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An evaluation of CORDEX regional climate models in simulating precipitation over Southern Africa

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Abstract

This article evaluates the ability of the Coordinated Regional Downscaling Experiment (CORDEX) regional climate models (RCMs) in simulating monthly rainfall variation during the austral summer half year (October to March) over southern Africa, the timing of the rainy season and the relative frequencies of rainfall events of varying intensities. The phasing and amplitude of monthly rainfall evolution and the spatial progression of the wet season onset are well simulated by the models. Notwithstanding some systematic biases in a few models, the simulated onset and end of the rainy season and their interannual variability are highly correlated with those computed from the reference data. The strongest agreements between the reference and modelled precipitation patterns are found north of about 20°S in the vicinity of the Inter Tropical Convergence Zone. A majority of the RCMs adequately capture the reference precipitation probability density functions, with a few showing a bias towards excessive light rainfall events.

Keywords: CORDEX – Africa; regional climate model evaluation; rainfall characteristics

1. Introduction

As the Earth's climate continues to change, the characteristics of regional precipitation and extreme events may change without necessarily being reflected in seasonal totals (Seneviratne *et al.*, 2012; Trenberth *et al.*, 2003). For example, changes in wet season timing may not affect calendar season totals, and changes in wet season duration may be balanced by changes in the intensity or frequency of daily precipitation during that season. Changes in the character of precipitation have important implications for a number of climate-sensitive sectors such as agriculture, forestry, water resources, ecosystem services and disaster risk management. For instance, steady, soaking, moderate rains are generally better for agriculture than the same amount of rainfall over a short period, which may result in rapid runoff and flash flooding, leaving the deeper soil layers dry. The timing and duration of the rainy season *inter alia* determine the planting dates and the selection of crop types. Despite their obvious importance, however, the changes in rainfall characteristics are seldom analysed in observations (e.g. Reason *et al.*, 2005) or regional-scale climate simulations in Africa.

Changes in the scale and shape of the rainfall distribution, which may alter tail probabilities, affect the physical and natural systems more than changes in its central tendency (Easterling *et al.*, 2000). An evaluation of the ability of climate models in simulating the entire precipitation probability distribution at regional scales (e.g. Perkins *et al.*, 2007) while clearly warranted has not yet been done for southern Africa. The present study attempts to address these issues by assessing the ability of the Coordinated Regional Downscaling Experiment (CORDEX) regional climate models (RCMs) in capturing monthly rainfall evolution, selected rainfall characteristics and the observed rainfall probability density functions (PDFs) in their control simulations of daily rainfall events over predefined rainfall regions (Shongwe *et al.*, 2009) in Africa south of 10°S.

Since the launch of the CORDEX Africa programme (Jones *et al.*, 2011), a few studies have evaluated the RCM performance over parts of the continent, including southern Africa (Nikulin *et al.*, 2012; Kalognomou *et al.*, 2013). Monthly and seasonal data have been used to assess the RCM's ability to simulate the main features of seasonal mean rainfall distribution and the rainfall annual cycle. Notwithstanding biases in some regions and seasons, such as a wet bias (dry bias) close to Lesotho (over northern Mozambique) during austral summer months, the models were found to adequately simulate precipitation patterns (Kalognomou *et al.*, 2013). However, monthly and seasonal averages or totals can conceal systematic biases in the simulated climate (e.g. Tadross *et al.*, 2005). Also, given that cumulative effects of weather events on daily time scales have a direct impact on natural systems and

human activities, an assessment of model ability to simulate the characteristics of daily rainfall events is clearly valuable.

Over southern Africa, seasonal rainfall characteristics have become a subject of interest in recent years/decades, particularly their relevance for agriculture (Tadross *et al.*, 2005, 2009). Tadross *et al.* (2005), using observation-based data up to 1997, showed that the mean onset occurs earlier (September or October) over eastern South Africa and later (November to December) over northern Mozambique and Botswana. A trend towards a later onset was found over northeastern South Africa. Using seven Coupled Model Intercomparison Project Phase 3 (CMIP 3) global climate models statistically downscaled to station data, Tadross *et al.* (2009) projected a reduction in mid twenty-first century (2046–2065) austral spring precipitation, and an increase in the autumn, suggesting a shift of the rainy season to later dates over southern Africa north of about 20°S. No attempt was made to quantify the uncertainty associated with the downscaling procedure. The CORDEX Africa programme produces large volumes of data necessary to provide future projections of high-frequency precipitation statistics and a quantification of the inherent uncertainties. This paper provides the necessary foundation for such analyses by assessing the models' ability to replicate some rainfall statistics in their control simulations.

2. Data and methodology

Monthly and daily rainfall simulated by 10 CORDEX RCMs over the common 17-year period (1991–2007), driven by the ERA-Interim reanalysis (Simmons *et al.*, 2006), are used. The RCMs include: (1) the Université du Québec à Montréal fifth-generation Canadian Regional Climate Model (CRCM5), (2) the Universidad de Cantabria Weather Research and Forecasting Model, version 3.1.1 (WRF3.1.1), (3) the Sveriges Meteorologiska och Hydrologiska institut (SMHI) Rossby Centre Regional Atmospheric Climate Model, version 3.5 (RCA3.5), (4) the Max Planck Institute Regional Model (REMO), (5) the Consortium for Small-scale Modelling (COSMO) Climate Limited-Area Model, version 4.8 (CCLM4.8), (6) the Centre National de Recherches Météorologiques Action de Recherche Petite Echelle Grande Echelle, version 5.1 (ARPEGE5.1), (7) the Abdus Salam International Centre for Theoretical Physics RCM, version 3 (RegCM3), (8) the University of Cape Town Providing Regional Climates for Impacts Studies (PRECIS), (9) the Danmarks Meteorologiske Institut HIRHAM, version 5 (HIRHAM5; the HIRHAM5 has days with missing data and has been omitted in the analysis of onset and withdrawal of the rainy season) and the Koninklijk Nederlands Meteorologisch Instituut Regional Atmospheric Climate Model, version 2.2b (RACMO2.2b). The RCM setup details and relevant

references are presented in Nikulin *et al.* (2012) and Kalognomou *et al.* (2013).

Owing to the dearth and/or inaccessibility of observational data over much of the study area, the ERA-Interim reanalysis is used as the reference data set to assess model performance. Throughout this paper, reference data refer to the ERA-Interim precipitation. Given the uncertainty associated with observation-based data sets (Kalognomou *et al.*, 2013; Sylla *et al.*, 2013), the Global Precipitation Climatology Project (GPCP; Huffman *et al.*, 2009) data, which are available from 1997, are also used for comparison.

The homogeneous rainfall regions over southern Africa defined by Shongwe *et al.* (2009) are adopted in this study. CORDEX simulation of monthly spatially averaged precipitation is assessed using Taylor diagrams (Taylor, 2001), which graphically synthesize the degree of correspondence between RCMs and the reference data in terms of the phase and amplitude of their evolution, measured by Pearson correlation coefficients, the centred root-mean-square error (RMSE) and a comparison of their variances. Taylor diagrams are widely used to evaluate the multiple aspects of complex models and gauging the relative skill of many different models (e.g. Kalognomou *et al.*, 2013).

Onset and cessation of the wet season is defined for each region in Figure 1, assuming spatial coherence of the timing across the individual regions, from anomalous precipitation accumulation in a given day [A (day)] as

$$A \, (\text{day}) = \sum_{n=1}^{\text{day}} R \, (n) - \overline{R} \qquad (1)$$

where $R(n)$ is the daily precipitation and $\overline{R}$ is the long-term annual daily mean (Liebmann *et al.*, 2007; Rauscher *et al.*, 2007). The calculation started on 1 July (climatologically, the driest month; see Figure 2 of Shongwe *et al.*, 2009). The onset of the rainy season is defined as the date on which the curve reaches a minimum, since after that date precipitation exceeds the annual daily climatology and before that date precipitation is less than the annual climatology. Prior to onset, there are often brief periods of precipitation causing the curve to move upward, but these are considered 'false' onsets, because the curve ultimately falls to its absolute minimum for the year. Similarly, cessation is defined as the date on which the curve reaches the maximum, since after that date precipitation is less than climatology (e.g. Figure 2 of Liebmann *et al.*, 2007). Pearson correlation coefficients and RMSE are computed between the simulated and reference onset and cessation dates. Statistical significance of the computed correlation is assessed using a parametric Student's *t*-test.

Regional PDFs are constructed for the reference data sets and CORDEX RCMs by considering all the grid points falling within a region, omitting daily precipitation values <0.1 mm day^{-1} at any given grid. The PDFs are compared visually.
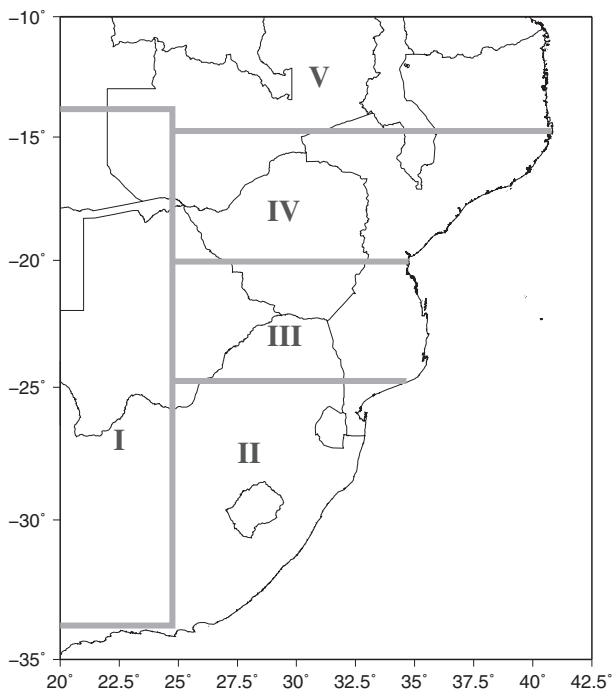
Figure 1. Location map of the Southern Africa homogeneous climate regions defined by Shongwe *et al.* (2009).

3. Simulation of monthly precipitation

There are notable spatial inhomogeneities and inter-model differences in simulating the phasing and amplitude of monthly rainfall evolution (Figure 2). Relative to the south (Figure 2(a)–(c)), the simulated monthly precipitation to the north of about 20°S (Regions IV and V) is in better agreement with the reference data (Figure 2(d) and (e)). Almost all RCMs attain correlation scores >0.5, centred RMS differences (the curved contours in each plot) ≤ 2 mm day^{-1} and have their intermonthly standard deviation close to the reference data in Regions IV and V. To the south (Regions I, II and III), the pattern correlation is lower (≤ 0.6) in most RCMs, but statistically significant (from re-randomization tests, not shown), indicating that the downscaled monthly precipitation can still provide useful information in these regions.

APERGE5.1 stands out as the RCM with the best agreement with the reference data. This model's pattern correlation exceeds 0.8 everywhere, and the RMS differences between this model's downscaled precipitation and the ERA-Interim reanalysis are the smallest. The WRF3.1.1 model, albeit comparable with the majority of the RCMs in its ability to simulate the phase of the monthly rainfall evolution, has the largest amplitude of precipitation variation.

4. Seasonal rainfall onset and withdrawal

The observed rainfall annual cycle plots for each climatic region are shown in Figure 2 of Shongwe *et al.* (2009). The rainy season begins first in the southeast

and progresses northward. Earlier onset over eastern South Africa (Region II) is associated with moisture advection from the warm Agulhas system and instabilities induced by mid-latitude disturbances (Tyson and Preston-Whyte, 2000). The spatial progression of the regional rainfall onset in the RCMs is broadly consistent with the reference and the GPCP data, which often present similar estimates of the rainy season timing for the common period 1997/1998–2007/2008, a notable exception being the 2002/2003 season. In ERA-Interim, the mean (median) rainfall onset date in Region II is 22 October (18 October), with an interannual standard deviation (σ) of 15 days. In the GPCP data, the mean onset date and σ for eastern South Africa (i.e. Region II) are 23 October and 17 days. Albeit not statistically significant, the trend towards later onset of 1 day year^{-1} in the GPCP data over eastern South Africa is consistent with Tadross *et al.* (2005) and the broadly held notion that in parts of southern Africa, the start of the rainy season has shifted to later dates in recent years/decades. In the ERA-Interim, a weaker delayed onset (4 days decade^{-1}) is only found in the late twentieth century.

Most of the CORDEX RCMs adequately capture the mean rainfall onset in Region II, falling within ± 7 days of the reference data (Figure 3(b)). To the southwest (Region I), the mean start of the rainy season occurs around 8 November and 16 November in the ERA-Interim and GPCP reference data sets, respectively. A trend towards a delayed onset (3 ± 2 days year^{-1}) is found during the last decade of the twentieth century. With reference to ERA-Interim, RegCM3 has the overall early mean onset bias of ≈ 14 days, while the onset in the CCLM4.8 is delayed by about 11 days. Except these two and the RCA35, the mean onset dates in the rest of the RCMs fall within a 7 day margin from the ERA-Interim estimate in Region I (Figure 3(a)). To the north, where moisture recycling ratios are relatively higher during austral summer months (Trenberth, 1999), the seasonal rainfall onset occurs slightly later, around 12 (09), 19 (14) and 11 (12) November in Regions III, IV and V in the ERA-Interim (GPCP) data, respectively, with a relatively low interannual variability (Figure 3(c)–(e)). In Region III, all the RCMs except the RegCM3 have onset dates between 07 and 19 November (Figure 3(c)). In the RegCM3, the mean rainfall onset occurs around 25 October. Over northern Zimbabwe and central Mozambique (Region IV), the onset bias is low, with the CCLM4.8 showing a slight late bias (Figure 3(d)). The onset bias is similarly quite low over the northern-most region (Region V) will almost all RCMs simulating mean onset dates within ± 7days of 11 November.

Correlations between reference and simulated onset dates are shown in Table 1. It is evident from the table that the RCMs capture the interannual variability of the rainfall onset reasonably well. In particular, the ARPEGE5.1 attains statistically significant correlations and lowest RMSE almost everywhere. There are a few cases when the RCM simulated onset dates are out of
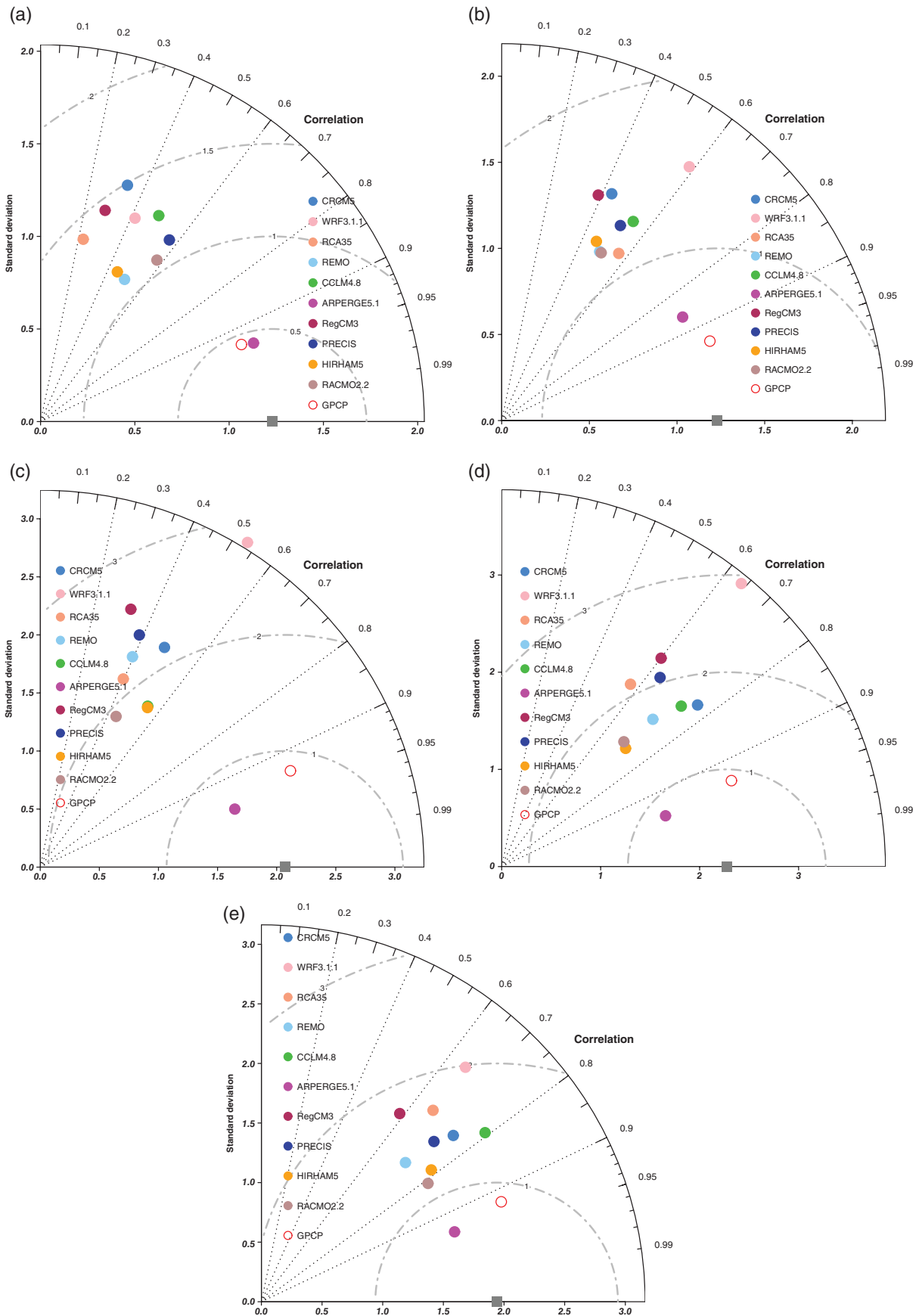
Figure 2. Taylor diagrams for area-averaged monthly precipitation in Regions (a) I, (b) II, (c) III, (d) IV and (e) V shown in Figure 1. The reference (ERA-Interim) data are shown by the grey square along the horizontal axis. The individual RCMs are shown by the solid circles and the GPCP by the open circle. The radial coordinate shows the standard deviation. The azimuthal axis shows the correlation between the RCMs and the reference data. The centred root-mean square error is indicated by the dashed grey semi-circles about the reference point.
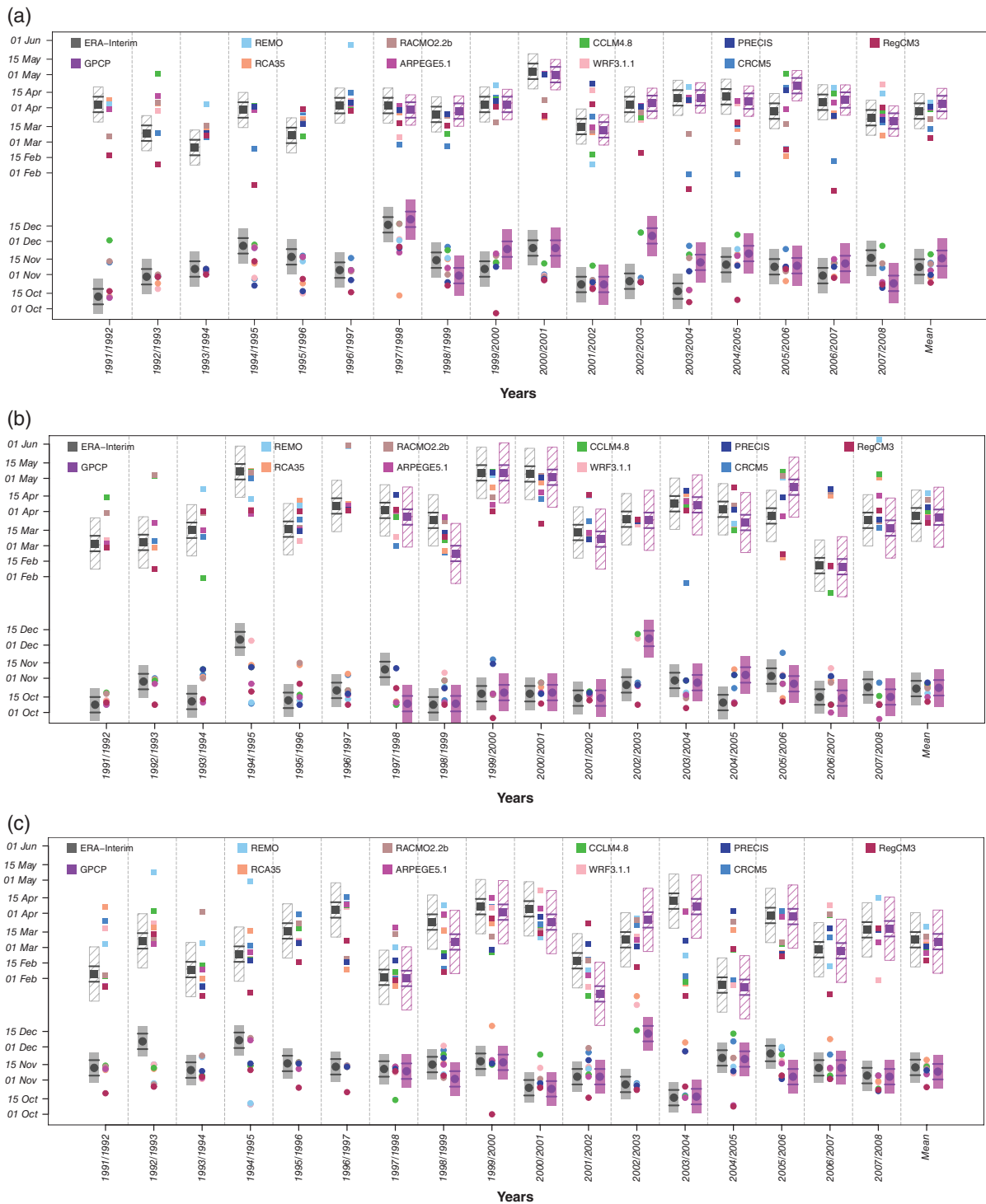
Figure 3. ERA-Interim (grey rectangles), GPCP from 1997/1998 (orchid rectangles) and CORDEX-simulated (individual points) interannual onset (solid circles) and cessation (solid squares) dates of the wet season for Regions (a) I, (b) II, (c) III, (d) IV and (e) V. In each figure, the onset (cessation) date is plotted at the lower (upper) ordinate running from 01 October to 15 December (01 February to 01 June). For the reference plots, the rectangles extend to $\pm 1\sigma$ of interannual variability from the estimated date, while the line segments within each rectangle extend to ± 7 days.

phase with the reference data (e.g. CRCM5 and REMO in Region II, RCA3.5 in Region III and WRF3.1.1 in Region IV). The weak correlation between the GPCP and ERA-Interim in Regions I and II demonstrates how different observational-based data sets may disagree on their representation of precipitation characteristics (e.g. Kalognomou *et al.*, 2013).

In the reference data, rainfall withdrawal does not show any notable spatial migration. Almost everywhere, except in Region III, the mean end date occurs between 28 March and 05 April (27 March and 06 April) in ERA-Interim (GPCP). In Region III, which has long been known to have strong ENSO teleconnections (Ropelewski and Halpert, 1987; Rocha
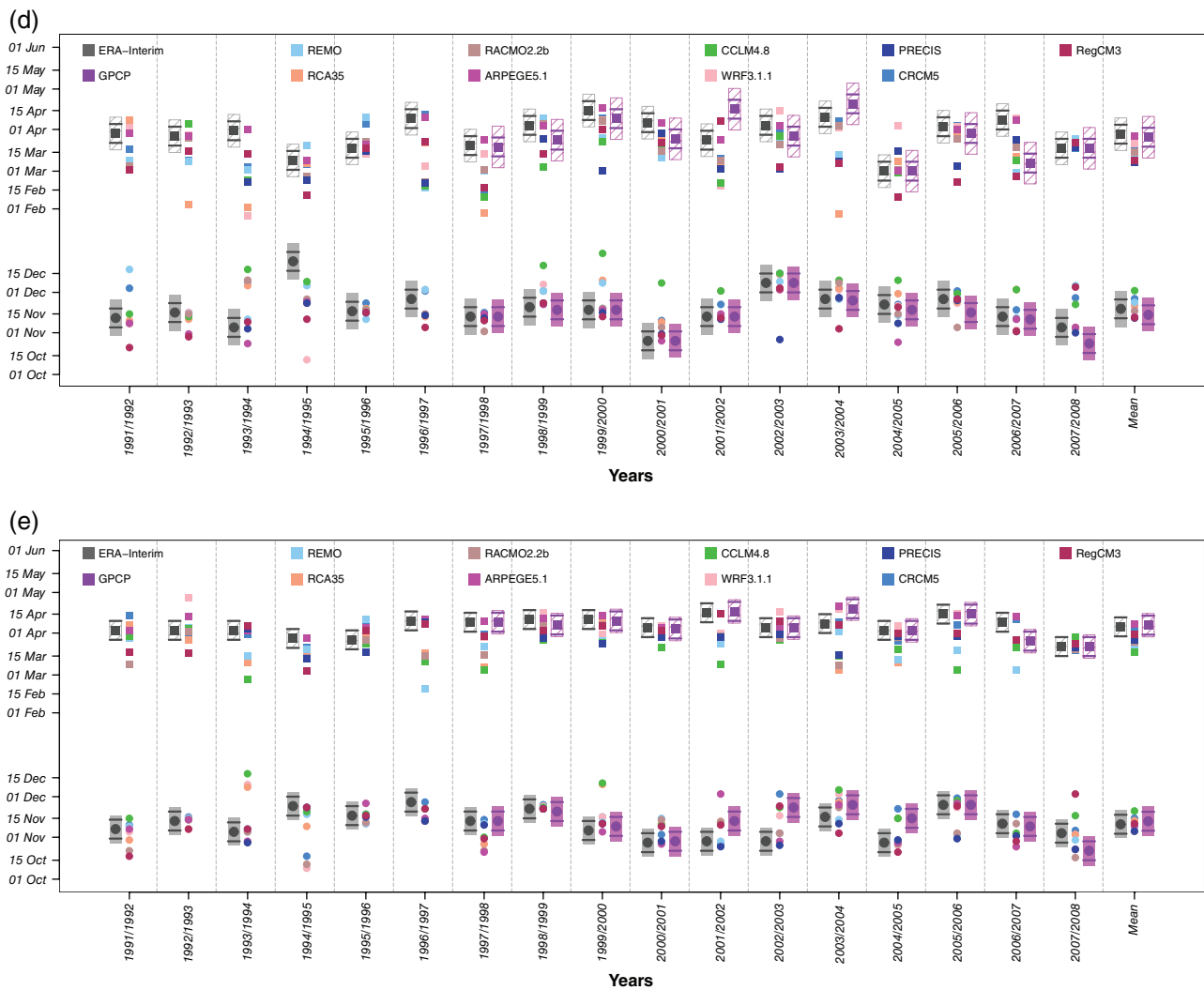
(d)

(e)

Figure 3. continued

Table 1. Correlation between the RCMs and the reference ERA-Interim onset dates.

RCM	Region I	Region II	Region III	Region IV	Region V
GPCP	0.48 (17)	0.13 (18)	**0.67**[**] (8)	**0.94**[**] (4)	**0.60**[**] (10)
ARPEGE5.1	**0.73**[**] (12)	**0.48** (13)	**0.59**[**] (12)	**0.69**[**] (10)	**0.49**[**] (13)
CCLM4.8	0.34 (16)	**0.45** (13)	0.29 (21)	0.16 (18)	0.15 (15)
CRCM5	0.16 (18)	−0.08 (21)	0.29 (23)	0.39 (13)	0.28 (14)
PRECIS	0.22 (16)	0.40 (15)	0.04 (15)	**0.46** (13)	**0.78**[**] (7)
RACMO2.2b	**0.56**[**] (13)	**0.46** (17)	0.34 (20)	**0.41** (13)	0.17 (15)
RCA3.5	0.18 (17)	0.08 (18)	−0.23 (31)	0.39 (14)	0.13 (16)
RegCM3	**0.63**[**] (13)	0.32 (14)	0.12 (23)	0.26 (15)	0.21 (15)
REMO	0.38 (17)	−0.09 (18)	**0.69**[**] (10)	**0.50**[**] (13)	**0.62**[**] (9)
WRF3.1.1	**0.67**[**] (12)	**0.46** (17)	**0.53**[**] (12)	−0.18 (22)	0.06 (18)

The RMSE (days) for each RCM is shown in brackets. Correlations that are significant at the 10% (5%) level are in bold (shown by two asterisks).

and Simmonds, 1997), the mean cessation, which occurs around 08 and 06 March in the reference data and GPCP, is influenced by six early cessation seasons (**1991/1992**, 1993/1994, **1994/1995**, **1997/1998**, 2001/2002 and **2004/2005**). In these extreme years, four (in bold font) of which coincided with a warm ENSO phase, the seasonal rainfall ends either late in

January (e.g. 2004/2005) or early to mid-February. Statistically significant correlations (at the 10% level) have been found between ENSO and early rainfall cessation over a number of stations in Zimbabwe, southern Mozambique and Malawi (Tadross *et al.*, 2009). Noteworthy, the southeastern regions (Regions II and III) have a high interannual variability ($\sigma \geq 25$ days) of the rainfall withdrawal (Figure 3(b) and (c)).

The pattern of rainfall cessation in the RCMs closely resembles that of the reference data, with some models showing an excellent agreement even during the unusual years. In Region I, all except two of the RCMs (RegCM3 and CRCM5) have end dates within ±7 days of the reference data. In RegCM3, the mean end date occurs quite early (04 March), while in CRCM5, the average cessation occurs around 13 March, 16 days earlier than in ERA-Interim. Over eastern South Africa (Region II), the largest biases are found in REMO and RACMO2.2 where the end of the rainy season is delayed by 21 and 14 days, respectively. In almost all the RCMs, the cessation dates vary greatly from year to year, in close agreement with the reference data (Figure 3(b)). In Region III, early withdrawals in the

Table 2. Correlation between the RCMs and the reference ERA-Interim cessation dates.

RCM	Region I	Region II	Region III	Region IV	Region V
GPCP	**0.84**** (7)	**0.88**** (12)	**0.93**** (11)	**0.54** (13)	**0.75**** (5)
ARPEGE5.1	**0.82**** (9)	**0.79**** (14)	**0.84**** (9)	**0.78**** (8)	**0.81**** (4)
CCLM4.8	**0.46** (19)	**0.60**** (9)	0.36 (28)	0.23 (16)	−0.29 (14)
CRCM5	−0.09 (29)	0.33 (31)	**0.43** (28)	**0.65**** (12)	**0.55**** (7)
PRECIS	**0.56**** (14)	**0.44** (21)	0.06 (31)	0.04 (17)	**0.48** (7)
RACMO2.2b	0.12 (18)	**0.72**** (15)	0.29 (30)	**0.47** (14)	0.25 (10)
RCA3.5	0.20 (18)	**0.46** (24)	0.07 (35)	0.17 (24)	0.17 (11)
RegCM3	0.36 (24)	**0.50**** (22)	**0.53**** (25)	**0.47** (15)	**0.55**** (8)
REMO	0.25 (27)	**0.61**** (18)	0.16 (38)	**0.64**** (19)	−0.19 (15)
WRF3.1.1	**0.47** (17)	0.38 (25)	**0.82**** (17)	0.37 (21)	0.32 (9)

The RMSE (days) for each RCM is shown in brackets. Correlations that are significant at the 10% (5%) level are in bold (shown by two asterisks).

RegCM3 occur often, which results in an average negative bias of 18 days. Further north (Region IV), where the ability to simulate monthly rainfall is highest, negative biases in RCM end dates in excess of 18 days are found in PRECIS, CCLM4.8, RCA3.5 and RegCM3. Over the north-most Region V, disagreements between average reference and models' end dates still persist (Figure 3(e)).

A much stronger agreement is found between the ERA-Interim and GPCP in terms of interannual variability of rainfall cessation (Table 2). The ARPEGE5.1 has the highest correlations in all the regions. With only a few exceptions (e.g. CCLM4.8 and REMO in Region V, and CRCM5 in Region I), the RCM simulated rainfall withdrawal is positively correlated with the reference dates indicating that the models are able to capture the interannual variation of the rainy season cessation.

5. Rainfall probability density functions

Daily precipitation PDFs for each region are shown in Figure 4(a)–(e). The x axes of the plots terminate at about 40 mm day^{-1} because at higher values exceeding 20 mm day^{-1}, the individual curves become almost indistinguishable. We show that very intense events ($\geq$40 mm day^{-1}) are simulated in both the reference data and in the RCMs, demonstrating that the models can provide useful information in relation to flood risks.

Although drizzle and light rainfall events $\leq$3 mm day^{-1} occur too often in a few of the RCMs (CCLM4.8, REMO and RCA3.5), in most regions, the majority have
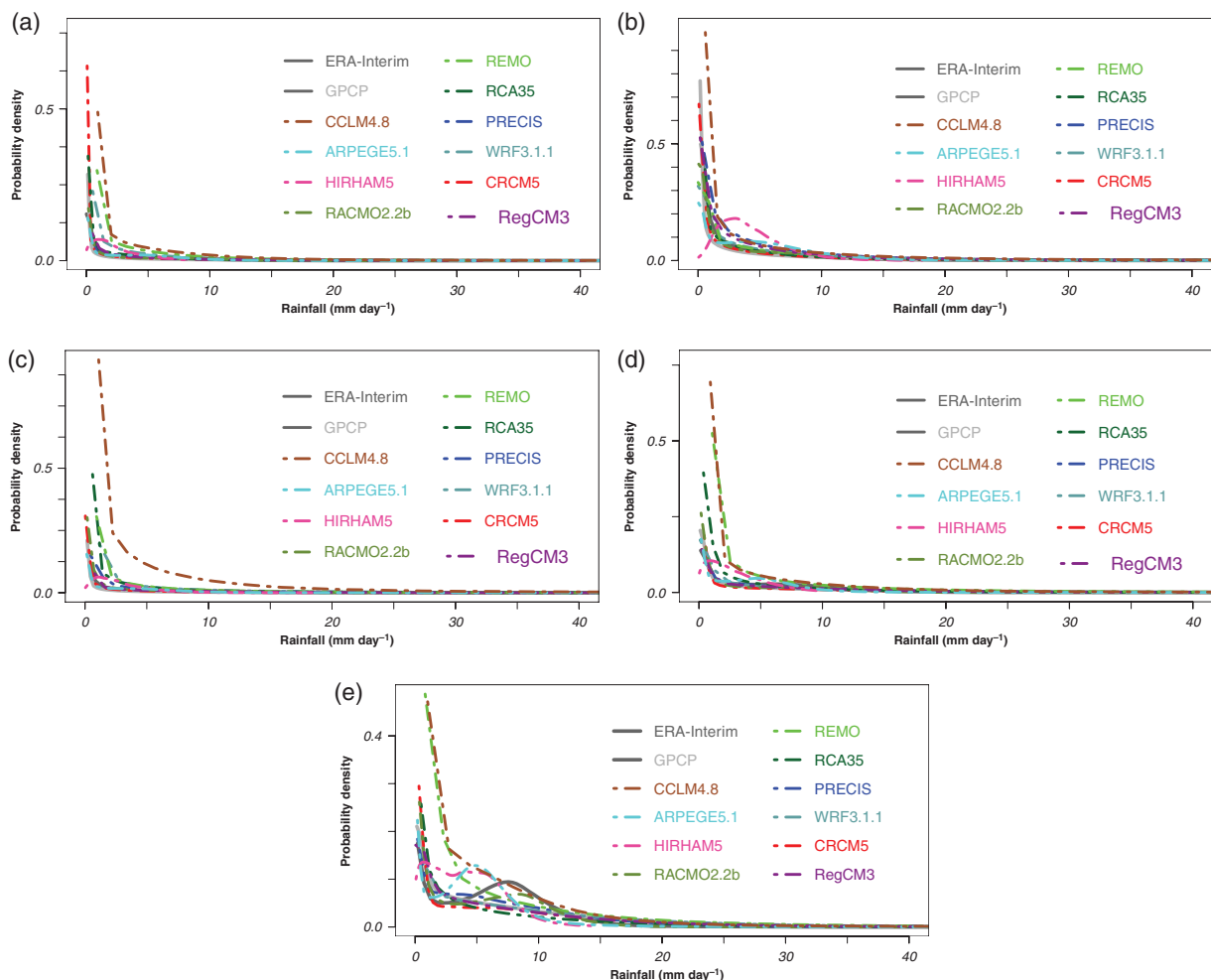
Figure 4. Reference (solid lines) and CORDEX (dot-dashed lines) precipitation probability density functions for Regions (a) I, (b) II, (c) III, (d) IV and (e) V.

low-tail probabilities comparable with the reference data. In most cases, the CCLM4.8, and in some cases, the REMO overestimate the probability of light rainfall by about 2–3 times. The RACMO2.2, the ARPEGE5.1 and the HIRHAM5 get very close to capturing the secondary peak probabilities located around 5–10 mm day^{-1} in the ERA-Interim data in Region V.

6. Summary and conclusions

The present study has enabled us to get to grips with how well the CORDEX RCMs simulate monthly rainfall amounts and some regional rainfall characteristics over southern Africa. The models have been evaluated against the ERA-Interim reanalysis, whilst the GPCP data have been used for comparison. In simulating monthly rainfall variability, the overall performance of the RCMs is good, particularly to the north of the study domain. The stretched grid ARPEGE5.1 appears to the best overall performer, in qualitative agreement with Kalognomou *et al.* (2013), where the individual RCM setups are presented. This RCM's correlation with the ERA-Interim data is highest almost everywhere in southern Africa and the biases are least. No attempt is made in this paper to identify the model physics and dynamics responsible for the differences in RCM performance. Other aspects of the simulated precipitation that are of practical significance such as rainy season timing and the relative frequencies of a spectrum of rainfall intensities have also been analysed. The spatial migration of the seasonal rainfall onset is well captured by the RCMs. The reference and simulated average onset and withdrawal dates are within a few days of each other, and the interannual variability is captured by the RCMs, a few notable biases notwithstanding. A visual comparison of the reference and simulated PDFs shows that a majority of the models do quite well in representing the probabilities of certain rainfall events.

There are prospects for the CORDEX RCMs to provide usable information on regional monthly precipitation, rainfall characteristics and probabilities of events of differing intensities over southern Africa, and their likely future changes, for climate change impacts assessments where impacts are related to precipitation. The uncertainties associated with the modelling process from the driving climate to impacts are yet to be quantified. One of the goals for future work is to investigate and compare the physical mechanisms underlying rainfall variability and changes in rainfall character in observations and in the models.

Acknowledgements

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