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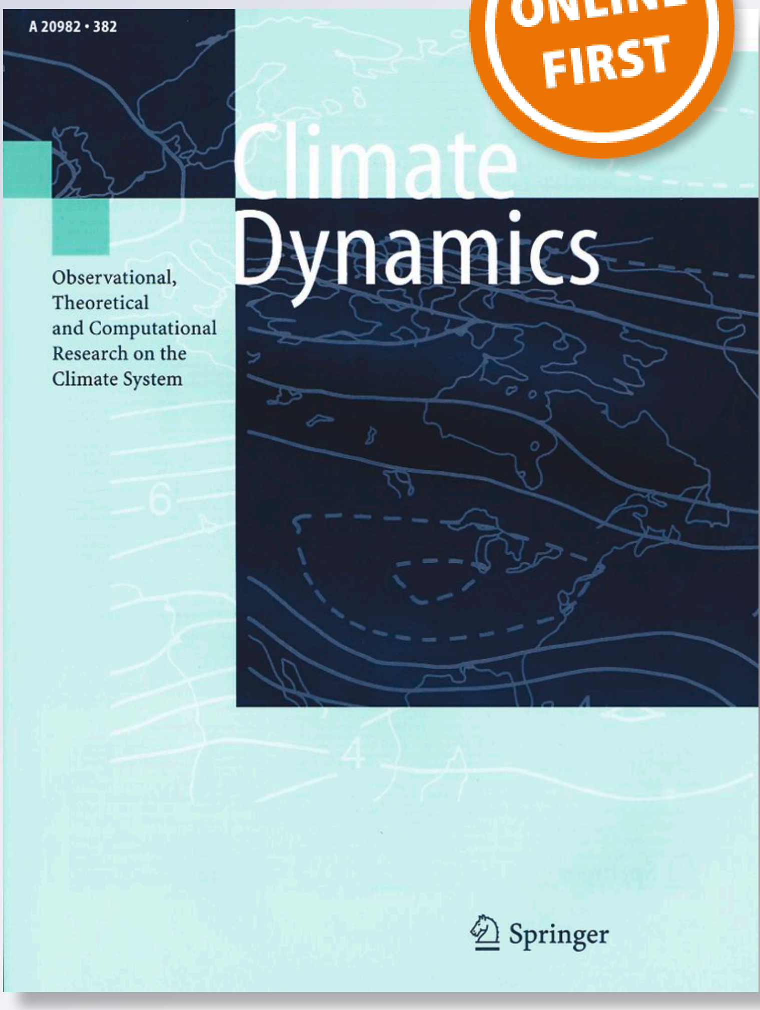
Climate Dynamics
Observational, Theoretical and Computational Research on the Climate System

ISSN 0930-7575

Clim Dyn
DOI 10.1007/s00382-017-3765-z

ONLINE FIRST



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Fronts and precipitation in CMIP5 models for the austral winter of the Southern Hemisphere

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Received: 30 December 2016 / Accepted: 9 June 2017

Abstract Wintertime fronts climatology and the relationship between fronts and precipitation as depicted by a group of CMIP5 models are evaluated over the Southern Hemisphere (SH). The frontal activity is represented by an index that takes into account the vorticity, the gradient of temperature and the specific humidity at the 850 hPa level. ERA-Interim reanalysis and GPCP datasets are used to assess the performance of the models in the present climate. Overall, it is found that the models can reproduce adequately the main features of frontal activity and front frequency over the SH. The total precipitation is overestimated in most of the models, especially the maximum values over the mid latitudes. This overestimation could be related to the high values of precipitation frequency that are identified in some of the models evaluated. The relationship between fronts and precipitation has also been evaluated in terms of both frequency of frontal precipitation and percentage of precipitation due to fronts. In general terms, the models overestimate the proportion between frontal and total precipitation. In contrast with frequency of total precipitation, the frequency of frontal precipitation is well reproduced by the models, with the higher values located at the mid latitudes. The results suggest that models represent very well the dynamic forcing (fronts) and the frequency of frontal precipitation, though the amount of precipitation due to fronts is overestimated.

Keywords Frontal activity · Precipitation · Present climate · CMIP5 models · Southern Hemisphere

1 Introduction

The atmospheric fronts are dynamic systems that control the day-to-day weather of the extratropical latitudes. The study of these systems is relevant since most of the precipitation that occurs at the mid and high latitudes of the Southern Hemisphere (SH) is associated with fronts (Catto et al. 2012). Under unstable atmospheric conditions fronts could be a dynamic mechanism that triggers convection and subsequent precipitation (Bjerknes and Solberg 1992; Browning and Roberts 1994). Moreover, it has been demonstrated that the frontal activity variability exerts an influence on precipitation variability at different timescales. Blázquez and Solman (2016, 2017) studied the variability of frontal activity and its connection with the variability of the atmospheric circulation and precipitation in the SH for the austral winter using reanalysis. They found that the variability of fronts at both the intraseasonal and interannual timescales exerts a strong control on the variability of precipitation, especially over the southern Pacific Ocean and South America.

Solman and Orlanski (2014) demonstrated that the moistening of the high latitudes and the drying of the

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mid-latitudes in the last 20 years in the SH are in agreement with the frontal activity change. Hence, it is natural to question the extent to which future changes in frontal activity may impact on future precipitation. However, the first step to study climate change scenarios is to analyse the present climate conditions, particularly in terms of the capability of the models in capturing the main features of the synoptic-scale systems and the associated precipitation. Several studies have focused on evaluating the ability of models in representing mid-latitude eddies. Among them, Chang et al. (2013) have analysed the performance of a group global climate models belonging to the Coupled Model Intercomparison Project Phase 3 (CMIP3) in representing the storm tracks over the SH. They found that most of the models represent adequately the equatoward migration and strengthening of the storm tracks during the cold season. Grieger et al. (2014) explored the ability of a subset of climate models in representing extratropical cyclones in the SH and found that most of the individual models reproduce satisfactorily the main cyclone features, compared against reanalysis data. It is known that both cyclone activity and storm tracks are related with frontal systems (Bjerknes and Solberg 1992; Houze 2014; Berry et al. 2011). Even though, in the literature few authors have analysed the capability of climate models in representing fronts. Among them, Catto el al. (2014) explored the ability of 18 CMIP5 models in reproducing the spatial distribution of front frequency and intensity in the present climate on a global basis. They found that the model ensemble is able in reproducing both front strength and frequency compared with the ERA-Interim reanalysis dataset. However, they focus their analysis on the ensemble mean, without taking into account the behaviour of individual models; which would allow studying in depth the main differences among models.

On the other hand, several recent studies have focused on evaluating the capability of the models in reproducing several precipitation features in different regions of the world. Particularly, Gulizia and Camilloni (2015) used CMIP3 and CMIP5 models to evaluate the representation of the mean precipitation over South America (SA) and found that some bias were reduced in the CMIP5 models over some regions of SA. Koutroulis et al. (2016) evaluated the performance of CMIP3 and CMIP5 models in representing daily precipitation metrics in the historical experiments over many regions of the world, including the SH. They found that the CMIP5 models represent better the intense events and the number of wet days compared with observational datasets compared with CMIP3 models. Mehran et al. (2014) explored the performance of CMIP5 models in representing continental precipitation and they found that monthly precipitation is well represented by the models, but not the upper quantiles of the precipitation distribution. As was mentioned previously, precipitation in the mid-latitudes of the SH is strongly associated with frontal systems, thus, it is worth to evaluate the extent to which CMIP5 models are able of capturing the precipitation associated with fronts. Accordingly, the foci of this work are twofold: first, to analyse how climate models represent the fronts' climatology over the SH and second, to explore the capability of a subset of CMIP5 climate models in representing the relationship between fronts and precipitation over the SH.

Since in a warming scenario the austral winter precipitation is projected to change over the SH (IPCC 2013), a companion paper focuses on evaluating to what extent changes in precipitation are associated with changes in frontal systems. Accordingly, the two objectives that are going to be achieved in this work are the starting point for studying the future projections.

This work is organized as follows: Sect. 2 describes the data and methodologies used in this study, results are presented in Sect. 3 and a summary of the results and the conclusions of the study are discussed in Sect. 4.

1.1 Data and methodology

To study how climate models represent the climatology of fronts over the SH and its relationship with precipitation, a subset of CMIP5 global models were selected (Taylor et al. 2012). The model selection was based on two criteria: model performance and climate sensitivity. First, the performance of CMIP5 models in terms of the representation of the interannual variability of the atmospheric circulation, as shown by Grainger et al. (2014), and the representation of mean precipitation discussed by Gulizia and Camilloni (2015), was identified with the aim of using observational constraints to reduce the uncertainty. Second, climate sensitivity evaluated by Forster et al. (2013) was taken into account with the aim of capturing the models' spread and avoid using a large number of models. This issue was addressed because in a second part paper the future projections are going to be analysed. After evaluating the results from the referred literature, a subset of eight global models was selected (listed in Table 1). Daily data from the historical period 1979–2005 was used.

The model data was contrasted with the European Centre Medium Range Weather Forecasts (ECMWF), ERA-Interim reanalysis (Simmons et al. 2007; Dee et al. 2011) with 1.5° resolution for the period (1979–2005) and with the Global Precipitation Climatology Project (GPCP) daily precipitation dataset (Huffman et al. 2001), with 1° of resolution for the period (1997–2005). For this database a shorter period was used due to lack of daily data before 1997.

To represent fronts the FIq index was used. This index was calculated as the product between monthly averages

Table 1 CMIP5 models used in this study

Model name	Institution (country)	Resolution (°lat × °lon)
CanESM2	Canadian Centre for Climate Modelling and Analysis (Canada)	Atm: 2.79 × 2.81 Oce: 0.93–1.14 × 1.41
CNRM-CM5	Centre National de Recherches Météorologiques, Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (France)	Atm: 1.4 × 1.41 Oce: rotated coordinates
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence (Australia)	Atm: 1.87 × 1.86 Oce: 0.93–0.95 × 1.86
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory (USA)	Atm: 2 × 2 Oce: 0.36–0.5 × 1
IPSL-CM5A-LR	Institut Pierre Simon Laplace (France)	Atm: 1.9 × 3.75 Oce: rotated coordinates
MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (Japan)	Atm: 1.4 × 1.4 Oce: 0.5 × 1.41
MPI-ESM-LR	Max Planck Institute for Meteorology (Germany)	Atm: 1.87 × 1.88 Oce: orthogonal curvilinear coordinates
NorESM1-M	Bjerknes Centre for Climate Research, Norwegian Meteorological Institute (Norway)	Atm: 1.89 × 2.5 Oce: rotated coordinates

of the daily horizontal gradient of temperature times the cyclonic relative vorticity at 850 hPa and the monthly mean specific humidity at the same level:

$$FIq = \overline{\left|\nabla T_{850\,\mathrm{hPa}}\right| \times \xi_{850\,\mathrm{hPa}}} \times \overline{q_{850\,\mathrm{hPa}}}$$

where the $\overline{(\ )}$ operator indicates the monthly mean. Note that the front definition requires the daily joint occurrence of a cyclonic system (represented by the cyclonic vorticity) and a thermal contrast (depicted by the temperature gradient). The presence of the humidity in the definition responds to the modulation of the intensity. With these variables, the index definition is taking into account both the dynamic and the thermodynamic characteristics of a frontal system. For the temperature gradient, values higher than 1 °C/100 km are used to compute the index to account for a minimum thermal contrast associated with fronts, as discussed in Hewson (1998). The threshold was defined after performing a sensitivity analysis of the frontal systems climatology to different values of this parameter. There are some authors that have used an index similar to FIq to represent frontal activity. The front index was first introduced by Solman and Orlanski (2010), who used the gradient of temperature and the cyclonic vorticity at 850 hPa to represent fronts. The same definition was then used in Solman and Orlanski (2014) to analyse the observed changes in frontal activity during the last decades; Blázquez and Solman (2016, 2017), used the index to explore the intra-seasonal and interannual variability of fronts, respectively. Solman and Orlanski (2016) introduced some modifications to the index by calculating the product between cyclonic vorticity and the specific humidity. Overall, the representation of fronts using these indices were found to be realistic. Other authors have analysed fronts based on the wet bulb potential temperature (Hewson 1998; Berry et al. 2011; Catto et al. 2012) and the main characteristics of fronts are similar to the results of the present study.

The study was performed for the austral extended winter: May–August (MJJA), the period when the strongest relationship between fronts and precipitation is expected to occur in the SH.

2 Results

2.1 Characteristics of fronts

As was mentioned previously, one of the objectives of this work is to study the performance of the models in representing the climatology of the frontal activity; therefore, the seasonal mean of fronts, represented by the FIq index for the period (1979–2005) is shown in Fig. 1. The ERA-Interim data presents the highest values between 60 and 70ºS and relative maxima are located over mid-latitudes of the Atlantic and Indian Oceans. This configuration of the frontal activity matches with Solman and Orlanski (2014), who used an index similar to the FIq. The models represent the general characteristics of the frontal activity climatology, however some differences can be found. CSIRO-MK3.6.0, GFDL-ESM2G and MIROC5 models overestimate the maximum values of FIq. In particular, GFDL-ESM2G and MIROC show values that exceed by two or three times the reanalysis over some regions of the southern oceans. On the other hand, some models depict systematic underestimation of the frontal activity the lowest low values of FIq compared with ERA-Interim. Note also

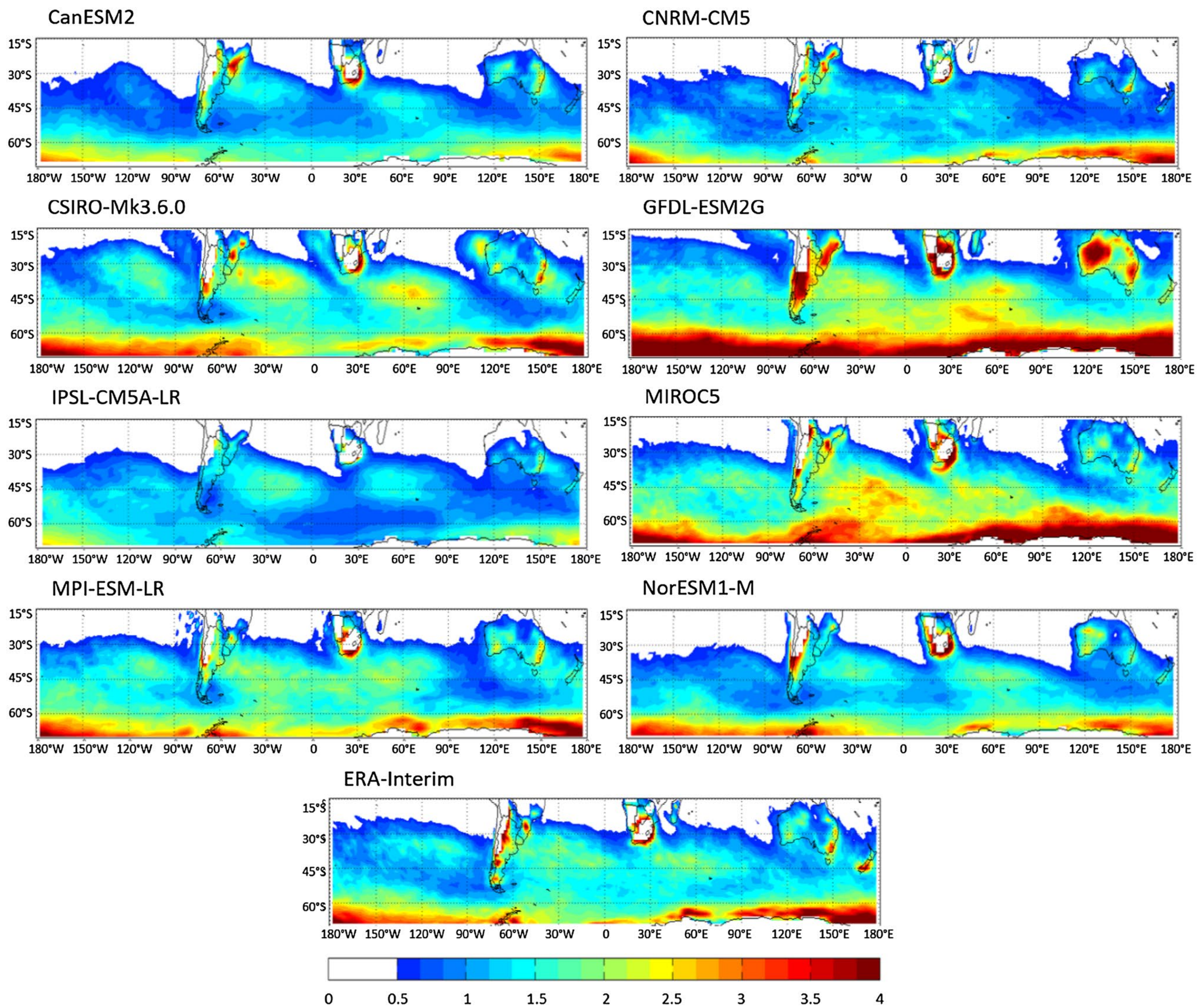

Fig. 1 Seasonal mean frontal activity for the period 1979–2005 as depicted by CMIP5 models and the ERA-Interim reanalysis for austral winter. Units are 1×10^{-13} °C/m/s

the local maxima over southeastern South America, southern Africa and southeastern Australia captured by both reanalysis and models. These regions are characterized by strong frontal and synoptic-scale activity, as reported by Sinclair (1995). Based on a visual inspection, NorESM1-M and MPI-ESM-LR models seem to display the best agreement with the reanalysis.

Not only the mean frontal activity is relevant, particularly when the relationship between fronts and precipitation is examined. Recall that fronts are defined on a daily basis and their relationship with precipitation also occurs on a daily basis. Accordingly, it is worth exploring the frequency of the frontal activity as shown in Fig. 2. The ERA-Interim reanalysis displays the maxima frontal activity frequency between 60 and 70ºS, reaching values between 30 and 45% while in mid-latitudes only a 10–20% of the days are affected by a frontal system. Taking into account that the total number of days considered in the analysis is 3321 (27 extended winters), the total number of fronts that develop at mid-latitudes is approximately one front per week, a reasonable estimate for the SH (Simmonds et al. 2012). Using another definition of fronts Catto et al. (2014) and Simmonds et al. (2012) found a similar structure of front frequency as depicted by the ERA-Interim reanalysis. The models represent very well the frequency of fronts in most of the regions; however, some differences can be found at the mid-latitudes of the Pacific Ocean, where IPSL-CM5A-LR and GFDL-ESM2G overestimate the frequency of fronts and in the extratropical latitudes of the Atlantic and Indian Oceans, where CNMR-CM5 and

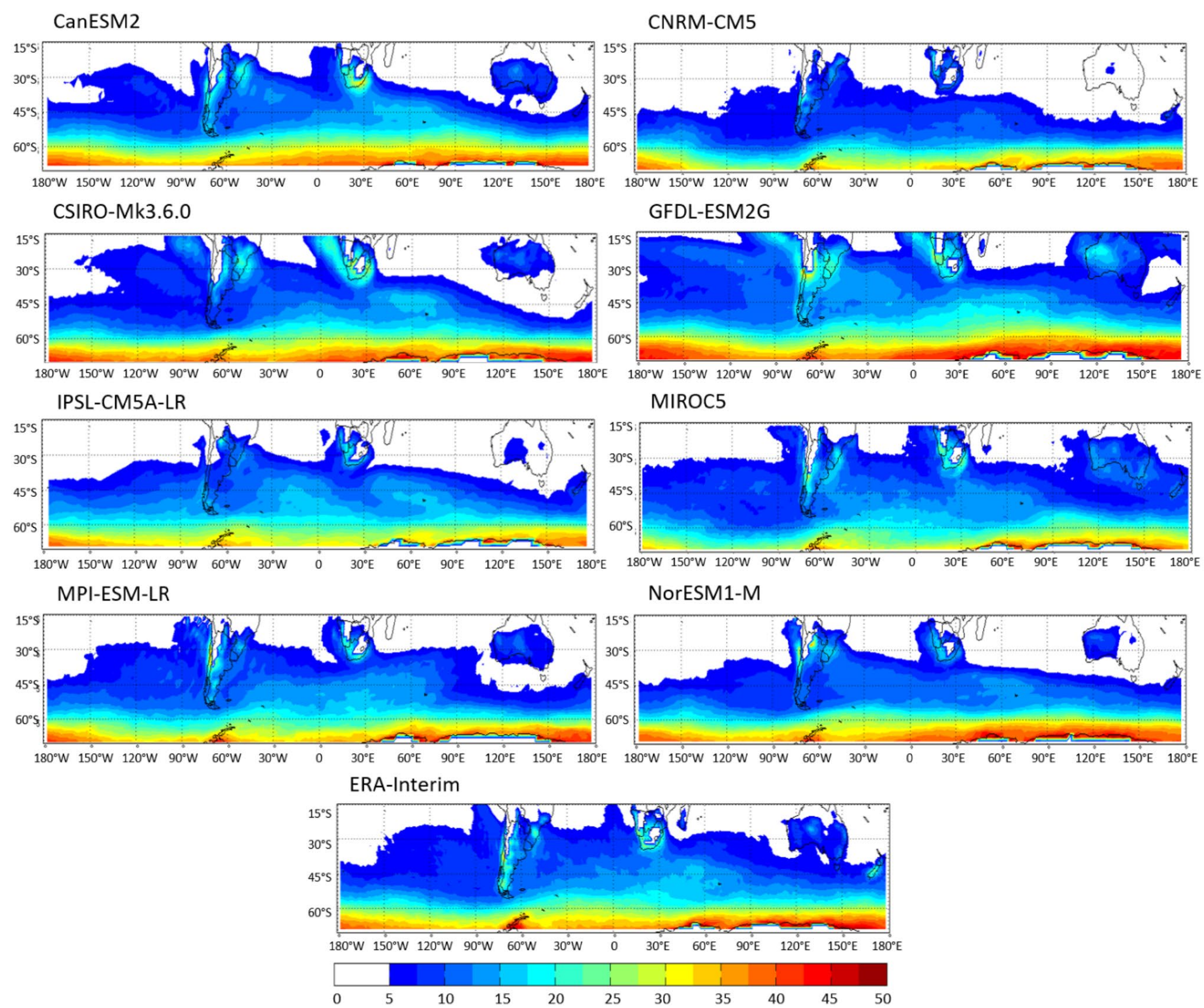

Fig. 2 Front frequency for the period 1979–2005 as depicted by CMIP5 models and the ERA-Interim reanalysis for austral winter. Units are %

NorESM1-M underestimate the number of days affected by fronts. Note also the local frontal frequency maxima over southeastern South America, southern Africa and New Zealand (Berry et al. 2011), a feature well reproduced by almost every model.

Differences among models in both seasonal mean and frequency of fronts could be associated to the different spatial resolution of the models, since the fronts are based on the cyclonic vorticity, which is strongly dependent on resolution. Overall, it can be concluded that the main characteristics of both the seasonal mean and frequency of fronts during the extended winter season in the SH are adequately represented by the set of global models selected in this study. This result agrees with Catto et al. (2014) who evaluated the capability of a subset of CMIP5 GCMs in reproducing the climatology of fronts on a global basis. They found that the multi-model ensemble mean produced a similar frequency of fronts and a similar front strength, though some biases were identified in the front frequency maxima. However, it is worth to remark that the multi-model ensemble mean may mask out the diversity in the performance of individual models. Inspection of individual model behaviour may lead to a better understanding of the relationship between fronts and precipitation, discussed below.

2.2 Characteristics of precipitation

As was said previously, another objective of this paper is to analyse how climate models represent the relationship between fronts and precipitation. First, the capability of the models in reproducing the spatial distribution of winter precipitation is explored. The seasonal mean precipitation has been computed from the daily values larger than 1 mm/day. This threshold was considered because most of the selected models overestimate the number of days with light precipitation (not shown), which is a common shortcoming in every model (Dai 2006). Other studies have also selected this threshold (e.g. Catto et al. 2015). In this case, not only the reanalysis dataset was used but also GPCP. It is worth to remember that for the latter database, the average was done in a shorter period (1997–2005). In Fig. 3 GPCP and ERA-Interim show a band of large precipitation values at mid-latitudes, with maxima over the oceans, New Zealand, South-eastern South America (SESA) and the western coast of South America. GPCP dataset displays higher amounts of precipitation than ERA-Interim over most of the SH. Most of the models overestimate the maximums over the oceans. In particular, CNRM-CM5 and MIROC5 display the largest values of winter precipitation compared with ERA-Interim and GPCP over the Pacific, Atlantic and Indian oceans. This result matches with Catto et al. (2015), who showed that the ensemble mean of 18 CMIP5 models also overestimates the precipitation over the mid-latitudes of the SH oceans. Over New Zealand and the southern tip of South Africa an overestimation of most of the models can be also observed. On the other hand, it can be noted that most models underestimate the maximum over the SESA region, where winter precipitation is mainly associated with frontal systems (Garreaud et al. 2009). The general pattern of precipitation reproduced by the models is in agreement with the multi model ensemble mean displayed in the last IPCC report (Flato et al. 2013); however, the intensity is

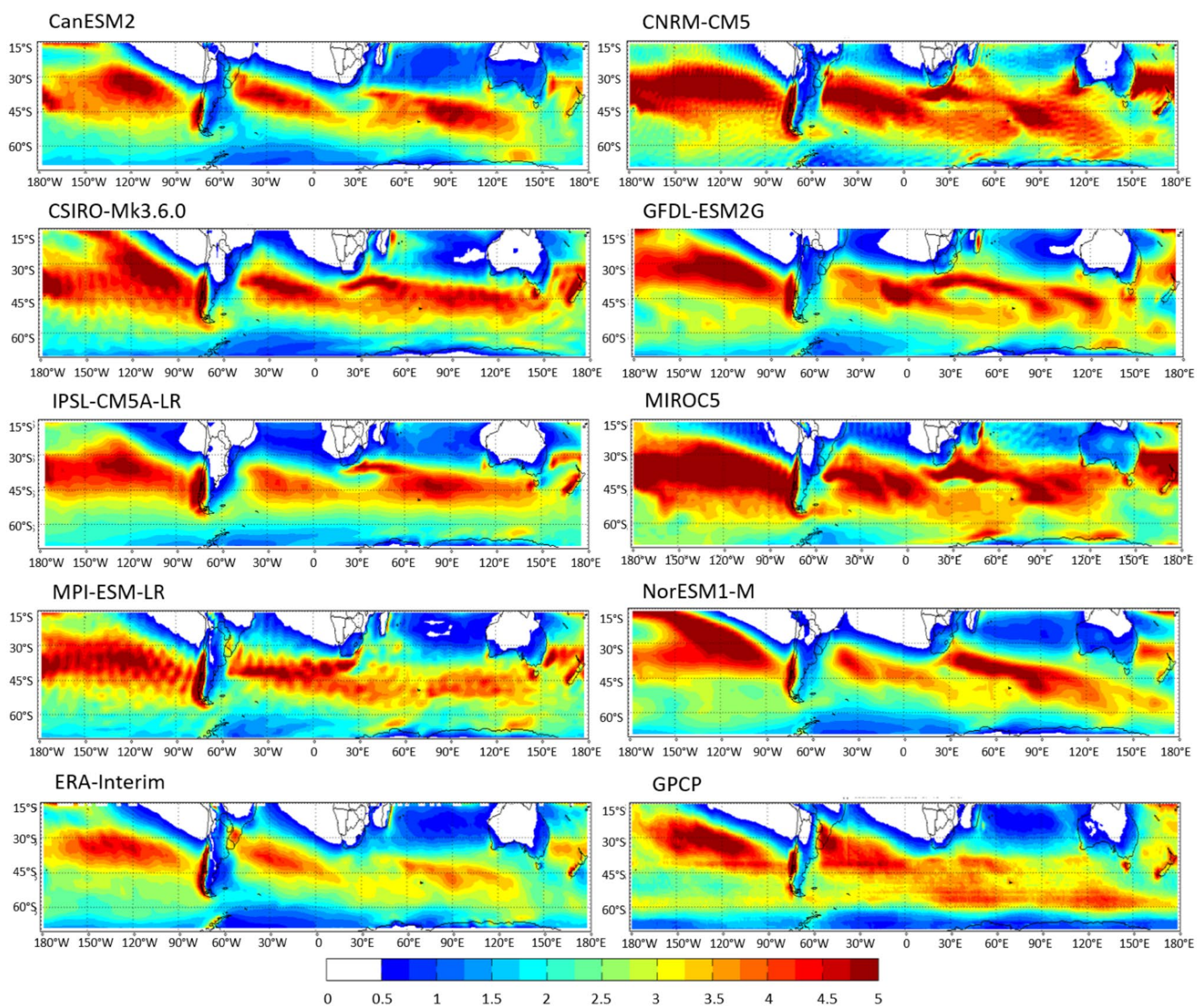

Fig. 3 Seasonal mean austral winter precipitation (larger than 1 mm/day) as depicted by CMIP5 models, the ERA-Interim reanalysis and GPCP. For models and reanalysis the average is calculated for the period 1979–2005 and for GPCP for the period 1997–2005. Units are mm/day

overestimated by the models chosen in this study. Sun et al. (2006) evaluated the precipitation frequency in climate models and found that the frequency of light precipitation (between 1 and 10 mm/day) is overestimated. This behaviour could contribute to explain the overestimation of the mean precipitation in some regions of the domain. Therefore, to explore this issue Fig. 4 shows the frequency of winter precipitation (note that only days with precipitation larger than 1 mm/day were considered). The reanalysis shows that between 60 and 75% of the days have precipitation at mid-latitudes, with peaks of 80–90% over the Indian Ocean. Over the continents, the maximum is located over the southern tip of Chile, where almost 80% of the days exhibit precipitation larger than 1 mm/day. On the other hand, the GPCP dataset shows values of frequency visibly lower than the reanalysis, although the mean precipitation were larger compared with ERA-Interim (see Fig. 3). It is important to take into account that daily precipitation data from GPCP is available for a shorter period. Computing the frequency of wet days for ERA-Interim for the period 1997–2005, for which GPCP data is available, resulted in higher frequencies of precipitation compared those obtained for the longer period (1979–2005). Hence, the shorter period is not the reason of the differences between ERA-Interim and GPCP. This difference can be due to the reanalysis overestimates the frequency of wet days, and particularly overestimates the frequency of light precipitation events and underestimate the frequency of heavy precipitation events, as remarked by Herold et al. (2016). Recall that precipitation is not

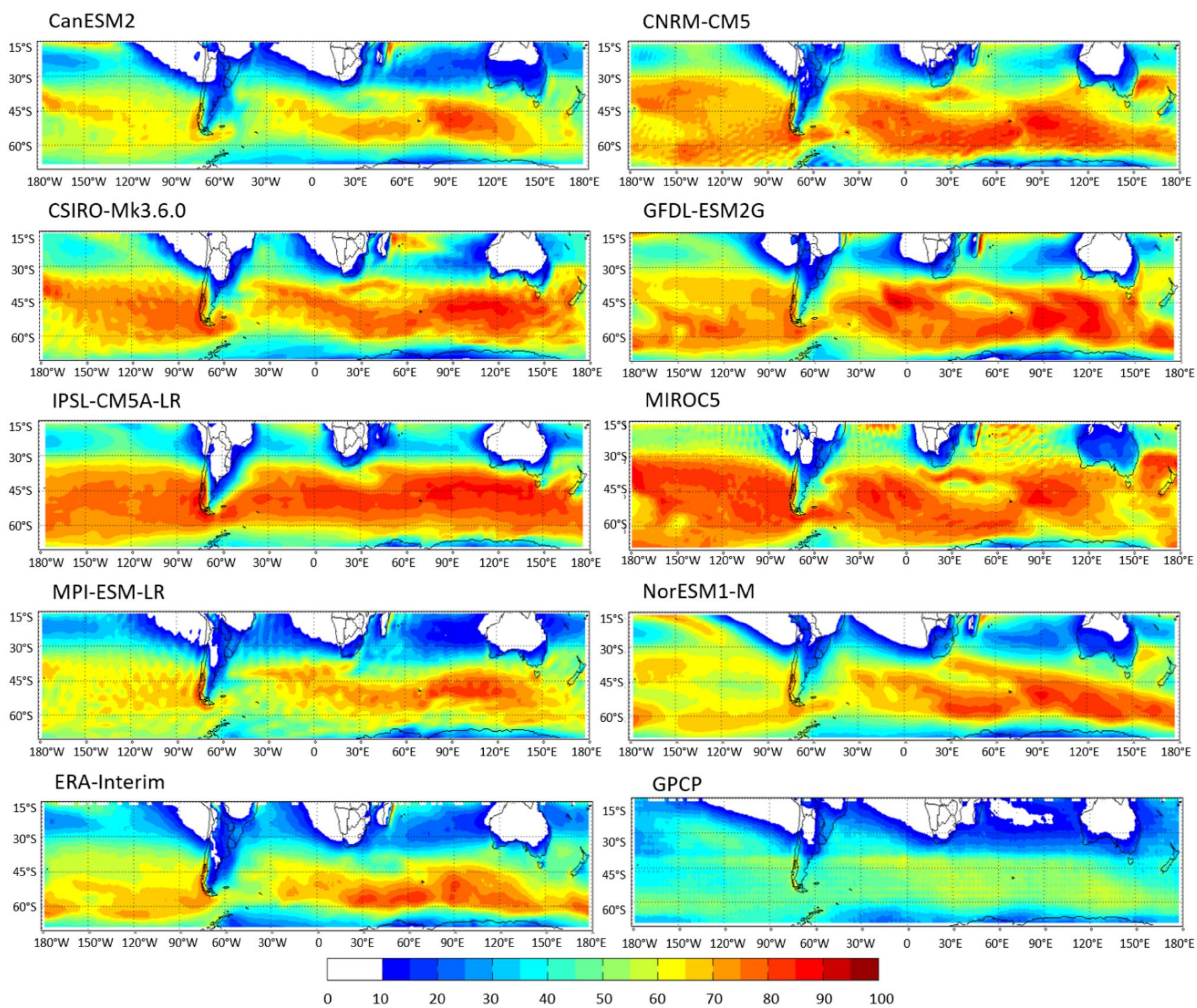

Fig. 4 Frequency of days with precipitation (larger than 1 mm/day) for winter as depicted by CMIP5 models, the ERA-Interim reanalysis and GPCP dataset. For models and reanalysis the frequency is calculated for the period 1979–2005 and for GPCP for the period 1997–2005. Units are %

assimilated in the ERA-Interim reanalysis, consequently, precipitation from ERA-Interim is purely the result of model physics. Hence, precipitation from the ERA-Interim reanalysis is expected to display some differences when compared with observational products, like GPCP, due to it is largely dependent on model parameterizations.

Most of the models overestimate the number of days with precipitation at the extratropical latitudes of the SH. CNRM-CM5, CSIRO-MK3.6.0, GFDL-ESM2G, IPSL-CM5A-LR and MIROC5 show values near 75–90%, clearly these models simulate more days with precipitation than ERA-Interim and GPCP. In these models the overestimation of the frequency of wet days may explain the overestimation of the mean precipitation, apparent from Fig. 3. This is a common shortcoming of most models, mainly due to they produce higher frequency of light rain (Pendergrass and Hartmann 2014). On the other hand, CanESM2, MPI-ESM-LR and NorESM1-M display frequencies that goes from 60 to 75%, resembling the reanalysis dataset.

2.3 Relationship between fronts and precipitation

In order to capture the relationship between fronts and precipitation, the correlation between the daily time series of frontal activity and precipitation at each grid point has been calculated. The results are displayed in Fig. 5. The ERA-Interim dataset displays positive values in most of the domain, as expected, with the largest correlation coefficients (around 0.6) over the West Indian Ocean and the Atlantic Ocean. Over the continents, high values are found in the centre and south of Argentina, New Zealand and some regions of Australia. This result indicates that fronts

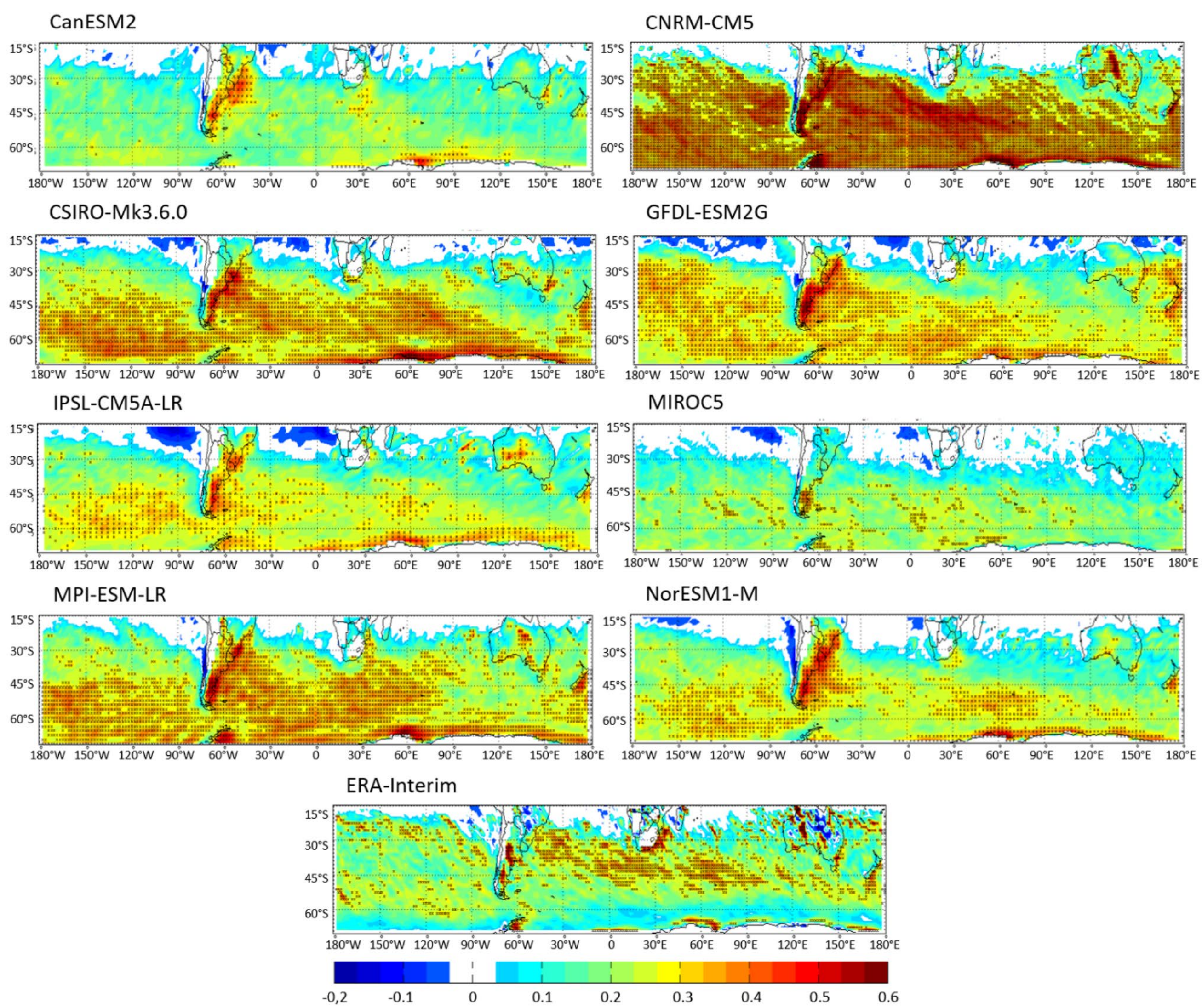

Fig. 5 Daily correlation (unitless) between fronts and precipitation for the period 1979–2005 as depicted by CMIP5 models and the ERA-Interim reanalysis for austral winter. *Dots* mean significant correlation values with a confidence level of 95% according to a Fisher test

and precipitation have a strong relationship at the daily timescales in the ERA-Interim reanalysis in mid and high latitudes of the SH for the winter season. As the correlation coefficient is positive in almost the whole of the domain, it can be asseverated that the presence of a front implies most of the times a precipitation event. However, it is also important to highlight that not all the frontal systems are associated with precipitation; in fact some fronts can be categorized as dry fronts. Moreover, from the ERA-Interim reanalysis it is apparent from Fig. 5 that a maximum of 36% of the daily precipitation variance can be associated with fronts. The models evaluated in this study display diverse capabilities in reproducing the correlation between fronts and precipitation. The majority of the climate models show higher correlation coefficients at mid and high latitudes, suggesting that fronts are more strongly linked with precipitation in the models than in the reanalysis. In particular, CNRM-CM5, CSIRO-Mk3.6.0, GFDL-ESM2G and MPI-ESM-LR models overestimate the correlation coefficients over most of the domain, and particularly over the Pacific Ocean, while CanESM2 and MIROC5 underestimate the correlation over the subtropics (between 30 and 40ºS). Over the continental areas, most of the models display the highest correlation values over SESA, central and southern Argentina, New Zealand and some areas of Australia, resembling the reanalysis dataset. The overestimation (underestimation) of the correlation coefficients indicates an overestimation (underestimation) of the percentage of the daily precipitation variance explained by fronts, suggesting that the models tend to trigger precipitation events more (less) frequently than the reanalysis. This behaviour may explain the differences in precipitation frequency discussed from Fig. 4.

The analysis of Figs. 1 and 2 allows concluding that in general terms the frontal activity, in terms of both mean and frequency of fronts, is well represented by the subset of CMIP5 models. On the other hand, the relationship between fronts and precipitation, quantified by means of the correlation coefficient, is also well reproduced by the models. However, the correlation accounts for the simultaneous occurrence of a frontal event and a precipitation event, but the precipitation amount associated with fronts cannot be quantified with this metric. In order to explore the extent to which the models can capture the fraction of precipitation due to fronts, the proportion between frontal and total precipitation is calculated. To compute the frontal precipitation, first a precipitation event larger than 1 mm/day is identified in a grid point and then if a front is detected in the same grid point or in any of the eight points around, then the precipitation is considered as frontal precipitation. Results of the proportion of precipitation associated with fronts are displayed in Fig. 6. The reanalysis shows the highest values between 60 and 70ºS, where more than 60% of the precipitation is due to fronts. At mid-latitudes, the percentage ranges from 40 to 60%, with larger values over the Atlantic and Indian Oceans and smaller values over the Pacific Ocean, in agreement with Fig. 5. Over SESA, southeastern Africa, and New Zealand more than 60% of the total precipitation is due to frontal systems. These results agree with Catto et al. (2012). Except MIROC5, all the models overestimate the proportion of frontal precipitation at high latitudes. Note that at mid-latitudes over the Pacific, the Atlantic and the Indian Oceans, where the largest total mean precipitation occurs (Fig. 3), most models overestimate the mean precipitation and also overestimate the precipitation due to fronts, with exception of the MIROC5 and CNMR-CM5 models. The total amount of precipitation due to fronts is also overestimated by the models (not shown), in agreement with the behaviour discussed above. A frontal system is associated with a cyclonic vorticity centre at the lower levels of the atmosphere, which may trigger upward motion so that the overestimation of precipitation may be due to the overestimation of the amount of the large-scale precipitation.

Deficiencies in the representation of the frontal precipitation may be due to deficiencies in the representation of the amount of precipitation associated with fronts and/or on deficiencies on the representation of the frequency of frontal systems. From the analysis of Fig. 4 it was noted that the frequency of days with precipitation is overestimated at the extratropical latitudes of the SH. On the other hand, from the analysis of Fig. 2, it was found that the models adequately reproduced the frequency of fronts over most of the SH. Thus to understand the differences highlighted in the analysis of the percentage of frontal precipitation (Fig. 6), the behaviour of the frequency of frontal precipitation is explored in Fig. 7. The ERA-Interim shows the maximum values (around 40%) at the high latitudes of the Pacific and the Indian Oceans. This pattern is consistent with the configuration of the frequency of total precipitation (Fig. 4). Even though the models represent adequately the pattern of the frequency of frontal precipitation, there are some models that overestimate (CanESM2, GFDL-ESM2G, IPSL-CM5A-LR, CSIRO-Mk3.6.0 and NorESM1-M) and others that underestimate the ERA-Interim values (CNRM-CM5 and MIROC5) in some parts of the domain. By comparing Figs. 4 and 7, it can be seen that the frequency of frontal precipitation is better reproduced by the models than the frequency of total precipitation. Moreover, these figures suggest that the models overestimate the number of precipitation events not associated with frontal systems. These results also indicate that the models are able in reproducing the dynamic forcing (the fronts) and the associated precipitation events. Consequently, the deficiencies in the modelled precipitation may be due to the amount of precipitation associated to fronts is not well represented (not

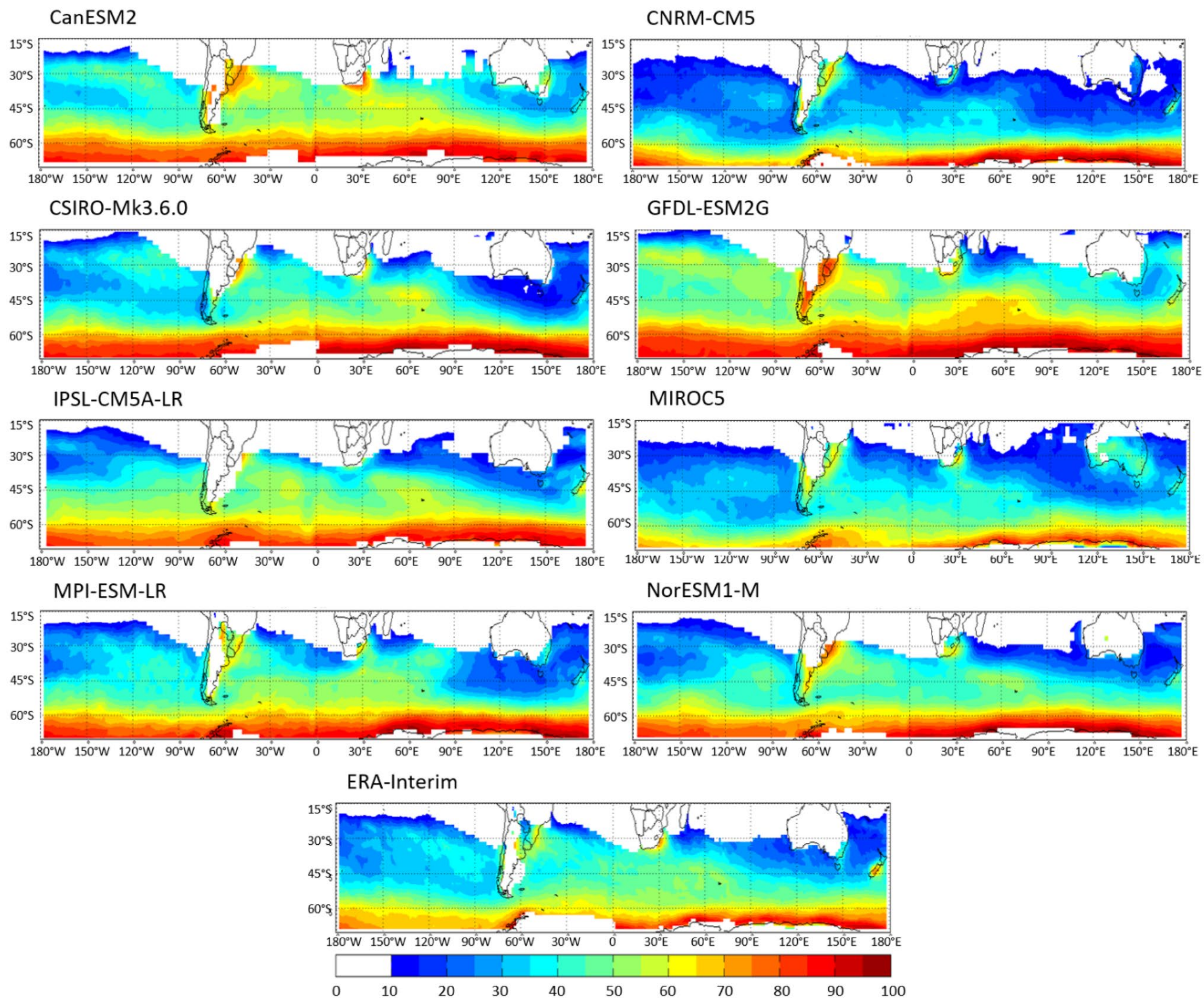

Fig. 6 Proportion between total and frontal precipitation for the period 1979–2005 as depicted by CMIP5 models and ERA-Interim for austral winter. Units are %

shown), since the frequency of frontal precipitation is well captured by the models. This behaviour may be due to deficiencies in the large-scale precipitation schemes.

3 Summary and conclusions

The climatology of the frontal activity depicted by a group of eight CMIP5 models over the SH and the relationship between fronts and precipitation were evaluated in this study. The analysis was performed for the austral winter. The frontal activity was represented by an index that takes into account the vorticity, the temperature gradient and the specific humidity at the 850 hPa level. The CMIP5 models were compared with the ERA-Interim reanalysis for the period 1979–2005 and GPCP dataset for the period 1997–2005.

The largest values of the wintertime frontal activity were found between 60 and 70°S and over the extratropical Atlantic and Indian Oceans. The models represent adequately the mean configuration of fronts being NorESM1-M and MPI-ESM-LR those with the largest agreement with observations. The front frequency from the ERA-Interim reanalysis dataset was found to range between 30 and 45% at the high latitudes (from 60 to 70°S) and between 10 and 20% at mid-latitudes. The models could represent adequately the rate of occurrence of fronts, even though IPSL-CM5A-LR and GFDL-ESM2G overestimate the frequency at the mid-latitudes of the Pacific Ocean and CNMR-CM5A and NorESM1-M underestimate the frequency at the extratropical latitudes of the Atlantic and Indian Oceans.

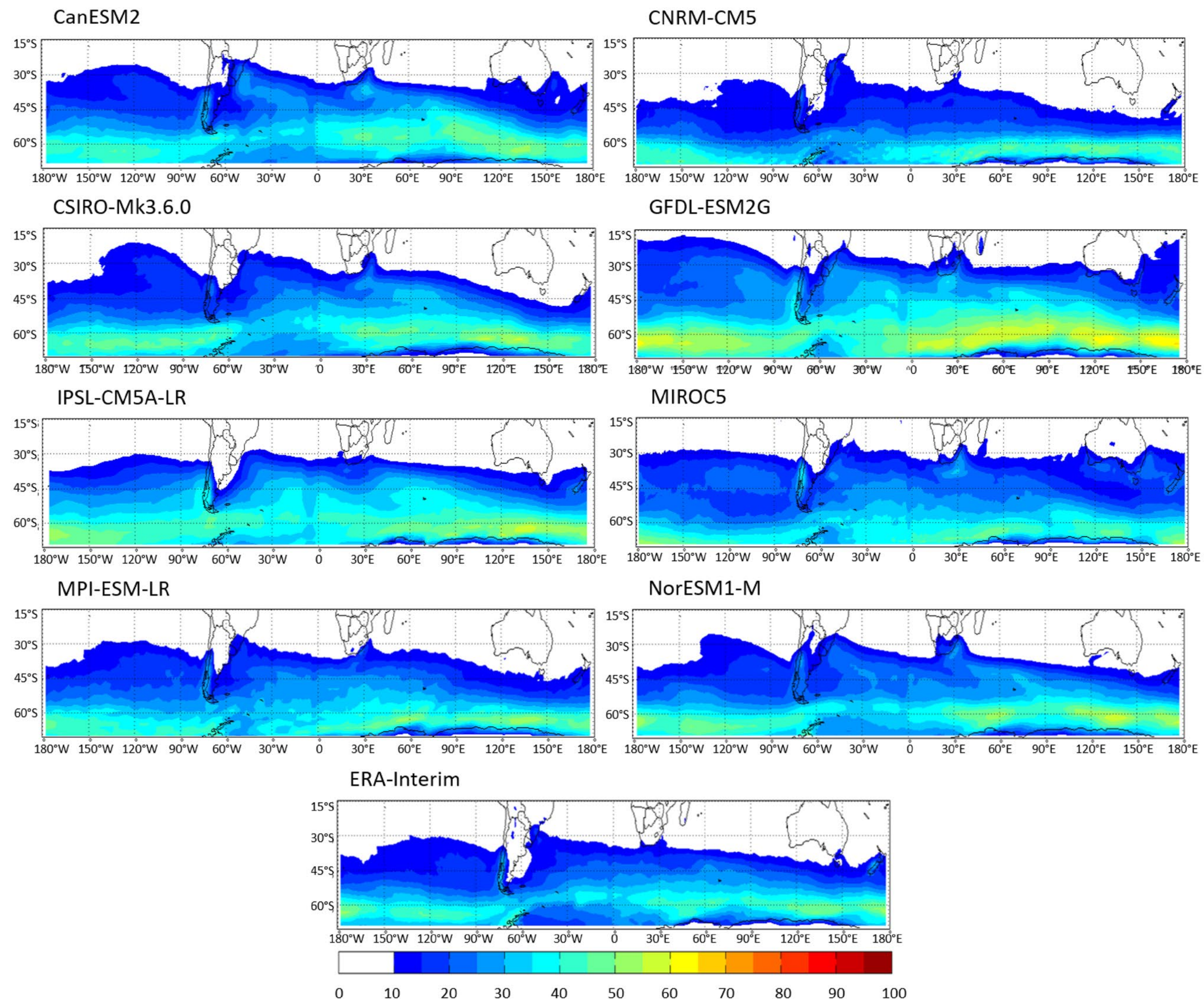

Fig. 7 Frequency of frontal precipitation (larger than 1 mm/day) for the period 1979–2005 as depicted by CMIP5 models and ERA-Interim reanalysis for austral winter. Units are %

Summarizing, there is an overall agreement between models and the ERA-Interim reanalysis dataset on the representation of the mean and frequency of occurrence of fronts during the winter season on the SH both in terms of the spatial distribution and magnitude.

In general terms, the models can represent adequately the pattern of the mean precipitation, compared with the reanalysis; nevertheless, most of them overestimate the maximums located over the oceans and over New Zealand and southern South Africa. In terms of frequency it was found that most of the models (CNRM-CM5, CSIRO-MK3.6.0, GFDL-ESM2G, IPSL-CM5A-LR and MIROC5) overestimate the amount of days with precipitation larger than 1 mm/day, which could explain the overestimation of mean precipitation in some regions.

With the aim of exploring to what extent fronts and precipitation are related in climate models, the correlation between the daily time series of fronts and precipitation at each grid point was analysed. From the ERA-Interim reanalysis it can be concluded that at mid-latitudes a 36% of the daily precipitation variance can be related with fronts. The models showed the highest correlation coefficients at the mid and high latitudes of the SH, displaying some differences compared with the ERA-Interim dataset, especially over the oceans. Most of the models overestimate the correlation between fronts and precipitation, indicating that the models produce a larger percentage of precipitation variance associated with fronts compared with the reanalysis. Even though, the positive coefficients imply that the majority of the fronts were associated with precipitation events in climate models. Taking into account this result and the outcome that the climatology of fronts is also well represented by the models, the proportion between winter frontal precipitation and total precipitation was explored. It was found in the reanalysis dataset that more than 60% of the precipitation is due to the frontal activity between 60 and 70°S and in some continental regions of the SH (SESA, southeastern Africa and New Zealand), whereas in most of the extratropical latitudes around 40% of the precipitation occurs in a presence of a front. In general terms, climate models agree with the reanalysis, although most of the models overestimate the fraction of precipitation due to fronts over most of the domain (with a few exceptions). Moreover, the overestimation of the mean precipitation may be due in part to the overestimation of the fraction of precipitation due to fronts. The rationale behind this statement is that though the models reproduce adequately the fronts, which provide the dynamical forcing for triggering ascending motions in the atmosphere, the amount of associated precipitation may be overestimated by the microphysics scheme. This statement may be reinforced by the analysis of the frequency of frontal precipitation that showed that models are capable of reproducing both the spatial pattern and intensity of this metric. At mid latitudes, both models and reanalysis depict frontal precipitation more or less 30–40% of the days. In contrast with the total precipitation frequency, the frontal precipitation frequency is well represented by the models.

To summarize, despite some differences, the eight climate models chosen to study the frontal activity and its relationship with winter precipitation over the SH had a good performance in the present climate. This result may be useful to analyse the future projections of precipitation, taking into account that models represent adequately the frontal systems and the number of precipitation events associated to fronts. However, the deficiencies in the large-scale precipitation parameterizations could be responsible for the inadequate representation of the amount of frontal precipitation. An ongoing study analyse this issue.

Acknowledgements We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in Table 1 of this paper) for producing and making available their model output. For CMIP the US Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. This work was supported by the following grants: FONCyT-PICT-2012-1972, FONCyT-PICT-2014-2730 and UBA-CYT2014 No. 20020130200233BA. We wish to thank the anonymous reviewers whose comments allowed substantial improvements to the manuscript.

References

Berry G, Reeder MJ, Jakob C (2011) A global climatology of atmospheric fronts. Geophys Res Lett 38:L04809. doi:10.1029/2010GL046451

Bjerknes J, Solberg H (1922) Life cycle of cyclones and the polar front theory of atmospheric circulation. Geophys Publ 3:1–18

Blázquez J, Solman SA (2016) Intraseasonal variability of wintertime frontal activity and its relationship with precipitation anomalies in the vicinity of South America. Clim Dyn 46:2327–2336. doi:10.1007/s00382-015-2704-0

Blázquez J, Solman SA (2017) Interannual variability of the frontal activity in the Southern Hemisphere: relationship with atmospheric circulation and precipitation over southern South America. Clim Dyn 48:2569–2579. doi:10.1007/s00382-016-3223-3.

Browning KA, Roberts NM (1994) Structure of a frontal cyclone. Q J R Meteorol Soc 120:1535–1557. doi:10.1002/qj.49712052006

Catto JL, Jakob C, Berry G, Nicholls N (2012) Relating global precipitation to atmospheric fronts. Geophys Res Lett 39:L10805. doi:10.1029/2012GL051736

Catto JL, Nicholls N, Jakob C, Shelton KL (2014) Atmospheric fronts in current and future climates. Geophys Res Lett 41:7642–7650. doi:10.1002/2014GL061943

Catto JL, Jakob C, Nicholls N (2015) Can the CMIP5 models represent winter frontal precipitation? Geophys Res Lett 42:8596–8604. doi:10.1002/2015GL066015

Chang EKM, Guo Y, Xia X, Zheng M (2013) Storm-track activity in IPCC AR4/CMIP3 model simulations. J Clim 26:246–260. doi:10.1175/JCLI-D-11-00707.1

Dai A (2006) Precipitation characteristics in eighteen coupled climate models. J Clim 19:4605–4630. doi:10.1175/JCLI3884.1

Dee DP et al (2011) The ERA-interim reanalysis: configuration and performance of the data assimilation system. Q J R Meteorol Soc 137:553–597. doi:10.1002/qj.828

Flato G, Marotzke J, Abiodun B, Braconnot P, Chou SC, Collins W, Cox P, Driouech F, Emori S, Eyring V, Forest C, Gleckler P, Guilyardi E, Jakob C, Kattsov V, Reason C, Rummukainen M (2013) Evaluation of climate models. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Forster PM, Andrews T, Good P, Gregory JM, Jackson LS, Zelinka M (2013) Evaluating adjusted forcing and model spread for historical and future scenarios in the CMIP5 generation of climate models. J Geophys Res: Atmos 118(3):1139–1150. doi:10.1002/jgrd.50174

Garreaud R, Vuille M, Compagnucci R, Marengo J (2009) Present-day South American climate. PALAEO 281(3):180–195. doi:10.1016/j.paleo.2007.10.032

Grainger S, Frederiksen CS (2014) Assessment of modes of interannual variability of southern hemisphere atmospheric circulation in CMIP5 models. J Clim 27:8107–8125. doi:10.1175/JCLI-D-14-00251.1

Grieger J, Leckebusch GC, Donat MG, Schuster M, Ulbrich U (2014) Southern Hemisphere winter cyclone activity under recent and future climate conditions in multi-model AOGCM simulations. Int J Climatol 34:3400–3416. doi:10.1002/joc.3917

Gulizia C, Camilloni I (2015) Comparative analysis of the ability of a set of CMIP3 and CMIP5 global climate models to represent precipitation in South America. Int J Climatol 35:583–595. doi:10.1002/joc.4005

Herold N, Alexander LV, Donat MG, Contractor S, Becker A (2016) How much does it rain overland? Geophys Res Lett 43:341–348. doi:10.1002/2015GL066615

Hewson TD (1998) Objective fronts. Meteorol Appl 5:37–65. doi:10.1017/S1350482798000553

Houze RA (2014) Cloud dynamics, 2nd edn. Academic Press, Oxford

Huffman GJ, Adler RF, Morrissey M, Bolvin DT, Curtis S, Joyce R, McGavock B, Susskind J (2001) Global precipitation at one-degree daily resolution from multi-satellite observations. J Hydrometeorol 2:36–50. doi:10.1175/1525-7541(2001)002<0036:GPAODD>2.0.CO;2

IPCC (2013) Climate change 2013: the physical science basis. Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge

Koutroulis AG, Grillakis MG, Tsanis IK, Papadimitriou L (2016) Evaluation of precipitation and temperature simulation performance of the CMIP3 and CMIP5 historical experiments. Clim Dyn 47:1881–1898. doi:10.1007/s00382-015-2938-x

Mehran A, AghaKouchak A, Phillips TJ (2014) Evaluation of CMIP5 continental precipitation simulations relative to satellite-based gauge-adjusted observations. J Geophys Res Atmos 119:1695–1707. doi:10.1002/2013JD021152

Pendergrass A, Hartmann DL (2014) Two modes of change of the distribution of rain. J Clim 27:8357–8371. doi:10.1175/JCLI-D-14-00182.1

Simmonds I, Keay K, Bye JAT (2012) Identification and climatology of Southern Hemisphere mobile fronts in a modern reanalysis. J Clim 25:1945–1962. doi:10.1175/JCLI-D-11-00100.1

Simmons A, Uppala S, Dee D, Kobayashi S (2007) ERA-interim: new ECMWF reanalysis products from 1989 onwards. ECMWF Newsl 110:25–35

Sinclair M R (1995) A climatology of cyclogenesis for the Southern Hemisphere. Mon Weather Rev 123:1601–1619. doi:10.1175/1520-0493(1995)123<1601:ACOCFT>2.0.CO;2

Solman SA, Orlanski I (2010) Subpolar high anomaly preconditioning precipitation over South America. J Atmos Sci 67:1526–1542. doi:10.1175/2009JAS3309.1

Solman SA, Orlanski I (2014) Poleward shift and change of frontal activity in the Southern Hemisphere over the last 40 years. J Atmos Sci 71:539–552. doi:10.1175/JAS-D-13-0105.1

Solman SA, Orlanski I (2016) Climate change over the extratropical Southern Hemisphere: the tale from an ensemble of reanalysis datasets. J Clim 29:1673–1687. doi:10.1175/JCLI-D-15-0588.1

Sun Y, Solomon S, Dai A, Portmann RW (2006) How often does it rain? J Clim 19:916–934. doi:10.1175/JCLI3672.1

Taylor KE, Stouffer RJ, Meehl GA (2012) An Overview of CMIP5 and the experiment design. Bull Am Meteorol Soc 93:485–498. doi:10.1175/BAMS-D-11-00094.1