Observed and predicted climate changes in Uruguay and adjacent areas*

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ABSTRACT: This study describes the climate conditions and primary climate influences in the greater Uruguay region and shows results of a climate change prediction for that region performed using a coupled ocean-atmosphere model. The study demonstrates the strong influences of the El Niño phenomenon on the region's precipitation variability, with flood conditions during El Niño and drought conditions during La Niña events. Future climate model simulations indicate temperature increases that reach about two degrees Celsius by the end of the 21st century. Precipitation in the greater Uruguay region increases by about 0.5 mm/day and most of the increase happens in the summer months. One worrisome feature of the model future climate simulation is an increase in the time scales of precipitation variability. This points to longer periods of drought and flood in a warmer climate. If such a prediction materializes it would worsen the already negative influences of the prolonged precipitation extremes that are already experienced in the region.
Key-words: *Climate change, Uruguay, El Niño, temperature, precipitation.*

ΠΕΡΙΛΗΨΗ: Η παρούσα μελέτη περιγράφει τις κλιματικές συνθήκες και τις κυριότερες κλιματικές επιδράσεις στην ευρύτερη περιοχή της Ουρουγουάη και περιγράφει το πιθανό μελλοντικό κλίμα στην Ουρουγουάη σύμφωνα με τις εκτιμήσεις κλιματικού μοντέλου. Η μελέτη παρουσιάζει τις σημαντικές επιδράσεις του φαινομένου Ελ Νίνιο στη μεταβλητότητα της βροχής στην Ουρουγουάη, με πλημμύρες κατά τη διάρκεια επεισοδίων Ελ Νίνιο και με συνθήκες ξηρασίας κατά τη διάρκεια επεισοδίων Λα Νίνια. Από τις εκτιμήσεις κλιματικού μοντέλου προκύπτει αύξηση της μέσης θερμοκρασίας στην Ουρουγουάη μέχρι το τέλος του 21ου αιώνα κατά δύο βαθμούς της κλίμακας Κελσίου. Οι εκτιμήσεις δείχνουν αύξηση της βροχής κατά 0.5 χιλιοστά ανά ημέρα, με τις μεγαλύτερες αυξήσεις να πραγματοποιούνται κατά τους καλοκαιρινούς μήνες. Κάτι ανησυχητικό που προκύπτει από τους υπολογισμούς του μοντέλου είναι η αύξηση των περιόδων ξηρασίας και βροχόπτωσης σε ένα θερμότερο κλίμα. Εάν οι εκτιμήσεις του μοντέλου επαληθευτούν τότε οι σημερινές-ήδη παρατεταμένες-περίοδοι ξηρασίας και βροχόπτωσης στην Ουρουγουάη θα έχουν ακόμα πιο δυσμενείς συνέπειες στην ευρύτερη περιοχή.
Λέξεις-κλειδιά: *Κλιματική αλλαγή, Ουρουγουάη, Ελ Νίνιο, θερμοκρασία, βροχή.*

INTRODUCTION

Uruguay is located between 53 and 58 west longitude and 30 and 35 south latitude. It is bounded on the west by Argentina, on the north and northeast by Brazil, and on the southeast by the Atlantic Ocean. To the south, it fronts the Río de la Plata, a broad estuary that opens out into the South Atlantic. Montevideo, the capital and major port, sits on the banks of the Río de la Plata. Uruguay is the second smallest sovereign nation in South America (after Suriname) with a land area of 176,220 square kilometers.

The climate in Uruguay is temperate: it has warm summers and cool winters. The predominantly gently undulating landscape is somewhat vulnerable to rapid changes from weather fronts. It receives the periodic influence of the polar air in winter, and tropical air from Brazil in summer. Seasonal variations are pronounced, but extremes in temperature are rare. This part of South America presents a small annual variation of air temperature with a range of about 8 °C, with maximum in January and minimum in July. Average highs and lows in summer (January) in Montevideo are 28 °C and 17 °C, respectively, with an absolute maximum of 43 °C. Uruguay and eastern Argentina and Paraguay get important rains from the Atlantic. Rainfall in Uruguay is fairly evenly distributed throughout the year, and annual amounts increase from southeast to northwest. Montevideo averages 950 millimeters annually, and Artigas receives 1235 millimeters in an average year. Thunderstorms occur rather frequently in the humid (eastern) parts of Paraguay and Argentina and in all of Uruguay. Thunderstorm activity in the Paraguayan-Argentine-Uruguayan Mesopotamia presents an annual occurrence of about 40 days per year (Landsberg, 1976).

High humidity and fog are common. The subtropical Atlantic coasts and the area of Rìo de la Plata have a high relative humidity ranging between 75-80%, while the elongated zone extending from northern Chaco over central and western Argentina to central Patagonia has a low relative humidity of 55-60%. Regarding cloudiness, Uruguay, Argentine

* Παρατηρούμενες και προβλεπόμενες κλιματικές μεταβολές στην Ουρουγουάη και στις γειτονικές περιοχές

mesopotamia, pampa and the eastern Chaco display small annual range with maximum in winter. The annual variation of cloudiness in this region ranges between 10-15%. As in all subtropical and maritime influenced regions the season of maximum cloudiness is winter. This relatively strong winter cloudiness (about 60%) starts in May, reaches a well defined maximum in June, and ends in October. The time of the lowest cloudiness (40-50%) is between November and April. Uruguay is particularly vulnerable to rapid changes from weather fronts, due to the absence of mountains, which act as weather barriers. The country experiences seasonally high winds, such as the pampero, which is a chilly and occasional violent wind that blows north from the Argentine pampas. Whereas the annual variation of wind speed is insignificant (within 1 m/sec), the daily variation of wind velocity is well expressed over the pampas, as over all large plains, and a pronounced land and sea breeze can be observed along the Atlantic coast (Landsberg, 1976).

Natural events such as floods, droughts and severe local storms have caused significant problems in Uruguay in the past decade. Among them were the severe floods in central and northern Uruguay in November 2009, the severe drought in January 2009 causing problems to the agricultural sector, the historical floods in the last fifty years in central, western and eastern Uruguay in May 2007, and the severe local storms in south and eastern parts of Uruguay in 2005. The present study describes the climate conditions and primary climate influences in the greater Uruguay region. It demonstrates the strong influences of Southern Oscillation on the region's precipitation variability, with flood conditions during El Niño and drought conditions during La Niña events, and present results of a climate change prediction for that region performed using the Geophysical Fluid Dynamics Laboratory (GFDL) climate model.

OBSERVED VARIATIONS: EL NIÑO – LA NIÑA RELATIONS WITH RAINFALL

Large-scale natural fluctuations such as the El Niño-Southern Oscillation (ENSO) are known to alter the distribution of large-scale weather patterns and affect the natural variability of various atmospheric parameters such as temperature, pressure, precipitation and cloudiness (Eleftheratos *et al.*, 2007). ENSO is a natural oscillation of the ocean-atmosphere system in the tropical Pacific Ocean with important consequences for weather around the world.

El Niño[1] refers to episodes of ocean warming caused by a warm countercurrent flowing southward along the coasts of Ecuador and Peru that replaces the cold Peruvian current. The opposite of El Niño is an atmospheric phenomenon known as La Niña[2]. When surface temperatures in the eastern Pacific are colder than average, a La Niña event is triggered. A typical La Niña winter blows colder than normal air over the Pacific Northwest and the northern Great Plains while warming much of the rest of the United Sates (Trenberth & Caron, 2000; Ahrens, 2001).

ENSO is associated with floods, droughts, and other disturbances in many regions around the world. An El Niño is associated with warm and very wet summers (December-February) along the coasts of northern Peru and Ecuador, causing major flooding whenever the event is strong or extreme. The effects during the months of February, March and April may become critical. Southern Brazil and northern Argentina also experience wetter than normal conditions but mainly during the spring and early summer. Central Chile receives a mild winter with large rainfall, and the Peruvian-Bolivian Altiplano is sometimes exposed to unusual winter snowfall events. Drier and hotter weather occurs in parts of the Amazon River Basin, Colombia and Central America. El Niño events influence weather at great distances from Peru and Ecuador. Two of the strongest El Niño events (1992-93 and 1997-98) were responsible for a variety of weather extremes in many parts of the world (Trenberth & Caron, 2000; Trenberth *et al.*, 2002; Trenberth *et al.*, 2007; Lutgens & Tarbuck, 2007).

The events are part of the global circulation and related to a seesaw pattern of atmospheric pressure between the tropical eastern and western Pacific Ocean waters called the Southern Oscillation. The strength of the Southern Oscillation is measured by the Southern Oscillation Index (SOI). The SOI is calculated from the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin, Australia, and it was provided by the Bureau of Meteorology of the Australian Government at (http://www.bom.gov.au/climate/glossary/soi.shtml). Negative values of the SOI indicate warm (El Niño) events and positive values indicate cold (La Niña) events.

To examine the effects of El Niño and La Niña phenomena on rainfall in Uruguay we have analyzed the long–term records of monthly total precipitation at Concordia Argentina (located on the Uruguay border) and Rosario Uruguay, which were provided by the National Climatic Data Centre of the National Oceanic and Atmospheric Administration of the United States Department of Commerce (http://www.ncdc.noaa.gov/oa/ncdc.html). The two stations were chosen because they provide long time series with very few missing data. The relation between rainfall and ENSO was determined with linear regression analysis. The correlation analysis was performed after removing the long-term average of rainfall at each region.

Fig. 1 shows the time series of rainfall at Concordia from

[1] El Niño (the Spanish term for boy child) was introduced in the nineteenth century by Peruvian fisherman to describe the appearance, around Christmas, of a warm ocean current off the South American coast.

[2] La Niña (the Spanish term for girl child) is referring to cold-water episodes in the central and eastern Pacific Ocean, which are opposite to warm-water (El Niño) conditions.

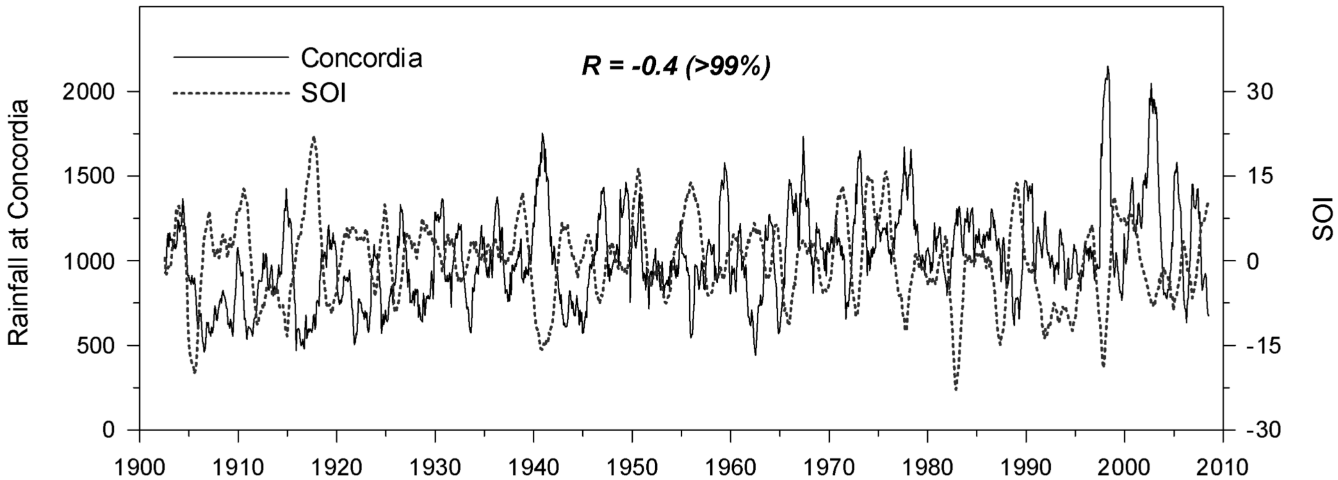

Fig. 1. Relation between rainfall at Concordia and the Southern Oscillation Index. R is the correlation coefficient between the two lines. The value in brackets refers to the statistical significance of the R.

1902 to 2008 versus the El Niño-Southern Oscillation index. As can be seen from that figure there is a negative correlation between precipitation at Concordia and SOI (R= -0.4) which is highly statistically significant (confidence level greater than 99%). The respective relation between rainfall at Rosario and SOI is presented in Fig. 2. The statistically significant correlation coefficients between the two variables suggest that Southern Oscillation and its associated events (warm and cold) play a significant role in the amount and intensity of precipitation over these regions. The effect of El Niño events on rainfall in Uruguay can be seen in Fig. 1 for negative values of the SOI. During warm (El Niño) events rainfall increases significantly in Uruguay and stays above normal levels for a long time period depending on the strength of the El Niño event.

Table 1 summarizes the annual mean rainfall at Concordia in the period 1902-2008, for the years with statistically significant increases in rainfall associated with strong El Niño events.

The opposite effect occurs during cold (La Niña) events. La Niña events are associated with significant reductions in rainfall in Uruguay and droughts. Table 2 summarizes the annual mean rainfall at Concordia in the period from 1902 to 2008, for the years with statistically significant rainfall deficit associated with strong La Niña events.

MODEL SIMULATIONS OF PAST AND FUTURE TEMPERATURE AND PRECIPITATION CHANGES IN THE GREATER URUGUAY REGION

A leading US climate model (GFDL) (Haywood *et al.*, 1997) is used to examine temperature and precipitation variations in the greater Uruguay region. Two runs from the IPCC AR4 archived are examined, one starting in 1860 and ending in

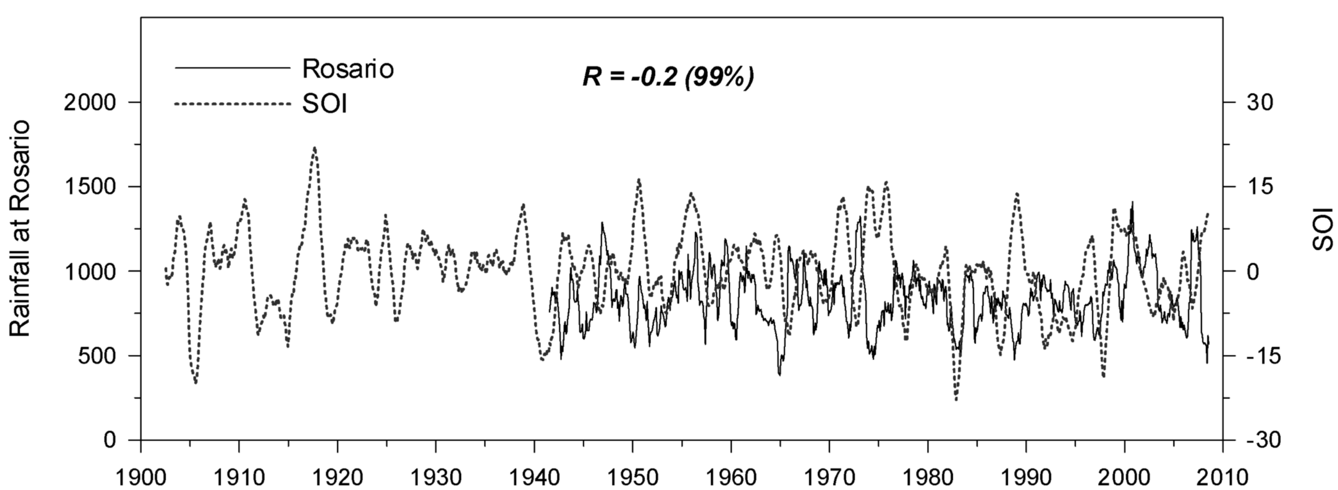

Fig. 2. Relation between rainfall at Rosario and the Southern Oscillation Index. R is the correlation coefficient between the two lines. The value in brackets refers to the statistical significance of the R.

TABLE 1
Annual mean rainfall and anomalies from the long-term 1902-2008 mean at northern Uruguay/Argentina, during El Niño years (station Concordia).

El Niño years	Annual rainfall at Concordia during El Niño years (in mm)	Anomaly from the long-term mean 1902-2008	
		(in mm)	(in %)
1918/19	1079	+60	+6%
1940/41	1437	+417	+41%
1946	1243	+223	+22%
1965/66	1178	+159	+16%
1972	1245	+226	+22%
1977/78	1456	+436	+43%
1986/87	1116	+97	+9%
1997/98	1525	+506	+50%
2002/03	1625	+606	+59%
2004/05	1095	+76	+7%
2006/07	1094	+75	+7%
Long-term mean 1902-2008	1019		

2000 and another starting in 2000 and ending in 2100. The 20th century climate simulations are run using historical series of atmospheric CO_2 and other greenhouse gases, sulfate aerosol direct effects, and volcanic and solar forcing. The 21st century climate simulations use the Sres A1B scenario**,** where atmospheric CO_2 concentrations reach 720 ppm in the year 2100 in a world characterized by low population growth, very high GDP growth, very high energy use, low land-use changes, medium resource availability and rapid introduction of new and efficient technologies. The greater Uruguay region is defined as the region between 25-40°S and 50-65°W, centered on the country of Uruguay and including parts of northern Argentina and southern Paraguay.

Temperature variations

Fig. 3 shows the annual mean surface temperature time series for the 20th century model run (left panel) and the 21st century model run (right panel). The 20th century climate simulation shows a small upward temperature trend mainly after 1980, that results in increases in the mean temperature of the region of about one degree Celcius over the whole time period.

TABLE 2
Annual mean rainfall and anomalies from the long-term 1902-2008 mean at northern Uruguay/Argentina during La Niña years (station Concordia).

La Niña years	Annual rainfall at Concordia during La Niña years	Anomaly from the long-term mean 1902-2008	
		(in mm)	(in %)
1906/07	565	-454	-45%
1909/10	717	-303	-30%
1916/17	567	-452	-44%
1920/21	756	-263	-26%
1922	710	-309	-30%
1924	571	-448	-44%
1927/28	706	-313	-31%
1929	856	-163	-16%
1942/43	775	-244	-24%
1945	846	-173	-17%
1962	442	-578	-57%
1988/89	909	-110	-11%
2007/08	963	-56	-6%
Long-term mean 1902-2008	1019		

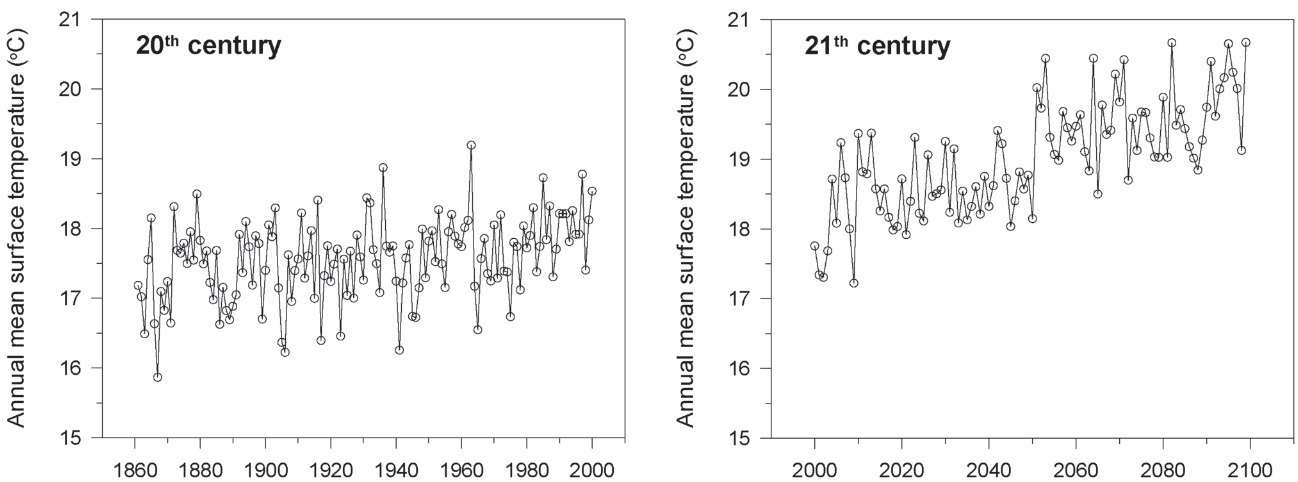

Fig. 3. Time series of annual mean surface temperature for the 20th century model run (left panel) and the 21st century model run (right panel) in the greater Uruguay region.

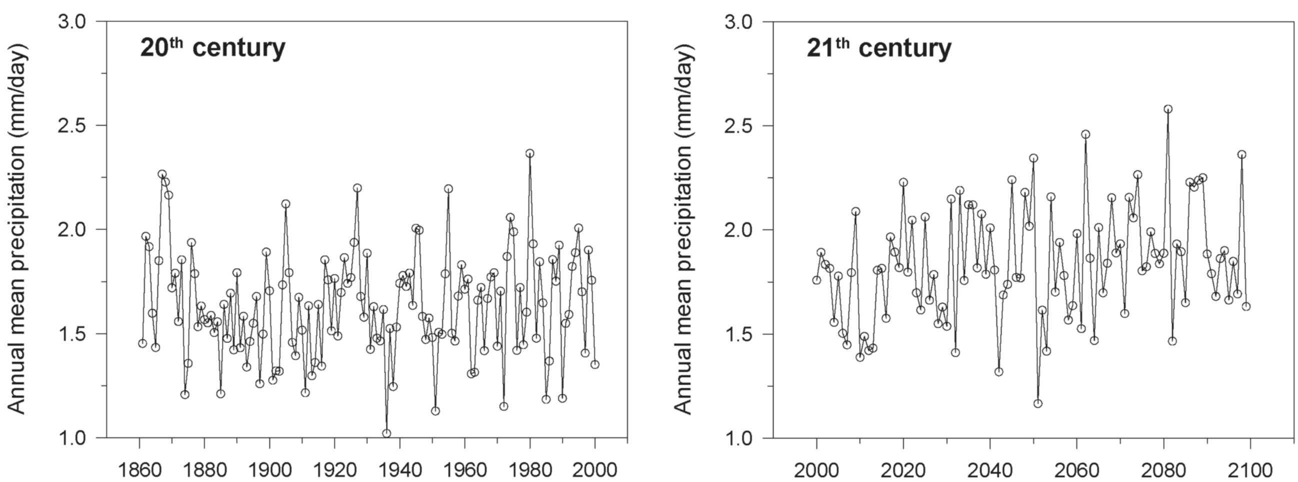

Fig. 4. Time series of annual mean precipitation for the 20th century model run (left panel) and the 21st century model run (right panel) in the greater Uruguay region.

The 21st century climate simulation on the other hand shows drastic temperature increases that reach about two degrees Celcius by the end of the time period. The range of interannual temperature variability is about one to one and a half degree Celcius for both the past and future climate runs of the model.

Precipitation variations

Fig. 4 shows the annual mean precipitation time series for the 20th century model run (left panel) and the 21st century model run (right panel). The 20th century climate simulation does not reveal any significant long term trend, while it shows potential modes of variability that need to be explored further. The 21st century climate simulation shows a weak upward trend that increases precipitation by about 0.5 mm/day by the end of the century. From a first look, the future climate run shows longer scales of variability than the present climate one. In that respect, several multi-year periods of extreme minima can be observed (e.g. 2004-2009, 2093-2100) that indicate the potential for long periods of drought in the region.

MODELED SEASONAL CHANGES IN PRECIPITATION IN GREATER URUGUAY AREA

Fig. 5 examines the seasonal variability of the change of the GFDL model precipitation prediction for the 21st century run. It can be seen that the small increase in annual mean 21st century precipitation shown in Fig. 4 is due mostly to increases in the summer (DJF) season and to a lesser degree in the fall (MAM) season. The time series of the winter (JJA) and spring (SON) seasons do not appear to include significant trends.

CONCLUSIONS

The present study presented a comprehensive analysis of the climate conditions and primary climate influences in the greater Uruguay region and showed results of a climate change prediction for that region performed using the GFDL climate model. The study demonstrated the strong influences of the El Niño phenomenon on the region's precipitation variability, with flood conditions during El Niño and drought conditions during La Niña events. The future climate model simulations indicate temperature increases that reach about two degrees Celsius by the end of the 21st century. Precipitation in the greater Uruguay region increases by about 0.5mm/day and most of the increase happens in the summer months. One worrisome feature of the model future climate simulation is an increase in the time scales of precipitation variability. This points to longer periods of drought and flood in a warmer climate. If such a prediction materializes it would worsen the already negative influences of the prolonged precipitation extremes that are already experienced in the region.

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REFERENCES

AHRENS, C.D. (2001). *Essentials of Meteorology: An invitation to the Atmosphere*. 3rd edition, ISBN 0-534-37200-7, Brooks/Cole, Printed in Canada, 464 pp.

ELEFTHERATOS, K., ZEREFOS, C.S., ZANIS, P., BALIS, D.S., TSELIOUDIS, G., GIERENS, K. & R. SAUSEN (2007). A study on natural and manmade global interannual fluctuations of cirrus cloud cover for the period 1984–2004. *Atmos. Chem. Phys.*, 7, 2631-2642.

HAYWOOD, J.M., STOUFFER, R.J., WETHERALD, R.T., MANABE, S. & V. RAMASWAMY (1997). Transient response of a coupled model to estimated changes in greenhouse gas and sulphate concentrations. *Geophys. Res. Lett.*, 24(11), 1335-1338.

LANDSBERG, H.E. (1976). *Climates of Central and South America*. World Survey of Climatology, Volume 12, (edited by W. Schwerdtfeger), ISBN 0-444-41271-9, Elsevier Scientific Publishing Company Amsterdam, Printed in the Netherlands, 529 pp.

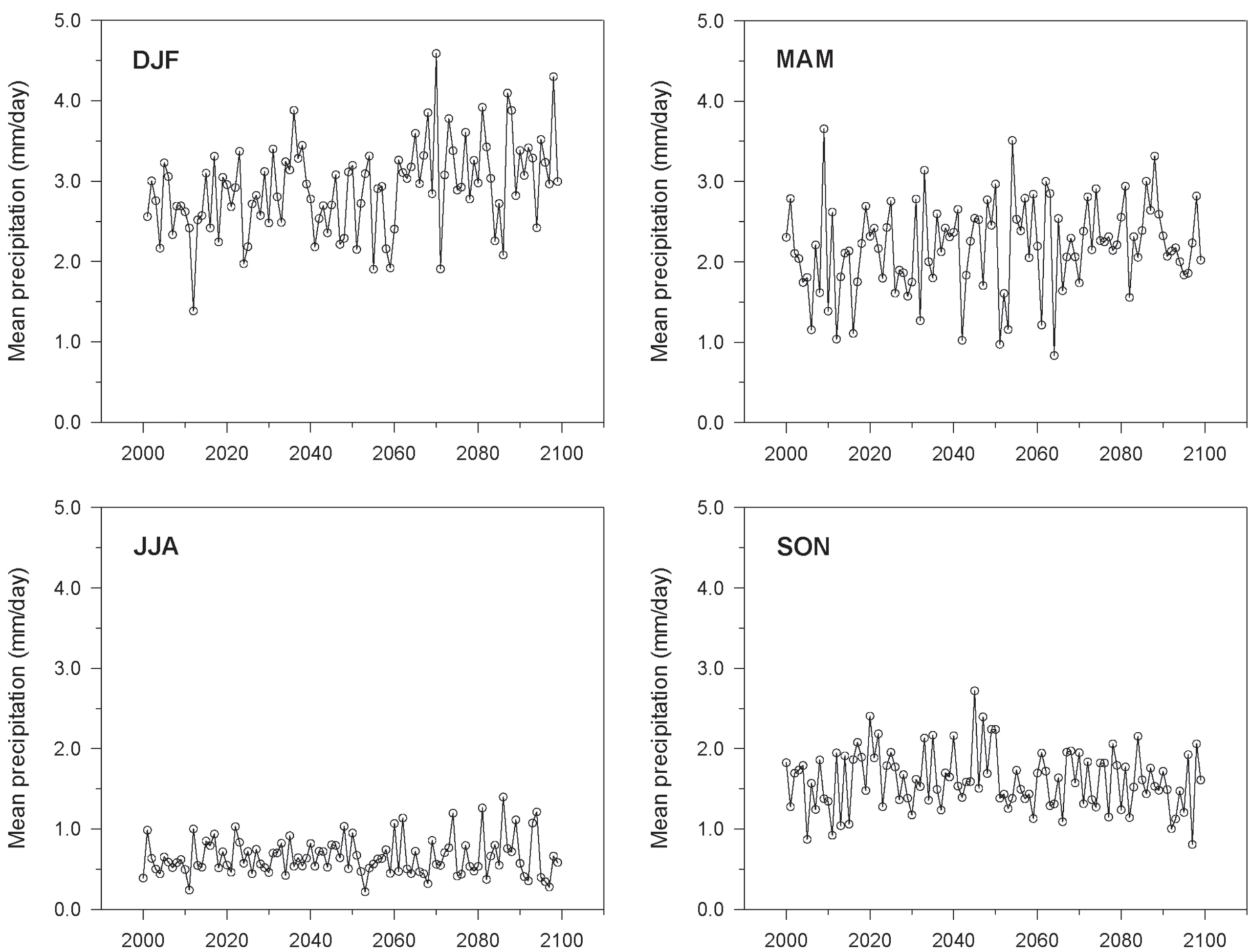

Fig. 5. 21st century (2000-2100) Precipitation for the region 20-40°S, 50-60°W from the GFDL model.

LUTGENS, F.K. & E.J. TARBUCK (2007). *The Atmosphere: an introduction to meteorology*. 10th edition, ISBN 0-13-187462-4, Pearson Education Inc, Printed in the USA, 520 pp.

TRENBERTH, K.E. & J.M. CARON (2000). The Southern Oscillation revisited: Sea level pressures, surface temperatures and precipitation. *J. Climate*, 13, 4358-4365.

TRENBERTH, K.E., CARON, J.M, STEPANIAK, D.P. & S. WORLEY (2002). Evolution of El Niño-Southern Oscillation and global atmospheric temperatures. *J. Geophys. Res.*, 107, 4065, doi:10.1029/2000JD000298.

TRENBERTH, K.E., JONES, P.D., AMBENJE, P., BOJARIU, R., EASTERLING, D., KLEIN TANK, A., PARKER, D., RAHIMZADEH, F., RENWICK, J.A., RUSTICUCCI, M., SODEN B. & P. ZHAI (2007). Observations: Surface and Atmospheric Climate Change. *In*: SOLOMON, S., QIN, D., MANNING, M., CHEN, Z., MARQUIS, M., AVERYT, K.B., TIGNOR, M. & H.L. MILLER (*Eds*), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 235-336 pp.