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Synoptic sea level pressure patterns–daily rainfall relationship over the Argentine Pampas in a multi-model simulation

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ABSTRACT: The ability of 17 global circulation models to simulate daily rainfall of the Pampas region is assessed for winter and summer, key seasons for crop production in the region. Principal Component Analysis combined with *k*-means Cluster Analysis is employed to examine the models' representation of the relationship between daily sea level pressure of southern South America and rainfall. Models represent this relationship better for winter, reflecting their ability to reproduce winter synoptic scale patterns associated with rainfall. They precipitate too frequently at low intensity and less frequently at high intensity. This characteristic is more accentuated in winter.

KEY WORDS GCMs; synoptic climatology; daily rainfall; Pampas Region

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1. Introduction

The fertile Pampas plain receives 900 mm of annual rainfall (Penalba and Vargas, 2008). The principal activity of the region is rain-fed agriculture of cereals and vegetable oils (soybeans, wheat, corn and sunflower are the main crops). The great importance of the agricultural sector for the Argentinean economy is given by the high production of crops in this region, and their export.

One of the main factors that affect the crop production in the Pampas region is the temporal and spatial variability of rainfall (Travasso *et al*., 2009). During the last decade changes in amount and spatial distribution of rainfall have been documented. From the 1960s, the Pampas region has been favoured by an increment of rainfall on both annual and seasonal scales (Liebmann *et al*., 2004). This hydrological condition has permitted the agricultural border to extend around 200 km to the west, favouring agricultural activity substantially, especially in the semiarid sub regions.

It is a big challenge for global climate models (GCMs) to simulate regional patterns, temporal variations and the correct combination of frequency and intensity of precipitation (Dai, 2006). GCMs have shown a good capacity to represent characteristics of the South American circulation climatology, on daily to decadal temporal scales (Di Luca *et al*., 2006; Solman and Le Treut, 2006; Penalba and Bettolli, 2011). On the other hand, the intermodel variability in the representation of monthly and seasonal characteristics of the rainfall and temperature in different regions of South America is high (Vera *et al*., 2006; Silvestri and Vera, 2008; Rusticucci *et al*., 2010).

Daily rainfall events depend principally on the large-scale atmospheric fields. The evaluation of the skill of the GCMs in representing the circulations associated with rainfall events over the Pampas region is very important as a first step towards, for example, seasonal prediction of crop yields. The study of the relationship between circulation types and rainfall is in general the basis for a great deal of the statistical downscaling methods. For the Pampas region, this relationship has been little explored (Penalba and Bettolli, 2011).

This study seeks to achieve two main objectives: (1) to analyse the ability of the GCMs to reproduce the observed daily rainfall in the Pampas region, and, (2) to compare the relationship between surface circulation patterns and daily rainfall events in the Pampas region as generated by GCMs to those derived from NCEP re-analysis data and observations.

2. Data and methods

To perform this analysis, different data sets were used from the period 1979–1999.

2.1. Observations

1. Daily mean sea level pressure (SLP) fields from NCEP reanalysis 2 (Kanamitsu *et al*., 2002), were used to represent observed circulation. The domain extends from 15 °S to 60 °S and from 42.5 °W to 90 °W on a 2.5° latitude-longitude grid (Figure 1).
2. Observed daily rainfall series from stations in the Pampas region were provided by the Argentine National Weather Service. The analysis was performed with five stations (Figure 1) that fulfil the quality requirements established (less than 10% of missing data and a continuity of their records).

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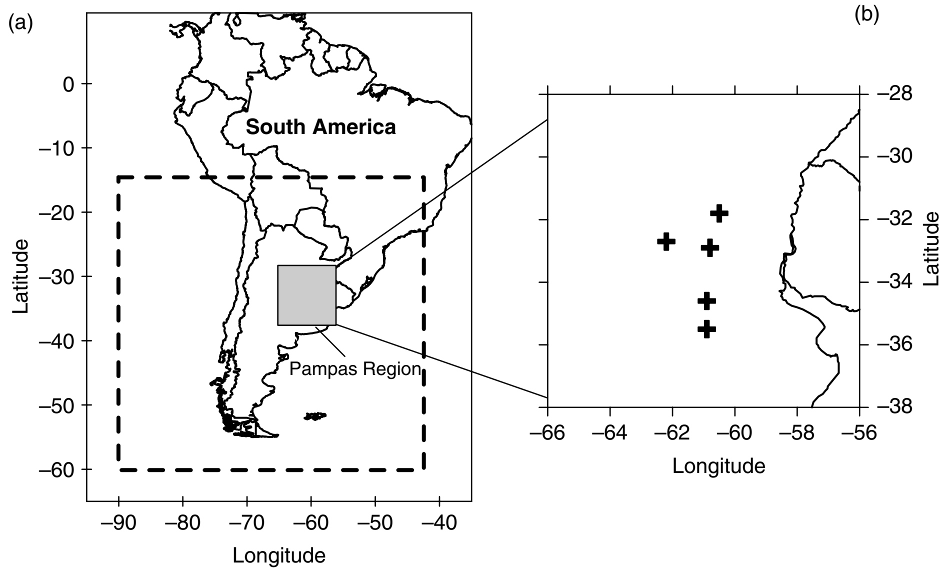


Figure 1. (a) The Argentine Pampas Region (shaded rectangle) and the domain chosen for the sea level pressure fields (dashed line). (b) Locations of the five meteorological stations.

Table 1. List of GCMs used in this study.

Project phase	Model designation	Original grid resolution (latitude × longitude)
CMIP3	BCCR-BCM2.0	2.7905° × 2.8125°
	CNRM-CM3	2.79° × 2.8125°
	CSIRO-Mk3.0	1.865° × 1.8750°
	ECHAM5/MPI-OM	1.865° × 1.8750°
	GFDL-CM2.0	2° × 2.5°
	GFDL-CM2.1	2° × 2.5°
	GISS-EH	3° × 5°
	GISS-ER	3° × 5°
	INGV-SXG	1.1215° × 1.125°
	IPSL-CM4	2.5352° × 3.75°
	UKMO-HadCM3[a]	2.5° × 3.75°
CMIP5	CanESM2	2.7906° × 2.8125°
	CNRM-CM5	1.4007° × 1.4063°
	CSIRO-Mk3.6	1.8652° × 1.875°
	HadGEM2-ES	1.25° × 1.8750°
	IPSL-CM5A	1.8947° × 3.75°
	NorESM1-M	1.8947° × 2.5°

[a] Available period for present climate: 1979–1989.

2.2. Models

1. Daily fields of SLP from a set of 17 GCMs were used to describe present low level circulation (Table 1). These simulations are available through the Program for Climate Model Diagnosis and Intercomparison and the ENSEMBLES CERA archives. The simulations correspond to the Coupled Model Intercomparison Project Phase 3 and 5 (CMIP3 and CMIP5) from which the 20C3M experiment and the historical experiment were used, respectively. The SLP fields of the models were interpolated to the NCEP reanalysis grid with an inverse distance weighting method in order to facilitate comparisons.
2. Daily GCM rainfall from the grid points that are included in the Pampas region were analysed (shaded rectangle in Figure 1). Modelled daily rainfall was not interpolated to a common grid due to its spatial discontinuity. The number of grid points analysed for each model (ranging from 4 to 12) depends on the models' grid and resolution.

The analysis focuses on winter (June, July, August) and summer (December, January, February), coinciding with key stages of the growing season of different main crops of the region (wheat, corn and soybean).

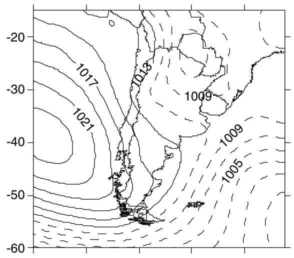
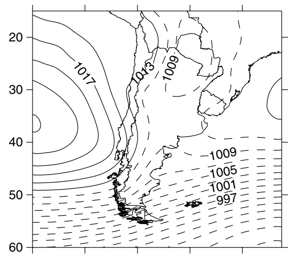
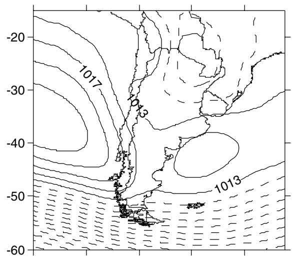
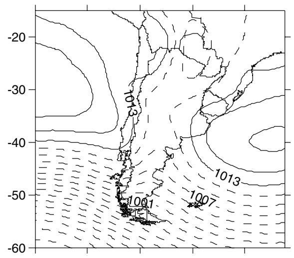
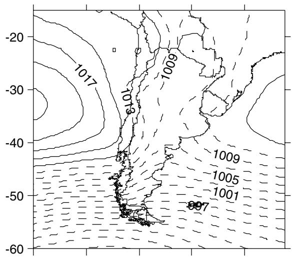
2.3. Methods

The NCEP SLP fields were classified into circulation types (CTs) by combining the Principal Component Analysis with the k-means Cluster Analysis (Huth *et al.*, 2008). This classification of the daily circulation in southern South America consists of five spatial structures for summer and seven for winter. The CTs will be identified by CT_{ij} where i represents its number ($i = 1–5$ for summer and $i = 1–7$ for winter) and j represents the season $j = \text{s}$ for summer and $j = \text{w}$ for winter). The resulting CTs are shown in the second column of Tables 2 and 3 adapted from Penalba and Bettolli (2011) and will be referred to as observed CTs in the following.

The SLP fields from the GCMs, were classified using the cluster centroids from the NCEP original typing. Each GCM SLP daily field was assigned to the observed CT that correlated best with the daily field. In this way, for each GCM, the daily SLP fields were classified in five categories for summer and seven for winter. These categories will be referred to as modelled CT1-5s and CT1-7w, respectively.

In order to define a quantitative measure to relate the rainfall events with CTs, two probabilities were compared by means of the Z statistic (Infante Gil and Zárate de Lara, 1984). These are the conditional probability (P) of occurrence of a given rainfall event R for a specific CT_i ($P(R/CT_i)$) and the probability of its occurrence for the rest of the days (Bettolli *et al.*, 2010). The Z statistic was calculated for the observed CTs and the observed rainfall and for the different modelled CTs and the modelled rainfall. Two confidence levels were used: 95 and 90%. A positive and significant statistic means that there is a high chance of rainfall event R occurrence for a specific CT_i.

Table 2. Observed summer circulation types (CTs).

Summer				
	CT	Dry events	R1	R10
CT1s		**−1.81****	**1.81***	−0.06
CT2s		**−2.01**	**2.01**	**2.25**
CT3s		1.21	**−1.21**	−0.99
CT4s		**2.82**	**−2.82**	**−3.05**
CT5s		−0.35	0.35	1.00

Z-statistics of the comparison between the conditional probability of occurrence of rainfall event (dry, R1 and R10) for each CT and the probability of occurrence of the same rainfall event for the rest of the CTs. If the Z-statistic value is positive (negative) and significant, the specific circulation pattern has (does not have) a significant contribution to the rainfall event. Bold: significant values at 95 and 90% (*).

3. Results

3.1. Daily rainfall in the Pampas Region

In this section the models' representation of the distribution of daily summer and winter rainfall in the Pampas region is analysed. A comparison between observed and modelled rainfall is a complex matter on the daily timescale. For that reason, it is important to establish an appropriate method of comparison. If each meteorological station is compared to the nearest grid point, the information would be duplicated in many cases and in other cases there wouldn't be information. Therefore, the rainfall data from the five meteorological stations and for the grid points covering the region (4–12 grid points depending on the model) for each model were used. For observations, the total sample size for calculations were 9450 for summer (5 daily values × 1890 days in summer) and 9660 for winter (5 daily values × 1932 days in winter). The sample sizes of models vary depending on the model (number of grid points and of days in summer and winter).

The histograms of summer and winter relative frequencies, to the total sample sizes, by individual rainfall categories are shown in Figure 2. The comparison of the relative frequencies of models and observations shows that in both seasons all models overestimate considerably the frequency of days in the first interval (0–0.1 mm). The observed frequency in the first interval is 0% for summer and winter, while the mean model frequency is 33.5 and 44%. The inter-model dispersion is very high, with values from 0% for the models CanESM2, CNRM-CM5, CSIRO-Mk3.6 and IPSL-CM5 to 64.9% for ECHAM/MPI-OM in summer and to 88.6% for GFDL-CM2.0 in winter. In general, most numerical models tend to generate precipitation too frequently at reduced intensity, especially over land (Dai, 2006). These results verify that this bias also occurs in the Pampas region.

During summer, the overestimation and the inter-model dispersion is lower for rainfall days in the intervals 0.1–1 and 1–5 mm. The overestimation of relative frequencies in these intervals is particularly observed in the CMIP5 models. For heavy rainfall (10–20 mm) the models underestimate the frequency and for very heavy rainfall days (more than 20 mm) the underestimation is larger. For winter, the behaviour of the frequencies in the interval 0.1–1 mm is similar to this interval in summer, while for daily rainfall over 1 mm the models underestimate the frequencies.

Another important aspect when evaluating the models' skill in representing daily rainfall over the region is to analyse how the total rainfall is distributed over the intervals. For this purpose, the percentage of contribution to total rainfall of each interval was calculated for summer and winter (Figure 3). In both seasons of the year, the large overestimations of the frequency in the interval 0–0.1 mm observed in Figure 2 do not contribute significantly to the total rainfall. In the interval 0.1–1 mm the contributions are overestimated, in particular during winter. The main contributions of the models are found in the intervals 1–<5, 5–<10 and 10–<20 mm, while for the observations the main contribution is from days with 20–50 mm of rainfall. In this last range, most models underestimate the contributions, but the inter-model dispersion is high. The very extreme observed rainfalls (over 50 mm day^{-1}) contribute with 26.25 and 8.8% of the total summer and winter rains, respectively. In this range the models show a very low contribution, confirming the well known difficulties of models to reproduce extreme rainfall. The evident exceptions are the models GISS-EH and GISS-ER, which overestimate the contribution of total rainfall from this category.

Since the analysis in the next section will focus on the circulation that conditions the days with or without rainfall, it is necessary to determine a threshold of rainfall to define a

Table 3. Idem Table 2 for winter.

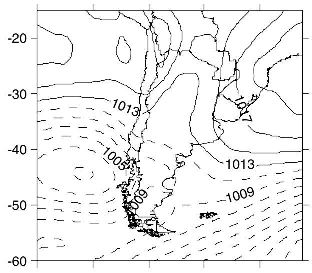
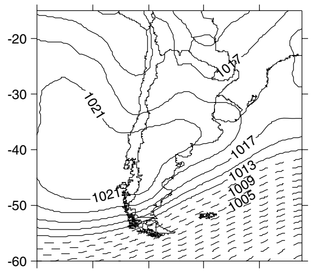
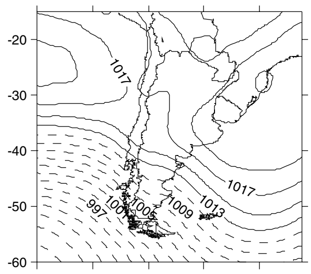
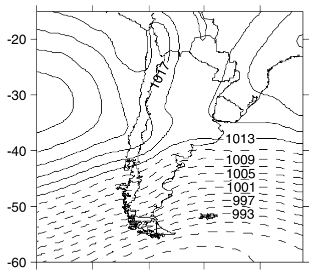
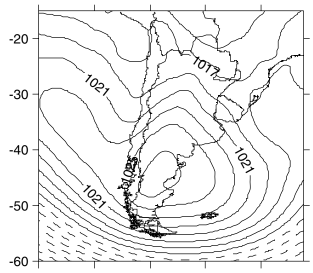
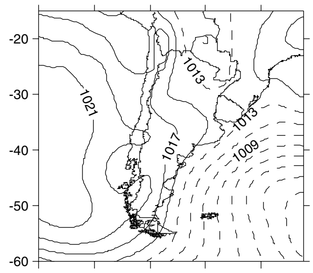
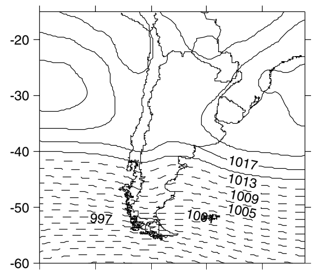
Winter				
	CT	Dry events	R1	R5
CT1w		0.05	−0.05	0.75
CT2w		**1.72***	**−1.72***	**−2.26**
CT3w		0.61	−0.61	−0.71
CT4w		**2.07**	**−2.07**	−1.36

Table 3. (*Continued*).

Winter				
	CT	Dry events	R1	R5
CT5w		**−4.17**	**4.17**	**3.06**
CT6w		**−2.59**	**2.59**	0.44
CT7w		0.99	−0.99	0.34

rain day and a dry day in the Pampas region. This threshold should be established with the purpose to make comparisons between observations and models possible.

Having in mind the previously analysed results (Figures 2 and 3), a threshold set to the trace of observed rainfall (0.1 mm) would imply an overestimation both of the frequencies of rain days and of the contributions from the models. For this reason, from here on, 1 mm of rainfall will be used as the threshold to differentiate a rain day from a dry day for both observed and modelled data, and for summer and winter.

Another common threshold, when comparing observations with models, is 10 mm day^{-1}, which is considered as heavy rain day. To evaluate if this threshold could be associated with an extreme condition in the Pampas region, the daily rainfall distribution for each season, is analysed. These distributions of daily rainfall greater than or equal to 1 mm, both for observations and models, are shown as box plots in Figure 4. The observed median value for summer is 10 mm and the same value is close to the 75th percentile of most models. On the other hand, in winter, 10 mm day^{-1} corresponds to the observed percentile 69 and, for the majority of the models it implies a very extreme rainfall day, exceeding the 75th percentile. Consequently, the threshold 10 mm day^{-1} is appropriate to define the heavy rainfall days of summer, but is very high for winter.

In order to establish an analogy between the threshold for summer and winter, the winter threshold is established as 5 mm day^{-1}, which approximates the observed median for winter and the 75th percentile for the models.

It is interesting to highlight the role of the models in representing the seasonal behaviour of the rainfall. The observed annual rainfall regime is characterized by two equinoxial maximum and abundant rainfall throughout the whole year with a winter minimum (Rusticucci and Penalba, 2000). In general, the models reproduce the difference between winter and summer distributions of rain days fairly well (Figure 4). However, there are exceptions, such as the model ECHAM5/MPI-OM for which this seasonality is inverted, in particular in the inter quartile interval and for the extreme values (95th percentile).

3.2. Daily rainfall events and circulation

The observed rainfall is related to some of the observed CTs (Penalba and Bettolli, 2011). This section investigates whether the same relationship between modelled CTs and rainfall is

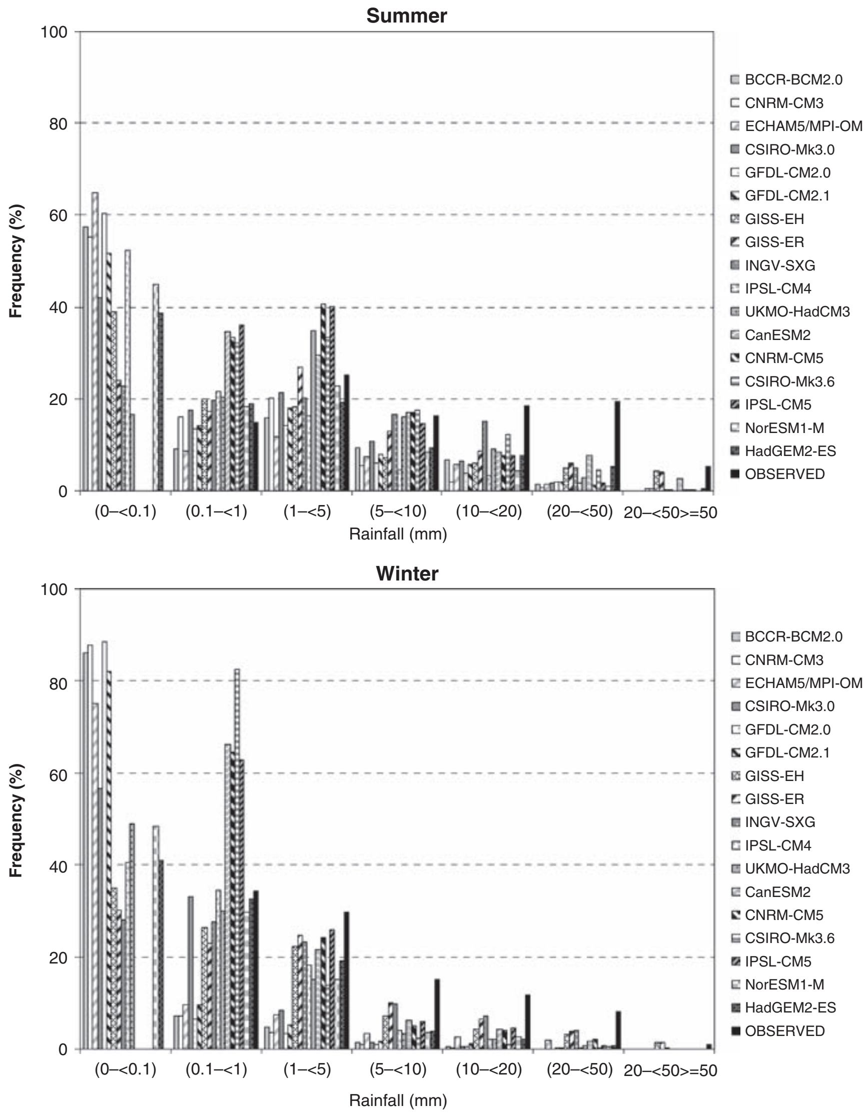


Figure 2. Summer and winter relative frequencies, to the total sample sizes, of daily rainfall (mm). The information considered corresponds to the five meteorological stations and 4–12 grid points depending on the model. Observations in black bars and models in grey bars.

represented by the models. This study is focused on the synoptic scale: therefore, the interest is in the occurrence or non-occurrence of a rainfall event over the region, and not in smaller scales or magnitudes of the event.

An observed rainfall event is considered when a day with rainfall equal to or larger than 1 mm in at least one of the five meteorological stations (20% of the stations) occurred (R1). An observed heavy rainfall event is defined when at least rains of 10 mm day^{-1} occurred in summer (R10) (5 mm day^{-1} in winter-R5) in at least one of the meteorological stations. An analogue spatial coverage was considered for the models. Depending on the model, the 25–33% of the grid points with rainfall data in the region were required to define a modelled rainfall event and a modelled heavy rainfall event (since the number of grid points vary between 4 and 12). The non-occurrence of a rainfall event (considered as a dry event) is the complementary event of a rainfall event.

3.2.1. Observed circulation types and daily rainfall

The relations between the observed CTs and the observed rainfall events (station data) were evaluated with the Z statistics (Tables 2 and 3).

For summer, CT4s has the highest contribution to the dry events, showing positive and significant values of the Z statistic for this condition. The configuration of SLP of CT4s corresponds to an intensification and expansion of the southern Atlantic anticyclone, which interrupts the passage of the western perturbations and diverts them to the south. Rainfall events (R1) are favoured by CT1s and CT2s (positive and significant values of the Z statistic) which represent a post-frontal intense anticyclone that moves forward across the continent and a cyclonic disturbance at the centre of the continent associated with a cold front passage, respectively. CT2s also shows the highest probability of having a heavy rainfall event (R10).

Winter dry events are significantly favoured by CT4w (highest positive and significant Z statistic), which represents a high pressure system that extends from the Atlantic Ocean to the centre of the continent. These events are also benefited by CT2w, a high pressure system that extends towards the south from the Pacific Ocean. Heavy rainfall events (R5) and rainfall events (R1) are significantly benefited by CT5w, which represents a high pressure system at the south of the continent, enhancing an anomalous flow from the east-southeast to the central region of Argentina and a corresponding moisture

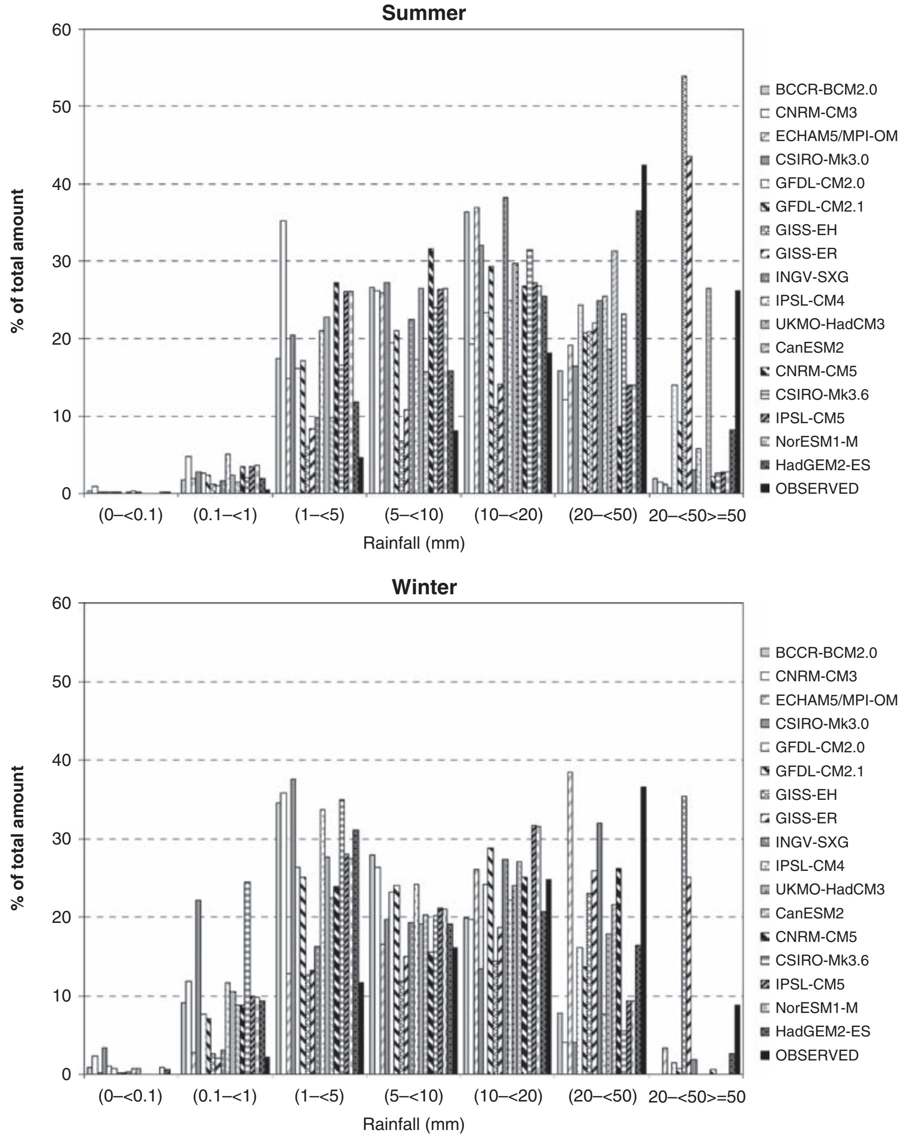


Figure 3. Contribution (%) to summer and winter total precipitation from the same precipitation categories as in Figure 2. Observations in black bars and models in grey bars.

advection at low levels. R1 are also favoured by a cold front that advances towards the northeast, with its postfrontal anticyclone generating southern advection when moving over the continent (CT6w) (Table 3).

3.2.2. *Simulated CTs and daily rainfall*

The capacity of GCMs in representing the sea level pressure patterns (CTs) for the period 1979–1999 was evaluated in Penalba and Bettolli (2011). The authors found that the models are capable of reproducing the full range of summer and winter circulation types found in the NCEP climatology and their main characteristics. In general, the GCMs are able to reproduce the structure and position of the atmospheric systems, although an inter-model variability in CTs frequencies was observed. In this section, the ability of the models to reproduce the relationship described above between observed CTs and daily rainfall in the Pampas region is analysed. For this purpose, the Z statistic for each modelled CT and modelled rainfall event were calculated (Table 4). The analysis was focused only in the cases for which the observed relationship is statistically significant for the extreme events, i.e., for heavy rainfall events and dry events. To determine if the link between modelled CTs and modelled rainfall is captured by the models, the Z-statistics should be positive and significant.

During winter the relationship between CT4w-dry event and the relationship CT5w-R5 is represented by 13 and 12 of the 17 models, respectively. For summer, eight models represent the relationship CT4s-dry event correctly, while only two models are able to reproduce the relationship CT2s-R10. These results show a clear difference between the models' capacities to represent the relationship circulation-rainfall during winter *versus* summer. In particular, the difficulty of the models in representing the circulation patterns that are related with extreme rainfall events during the warm season is noticed. The reason for this could be that the models are better at representing the synoptic systems, such as frontal systems and perturbations that dominate the generation or inhibition of rainfall during winter, than at representing the complexity of the rainfall processes involved during summer in the region (perturbations at smaller scales, air mass storms, the low level jet).

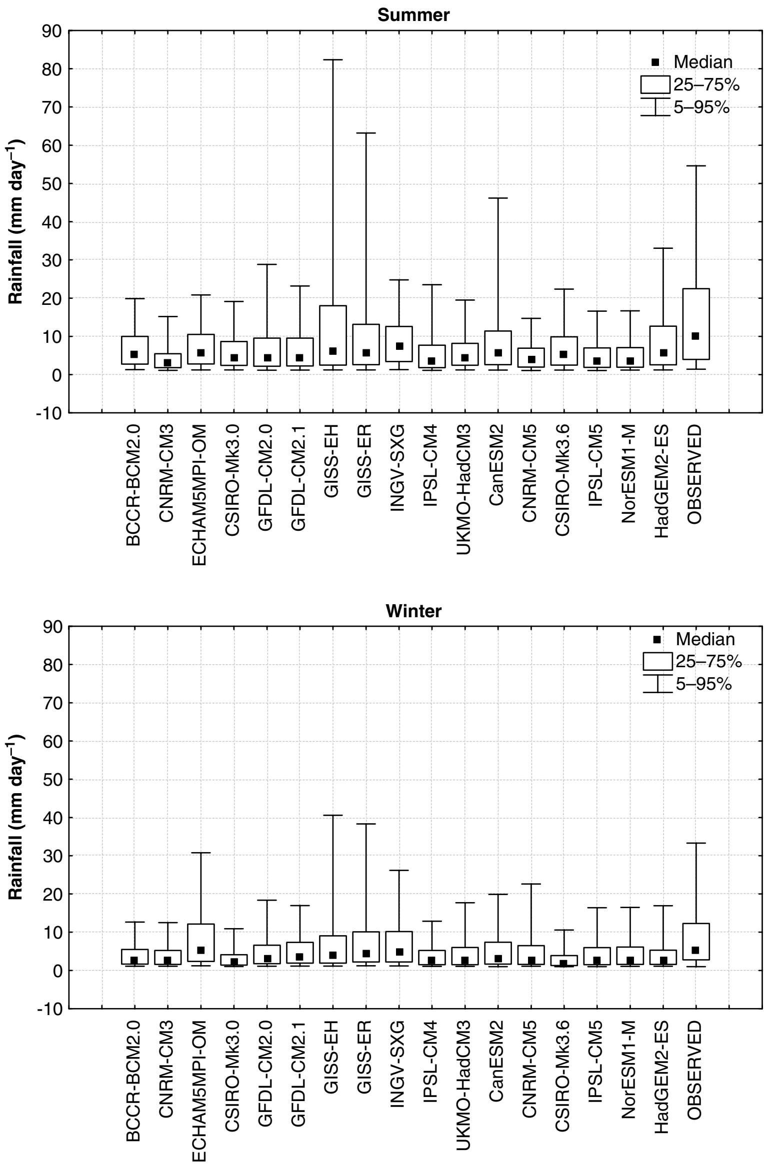


Figure 4. Box plots of observed and modelled daily precipitation greater than or equal to 1 mm for summer and winter.

4. Conclusions

Taking into account the present and future relevance of the Pampas region for the economy of the country, it is very important to analyse rainfall and circulation for model evaluation and development. This kind of study facilitates the selection of tools to permit the assessment of the impact of a possible change of the rainfall distribution in the region, related to climate change.

The common characteristic of the models to precipitate too frequently at low intensity and less frequently at high intensity was confirmed over the Pampas region. Even if this characteristic was observed for both seasons, it is more accentuated in winter. It is important to highlight that the inter-model dispersion is considerably large within each season. Although not the focus of this study, it was hereby shown that this bias exists over the Pampas region in the newest generation of models.

This bias is present for days with rainfall equal to or higher than 1 mm, although the bias is smaller and the model dispersion is lower. According to this analysis, 1 mm was chosen as an appropriate threshold to differentiate a dry event from a rainfall event in the comparison between observed and modelled rainfall.

Most models are able to reproduce fairly well the differences between daily summer and daily winter rainfall distribution observed in the Pampas region. This is probably related to the difference between the mechanisms that generate rainfall for the two seasons, and the capacity of the models to reproduce this difference. To verify this, the low level circulation of southern South America was analysed together with the relationship between the circulation and the daily rainfall in the Pampas region. The results show that the models tend to represent this relationship better in winter. This reflects the ability of the models in reproducing the synoptic scale patterns associated with rainfall during the winter (fronts and perturbations). The relationship circulation-rainfall during summer is very poor, indicating a deficiency of the models in representing small scale processes involved in the generation of summer rain.

This work shows the relationship between daily rainfall and sea level pressure. In the future it would be of interest to study

Table 4. Z-statistic for each modelled CT and modelled rainfall event for the cases where the observed relationship is statistically significant for heavy rainfall events and dry events.

	Summer		Winter	
	CT4s-dry events	CT2s-R10	CT4w-dry events	CT5w-R5
BCCR-BCM2.0	**2.74**	0.19	**3.98**	**−9.26**
CNRM-CM3	**5.85**	**−1.76***	**2.35**	1.43
CSIRO-Mk3.0	1.41	1.08	**2.22**	**2.65**
ECHAM5/MPI-OM	**3.58**	−0.43	**3.03**	**4.17**
GFDL-CM2.0	0.22	1.09	0.25	**3.49**
GFDL-CM2.1	−0.52	**−2.41**	**3.69**	**2.12**
GISS-EH	**3.03**	**1.99**	**5.51**	**4.66**
GISS-ER	0.21	**−3.78**	**6.22**	**6.63**
UKMO-HadCM3	−0.70	**−2.65**	**6.55**	**1.79**
INGV-SXG	**5.37**	−0.05	0.23	**3.19**
IPSL-CM4	**4.08**	−1.06	**2.94**	**2.72**
CanESM2	**1.87**	−0.89	**2.71**	**4.82**
CNRM-CM5	1.10	−0.31	**4.12**	1.51
CSIRO-Mk3.6	**−2.34**	**−2.16**	0.34	−1.49
HadGEM-ES	−0.64	0.39	−0.43	0.94
IPSL-CM5A	**−2.97**	**−2.12**	**4.14**	**1.65***
NorESM1-M	**2.00**	**2.03**	**4.91**	**2.51**
Observed	**2.82**	**2.25**	**2.07**	**3.06**

Bold: significant values at 95%. * : significant values at 90%.

how the GCMs reproduce other dynamic and thermodynamic variables, and their possible relation with rainfall.

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