than the flood season for the upper Paraguay River. Without the Pantanal, the 2 flood seasons would be simultaneous, with severe consequences for downstream inhabitants.

Therefore, climate change could have severe impacts on the hydrology of the Pantanal (Ioris et al. 2014), with serious socioecological consequences (Bergier 2013). Furthermore, changes in climate conditions in the region may also cause significant disturbances in the functioning of the ecosystem, mostly by altering precipitation and evapotranspiration rates, which in turn may affect river flow regime and floodplain inundation dynamics. The impacts of climate change may even amplify and worsen undesirable consequences of some human interventions on hydrologic conditions of the basin (Bravo et al. 2014).

This paper focuses on estimating the effects of climate change on climate and hydrology of the region up to the end of the 21st century. For this we review some of the model projections of climate generated from the IPCC AR4 as derived by Bravo et al. (2014), and the IPCC AR5 as derived by Torres & Marengo (2013) and Marengo et al. (2014). With this background, we assess the regional climate change projections for the Pantanal region as generated from the dynamic downscaling of the HadGEM2-ES global IPCC AR5 model using the Eta regional model run with a resolution of 20 km latitude−longitude generated by Chou et al. (2014a,b). The changes in rainfall, temperature, and water balance (precipitation minus evaporation, P−E) are considered in order to investigate comprehensively the possible impacts of climate change over the Pantanal region in this study. This paper is one of the contributions of the CLARIS LPB project.

2. CLIMATE AND HYDROLOGY FEATURES IN THE PANTANAL

The Pantanal is a semi-arid region. The rainy season begins in October and ends in April, bringing monthly precipitation ranging from approximately 100 to 300 mm. In the dry period, monthly precipitation ranges from 0 to 100 mm, with lower year-to-year variability than in the rainy period. During the years 1968−2000, annual average precipitation ranged from 920 to 1540 mm, with a mean value of 1320 mm (Bravo et al. 2014). Rainfall shows inter-annual variability with higher or lower rainwater amounts that have caused either severe floods or pronounced dry seasons that influence the flooding. Large-scale climate phenomena such as El Niño, La Niña, or the variability linked to the Atlantic Ocean as well as regional-scale water balance, soil wetness, and soil moisture storage influence the seasonality of floods and droughts in the Pantanal (Bergier 2010).

Regarding long-term rainfall variability, Marcuzzo et al. (2010) and Cardoso & Marcuzzo (2010) analyzed the monthly trends in precipitation from 1977−2006 from 12 rain gauge stations in the Brazilian Pantanal and noted a small decrease in precipitation with a pronounced inter-annual variability. The La Plata Basin in general has seen an increase in annual precipitation in the last 40 yr, on the order of 10% over most of the region, but in some places it has reached 30% or more (Castañeda & Barros 1994).

Furthermore, the role of land surface processes in the hydrology of the Pantanal was highlighted by Clarke (2005). Collischonn et al. (2001) assessed the flow records from the Paraguay, Paraná, Negro, and Uruguay Rivers in the La Plata Basin, and rainfall records from other parts of South America, and found strong evidence of changes in the runoff regime of the La Plata basin during the last 40 yr, not all of which can be attributed to land-use change.

Analysis of the 105 yr record of annual flood peaks of the Paraguay River at Ladário, downstream of the Pantanal wetland, shows strong evidence of a serial correlation between flood peaks in successive years, and the sequence of annual flood peaks is well-represented by a lag-1 autoregression (Clarke 2005). Clarke (2005) found that no direct relation could be established between Ladário flood peaks and the limited records of Pantanal rainfall and also showed that there appears not to be any relation between Ladário flood peaks and El Niño/La Niña events. Fig. 1 shows that there is no consistency in the signals from El Niño or La Niña and peaks or lows in the Ladário records. The large volume of natural storage within a drainage

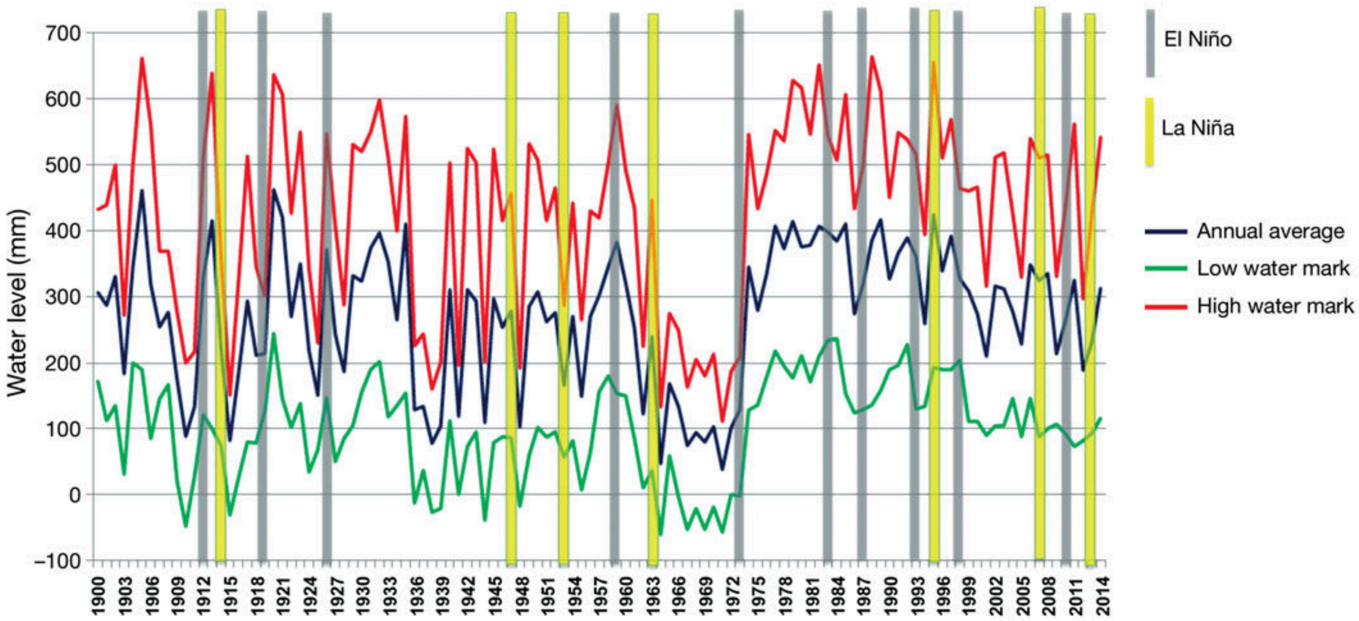

Fig. 1. Time series of the Rio Paraguay water levels (mm) at Ladario/Paraguay. Source: Agencia Nacional de Aguas, Brazil (www.ana.gov.br). The occurrences of El Niño and La Niña are indicated by grey and yellow bars, respectively (www.cptec.inpe.br)

basin has a marked effect on its regime of hydrologic extremes. This is somewhat responsible for the lower climate predictability in the region, since soil moisture and natural water storage are still not well represented in climate models (Marengo et al. 2003).

Alho & Silva (2012) showed that during the period from 1962/1963–1972/1973 the Pantanal was unusually dry, as shown in Fig. 1. This was then followed by a long wet period, which lasted until at least 2000. During the 11 yr dry period, there were no records of flooding, except for 1965–1966, when the observed water level was 16 cm above the 0 mark (82.4 m in relation to sea level), and the majority of the flooding peaks were between 1 and 2 m. Since 1973/1974, the Pantanal has been experiencing a period of inundations, with the flood gauge registering its peak at Ladário in 1988, with a 6.64 m reading. This was considered the Pantanal's greatest-ever inundation. This wet period, which has already lasted for 38 yr, is the longest recorded for the region and is different from the previous periods in that the phreatic water (the upper surface of the soil, which forms the water table) rises throughout the entire year, which results in lower intra-annual and interannual variation in droughts and floods. Furthermore, the position of the average river watermark has remained between 3 and 4 m and the minimum mark between 1 and 2 m for the greater part of each year (Marengo et al. 2014)

In 2006, the Ladário station registered a level of 5.40 m, which was considered by Soares et al. (2008) as the highest flood peak since 1997, but according to Gonçalves et al. (2011), the year with the most memorable floods due to high Paraguay River levels was 1988. During the record flow in 1988, about 95% of the Pantanal plain was flooded. During the outflow of 2007, the Ladário station registered one of the lowest minimum levels of the last 34 yr, viz. 88 cm on 3 November 2007. A dry period between 2010 and 2012 showed a water level of 85 cm; however, the lowest on record was in 1964–1973 with 75 cm (Fig. 1). According to Fantin-Cruz et al. (2011), the highest flood was that of 1995, when the floodplain was flooded to a mean depth of 2.56 m. The median flood event (return period 2 yr) produced a mean flood depth 1.80 m and lasted 119 d.

3. DESCRIPTION OF GLOBAL AND REGIONAL MODELS USED TO DERIVE REGIONAL CLIMATE CHANGE PROJECTIONS FOR THE PANTANAL

For the purposes of this study, we used the regional climate change scenarios derived from the downscaling of the HadGEM2-ES (Collins et al. 2011) global model via the Eta regional model, run at a horizontal resolution of 20 km, as generated by Chou et al. (2014a,b). Global climate models are the major tool used to provide information on climate change under different greenhouse gas emission scenarios; however, the grid sizes of these models are about 200 to 100 km. Local features, such as topography, river basins, and coastlines, may not be sufficiently captured in the simulations carried out by those global models. The regional climate models play the important role of downscaling the global climate simulations to smaller grid sizes in the area of interest where the impact studies can be carried out.

The following review by Chou et al. (2014a,b) describes the global and regional models used, the emission scenario Representative Concentration Pathways (RCPs) used, and the projections from the HadGEM2-ES global and the Eta-HadGEM2-ES regional climate projections. The HadGEM2-ES is a global climate model of earth system category developed by the Hadley Centre (Collins et al. 2011, Martin et al. 2011). The latitude–longitude resolution is about 1.875 × 1.275°, and there are 38 levels in the atmosphere. It has a dynamic vegetation scheme with carbon cycle representation. A list of major characteristics and references for this model can be found in Table 9.A.1 in Chou et al. (2014a).

The Eta model has been adapted to run for long-term integrations (Pesquero et al. 2010, Chou et al. 2012, Marengo et al. 2012). The dynamics of the model are developed in the eta vertical coordinate (Mesinger 1984), which is the most suitable to operate in regions of steep orography such as the Andes Cordillera in South and Central America. The model updates the equivalent CO_2 concentration every 3 yr. Vegetation greenness varies monthly, but the type of vegetation is kept the same during the integration period. The model does not have ocean dynamics. The sea surface temperature is taken from each global model output and is updated daily in the regional Eta model. Initial soil moisture and soil temperature come from the respective GCMs. Update of soil conditions follows the NOAH land surface scheme (Ek et al. 2003). Lateral boundaries are updated with global model state variables at 6 h intervals. The regional model resolution is approximately 20 km in the horizontal and 38 layers in the vertical. The top of the model is at 25 hPa.

The model domain encompasses most of South America and Central America and part of the adjacent oceans, but our analyses will be focused on the Pantanal area. In this work, the version of the Eta model updated by Mesinger et al. (2012) is adapted for climate change studies and it is applied to develop impact and vulnerability studies (Resende et al. 2011, Rodrigues et al. 2011, Matos et al. 2012) and for the Brazilian Third National Communication to the United Nations Framework on Climate Change Convention (UNFCCC).

The emission scenarios used for the Eta-HadGEM2 ES runs were the RCP scenarios RCP8.5 and 4.5, which correspond to the range from pessimistic to optimistic (Van Vuuren et al. 2012). The RCP8.5 represents a larger radiative forcing and is similar to a high-emission scenario (SRES A1 or A2), while RCP4.5 represents an intermediate scenario, similar to SRES A1B. The global climate models used in the IPCC AR5, in general, have shown improvement over the previous models used in IPCC AR4, in particular the simulations of precipitation over the tropical areas. The Eta-HasGEM2 ES model was run for RCP4.5 and 8.5, for the time slices 2011–2040, 2041–2070, and 2071–2100, with the baseline of 1961–1990. However, in this study we focus on the RCP8.5-based projections.

In the following, we show a review of simulations and future climate change projections from the Eta-HadGEM2 ES for South America and the La Plata basin, followed by a review of projections from the CMIP3 and CMIP5 models for the Pantanal region.

3.1. Present climate from the Eta-HadGEM2 ES

Chou et al. (2014a) indicated that the Eta-HadGEM2 simulations of the present (1961–1990) reproduce the general regional-scale climatological features over the South American continent. However, temperature is generally underestimated in the Eta simulations as shown in the spatial distribution and the mean annual cycle, and the simulations also show a large negative bias in precipitation in northern Brazil during summer, with a positive bias in the southern part of Amazonia in winter. Some error features are inherited from the global model HadGEM2-ES, such as the double precipitation band of the ITCZ. Model bias over mountainous areas, either for temperature or precipitation, is still uncertain due to the scarcity of observations over those areas.

The amplitude of the annual cycle of precipitation simulated by the Eta-HadGEM2 ES model is generally smaller than the respective driver global model precipitation, especially during the austral summertime rainy season (DJF). This causes the Eta simulations to reproduce a better annual cycle of precipitation in the central and northeastern regions of Brazil, where global model precipitation is excessive during the rainy period.

In the Amazon region, precipitation is underestimated by the Eta-HadGEM2 ES and by the global HadGEM2-ES models. Despite the errors shown in the evaluation of the simulated present climate by Chou et al. (2014a), the nested simulations contain the major features of the South American climatology.

3.2. Future climate from the Eta-HadGEM2 ES

For the future, Chou et al. (2014b) assessed the 4 sets of downscaling simulations based on the Eta regional model forced by the HadGEM2-ES for the 2 RCP scenarios, 8.5 and 4.5. Focusing on the RCP8.5 scenario, there is a projected warming in the central part of Brazil. In austral summer, there is a reduction of precipitation in the central part of Brazil and in northeastern Brazil, while there is an increase in the southeastern part of the continent toward the end of the century. In austral winter, a precipitation decrease is found in the northern part of South America and in most of Central America. A major change is the reduction in precipitation in southeastern Brazil toward the end of the century. The northern part of northeastern Brazil shows negative rainfall anomalies in the RCP8.5 Eta-HadGEM2 ES scenario. The frequency distributions of temperature and precipitation show the inclusion of extreme high values as the time slices advance toward the end of the 21st century.

In the La Plata Basin (LPB), a warming of about 3–5°C is projected during summer and winter by the end of the century, while increases in precipitation of about 2–4 mm d^{-1} are projected for the LPB region in summer. In winter this increase is about 1–3 mm d^{-1} but is concentrated mostly over the coastal region. Events of extreme heavy rainfall become more frequent in southeastern South America, and in 2071–2100, a reduction in consecutive dry days is detected. This increase in rainfall extremes is consistent with a wetter LPB by the end of the century, mainly in summer (Chou et al. 2014b).

4. ASSESSMENT OF GLOBAL AND REGIONAL CLIMATE CHANGE PROJECTIONS FOR THE PANTANAL BASED ON IPCC AR4 AND AR5 MODELS: A REVIEW

We use the following studies as the main references for the climate change projections in the region based on the ensemble of global climate models: Bravo et al. (2014) for the CMIP3 IPCC AR4 global models, and Torres & Marengo (2013), Marengo et al. (2014), and Kirtman et al. (2013) for the CMIP5. The CMIP3 models used the A2 and B2 emission scenarios while the CMIP5 models used the RCP4.5 and 8.5. Climate changes simulated in the CMIP3 and CMIP5 ensembles are not directly comparable because of the differences in prescribed forcing agents (e.g. CO_2 and aerosols) between the SRES and RCP scenarios. Furthermore, the models may respond differently to a specific radiative forcing due to different model-specific climate sensitivities. However, based on the underlying radiative forcing (or CO_2 concentrations), one can compare projected changes in the temperature and precipitation indices and provide an estimate of uncertainty related to the different emission scenarios.

4.1. Ensemble of CMIP3 models

For the A2 scenario in terms of areal average values over the basin, and considering the mean values among all the CMIP3 models, the monthly temperature anomalies projected for scenario A2 for 2010–2040 (Bravo et al. 2014) ranged from +0.88°C in February up to +1.48°C in October. A pattern of positive anomalies was very clear for the projections throughout the entire year, despite the dispersion among results of the models. For each month, the difference among results of the 20 CMIP3 models was relatively large, with more discrepancies in February, March, and April, when both temperature increases and decreases are projected, and in September and October, where there was the largest range of projected temperature increases (from +0.29 to +3.3°C in September, and from +0.66 to +6.07°C in October).

The precipitation anomalies show large dispersion, being projected as either an increase or decrease in precipitation rates. Projected precipitation anomalies considering areal average values over the basin show that there are large anomalies predominating, but with quite a large dispersion among the results of the 20 AOGCMs. The largest anomalies projected for the months of the dry season (JJA) are due to the relatively low precipitation rates during these months.

Bravo et al. (2014) indicated that the dispersion among the AOGCM results is considerably larger during the low rainfall period as well as during the rainy period. Projected anomalies of precipitation for January (Scenario A2), the wettest month, present a mean value of +3.5% and the interval defined by mean ± SD is from –8.2% to 15.3%, with a maximum

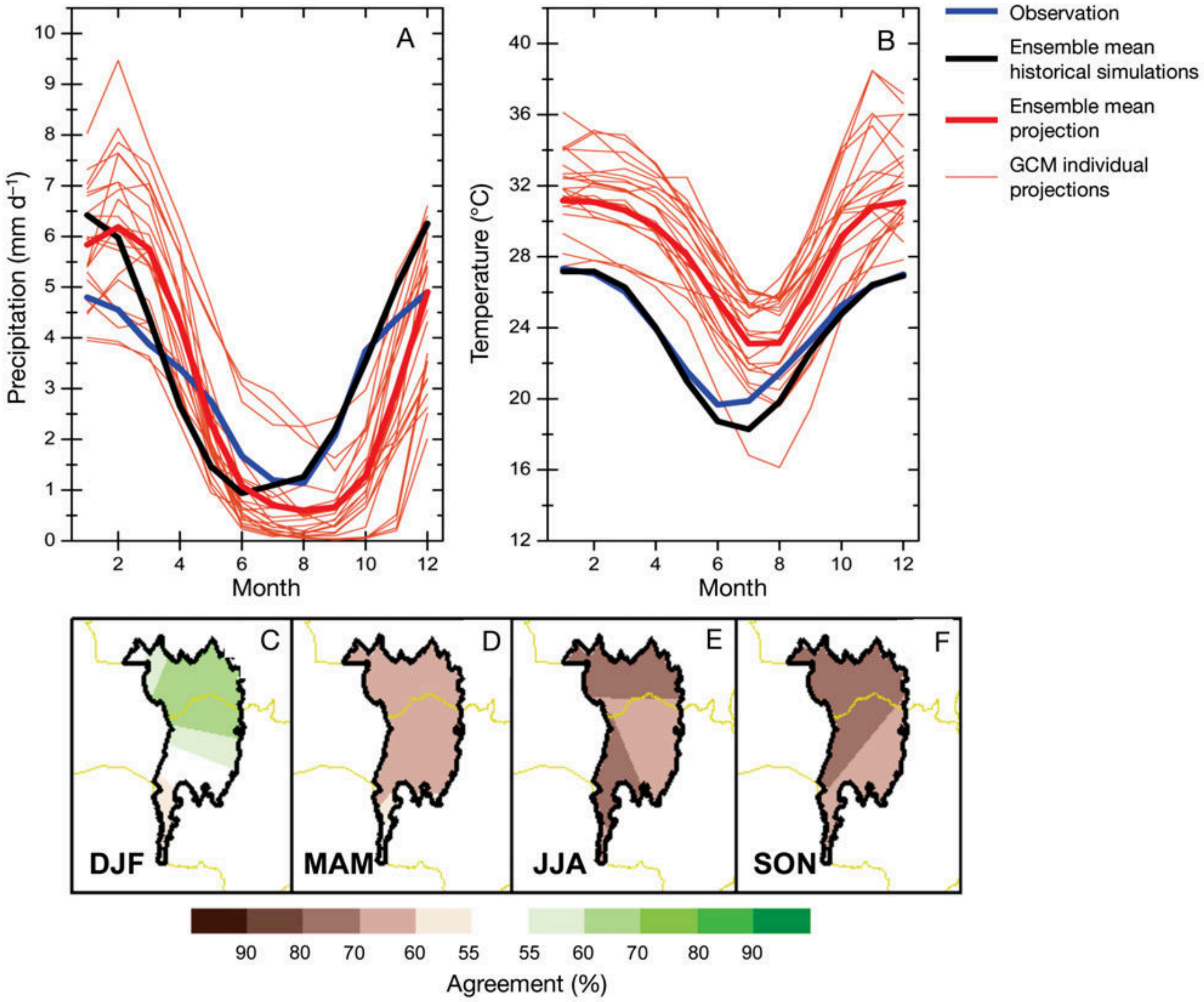

Fig. 2. Annual cycle of (A) precipitation (mm d^{-1}) and (B) temperature (°C) for the Brazilian Pantanal region as derived from the IPCC AR5 models. Thick blue/black lines represent the CRU 1961–1990 observed climatology/mean of historical simulations (simulation of the present); thick red lines represent the ensemble mean of the IPCC AR5 models for the 2071–2100 RCP8.5 scenario; thin red lines represent the individual model projections. (C–F) Agreement (%) among models in the change of rainfall at the seasonal level. Agreement is represented as the percentage of models that show a similar tendency (direction of change, not magnitude), as indicated in the color scale

projected anomaly of 44.6% and a minimum of −11.4%. The values for the long-time horizon present even more dispersion among the AOGCMs. For instance, for January Scenario A2, the mean projected anomaly is +10.7% and the mean ± SD interval is between −23.9% and 44.5%, while maximum and minimum anomalies are −33.1% and 130.3%, respectively.

4.2. Ensemble of CMIP5 models

In the following, we make an assessment of projections of changes in summer and wintertime temperatures and rainfall from the CMIP5 models focusing on the RCP8.5 only, because changes in the RCP4.5 show the same tendency but with lower magnitude. Projected warming in the RCP8.5 varies between 4 and 7°C for the Pantanal, and the increases in air temperature are more noticeable in both summer (DJF) and fall (MAM) seasons, reaching up to 6°C in 2100, and varying between 3.5 and 9°C among models. In the near term (up to 2040), the warming could reach 2–3°C and by 2070, it may reach 4–5°C.

Agreement among the CMIP5 models is shown in Fig. 2C–F. For rainfall changes in the summer season (DJF), 70% of the models show rainfall increases in the northern and central parts of the basin, while in the rest of the year, between 60 and 80% of the models show rainfall reductions. During the austral winter (JJA), the model ensemble suggests rainfall reductions between 60 and 70%. The tendency is strong in the second half of the 21st century, but the scatter among model members is extremely large, suggesting high uncertainty in rainfall projections, particularly for the dry season.

In sum, global models from both CMIP3 and CMIP5 project warming for the medium- and long-term horizons until 2100 that can reach up to 4°C or more, while changes in rainfall during the summer peak and during the winter dry season are uncertain, as shown by the large intermodel divergence. Furthermore, while the model ensemble shows total rainfall as expected to decrease both in summer and winter, and the possibility of increased soil moisture deficiency, it is hard to make conclusions about projected changes in the flood pulse in the Pantanal region for the future.

Over the La Plata basin, for both CMIP3 and CMIP5 datasets, Marengo et al. (2014) showed an increase in temperature throughout the basin and a slight increase in precipitation located mainly in the Brazilian state of Rio Grande do Sul, Uruguay, and northeastern Argentina. The projections of increases in temperature in the CMIP3 ensemble vary from 2°C (SRES B2) to 3.5°C (SRES A2), while in CMIP5 this increase can vary from 1.5°C (RCP2.6) to 5°C (RCP8.5). Regarding precipitation, despite the enormous uncertainties related to this variable, there is good agreement among the CMIP3 and CMIP5 models for a small increase of precipitation of 0.1–0.3 mm d^{-1}, mainly in austral summer.

5. REGIONAL CLIMATE CHANGE PROJECTIONS FOR THE PANTANAL REGION ETA-HADGEM2 ES

Climate change in regions that are naturally stressed by low water availability will intensify ecological impacts on aquatic systems (Roland et al. 2012). Since the Pantanal functions as a gigantic flood regulation system for the Paraguay River watershed, alterations in rainfall can significantly affect the system's capacity to retain and control flood events. This section is based on the projections from the Eta-HadGEM2 ES at annual time scales for the RCP8.5 until 2100; seasonal changes were also assessed but are not shown here.

Projected annual mean warming (Fig. 3) in the region varies from 2.5–3.5°C in 2011–2040, up to above 5–7°C in 2071–2100, in agreement with the projections by the CMIP5 models. As for precipitation (Fig. 4), the Eta-HadGEM2 ES projects rainfall reductions of the order of 10–20% in 2010–2040, and of 30% by 2071–2100, with a strong variability among time slices particularly in summer (not shown). Projected changes from the Eta regional model nested on the MIROC5 global model as shown by Chou et al. (2014b) for the Pantanal also show temperature increases and rainfall decreases during summer and winter. These projections are consistent with those derived from the Eta-HadCM3 for the A1B scenario that was run with a resolution of 40 km (Marengo et al. 2012).

Changes in P–E are analyzed to investigate the possible impacts of climate change on water resource conditions in the region (Fig. 5). P–E changes suggest that the region will become drier in the future. There is a broad signal that the magnitudes of the P–E will decrease, with a mean value of approximately 40% during the 21st century, particularly in the central and eastern part of the basin, in agreement with negative anomalies shown by Kirtman et al. (2013) based on the ensemble of the CMIP5 models for the region. Thus, we conclude that the P–E changes up to 2071 are consistent with higher temperatures and rainfall reductions by the end of the 21st century, which suggests a reduction in the water budget, expressed as percentages (Fig. 5). This is also consistent with Chou et al. (2014b), who, for the Eta-HadGEM2-ES for 2100, detected reductions in consecutive wet days and increases in consecutive dry days that are indicators of dry spells and droughts for the region.

Monthly mean temperature anomalies projected for the RCP8.5 scenario are given in Fig. 6. Clearly, there is a small yearly cycle, but a much larger spread of temperatures in the winter months, i.e. from May to July, is also evident. There is also some indication that the extremes (maximum and minimum values) are changing with the season, and there is a clear increase in the yearly median value over time. The range of the entire series is approximately +6°C in July to 8.5°C in December for the end of the 21st century.

Fig. 7 shows projected precipitation anomalies considering areal average values over the basin. The mean and range of values over the 3 time slices appear to remain more or less the same, except for the extreme values. The range of these series is quite small compared to that of the monthly temperatures. In most months (summer and spring), the simulated extreme changes are more pronounced for both maximum and minimum values. Overall, the rainfall projections for the Pantanal show negative anomalies

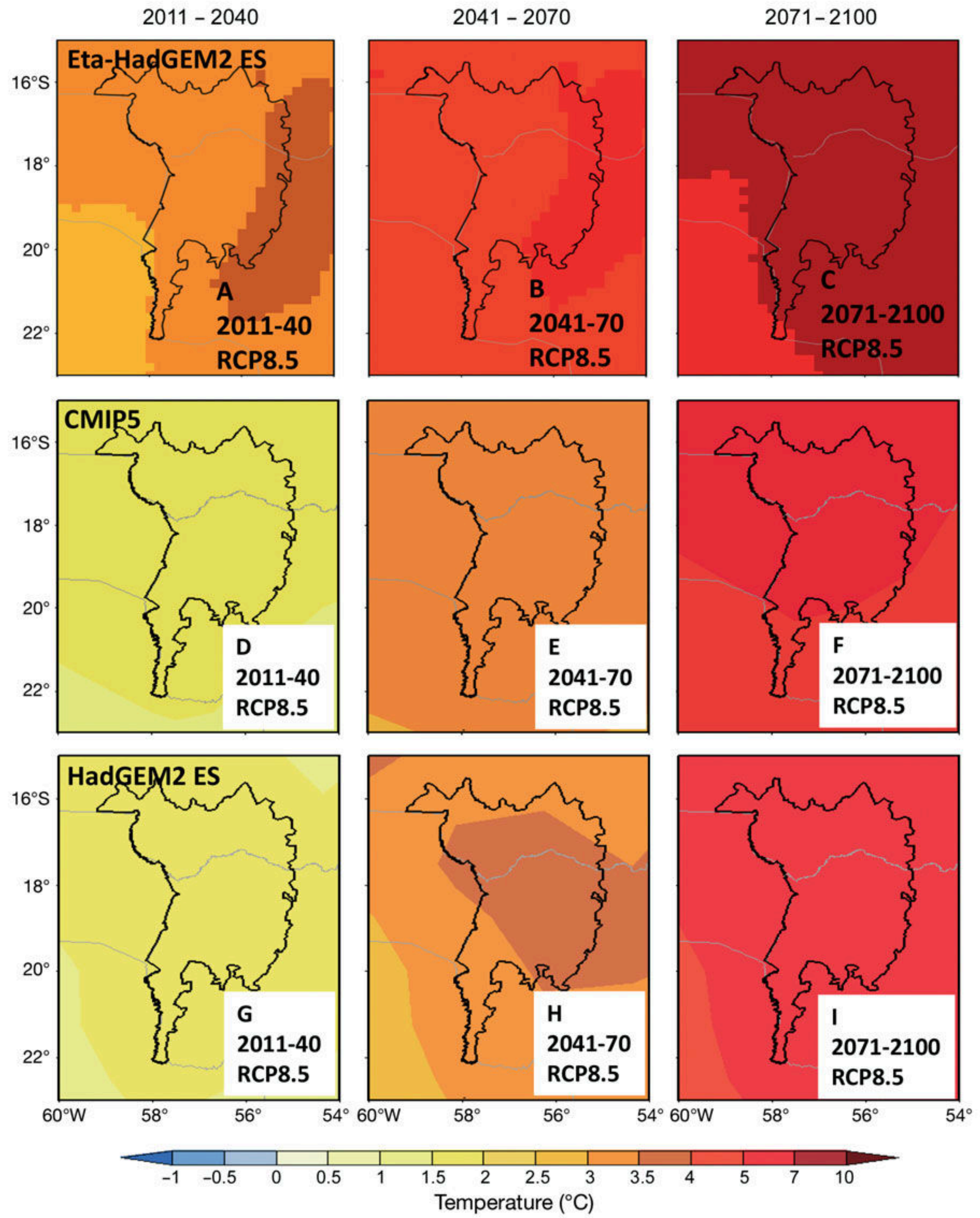

Fig. 3. Projected change in annual average temperature (°C) for (A) 2011–2040, (B,E,H) 2041–2070, and (C,F,I) 2071–2100, relative to the reference 1961–1990, under the RCP8.5 scenario. Color scale is located below the panel

all year long, at a rate of approximately −1 mm d^{-1}.

In sum, for the Pantanal region, future climate-change scenarios predict rising temperatures and alterations in seasonal and interannual weather extremes (including droughts, heat waves, and floods). As pointed out by Roland et al. (2012), these changes would favor harmful cyanobacterial blooms in eutrophic waters and enhanced vertical stratification of aquatic ecosystems.

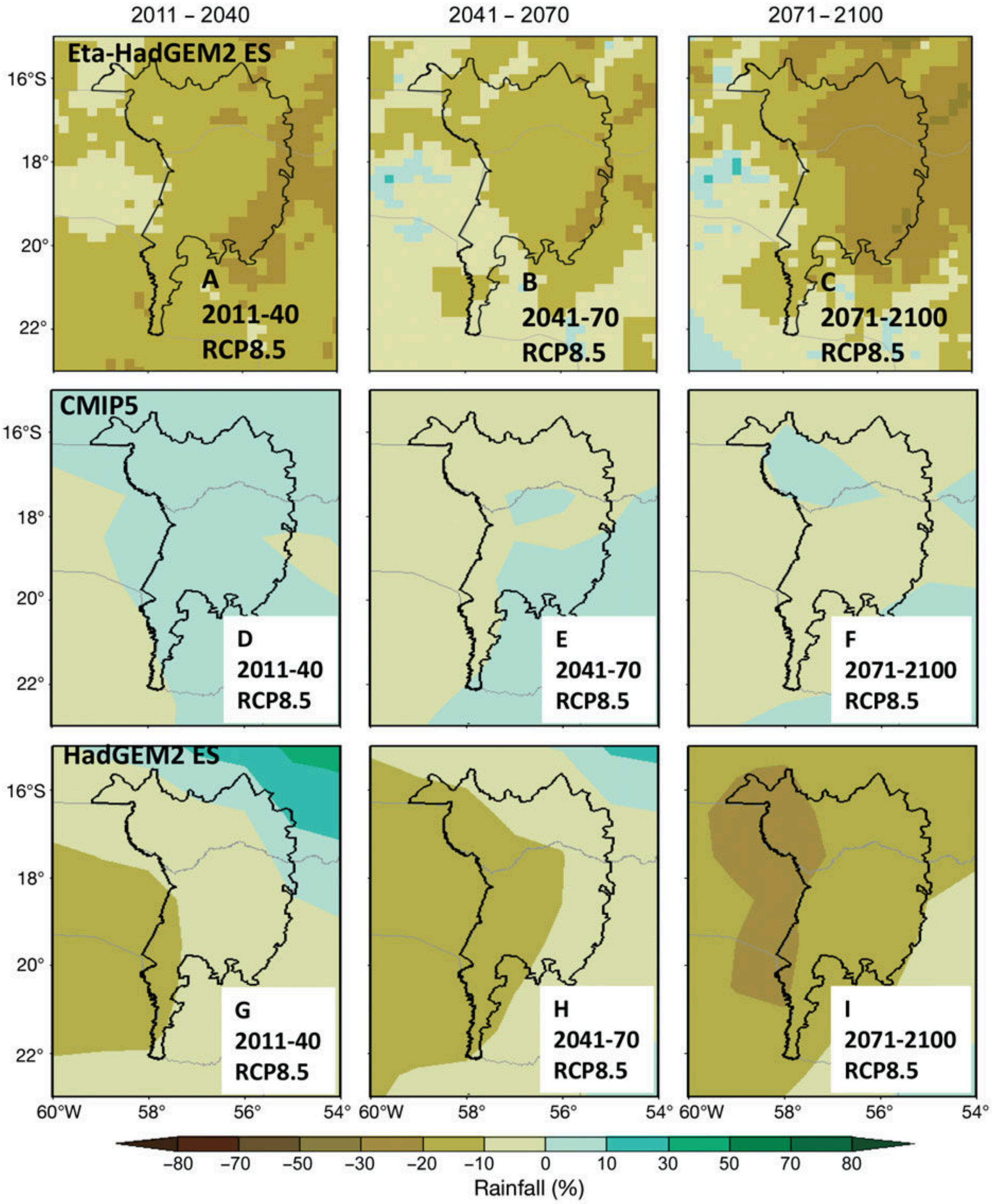

Fig. 4. As in Fig. 3, but for precipitation change (%)

6. SUMMARY AND CONCLUSIONS

Hydrometeorological conditions in the Brazilian Pantanal, which is recognized as a sensitive ecosystem due to its climate and other geographical features, exhibit a large interannual variability, which seems to be independent of El Niño/La Niña. The river records at Ladario show decadal-scale variations, with a dry period through most of the 1960s extending to the early 1970s.

Based on the regional climate change projections derived from the Eta-HadGEM2 ES regional models

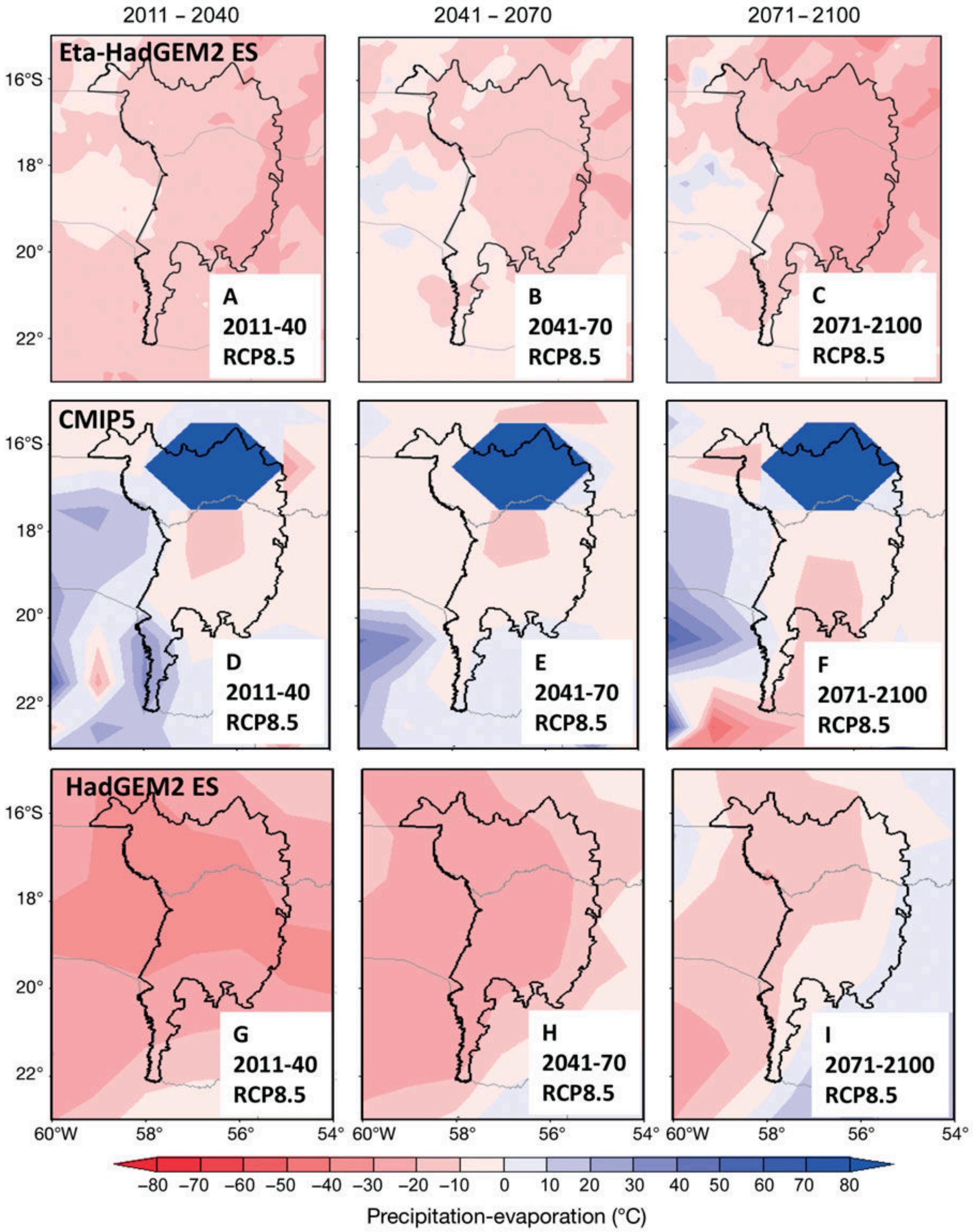

Fig. 5. As in Fig. 3, but for precipitation–evaporation (indicator of the water balance) (%)

with 20 km latitude–longitude resolution for the RCP8.5 for 2010–2100, future climate projections show a mean annual warming varying from 2.5–3.5°C in 2011–2040 up to above 5–7°C for 2071–2100. For precipitation, the model projects mean annual rainfall reductions on the order of 10–20% in 2010–2040, and 30% by 2071–2100. However, in general we noted a reduction in rainfall by 2100, with a strong variability among time slices, particularly in summer. The CMIP5 models show an agreement of

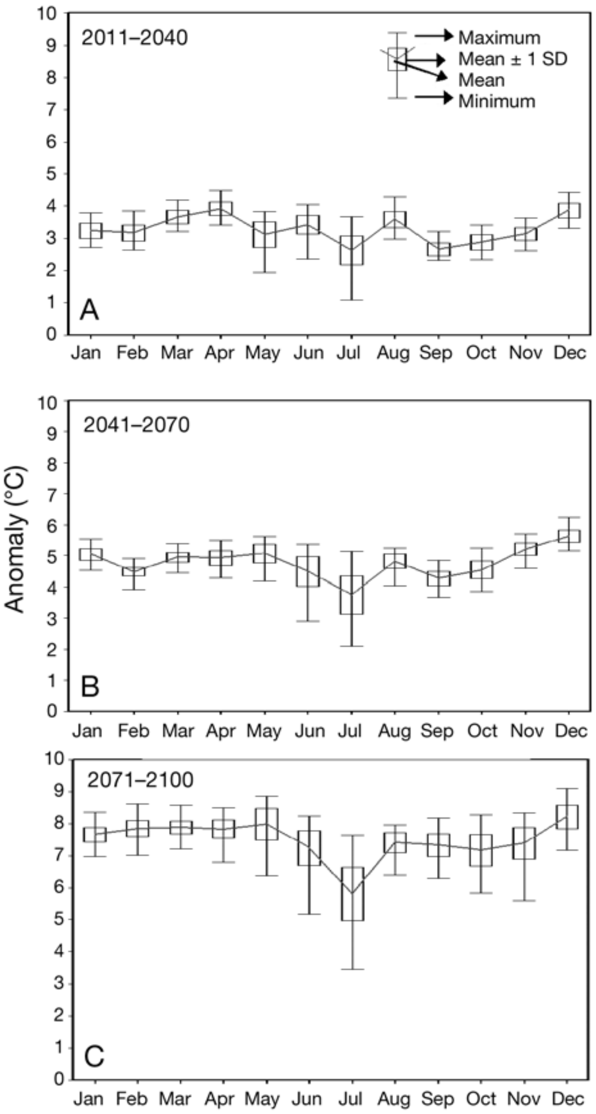

Fig. 6. Monthly projected air temperature anomalies (°C) over the Brazilian Pantanal area for RCP8.5: mean, minimum, and maximum values from the Eta/HadGEM2-ES, for (A) 2010–2040, (B) 2041–2070, and (C) 2071–2100. The box represents the mean ± SD

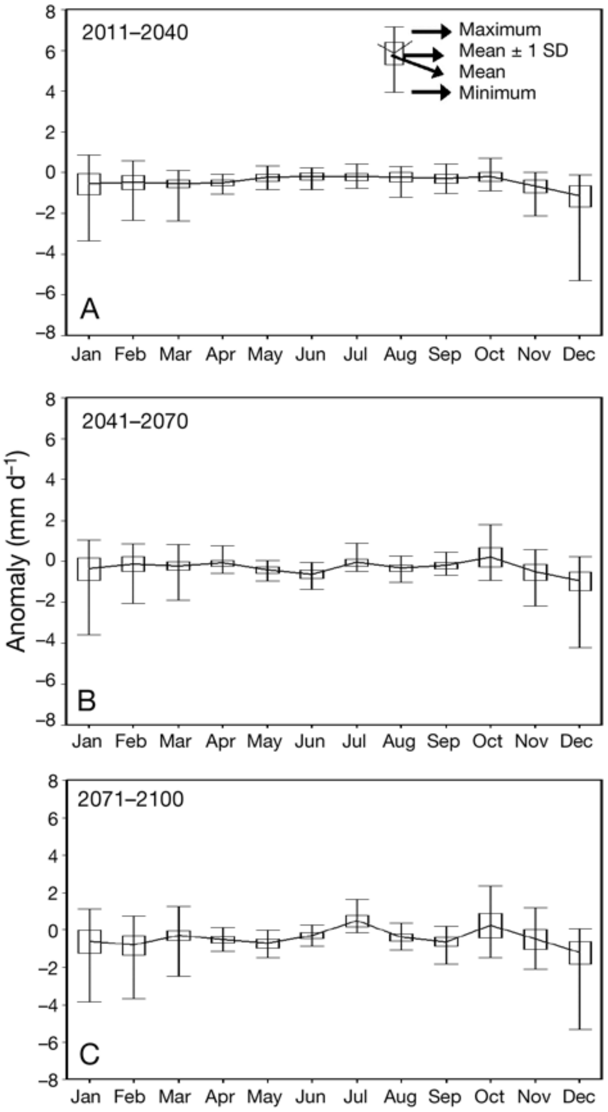

Fig. 7. As in Fig. 6, but for rainfall anomalies (mm d^{-1})

at least 70 % of the models toward drier conditions in the basin from fall to spring.

Regarding the water balance in the region, with higher temperatures and rainfall reduction by the end of the 21st century, a reduction would be expected in the water budget, expressed as P–E (Fig. 4). The changes are more pronounced in the central and eastern side of the basin and during spring and summer and would affect the pulse of the Paraguay River. They are consistent with the projected changes using the same Eta regional model nested in the MIROC5 global model at annual and seasonal levels shown by Chou et al. (2014b). However, as Bravo et al. (2014) suggested, changes in the hydrology of the Pantanal are uncertain because of land surface processes that may not be well represented by climate models. While most of the model projections from regional and global models show increases in rainfall and in the discharges of the Paraguay Basin in austral summer, they also show reductions during the rest of the year, with a possible late rainfall onset and shorter rainy season.

Projections of the impacts of climate change on wetlands, including effects in the Pantanal and its watershed, may be still too divergent; these uncertainties may make it insufficient for describing climate change impacts in this ecoregion. However, our results can allow the identification of research that needs to be carried out on climate and environmental change, as well as on the design of strategies that reduce the vulnerability of the watershed in the face of climate change. Therefore, while there is the potential for very large impacts on the hydrology, the models are not yet able to give us useful information on rainfall changes due to uncertainty in the rainfall projections.

Knowledge of severe floods and droughts, which characterize natural disasters, is fundamental for wildlife management and nature conservation for the Pantanal. In addition, human activities are also affected, since cattle ranching and ecotourism are economically important in the region; therefore, when seasons with unusual floods or droughts occur, areas with human settlements are impacted.

Lastly, as indicated by Petry et al. (2011), the development of an ecological risk assessment is the first step in understanding the Pantanal's vulnerability to climate change, beginning with identification and assessment of existing stressors (i.e. non-climate stressors); thus climate change projections would be useful to identify which existing stressors will be most important in the future, and also where and how these stressors will occur. This makes it possible to design and implement effective adaptation actions.

Acknowledgements. The research leading to the results reported here received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement no. 212492 (CLARIS LPB – A Europe–South America Network for Climate Change Assessment and Impact Studies in La Plata Basin), Rede-CLIMA, the National Institute of Science and Technology (INCT) for Climate Change funded by CNPq Grant no. 573797/2008-0 and FAPESP Grant no. 57719-9, and the CNPq-IRD Project Mudancas, variabilidade e tendencias do clima no passado, Presente e future e desastres naturais nas Regioes tropicais e Subtropicals do Brasil: observacoes e Modelagem (PRIMO), Ref: 590172/2011-5.

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Editorial responsibility: Enrique Sanchez, Toledo, Spain

Submitted: February 2, 2015; Accepted: June 29, 2015
Proofs received from author(s): •, 2015