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Congo Basin rainfall climatology: can we believe the climate models?

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The Congo Basin is one of three key convective regions on the planet which, during the transition seasons, dominates global tropical rainfall. There is little agreement as to the distribution and quantity of rainfall across the basin with datasets differing by an order of magnitude in some seasons. The location of maximum rainfall is in the far eastern sector of the basin in some datasets but the far western edge of the basin in others during March to May. There is no consistent pattern to this rainfall distribution in satellite or model datasets. Resolving these differences is difficult without ground-based data. Moisture flux nevertheless emerges as a useful variable with which to study these differences. Climate models with weak (strong) or even divergent moisture flux over the basin are dry (wet). The paper suggests an approach, via a targeted field campaign, for generating useful climate information with which to confront rainfall products and climate models.

1. Introduction

The Congo Basin is one of the three core regions of convection in the global tropics, the other two being the Maritime continent of the tropical West Pacific and Eastern Indian Oceans and the Amazon basin [1]. Together, these regions drive large-scale tropical circulation. Congo Basin latent heating from convection exceeds 120 W m^{-2} [2], second only to the Maritime continent. The basin is also the region of highest lightning strike frequency on the planet. Congo River discharge to the ocean exceeds 60 000 m^{3} s^{-1} seasonally with a mean annual flow of 40 000 m^{3} s^{-1}, contributing roughly 3.5 mm yr^{-1} to global sea level [3]. In the transition seasons, the Congo Basin dominates the global tropical rainfall distribution. Rainfall amounts and dry season climate characteristics over the Congo Basin are also sufficient to support one of the world's largest tropical humid forests [4]. The Congo Basin's role in the planetary circulation and the Earth system is undisputed.

The Maritime continent, as the most spatially extensive region of tropical convection and the core of the Walker circulation, has unsurprisingly been widely studied [5,6]. Similarly, the Amazon has long been the focus of attention in both theoretical and observational studies, with the latter being underpinned by major field programmes such as the Large-Scale Biosphere Atmosphere Experiment in Amazonia (LBA) [7] and more recent programmes such as the South American Biomass Burning Analysis (SAMBBA). Within Africa, knowledge of the climate system is concentrated in three areas. The multi-decadal Sahel drought dominates the African climate science research focus while study of the West African Monsoon culminated in the largest ever land-based climate experiment, AMMA [8]. In southern African, multi-decadal and interannual rainfall characteristics have resulted in a legacy of both observational and modelling efforts, while East Africa, with its unusually high potential predictability on seasonal timescales, particularly in October to December, emerges as the third most studied region [9]. The Congo climate regime, on the other hand, is the most understudied climate regime in Africa [9] and the most under researched large-scale convective region in the global tropics.

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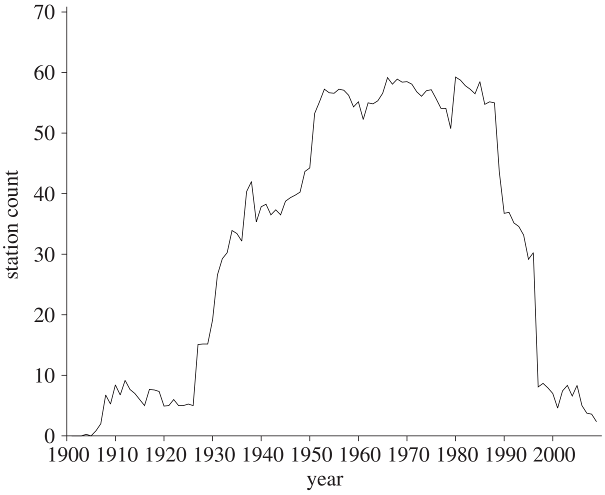

Figure 1. Number of rain gauges per year over the region 5° S–5° N, 12.5–30° E in the CRU 0.5° rainfall dataset. See box in figure 3*a* for domain.

A key reason for the paucity of work on the Congo, notwithstanding its global importance, is the dearth of available climate observations from the region, particularly during the satellite data era. Only three meteorological stations from the Democratic Republic of Congo, for example, reported to the Global Telecommunication System in 2013. There was a dramatic decline in the number of rain gauges from more than 50 gauges between 1950 and 1980, following the work on collating the available record [10], to fewer than 10 over the 20 year period to 2010 (figure 1). As a result, analyses of African rainfall based on gauge data have generally excluded the Congo Basin even though recent satellite-based studies show the region to capture the leading mode of Africa-wide rainfall [11]. To compensate for the lack of observed climate data, studies have tended to adopt proxies such as streamflow to represent rainfall quantities [12] or satellite altimetry to evaluate water resources and climate [13].

Given the importance of the Congo, several recent studies have probed the vulnerability of the region to climate change [14,15] and the nature and controls on climate variability [2,16–18]. These studies necessarily rely heavily on satellite data, numerical model products such as the reanalyses and/or coupled climate models (see the electronic supplementary material). The relative performance of these tools over the Congo region is difficult to assess and compare because individual studies of the climate system tend to depend heavily on one type of data source without comparison across data products. Given that satellite rainfall products alone differ by a factor of 2–3 [19] and up to 2000 mm per annum in absolute terms [3], a basic assessment of the climatology of the Congo as represented by a variety of frequently used key products is much needed. The aims of this paper are therefore to

— assess the rainfall climatology in two key rainfall seasons in rainfall datasets and as simulated in reanalysis and coupled climate models,
— evaluate the role of spatial model resolution in simulated Congo rainfall, and
— compare the basic state of moisture flux in reanalysis data and historical coupled model runs.

Section 2 outlines the data, §3 the rainfall climatologies and §4 the moisture flux regime. The final section is a summary of the results.

Table 1. CMIP5 models used in this study.

model name[a]	modelling group	atmospheric resolution[b]
CanESM2	CCCMA, Canada	2.8° × 2.8° L35
CNRM-CM5	CNRM-CERFACS, France	1.4° × 1.4° L31
CSIRO-Mk3.6.0	CSIRO-QCCCE, Australia	1.9° × 1.9° L18
GISS-E2-H	NASA GISS, USA	2.0° × 2.5° L40
GISS-E2-R	NASA GISS, USA	2.0° × 2.5° L40
HadGEM1-ES	MOHC, UK	1.3° × 1.9° L38
MPI-ESM-LR	MPI-M, Germany	1.9° × 1.9° L47
MRI-CGCM3	MRI, Japan	1.1° × 1.1° L48
NorESM1-M	NCC, Norway	1.9° × 2.5° L26

[a]Naming conventions are taken from PCMDI http://cmip-pcmdi.llnl.gov/cmip5/docs/CMIP5_modeling_groups.pdf.
[b]Horizontal resolution is expressed as approximate degrees latitude by longitude. Vertical resolution (L) is the number of vertical levels.

2. Data

This section outlines the data products used in this analysis. Years used for each dataset are defined in the relevant results section.

The following rainfall data have been used: standard monthly satellite-based products from CMAP (Climate Prediction Centre Merged Analysis of Precipitation) [20] and Global Precipitation Climatology Project (GPCP) [21], both available at 2.5° spatial resolution, monthly 0.5° resolution rain gauge-based datasets from Climatic Research Unit (CRU) [22], monthly TAMSAT satellite derived data at 0.0375° spatial resolution [23], monthly CMORPH (CPC Morphing Technique) satellite derived data at 0.0727° spatial resolution [24] and data from the Tropical Rainfall Monitoring Mission (TRMM version 3B43V7 [25] available at 0.25° spatial resolution (see ftp://meso-a.gsfc.nasa.gov/pub/trmmdocs/3B42_3B43_doc.pdf). CMAP rainfall rates are obtained from five satellite estimates (not including TRMM). Although gauge data are merged in TRMM and GPCP, its impact over the Congo Basin may be expected to be minimal given the paucity of gauge data there.

Reanalyses data (see the electronic supplementary material) include NCEP/NCAR [26], CFSR [27], ECMWF reanalysis products including ERA-40 [28] and ERA-Interim [29]. These are used to evaluate the circulation controls on rainfall and rainfall itself. Monthly data from Coupled Model Intercomparison Project 3 (CMIP3) [30] for 24 climate models forced with historical estimates of variables known to be important to climate (e.g. greenhouse gases, sulfates, ozone and halocarbons) during the twentieth century (20C3M) are used in part to evaluate the numerical models used in climate change assessments to date (see [31] for details). Since CMIP5 (http://cmip-pcmdi.llnl.gov/cmip5/index.html) will supersede CMIP3, this newly released set of climate model runs that will dominate analyses in forthcoming years is also inspected (see table 1 for details). CMIP3 and CMIP5 model data were interpolated to a common grid of 1.9° × 1.9° resolution. Ensemble means of CMIP3 and CMIP5 have been calculated from the common grid with even weighting applied to all models.

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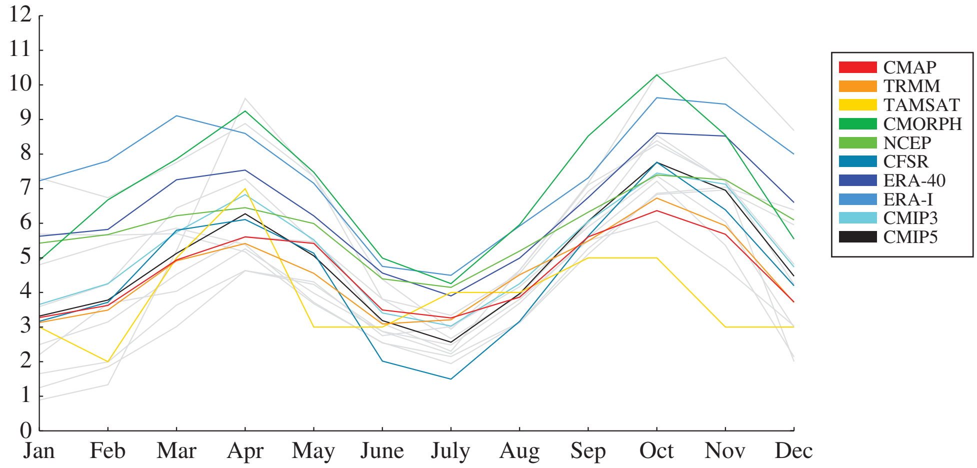

Figure 2. Long-term mean annual cycle of rainfall (mm d^{-1}) for Equatorial Central Africa over the region 5° S–5° N, 12.5–30° E for the following datasets: CMAP, TRMM, TAMSAT, CMORPH, NCEP, CSFR, ERA-40, ERA-Interim, ensemble mean of CMIP3 and CMIP5. Individual CMIP5 models are shown in grey. Years as defined in text.

3. Congo rainfall climatology

In this section, the rainfall climatology of NCEP, CSFR, ERA-40, ERA-Interim, TRMM, CMAP, TAMSAT, CMORPH, CMIP3 ensembles and CMIP5 ensembles are evaluated.

(a) Annual cycle of rainfall

Long-term monthly rainfall means (1961–1990 in the case of NCEP, ERA-40, CMIP3 ensemble and CMIP5 ensemble and 1979–1990 for ERA-Interim, CSFR and CMAP, 1998–2011 for TRMM and TAMSAT and 2002–2011 for CMORPH) have been computed for data interpolated to 1.9° × 1.9° latitude–longitude resolution (figure 2) over the largely forested sector of the Congo Basin, namely 5° S–5° N, 12.5–30° E (see box in figure 3*a*) [17]. All data products correctly feature the well-known bimodal rainfall distribution for the Congo Basin with peak rainfall in the transition seasons of September to November (SON) and March to May (MAM). SON is wetter than MAM in all datasets apart from TAMSAT and TRMM. There is broad agreement in the phase of the peak rainfall months (April and October) with the exception of ERA-Interim where MAM rainfall peaks a month earlier than any dataset. Minimum rainfall in the June to August season (JJA) is reached in July in all but the TAMSAT and TRMM data which show a May and June minimum, respectively. The minimum in the JJA season is lower than the December to February dry season minimum in all datasets with the exception of three model members of the CMIP5 ensemble and TAMSAT. The phase of the annual rainfall cycle is therefore well captured by these rainfall datasets. As reported previously [3], the problem with the Congo rainfall datasets lies in the spread of rainfall magnitudes. This spread is clear in figure 2 and varies across the datasets by a factor greater than 2 in both the rainy and dry seasons. When individual model members of the CMIP5 ensemble are considered, the spread reaches an order of magnitude in the DJF dry season. The reanalyses datasets (ERA-Interim and ERA 40) and CMORPH are the wettest across all months in the rainy season and some of the individual CMIP5 models together with TAMSAT are the driest of the datasets considered here. These disparities are very large when compared with other regions of the planet.

(b) Spatial distribution of rainfall

In MAM, all datasets capture the core convective regions of the Guinea coast, Congo Basin, Ethiopian highlands and the equatorial western Indian Ocean (figure 3). In some, such as CMAP, the rainfall distribution is zonally even, whereas others show a marked distinction between the Congo Basin and the Indian Ocean convective centres (e.g. NCEP and especially ERA-40, ERA-Interim, CMIP3 and CMIP5). In TAMSAT, the Congo Basin rainfall is dominant relative to other areas. The southwest to northeast orientation of the Congo Basin southern rainfall boundary is strongly represented in TRMM, CMORPH, NCEP, ERA-Interim and CMIP3 and CMIP5. Some products show a rainfall maximum in the western Congo (ERA-Interim, TRMM) while others an eastern Congo Basin maximum (e.g. NCEP, CMORPH and CMIP3). Individual CMIP5 models (see the electronic supplementary material, figure S1) show a greater degree of spatial difference than that evident in figure 3. Several models simulate a dry Congo Basin (e.g. MRI, GISS and HadGEM2) with others (CNRM, CSIRO, CanESM2, GISS) featuring a rainfall maxima over the equatorial Atlantic Ocean, most probably associated with the warm ocean eastern equatorial Atlantic bias of almost all CMIP5 coupled models (not shown).

Spatial agreement of rainfall distribution is generally higher in the rainfall datasets in SON (see the electronic supplementary material, figure S2). All datasets show a coherent Congo Basin rainfall regime and a southwest to northeast orientation of the rainfall on the eastern side of the basin. A western basin maximum is evident in TRMM, CMAP, CFSR and NCEP while CMORPH and CMIP3 and CMIP5, the datasets used for climate projections, favour a maximum in the eastern Basin. Taken individually, the CMIP5 models in SON (see the electronic supplementary material, figure S3), with the exception of CNRM and MPI, simulate a maximum over the Congo Basin. The diagonal eastern edge is evident in all models although the rainfall structure is latitudinally extensive in some (NorESM1, CSIRO). Four models place the rainfall maximum in the western Congo Basin and four in the east. A five year climatology of mesoscale convective complexes based on analyses of TRMM data over the Congo Basin identified four spatial maxima which they relate in part to orography and associated circulation systems some of which collocate with the maxima discussed here [16]. Similarly, a

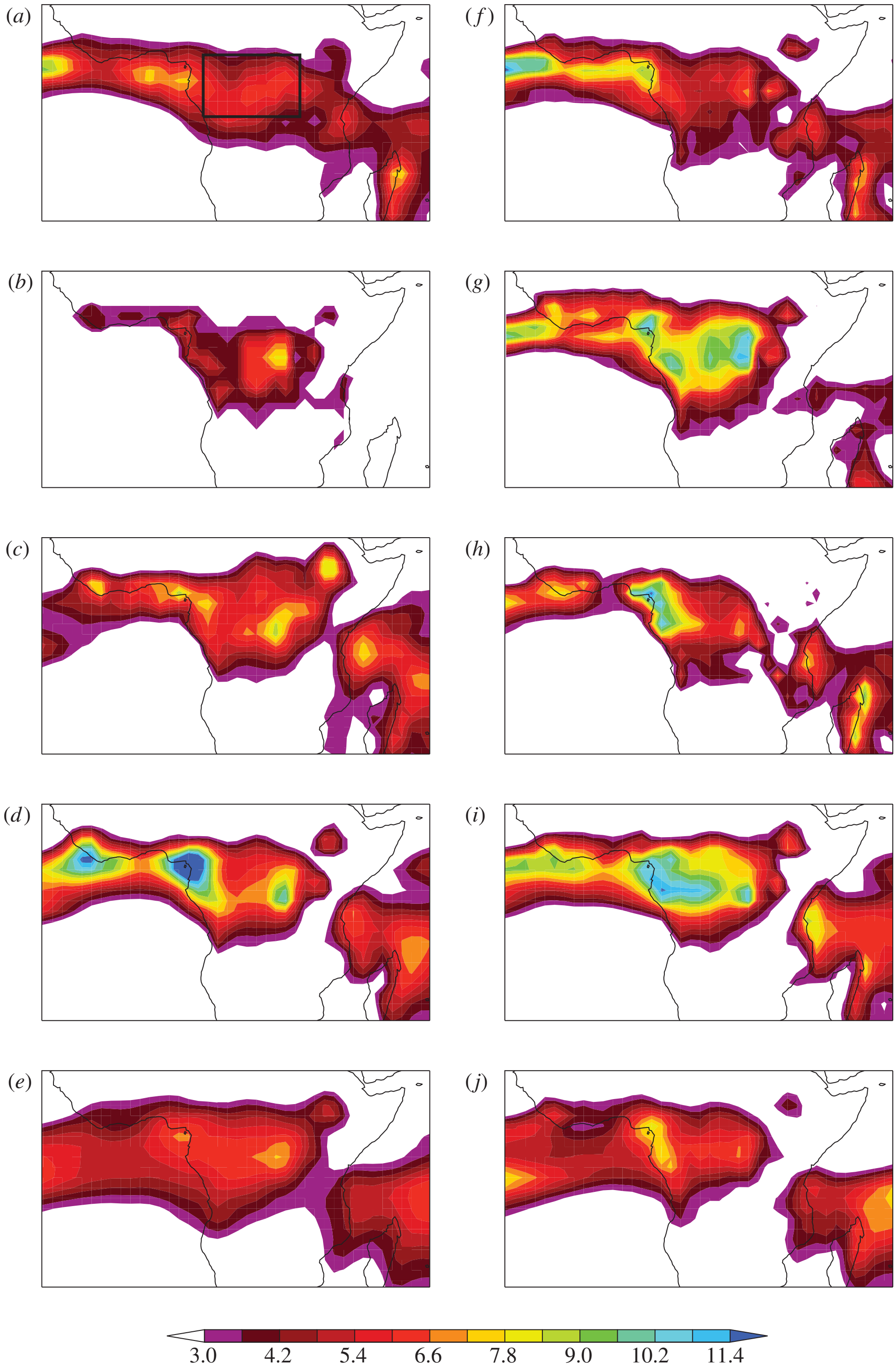

Figure 3. Rainfall climatologies (mm d^{-1}) during MAM for the following datasets: (*a*) CMAP, (*b*) TAMSAT, (*c*) NCEP, (*d*) ERA-40, (*e*) ensemble mean of CMIP3, (*f*) TRMM, (*g*) CMORPH, (*h*) CFSR, (*i*) ERA-Interim, (*j*) ensemble mean of CMIP5. Years as defined in text. Box in (*a*) plot corresponds to area average used to derive data in figures 1 and 2.

study also using TRMM data, draws attention to the extreme spatial heterogeneity of interannual variability which maps on to the complex climatology [18]. Diagnosing the controls on climate is made more uncertain by the extent of differences in the distribution of rainfall in these climatologies.

Differences among the rainfall totals for the datasets over the region 5° S–5° N, 12.5–30° E for MAM and SON (figure 4) are demonstrably greater in SON where the driest dataset (TAMSAT) is some 50% of the wettest (CMORPH). Interestingly, the range of individual models in the CMIP3 ensemble spans the range of the non-numerical model products. The same is true for MAM although the differences among the data products are smaller in that season.

(c) Regional models

Regional climate models (RCMs) are of growing importance as a source of detailed climate change projections partly because high spatial resolution (typically 50 km) allows the models to capture regional and local scale climate forcings

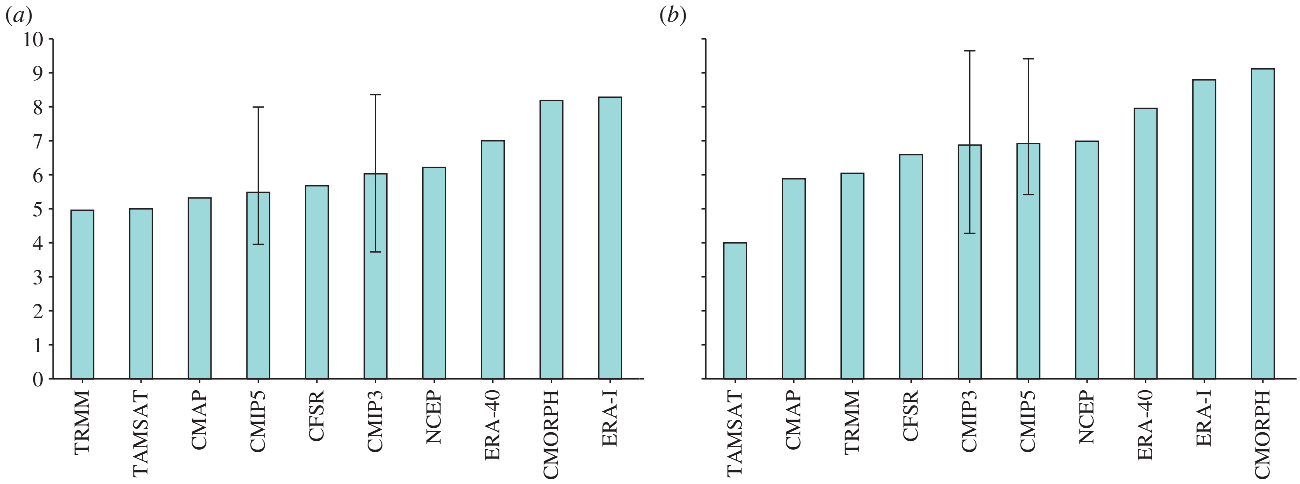

Figure 4. Rainfall climatologies for (*a*) MAM and (*b*) SON for the 10 datasets used in figure 2. (Online version in colour.)

[32], and associated potential improvements in model physical and dynamical formulations (e.g. representation of circulation controls on rainfall and land-surface feedbacks) compared with global climate models run at much coarser resolution (typically 250 km). The Coordinated Downscaling Experiment (CORDEX) [32], has Africa as its priority domain. The ensemble mean CORDEX simulations for the historical record (1989–2008) from 10 regional models run over Africa demonstrate that the regional models simulate the annual cycle reasonably well [33] although as with the CMIP simulations and the satellite derived and reanalysis datasets, the details of the annual cycle differ from model to model. Similarly, without the benefit of a gauge derived observed rainfall dataset at a resolution appropriate to the regional models, it would be difficult to confront the regional model climatologies definitively. Instead, the approach taken here is a comparative one. The Met Office Unified Model global atmospheric model GA3 is run continuously from 1982 to 2008 at 135 km horizontal resolution and the results are compared against that of the derived GA3 RCM, which is nested within quasi-observed atmospheric conditions from ERA-Interim reanalysis and run separately with two horizontal resolutions (135 and 50 km). The GA3 GCM RCM simulations are forced with common observed daily oceanic boundary conditions and the results are assessed over the period 1996–2006. The advantage of this approach is the consistency in model physics across the global and regional models—which are unique to the Unified Model of the Met Office—an approach not possible in CORDEX framework.

The rainfall climatology of the model in all three configurations is wetter over the northern Congo than the comparative observed datasets in MAM (see the electronic supplementary material, figure S4). The model Congo rainfall region is larger and more continuous than any of the observed datasets. In addition, the models are wetter in the eastern part of the basin west of the Great Lakes and in the far west of the basin. The general distribution of rainfall in the models is similar although at higher resolution (50 km) the eastern rainfall maximum is higher than either the coarser resolution regional model or the global model. At the same resolution (135 km), the global model is drier than the regional model. The difference between the global and regional model pertains to the forcing fields of the regional model (ERA-Interim). In SON (see the electronic supplementary material, figure S5), the modelled rainfall over the Congo is again wetter than the observed datasets although the models produce a wetter eastern Congo and a drier western Congo compared with the observed. The eastern maximum in the model is least distinct in the global model and the finer resolution regional model but peaks in the coarser resolution regional model. It is important to note that these features fall into a particularly data sparse region with respect to gauge data. Even when using a physically consistent set of modelling tools, it is difficult to be precise about which resolution of regional model is better at simulating Congo rainfall although the differences resulting from spatial resolution are even more pronounced when higher order statistical moments (variance, extremes, etc.) are analysed.

4. Moisture flux climatology

Differences between rainfall climatologies revealed in §3 derive in part from the algorithms used to detect rainfall in the case of satellites and the parametrization schemes used in the case of reanalysis and coupled model simulations. Where observed gauge data are not available to constrain, confront or develop these tools, there is a tendency for the median representation of the rainfall climatology to be taken as the best estimate [33]. There are seldom strong physical grounds for this decision. One way of evaluating the products without comparing rainfall itself, is to examine the underlying mechanisms closely associated with rainfall. Provision of water vapour through the moisture flux is one, albeit important, step in the process of rainfall generation. An advantage of evaluating moisture flux is that winds exert a strong control on the quantity and winds are generally better simulated in models than rainfall. If models are seen to diverge substantially in their moisture flux climatology, then reasons beyond different convective parametrization schemes could underlie the reasons for the divergent rainfall climatologies. For these reasons, moisture flux over the Congo Basin is evaluated in this section.

We start with the annual cycle of column stratified moisture flux convergence over the basin [17] by representing this field along the meridional and zonal boundaries of the basin in three numerical datasets (see the electronic supplementary material, figure S6). Moisture convergence in MAM derives

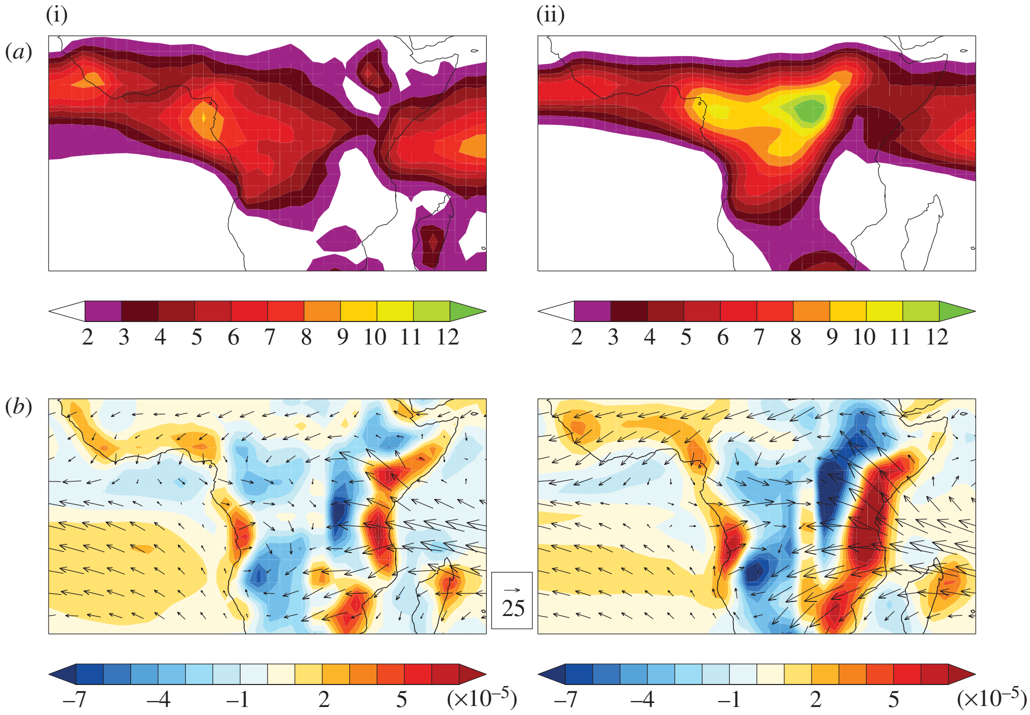

Figure 5. (*a*) Rainfall (mm d^{-1}) and (*b*) moisture flux at 850 hPa climatologies for (i) the driest (CNRM-CM5) and (ii) wettest (NorESM1-M) models in SON. Units are mm d^{-1} in (*a*) and g kg^{-1} m s^{-1} in (*b*) with contours of divergence (g kg^{-1} s^{-1}).

from upper level (850–300 hPa) meridional convergence resulting from the northern branch of the African Easterly Jet. The second maximum in SON is due to zonal moisture convergence from the Atlantic Ocean in the near-surface layer up to and including 850 hPa. Upper and lower layer net fluxes have opposite signs through most months pointing to Hadley and Walker-type circulations in the region. Reassuringly the three model products considered here (NCEP, ERA-Interim and CMIP5 ensemble) agree well in their basic structure and values of moisture flux through the Congo Basin boundaries although there are notable differences in the transition steepness and depth of the flow to and from the moist seasons. The differences in the net flux are larger between the two reanalysis products than between CMIP5 and ERA-Interim. Next, we consider the within basin details. To simplify the maps, we use 700 hPa for MAM (see the electronic supplementary material, figure S7) and 850 hPa for SON (see the electronic supplementary material, figure S8).

At 700 hPa in MAM, strong moisture flux divergence dominates west Africa and the Horn of Africa. Divergence over these regions is strongest in NCEP and ERA-Interim and substantially weaker in CMIP5. All three datasets show moisture flux convergence over the Congo Basin. The wettest of the three, ERA-Interim, features convergence furthest to the east of the basin while the driest in the east has the most bounded eastern interface between moisture convergence and divergence. These fields offer a simple insight into the differences in the model rainfall climatologies.

The SON moisture flux fields (see electronic supplementary material, figure S8) are more complex. Strong convergence in the north of the Congo Basin is separated from convergence into the Angolan low by weak convergence across much of the basin itself in two datasets (ERA-Interim and CMIP5) but weak divergence in the case of NCEP. In all three, moisture flux is strongly convergent in the east of the basin. Best agreement between all three is the strongly divergent coast of East Africa—a region known to be anomalously dry for its latitude. As with MAM, there is a simple mapping between the strength of the moisture convergence in the Congo Basin and the model rainfall. The wetter models (ERA-Interim and CMIP5) feature convergence while the driest (NCEP) features divergence. These differences in the distribution of convergent moisture flux are even more stark in the case of individual CMIP5 models during MAM (not shown) and SON (see the electronic supplementary material, figure S9) where five of the nine models have very weak or no convergence in the central basin. Taking the extremes in CMIP5 model rainfall, the driest model (figure 5), CNRM in SON, features no moisture flux convergence in the core of the basin while moisture flux is convergent in the wettest, NorESM1, from 6° N, through the core of the basin, to south of 30° S. These results suggest that observations of moisture flux convergence are a promising field with which to confront the models.

5. Summary

The primacy of the Congo Basin in Earth system dynamics is undisputed. The basin forms one of three major convective regions on the planet. During the transition seasons, this convection is larger than any other region in the global tropics. A dearth in observed meteorological data over the basin severely constrains progress with understanding the climate system. Satellite derived datasets differ by a factor of at least 2 and, in absolute terms, by up to 2000 mm yr^{-1}. An order of magnitude separates rainfall simulated in some coupled models in the dry season and rainfall simulated in reanalyses datasets. There are fundamental ambiguities such as whether the western or eastern Congo Basin is wetter.

It turns out that moisture flux is a particularly useful quantity with which to compare model rainfall products since there is a simple mapping between the strength of the moisture convergence in the Congo Basin and model rainfall. Wet models feature well-defined moisture flux convergence. Very dry models show moisture flux divergence. Long-term rain gauge-based monitoring over the basin is unlikely to be put in place in time to understand the dynamics of climate change. A different approach is therefore needed. What these results point to is the potential utility of short-period intensive observation campaigns which target atmospheric circulation, notably water vapour transport in concert with rainfall measurements. A short-term network of radiosonde stations over the Congo Basin in combination with weather radar and Aircraft Meteorological Data Relay (AMDAR) could provide the data to develop the tools, both from instruments on satellites and numerical models, much needed in climate research of the region. These data could be used to confront climate models and potentially establish which models are producing a realistic simulation of Congo rainfall. Without such steps, we are left to deal with the spectrum of possibilities of both current and future simulations of Congo rainfall. Given the importance of the basin, this is not a good position to be in.

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