Call: H2020-SC5-2014-two-stage
Topic: SC5-01-2014

**PRIMAVERA**
Grant Agreement 641727

**PRocess-based climate sIMulation: AdVances in high resolution modelling and European climate Risk Assessment**

# Deliverable D*3.2*
## *Land surface-atmosphere coupling*

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| Deliverable Title | *Land surface-atmosphere coupling* | |
| Brief Description | This deliverable contains a multi-model assessment of the resolution effects on the land-atmosphere interaction. | |
| WP number | 3 | |
| Lead Beneficiary | *UREAD* | |
| Contributors | *Omar Müller (UREAD)*<br>*Pier Luigi Vidale (UREAD)*<br>*Bennoît Vannière (UREAD)*<br>*Reinhard Schiemann (UREAD)* | |
| Creation Date | 30/04/2019 | |
| Version Number | 1 | |
| Version Date | 30/04/2019 | |
| Deliverable Due Date | 31/10/2019 | |
| Actual Delivery Date | 14/06/2019 | |
| Nature of the Deliverable | R | *R - Report* |
| | | *P - Prototype* |
| | | *D - Demonstrator* |
| | | *O - Other* |
| Dissemination Level/ Audience | PU | *PU - Public* |
| | | *PP - Restricted to other programme participants, including the Commission services* |
| | | *RE - Restricted to a group specified by the consortium, including the Commission services* |
| | | *CO - Confidential, only for members of the consortium, including the Commission services* |

| **Version** | **Date** | **Modified by** | **Comments** |
|---|---|---|---|
| 1 | 20-05-2019 | PVDL | Final |
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## 1. Executive Summary

The following note presents the quantification and evaluation of land-atmosphere coupling strength in the new generation of high-resolution global models. The land-atmosphere strength is computed using one of the state-of-the-art techniques which highlights regions where the soil dynamics, contributes, to a varying degree measured by the index, to drive the surface fluxes, and thereby, the overlying atmosphere. The results suggest that enhancing the model resolution improves the large-scale circulation overall (e.g. see Vanniere et al. 2019), but, specifically for the Sahel region, leading to a more accurate representation of the interplay among rainfall, soil moisture and evapotranspiration. This improvement in models could benefit the simulation of processes with regional to global impact, such as, the West African Monsoon and the African Easterly Waves that trigger tropical cyclones.

## 2. Project Objectives

With this deliverable, the project has contributed to the achievement of the following objectives (DOA, Part B Section 1.1) WP numbers are in brackets:

| No. | Objective | Yes | No |
|---|---|---|---|
| A | To develop a new generation of global high-resolution climate models. *(3, 4, 6)* | | |
| B | To develop new strategies and tools for evaluating global high-resolution climate models at a process level, and for quantifying the uncertainties in the predictions of regional climate. *(1, 2, 5, 9, 10)* | | |
| C | To provide new high-resolution protocols and flagship simulations for the World Climate Research Programme (WCRP)'s Coupled Model Intercomparison Project (CMIP6) project, to inform the Intergovernmental Panel on Climate Change (IPCC) assessments and in support of emerging Climate Services. *(4, 6, 9)* | | |
| D | To explore the scientific and technological frontiers of capability in global climate modelling to provide guidance for the development of future generations of prediction systems, global climate and Earth System models (informing post-CMIP6 and beyond). *(3, 4)* | | |
| E | To advance understanding of past and future, natural and anthropogenic, drivers of variability and changes in European climate, including high impact events, by exploiting new capabilities in high-resolution global climate modelling. *(1, 2, 5)* | | |
| F | To produce new, more robust and trustworthy projections of European climate for the next few decades based on improved global models and advances in process understanding. *(2, 3, 5, 6, 10)* | | |
| G | To engage with targeted end-user groups in key European economic sectors to strengthen their competitiveness, growth, resilience and ability by exploiting new scientific progress. *(10, 11)* | | |
| H | To establish cooperation between science and policy actions at European and international level, to support the development of effective climate change policies, optimize public decision making and increase capability to manage climate risks. *(5, 8, 10)* | | |

## 3. Detailed Report

### 3.1 Objectives and methodology

The land surface is recognized as a key driver of the climate variability and predictability at different time scales (Koster et al., 2000). Changes in soil conditions can affect the land-atmosphere feedbacks and, therefore, the regional climate (Dirmeyer, 2000). There are particular regions of the Earth with strong land-atmosphere coupling, where the land surface state represented by the soil moisture have a direct effect on the overlying atmosphere. On these hotspots, soil moisture modulates land-atmosphere feedbacks through the exchanges of latent and sensible heat fluxes (Koster et al., 2004). It also interacts and modifies runoff, leading to potential changes in river flows. Through these processes, the state of the land-atmosphere coupling can modify the persistence and intensity of droughts or wet spells. For instance, it has been suggested that the land-atmosphere coupling can determine a significant portion of the summer climate variability and extremes in the European region primarily through the soil moisture-evapotranspiration feedback (Seneviratne et al., 2006). Soil moisture has been shown in modelling studies to act as a precursor of extreme maximum temperature and drought in the European region (Fischer et al. 2007; Zampieri et al. 2009, Quesada et al. 2012, van der Linden 2019).

The objective of this deliverable is to evaluate the effect of the increasing GCMs resolution on the simulation of land-atmosphere coupling. To this end, we (a) quantify the seasonal land-atmosphere coupling for a set of simulations at different resolution, and (b) advance in the understanding of resolution effects on the interplay between soil moisture and surface fluxes and the potential links to changes in global circulation patterns. We will make use of both uncoupled (atmosphere-land-only) and coupled (atmosphere-land-ocean) simulations under different resolutions (from WP2 and WP4) for a set of GCMs simulations of the CMIP6 HighResMIP experiments. Table 1 provides a description of the simulations used on this report indicating the GCMs and the corresponding land-atmosphere resolution.

| GCM | Low Resolution Grid (Res at 50°N) | High Resolution Grid. (Res at 50°N) |
|---|---|---|
| HadGEM3.1 | 192x144 (~135km) | 1024x768 (~25 km) |
| EC-Earth3 | 360x181 (~ 80km) | 760x361 (~39 km) |
| MPIESM-1-2 | 384x192 (~ 64km) | 768x384 (~32 km) |
| ECMWF-IFS | 512x256 (~ 50km) | 1024x512 (~25 km) |

**Table 3.1.1.** GCMs resolution used to compute the land-atmosphere coupling.

The metric used to quantify the coupling is the Terrestrial Coupling Index (Dirmeyer, 2011) which highlights regions where soil moisture changes drive surface fluxes variability. It is defined as: $TCI = \frac{covar(SM,FLUX)}{var(SM)} sd(SM)$. The first factor of the product calculates the slope of the linear regression of fluxes (sensible or latent heat FLUX) against soil moisture (SM). The second factor weights the slope by the soil moisture variability, aiming to smooth the index value on sites with large correlation and slope, albeit nearly invariant soil moisture. Figure 3.1.1 shows and example of the relationship between soil moisture and latent heat flux for different sites. On dry regions (yellow dots) any increment in soil moisture produce evapotranspiration, but soil moisture varies in a narrow range and the land-atmosphere interaction is not significant. This feature is captured by low *sd(SM)* and the index is indicative of weak coupling. Wet regions (blue dots) evapotranspire near their maximum rate and any change in soil moisture does not produce a strong effect on latent heat. In these cases the index is low, due to a small slope. On the other hand, strong coupling is obtained in arid regions (green dots) where there is a good spread of soil moisture conditions, which drives the evapotranspiration variability.

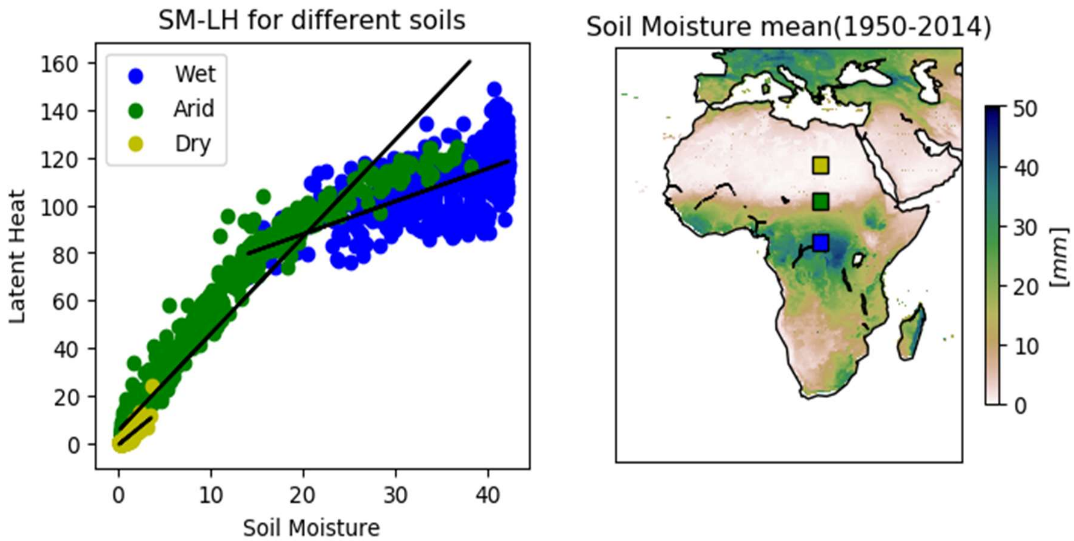


**Figure 3.1.1.** Example of monthly soil moisture – latent heat flux relationship (left panel) for sites with different soil moisture conditions as indicated in the right panel. The black lines show the linear regression for each site.

The results of the multi-model assessment of the land-atmosphere coupling is presented in section (3.2). In section (3.3) we advance in the understanding of resolution effects on the land-atmosphere interaction focusing the analysis on regions where the resolution modifies the coupling features.

## 3.2 Multi-model assessment of land-atmosphere coupling

The TCI was computed for the simulations presented in Table 3.1.1 using the following technical setup:

- Seasonal quantification of the index (MAM, JJA, SON, DJF) based on monthly data for the period 1950-2014.
- For soil moisture, the top three layers of each model was used, to account for water content availability for evaporation (first layer), but also for transpiration (second and third layers). The layers thickness varies from model to model: for HadGEM3.1, EC-Earth3 and ECMWF-IFS the top three layers depth is 1.0m, for MPIESM-1-2 the depth is 1.24m. The unit was volumetric content $[m^3/m^3]$ to avoid discrepancies caused by differences in soil layer thickness among models.
- As showed in (3.1) the coupling index is a statistical technique and all general caveats related to significance apply. Consequently, grid points where the soil moisture – flux correlation have a confidence level < 99% where masked out.

The results for low resolution simulations are presented in Fig. 3.2.1. The ‘hot spots’ of land-atmosphere coupling where the soil moisture condition drives the latent heat flux are those with highest values. The models show a notable agreement in the identification of hot spots, with slight variations in their intensity. In particular MPIESM-1-2 shows largest values suggesting a strongest dependence of soil state on the estimation of evapotranspiration. The multi-model ensemble TCI mean (see Fig. 3.2.2 top left panel) shows that the main hot spots per season are:

- MAM: Brazilian savanna, Sahel, southern Africa, northern Australia.
- JJA: Great Plains US, Sahel, western steppe of Eurasia, India.
- SON: Brazilian savanna, Sahel, southern Africa, India.
- DJF: Argentinian Pampas, southern Africa, northern Australia.

In other areas, the coupling is weak because the soil is too dry and there is not enough water content for soil evaporation or plants transpiration, else the soil is too wet and any increase in soil moisture does not produce significant changes in evapotranspiration. All GCMs produce hot spots in regions with semi-arid climate, particularly those with hot semi-arid climate, where the precipitation anomalies modify the soil and vegetation state, which in turn affect the surface fluxes into the overlying atmosphere. In terms of seasonality, in general the hot spots take place during the transition from dry to wet monsoon seasons. During these months the monsoon circulations provide strong precipitation variability, enhancing the potential land-atmosphere interactions. Overall, the land-atmosphere coupling hot spots identified by GCMs present a strong resemblance with those previously reported by Dirmeyer (2011) and Koster et al. (2004, 2006) for boreal summer.

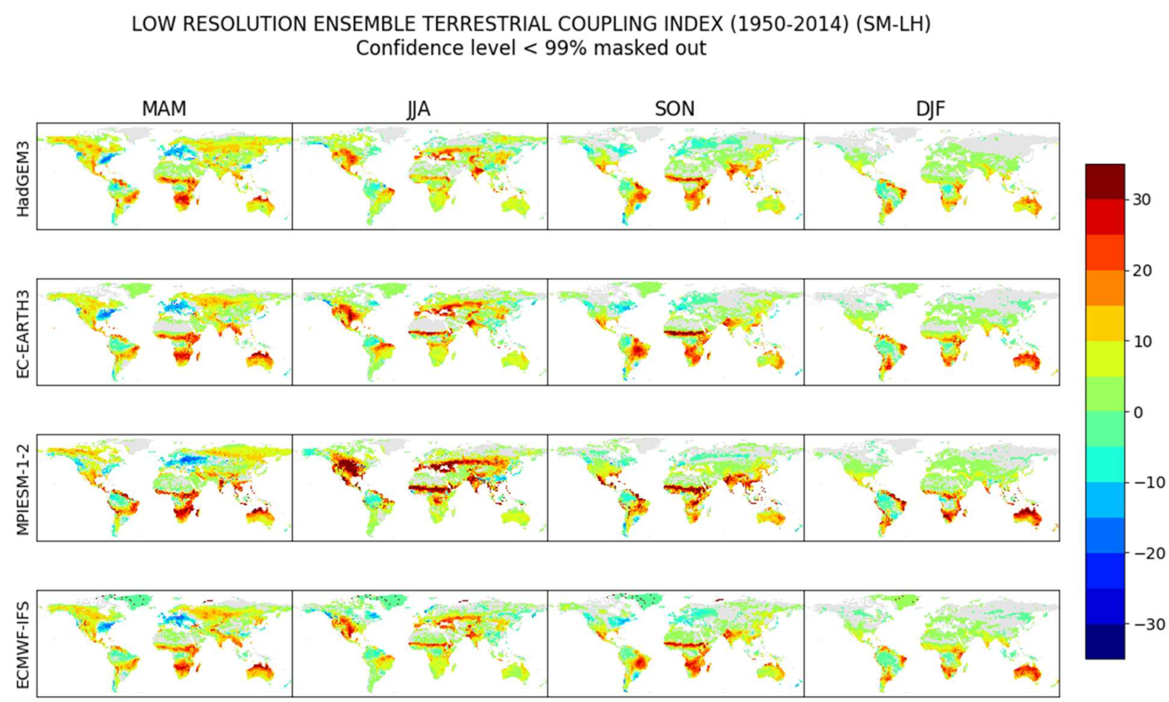


**Figure 3.2.1.** Seasonal TCI for each GCM at low resolution for the period 1950-2014. Grey shades indicate masked out grid cells where the correlation between soil moisture and latent heat are not significant at the 99% confidence level.

The top right panel of Fig. 3.2.2 shows the multi-model ensemble TCI mean for GCMs at high resolution, while the bottom panels show the differences (high minus low resolution) for uncoupled (left) and coupled (right) simulations. The enhanced GCMs resolution do not produce significant differences in hotspots. There is an increment of less than 1% of grid-cells with high coupling ($TCI > 20\ W/m^2$) at high resolution. However, a particular change is observed in the Sahel hotspot, where there is a clear northward shift in the coupling at high resolution, i.e. reduced coupling to the south and enhanced coupling to the north. The coupling shift starts in JJA and persists until SON. This shift is produced by all GCMs and it is more remarkable for land-atmosphere-ocean simulations.

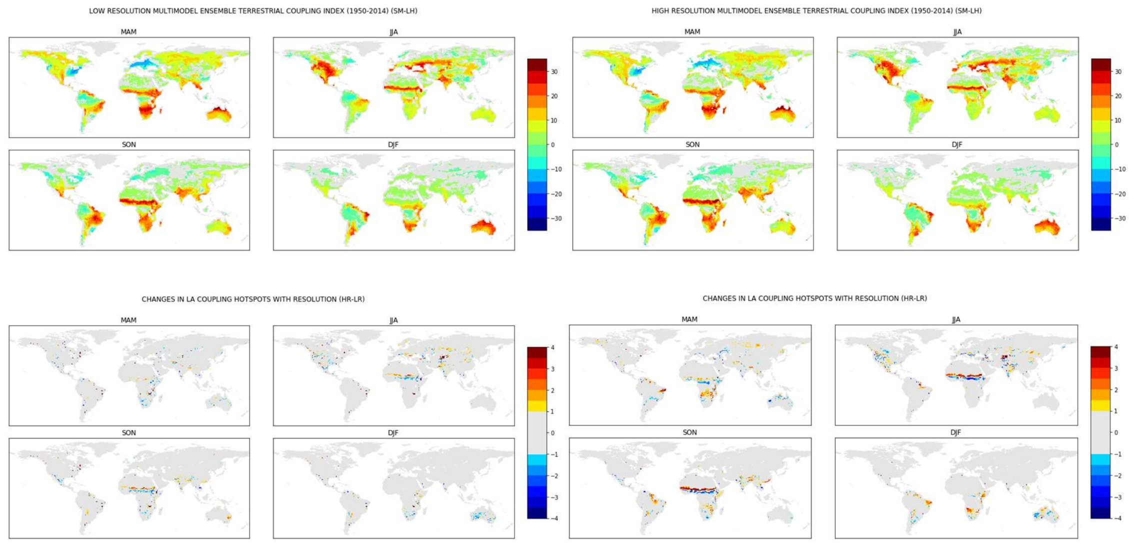


**Figure 3.2.2.** Multi-model seasonal TCI for uncoupled (atmosphere-land-only) simulations at low (top left) and high resolution (top right), their differences (bottom left) and the resolution differences for coupled (atmosphere-land-ocean) simulations (bottom right). In the bottom panels only hotspots were considered ($TCI > 5\,W/m^2$ in both resolutions).

## 3.3 Effects of horizontal resolution in the Sahel hot spot

A zoom over the Sahel hot spot is done in Fig. 3.3.1 showing the differences in TCI, but also in a set of atmospheric and surface variables that allow a plausible explanation of the shift observed in high resolution models. The shift starts in boreal summer (left column) due to changes in the atmospheric conditions. At high resolution the mountains in the Horn of Africa (blue-green shades in second row) are better defined and modify the African Easterly Jet (AEJ). There is a strong decrease of easterlies south of 12.5N (dotted line) and, on the other hand, a slight increase north of 12.5N that leads to a stronger background horizontal wind shear. The changes in AEJ magnifies the relative vorticity, dominated by anticyclonic systems to the north and cyclonic circulation to the south. The enhanced instability favours precipitation events, and thereby, wetter soil conditions. This process (a) helps to increase the evapotranspiration where the soil was dry at low resolution enhancing the coupling above 12.5N, and (b) produce more runoff where the soil was already wet at low resolution reducing the coupling below 12.5N.

In boreal autumn (right column) the TCI shift has a notably resemblance with that observed in the previous season, however the changes in coupling are triggered by the soil conditions rather than the atmospheric conditions. There is a slight increase in relative vorticity and precipitation at high resolution, which explain in part the positive difference in soil moisture. However, the increment of soil moisture is mostly explained by the precipitation occurred in the previous season, which persists due to the soil ‘memory’ effect (Koster and Suarez, 2001, Wu and Dickinson, 2004, Seneviratne et al. 2006). The lagged effect of precipitation is clearly visible in Fig. 3.2.2 (left panel) which shows the maximum soil moisture in September, one month after the rainy season. Moreover, the right panel shows that the summer soil moisture is well correlated with the summer precipitation, while the autumn soil moisture is highly correlated with the precipitation in JAS, demonstrating how the soil ‘remember’ the wet atmospheric conditions in previous months. As a result, the wetter soil has a positive feedback with evapotranspiration to the north strengthening the coupling, and on the other hand, it produces more runoff to the south, weakening the land atmosphere interaction.

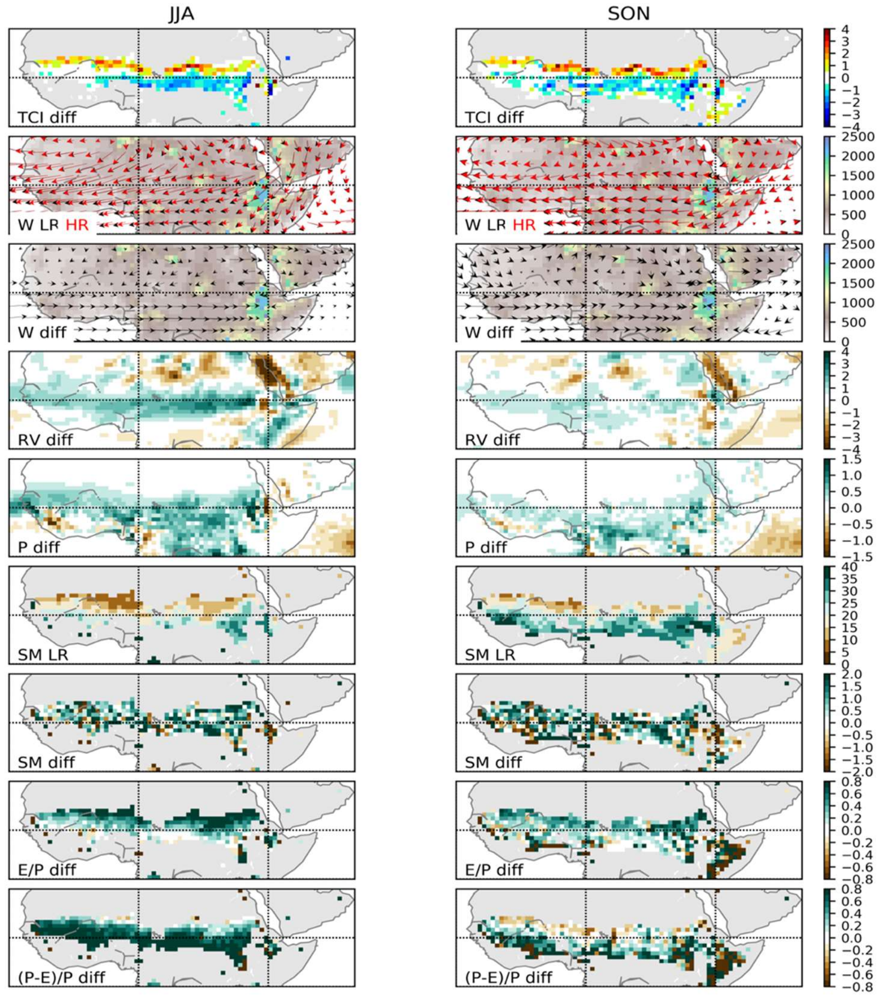


**Figure 3.3.1.** Differences in TCI, atmospheric and soil variables over the Sahel hotspot caused by changes in GCMs resolution during summer (left column) and autumn (right column). From top to bottom: TCI (HR-LR), winds at 600hPa (LR and HR), winds at 600hPa (HR-LR), relative vorticity (HR-LR), precipitation (HR-LR), top 3 layers soil moisture (LR), top 3 layers soil moisture (HR-LR), fraction of precipitation partitioned as evapotranspiration (HR-LR) and as runoff (HR-LR). Grid cells outside the hotspot were masked out for TCI and soil variables.

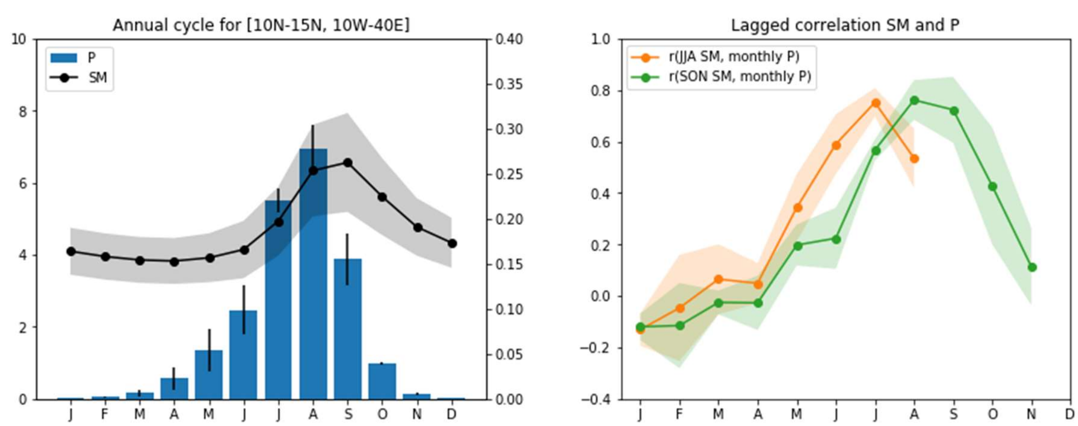


**Figure 3.3.2.** Precipitation and soil moisture relationship in high resolution AMIP-type simulations. Left panel: Mean annual cycle of precipitation and soil moisture. Right panel: lagged correlation between seasonal soil moisture (JJA and SON) and monthly precipitation. The bars and curves show the multi-model ensemble mean, while error bars and shades show the ensemble standard deviation.

The overall differences in the Sahel coupling starts with an increase of atmospheric instability, which produces more rain at high resolution. This effect of model resolution in the Sahel was previously reported by Vellinga et al. (2016) in a research based on single model (HadGEM3-GA3) simulations. Using high-frequency precipitation (3-hourly), they found that high resolution simulations are able to produce and propagate westward intense convective systems. Although high resolution HadGEM models still underestimate intense rainfall events, they better compare with observations than low resolution HadGEM, e.g. when compared to TRMM. In this work, the change in location and amount of rainfall, which governs the coupling shift, is a consistent result, observable by all GCMs. However, the Sahel is a region with an important scarcity of in-situ observations for the analyzed period preventing a reliable evaluation of the realism of the shift. An alternative way to evaluate the water balance is to compare model against observed river discharge, considering it as an integrator of the water budget at catchment scale. The Fig. 3.2.2 presents the Niger basin discharge at Lokoja, Nigeria with observed data provided by Dai (2017). The observations (black) shows that Niger flow has a marked annual cycle with maximum in October when the river collects the precipitation produced during the wet season (from July to September) of the West African Monsoon (WAM), and minimum discharge in May after the dry monsoon season. This seasonal evolution is correctly simulated by models at both resolutions, although with significant negative biases at low resolution (blue), that are partially corrected at the high resolution (orange). The Table 3.3.1 shows the notably improvement at high resolution reducing the annual and the autumn biases from about -40% to about -6%, and the summer bias from -40% to -20%. This assessment suggests that the water cycle, and thereby, the estimated precipitation by models at high resolution is notably closer to the reality than the low resolutions estimates. However, the Niger basin does not cover the whole Sahel and the evaluation should be complemented with satellite products.

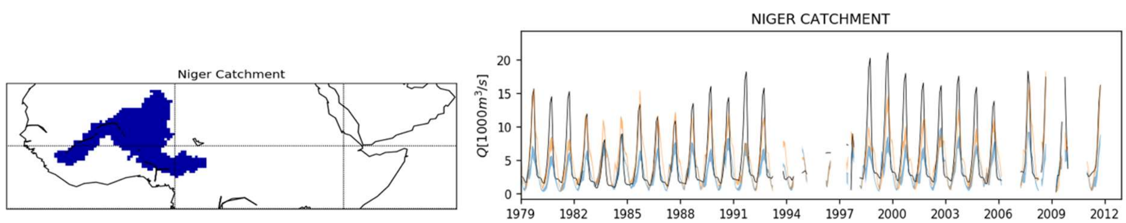


**Figure 3.3.3.** Niger catchment closed at Lokoja, Nigeria (left) and its discharge (right) for observations (black), HadGEM3.1 at low resolution (blue) and high resolution (orange).

| | Annual Q $[10^3 m^3/s]$ | Bias [%] | JJA Q $[10^3 m^3/s]$ | Bias [%] | SON Q $[10^3 m^3/s]$ | Bias [%] |
|---|---|---|---|---|---|---|
| Obs | 5.3 | | 5.4 | | 6.1 | |
| Low Res | 3.2 | -39.6 | 3.1 | -42.6 | 3.7 | -39.3 |
| High Res | 5.0 | -5.7 | 4.3 | -20.4 | 5.7 | -6.6 |

**Table 3.3.1**. Niger river mean annual, JJA and SON discharge for observations and HadGEM at low and high resolution and the corresponding mean percentage biases.

## 3.5 References

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## 4. Lessons Learnt

- The evaluated CMIP6 GCMs correctly identify the regions with strong land-atmosphere interaction reported by Koster et al (2004), Dirmeyer (2011) among others.

- Land-atmosphere coupling in the GCMs analyzed here is sensitive to both resolution and ocean-land-atmosphere coupling, with the latter playing a larger role in the Sahel region.

- It is not clear that the increase of model resolution is sufficient to cause, per se, any effect on the land-atmosphere coupling. However, our analyses suggest that the better resolved orography at high resolution improves the large-scale circulation upstream of the circulation that governs the precipitation location and timing, thus leading to a more realistic representation of the land-atmosphere hotspots.

- At high resolution, all GCMs agree with a northward shift in the Sahel hotspot that starts in boreal summer and continues in autumn. The shift is originated by changes in atmospheric conditions during JJA. The enhanced orography favours the horizontal wind shear, increasing vertical atmospheric instability and producing more rain and soil moisture over the Sahel. It leads to a positive feedback (a) with evapotranspiration to the north of Sahel increasing the coupling, (b) with runoff to the south of Sahel reducing the coupling. In the next season (SON) the atmospheric differences between high and low resolution are weak. However, the coupling shift persists due to the soil moisture memory that keeps the same conditions in the land-atmosphere interplay.

- The river discharge evaluation is a plausible diagnostic to test the water balance at catchment scale on regions with low density of in-situ observations (e.g. on this work, the Niger discharge observations were used to assess the catchment water balance, and the results show that it is better resolved by high resolution models, suggesting that the coupling is more realistic when the resolution is enhanced).

## 5. Links Built

- The diagnostics used on this report were applied on simulations provided by WP2 and WP4 and will be available for application for model simulations in WP3. These diagnostics will be adopted by WP1 as a metric to evaluate land-atmosphere interactions.

- The activities carried out on this work have a link with projects that are not funded directly under this (eg. PORCELAIN and the International Soil Modeling Consortium).