Land-Atmosphere Coupling Regimes in a Future Climate in Africa: From Model Evaluation to Projections Based on CORDEX-Africa

Pedro M. M. Soares1, João A. M. Careto1, Rita M. Cardoso1, Klaus Goergen2.3, and Ricardo M. Trigo1.4

1Faculdade de Ciências, Instituto Dom Luiz (IDL), Universidade de Lisboa, Lisboa, Portugal, 2Institute of Bio- and Geosciences, Agrosphere (IBG-3), Research Centre Jülich, Jülich, Germany, 3Centre for High-Performance Scientific Computing in Terrestrial Systems, Geovrverbund ABC/J, Jülich, Germany, 4Departamento de Meteorologia, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brasil

Abstract  Land-atmosphere coupling plays a crucial role in determining the evolution of weather and climate. In the current study, the full ensemble of CORDEX-Africa climate change simulations is used to understand how strong and weak coupling regions in Africa will evolve in the future. The ability of the regional climate models to capture the coupling signal relies on a reasonable representation of near surface air temperature, precipitation, surface fluxes, and soil moisture. A thorough model evaluation reveals typical shortcomings in the representation of the African climate, in particular seasonal precipitation. The multimodel ensemble mean outperforms the individual models and is therefore used for the investigation of the land-atmosphere coupling. This ensemble mean shows a widespread warming in Africa and changes in precipitation, such as a decrease in the Sahel during summer and an increase in western Africa during summer and autumn. The coupling analysis relies on surface fluxes, the related evaporative fraction and their correlations as well as the correlation between evaporative fraction and soil moisture. Overall, water-limited regions that exhibit a strong land-atmosphere coupling are projected to expand further southward in West Africa and further northward in southern Africa. This is particularly true over the Sahel during spring and summer, when the strong coupling region shifts southward, indicating a potential expansion of the semiarid and arid regions. A transition of energy limited regimes, with weak coupling, to water-limited regimes where soil moisture plays a more important role, is projected for the end of the 21st century as drying continues.

1. Introduction

Land-atmosphere coupling investigates the interactions between the subsurface, land surface, and the atmosphere through the exchange of mass and energy, affecting several key mechanisms including, boundary layer mixing, convection, cloudiness, or precipitation (Dirmeyer, 2011; Seneviratne et al., 2006). Coupling is an integrative metric that describes how variables are linked with each other (Seneviratne et al., 2010); the strength of the coupling is defined by Koster et al. (2006) as the degree to which land surface anomalies affect the atmosphere. Soil moisture is thereby a key state variable that controls flux partitioning with impacts on the soil moisture-temperature and soil moisture-precipitation feedbacks (Seneviratne et al., 2010).

Multiple metrics designed to quantify coupling strength have been developed for various feedback processes and variables, mostly incorporating either the sensible or latent heat flux (e.g., Decker et al., 2015; Dirmeyer, 2011; Findell et al., 2011; Knist et al., 2017; Miralles et al., 2012; Seneviratne et al., 2006). These metrics are used to distinguish between dry, moisture-limited–strong–coupling regimes, where the latent heat flux to compensate for the atmospheric moisture deficit is constrained by soil moisture content, and energy-limited–weak–coupling regimes, where the soil moisture content is always sufficiently high, and the latent heat flux is controlled by the state of the boundary layer and of the net radiation. The land-atmosphere interactions, via the associated feedbacks, can intensify the hydrologic cycle (Huntington, 2006) and the related dry and wet spells (Mueller & Seneviratne, 2012). Droughts and heat waves might also positively feedback in a strong coupling regime (Miralles et al., 2012, 2014). Transition zones between strong and weak coupling regimes are thereby prone to large spatial and temporal fluctuations in latent and sensible heat fluxes at intra and interannual scales (i.e., near surface air temperatures and evapotranspiration; Koster et al., 2006; Seneviratne et al., 2010; Knist et al., 2017).
The transition zones between weak and strong coupling regimes are particularly susceptible to major changes in the flux partitioning and, therefore, on the amplitude of both soil moisture-temperature and soil moisture-precipitation feedbacks. Hence, these areas are expected to shift with the predicted changes in large-scale precipitation regimes, projected by global climate models (GCMs; Seneviratne et al., 2006; Dirmeyer et al., 2014; Intergovernmental Panel on Climate Change (IPCC), 2014). A region, which is characterized, in the Global Land-Atmosphere Coupling Experiment by Koster et al. (2006), as a so-called “hot spot” region with a relatively high coupling strength is the Sahel, in Africa. In this region, small shifts in the transition zones might affect the evolution and statistics of extremes such as droughts and heat waves. In the IPCC’s 5th Assessment Report WGII Africa chapter, by Niang et al. (2014), a mean annual near surface air temperature increase of 0.5 °C for most parts is reported for the past 50 to 100 years. Whereas the observed precipitation trends are unclear due to a lack of observational data. In the Coupled Model Intercomparison Project Phase 5 (CMIP5), GCM projections of a mean annual temperature increase over all African land areas are considered very likely, according to the model ensemble mean, for the middle and late 21st century. The increase exceeds 2 °C for the Representative Concentration Pathway (RCP) 2.6 and 4 °C for RCP8.5 with reference to the late twentieth century baseline. The precipitation projections are more uncertain about the change signal, which shows large seasonal and regional dependencies. The Mediterranean region in northern Africa, as well as southern Africa, see under the RCP8.5 scenario a very likely decrease in precipitation. The projections for central and eastern Africa exhibit a likely increase in rainfall. However, the report notes that the low to medium confidence over Africa with respect to the robustness of the projected regional precipitation change signals might be altered by the use of regional climate models (RCMs).

RCMs provide several advantages in reproducing regional climate features over GCMs. Besides their higher spatial resolution, in particular, RCMs are capable of a more detailed representation of atmospheric processes as well as land-atmosphere interactions, due to the higher resolution of surface properties and heterogeneities (Flato et al., 2013; Giorgi & Mearns, 1991; Rummukainen, 2010, 2016). The latest RCM community experiment is the World Climate Research Programmer’s Coordinated Regional Downscaling Experiment (CORDEX) project, a diagnostic model intercomparison project for CMIP6 (Giorgi et al., 2009; Gutowski et al., 2016). In its framework state-of-the-art RCMs dynamically downscale CMIP5 GCMs (Taylor et al., 2012) for the RCP2.6, RCP4.5, and RCP8.5 (Moss et al., 2010) through a coordinated multimodel, multiphysics experiment to provide high resolution, regional climate information. The CORDEX-Africa common model domain (Figure 1) covers the full African continent at a 0.44° resolution, and model data is available in the Earth System Grid Federation Data nodes (Cinquini et al., 2014). This ensemble constitutes, at present, a major climate change assessment data set for the African continent.

In the context of CORDEX-Africa, the ERA-Interim driven evaluation simulations and the regional climate change projections have been extensively analyzed. Using evaluation simulations driven by ERA-Interim, Nikulin et al. (2012) did a thorough assessment of the precipitation climatology which shows significant biases in some subregions and seasons. It is important to stress though that the biases in the multimodel average are comparable to the differences seen between observational data sets. Nikulin et al. (2012) results are important for this study as precipitation is the first order driver of the coupling regimes. Complimentary to the aforementioned study, Kim et al. (2014) also evaluated the ERA-Interim driven multi-RCM ensemble. Again, the multimodel ensemble outperforms individual RCMs, and the western Africa and tropical precipitation are well captured. Yet, Brands et al. (2013) found that the ERA-Interim reanalysis has shortcomings over Africa, and hence, the ERA-Interim driven evaluation run performance may be negatively impacted. Applying a heatwave magnitude index to reanalysis data, Russo et al. (2016) reveal that in recent years heat waves have become hotter, lasted longer, and have been more widespread. Using CORDEX-Africa data, the previous study projects that the recent kind of heat waves will become more common under a RCP8.5 scenario. On the large river catchment scale of the Niger in western Africa, Mascaro et al. (2015) investigated, using CORDEX-Africa data, how the hydrological cycle is changing; their study stressed major caveats, namely, that the water balance is in many RCMs not closed, which is attributed to individual parametrization schemes more than to the driving models. In Dosio et al. (2015), the individual COSMO-CLM model system's performance in adding value to dynamically downscaled CMIP5 GCMs is analyzed. Seasonal statistics are not always improved with reference to the GCMs, but the southern and western Africa precipitation
annual cycle can be better captured including the West African Monsoon system. Three different, widely used observational data products, FEWS, TRMM, and GPCP, are compared with each other and the RegCM3 model for Africa in Sylla et al. (2013). This study shows large differences in mean rainfall and in higher order daily precipitation statistics. This is as well one of the reasons for this study, to use more than one data set for model evaluation. In Nikulin et al. (2018), the potential impacts of a 1.5, 2.0 °C or more global warming are investigated using CORDEX-Africa RCMs. The warming signal in Africa exceeds the global average warming and precipitation in some areas might slightly increase. The impact, ranging from 1.5 to 2.0 °C, shows a robust change.

Combining TRMM satellite observations and ERA-Interim reanalysis, Taylor (2008) investigates cause and effect relationships around land-atmosphere interactions and the West African Monsoon. Soil moisture changes and the corresponding variability in the coupling regime has impacts on the low-level atmospheric circulation, which feeds again back on precipitation. In line with Koster et al. (2006), a study by Yamada et al. (2013) analyzing GCMs finds over the western Sahel an increase in coupling prior to the wet season. van den Hurk and van Meijgaard (2010) used the RegCM RCM over the West African Sahel looking at correlations between soil moisture, evaporation, and the recycling ratio of water. They conclude that the seasonal cycle of the atmospheric properties limits the effects of soil moisture in the coupling feedback loops.

This study complements existing analyses on various aspects of the African precipitation and land-atmosphere coupling regimes, by assessing changes in land-atmosphere coupling regimes in a future climate, using the CORDEX-Africa RCM ensemble. As a baseline, important variables for the land-atmosphere coupling from the CORDEX-Africa historical simulations are validated against different observational based data products because the assessment of coupling in the EURO-CORDEX evaluation runs in Knist et al. (2017) revealed a tendency of the RCMs toward a too strong coupling throughout the ensemble, when compared to observations over, and many of the cited studies above indicate deficiencies in the CORDEX-Africa ensemble, for example, with respect to the spatial and temporal precipitation distributions and amounts. Changes in coupling strength and the spatial distribution of coupling regimes in the CORDEX-Africa multimodel RCM ensemble are assessed from future projections with reference to the historical simulations for the RCP4.5 (supporting information) and the RCP8.5 climate change scenarios. We focus on the terrestrial segment of the land-atmosphere feedback loop. The characterization of the coupling relies on diverse metrics, which include the 10-day nonoverlapping correlation between total soil moisture and evaporative fraction and the 10 days of nonoverlapping correlation between latent and sensible heat flux (Careto et al., 2018; Knist et al., 2017).
A brief overview of RCM ensemble members and the comparison data, the coupling metrics, including the definition of the model domain with its analysis regions, is provided in section 2. Historical simulation results and coupling metrics derived are evaluated in section 3. The coupling in the projection simulations is analyzed in section 4. Finally, summary and conclusions are provided in section 5.

2. Data and Methods

2.1. CORDEX-Africa Models and Simulations

In the current study, nine RCM simulations from the CORDEX effort for the African domain were considered (Table 1). All model data was retrieved from the Earth System Grid Federation portal (https://esgf-node.ipsl.upmc.fr/projects/esgf-ipsl/), except CCCma, which is available at the model’s specific site (http://climate-modelling.canada.ca/climatemodeldata/canrcm/CanRCM4/index_cordex.shtml). The CORDEX-Africa simulations include hindcast, historical, and future simulations. The hindcast runs were driven by the ERA-Interim reanalysis (Dee et al., 2011) for the 1989–2008 period and were extensively validated in the context of model performance evaluations (Kim et al., 2014; Nikulin et al., 2012) and for land-atmosphere coupling (Careto et al., 2018).

The historical and future simulations were forced by different GCMs (Table 1) for the 1960–2100 period. The future period simulations follow the RCP4.5 and RCP8.5 scenarios. In this study, the historical (hereafter termed “Historical”) and future periods (hereafter termed RCP4.5 or RCP8.5) analyzed encompass the control time span from 1971 to 2000 and the projection time span from 2071 to 2100, at 0.44° horizontal spatial resolution for all of Africa (Figure 1) and a daily temporal resolution. Variables used are surface upward latent heat flux (or hfls), surface upward sensible heat flux (or hfss), total, vertically integrated, soil moisture (or mrso), surface precipitation (pr), surface maximum (or Tmax), and minimum (or Tmin) air temperatures.

The CORDEX-Africa domain is shown in Figure 1; seven subregions (red delimited; see Table S1 for exact definitions) are analyzed in further detail. These regions were chosen based on their climate classification (Peel et al., 2007) and land-atmosphere coupling features according to previous studies (e.g., Careto et al., 2018; Koster et al., 2006; Miralles et al., 2012; Seneviratne et al., 2006, 2010). Additionally, two other regions (dark blue) and several countries are also highlighted to facilitate the descriptions in the text.

### Table 1

| AOGCM MODEL ID | Institution | RCM MODEL ID | Institution | Acronym |
|----------------|-------------|--------------|-------------|---------|
| CanESM2        | Canadian Centre for Climate Modelling and Analysis | CanRCM4 | Canadian Centre for Climate Modelling and Analysis | CCCma |
| CNRM-CM5       | Centre National de Recherches Météorologiques/Centre Européen de Recherche et de Formation Avancées en Calcul Scientifique, France | CCLM4-8-17 | Climate Limited-area Modelling Community | CNRM-CLM |
| CSIRO-MK3      | Commonwealth Scientific and Industrial Research Organization in collaboration with the Queensland Climate Change Centre of Excellence, Australia | RCA4 | Swedish Meteorological and Hydrological Institute, Rossby Centre | CSIRO-SMHI |
| EC-EARTH       | EC-EARTH consortium | CCLM4-8-17 | Climate Limited-area Modelling Community | ICHEC-CLM |
| EC-EARTH       | EC-EARTH consortium | HIRHAM5 | Danish Meteorological Institute | ICHEC-DMI |
| EC-EARTH       | EC-EARTH consortium | RACMO22T | Royal Netherlands Meteorological Institute, De Bilt, The Netherlands | ICHEC-KNMI |
| HadGEM2-ES     | Met Office Hadley Centre | CCLM4-8-17 | Climate Limited-area Modelling Community | MOHC-CLM |
| HadGEM2-ES     | Met Office Hadley Centre | RACMO22T | Royal Netherlands Meteorological Institute, De Bilt, The Netherlands | MOHC-KNMI |
| ESM-LR         | Helmholtz-Zentrum Geesthacht, Climate Service Centre, Max Planck Institute for Meteorology | CCLM4-8-17 | Climate Limited-area Modelling Community | MPI-CLM |

A brief overview of RCM ensemble members and the comparison data, the coupling metrics, including the definition of the model domain with its analysis regions, is provided in section 2. Historical simulation results and coupling metrics derived are evaluated in section 3. The coupling in the projection simulations is analyzed in section 4. Finally, summary and conclusions are provided in section 5.
2.2. Observational Data Sets

The present investigation does not intend to extensively evaluate the historical RCM results with respect to the models’ setups, physical parametrizations, or the impacts of the lateral GCM forcing. Still, an attempt was made to evaluate the model results and assess the RCMs in representing coupling-related variables. The observational data sets include: the Climate Research Unit Time series version 4 (CRU TS v. 4.01; Harris & Jones, 2017) for surface temperatures and precipitation, the Global Precipitation Climatology Centre Full Data Reanalysis Version 7.0 (Schneider et al., 2015) for precipitation, the Global Land Evaporation Amsterdam Model (GLEAM) data set v3.1a (Armstrong et al., 2005; Beck et al., 2017; Liu et al., 2011; Martens et al., 2016, 2017; Miralles et al., 2010, 2011, 2012; Priestley & Taylor, 1972; Seneviratne et al., 2010; Wagner et al., 2012) for surface latent heat flux and soil moisture, and the Global Energy and Water Exchanges (GEWEX; Darnell et al., 1992; Gupta, 1989; Pinker & Ewing, 1985; Pinker & Laszlo, 1992) and GLEAM are used for surface sensible heat flux. A brief, more technical description of these data sets is given in the supporting information.

2.3. Land-Atmosphere Coupling Metrics

The evaporative fraction (evapfr) is defined as the latent heat flux (hfls) divided by the sum of the latent and the sensible heat flux (hfls) and used to assess how the RCMs represent the regional land-atmosphere coupling. Low values, close to 0, indicate dry areas, where the latent heat flux is low in comparison to the sensible heat flux; whereas values close to 1 identify humid zones, where latent heat flux is the dominant surface heat flux. In general, the evaporative fraction is highly influenced by precipitation regimes with higher values occurring in areas of larger rainfall rates (e.g., central regions of the West African monsoon rain band). As for intermediate evaporative fraction values, which are linked to transition regions between dry and wet zones, the mean rainfall values are lower and more variable throughout the year.

The soil moisture-temperature coupling is defined as the correlation between the 10-day nonoverlapping mean total soil moisture and evaporative fraction (or correlation [evapfr-mrso]; Knist et al., 2017; Careto et al., 2018). This metric is used to assess the relationship between soil moisture and the flux partitioning, where higher values are expected in regions where evapotranspiration is strongly affected by soil moisture availability and low values over deserts, where nearly no evapotranspiration occurs at the surface.

In addition, the correlation between the 10-day nonoverlapping mean of the latent and sensible heat fluxes (or correlation [hfls-hfls]) is a correlation metric that relates to the second leg in the soil moisture temperature feedback (Careto et al., 2018), where latent and sensible heat fluxes must vary interdependently to maintain the surface energy balance (Seneviratne et al., 2010). High positive correlations are expected in energy limited regimes (i.e., the available energy limits evapotranspiration, characteristic of humid areas), while low correlations might be observed over deserts where all the available energy goes into the sensible heat flux. Negative correlations are expected over the transition areas between humid and dry environments, as these are regions where water availability gradually limits evapotranspiration. The values of this correlation should also be related with the type of climate identified in evaporative fraction. The correlation between latent and sensible heat flux, together with other similar correlations (Knist et al., 2017; Seneviratne et al., 2006, 2010), is useful metrics to identify regions where temperature is strongly affected by changes in evapotranspiration.

2.4. Evaluation Methods and Multimodel Ensemble Mean

To compare precipitation, near-surface maximum and minimum air temperatures, from the Historical RCM runs against the CRU and (GPCC) Global Precipitation Climatology Centre data sets, an interpolation was performed with the Climate Data Operators remapcon command (Schulzweida et al., 2006), from the CORDEX-Africa native resolution of 0.44° to a 0.5° regular latitude-longitude grid (resolution of both observational data sets). Then a direct comparison was made at a seasonal time scale. Winter is defined as December–February, Spring as March–May, Summer as June–August, and Autumn as September–November. Bias and Taylor diagrams (Taylor, 2001) were computed to characterize the RCMs’ ability to reproduce Tmin, Tmax, and pr.

By multiplying evapotranspiration from GLEAM with the latent heat of vaporization (λ = 2.451 MJkg⁻¹; Shi & Liang, 2014), it was first converted to latent heat flux λ = 2.451 MJkg⁻¹. Subsequently, latent heat flux and the root zone soil moisture from GLEAM were interpolated, from their original 0.25° grid, to the CORDEX-Africa generic grid at 0.44° resolution, with Climate Data Operator remapcon.
To infer a quasi-observational sensible heat flux, the GLEAM latent heat flux is interpolated to the GEWEX surface radiative balance at 1° spatial resolution; the estimated sensible heat flux was obtained by subtracting latent heat flux from the surface radiative balance, assuming that the ground heat flux is negligible (Jimenez et al., 2011). Accordingly, the sensible heat flux from the CORDEX-Africa RCM models is also interpolated to the same 1° resolution. Taylor diagrams were then used to assess both surface fluxes. Regarding soil moisture, due to the different soil moisture definitions considered in CORDEX-Africa models (i.e., total soil moisture relative to root zone soil moisture), only a seasonal spatial correlation was performed for all models.

In agreement with previous CORDEX-Africa evaluation studies (Kim et al., 2014; Nikulin et al., 2012), the model biases in land-atmosphere coupling metrics, in the hindcast CORDEX-Africa runs, depend on the region and metric examined (Careto et al., 2018). A common method to obtain meaningful information from an ensemble of RCM results has been the assembly of ensemble means. An ensemble mean using equal weighting for all models has been shown to potentially outperform individual models (Knutti et al., 2010), and the allocation of higher weights to better performing models has been used to reduce uncertainties (Giorgi & Mearns, 2002; Tebaldi & Knutti, 2007). Yet, Christensen et al. (2010) found that in comparison with equal weighting schemes, the use of weights in ensemble building did not improve the description of the mean climate. A multimodel ensemble mean with equal weights (ENS) was built in order to improve the mean climate description for all surface variables and hence coupling metrics derived (Cardoso et al., 2018; Nogueira et al., 2018; Soares et al., 2015; Soares et al., 2017; Soares et al., 2017). It is fair to expect that ENS will outperform individual RCMs for mean quantities, giving a more robust view of the land-atmosphere coupling properties in Africa (Careto et al., 2018). Hence, the ENS was firstly evaluated in a similar manner as the individual models.

A Student’s *t* test distribution at the 95% significance level was used as a statistical significance test to assess the relevance of the differences between the ENS and observations, for all seasons and coupling metrics. Besides this test, a Fisher’s *z* transformation at the 95% confidence interval was used for each individual model and the ENS, for all seasons, to measure the significance of the correlations against the null-hypothesis. Also, for all future projections the statistical significance is computed following a Student’s *t* test distribution at the 95% confidence interval. The robustness of the climate change projections was determined through the evaluation of the percentage of models with the same sign of change. Second, the uncertainty/spread of the model projections was assessed through the analysis of the inter-model standard deviation.

### 3. Historical Simulations—Evaluation and Coupling

#### 3.1. Precipitation and Temperatures

Land-atmosphere coupling, even with its terrestrial leg only, is largely controlled and modulated by precipitation, that is, the available water for evapotranspiration and hence flux partitioning and near-surface temperature (and vice versa). Therefore, the RCMs ability to reproduce these variables is fundamental. Figures 2 and 3 show the seasonal differences between the Historical simulations of the CORDEX-Africa RCMs and the CRU data sets for precipitation and maximum and minimum temperatures from 1971 to 2000. The bias between the ENS and observations is also shown (black bold square). The observational seasonal climatologies for the three variables are presented in Figure S1 in supporting information. For precipitation, both the CRU (Figure 2 in millimeter and Figure S2b in percent) and the GPCC (Figures S3 and S4) data sets are considered. For temperatures, only CRU is used (Figure 3). Finally, the corresponding seasonal Taylor diagrams are plotted in Figure 4 (CRU) and Figure S5 (GPCC).

For all seasons, the CORDEX-Africa models show a limited ability to represent the seasonal precipitation over Africa, and a large spread dominates the ensemble. The seasonal biases against the CRU observations are rather high in absolute (Figure 2) as well as in relative values (Figure S2). Seasonal absolute biases range from +200 to −200 mm for all seasons. Seasonal relative differences are often around 100%. Not surprisingly, the largest differences correspond to regions characterized by relatively small amounts of seasonal rainfall in northern and southwestern and southern parts of Africa, where the RCMs show generally low, albeit too high precipitation amounts with reference to observations (too much drizzle due to the RCMs microphysics schemes). The most relevant biases correspond to the wetter regions, for example, in central Africa, where RCM biases reach values in the range of −50% to +50%.
In winter, the majority of RCMs overestimate the precipitation in large regions of southern Africa and underestimate precipitation in smaller areas of central and southeastern Africa. In spring, models generally underestimate rainfall in large areas of south-central Africa and overpredict the seasonal precipitation in the contiguous northern desert areas and southern Africa. Following the northerly displacement of the Intertropical Convergence Zone and of the larger summer precipitation amounts, the smaller relative biases occur in a broad band across a central area of Africa. Most of the models underestimate the summer rainfall over the western coastal and central regions and overestimate largely the precipitation in the Sahel. This is also true to some extent for autumn, nevertheless, with a higher degree of model differences and spatial shifts. Summarizing, there is a tendency of the RCMs throughout the seasons to overestimate precipitation in dry areas in the northern and southern parts of Africa and to underestimate precipitation in more humid central parts of Africa.

As expected, the ENS seasonal biases share these features however in a mitigated manner. In fact, the ENS shows smaller differences when compared with the CRU data set and, in general, improves the representation of the seasonal rainfall as can also be seen in the Taylor diagrams in Figure 4. Although these results are for the GCM-driven Historical simulations, the biases are in line with Careto et al. (2018) and Nikulin et al. (2012), where reanalysis-driven hindcast results were scrutinized.

The precipitation biases, when considering the GPCC data set (Figure S3), are similar to the preceding, except for the dry bias, in winter in northern Africa where very low precipitation occurs. On an annual basis (not shown), models tend to overestimate precipitation in dry areas, over the Sahara, Sahel, and southern Africa and underestimate rainfall in central Africa, in the coastal areas in the Gulf of Guinea and in the Mediterranean coast.

The clear majority of RCMs poorly captures the seasonal Tmax, underestimating it in large parts of Africa (Figure 3a) and showing biases that can reach −9 °C, in some localized areas and for some models. These high biases are also present in the hindcast simulations (Careto et al., 2018) and reflect the problems of
the RCMs to represent seasonal extreme temperatures. Exceptions to a general seasonal Tmax underprediction are the models CCCma and CSIRO-SMHI. Throughout the full seasonal cycle, models overall show similar bias patterns. This predominance of large negative biases impacts negatively on the quality of the ENS which shows, in all seasons, an underestimation of the seasonal Tmax, with bias values between $-1 \, ^\circ C$ and $-5 \, ^\circ C$. However, in some confined coastal areas of the coast of Angola and Namibia, the ENS also shows some positive biases that can reach $+3 \, ^\circ C$.

For minimum temperatures, the RCMs behavior is much more diverse and with overall smaller biases (Figure 3b) than the equivalent results for maximum temperature. Some models present a tendency to underestimate Tmin in large areas, and others show a clear Tmin overestimation for much of the African continent. For each model, the seasonal Tmin and Tmax biases are roughly similar throughout the year. Models that in general overpredict seasonal Tmin are ICHEC-DMI, MOHC-CLM, and MPI-CLM. Other CCLM runs do not show this behavior, for example, the ICHEC-CLM or the CNRM-CLM. These differences in the models’

Figure 3. Seasonal mean near-surface air (a) maximum temperature and (b) minimum temperature biases between CORDEX-Africa models and ENS against the CRU database for the Historical period (1971–2000).
ability to represent Tmin results in an improved bias pattern by the ENS when compared with the individual models. In fact, the ENS shows vast areas with Tmin biases between $-2 \, ^\circ C$ and $+2 \, ^\circ C$ for all seasons but, in some localized regions, reveals overestimations up to $5 \, ^\circ C$ in summer, for example, in Southern Africa. One reason for this RCM behavior in the reproduction of near surface temperature extremes could be that excess precipitation leads to a too high latent heat flux which is dampening the temperature extremes. This precipitation surplus might partly be attributed to the driving GCMs that determine the water budget of the RCMs in the dynamical downscaling approach.

To summarize the RCMs' and ENS's precipitation and temperatures behavior, the corresponding Taylor diagrams are presented in Figures 4a–4c (Figure S5 shows the precipitation Taylor diagram for GPCC precipitation). These figures show some spread between models, for Tmin, Tmax and pr, more significant in the intermediate seasons and summer for precipitation and Tmax. For all seasons and variables, the seasonal correlations are above 0.8, except for autumn Tmax and Tmin. Regarding the ENS, the clear majority of

Figure 4. Seasonal mean climate Taylor diagrams for (a) precipitation, (b) maximum surface air temperature, (c) minimum surface air temperature for CORDEX-Africa models and ENS against the CRU database for the Historical period (1971–2000), (d) upward latent heat flux for 1980–2000 period against the GLEAM database, and (e) upward sensible heat flux for 1985–2000 period relative to GEWEX surface radiative balance minus GLEAM latent heat flux, for CORDEX-Africa models and ENS. The axis refers to the standard deviation, the green lines to the root mean square error and the quarter circle to the spatial correlation.
Overall, for seasonal precipitation the ENS has the best performance when compared with individual models. For temperatures this is often not the case, however, for both temperatures the ENS is amongst the best performing models in all seasons.

### 3.2. Surface Fluxes and Soil Moisture

In the current section, the evaluation of the surface properties is presented. Figures 4d and 4e show the Taylor diagrams for the latent and sensible surface fluxes, comparing the Historical RCM results and the GLEAM-GEWEX mix product as described in section 2.2. In general, models present a lower ability to represent the sensible heat flux than latent heat flux, with larger spread for all seasons. In particular, RCMs reveal larger errors in capturing the sensible heat flux in spring and summer. This may partially be due to the indirect way sensible heat flux data set was computed. More importantly, the Taylor diagrams disclose that the ENS outperforms the individual models for both surface fluxes in all seasons. In fact, the ENS seasonal spatial correlations for the latent heat flux are high with a correlation coefficient of ~0.95 and much smaller for the sensible heat flux, in the range of 0.6 and 0.9. Again, the improvement observed for the ENS is consistent with previous works (Nikulin et al., 2012), since some of the regional bias errors attained by individual RCMs tend to cancel each other out.

In Table 2, the seasonal Pearson correlations between Historical total soil moisture and root zone soil moisture, taken from the GLEAM data set, are shown. For the full African domain and the four seasons, models display reasonable correlation values, all above 0.5. Again, regarding soil moisture, the ENS outperforms all individual CORDEX-Africa RCMs presenting much higher correlations in all seasons. In general, the individual RCMs have correlations ~0.60, and the ENS displays seasonal correlations of 0.77, 0.81, 0.84, and 0.86, for winter, spring, summer, and autumn, respectively.

### 3.3. Land-Atmosphere Coupling

The seasonal mean values of the evaporative fraction for all RCMs, the ENS, and observations are depicted in Figure 5. For all seasons and models, it is roughly possible to identify the regions where evaporative fraction is low, that is, the sensible heat dominates the surface fluxes. These correspond to the broad northern areas, the horn of Africa and the southwestern tip of Africa, where vegetation is sparse or desert prevails. In an opposite manner, in the wetter central region of Africa the latent heat flux is dominant, and therefore, the evaporative fraction is larger and closer to 1.

As expected, the CORDEX-Africa RCMs evaporative fraction spread is greatly controlled by the model's representation of precipitation within the wetter regions of Africa and the transition zones. For example, in winter and spring, the CSIRO-SMHI simulation underpredicts precipitation in the Sahel, the West, and East Africa regions (see Figure 1), leading to smaller evaporative fraction values when compared with observations and other models. An opposite example is the too high evaporative fraction in the Sahel, caused primarily by the large overestimation of precipitation by CNRM-CLM in summer and autumn. Yet, most of the models describe the expected climate-related seasonal patterns in flux partitioning fairly well expressed by the mean evaporative fraction. Nevertheless, the ENS gives us the best synthesis of this partitioning between latent and sensible heat fluxes when compared with observations. Despite this qualitatively acceptable comparison, the statistical significance test reveals that the differences between the ENS and the OBS, when comparing per grid cell ENS and OBS time series, are statistically significant in most regions, and

| Seasons | Models |
|---------|--------|
| CCCma   | CNRM-CLM | CSIRO-SMHI | ICHEC-CLM | ICHEC-DMI | ICHEC-KNMI | MOHC-CLM | MOHC-KNMI | MPI-CLM | ENS |
| CORDEX-Africa | DJF 0.58 | 0.60 | 0.51 | 0.66 | 0.52 | 0.55 | 0.58 | 0.55 | 0.65 | 0.78 |
|          | MAM 0.60 | 0.64 | 0.52 | 0.67 | 0.55 | 0.60 | 0.65 | 0.51 | 0.68 | 0.82 |
|          | JJA 0.64 | 0.71 | 0.53 | 0.68 | 0.57 | 0.63 | 0.72 | 0.47 | 0.69 | 0.85 |
|          | SON 0.65 | 0.75 | 0.59 | 0.66 | 0.60 | 0.66 | 0.72 | 0.54 | 0.72 | 0.87 |

the seasonal correlations are around 0.9. Overall, for seasonal precipitation the ENS has the best performance when compared with individual models. For temperatures this is often not the case, however, for both temperatures the ENS is amongst the best performing models in all seasons.

### 3.2. Surface Fluxes and Soil Moisture

In the current section, the evaluation of the surface properties is presented. Figures 4d and 4e show the Taylor diagrams for the latent and sensible surface fluxes, comparing the Historical RCM results and the GLEAM-GEWEX mix product as described in section 2.2. In general, models present a lower ability to represent the sensible heat flux than latent heat flux, with larger spread for all seasons. In particular, RCMs reveal larger errors in capturing the sensible heat flux in spring and summer. This may partially be due to the indirect way sensible heat flux data set was computed. More importantly, the Taylor diagrams disclose that the ENS outperforms the individual models for both surface fluxes in all seasons. In fact, the ENS seasonal spatial correlations for the latent heat flux are high with a correlation coefficient of ~0.95 and much smaller for the sensible heat flux, in the range of 0.6 and 0.9. Again, the improvement observed for the ENS is consistent with previous works (Nikulin et al., 2012), since some of the regional bias errors attained by individual RCMs tend to cancel each other out.

In Table 2, the seasonal Pearson correlations between Historical total soil moisture and root zone soil moisture, taken from the GLEAM data set, are shown. For the full African domain and the four seasons, models display reasonable correlation values, all above 0.5. Again, regarding soil moisture, the ENS outperforms all individual CORDEX-Africa RCMs presenting much higher correlations in all seasons. In general, the individual RCMs have correlations ~0.60, and the ENS displays seasonal correlations of 0.77, 0.81, 0.84, and 0.86, for winter, spring, summer, and autumn, respectively.

### 3.3. Land-Atmosphere Coupling

The seasonal mean values of the evaporative fraction for all RCMs, the ENS, and observations are depicted in Figure 5. For all seasons and models, it is roughly possible to identify the regions where evaporative fraction is low, that is, the sensible heat dominates the surface fluxes. These correspond to the broad northern areas, the horn of Africa and the southwestern tip of Africa, where vegetation is sparse or desert prevails. In an opposite manner, in the wetter central region of Africa the latent heat flux is dominant, and therefore, the evaporative fraction is larger and closer to 1.

As expected, the CORDEX-Africa RCMs evaporative fraction spread is greatly controlled by the model's representation of precipitation within the wetter regions of Africa and the transition zones. For example, in winter and spring, the CSIRO-SMHI simulation underpredicts precipitation in the Sahel, the West, and East Africa regions (see Figure 1), leading to smaller evaporative fraction values when compared with observations and other models. An opposite example is the too high evaporative fraction in the Sahel, caused primarily by the large overestimation of precipitation by CNRM-CLM in summer and autumn. Yet, most of the models describe the expected climate-related seasonal patterns in flux partitioning fairly well expressed by the mean evaporative fraction. Nevertheless, the ENS gives us the best synthesis of this partitioning between latent and sensible heat fluxes when compared with observations. Despite this qualitatively acceptable comparison, the statistical significance test reveals that the differences between the ENS and the OBS, when comparing per grid cell ENS and OBS time series, are statistically significant in most regions, and
therefore relevant (nonshaded areas), for all seasons. Following the seasonal cycle, in winter and spring, the areas of evaporative fractions above 0.7 are localized in the central-south of Africa (NWCA, SWCA, and SA), migrating further north in summer and autumn (SAHEL, EA, and NWCA). Simultaneously, in these seasons the large values of evaporative fraction are enhanced, resulting in the sharpening of the gradients of evaporative fraction. The regions with evaporative fraction above 0.1 and below 0.5 are regions with

**Figure 5.** Seasonal mean evaporative fraction for the CORDEX-Africa models and ENS, for the Historical period (1971–2000). Also shown is the seasonal evaporative fraction for observations and the difference between the ensemble mean and observations for the 1983–2000 period. Dotted where the anomalies are not statistically significant at the 95% confidence.
strong soil moisture atmosphere coupling where the sensitivity of latent heat flux to soil moisture is high (Dirmeyer, 2011). These areas correspond to strong land-atmosphere coupling regions and are localized in between the desert areas and the regions where evaporative fractions are large. The evaporative fraction differences between the ENS and observations are also shown in Figure 5 (lower right corner per subpanel+). In all seasons, the transition regions between strong and weak coupling regimes (SA, SWCA, and EA), the differences are as well nonstatistically significant. In the vicinities of the Sahel, the evapfr differences are statistically significant.

As the evaporative fraction is crucial for the coupling, Table 3 shows the mean regional values of evaporative fraction for the regions defined in Figure 1. NWCA is the region with year-round larger evaporative fractions, in the range of 0.69 in summer and 0.80 in spring. The contiguous southern region (SWCA), only in winter, shows a significant evaporative fraction of ~0.72. EA presents large evapfr values in half of the year (summer and autumn), and WA in autumn reveals the largest seasonal value of ~0.90.

The seasonal link between soil moisture and surface sensible and latent heat flux partitioning is indicated by the nonoverlapping 10-day mean correlation between total, vertically integrated soil moisture and the evaporative fraction (Figure 6). In general, the RCMs’ positive correlations occur over most of
the continent. A decrease (increase) of soil moisture results in a shrinking (increasing) of evaporative fraction. Small positive and negative (noisy) correlation patterns exist especially during winter in very dry areas where both latent heat flux and soil moisture are close to zero and that are clearly statistically non-significant.

Figure 6. Seasonal nonoverlapping 10-day means correlation between total soil moisture and evaporative fraction for the CORDEX-Africa models and ENS, for the Historical period (1971–2000). Also shown is the 10 days of nonoverlapping means correlation between observational soil moisture and evaporative fraction (OBS) and the difference against the ensemble mean, both for the 1983–2000 period (ENS-OBS). Dotted where the null correlation hypotheses cannot be discarded. The ENS-OBS are also dotted where the anomalies are not statistically significant at the 95% confidence.
From observations, the smaller correlations in winter are found in central Africa (NWCA and SWCA), an energy-limited area, where the increase of soil moisture (due to precipitation) does not mean a latent heat flux increase response. Differently, still in winter, the water-limited regions (WA, EA, ECA, and SA) present the highest correlations of soil moisture and latent heat since seasonal sharp decreases in soil moisture results in a reduction of evapotranspiration. In these areas, the high temperatures provide sufficient energy for surface moisture evaporation (Figure S1c). The RCMs in Figure 5 show a reasonable spread which may also be attributed to the soil moisture calculation within each model as well as the vertical discretization in the subsurface (Knist et al., 2017). In winter, the high dry biases in the wettest areas affect the soil moisture, and the RCMs ensemble indicate incorrectly these regions as strong coupling areas. Again, the unrealistic dry characteristics of the CSIRO-SMHI simulation in the wettest regions stands out implying widespread high correlation values. A similar pattern emerges in the other seasons over the regions associated with high precipitation. Those areas are considered under an energy-limited regime since both evaporative fraction and soil moisture are large.

Overall, the ENS can represent the high correlation patterns of the strong coupling regions, associated to the moisture-limited zones. Yet, in autumn, the correlations are lower than observed due to the overestimation of autumn precipitation. The wet biases in spring and summer in coastal areas of South Africa and over the Sahara Desert also imply lower than observed coupling. The statistical significance of the differences between the ENS and observations is spatially heterogenous and shows large areas where the differences are statistically significant and hence interpreted as important (nonshaded areas). Overall, in winter the arid and semiarid regions show differences that are not statistically significant. And, the other areas where the differences are nonstatistically significant are often associated with the wettest regions. In Table 3, two correlation (evapfr,mrso) values stand out, 0.70 and 0.75, for the WA winter and for the SWCA summer, respectively. In general, the individual RCMs have only limited areas where the null correlation cannot be discarded (shaded areas), while the ENS correlations are statistically significant for all analysis domains.

A measure of the seasonal coupling strength between the land and the atmosphere can be obtained from the correlation between latent heat flux and sensible heat flux. In Figure 7, the nonoverlapping 10-day mean correlation is shown. During winter, the OBS data set clearly show the regions that coarsely include WA, EA, ECA, SWCA, and SA as strong coupling regions (large negative correlations). In spring, these regions are limited to the central African belt (WA, EA, and north of ECA). The strong coupling regions, in summer, appear displaced to the Sahel and areas of SWCA and ECA. Finally, in autumn the stronger coupling regions are mainly localized in SWCA and ECA. All these regions reveal large negative correlations between the surface heat fluxes linked to inherently water-limited regimes.

A first inspection of the RCM correlation results reveals a range of local coupling signals and large regional disagreements with observations, except in winter. In autumn, spring, and summer, there is an overestimation of the spatial extent of the strong coupling regions. The RCMs and, in particular, the ENS higher negative correlations (strong coupling) are similar to the observations; however, the positive correlations (weak coupling) are larger than in the observations. The latter are located in regions mostly associated with an underestimation of precipitation by the models. However, in this assessment, it is also important to keep in mind the limited quality of the observed surface heat fluxes, especially of the sensible heat flux, and that these disagreements may be attributable to this. As in the case of EURO-CORDEX (Knist et al., 2017), it seems that the observed coupling strength, given by the correlation of sensible and latent heat, seems somewhat weaker than for the individual RCM simulations. Moreover, most of the models show large areas, in particular in arid and transition zones of those to wetter regions, where a null correlation cannot be discarded (shaded).

In winter, most of the models show regions of weak coupling (positive correlations) linked to the wetter regions, albeit stronger when compared with the observations. In the ENS, these regions correspond to areas of NWCA and SWCA, for example, including roughly the countries Congo, Angola, and Zambia, and the southeastern tip of South Africa. In summer, the weak coupling regions are located further north in western Ethiopia and a band that extends from Central African Republic to the Gulf of Guinea countries like Sierra Leone and Guinea. In the intermediate seasons, the positive correlations are smaller, but looking at the ENS correlation results in autumn, the regions are quite the same as in summer, and in spring, the weaker
Coupling areas are confined to more restricted zones, including the southeast of South Africa, and the north of the Democratic Republic of Congo to Gabon. The local maxima of positive correlations (weak coupling) regions of Western Ethiopia in summer and autumn and southeast of South Africa are associated with the steep topography and the local enhancement of rainfall. As in Figure 6, the excessive precipitation in Figure 7. Seasonal nonoverlapping 10-day means correlation between sensible and latent heat fluxes for the CORDEX-Africa models and ENS, for the Historical period (1971–2000). Also shown is the 10 days of nonoverlapping means correlation between observational latent and sensible heat fluxes (OBS) and the difference against the ensemble mean, both for the 1983–2000 period (ENS-OBS). Dotted where the null correlation hypotheses cannot be discarded. The ENS-OBS are also dotted where the anomalies are not statistically significant at the 95% confidence. 
South Africa induces a mismatch in the coupling signal, transforming this region into a strongly coupled region in summer and autumn, revealing the model and observations shortcomings, especially linked to the inference of sensible heat flux, regarding some areas and seasons to reach accurate representation of the land-atmosphere coupling.

The ENS strong coupling (large negative correlations) regions display a striking resemblance to the highest values of the sensitivity index of latent heat to variations in soil moisture of Dirmeyer (2011). In general, these are broader than in the observations, particularly due to the wet biases in the Sahara and northern Sahel, providing just enough water for latent heat to evaporate the soil moisture and decrease the sensible heat flux associated to an increase in cloud cover.

The strong coupling corresponds crudely, in winter, to the band south of the Sahel, from Guinea to Somalia (WA and EA), and Namibia to the western South Africa. In spring, the negative correlation values are in absolute values smaller and confined to localized areas in Sahel, WA, and EA. The narrow band of strong coupling displayed in observations is not well reproduced by the considerably wider ENS band. In summer, the regions of strong coupling are wider than in observations, including vast areas of the Sahara, Sahel, and a large area reaching from eastern EA to Angola. The description of the strong coupling regions by the multimodel ensemble mean is better in autumn, and those areas include Ethiopia, ECA and SWCA. In general, for all seasons the differences in the correlation between the ENS and observations are nonstatistically significant in the areas of strong coupling. But, in the wetter and thus weak coupling regions, those differences are statistically significant.

Table 3 gives a regional summary of the surface heat fluxes correlation, indicating strong regional coupling for winter and spring in the EA (−0.67 and −0.69, respectively) and for SWCA in both summer and autumn (−0.68 and −0.66, respectively).

Transition or boundary regions are defined by the frontier between the weak and strong coupling regions. In summer, these roughly coincide, with the southern limit of the Sahel, the western border of Uganda, the central regions of the DCR, and from Namibia to Botswana. Approximately, these boundary regions subsist in autumn, except for the Sahel. In spring, the border areas are more spatially limited to small areas in central Africa, and in winter, these correspond to areas in the Sahel, in the north of the Congos to the southern areas of Zambia and Angola.

4. Future Climate and Land-Atmosphere Coupling

4.1. Precipitation and Temperature Projections

The future land-atmosphere coupling in Africa is greatly dependent on the precipitation and temperature evolution. The future ENS precipitation anomalies (Figure 8a in millimeter and Figure S6 in percent), in agreement with the RCP8.5 scenario project significant changes in seasonal absolute amounts, in summer and autumn. In relative values, with respect to present climate, the changes are important all-year round. In Figure 8, the statistical significance of the projected changes is also shown.

In winter, the larger absolute precipitation changes are confined to relatively small areas, such as an increase above 100 mm in the northwest of Angola and southern areas of Kenya. These correspond to relative gains in rainfall of ~+15% and ~+40% w.r.t. present climate, respectively, and are statistically significant. Larger spatial gradients in the winter precipitation in Angola are projected for the future, since it is also projected a significant decrease in the southern regions (up to ~80 mm). Similarly, a decrease in winter rainfall is also projected in Namibia, in the wetter coastal mountainous regions of South Africa, and to a lesser degree in the DRC and northern Morocco (the vast majority of these are statistically significant). In winter, there are large areas of the north-central regions of Africa where large relative changes of rainfall are estimated (Figure S6), but these are areas where little amounts occur in present climate, and changes are not significant. Conversely, in the horn of Africa and contiguous regions a significant increase of rainfall is projected. In spring, most of the continent will probably see precipitation reductions, in particular, in northwestern coastal areas and southern Africa, where these can be up to ~−40% (~−80 mm). Yet, only in Senegal, SA, and SWCA, those reductions are significant. In summer, absolute values of precipitation are expected to change significantly in the western Sahel and the countries further south, that is, decreases, for example, in Mali, Senegal, and Eritrea, and important increases in the Gulf of Guinea northern countries, as well as
in regions of Somalia and Ethiopia. In some of these areas the precipitation increase may be \(\pm 100\) mm, that is, more 30\%-50\% w.r.t. present climate. Overall, these changes are relevant since they occur in great measure in the vicinities of the boundary zones.

The robustness of the climate change signal can be inferred by the agreement of the change signal within the RCMs, which is depicted in Figure S7. Notably, for precipitation, the RCMs show a strong agreement in the climate change signal across the areas where the larger and statistically significant future changes are projected. In fact, for those regions more than 70\% of RCMs accord in the projection signal. Additionally, to illustrate the model projections' uncertainty the intermodel standard deviation of the precipitation changes is presented in Figure 9a. Although the large signal agreement in some of the previous regions, it is fair to acknowledge that models also show a large spread in precipitation change (e.g., Angola and Namibian coastal areas in winter and Western and Eastern Africa in summer). This results in an important degree of projections uncertainty. In spring and autumn, the intermodel spread is rather low as well as the precipitation changes uncertainty.

Figure 8. Seasonal anomalies for the ENS (Future minus past) between Historical (1971–2000) and Future RCP8.5 scenario (2071–2100) for (a) absolute precipitation, (b) surface maximum air temperature, (c) surface minimum surface air temperature, (d) upward latent heat flux, and (e) upward sensible heat flux. Dotted where the anomalies are not statistically significant at the 95\% confidence.
The projected seasonal changes of Tmax and Tmin (Figures 8b and 8c) are roughly similar for the full African continent. The larger temperatures increases are expected to occur in southern Africa, in areas of Angola, Namibia, South Africa, and Botswana with increases of both Tmax and Tmin of up to 6 °C. Similar warming is projected for the broad area of the Sahara and Sahel, especially in summer and autumn. Some wet and coastal regions will see somewhat mitigated temperature increases to values ~3 °C–4 °C, like in the Gulf of Guinea and in the Horn of Africa. All temperature changes are statistically significant and robust. As expected, all models agree in the sign of temperature change. Projections for Tmax show a higher spread than for Tmin (Figures 9b and 9c). The larger temperature projection spread is mostly related to the regions where stronger warming is expected. But this is not always true, since the broader Sahel band shows a larger disagreement between RCMs in the magnitude of the changes, in all seasons. This is also true in southern Africa in summer and autumn.

In general, the future increases of surface temperatures are closely linked with larger surface heat fluxes (Figures 8d and 8e) but mediated by the changes on precipitation and surface water availability. These will affect the flux partition and the coupling in future climate. Surface latent heat fluxes is projected to

**Figure 9.** Seasonal standard deviations across individual models between future RCP 8.5 scenario (2071–2100) against Historical period (1971–2000) for (a) precipitation, (b) surface maximum air temperature, (c) surface minimum air temperature, (d) surface upward latent heat flux, and (e) surface upward sensible heat flux.
significantly increase in large areas of central Africa due to the higher future near air surface temperatures and the seasonal availability of water, for example, in NWCA and ECA in winter and spring and WA in summer and autumn. To the south and north of those regions, a statistically significant decrease of latent heat flux is projected, since no water will be available for evaporation. Highly significant is the decrease of latent heat flux in the western Sahel accompanied by its growth further south, both in summer and autumn. Additionally, in all seasons, the latent heat flux is projected to decrease substantially in the SA region, and in the SWCA mainly in summer and autumn. Some boundary regions show nonstatistically significant changes. Conversely, the surface sensible heat fluxes increase significantly in vast regions of the south of Africa and in particular in the aforementioned Sahel areas, SA, and SWCA. Additionally, in some confined regions where rainfall is expected to increase the sensible heat flux diminishes, examples may be seen in winter in Kenya, Ethiopia, small areas of the Gulf of Guinea (except in summer) and the Horn of Africa in autumn.

Again, the regions where fluxes are projected to change greatly and significantly the RCMs show an agreement on the signal of change (Figures S7d and S7e). The latent heat projections show much larger uncertainty than sensible heat flux (Figures 9d and 9e). The magnitude of latent heat flux changes is rather different within RCMs in the western Africa and EA, in spring and summer. Although most of the models

Figure 10. Seasonal mean (a) evaporative fraction, (b) 10 days of nonoverlapping means correlation between evaporative fraction and total soil moisture, and (c) 10 days of nonoverlapping means correlation between latent and sensible heat fluxes for the Future RCP 8.5 scenario ENS (2071–2100).
agree in the sign of change (Figure S7d). The model projections for sensible heat flux reveal a small spread between RCMs, except in confined areas of SWCA in winter and autumn, western coastal areas in spring, and a narrow Sahel band in summer.

4.2. Projections for the Future Land-Atmosphere Coupling
The future surface flux changes impact directly in the evaporative fraction, especially in regions where notable changes in water availability is projected. The future values of evaporative fraction and changes between the far future and control time spans are shown in Figures 10a and 11a. As was already perceptible by the changes in the surface fluxes, most of the African continent will experience a decrease in the evaporative fraction. This is particularly true in boundary zones (transition regions between strong and weak coupling areas), that is, the Sahel region in winter and spring, along the Intertropical Convergence Zone in summer and autumn (border between the Sahel and Sahara), and areas of the southern Africa in all seasons. Conversely, in the horn of Africa, WA, EA, and northern ECA, a small increase of evaporative fraction is projected. These changes are statistically significant and robust (Figure S11a). In humid areas, where evapfr > 0.7, weak positive/negative anomalies during most of the year are visible (this implies an increase of both sensible and latent heat fluxes). However, summer anomalies are slightly stronger, with a clear negative tendency over the Sahel and large parts of WA and EA. These changes are in

Figure 11. Seasonal anomalies between the ENS of future scenario RCP8.5 (2071–2100) minus Historical period (1971–2000) for (a) evaporative fraction, (b) 10 days of nonoverlapping means correlation between evaporative fraction and total soil moisture, and (c) 10 days of nonoverlapping means correlation between latent and sensible heat fluxes. Dotted where the anomalies are not statistically significant at the 95% confidence.

10.1029/2018JD029473
close connection with the projected precipitation changes in Figure 8 and are not severely affected by uncertainty (Figure 12a).

The seasonal anomalies of the correlation of evaporative fraction and soil moisture are depicted in Figure 10b. In large areas, the changes are not statistically significant. However, some changes can be disentangled, like a clear correlation increase in spring in the eastern part of South Africa and in central DRC which corresponds to a future enlargement of the areas where very high correlations will occur due to an enhancement of the water-limited regime and, therefore, to a stronger evaporation. In summer, the present climate energy-limited region of Central African Republic is projected to be transformed into a water-limited region since a sharp increase of correlation is expected. A similar but smaller trend seems to arise in the autumn for a broad area of central Africa. Additionally, in winter the Sahel shows some areas where the correlations of evaporative fraction and soil moisture decrease.

The aforementioned modifications are coherent but, spatially much broader, when the anomalies of the correlations of the surface fluxes are inspected (Figure 11c). Significant changes in the surface heat fluxes correlations include strong decreases in almost all areas of southern Africa (SA, SWCA, and NWCA) in winter and spring. These reductions are to a large extent linked to the evolution of the weak coupling regions, in
present climate, to boundary regions or regions with a weaker coupling, in future climate, as in areas of Angola and DRC. Here the precipitation decline is followed by reductions in latent heat and sharp increase of sensible heat. Yet, in the southwest of SA a significant increase of correlation is seen, which seems connected to a future loss of land-atmosphere coupling in winter and spring, due to projected reduction of precipitation (Figure 8). Still, extensive negative large anomalies of the surface heat flux correlations are projected for summer in the regions of Sahel, WA, EA, NWCA, Somalia, and southeastern SA. These correspond to an intensification of the coupling, for example, in the Sahel, and the future evolution of some areas of WA and EA to boundary coupling regions. In autumn, the changes in coupling are similar and covering smaller areas. The changing patterns in northern Africa (Sahara Desert) are not interpreted, since the correlation [hfls,hfss] are not statistically significant in areas where very low evapotranspiration already exist in present climate (Seneviratne et al., 2010). Regarding the regions of Figure 1, large changes in the surface fluxes correlations are projected for the intensification of the coupling in winter and spring in EA and in winter in WA and in summer in Sahel. As before, these correlation results are supported by a general good agreement between models (Figures S11c and S11d) but have a clear caveat linked to the wide magnitudes of the changes (Figures 12b and 12c).

In summary, the comparison of the ensemble results of Figures 5–7 (present climate) with Figure 10, mediated by the corresponding anomalies in Figure 11 allows to identify (i) a further enhancement of land-atmosphere coupling strength in already dry areas (e.g., southern Africa in all seasons and Sahel in winter, autumn and spring); (ii) a migration southward of the strong coupling region that in summer covers Sahel; (iii) a northward migration of the strong coupling region that covers the SWCA; and (iv) an increase in coupling strength occurs in the wetter NCWA, WA, and EA regions in summer and autumn similar to the wet/dry transition areas between SWCA and SA.

5. Summary and Conclusions

Land-atmosphere energy and mass exchanges are fundamentally linked to soil moisture. The distribution of the planets’ biomes relies to a large extent on surface-atmosphere coupling, since soil moisture and temperature feedbacks have a strong influence on plant transpiration and photosynthesis (Seneviratne et al., 2010). Changes in transition zones, between strong and weak coupling, will have a significant impact on vegetation survival rates and species distribution and on the intensity of droughts and heat waves (Seneviratne et al., 2010). Africa is one of the most vulnerable continents to climate change. In particular, water availability and the corresponding changes in land-surface feedbacks may lead to unprecedented compound extreme events (IPCC, 2014; Russo et al., 2016; Russo et al., 2018). The understanding of the future evolution of the land-atmosphere coupling in the context of climate change is of paramount importance.

The CORDEX-Africa land-atmosphere coupling for historical and future climate was analyzed here. As in the hindcast model evaluation (Caretto et al., 2018), hot/dry biases were found over humid areas, while cold/wet biases occur over strong coupling areas. The land-atmosphere coupling biases reflect the former. Despite these deficiencies, the CORDEX-Africa RCMs are able to reasonably depict the continents’ climate and the seasonal partition of surface heat fluxes (latent and sensible), as well as the land-atmosphere coupling, albeit with a wide range of biases among the different RCMs. Nonetheless, the ENS improves substantially the representation of the vast majority of the variables and subsequently of the land-coupling metrics.

The comparison of historical and future results of the ENS, following the RCP8.5 greenhouse gas emissions scenario, projects important precipitation increases that are confined to areas in the vicinities of Kenya and Angola in winter and spring and to broader regions in WA and the Horn of Africa in summer and autumn. Yet, from season to season, also large precipitation reductions are estimated. In winter and autumn these are especially seen in SA, in spring also in areas of WA, and in summer very significantly in the Sahel region and EA. By the end of the 21st century, in agreement with the RCP8.5 scenario, temperatures are expected to be at least 3 °C above historical values over the whole continent, but much larger warmings are projected in some localized areas, for example, in Sahel, which can reach 7 °C. In general, these projections are statistically significant, the majority of RCMs agree on the change signal, but nonnegligible uncertainty subsists.

The precipitation and temperature projections lead to increases of latent heat fluxes in central Africa during winter and spring and over WA, EA, and areas of NWCA during summer and autumn. Conversely, a reduction of latent heat flux is projected for southern Africa and the Sahel, in particular in summer and autumn.
The regions where an intensification of precipitation is expected are areas with projected reductions of sensible heat fluxes. In contrast and in line with the temperature upsurge, sensible heat fluxes are amplified in most of the continent.

Overall, a decline of evaporative fraction is expected over the strong coupling areas, including SA in all seasons, and the Sahel in summer and autumn. In these areas, a future shrinking of strong coupling leading to an enhancement of the water-limited regions. This is particularly strong over the SA all year-round where an strong coupling region migrates northward and to a lesser extent in Sahel during spring and summer, where the strong coupling band migrates slightly southward, indicating a possible expansion of the Sahara Desert. A transition of energy limited regimes, with weak coupling, to regimes where soil moisture plays a more important role, is projected for the end of the 21st century. This signal is particularly strong in western central Africa in winter and spring.

Acknowledgments

P. M. S. J., J. C., and R. M. C. wish to acknowledge the SOLAR (PTDC/GEOMET/7078/2014) project. This work was also supported by project FCT UID/GEO/50019/2019—Instituto Dom Luíz. R. M. T. was supported by the project Improving Drought and Flood Early Warning. Forecasting and Mitigation using real time hydroclimatic indicators (IMDRFLOOD) funded by Fundação para a Ciência e a Tecnologia, Portugal (FCT, Portugal; WaterJPI/0004/2014). The authors would also like to acknowledge the World Climate Research Program Working Group on Regional Climate and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5. The authors also thank the climate modeling groups (listed in Table 1 of this paper) for producing and making available their model output, which can be accessed through the Earth System Grid Federation portal (Earth System Grid Federation; https://esg.dnl.nsc.liux.se/projects/esgf‐liu/), except CanESM2, which is available at http://climate‐modelling.canada.ca/climate‐modellista/canrcm/CanRCM4/index_cordex.shtml website. Finally, we would also like to thank the Global Land Evaporation Amsterdam Model (https://www.gleam.eu/), Climate Research Unit (http://data.ceda.ac.uk/badc/cru/data/cru_ts/cru_ts_4.01/), Global Precipitation Climatology Centre (https://www.esrl.noaa.gov/psd/data/gridded/data.gpcc.html), and the NASA Langley Research Center, Atmospheric Science Data Center, the Global Energy and Water Exchanges (https://gewex‐srh.larc.nasa.gov/) for the availability of observational data used in this work.

References

Armstrong, R. L., Brodzik, M. J., Knowles, K., & Savoie, M. (2005). Global monthly EASE Grid snow water equivalent climatology. Boulder, CO: National Snow and Ice Data Center, Digital media.
Beck, H. E., van Dijk, A. J. M., Leviszani, V., Schellekens, J., Miralles, D. G., Martens, B., & de Roo, A. (2017). MSWEP: 3-hourly 0.25° global gridded precipitation projection (1979–2015) by merging gauge, satellite, and reanalysis data. *Hydrology and Earth System Sciences, 21*, 589–615. https://doi.org/10.5194/hess-21-589-2017
Brands, S., Herrera, S., Fernández, J., & Gutiérrez, J. M. (2013). How well do CMIP5 Earth System Models simulate present climate conditions in Europe and Africa? *Climate Dynamics, 41*(3–4), 803–817. https://doi.org/10.1007/s00382-013-1742-8
Cardoso, R. M., Soares, P. M., Lima, D. C., & Miranda, P. M. (2018). Mean and extreme temperatures in a warming climate: EUROCORDEX and WRF regional climate high-resolution projections for Portugal. *Climate Dynamics, 52*(1–2), 129–157. https://doi.org/10.1007/s00382-018-4124-4
Caretto, I. A. M., Cardoso, R. M., Soares, P. M. M., & Trigo, R. M. (2018). Land-atmosphere coupling in Africa-CORDEX: Hindcast regional climate simulations. *Journal of Geophysical Research: Atmospheres, 123*, 11,048–11,067. https://doi.org/10.1029/2018JD028378
Christensen, J. H., Kjellström, E., Giorgi, F., Lenderink, G., & Rummukainen, M. (2010). Weight assignments regional climate models. *Climate Research, 44*(2–3), 179–194. https://doi.org/10.3354/cr00916
Cinquini, L., Crichton, D., Mattmann, C., Harney, J., Shipman, G., Wang, F., et al. (2014). The Earth System Grid Federation: An open infrastructure for access to distributed geospatial data. *Future Generation Computer Systems, 36*, 400–417. https://doi.org/10.1016/j.future.2013.07.002
Darnell, W. L., Staylor, W. F., Gupta, S. K., Ritchey, N. A., & Wilber, A. C. (1992). Seasonal variation of surface radiation budget derived from International Satellite Cloud Climatology Project CI data. *Journal of Geophysical Research, 97*, 15741–15760. https://doi.org/10.1029/92JD00675
Decker, M., Pitman, A., & Evans, J. (2015). Diagnosing the seasonal land-atmosphere correspondence over northern Australia: Dependence on soil moisture state and correspondence strength definition. *Hydrology and Earth System Sciences, 19*(8), 3433–3447. https://doi.org/10.5194/hess-19-3433-2015
Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society, 137*(656), 553–597. https://doi.org/10.1002/qj.828
Dirmeyer, P. A. (2011). The terrestrial segment of soil moisture-climate coupling. *Geophysical Research Letters, 38*, L16702. https://doi.org/10.1029/2011GL048268
Dirmeyer, P. A., Wang, Z., Mbuji, M. J., & Norton, H. E. (2014). Intensified land surface control on boundary layer growth in a changing climate. *Geophysical Research Letters, 41*, 1290–1294. https://doi.org/10.1002/2013GL058826
Dosio, A., Panitz, H. J., Schubert-Frisius, M., & Lüthi, D. (2015). Dynamical downsampling of CMIP5 global circulation models over CORDEX-Africa with COSMO-CLM: Evaluation over the present climate and analysis of the added value. *Climate Dynamics, 44*(9–10), 2637–2661. https://doi.org/10.1007/s00382-014-2262-x
Findell, K. L., Gentile, P., Lintner, B. R., & Kerr, C. (2011). Probability of afternoon precipitation in eastern United States and Mexico enhanced by high evaporation. *Nature Geoscience, 4*(7), 454–459. https://doi.org/10.1038/NGEO1174
Flato, G., Marotzke, J., Aebi, D., Braconnot, P., Chou, S. C., Collins, W., et al. (2013). *Climate change 2013: The physical science basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, chap. Evaluation of Climate Models (pp. 741–866). Cambridge, United Kingdom and New York, NY, USA: IPCC Assessment Reports, Cambridge University Press.
Giorgi, F., Jones, C., & Asrar, G. R. (2009). Addressing climate information needs at the regional level: The CORDEX framework. *Bulletin of the American Meteorological Society, 89*(3), 175–183.
Giorgi, F., & Mearns, L. O. (1999). Approaches to the simulation of regional climate change: A review. *Reviews of Geophysics, 29*(2), 191–216. https://doi.org/10.1029/90RG02636
Giorgi, F., & Mearns, L. O. (2002). Calculation of average, uncertainty range, and reliability of regional climate changes from AOGCM simulations via the "reliability ensemble averaging" (REA) method. *Journal of Climate, 15*(10), 1141–1158. https://doi.org/10.1175/1520-0442(2002)015<1141:COAURA>2.0.CO;2
Gupta, S. K. (1989). A parameterization for longwave surface radiation from sun-synchronous satellite data. *Journal of Climate, 2*(4), 305–320. https://doi.org/10.1175/1520-0442(1989)002<0305:APFLSR>2.0.CO;2
Gutowski, W. J., Jr., Giorgi, F., Timbal, B., Frigon, A., Jacob, D., Kang, H. S., et al. (2016). WCRP Coordinated Regional Downscaling Experiment (CORDEX): A diagnostic MIP for CMIP6. *Geoscientific Model Development, 9*(11), 4087–4095. https://doi.org/10.5194/gmd-9-4087-2016
Harris, I. C., & Jones, P. D. (2017). CRU TS4.01: Climatic Research Unit (CRU) Time-Series (TS) version 4.01 of high-resolution gridded data of month-by-month variation in climate (Jan. 1901- Dec. 2016). University of East Anglia Climatic Research Unit, Centre for Environmental Data Analysis, https://doi.org/10.5285/58a8802721c946c66a4e53b4a8d814d0, Release Notes: https://crudata.uea.ac.uk/cru/data/hrg/cru_ts.4.01/Release_Notes_CRU_TS4.01.txt

Huntington, T. G. (2006). Evidence for intensification of the global water cycle: Review and synthesis. *Journal of Hydrology*, 319(1-4), 83–95. https://doi.org/10.1016/j.jhydrol.2005.07.003

Intergovernmental Panel on Climate Change (IPCC) (2014). Climate change 2014: Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC Assessment Reports, 151 pp., IPCC, Geneva, Switzerland.

Jimenez, C., Prigent, C., Mueller, B., Seneviratne, S. I., McCabe, M. F., Wood, E. F., & Fisher, J. B. (2011). Global intercomparison of 12 land surface heat flux estimates. *Journal of Geophysical Research*, 116, D01203. https://doi.org/10.1029/2010JD014545

Kim, J., Waliser, D. E., Mattmann, C. A., Godale, C. E., Hart, A. F., Ziminars, P. A., et al. (2014). Evaluation of the CORDEX-Africa multi-RCM hindcast: Systematic model errors. *Climate Dynamics*, 43(5-6), 1189–1202. https://doi.org/10.1007/s00382-013-1751-7

Knisel, S., Goergen, K., Buonomo, E., Christensen, O. B., Colette, A., Cardoso, R. M., et al. (2017). Land-atmosphere coupling in EURO-CORDEX evaluation experiments. *Journal of Geophysical Research: Atmospheres*, 122, 79–103. https://doi.org/10.1002/2016JD025476

Knutti, R., Furrer, R., Tebaldi, C., Cermak, J., & Meehl, G. A. (2010). Challenges in combining projections from multiple climate models. *Journal of Climate*, 23(10), 2739–2758. https://doi.org/10.1175/2010JCLI3361.1

Koster, R. D., Sud, Y. C., Guo, Z., Dirmeyer, P. A., Bonan, G., Oleson, K. W., et al. (2006). GLACE: The global land–atmosphere coupling experiment. Part I: overview. *Journal of Hydrometeorology*, 7(4), 590–610. https://doi.org/10.1175/JHM510.1

Liu, Y. Y., de Jeu, R. A., McCabe, M. F., Evans, J. F., & van Dijk, A. I. (2011). Global long-term passive microwave satellite-based retrievals of vegetation optical depth. *Geophysical Research Letters*, 38, L18402. https://doi.org/10.1029/2011GL048684

Martens, B., Miralles, D., Llovens, H., Fernández-Prieto, D., Verhoest, N. E. (2016). Improving terrestrial evaporation estimates over continental Australia using assimilation of SMOS soil moisture. *International Journal of Applied Earth Observation and Geoinformation*, 48, 146–162. https://doi.org/10.1016/j.jgso.2015.09.012

Martens, B., Miralles, D., Llovens, H., van der Schalie, R., de Jeu, R. A., Fernández-Prieto, D., et al. (2017). GLEAM v3: Satellite-based land evaporation and root-zone soil moisture. *Geoscientific Model Development*, 10(5), 1903–1925. https://doi.org/10.5194/gmd-10-1903-2017

Mascaro, G., White, D. D., Westerhoff, P., & Bliss, N. (2015). Performance of the CORDEX-Africa regional climate simulations in representing the hydrological cycle of the Niger River basin. *Journal of Geophysical Research: Atmospheres*, 120, 12,425–12,444. https://doi.org/10.1002/2015JD023905

Miralles, D. G., Holmes, T. R. H., De Jeu, R. A. M., Gash, J. H. C., Meesters, A. G. C. A., & Dolman, A. J. (2011). Global land-surface evaporation estimated from satellite-based observations. *Hydrology and Earth System Sciences*, 15(2), 453–469. https://doi.org/10.5194/hess-15-453-2011

Miralles, D. G., Teuling, A. J., van Heerwaarden, C. C., & Vilà-Guerau de Arellano, J. (2014). Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. *Nature Geoscience*, 7(5), 345–349. https://doi.org/10.1038/ngeo2141

Miralles, D. G., Van Den Berg, M. J., Teuling, A. J., & De Jeu, R. A. M. (2012). Soil moisture-temperature coupling: A multiscale observational analysis. *Geophysical Research Letters*, 39, L21707. https://doi.org/10.1029/2012GL053703

Moss, R. H., Edmonds, J. A., Hibbard, K. A., Manning, M. R., Rose, S. K., van Vuuren, D. P., et al. (2010). The next generation of scenarios for climate change research and assessment. *Nature*, 468(7327), 747–756. https://doi.org/10.1038/nature09823

Mueller, B., & Seneviratne, S. I. (2012). Hot days induced by precipitation de"
