



Process-based assessment of the impact of reduced turbulent mixing on Congo Basin precipitation in the RCA4 Regional Climate Model

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Abstract

In regions featuring strong convective activity (such as the Congo Basin, CB), turbulent mixing in the planetary boundary layer strongly affects the water budget. In this study, we use a process-based evaluation to assess the performance of the Rossby Centre Regional Climate Model (RCM) RCA4 in simulating the September–November CB rainfall, under conditions of strong and weak turbulent mixing. To this regard, results from two different versions of model are analysed: the version used in the COordinated Regional climate Downscaling EXperiment framework (RCA4-v1), and a modified version (RCA4-v4), in which turbulent mixing is reduced. Experiments are driven with boundary conditions from the ERA-Interim reanalysis. Results show that RCA4-v4 improves the CB rainfall climatology compared to RCA4-v1. This result is further related to the models' different representations of the relevant driving mechanisms and processes. The model version with a reduced turbulent mixing (RCA4-v4) shifts less moisture from the lower troposphere towards the free troposphere. As the shallow convective mixing is reduced (owing to the reduction of the turbulent mixing), lower layers are moistened, and low level cloud fraction increases over Equatorial Africa. This increase is stronger over the West Equatorial African (WEA) coast than over the CB. The result is that surface solar radiation decreases more over the WEA coast than over the CB, which would result in a lower surface temperature over WEA coast than over the CB. An enhanced pressure gradient between the WEA and the CB is created as a result, thus enhancing the Congo low level cell, and low level westerlies (LLWs). LLWs are faster, meaning that more moisture flows through the CB Cell, is uplifted in eastern up-branch, and enters African Easterly Jets (AEJs), which, in turn, are intensified due to the increase in the surface temperature gradient. Intensification of the CB cell and mesoscale convective systems (MCSs) is the cause of the higher rainfall and is what improves the CB rainfall climatology in RCA4-v4. In addition, the increase in rainfall causes an increase in soil moisture in RCA4-v4 in both the north and south of the CB. Higher soil moisture does not affect evaporation in the north as soils are already saturated in RCA4-v1. However, the increase in rainfall increases soil moisture in the south in RCA4-v4, which increases evaporation as soils were initially unsaturated. This higher evaporation is exported out of the basin towards Southern Africa, does not recirculate through the Cell, and does not therefore contribute to further improving the rainfall bias over the Congo. Our results show that reducing turbulent mixing results in a better representation of the dynamics of the climate system over the CB and, in turn, improved precipitation.

Keywords Turbulent mixing · Rainfall biases · Process-based evaluation · Congo basin · RCA4

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1 Introduction

Improving the present and future simulation of the climate system is one of the challenges in the climate modeling community. This is especially needed to support decision-makers in e.g. the assessment of the most severe climate impacts and the development of efficient adaptation measures. Models' improvement requires a prior evaluation of their performance. In Central Africa, previous studies have highlighted considerable uncertainties in the abilities of both global and regional climate models (GCMs and RCMs, respectively) to simulate present and future climate (e.g., Nikulin et al. 2012; Aloysius et al. 2016; Dosio and Panitz 2016; Fotso-Nguemo et al. 2016; Sonkoué et al. 2018; Dosio et al. 2019, 2020), in particular over the Congo Basin (CB) (e.g., Creese and Washington 2016, 2018; Tamoffo et al. 2019a,b). Although a substantial added value of downscaling was noticed (e.g. Nikulin et al. 2012; Laprise et al. 2013; Moufouma-Okia and Jones 2014; Dosio et al. 2015; Fotso-Nguemo et al. 2017; Fotso-Kamga et al. 2019; Taguela et al. 2020), considerable biases persist, especially for precipitation. Added-value found must be interpreted with some caution, as it can result from the cancellation of biases in processes and does not necessarily imply improvements in related drivers (James et al. 2018; Tamoffo et al. 2020).

Within the COordinated Regional climate Downscaling Experiment (CORDEX; Giorgi et al. 2009) project, Tamoffo et al. (2019b) investigated the atmospheric circulation processes associated with RCM biases in CB rainfall, using an ensemble of simulations from the fourth version of the Rossby Centre Atmospheric RCM (RCA4). They found that although this model is suitable for modeling precipitation system (rainfall climatology and some key related drivers), it also shows persistent dry biases, related to an excessively strong mid-tropospheric moisture divergence (MD), in turn, associated with a misrepresentation of African Easterly Jets (AEJs; Nicholson and Grist 2003): in fact, AEJs are too strong at the western boundary compared to the eastern boundary, and the net result is that too little moisture is imported into the region, which unbalances the water balance equation.

However, biases in model turbulent mixing could be a second source of model dry precipitation biases: in fact, the CB is one of the main hotspots of convective precipitation worldwide with the highest rainfall amount recorded in transition seasons from March to May (MAM) and September to November (SON) (Jackson et al. 2009; Washington et al. 2013). Convection can be strongly impeded in the planetary boundary layer (PBL) due to anomalies in large eddies, which are the main mechanism for heat and moisture transport through the bulk of the PBL (Holtslag

and Moeng 1991). A number of studies have addressed the role of turbulent mixing (e.g. Troen and Mahrt 1986; Holtslag and Moeng 1991). For instance, Xie and Fung (2014) showed that the formulation of the turbulent mixing strongly affects heat transport. Turbulent mixing also plays a pivotal role in the atmospheric circulation through the moisture transport, which, in turn, strongly influences rainfall climatology by accentuating or decreasing moisture convergence (MC). Changes in the turbulent mixing could impact low level cloud cover (Pokam et al. 2014; Garcia-Carreras et al. 2015), which in turn may influence the surface solar radiation, and impact upon the structure of the region's climate system, resulting in precipitation changes.

A recent work by Wu et al. (2020) assessed the performance of two sets of runs by RCA4 at various horizontal resolutions over the CORDEX-Africa domain. The first set of runs used the standard version employed in CORDEX, named RCA4-v1. The "v1" acronym is used to distinguish the configuration version of the model over Europe, Arctic, Africa, South East Asia, and Central and North America domains, from "v2" configuration of South Asia domain, and from "v3" configuration of South America. The second set used a new version (RCA4-v4), developed to reduce systematic dry biases previously recorded over Central Africa (Tamoffo et al. 2019b). In particular, the new parameterization reduces the turbulent mixing in the stable boundary layer (in particular the momentum mixing; see Wu et al. 2020; Xie and Fung 2014). Wu et al. (2020) demonstrated the dominance effect of the model's physics parameterization over the resolution on precipitation climatology: in fact, the model physics controls the spatial pattern of seasonal rainfall biases while the resolution mainly influences the precipitation intensity. These results also confirm previous findings by Panitz et al. (2014) and Vondou and Haensler (2017) who showed that when using parameterized convection, the sole refinement of the model's resolution does not add substantial improvements. Wu et al. (2020) showed that the modified version RCA4-v4 attenuates dry biases of RCA4-v1, and improves the annual cycle of precipitation in Central Africa (Wu et al. 2020). By addressing the need of model improvement for a better representation of the African climate, this study highlighted the importance of turbulent mixing processes in the generation of rainfall, especially in the CB. However, while Wu et al. (2020) investigated the response of a reduced turbulent mixing on the rainfall climatology simulated by RCA4-v4, little is known on how related processes react, which is an important knowledge gap to assess the credibility of this model version to represent the Central Africa climate system.

The aim of this work is to investigate processes responsible for the better performance of RCA4-v4 (with reduced turbulent mixing) in simulating CB precipitation climatology

compared to RCA4-v1 CORDEX version (with more turbulence): in fact, although Wu et al. (2020) found that RCA4-v4 precipitation is improved, they did not investigate the reasons and mechanisms behind the better performance. Investigating the linkage and interaction between processes can be very useful to establish model credibility to represent the historical climate, to assess the plausibility of projections (James et al. 2015) and to verify whether a model's results have been improved for the right reasons (for e.g. in understanding how a new version of a model behaves in simulating the mechanisms relevant for the process under scrutiny).

The paper is organized as follows: Sect. 2 describes the model, the experimental design and observational data, and presents evaluation metrics used for analyses. Section 3 focuses on the evaluation of precipitation climatology. Section 4 examines the physical processes associated with the differences between RCA4-v1 and RCA4-v4. Section 5 discusses the results and provides a summary.

2 Data and methods

The region known as Congo Basin (CB, defined as 10° S–10° N; 10°–35° E as in Tamoffo et al. 2019b) is characterized by complex topography and a dense hydrographic network. The region is characterized by two wetter seasons, March–May (MAM) and September–November (SON), and two drier seasons, December–February (DJF) and June–August (JJA), which are associated to the maxima and minima in the MC at these times of year (Pokam et al. 2012).

In the current study, investigated processes include the regional atmospheric circulations, including the MC, low-level (975–850 hPa) westerlies (LLWs; Pokam et al., 2014),

and African Easterly Jets (AEJs; Nicholson and Grist 2003), and the land–atmosphere coupling, including evaporation, SM, and the surface temperature gradient. We have also evaluated the relationship between turbulent mixing and the Congo Basin cell, recently highlighted by Longandjo and Rouault (2020). This Cell owes its existence to the land–ocean thermal contrast between the warm central African landmass and cold eastern equatorial Atlantic Ocean. The cell exists throughout the year, peaking in August–September and with a minimum in May. The functioning of the cell consists in a zonal pressure gradient between the warm continent and neighboring cold Oceans which induces moisture convergence into the region. This moisture then moves towards the eastern basin border, rises in the up branch of the Walker-like cell and feeds the AEJs at 600 hPa. The moisture enters the mesoscale convective systems embedded within AEJs, which propagate to the west and are responsible for much of the convective rainfall over the basin. The seasonal cycle of rainfall over Central Africa is therefore linked to the strength of this cell. In the present study, we evaluate how reducing turbulent mixing affects the CB Cell, by assessing differences in moisture convergence (column/low level), LLW strength, AEJ strength and land–atmosphere coupling between RCA4-v1 and RCA4-v4. This will be useful to describe the mechanism by which reducing turbulent mixing adjusts the cell and increases rainfall delivery in RCA4-v4.

Meteorological data used in this study are taken from two sets of runs by the Rossby Centre regional atmospheric climate model (RCA4) RCM, (RCA4-v1 and RCA4-v4). They have been run using the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-Interim, Dee et al. 2011; further details are shown in Table 1) as boundary condition (named as ECMWF-v1 for RCA4-v1 run and

Table 1 Details of reanalysis and satellite or gauge products used in this study

Dataset	Institution	Native resolution	References
NIC131-Gridded	New rainfall datasets recently developed for equatorial Africa	2.5° × 2.5°	Nicholson et al. (2019)
NCEP-2	National Center for Environmental Prediction and the National Center for Atmospheric Research (NCAR)	2.5° × 2.5°	Kanamitsu et al. (2002)
ERA5/ERA-Interim	European Centre for Medium-Range Weather Forecasts	0.75° × 0.75°	Hersbach et al. (2020)
GPCP	Global Precipitation Climatology Project World Climate Research Programme (WCRP)	2.5° × 2.5°	Adler et al. (2003)
GPCC-v7	Global Precipitation Climatology Centre	0.5° × 0.5°	Schneider et al. (2014)
CRU-v3.23	Center for Atmospheric Research (NCAR) Climate Research Unit, University of East Anglia (v3.23)	0.5° × 0.5°	Harris et al. (2014)
CMAP	Climate Prediction Centre Merged Analysis of Precipitation, NOAA NCEP	2.5° × 2.5°	Xie and Arkin (1997)

ECMWF-v4 for RCA4-v4 run hereafter) over the CORDEX-Africa domain, at ~50 km horizontal resolution (following the CORDEX protocol), from January 1979 to December 2010. RCA4 configuration and physics parameterization are extensively presented in Strandberg et al. (2015), Tamoffo et al. (2019b) and Wu et al. (2020). As the runs are driven by the same boundary conditions, differences among them will be solely due to differences in model formulation.

It must be also noted that in the CB, there are considerable discrepancies in rainfall intensity and spatial pattern across rain-gauge, satellite and reanalysis products (Washington et al. 2013), and choosing which reference dataset to compare models with is therefore problematic. Comparing model results with a reduced number of observations would be subjective, and would not provide information on the real capabilities of models. For these reasons, further assessment of performance of RCA4-v4 in simulating CB precipitation was performed in this paper, using multiple reanalysis and observational datasets (see details of each dataset in Table 1). These reference data were employed, after remapping them on the model grid. GPCC-v7 is here considered as a point of reference, because it compares favourably to the NIC131-Gridded gauge-based data set (Nicholson et al. 2019) ($r \sim 0.95$, $STD < 0.75$ and $RMSD < 0.5$).

Besides precipitation, other model variables used in the evaluation include horizontal wind components, specific humidity (from surface up to 300 hPa), surface pressure, evaporation, surface temperature, and soil moisture (SM), all at a monthly time scale and spanning from 1981 to 2005.

We focus on the SON rainiest season throughout the work, which matches with the time of the presence in the region, of the two components of the AEJs. This is also the time of intense MC into the region (Pokam et al. 2012; Dyer et al. 2017), e.g. featuring also strong convection (Jackson et al. 2009) and low-level westerlies (Dezfuli and Nicholson 2013; Nicholson and Dezfuli 2013; Pokam et al. 2014).

As a metric for the difference between the two run versions statistical significance is assessed by student t-test with confidence level fixed at 95%; in the figures, statistical significance is represented by stippling.

3 Evaluation of precipitation climatology

As mentioned earlier, the ability of both versions of RCA4 to model the African climatology was recently evaluated by Wu et al. (2020). Here, we first briefly summarize the RCA4 performances, with a special focus over the CB, in order to facilitate the following analyses.

Figure 1 shows observed and modeled spatial distribution of SON precipitation from GPCC-v7 observational data (Fig. 1a) and from ECMWF-v1 (Fig. 1b) and ECMWF-v4 (Fig. 1c) experiments. None of the runs capture the observed

peak of precipitation over the western CB, whereas the eastern peak is better simulated by ECMWF-v4. In the rest of the region, ECMWF-v4 outperforms ECMWF-v1. The two sets of runs capture satisfactorily the spread of the rain-band, with very few differences within the region. However, ECMWF-v1 shows a dry bias over most of the CB (Fig. 1d) whereas ECMWF-v4 does so just along coastal areas and in the centre of the regions (Fig. 1e). Although the newest version RCA4-v4 still presents dry biases in most parts of the region, their magnitudes are greatly reduced compared to RCA4-v1, especially in wetter seasons, as also reported by Wu et al. (2020).

We quantified the statistical performances of each set of simulations with a Taylor diagram (Fig. 2), which compares the root-mean-square difference (RMSD), the pattern correlation coefficient (r), and the spatial standard deviation (STD), with respect to the observed field GPCC-v7. Analyses reveal the overall better performances of RCA4-v4 ($RMSD < 1$, $r \sim 0.60$ and $STD \sim 1$) compared to RCA4-v1 ($RMSD \sim 1$; $r \sim 0.55$, and $STD > 1$). The question that needs to be answered is if this improvement in performances is associated with a better representation of the physical underlying processes, which conditions the model credibility to simulate the historical and future climatology.

4 Sources of differences between RCA4-v1 and RCA4-v4

4.1 Precipitation and moisture convergence/divergence relationship

The role of moisture flux in modulating rainfall in the CB is known. Especially during SON, large amounts of moisture from the Atlantic Ocean are transported towards the interior of CB in the lower layers, by low-level westerlies (Pokam et al. 2014). Additionally, moisture fluxes originating from the Indian Ocean, are identified by Dyer et al. (2017) as a major source of moisture in Central Africa. These low-level convergences associated with mid-level circulations, contribute to sustain deep convection, which is most intense at this time of year (Jackson et al. 2009; Taylor et al. 2018).

Therefore, we investigate the influence of the simulated total column MC on the rainfall differences between ECMWF-v1 and ECMWF-v4. The correlation between the difference in precipitation and that in MC between the two versions (v4 minus v1) is shown in Fig. 3. Note that MC fluxes are vertically integrated from the lower layer (975 hPa) to upper troposphere (300 hPa) so as to account for the contribution of each pressure level and for local and large scale effects. The two RCM versions feature a strong positive correlation (0.71), highlighting the strong dependence of rainfall difference to MC difference. Creese and

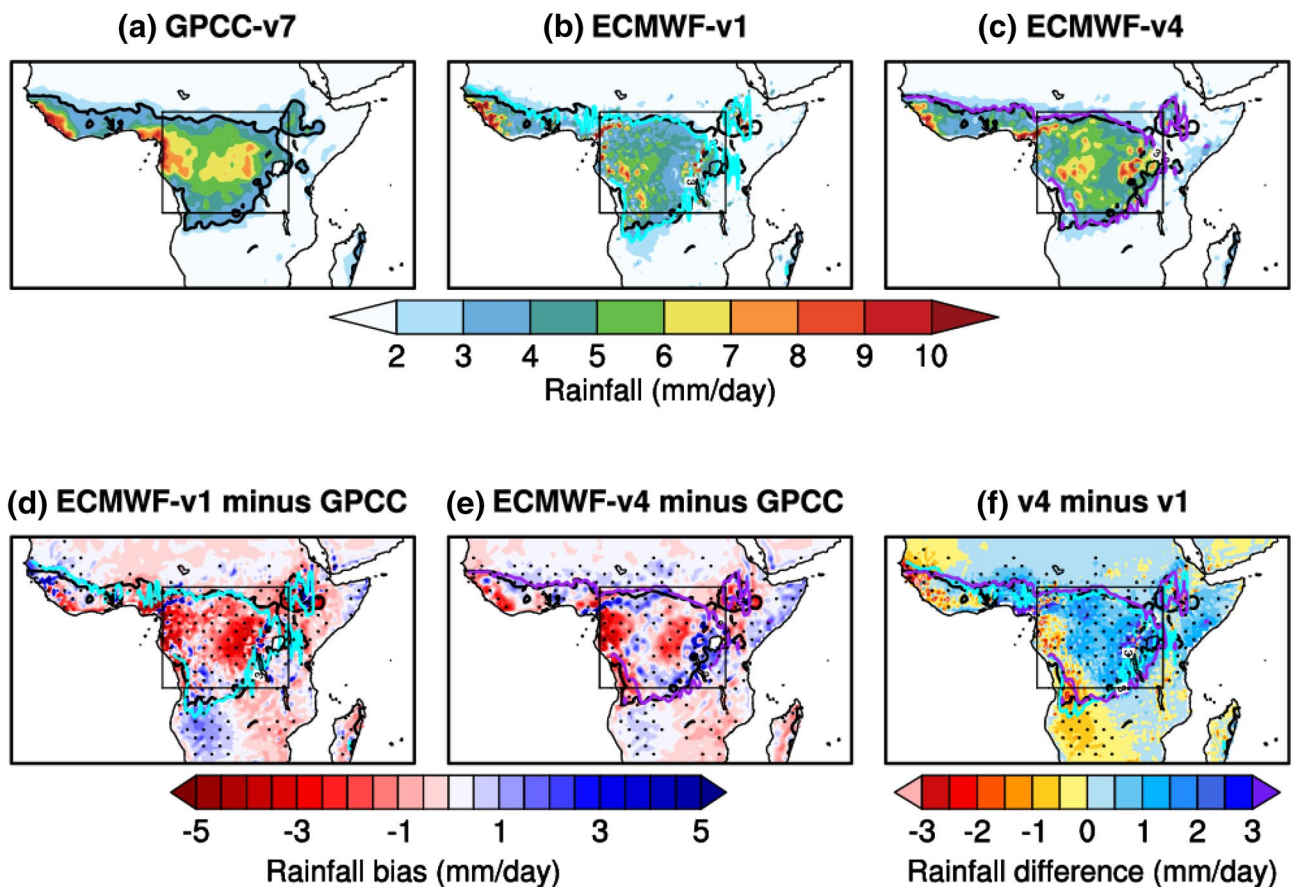


Fig. 1 Mean (1981–2005) SON precipitation ($\text{mm}\cdot\text{day}^{-1}$) from **a** GPCC-v7, from experiments, **b** ECMWF-v1 and **c** ECMWF-v4. Rainfall biases (runs minus GPCC-v7) are shown in **d** ECMWF-v1 minus GPCC and **e** ECMWF-v4 minus GPCC. **f** presents the difference ECMWF-v4 minus ECMWF-v1. The contours indicate the posi-

tion of the rain-band (i.e. precipitation larger than $3 \text{ mm}\cdot\text{day}^{-1}$) from GPCC-v7 (black, shown in every panel for reference), from ECMWF-v1 (cyan) and from ECMWF-v4 (purple). Stippling indicates 95% significance level using a t-test. The black box denotes the CB region

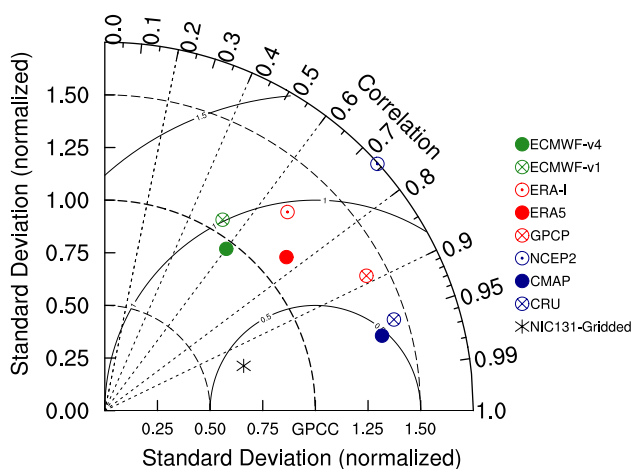


Fig. 2 Taylor diagram of the spatial distribution of mean SON precipitation as simulated by the two model versions compared to GPCC-v7, used as reference. Other observation and reanalysis data (NIC131, CMAP, CRU, NCEP2, GPCP, ERA5 and ERA-I) are also shown to account for observational uncertainties

Washington (2016) reported a similar result using CMIP5 GCMs, although they used a single pressure level (850 hPa). This result shows that the model formulation greatly influences MC, and, in turn, precipitation.

4.2 Analysis of the vertical profile of moisture convergence

Figure 4a–d shows differences (ECMWF-v4 minus ECMWF-v1) of vertical profiles of MC across each CB border, which helps to distinguish sources of moisture surplus or deficit. Also shown are differences in the balance of the net zonal (west minus east, Fig. 4e), the net meridional (South minus north, Fig. 4f), and the total (zonal plus meridional, Fig. 4g) contributions to MC in the region. Tamoffo et al. (2019b) found that dry biases in RCA4-v1 are associated with stronger simulated moisture divergence (MD) in the mid-troposphere, resulting from a western outflow stronger than the eastern inflow and related to an erroneous

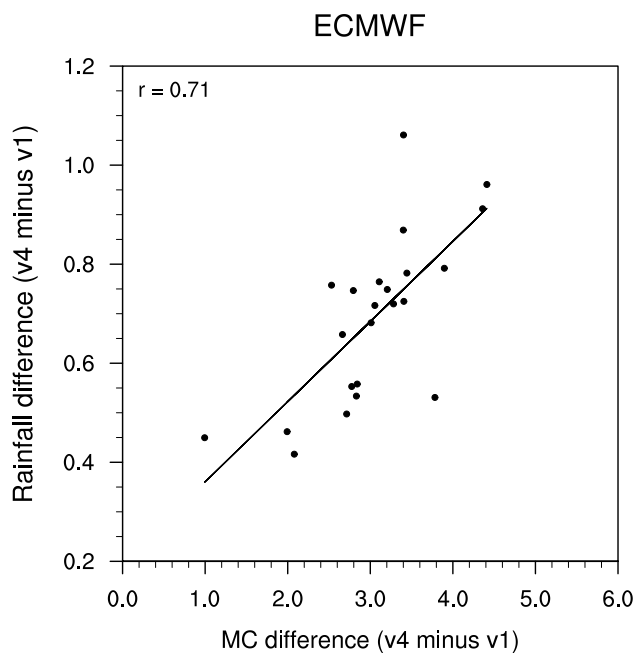


Fig. 3 Relationship between mean SON precipitation (mm.day^{-1}) difference (ECMWF-v4 minus ECMWF-v1) and mean SON MC ($10^{-5}\text{kgm}^{-2}\text{s}^{-1}$) difference (ECMWF-v4 minus ECMWF-v1). Each dot represents the yearly value of the spatially averaged (over CB) difference

simulation of the northern component of AEJ. In general, ECMWF-v4 shows a stronger zonal MD (Fig. 4e) in the mid-troposphere (700–600 hPa) compared to ECMWF-v1, as the western outflows (Fig. 4a) remain stronger than the eastern inflows (Fig. 4b) at this layer. At the same time and in the same layer, the two model versions show close values of the meridional MC (with ECMWF-v4 slightly more convergent than ECMWF-v1; Fig. 4f). This is due to the fact that ECMWF-v4 features larger MC across the south (Fig. 4c) and north (Fig. 4d) boundaries than ECMWF-v1. In the lower layers (975–850 hPa), ECMWF-v4 produces higher zonal MC relative to ECMWF-v1 (Fig. 4e), as a result of stronger low-level MC across the west boundary (Fig. 4a), but rather closer values across other ones (ECMWF-v4 is slightly more divergent in the south than ECMWF-v1). Thus, the total vertical profile of moisture flux difference features higher mid-tropospheric MD and higher low-level MC, strongly modulated by the zonal component (Fig. 4g). However, as demonstrated above, RCA4-v4 is wetter than RCA4-v1 and is closer to the observed climatology. This prompts a separate investigation of the processes in each layer (low-level westerlies in the lower layers (975–850 hPa), and African easterly jets in the mid-layers (700–600 hPa).

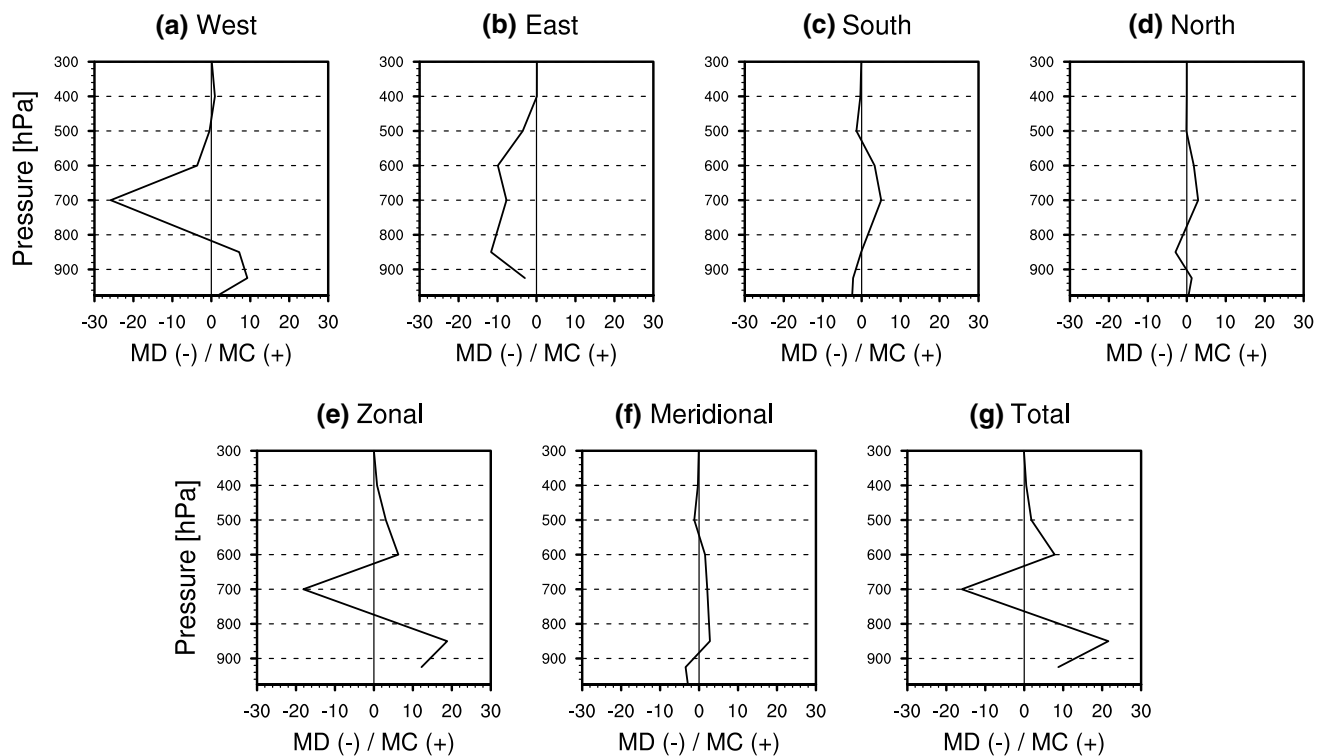


Fig. 4 Vertical profile of SON MC difference (v4 minus v1, in $\text{Kg.m}^{-1}.\text{s}^{-1}$) across **a** West (10°E), **b** East (35°E), **c** South (10°S) and **d** North (10°N) borders. The balance in each direction is also shown

as **e** the net zonal difference (West minus East) and **f** the net meridional difference (South minus North). The total difference is summarized in **(g)**

4.3 Low-level circulations

To confirm that stronger LLWs are the reasons for the reduction in the precipitation dry biases in RCA4-v4, the SON mean climatology of the bottom layer (975–850 hPa) zonal integrated moisture flux as well as the bottom layer total moisture transport have been investigated. Some works (e.g. Dezfuli et al. 2015; Longandjo and Rouault 2020) demonstrated the important role of westerlies in supplying moisture from the western to the eastern South equatorial Africa and for promoting convergence in the lower layer when they reach mountains; due to the topographic effect, they contribute to the ascent branch of the zonal asymmetric pattern (ZAP) and thus intensify the convection in the region.

The two RCM runs are consistent on the spatial patterns of moisture transport (Fig. 5a, b), but indeed ECMWF-v4 features more intense LLWs entering the CB from the north west flank (which have recirculated from the Atlantic) than ECMWF-v1 (Fig. 5c). In this season, LLW advection into the region is prominent, as the northern influx is weak while the southern circulation is dominated by advection from the Indian Ocean, which recirculates towards southern Africa. This result agrees with previous findings by Dyer et al. (2017) who found stronger LLWs in wet composites in SON, using the National Center for Atmospheric Research's Community Earth System Model (NCAR/CESM). Intensification of LLWs intensifies the convection, by increasing the moisture availability into the region, thus increasing rainfall. This process is further explained below. This result confirms that a model formulation can greatly impact the representation of structures of lower level circulation. This might also suggest differences in the representation of sea or land–atmosphere feedback processes driving the regional circulation. For instance, the reduction of the turbulent mixing could strongly impact the surface heat (Xie and Fung 2014), which can highly modify surface-atmosphere interactions.

Pokam et al. (2014) showed that the main source of heating over west equatorial Africa (WEA) in SON displaced southward, and the zonal (meridional) component of the divergent flow strengthens (weakens) over the Ocean, thereby inducing an enhancement of the LLWs. Likewise, they demonstrated that moisture source peaking at 925 hPa responds to a peak of turbulent transports of moisture from the surface, and which contributes to the prevalence of low-level cloud cover. However as seen in Fig. 6, the reduction of the turbulent mixing in RCA4-v4 has rather induced an increase of low level cloud cover over Equatorial Africa. The increased low level cloud cover as a response to the modification of the turbulent mixing was also demonstrated by Sherwood et al. (2014) and Vial et al. (2016). They showed that a reduced low level cloud fraction (here in RCA4-v1) is associated with an increased lower-tropospheric convective mixing, with the magnitude of the reduction depending on the coupling between the surface latent heat flux and the convective mixing on the one hand, and the boundary-layer cloud radiative effects on the other. Indeed, the convective mixing elicits a dryness of the lower-troposphere in response to an enhanced latent heat flux, which attenuates the reduction of the low-cloud fraction; likewise, the low level cloud fraction reduces further in stable tropospheric conditions once the low-cloud radiative cooling diminishes, associated with a reduction of the latent heat flux, these two different processes being function of the closure of the convective parameterization. Thus, a stronger turbulent mixing in lower layers promotes a stronger dryness of the lower-troposphere and more reduces the low level cloud fraction. Our results show that in RCA4-v4 the low level cloud cover has indeed increased more over WEA coast than over the CB (Fig. 6). The surface solar radiation has reduced more over the WEA coast than over the CB as a result (Fig. 7). In response, surface temperatures would be lower over the WEA coast relative to the CB. Higher temperatures over the CB would

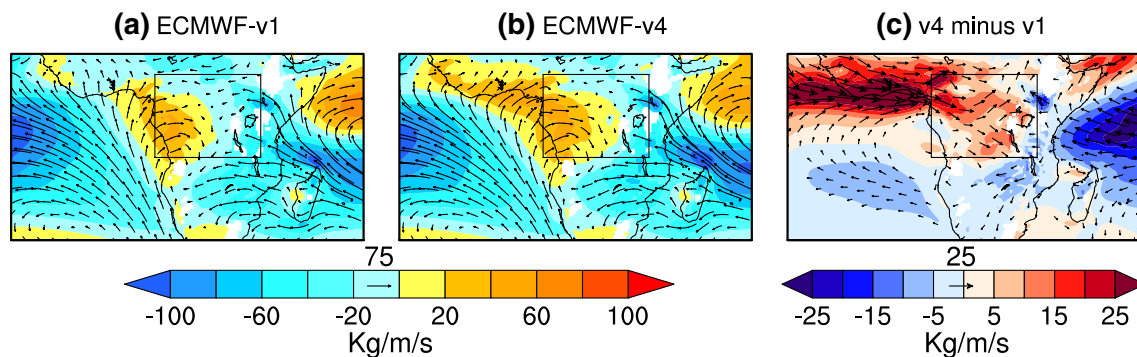


Fig. 5 SON mean climatology of the lower layers (975–850 hPa) zonal integrated moisture flux ($\text{Kg m}^{-1} \text{s}^{-1}$; shaded) superimposed with vertically integrated (975–850 hPa) moisture transport ($\text{Kg m}^{-1} \text{s}^{-1}$; vectors), from **a** ECMWF-v1 and **b** ECMWF-v4. **c** Mean dif-

ference (v4 minus v1). Here, only moisture transport vectors greater than 5 kg/m/s are represented. Negative values indicated divergence and positive values convergence. Boxes denote the CB

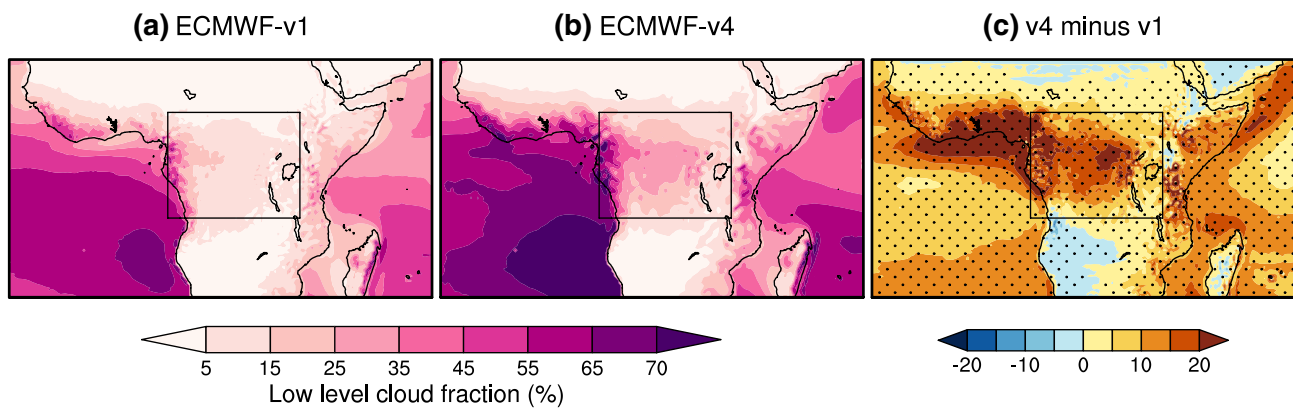


Fig. 6 Mean SON climatology of Low level cloud fraction (in %), from **a** ECMWF-v1 and **b** ECMWF-v4. **c** Mean difference (v4 minus v1, in %). Stippling indicates grid points where the difference is statistically significant

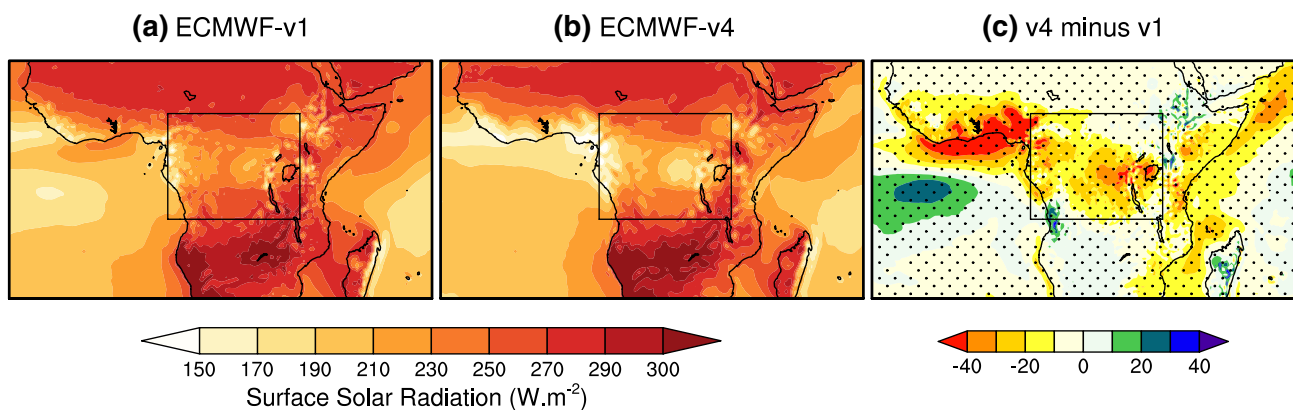


Fig. 7 Mean SON climatology of Surface Solar Radiation (in W.m^{-2}), from **a** ECMWF-v1 and **b** ECMWF-v4. **c** Mean difference (v4 minus v1, in W.m^{-2}). Stippling indicates grid points where the difference is statistically significant

favor air upward motions, thus inducing lower pressure over the Congo relative to WEA. Therefore, this change impacts upon the pressure gradient between the WEA and the CB, explaining why LLWs are enhanced (Longandjo and Rouault 2020). Faster winds cause more moisture to be picked up by ocean per unit time, and carried into the CB (Fig. 8). This moisture surplus enhances ascent motions in the eastern CB in turbulent conditions, despite the reduction of the turbulent mixing. Notably RCA4-v4 outputs for low level cloud and surface solar radiation have also been improved (compared to ERA5 and MERRA2 reanalyses, not shown), thus confirming the plausibility of these mechanisms.

The fact that a reduced turbulent mixing causes stronger increase in low level cloud cover over WEA as opposed to over the CB may suggest different processes driving the low level cloud cover formation in these two areas. Studies on low level cloud formation have advanced over WEA (e.g. Babić et al. 2019; Dione et al. 2019; Kniffka et al. 2019; Lohou et al. 2020) compared to Central Africa (Dommo

et al. 2018; Philippon et al. 2019). Despite this progress, investigation of the weight of the turbulent mixing within the processes of low level cloud formation remain undiscussed.

4.4 The mid-tropospheric circulations

The mid-troposphere of the Central Africa region is dominated by easterly flows, namely the AEJs through their southern (AEJ-S) and northern (AEJ-N) components (Dezfuli and Nicholson 2011). Broadly, AEJs are located between 600 and 700 hPa and owe their existence to the surface temperature gradient produced by the contrast between the hot Sahara and the moist southern sea border regions (AEJ-N), and, similarly, from the surface temperature contrast between semi-arid regions of Southern Africa and sub-humid vegetated lands of the Equatorial Central Africa (ECA) (AEJ-S; Kuete et al. 2019). AEJ-N migrates within the latitudes 5° – 15° N and is present throughout the year. Its core is located at 600 hPa from January to July, and at

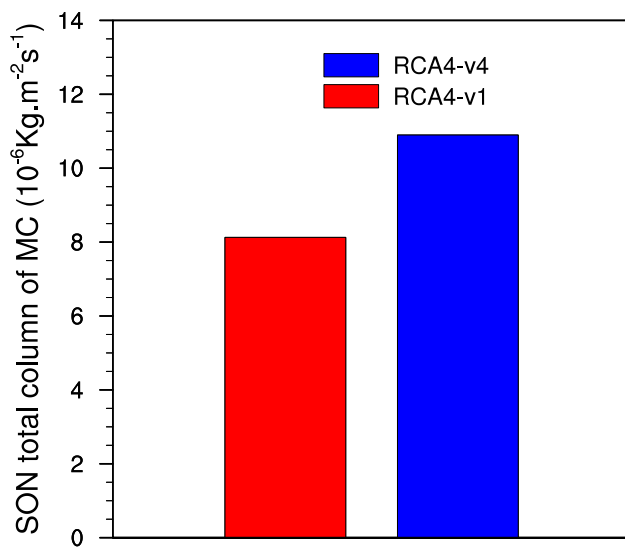


Fig. 8 Mean SON of total column atmospheric moisture convergence (in $10^{-6} \text{ Kg/m}^2.\text{s}$), scaled by the area of the region, from RCA4-v4 (blue) and RCA4-v1 (red)

700 hPa in the rest of the year, with wind speed reaching 10 m/s from May to June; AEJ-S meanwhile is visible only from August to November between 5° and 10° S, being better developed near 650 hPa. Its core speed varies between 6 m/s in August to 10 m/s in October (Nicholson and Grist 2003). The peak of SON's MC is generally associated with the presence of the two components of Jet into the CB at this time of year (Nicholson and Grist 2003), and that of MAM to the AEJ-N, stronger than the two jets (Dyer et al. 2017).

First of all, differences between RCA4-v1 and RCA4-v4 in the connection of the CB low level cell and the mid-tropospheric circulation are examined (Fig. 9c). To this, the mean climatology of the 600 hPa zonal moisture flux, as well as that of the total moisture transport in this layer are analyzed. It appears that RCA4-v4 (Fig. 9b) produces

a stronger moisture flux towards the Atlantic Ocean at this level compared to RCA4-v1 (Fig. 9a). As described in Sect. 2, this may be related to a stronger low level moisture transport from the WEA in this new version, which reinforces upward motions at the eastern CB boundary, feeding mesoscale convective systems embedded within the AEJs (Jackson et al. 2009; Longandjo and Rouault 2020).

RCA4-v1 was also found to simulate a dry upper-tropospheric layer, due to a modeled more westward and weaker AEJ-N core, thus promoting stronger mid-tropospheric MD (Tamoffo et al. 2019b). The ability of RCA4-v4 to reproduce these processes has also been evaluated (Fig. 10a, b). Although there is a good agreement between ECMWF-v4 and ECMWF-v1 runs on the latitudinal positions of the two jet cores (Fig. 10a), considerable differences on their zonal spatial extent (Fig. 11) and on their intensity (Fig. 10b) exist. ECMWF-v4 generally produces stronger Jet cores speed than RCA4-v1 (Fig. 10b), related to a modeled stronger meridional surface temperature gradient (Fig. 10a) (Nicholson and Grist 2003): in fact, as seen in Fig. 6, the low level cloud cover has increased more over equatorial Africa than over the Sahara and Southern Africa. RCA4-v4 features reduced surface solar radiation over the equatorial Africa whereas it does not change much over the Sahara and southern Africa (Fig. 7), which would result in a lower surface temperature over equatorial Africa than over the Sahara and southern Africa. An enhanced positive (negative) temperature gradient between the Sahara (southern Africa) and the equatorial Africa is created as a result, thus enhancing the AEJ-N (AEJ-S). Likewise, ECMWF-v4 places Jet cores more eastward than ECMWF-v1 (dashed and solid lines in Fig. 11 respectively), which would strengthen the feeding of MCSs with moisture, thereby increasing convective precipitation amount. Thus, intensification of mid-tropospheric westward moisture fluxes in RCA4-v4 compared to RCA4-v1 can be associated with the increase of jet cores speed.

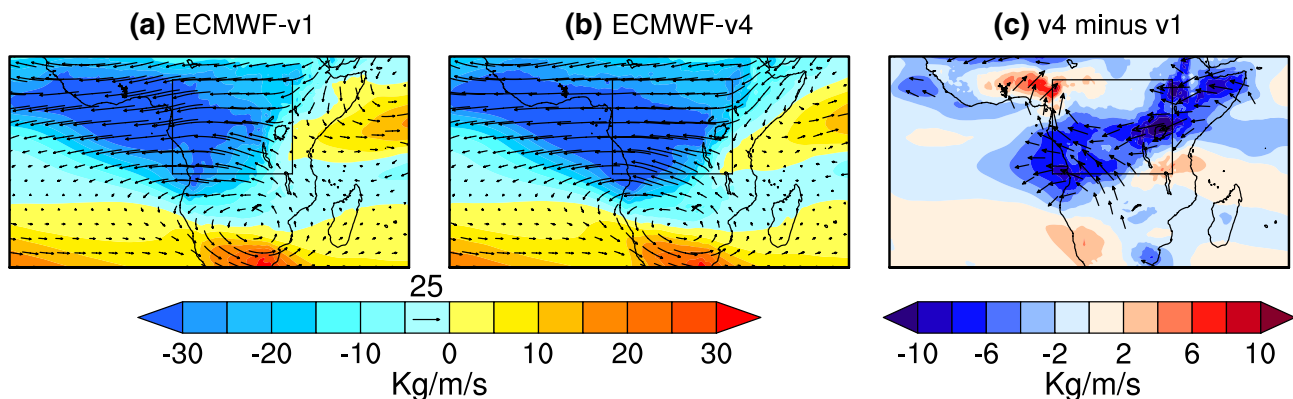


Fig. 9 Same as in Fig. 5, but at 600 hPa pressure level only

Fig. 10 **a** Mean surface temperature gradient difference ($v4$ minus $v1$; in 10^{-5} K/m) at 925 hPa, averaged over longitudes 12° – 24° E. Black ($v1$) and Blue ($v4$) lines denote the mean positions of AEJ-N, red ($v1$) and green ($v4$) show the mean positions of AEJ-S. The ERA5 reanalysis (cyan) is also shown for reference. Stippings are grid points where the difference is statistically significant (95% based on t-test); **b** Mean intensity of jet cores (monthly averages in m/s)

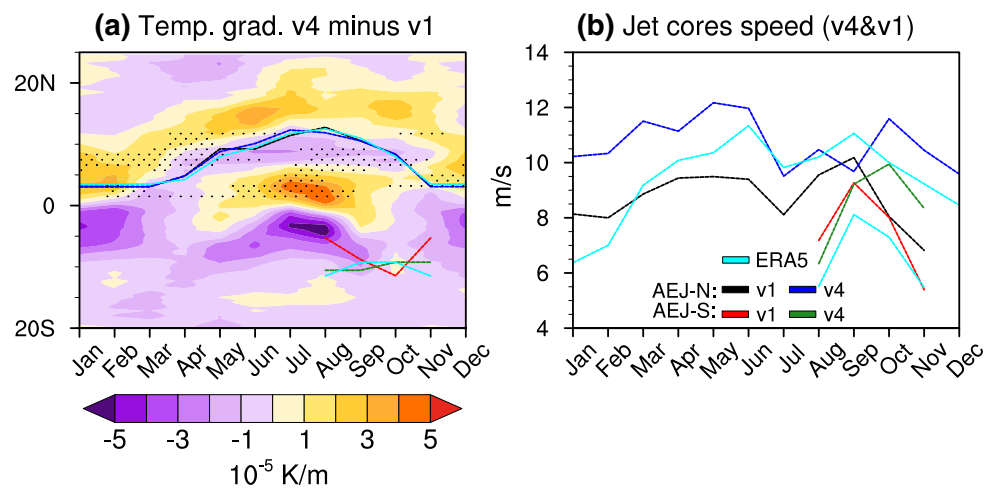
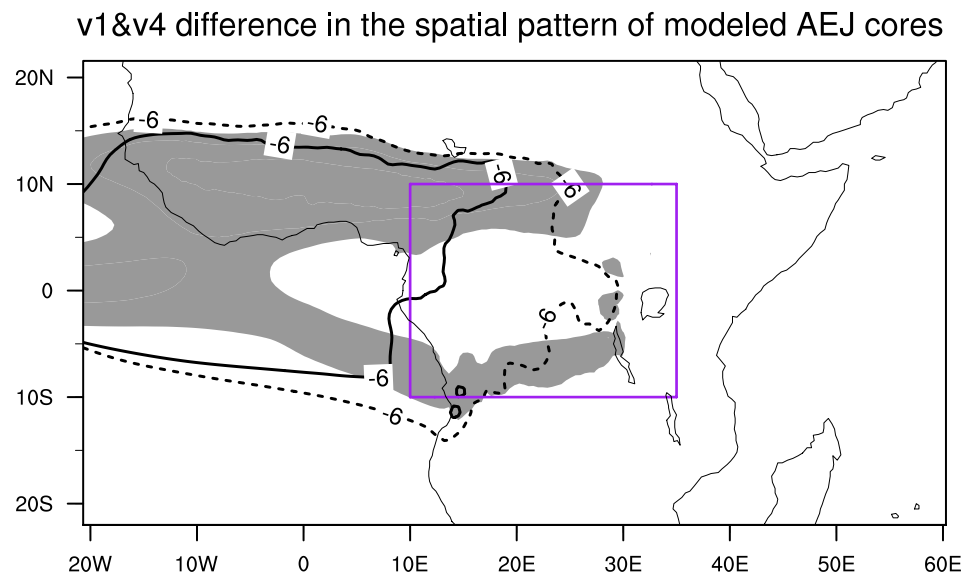


Fig. 11 Spatial pattern of AEJ cores (700–600 hPa) differences in SON as modeled by ECMWF-v1 (solid line) and ECMWF-v4 (dashed line). The shaded gray band shows AEJs cores from ERA5. The purple box denotes the CB



4.5 Surface-atmosphere feedback

In the previous section we argued that the reduction of the turbulent mixing would impact the surface heating, thereby modifying the land–atmosphere coupling. The (SM, evaporation) coupling is an useful metric for understanding surface-atmosphere interactions, particularly in tropical regions (like the CB) where precipitation are strongly influenced by soil moisture availability; SM and evaporation positively correlate, as SM anomalies reinforce local precipitation anomalies through positive feedback (Dirmeyer et al. 2009; Pokam et al. 2012). As moisture recycling is important in the CB (Dyer et al. 2017; Sorí et al. 2017), we examine whether the increased rainfall in RCA4-v4 causes more evaporation, which would then feedback to rainfall and further reduce the precipitation dry biases.

From this perspective, we have analysed modeled surface-atmosphere feedback using simulated evaporation (Fig. 12)

and SM (Fig. 13). The two runs feature a very similar spatial pattern of evaporation (Fig. 12a,b) and SM (Fig. 13a,b) with strong spatial correlation values of $r=0.98$ and $r=0.99$ respectively. However, ECMWF-v4 generally shows higher evaporation than ECMWF-v1 over the continent and over most parts of Oceans, with minimum values located in the north part of CB (Fig. 12c). The two model versions feature similar amounts of evaporation in the north, whereas the evaporation is a lot stronger in RCA4-v4 than RCA4-v1 in the south. Recently, Crowhurst et al. (2020) showed that evaporation is lower in SON than MAM in the CB, while Crowhurst et al. (2021) showed that CB evaporation is lower in SON owing to limited radiation rather than SM. However, we find here that higher rainfall causes higher SM in RCA4-v4 than RCA4-v1 across the Basin, which leads to higher evaporation in certain locations. In the north, soils are close to saturation (Fig. 13), and surface solar radiation does not change between RCA4-v1 and RCA4-v4 (Fig. 7). Therefore,

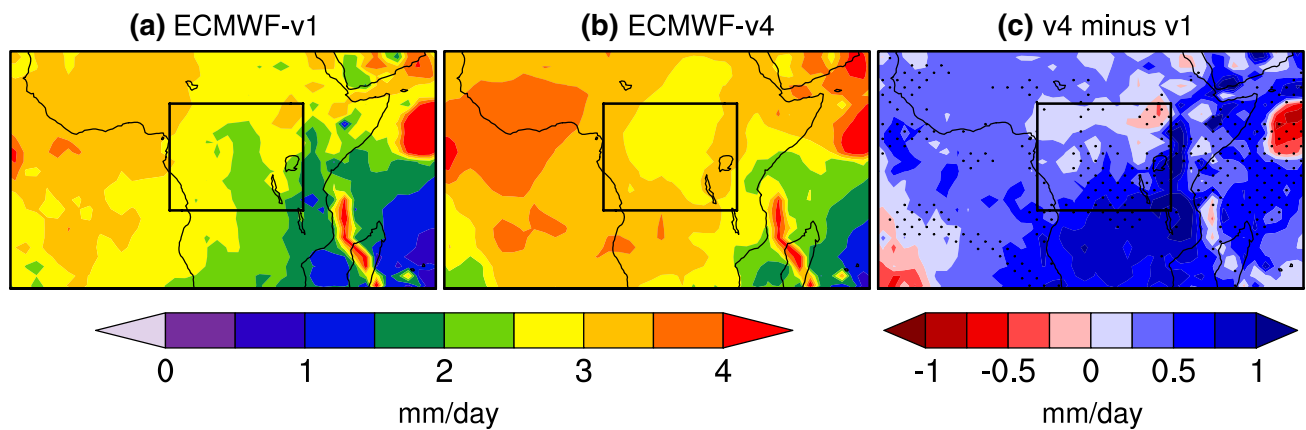


Fig. 12 Mean SON climatology of total evaporation (evaporation, in mm.day^{-1}), from **a** ECMWF-v1 and **b** ECMWF-v4. **c** Mean difference (v4 minus v1, in mm.day^{-1}). Stippling indicates grid points where the difference is statistically significant

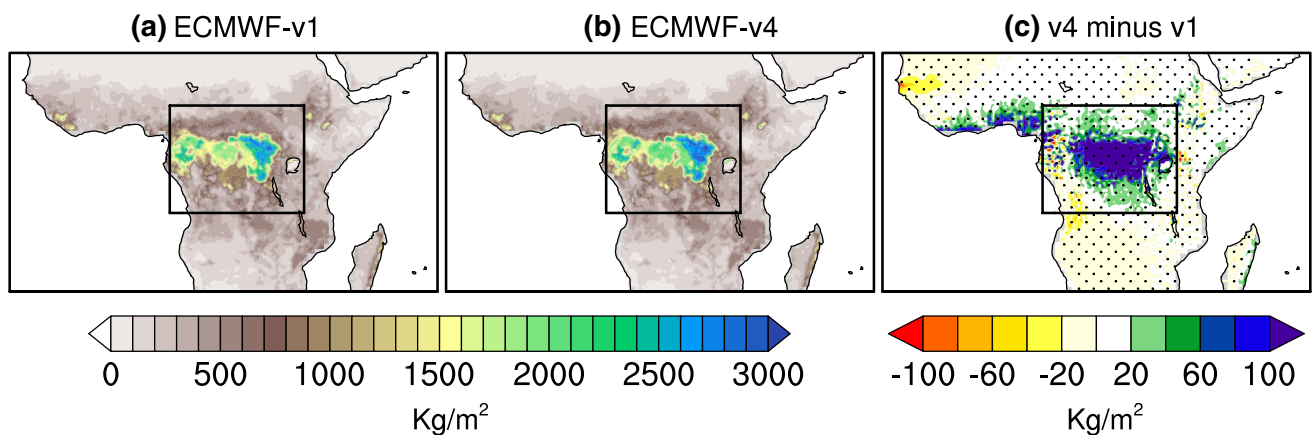


Fig. 13 Same as Fig. 12, but for the total soil moisture content (SM, in Kg/m^2)

increasing rainfall in response to the strengthening of the CB Cell would not influence evaporation in the northern part as soils are already saturated. In the south, soils are rather far from saturation (Fig. 13), so higher SM here is responsible for higher transpiration/leaf area, and higher evaporation. However, Fig. 5 shows a stronger moisture transport in southern CB out of the basin to the south. This indicates that the higher evaporated moisture in the southern Congo in RCA4-v4 is exported out of the basin towards southern Africa in the model rather than recirculating through the cell, and does not feedback to improve rainfall biases over the CB in RCA4-v4.

5 Summary and discussion

By means of a process-based evaluation, this study examines whether the modified version of the Rossby Centre regional atmospheric model RCA4-v4 (with reduced turbulent

mixing) produces improved rainfall over the CB compared to the CORDEX version RCA4-v1, in order to determine the processes responsible for the difference in rainfall between the two model versions. Analyses are focused on the SON rainiest season, which is the time when the most relevant processes driving the region's climate system are active. Results show that strong dry biases in RCA4-v1 are attenuated in RCA4-v4 over most parts of the region. RCA4-v4 shows better performances in simulating precipitation climatology (spatial distribution and seasonality). This improvement is found to be associated with changes in a chain of processes whose plausible mechanisms are as follows:

1. The excessive turbulent mixing in RCA4-v1 displaces too much moisture from the lower troposphere towards the free troposphere. Consequently, the shallow convective mixing (mixing in the lower layers troposphere) deepens boundary-layer clouds and dries lower layers, thus reducing the low level cloud fraction (Sherwood et al.

2014). This process would be damped in RCA4-v4 with the reduction of the turbulent mixing, explaining the densification of the low level cloud cover across equatorial Africa.

2. The low level cloud cover increases more over WEA coast than over the CB and the surface solar radiation reduces more over the WEA coast than over the CB as a result. In response, the surface temperatures are lower over the WEA coast relative to the CB. Higher temperatures over the CB would favor air upward motions, thus inducing lower pressure over the Congo relative to WEA.
3. The pressure gradient between the WEA coast and the CB strengthens, which strengthens LLWs across the north west flank of the CB, and enhances the strength of the CB low level cell.
4. The Congo low level cell being strengthened, feeds mesoscale convective systems with moisture through AEJs, thereby contributing to convective rainfall.
5. RCA4-v4 represents stronger and more eastward AEJs, in response to a stronger surface temperature gradient.
6. The evaporation in the southern CB increases, as a result of increasing SM, which increases leaf area/transpiration, but this increased evaporated moisture is exported out of the basin to the south and does not further adjust the rainfall biases in RCA4-v4.

Producing reliable climate simulations for Africa is a critical need for a range of users including decision-makers; therefore, assessing the plausibility of mechanisms producing differences between RCA4-v1 and RCA4-v4 is crucial for the credibility of projections. To this regard, we found that the difference in rainfall between the two model versions is strongly correlated with the difference in MC, indicating that a good simulation of moisture fluxes is of great importance for a better representation of the CB precipitation climatology. This result was also highlighted in numerous previous studies in this region (e.g. Pokam et al. 2012; Washington et al. 2013; Creese and Washington, 2016; Tamoffo et al. 2020) and over the Amazon, another tropical region and hotspots of convective precipitation (Yin et al. 2013). Increased low level cloud cover in RCA4-v4 is associated with decreased low level turbulent mixing as suggested by e.g. Sherwood et al. (2014). When investigating the reasons for the wetter character of RCA4-v4 relative to RCA4-v1, it is found that this newer version with a reduced turbulent mixing produces stronger and more eastward extended jet cores. This is consistent with previous findings by Nicholson (2009) who showed that drier years feature more westward and weaker northern components of African easterly jet (AEJ-N), contrasting with what is observed during wetter years. RCA4-v4 is likely to have improved the horizontal

(vertical) wind shear as demonstrated by the amelioration of seasonal positions (Fig. 10) and core speed (Fig. 9b) of AEJ-N. This would be consistent with the fact that their migrations are related to the displacements of AEJ-N (Nicholson and Grist, 2003). The pattern of precipitation climatology is also related to differences in the lower and mid-tropospheric moisture transport (higher LLWs which compensate for excessive mid-tropospheric MD). This result was also reported by Hua et al. (2019) using a set of reanalysis data over the Central Equatorial Africa. RCA4-v4 simulates stronger LLWs and mid-level westward moisture fluxes, consisting with the structure of the Congo basin cell, as demonstrated in Longandjo and Rouault (2020). Moreover, comparing simulated LLWs against those from ERA5 reanalysis (not shown), we found that RCA4-v4 better represents LLWs compared to RCA4-v1. Likewise, RCA4-v4 improves the representation of low level cloud cover and surface solar radiation.

Analyses in this study show that reducing turbulent mixing in RCA4 results in a better understanding and simulation of the processes driving the CB rainfall climatology. Other studies showed that, for instance, over ECA, an area of predominance of low-level cloud (non-precipitating), the wind shear reinforces mechanically the vertical mixing of the air mass, and highly influences the water budget (Schuster et al. 2013). These low stratiform clouds might result from turbulent mixing processes.

Our results may be very informative from a dynamical perspective, because there is a large amount of lightly precipitating, low-level cloud over the Congo Basin rainforests (Dommo et al. 2018), and convective clouds are not believed to produce much of the rainfall here (see explanation in Jackson et al. 2009). A study by Pokam et al. (2014) showed that low-level clouds are generated as a result of turbulent mixing processes. The present work shows that a stronger convective mixing would disadvantage low level stratiform clouds's formation (consistently with previous works by Vial et al. 2016 and Sherwood et al. 2014) while increasing moisture availability into the region via the CB Cell, so as to over feed the convection, thereby raising the rainfall amount. The fact that the version with reduced turbulent mixing (RCA4-v4) shows an improved rainfall climatology by increasing the rainfall amount suggests the importance of this process for the generation of rainfall over the CB. This finding could also have consequences for improving climate models, as it would suggest that many models may misrepresent the amount of turbulent mixing. However, the robustness of these results must be further assessed: this can be achieved either by studying the effect of reduced turbulent mixing in different RCMs, or by testing the performances of RCA4-v4 over other tropical convective regions. This will be the focus of future work.

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