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Evaluation of present-climate precipitation in 25 km resolution regional climate model simulations over Northwest Africa

Raquel Romera[1,*], Enrique Sánchez[2], Marta Domínguez[3], Miguel Ángel Gaertner[2], Clemente Gallardo[2]

[1]Environmental Sciences Institute, and [2]Environmental Sciences Faculty, University of Castilla-La Mancha, 45071 Toledo, Spain
[3]Physics Sciences Faculty, University Complutense of Madrid, 28040 Madrid, Spain

ABSTRACT: Risks related to characteristics of future precipitation change over northern Africa (decreasing mean precipitation, floods and droughts) have been highlighted by several authors, but the scarcity of studies in this area of Africa has been noted by IPCC. We analysed the northwestern African domain for present-day climate (1989 to 2008) precipitation features from a set of 5 high-resolution (25 km) regional climate models (RCMs) from the Spanish ESCENA project. The evaluation of present-climate RCMs simulations was done by comparing the results with 4 different observational databases. The analysis of the spatial distribution of mean precipitation and the annual cycle revealed a complex spatial distribution of rainfall depending on area; hence, a more specific analysis subdividing the domain into 8 subregions was conducted. The spatial and temporal heterogeneity of the precipitation pattern in the studied domain is exemplified by the extreme events (heavy precipitation days oscillated between 4 and 16 d yr^{-1} and consecutive dry days between 240 and 330 d) and annual anomalies analyses (values between −50% and +100%). The study reveals many robust precipitation features over the region, but also significant differences between the models, with a spread larger than 70% in some subregions, pointing to the need for a set of RCMs and the importance of high resolution in a very complex domain. As regional models are able to describe the basic precipitation features over the region, they can be used to assess the changes projected by climate change simulations.

KEY WORDS: Northern Africa · Precipitation · Climate extremes · Regional climate models · Droughts · Heavy precipitation

1. INTRODUCTION

According to IPCC (2014), Africa will be strongly affected by climate change due, in part, to its limited adaptive capacity. The report also highlights the scarcity of studies and observed data in Africa. Climate model studies over Africa have been localized in Western Africa (Wang & Eltahir 2000, Druyan 2011), East Africa (Sun et al. 1999) and South Africa (Hudson 1997, Joubert & Hewitson 1997), but rarely reach the north coast of the continent, especially the coast of Morocco, Algeria and Tunisia where the populated areas are very important. Other studies have been centered in the north of Africa (Driouech et al. 2010 in Morocco; Bargaoui et al. 2014 in Tunisia), but most of them do not use RCMs (Knippertz et al. 2003).

The northwest Maghreb (Morocco, Algeria and Tunisia) is critically dependent on climate because the main occupation of their populace is subsistence agriculture, so any increase in rainfall variability could seriously affect whole countries (Mougou et al. 2011). The knowledge of the present climate and the pro-

*Corresponding author: raquel.romera@uclm.es

jected changes is crucial to aid in the modifications that will be needed to help the agricultural system adapt (Rosenberg 1992).

The Maghreb is an area of dense settlement bounded by desert to the south and by large water bodies in other directions. The complexity of the orography of these countries is a great challenge to the RCMs, as it includes the coast, agriculture areas, very high mountains (>4000 m) and even desert areas, so the resolution of the RCMs is very important (Knippertz et al. 2003, Huebener & Kerschgens 2007, Born et al. 2008b). Therefore, this region is very interesting in terms of precipitation as it includes areas with precipitation as high as 2000 mm yr^{-1}, mountainous areas (orographic precipitation), synoptic forcings with differences on the Atlantic and Mediterranean sides, and a large desert (the Sahara) with almost no rain year-round.

During the 20th century, the Maghreb has been the area that has undergone the most extensive warming over whole of Africa (Hulme et al. 2001). According to Driouech et al. (2010), Morocco can expect a decrease in mean precipitation and a change in extreme events by the middle of the century. Agricultural areas in the mid-latitudes are very vulnerable to projected changes, such as intense precipitation occasioning floods, and decreasing water availability (Born et al. 2008b). Precipitation in Morocco has been decreasing since the 1960 (Knippertz et al. 2003), which has increased the frequency and persistence of droughts (Benassi 2008).

The Maghreb area has not been included in the domain of the most important Mediterranean projects with ensembles of RCMs, e.g. PRUDENCE (Christensen & Christensen 2007) or ENSEMBLES (Van der Linden & Mitchell 2009), which could explain the scarcity of studies over this region. However, there has been some effort to analyse the climate over northwest Africa using data from ENSEMBLES, e.g. a study of extreme precipitation in Morocco (Tramblay et al. 2012) and a study of seasonal precipitation variability in the north of Tunisia (Bargaoui et al. 2014). There have been other efforts at studying the African climate through RCM simulations, such as the AMMA (Redelsperger et al. 2006) and IMPETUS (Born et al. 2008a) projects centered over West Africa, and other studies (e.g. Patricola & Cook 2010). Climate studies using statistical downscaling have also included the north of Africa (Hertig & Jacobeit 2008, Hertig et al. 2012, 2013, Jacobeit et al. 2014).

Due to the small number of RCMs simulations over this continent, the CORDEX (COordinated Regional climate Downscaling Experiment) project has centered its first runs and results over this domain (Giorgi et al. 2009) for the purpose of improving climate simulations. In this project, 50 km RCM runs have been performed over the whole African continent. Recently, many evaluation studies with RCMs over Africa have been published: some studies have been centered in a specific region of the continent, as Endris et al. (2013) in Eastern Africa, Gbobaniyi et al. (2014) in Western Africa or Kalognomou et al. (2013) in Southern Africa, but none have focused their efforts in the northern part of the continent. Other studies (Hernández-Díaz et al. 2013, Laprise et al. 2013, Kim et al. 2014) analysed the whole continent and propose specific analysis over smaller subregions, the Maghreb being one of them, but they do not show any explicit result for this region.

The principal weakness of CORDEX simulations to study the Maghreb climate is the resolution, as the CORDEX resolution is not high enough to reproduce the complex Maghreb orography (Knippertz et al. 2003). Nikulin et al. (2012) analysed the complete African domain, concluding that RCMs simulations reproduce the details of African climatology but, at the same time, present important biases depending on the region and the season. In the framework of CORDEX, new RCM simulations at a higher spatial resolution (12 km) are becoming available (Euro-CORDEX; Vautard et al. 2013, Kotlarski et al. 2014, and Med-CORDEX) for northern Africa, providing a very useful tool to analyse the climate of this region (Tramblay et al. 2013).

Panitz et al. (2014) also analysed the complete African domain as well as studying different regions, the Maghreb among them; in this case 50 and 25 km simulation resolutions were used, but they used only 1 RCM. The study concluded that a higher resolution does not improve the results over the continent. In Panitz et al. (2014), the Maghreb is regarded as one region, despite its climatic diversity, and they conclude that it is a very low-precipitation region; however, only 2 seasons (JFM and JAS) were studied, so the complete rainy season of the region was not represented. A more detailed analysis shows the existence of a notable North African rainy season. Liebmann et al. (2012) determined the average start and end dates of wet season were October and March, respectively, and these were the dates used in Driouech et al. (2009) (where it was called extended winter). Another study included April in the rainy season (Schilling et al. 2012), and Hertig & Jacobeit (2008) defined the rainy season as October to May — but this latter study included all the Mediterranean coast, so there was a broader range of climates and wet seasons.

The present study also included the Canary Islands, an archipelago of volcanic origin ca. 60 km off the southwest Moroccan coast. This archipelago also has a very complex orography, with a total area of less than 7500 km^2 and 7 principal islands. Its highest summit reaches more than 3700 m (Teide). Despite its limited extent, the climate presents a noticeable heterogeneity, with a marked influence from the ocean but also being affected by the dry dusty wind from the Sahara. The ocean currents, trade winds and the abrupt orography makes some of the islands much wetter than expected (Herrera et al. 2001). García-Herrera et al. (2003) detected a strong, decreasing trend in the Canary Island precipitation during the second half of 20th century, making the study of future precipitation changes at this location an interesting proposition.

As Tramblay et al. (2013) remark, the study of precipitation extremes (dry days and heavy daily precipitation) is very important in an area with a strong variability of precipitation, where the agriculture is the principal economic activity, highly dependent on precipitation. Several publications have proved the need for RCMs for this kind of study, as they are a better way to reproduce extreme precipitation (Sánchez et al. 2004, Gao et al. 2006, Domínguez et al. 2013) compared with General Circulation Models (GCMs) which are not able to reproduce frequency and magnitude of extreme precipitation (Frei et al. 2006, Fowler et al. 2007, Giorgi & Lionello 2008).

2. METHODS

2.1. Regional climate simulations

The Maghreb climate (Moustadraf et al. 2008) ranges from arid to semi-arid Saharan climate in the southern part, oceanic in the western part and Mediterranean in the northern part; these different zones are delimited by important mountain ranges (Atlas and Rif) with mountainous climates. This climatic heterogeneity is very similar to the nearby European region of Spain and Portugal, especially in the winter season (Driouech et al. 2009). Therefore, RCMs from the Spanish ESCENA project, already evaluated in the Iberian Peninsula (Domínguez et al. 2013, Jiménez-Guerrero et al. 2013), have been used in this study.

Five RCMs simulations from the project ESCENA have been analysed: PROMES (Domínguez et al. 2010), 2 different versions of WRF (Weather Research and Forecasting) (Skamarock et al. 2008, Fita et al. 2010), MM5 (Grell et al. 1995, Gómez-Navarro et al. 2010) and REMO (Jacob 2001). The 1989–2008 high resolution (25 km) runs are nested in ERA-Interim reanalysis. For further information about the RCMs, the simulations and the ESCENA project see Jiménez-Guerrero et al. (2013) and Domínguez et al. (2013).

2.2. Observational datasets

In order to evaluate the RCM simulations, 4 gridded 0.5° resolution observational databases have been used in this analysis including 3 monthly precipitation datasets (Climate Research Unit Data, CRU, from the University of East Anglia [Mitchell & Jones 2005], terrestrial precipitation from the University of Delaware [UDEL] [Willmott & Matsuura 2000] and Global Precipitation Climatology Center [GPCC] [Schneider et al. 2011]) and 1 daily precipitation dataset that were needed to analyse precipitation extremes (NOAA, National Oceanic and Atmospheric Administration, Climate Prediction Center [CPC] [Chen et al. 2008]). The use of several different observations databases is important due to the spread found among them (Waliser et al. 1999, Kim & Lee 2003, Nikulin et al. 2012), especially in areas with complex orography with a scarce number of stations (IPCC 2014).

2.3. Methodology

The complete domain simulated by all the RCMs is shown in Fig. 1 (left panel). Due to the heterogeneity of the studied domain, both climatically and orographically, the division into smaller subregions is necessary (Panitz et al. 2014). Fig. 1 (right panel) shows the 8 subregions proposed in this study: Northern Rif (NR), Southern Rif (SR), Western Atlas (WA), Eastern Atlas (EA), Mediterranean Coast (MC), Inner Algeria (IA), Tunisian (TU) and Canary Islands (CI). As the southern part of the domain corresponds to the Sahara desert with effectively no precipitation, no subregions in that area were demarcated because a more specific precipitation analysis would be unlikely to yield disparate results. Although any distribution of subregions is always somewhat arbitrary, our demarcations have the goal of more homogeneous precipitation values over smaller areas (i.e within subregions) compared with the whole domain.

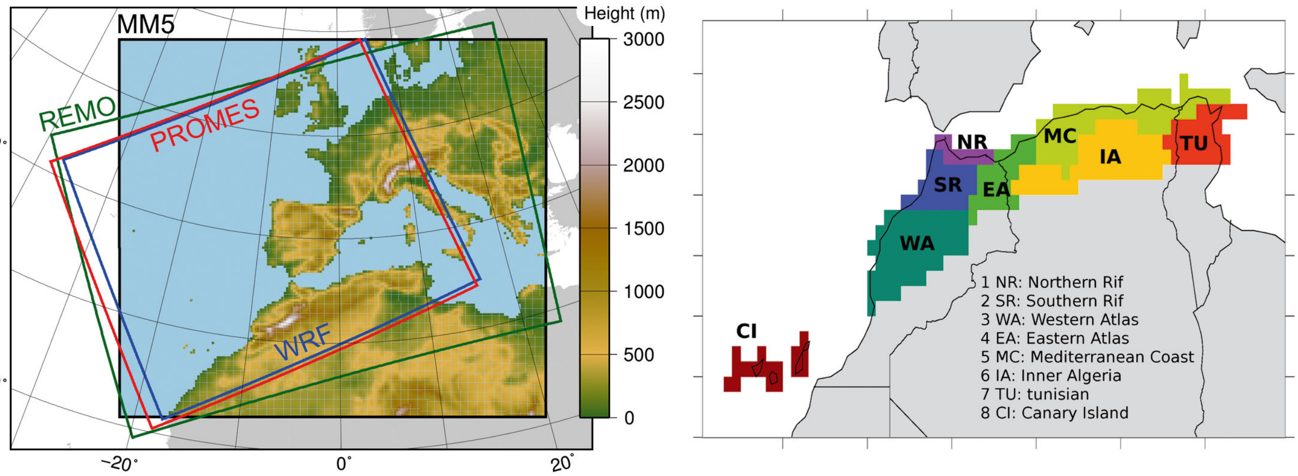

Fig. 1. Left panel: RCMs study domain including orography. Right panel: proposed subregions of the northwest African domain: Northern Rif (NR), Southern Rif (SR), Western Atlas (WA), Eastern Atlas (EA), Mediterranean Coast (MC), Inner Argelia (IA), Tunisian (TU) and Canary Island (CI)

Section 3.1 describes in more detail how annual precipitation is calculated as the mean over the 20 yr of accumulated annual precipitation. The mean (1989 to 2008) precipitation biases (relative difference; Kotlarski et al. 2014) between the CPC database and every observational dataset and every RCM were calculated over each subregion for the rainy season (October to March). Also the annual cycle for each subregion (spatial average) was studied.

Precipitation extremes are analysed in Section 3.2 by means of 2 different precipitation core ETCCDI (Expert Team on Climate Change Detection and Indices) indices in each different region (R10MM and CDD). The heavy precipitation days index (R10MM) is calculated as the 20 yr mean number of days with precipitation >10 mm. Both the spatial distribution and the subregions-averaged histogram are shown. The consecutive dry days index (CDD) is the subregions-averaged maximum period of consecutive dry days in 20 yr (histogram shown), where dry days are defined as days with precipitation <1 mm. The observational CPC database is used to validate the simulated extreme indices, as it is the only daily observed dataset.

In section 3.3 spatial averaged annual precipitation anomalies bring into focus the variability of the climate in the different subregions. The anomalies were calculated in each region as the difference between the annual accumulated precipitation and the 20 yr mean precipitation; the anomaly was normalized by dividing by the 20 yr mean precipitation (Panitz et al. 2014) and is expressed as a percentage.

3. RESULTS

3.1. Mean precipitation

A first overview of the annual precipitation fields obtained from the 4 observational datasets (Fig. 2) indicate that this region is very complex in terms of the rainfall distribution. There are 2 clear maximum areas, around the Gibraltar Strait and also around the border between Algeria and Tunisia on the Mediterranean coast. Also evident is a relative minimum in precipitation on the Mediterranean coast between the two maximum areas. In Algeria and Tunisia, rainfall amounts decrease from the coast to the inner regions, to almost zero values when reaching the Sahara desert. In Morocco, orographic maxima can be seen over the Atlas and Rif mountain chains. Over the Atlantic coast of Morocco, a clear reduction in precipitation from the maximum values at Gibraltar Strait is also observed.

Despite these common precipitation features, we also discovered relevant differences when these 4 precipitation datasets were compared. The CRU dataset underestimates maximum values when compared with the other datasets, giving (for example) values around 600 mm yr^{-1} for the Algeria-Tunisia maximum, meanwhile other dataset gave estimated precipitation values of >1000 mm yr^{-1}. Orographic features over the Atlas or Rif can be seen for GPCC and UDEL datasets, but CPC and CRU exhibit a much smoother pattern. We have to consider that there are likely only a few surface rain-gauge stations over the domain of study, so the interpolation procedures and their representativity of the sur-

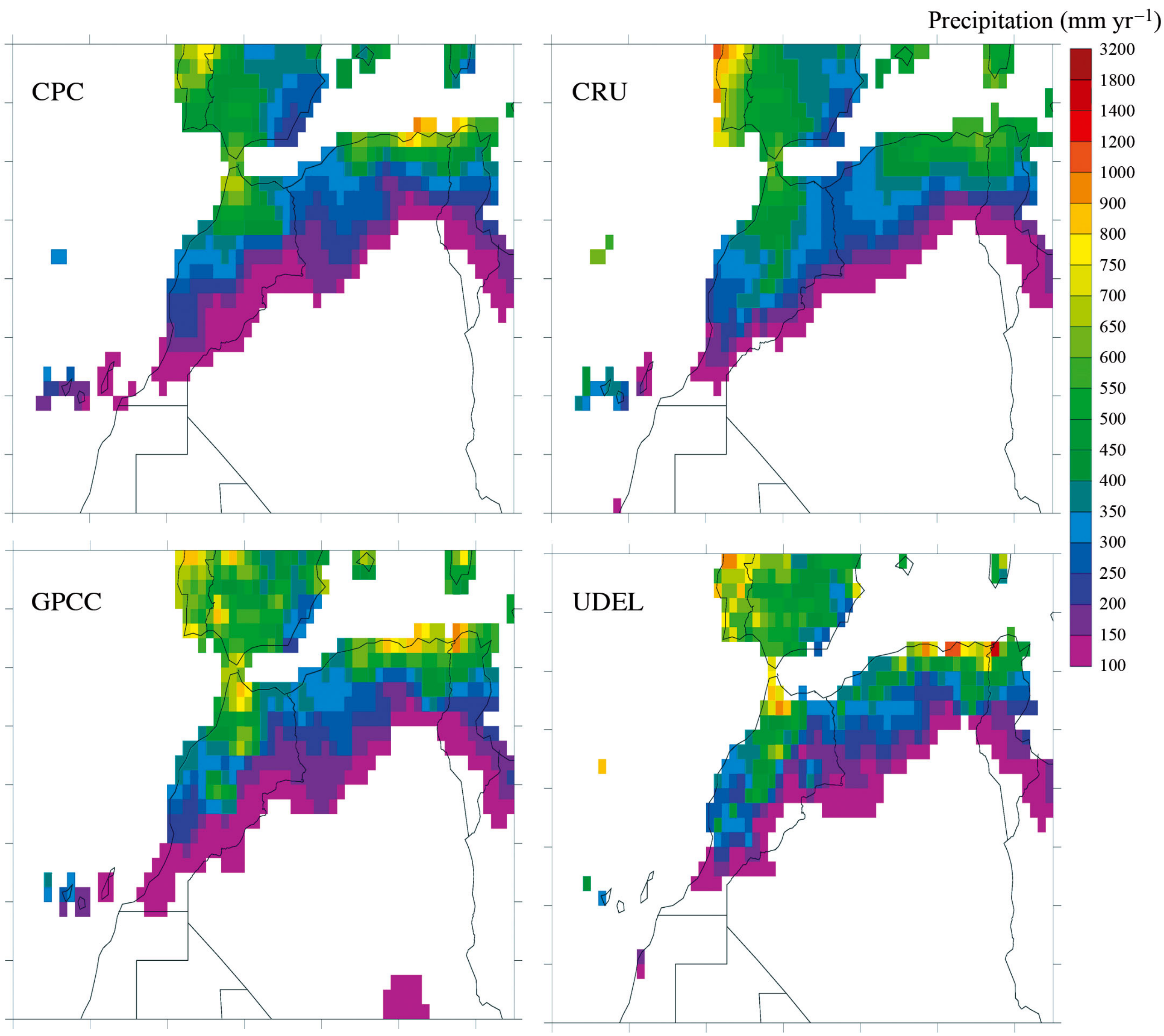

Fig. 2. Observational datasets for mean accumulated annual precipitation from 1989 to 2008. Datasets described in Section 2.2

rounding regional climate might be highly questionable. This uncertainty on the comparison among observational results is highly relevant when analysing the results obtained from the RCM simulations.

Regional climate modeling results from the 5 RCM simulations (Fig. 3) are able to reproduce the same global patterns described by the observational datasets, that is, the location of the maximum precipitation values, the gradient of decrease over the inner part of the continent, and also the reduction over the Atlantic coast. RCMs tended to give a more detailed description over the mountainous areas, which is likely to be the result of the higher resolution of the RCMs against the observational datasets (50 vs. 25 km), together with the additional reduction of observational information over mountain regions (Briggs & Cogley 1996), and perhaps the tendency of regional models to overestimate orographical precipitation. As shown in Nikulin et al. (2012), 50 km simulations were not able to reproduce orographical precipitation over the Atlas Mountains. It is interesting to note the relative minimum of precipitation obtained by all the RCMs not only over the Mediterranean coast between both maximums, but over all the Alboran Sea and the Almeria region in Spain. The Canary Islands, despite the limited amount of land points used by the RCMs, exhibited an interesting pattern: all the RCMs showed a relative minimum of precipitation on its southern part. This agrees with detailed observational information (Herrera et al. 2001). This pattern is a well-known feature, due to their steep orography, combined with the typical trade-wind synoptic conditions of this region.

We observed some discrepancies both among the RCMs and also when they were compared with observations (noted by Jiménez-Guerrero et al. 2013), while analysing mean climate conditions simulated over the Iberian Peninsula; e.g. the overestimation of precipitation values obtained by PROMES or the more smoothed results by MM5. Comparing high resolution observations to datasets based on a limited number of stations, Herrera et al. (2012) concluded that observational datasets underestimate the maximum values over the nearby Iberian Peninsula. Fig. 4 shows the mean 1989 to 2008 rainy season (October to March) relative precipitation bias for each observational dataset and each RCM vs. CPC. The spread among observational datasets is smaller than the spread among RCM in every region except CI, where the number of grid points is very scarce. UDEL and GPCC biases were very similar over every region (Fig. 2 also shows a very similar pattern between both observational datasets), except MC and CI. The largest bias (more than 100%) is presented by UDEL over CI, where the grid points are very scarce, as can be seen in Fig. 2.

In most of the regions, except NR, IA and CI, the spread among the observations was smaller than 25% —EA being the region with the smallest differences. The bias presented by the RCMs, as compared to observations, was negative in all the regions. Only 2 RCMs change this pattern: REMO in SR with respect to CRU and in WA with respect to CPC and PROMES, that only present a negative bias over NR. These results agree with Jiménez-Guerrero et al. (2013) that uses the same RCMs over the neighbouring Iberian Peninsula, where only REMO in 2 seasons and PROMES in every season had positive biases. Our results also agree with Bargaoui et al. (2014)'s conclusion of a 20% underestimation of the precipitation by RCMs in Tunisia.

The complexity of the precipitation patterns shown in Fig. 2 points to importance of separating the domain of study into several subregions for a more detailed analysis (see Fig. 1). This subregional description allows us, for example, to describe the structure of the annual cycle of precipitation over each of the subregions, as can be seen in Fig. 5.

In Fig. 5, the observational datasets (dashed lines) allow for a detailed description of the monthly precipitation evolution throughout the year for all the subregions. For most of them, the summer minimum and the winter maximum are very apparent, highlighting 2 seasons: the rainy season (October to March) and a very dry summer (JJA). Nevertheless, some regions exhibited a much larger winter precipitation maximum, e.g. NR, SR and MC, with values up to 70 mm mo^{-1} for several months. In contrast, winter precipitation over EA and IA hardly exceeds 40 mm mo^{-1}, showing a more homogeneous rainfall pattern compared to the other subregions. EA's annual cycle is clearly different from the neighbouring NR or MC subregions. As expected, IA has the lowest precipitation of all subregions due to its location close to the Sahara desert. Other neighbouring regions with very different precipitation results are TU and MC. It is interesting to see that NR and SR show a comparable annual cycle, although one is related to Mediterranean forcings, and the other to more Atlantic influence. The WA subregion is quite different compared to SR, due to their more southern position, despite the fact that both are influenced by the Atlantic Ocean. The spread among observational datasets is large for NR during autumn, winter and spring, with values ranging from 50 to 80 mm mo^{-1} over some months. This is also the case for the CI subregion, with an even larger spread in November (50 mm mo^{-1}). This latter variability is likely due to the presence of just a few stations, potentially located at different sites for each observational database, that were used to compute precipitation values on this island chain.

These annual cycles contrast with the one published by Panitz et al. (2014), where Northwest Africa is presented as a very dry area throughout the year, with precipitation lower than 30 mm mo^{-1}. These results point out the interest of the present analyses over the studied domain.

Regional model description of annual cycles show the capability of the simulations to describe the climatological evolution of precipitation during the year for each of the 8 selected subregions. Most of the subregions exhibited a relatively good agreement among models and observations, but others presented a larger spread. Thus, both RCMs and observational datasets present an important spread over NR during the rainy season; however, all the RCMS underestimated the observed values (which can also be seen in Fig. 4). This is partly the case for the SR subregion, where some RCMs clearly underestimate observed values, but PROMES actually slightly overestimated observed time series. PROMES, as seen on the spatial maps and highlighted by the calculated biases, is the RCM that gives larger precipitation values, resulting in some clear overestimation compared with observations over subregions other than SR, as is the case for IA, MC or TU. This overestimation is largest in spring and in the transition from summer to autumn, when convective precipitation contributes much to total precipitation. The other models, and

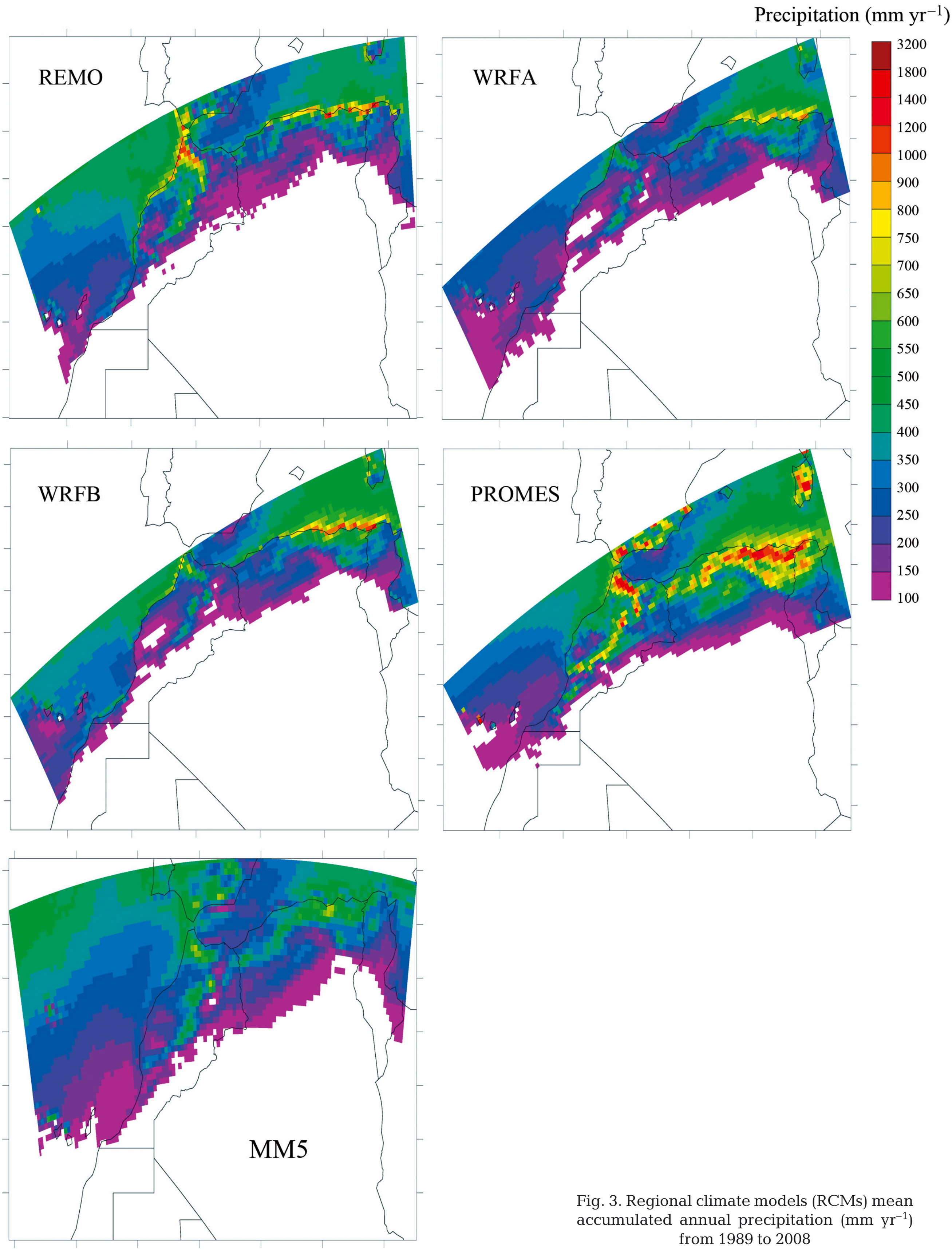

Fig. 3. Regional climate models (RCMs) mean accumulated annual precipitation (mm yr^{-1}) from 1989 to 2008

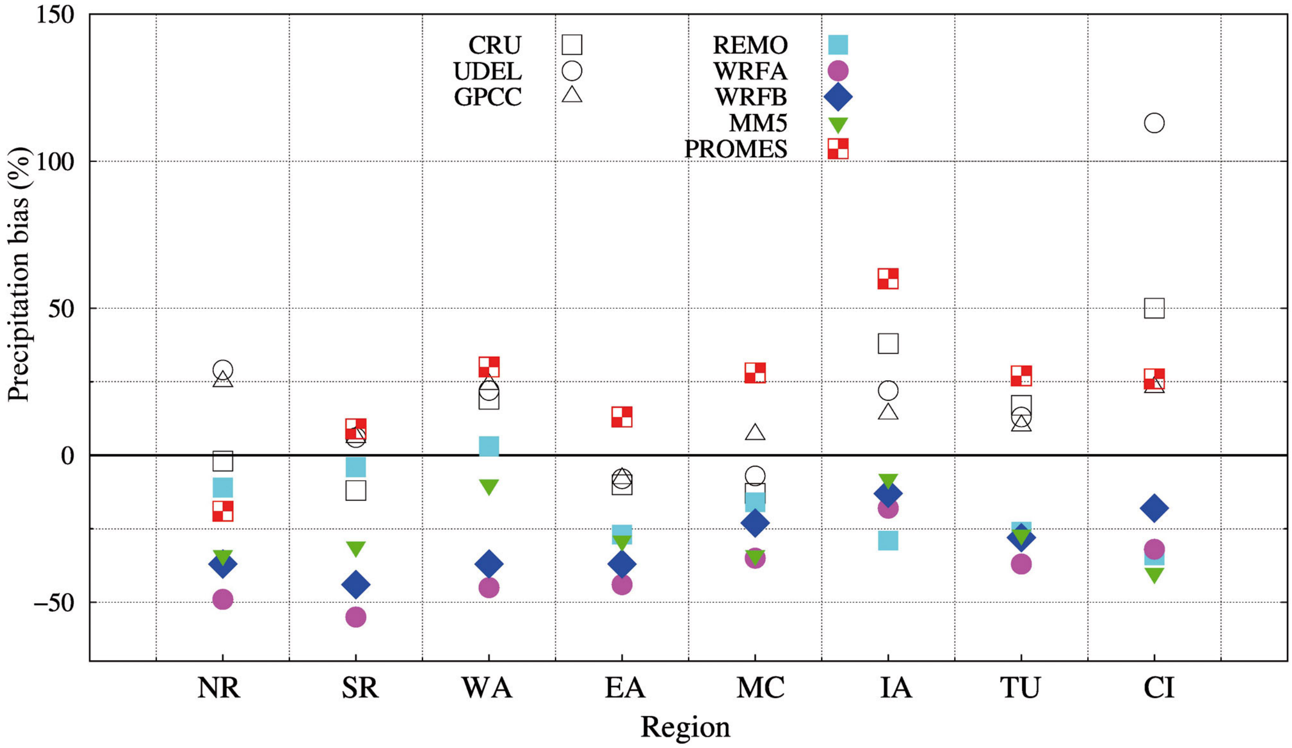

Fig. 4. Mean relative precipitation bias during the rainy season (October to March) from 1989 to 2008 with respect to CPC for observational datasets (CRU, UDEL and GPCC) and for models: (REMO, WRFA, WRFB, MM5 and PROMES) over 8 northwestern Africa subregions given in Fig. 1

particularly WRF and MM5, underestimate precipitation in all subregions, for most of the rainy months, with a negative bias larger than 25% with respect to CPC over most of the subregions. This underestimation is particularly noteworthy for winter precipitation over the Atlantic subregion, where WRF presents a negative bias of 50%, which is mostly linked to relatively large scale Atlantic depressions. In contrast, winter precipitation is well captured by PROMES, which points to very different origins of biases among the models. A special case is the CI islands chain, where the complex orography results in a very irregular precipitation distribution that can hardly be described with either the gridded observations or the RCMs at the resolution used here.

3.2. Extreme events

In order to analyse the extreme events over the region, the R10MM and the CDD indices have been chosen. The projected change of dry days over the studied domain could reach high values in a medium-term climate (2041 to 2070) (Bouagila & Sushama 2013), so a good evaluation of RCMs ERA-Interim performance is crucial.

Regarding heavy precipitation episodes (R10MM), the CPC observations had a spatial distribution with north-south gradient, showing a clear dipole of maximums (Fig. 6, upper-left panel and Fig. 7, left panel): one peak over strait of Gibraltar and surrounding areas (NR and SR subregions) and another covering most of MC. This pattern is very similar to the pattern observed in Fig. 2, where the mean accumulated annual precipitation is represented, and it is consistent not only with the precipitation regime of CPC but also with all observational databases used in this study. The maximum values reach up to 37 d yr^{-1}.

In general, all the models simulate a similar spatial distribution of observed R10MM (Fig. 6), having remarkable differences among them. These differences are clearer when spatially averaged, as in Fig. 7 (left panel). Fig. 6 shows that the RCMs underestimated the observed values, except PROMES, with values above 50 d yr^{-1}. Both versions of the WRF model show a similar distribution, while the model with the values more similar to the observations is REMO. MM5 does not simulate properly the R10MM amplitude, with values below 12 d yr^{-1} over all the subregions (Fig. 7).

Based on CPC results, the CDD index seems to have an east–west gradient, with the regions with

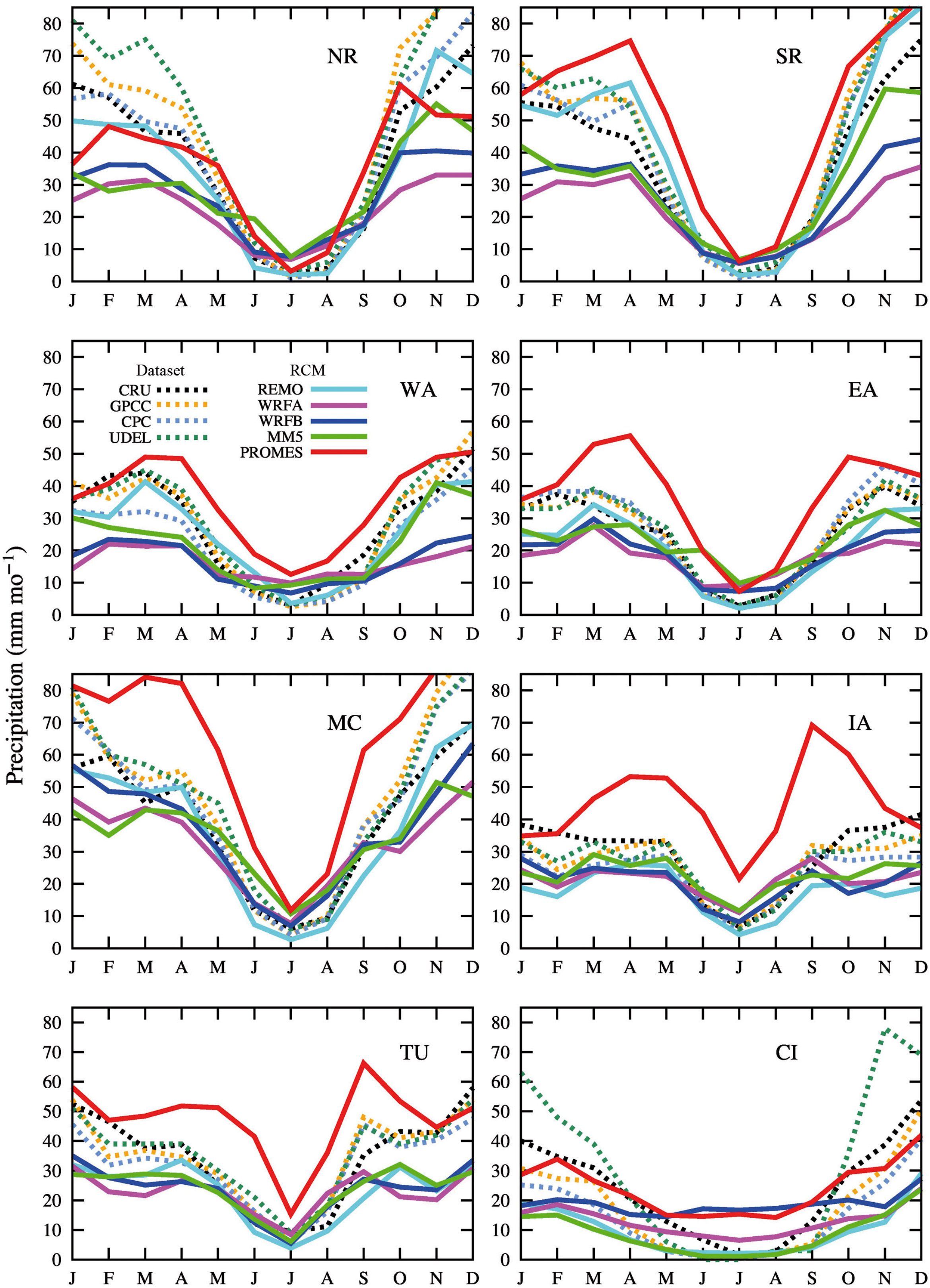

Fig. 5. Annual cycles of mean monthly precipitation from 1989 to 2008 over the 8 northwest Africa subregions given in Fig. 1. Dashed lines: observational datasets (CPC, UDEL, GPCC, CRU). Solid lines: regional climate models RCMs (MM5, PROMES, WRFB, WRFA, REMO)

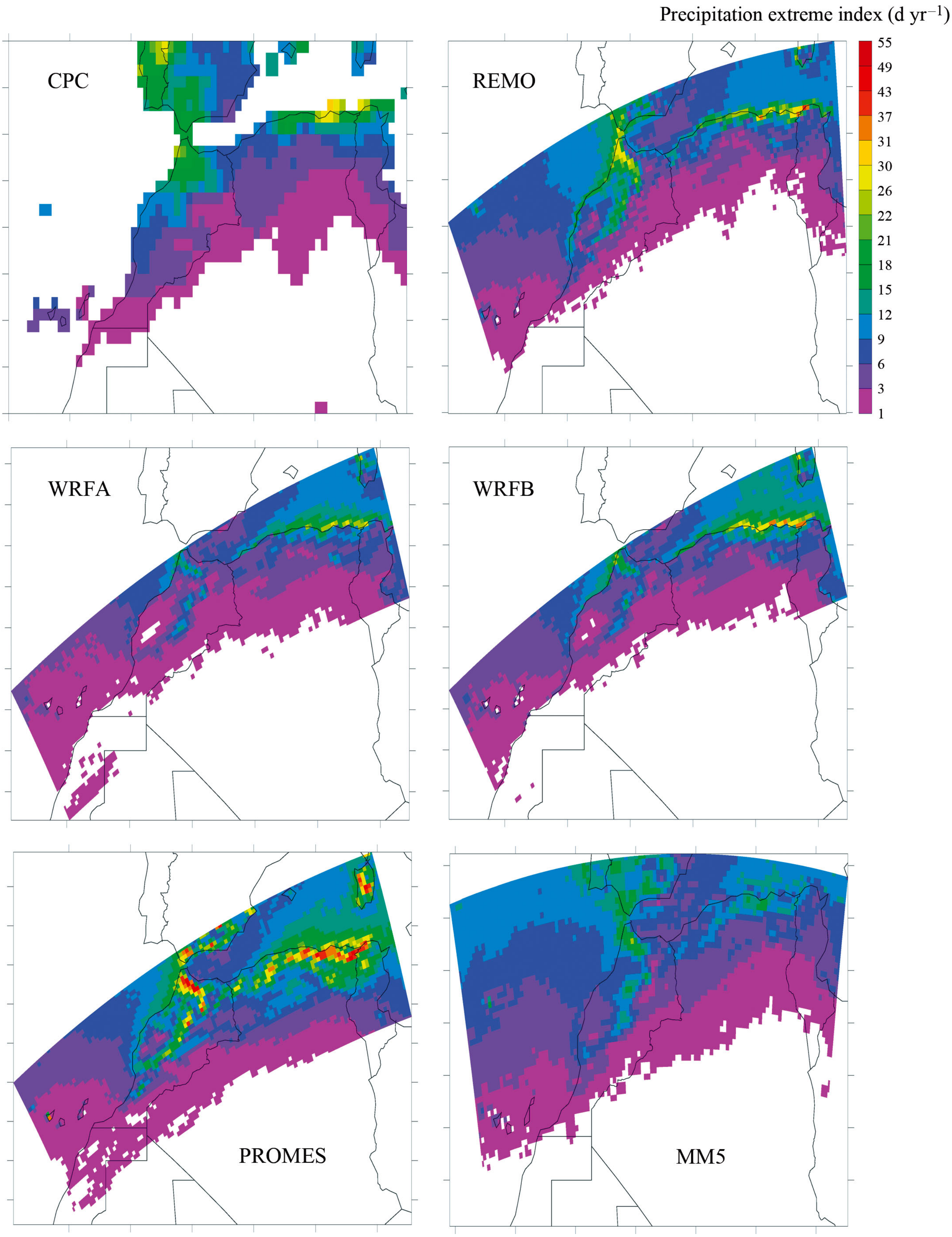

Fig. 6. Spatial distribution of R10MM precipitation extreme index from CPC observed data and from ERA-Interim regional climate simulations (REMO, WRF-A, WRF-B, PROMES and MM5)

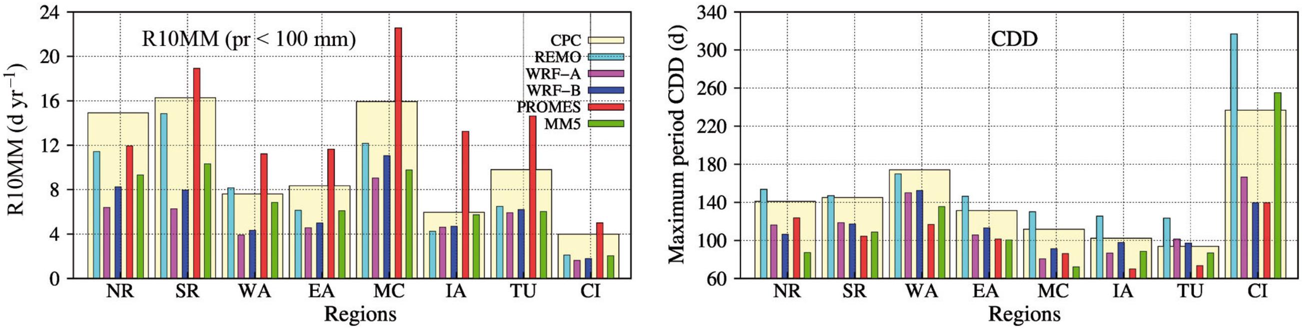

Fig. 7. Precipitation indices histograms for 8 northwest Africa subregions (see Fig. 1): R10MM (left) and CDD (consecutive days per 20 yr, right) from CPC observed data and from regional climate models (REMO, WRF-A, WRF-B, PROMES and MM5)

Atlantic influence (CI, WA and SR) presenting the greatest value of maximum period of CDD (Fig. 7). CI is the subregion with larger CDD period, possibly due to the scarce number of land points and the underestimation of the relief as the main factors that affect the local rainfall estimates (Herrera et al. 2001). A similar pattern has been found in the annual mean CDD (not shown). IA is one of the regions with the smallest values of both indices (R10MM and CDD), following CI (R10MM) and TU (CDD).

Most of the models underestimate CDD index. REMO (Fig. 7, sky blue bar) is the RCM which present values closer to the observations, overestimating the index in some regions. Differences among models are smaller for the annual mean CDD, remaining REMO close to CPC while the spread among RCMs is reduced.

While PROMES (Fig. 7, red bar) and REMO overestimated 1 of the 2 extreme indices calculated, the rest of the models (MM5 and 2 versions of WRF) present a smoother distribution among subregions, underestimating both extreme precipitation events and dry periods. These results agree with the ones obtained by Domínguez et al. (2013) over the neighbouring Iberian Peninsula.

3.3. Annual anomalies

In Fig. 8 simulated and observed annual precipitation anomalies with respect to the climatology (1989 to 2008) in each subregion are presented. It is possible to divide the regions into 2 larger groups: NR, SR and WA (Morocco, Atlantic Sea) have important precipitation anomalies, especially positive ones (1996 and 2008) while the rest of the regions present a smoother evolution, balancing out positive and negative anomalies. The year with the highest precipitation in Morocco during the study period was 1996, and as reflected in Benassi (2008), this positive anomaly is very important in NR, SR and WA, even exceeding 100 %, while in the rest of the regions this anomaly was lower than 40 %, although always positive. The negative anomaly from 1998 to 2002 was present in all the regions, with a unique little break in 1999 in MC, pointing to a very persistent drought over all the studied domain.

All the observational databases present very similar behaviour, coinciding both in the positive anomalies (1996 in NR; SR, WA and CI, 2005 in TU and CI and 1989 in CI) as well as in the negative ones (1994 and 1998 in NR, SR, WA and EA and 2000 in MC, IA, TU and CI), with small differences in specific years and regions, as CPC in WA in 2003 or CRU in TU in 1996. In TU and CI, the spread among databases is more notable, possibly due to the small size of the regions and the longer coastline, so the land–sea masks of the databases can present more differences among them.

The spread among the RCMs anomalies depends on the region. In SR and WA, all RCMs have a very similar behaviour, while in NR, EA, MC or TU there are some noticeable differences, e.g. NR in 1999–2000, EA in 1989–1990, and MM5 with respect to the rest of the models in MC and TU in 1998. In IA, TU and CI the differences among RCMs anomalies are notable, as there are several years in which different models show anomalies of different sign. The spread among observational datasets in these subregions is also larger than in the others.

4. CONCLUSIONS

The ability of 5 high resolution (25 km) RCM simulations from the ESCENA Spanish project to reproduce the present climate precipitation in Northwest Africa was analysed in this study. The scarcity of RCMs studies over such region gives an added value

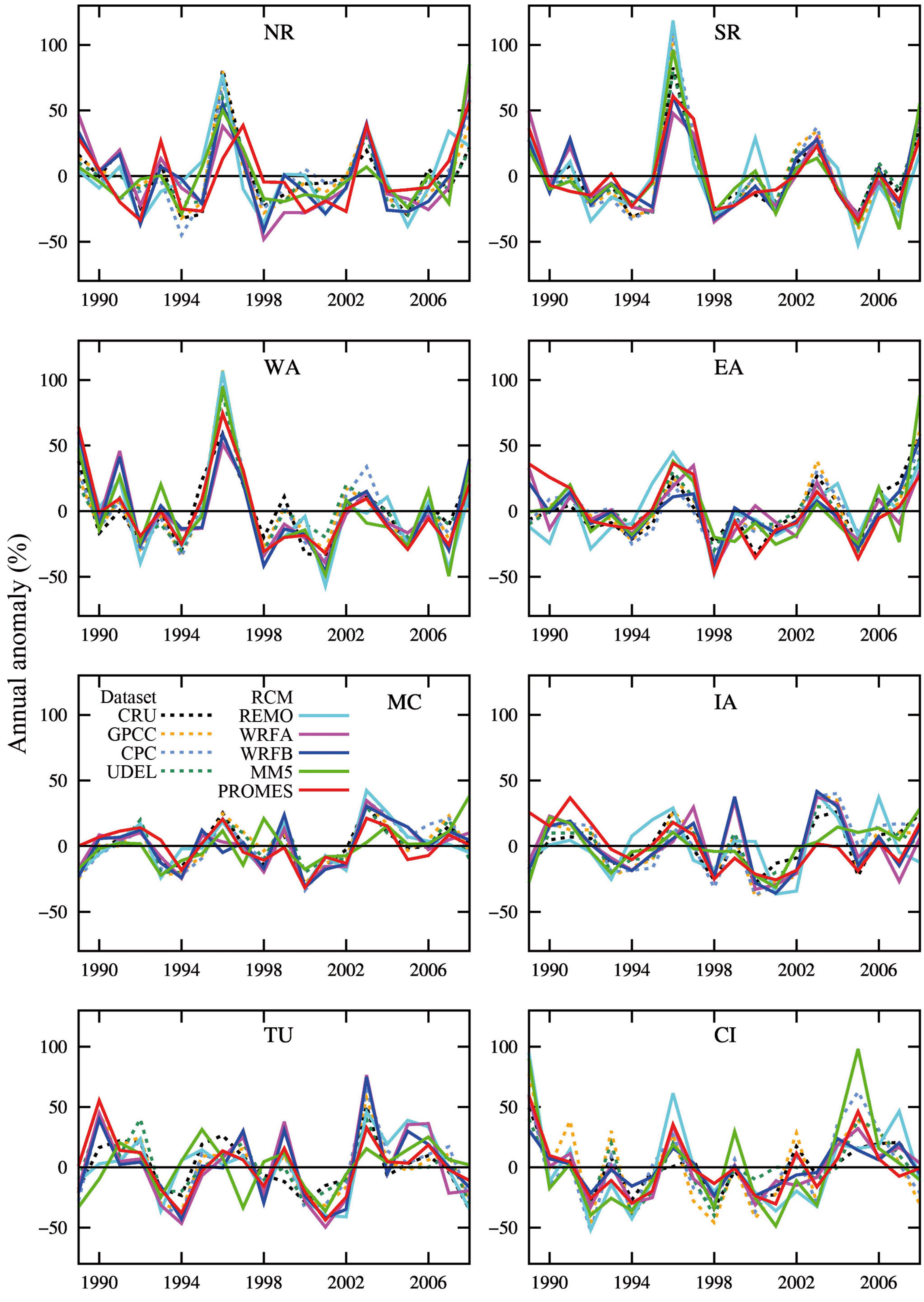

Fig. 8. Normalized annual precipitation anomalies for 8 northwest Africa subregions (see Fig. 1). Dashed lines: observed data (CRU, GPCC, CPC, UDEL); solid lines: simulated data (REMO, WRFA, WRFB, MM5, PROMES)

to the present one; for this reason a wide range of precipitation characteristics has been analysed: spatial and temporal distribution, mean values, extreme events (high precipitation episodes and dry periods) and seasonality. The analysis reveals both orographic and climatic heterogeneity posing an important challenge to the RCMs involved in the study.

The studied region also presents a great difficulty regarding the observational databases as demonstrated by the spread obtained among them in all parameters analysed. CPC and CRU observational databases show a spatially smoother precipitation while GPCC and UDEL are able to show clearer orographic precipitation maxima. The basic spatial distribution of the annual accumulated precipitation is reproduced by the models: the maxima and the relative minimum along the Mediterranean Coast, as well as the N-S gradient from the Mediterranean Sea to the Sahara Desert and the orographic precipitation (Atlas and Rif Chains), presenting a positive mean rainy-season relative bias in the case of PROMES and a negative one for the rest of models in almost all the regions. The spread among RCMs is larger than the spread of observations over all the subregions.

The annual cycle and the annual anomalies of precipitation in each of the 8 subregions proposed show a large spatial heterogeneity. The neighbouring NR and SR subregions, despite their different forcings (Mediterranean and Atlantic, respectively), reveal a very similar annual cycle with a long and important wet season, in contrast to other regions, as IA or WA, with less precipitation during the same season. IA and TU regions are the only ones with significant precipitation during the summer. RCMs reproduced both spatial distribution and seasonality of precipitation over the studied domain, with the most noteworthy aspects being the precipitation overestimation by PROMES and the smoothed precipitation by MM5.

In a region where floods and droughts largely affect the population, the simulation of precipitation extremes is important. Two precipitation extreme indices were chosen: R10MM to study heavy precipitation events and CDD to study dry periods. The coastal regions NR, SR and MC present higher values of R10MM with 15 or 16 d yr^{-1} while the greatest number of CDDs over 20 yr varied from 100 d in TU to 180 d in WA (apart from CI), where the dry season is longer, as was reflected in the annual cycle. Worth mentioning is the case of CI with the greatest values of CDD and the lowest of R10MM; the complex orography of the islands over a very limited extension of terrain and the ocean influence present a true challenge to the RCMs. PROMES and REMO better represent some aspects of these extreme indices, while MM5 and 2 versions of WRF present smoother results, underestimating both indices.

The analysis of the annual anomalies show the ability of the RCMs to reproduce the temporal series in each region. All the models reflect the relatively flat behaviour of the annual anomalies in MC, the rainy 1996 in NR, SR, WA and IA and the dry years in WA and EA.

Biases between models and against observations can be related to the convection scheme employed, when interacting with the complex orography of the region, as also shown in Nikulin et al. (2012) for the whole African continent and in Jiménez-Guerrero et al. (2013) and Domínguez et al. (2013), with the same models focused over the Iberian Peninsula. Similar overestimations were obtained in Paxian et al. (2015).

This paper presents a global vision of the ability of 5 RCMs to reproduce present climate over a domain presenting a high climate heterogeneity (from desert to high mountain climate) and a very complex orography (from coast to very high mountains) and showing that the precipitation over Northwest Africa should not be analysed as a single region. This study presents a starting point to analyse future climate with the future climate simulations available from the ESCENA project with the same ensemble or RCMs.

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