Possible influence of climate change on water balance over West Africa under the global warming levels of 2 and 3 °C

Mojisola Oluwayemisi Adeniyi

ABSTRACT

Reliable projection of water balance components for the future over a climate change vulnerable region such as West Africa is exigent for proper adaptation strategies. This paper analyses the expected water balance in the 21st century over West Africa at 2 and 3 °C global warming level (GWL) based on Rossby Centre Regional Atmospheric Climate Model (RCA4) downscaled projections. Precipitation is expected to increase at the south-western (−5 to 10°N, 15 to 25°W) ocean area of West Africa domain with SW–NE orientation, towards the Sahel, while other areas would be drier, at 2 °C GWL. This would intensify under 3 °C GWL. Responses of evapotranspiration and storage change are similar to that of precipitation except for more spatial spread of increased evapotranspiration on the ocean. Runoff would increase over the ocean, Sahara and part of Sahel and reduce in Savannah and Guinea Coast under 2 °C GWL, but reduce under a warmer world with isolated increase.

Key words | evapotranspiration, GWL, RCA4, runoff, storage change, water balance

HIGHLIGHTS

- Precipitation would increase during AMJJAS from the Atlantic Ocean to the Sahel with SW–NE orientation under 2 °C Global Warming Level (GWL).
- Wetness along SW–NE would intensify with increasing GWL.
- Evapotranspiration and storage change would increase with increasing GWL during AMJJAS.
- Runoff would increase over the ocean and high latitudes, while it would reduce at the lower latitudes under 2 °C GWL during AMJJAS.

INTRODUCTION

Limiting the global warming level (GWL) to below 2 °C as agreed in Paris at the 21st session of the United Nations Framework Convention on Climate Change Conference of the Parties (COP21) in 2015 (Falkner 2016) would require a new set of IPCC climate scenarios that would specifically target the different GWLs. However, such scenarios are not yet available. To worsen the situation, the low emission scenario currently in use, Representative Concentration Pathway (RCP) 2.6, which can produce below 2 °C, is an ambitious one, since it is difficult for the countries and individuals whose economies are dependent on greenhouse gas (GHG) emissions to reduce the emission to RCP 2.6 level. The medium scenario (RCP 4.5) seems to be achievable and should be considered for probable achievement of the required GWLs. The 1.5, 2.0, 2.5 and 3.0 are all achievable from RCP 4.5 but the global climate models (GCMs) that projected up to 3 °C GWL are few, so the 3 °C window of
possible GWL in RCP 4.5 has been generally neglected in most analyses. Those that considered 3°C GWL did so under RCP 8.5 (Weber et al. 2018), which is the high emission scenario. It is important to study the possible influence of 3°C GWL in RCP 4.5 on the climate of a climate change impact vulnerable region such as West Africa (Weber et al. 2018). This region is vulnerable due to insufficient adaptation strategies and infrastructure as a result of uncertainties in projected future climate changes (Yira et al. 2017; Weber et al. 2018). The GCMs remain the best at simulating changes in climate based on various levels of GHGs in the atmosphere. However, such simulations do not represent the local climate well; they are more reliable on a continental scale. This makes downscaling with the use of RCMs necessary for climate impact studies (Schleussner et al. 2016; Nikulin et al. 2018). Studies on climate change that used downscaled data did not consider water budget over West Africa (Gutowski et al. 2016; Nikulin et al. 2018). Moreover, most analyses have been based on specific timing in the future and not GWLs. Those that also considered GWLs mostly used the 1.5 and 2°C GWLs (Deque et al. 2017; Nikulin et al. 2018). The 3°C GWL in RCP 4.5 has been somehow neglected as a result of the low number of models in the subset, based on the GLWs analysis of Nikulin et al. (2018). Nikulin et al. (2018) documented the effects of 1.5°C and 2°C warming on Africa in the Coordinated Regional Downscaling Experiment (CORDEX) ensemble basically because the 2°C target has attracted research attention as the value that is close to the tolerable global temperature. The 1.5°C target was later included for possible attainment above preindustrial level (Nikulin et al. 2018). Although interest has shifted to 1.5–2°C warming, 3°C warming from the medium scenario (RCP 4.5) is also a possibility since the future is not known. Furthermore, only a 0.5°C increase in temperature is expected to have a significant effect on the regional climate of West Africa (Nikulin et al. 2018), so 1 to 1.5°C increase would have a greater impact. Weber et al. (2018) considered extended windows of GWLs: 1.5°C, 2°C and 3°C. They revealed the influence of 3°C warming on the significant increase in number of hot nights. However, the 3°C GWL has not been fully explored over West Africa. A number of publications are available on impacts of climate change on precipitation over Africa or a subregion of Africa (Abiodun et al. 2017; Fotso-Nguemo et al. 2017). Previous analyses of the impact of climate change on the climate of Africa have been based on either an ensemble of downscaled climate at the same time period (early, mid or late 21st century) or GWLs (1.5, 2, or 3°C). The studies on precipitation did not fully explore the projected water balance components using the same time periods and GWLs. This study combines the two approaches to provide refined sub-regional seasonal information by using the same time period of simulation for each GWL from the different GCMs.

With the assumption that the medium scenario is achievable, there is still some probability of having a GWL of 3°C. This paper considers the RCA4 downscaled water balance components from two GCMs under RCP 4.5 and 2 and 3°C GWLs. The ensemble from the two GCMs that reached 3°C under RCP 4.5 is considered at the same time period to provide possible expected influence of GWL of 2 and 3°C under the medium scenario RCP 4.5 on water balance components over West Africa. This would be considered for the first time over West Africa using RCM downscaled projections from GCMs under GWLs 2 and 3°C. The influence of 2 and 3°C GWL on water balance is also considered under RCP 8.5 for comparison. The downscaled output of two GCMs has been used in this paper to analyse the seasonal water budget over West Africa under 2°C and 3°C GWLs based on the IPCC RCPs 4.5 and 8.5 in the atmosphere. This study aims at identifying the areas prone to moisture deficit and those prone to moisture surplus over West Africa. Such information would help in policy and strategies for adaptation against climate change impacts over the region.

DATA AND METHODOLOGY

Model set-up

This study uses downscaled product from CORDEX based on version 4 of the Rossby Centre Regional Atmospheric Climate Model (RCA4). The model outputs are available at: https://esg-dn1.nsc.liu.se/search/cordex/. The RCA4 model was developed at the Swedish Meteorological and Hydrological Institute (SMHI). High Resolution Limited Area Model (HIRLAM) (Unden et al. 2002) was the basis of RCA4 and the latter has evolved with improved physical,
dynamical parameterizations (Strandberg et al. 2015) and land surface scheme (LSS) (Samuelsson et al. 2015). The most important aspects of the surface scheme that were changed with respect to RCA3 were: (i) a new physiography database was used; (ii) the number of soil layers with respect to soil moisture were increased from two to three and there were also separate soil columns with respect to soil water under forest and open land, respectively; (iii) an exponential root distribution was used; (iv) the density of organic carbon was used to modify soil properties; (v) the prognostic snow albedo was modified to perform better in cold-climate conditions; (vi) Flake was introduced as a lake model and lake depth was defined from a global lake-depth data base; and (vii) the dynamic vegetation model Lund-Postdam-Jena-General Ecosystem Simulator (LPJ-GUESS) was introduced for vegetation-climate feedback studies (Strandberg et al. 2015).

The Kain–Fritsch (Kain 2004) convection scheme was used for parameterization of convection. The HIRAM’s radiation scheme (Sass et al. 1994) was modified for proper treatment of carbon dioxide absorption and water vapour cycle. Noilhan & Planton (1989) vegetation-dependent land-surface parameters were employed. Semi-Lagrangian and semi-implicit schemes were applied to the prognostic variables (Jones et al. 2004). Strandberg et al. (2015) documented the detailed improvement on RCA3 in RCA4.

The RCA4 simulations were carried out over the CORDEX-Africa domain on 0.44° × 0.44° horizontal grids (Figure 1). The historical simulations from the Canadian Centre for Climate Modelling and Analysis Earth System Model version 2 (CanESM2) and Medium Resolution Institute Pierre-Simon Laplace Coupled Model version 5 (IPSL-CM5A-MR) were used as the initial and lateral boundary conditions for the RCA4 simulations from January 1950 to December 2005 for downscaling of the historical simulations. The climate projections run from 2006 to 2100 under RCPs 4.5 and 8.5 scenarios (Samuelsson et al. 2015) from the two GCMs were also downscaled using RCA4. These simulations were all performed under the CORDEX experiments.

**Choice of GCMs**

The GWL method of Nikulin et al. (2018) has been used to select the models under RCP 4.5 that reach 3 °C with reference to the preindustrial period of 1861–1890. Based on
Nikulin et al. (2018), the timing of GWLs used in this study is the time (centre year) that the 30-year moving averages of global temperature first go beyond 2°C or 3°C with respect to 1861–1890 temperature climatology. The models that satisfy the 2°C and 3°C GWLs conditions under RCP 4.5 are also used for the RCP 8.5 projections for comparison. The timing of the GWLs for the selected models under RCP 8.5 is also determined using a similar method (Nikulin et al. 2018). RCPs 4.5 and 8.5 are considered because they represent the medium and high scenarios, which are achievable as people comply with emission reduction or continue with business as usual, respectively. The 2°C GWL seems to be easily achievable with little effort of emission reduction by the population. The 2°C and 3°C GWLs are considered because the 3°C GWL under RCP 4.5, which is also a possibility, has been neglected. This study considered 3°C under RCP 4.5 to reveal the possible influence of the GWL under RCP 4.5 on the climate of West Africa. The same 20-year time period of at least 20 years, but not up to 30 years. The time range, which allows ensemble averaging at the same time period of at least 20 years, but not up to 30 years. The construction of the ensemble is based on equal weight. The CTRL period 1986–2005 has been chosen for this study for reliable observational data availability and also based on the end of historical simulation in 2005. Only two models that reached 3°C GWL under RCP 4.5 are used in this study, so the projections are limited in spread.

**Evaluation data**

The ability of the RCA4 downscaled historical GCM output to represent reality is assessed using precipitation, runoff, evapotranspiration and storage from ERA5 reanalysis data on 25 km × 25 km grids (C3S 2017). Furthermore, observed gridded precipitation and potential evapotranspiration from Climate Research Unit (CRU) 4.02 time series on 0.5 × 0.5 degrees grid (Harris et al. 2014) are compared with simulations. The datasets are re-gridded to the grid size of the downscaled output (0.44° × 0.44°) before use.

**Water budget**

The change in storage water is computed from Equation (1) using Healy et al.’s (2007) water balance equation:

\[
\text{PRE} = \text{RO} + \text{EVA} + \text{SC}
\]  

(1)

where PRE is precipitation, RO is runoff, EVA is evapotranspiration and SC is change in storage. The water budget equation equates the inflow and outflow of water in a particular location at a particular period. Precipitation is the main inflow (input) in Equation (1). Evapotranspiration is the amount of moisture loss into the atmosphere through evaporation and transpiration from the soils, surface-water bodies and plants. Runoff is the total flow of water out of the location and change in storage is the additional water added or removed from the soil water storage to balance Equation (1). Closure is not usually achieved without introducing the change in storage term. The water budget for the future is considered under three different seasons, which are the pre-planting (JFM), planting (AMJJAS) and post-planting (OND) seasons. The annual budget is also considered at 2 and 3°C GWL in RCPs 4.5 and 8.5 Wm⁻².

**Table 1 | Timing of GWLs 2°C and 3°C in downscaled models**

<table>
<thead>
<tr>
<th>S/M</th>
<th>Model</th>
<th>RCP 45</th>
<th>RCP 85</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2°C</td>
<td>3°C</td>
</tr>
<tr>
<td></td>
<td>Analysis periods</td>
<td>2027–2046</td>
<td>2068–2087</td>
</tr>
</tbody>
</table>
The biases in downscaled historical (CTRL) water balance components are calculated by finding the difference between the CTRL simulation and observation or reanalysis (CTRL-observation). The projected changes in the water balance components are computed as ‘downscaled projected value – CTRL value’. Bias correction for future projection is usually based on two major assumptions, which are constant bias or constant relation. If bias is constant, the change which is calculated as ‘scenario-control’ does not contain any bias since the biases cancel out. With the constant bias assumption, bias correction is not necessary since they will cancel out. On the other hand, if constant relation is assumed for the bias, biases exist but the estimation of bias requires comparison of the projected future values and observation. However, there exists no observation for the future, so the pseudo-reality approach is usually employed by selecting one model as the reference (Kerkhoff et al. 2014) to represent observation. This process introduces another bias into the projected climate, so the assumption of constant bias is assumed in this study. The biases cancel in the calculated change, such that bias correction is not necessary.

**RESULTS AND DISCUSSION**

**Evaluation of downscaled components of water balance**

The biases in the downscaled historical JJAS water balance components over West Africa with respect to CRU observations and ERA5 reanalysis are shown in Figure 2. The spatial pattern of bias in RCA4 downscaled precipitation with respect to CRU (Figure 2(a)) and ERA5 (Figure 2(b)) are similar with little or no bias at the north above 15°N and overestimation at the mountains. Precipitation is also overestimated at the coasts below 15°N (with the exception of south-south Nigeria) and at the ocean between 0 and 12°N. Bias has a magnitude of ≤2. The biases agree with documentations (Tamoffo et al. 2019) based on larger ensemble members. The bias in downscaled runoff is similar to that in downscaled precipitation over land and ocean area above 15°N (Figure 2(a)–2(c)). Evapotranspiration in the RCA4 is simulated without bias on land above 15°N but underestimated at the south below 15°N on land. Overestimation also prevails over the ocean (Figure 2(d)). However, there is little underestimation of runoff at the ocean below 15°N as against the overestimation in precipitation and evapotranspiration at this area (Figure 2(a)–2(c)). This is expected, since runoff is the excess water after the occurrence of evapotranspiration. Storage change is underestimated on land below 15°N, while it has no bias at the north above 15°N. Storage change is underestimated over the ocean but well represented at the portion of the ocean with wet bias (precipitation overestimation) (Figure 2(a), 2(b) and 2(e)) and this is also expected for closure achievement of the water balance equation.

**Projected water balance components**

**Projected water balance components under GWL 2 and 3 °C based on RCP 4.5 during pre-planting season (JFM)**

Figure 3 shows the downscaled projected changes in water balance components for 2 and 3 °C GWLs based on RCP 4.5 during the pre-planting season. Under 2 °C GWL, precipitation is expected to increase along the West Africa domain diagonal in a southwest–northeast (SW–NE) orientation, while the other areas would experience reduction in precipitation. For 3 °C GWL, precipitation over the ocean increases further both spatially and in magnitude (Figure 3(b) and 3(c)). Wetness change shifts to the western side of West Africa, including the ocean (Figure 3(b) and 3(c)). Some areas such as southern central and eastern ocean and land areas are projected to become drier (Figure 3(c)). Runoff under 2 °C GWL is projected to reduce in most part of West Africa except at south central and north central coastal areas (Figure 3(d)). However, for 3 °C GWL, widespread increase in runoff is projected over the ocean and land areas except south central coast, north central coast and land areas below 5°N (Figure 3(e) and 3(f)). At 2 °C GWL, evapotranspiration is projected to increase over the ocean and south-west to north-east diagonal of the West Africa domain (Figure 3(g)). A similar pattern is projected for 3 °C GWL with intensified evapotranspiration increase at the ocean and central land areas (Figure 3(h) and 3(i)). Storage change would reduce over ocean and increase at the coast and Savannah at 2 °C.
GWL. It would reduce in other areas of the West Africa domain (Figure 3(j)). Intensified reduction in storage change is projected at 3 °C GWL over the ocean areas and land. North-western coast and land areas are projected to experience increase in storage change (Figure 3(k) and 3(l)). Warming would usually lead to increased evapotranspiration from surfaces that contain water and vegetation, while dry and non-vegetated areas have no water for evapotranspiration. Figure 3(g) and 3(h) show increased evapotranspiration on the sea and low latitudes where there is usually vegetation. Increased warming causes more evapotranspiration at such places, especially where precipitation increases. With the increase in runoff at 3 °C GWL, storage would reduce generally over West Africa, but dilution, reduced salinity and fresh water would increase in the water bodies (Skliris et al. 2016).

Projected water balance components under GWL 2 and 3 °C based on RCP 8.5 during pre-planting season (JFM)

The projected changes in water balance components for 2 and 3 °C GWLs based on RCP 8.5 during the pre-planting season are presented in Figure 4. During the pre-planting season, isolated precipitation increase along the diagonal
of the West Africa domain with SW–NE orientation is projected (Figure 4(a)). Most parts of the ocean are expected to be drier. Under 3 °C warming, dryness over land is projected to increase, while wetness is expected to intensify over the south-eastern land area of the West Africa domain. Part of the ocean with wetness (south-western area) would also become wetter (Figure 4(b) and 4(c)). Runoff is projected to reduce all over the West Africa domain under 2 °C GWL, but the reverse is the case under 3 °C GWL (Figure 4(d) and 4(e)). Runoff is expected to increase all over West Africa except at southern land areas and the coastal north-west of the West Africa domain under 3 °C GWL (Figure 4(e) and 4(f)). Evapotranspiration under 2 °C GWL increases diagonally along SW–NE orientation on the West Africa domain (Figure 4(g)). It is projected to reduce at the south below 5°N on the land areas except at Gabon. With 3 °C GWL, evapotranspiration increases over the ocean, Sahel and south-eastern land areas of the West Africa domain are projected to intensify (Figure 4(h) and 4(i)). Storage change would reduce over
the ocean and south coast, while it would increase over the Sahara and part of Sahel under 2 °C GWL (Figure 4(j)). The 3 °C GWL would lead to intensified reduction in storage change at the ocean and land areas (Figure 4(k) and 4(l)).

RCPs 4.5 and 8.5 projected a similar pattern of changes in water balance components, with RCP 4.5 showing clearer signals of the changes. However, the change signals in precipitation are significant only at the ocean and coastal areas, whereas projected change signals for other water balance components are significant over a wider spatial area (Figure 3(a) and 3(b); Figure 4(a) and 4(b)). The projected above average precipitation over the Sahel and Savannah during the pre-planting season is not reliable.

**Projected water balance components under GWL 2 and 3 °C based on RCP 4.5 during planting season (AMJJAS)**

The expected responses of water balance components to 2 and 3 °C GWLs are shown in Figure 5. Based on the down-scaled projection, at 2 °C GWL, precipitation is expected to
increase at the south-western area of the ocean (−5 to 5°N, 15 to 25°W, Figure 5(a)) and reduce in other ocean areas. It is also projected to increase in the Sahel, along the SW–NE diagonal of the West Africa domain. With the increase of GWL to 3 °C, wetness over the ocean and the Sahel is projected to intensify (Figure 5(b) and 5(c)). Runoff would increase over the ocean and land at the southern part of West Africa, while it would reduce at the north at 2 °C GWL (Figure 5(d)). With increase in GWL to 3 °C, runoff is expected to reduce all over the entire West Africa domain except at the south-western coast and land (Figure 5(e) and 5(f)). During the planting season, evapotranspiration is projected to increase at the south, both over the ocean and land area (Figure 5(g)). Increase in GWL to 3 °C would increase evapotranspiration over the ocean and reduce it over the southern land area of West Africa (Figure 5(h) and 5(i)). Change in storage change is projected to have the same pattern as precipitation during AMJJAS with increase at the ocean between 5 and 10°N and 5–25°W. Reduction in storage change is projected at other southern ocean areas and Guinea Coast. However, Sahel is expected to have increased storage change (Figure 5(j)). With 3 °C warming, areas with increased storage change such as the Sahara and Sahel would have

Figure 5 | The AMJJAS RCP 4.5 projected changes (mmday$^{-1}$) in water balance components in response to 2 °C and 3 °C GWLs. Responses to 2 °C GWL are in column 1 (a, d, g, j), the projected changes under 3 °C GWL are in column 2 (b, e, h, k), while the difference between the projected changes under 3 °C and 2 °C GWLs are in column 3 (c, f, i, l). Stippling indicates significant change at 5% level.
intensified increase and vice versa (Figure 5(k) and 5(l)). Soil water level would increase at the Sahel to support agricultural productivity.

**Projected water balance components under GWL 2 and 3 °C based on RCP 8.5 during planting season (AMJJAS)**

Water balance responses to 2 and 3 °C GWLs are displayed in Figure 6. Precipitation is expected to increase at the ocean from −5 to 10°N, 15 to 25°W diagonally over the West Africa domain with SW–NE orientation to the Sahel (Figure 6(a)), and increased wetness is also expected at the eastern coast. The wet areas as a result of 2 °C GWL are projected to become wetter, while the dry areas are expected to become drier under 3 °C global warming (Figure 6(b) and 6(c)). In wet areas, warming would increase evaporation, which would in turn increase precipitation through cloud formation, but in a dry area there is no available water for evaporation, so wet areas would be wetter, while dry areas would be drier. This corroborated the findings of Putnam & Broecker (2017). Runoff would increase at the ocean, some coastal areas and the Sahara, and isolated increase on the Sahel is also projected under 2 °C warming (Figure 6(d)). Increased warming of 3 °C would lead to reduction in runoff over the ocean and Sahara, but isolated increase in runoff over part of Guinea Coast, Savannah and

![Figure 6](image-url)
Sahel (Figure 6(e) and 6(f)). Evapotranspiration would increase at the Southern Ocean area of the West Africa domain having SW–NE orientation towards the Sahel under 2 °C GWL (Figure 6(g)). Evapotranspiration would also increase at the northwestern coast (Figure 6(h) and 6(i)). Evapotranspiration increase would intensify at the south and on the ocean (Atlantic and Mediterranean Sea) under a warmer globe (3 °C). Storage change would increase diagonally along SW–NE orientation from the ocean at −5 to 10°N, 15 to 25°W (Figure 6(j)) and reduce in other areas under 2 °C GWL. Increase in GWL to 3 °C enhances storage change increase over the Sahel, while it intensifies reduction in storage change in the areas of storage change reduction under 2 °C GWL (Figure 6(k) and 6(l)). Change signal in RCP 8.5 is clearer during AMJJAS. The projected increase in precipitation during the pre-planting season at the Savannah and Sahel (Burkina Faso, Ghana, Ivory Coast, Togo, Benin, eastern Niger, northern Chad) is enhanced during the planting season with the exception of central Nigeria and Ghana. Those areas with enhanced precipitation increase show continuation in the rainfall that started during the pre-planting season. This can be explained as early onset with respect to climatology. On the other hand, the areas with reduced precipitation during the planting season following an increase during the pre-planting season are showing false onset. This may affect crops negatively, if a proper adaptation strategy is not in place. The farmers in central Nigeria and Ghana should be aware of the looming false rainfall onset beginning from the 2020s. This corroborates the findings of Adeniyi (2016), who reported that false rainfall onset should be expected at the central Guinea coast, which includes these areas.

Projected water balance components under GWL 2 and 3 °C based on RCP 4.5 during post-planting season (OND)

Figure 7 shows the response of water balance components to climate change under GWLs of 2 and 3 °C during OND from RCP 4.5 simulations. During the post-planting season, at 2 °C warming, the ocean (−5 and 5°N, 0–25°W) and part of the Sahel would experience increased precipitation, while most of the other areas in West Africa would be drier (Figure 7(a)). The 3 °C warming would lead to intensified wetness at the regions of wetness over the ocean with spatial extension to the southern coast areas. The increase at the eastern Sahara would extend spatially. However, the other areas would be drier than is projected for the 2 °C warming (Figure 7(b) and 7(c)). Runoff is expected to increase at 2 °C warming all over West Africa except at the southern coastal areas and land areas below 5°N (Figure 7(d)). At 3 °C warming, runoff would reduce all over West Africa but some isolated increase is also projected (Burkina Faso, Sierra Leone, southern Mali, southern Chad and Gabon) (Figure 7(e) and 7(f)). Evapotranspiration would increase over the ocean, eastern and central Sahel with 2 °C warming (Figure 7(g)). This would intensify at 3 °C GWL (Figure 7(h) and 7(i)). Storage change is projected to reduce generally over West Africa under 2 °C warming (Figure 7(j)). Increase in storage change is projected only at the ocean between 15–25°W, −5 to −2°N and isolated coastal areas. Increase in GWL to 3 °C would lead to intensified reduction of storage change over areas with reduced storage change and intensified increase in storage change over areas with increased storage change under 2 °C warming (Figure 7(k) and 7(l)).

Projected water balance components under GWL 2 and 3 °C based on RCP 8.5 during post-planting season (OND)

Figure 8 shows the response of water balance components to climate change under GWLs of 2 and 3 °C during OND from RCP 8.5 simulations. Response of precipitation to 2 °C GWL is isolated increase from the ocean along the diagonal of the West Africa domain having SW–NE orientation towards the Sahel, increase at coastal areas below 0°N and dryness in other areas (Figure 8(a)). The 3 °C warming intensifies precipitation increase over areas of increased precipitation at south-western ocean, coast and land areas below 0°N. It intensifies dryness at the south-eastern ocean area of the West Africa domain (Figure 8(b) and 8(c)). At 2 °C GWL, there is reduction of runoff over the ocean, Sahel and Sahara, but runoff is projected to increase at the coast (Figure 8(d)). Runoff under 3 °C GWL would reduce further everywhere except on land areas below 0°N and isolated southern land areas (Figure 8(e) and 8(f)). Evapotranspiration under 2 °C GWL would increase over eastern Sahel, southern and western ocean areas and the
Mediterranean and also at coasts below 0°N (Figure 8(g)). Evapotranspiration increase would intensify under a warmer world (3 °C) at central and eastern Sahel, also at the southern coast and land areas (Figure 8(h) and 8(i)). Isolated increase in storage change is projected at southwestern ocean, coastal areas and Sahara (Figure 8(j)). The increase in storage change would intensify at 3 °C warming at the coasts, land areas below 0°N and Sahara (Figure 8(k) and (l)). Similar change signal patterns are obtained from both RCPs 4.5 and 8.5 (Figure 7(d) and 8(d)). However, the signals are clearer for negative and positive change differently for different variables and RCPs. Precipitation change signals in the three seasons reveal a shift in rainfall season at southern Chad based on lower precipitation than climatology in JFM, scanty precipitation during the planting season and enhanced precipitation with respect to climatology during the post-planting season. Extension of the rainfall season is projected at Southern Niger, with increased precipitation in all the three seasons considered with respect to climatology (Figures 3–8).

Figure 7 The OND RCP 4.5 projected changes (mm day⁻¹) in water balance components in response to 2 °C and 3 °C GWLs. Responses to 2 °C GWL are in column 1 (a, d, g, j), the projected changes under 3 °C GWL are in column 2 (b, e, h, k), while the difference between the projected changes under 3 °C and 2 °C GWLs are in column 3 (c, f, i, l). Stippling indicates significant change at 5% level.
Annual projected water balance components under GWL 2 and 3 °C based on RCP 4.5

The overall annual responses of precipitation, runoff, evapotranspiration and storage change to global warming at 2 and 3 °C levels under RCP 4.5 are depicted in Figure 9. Annual precipitation increase is projected with SW–NE orientation from the ocean to the Sahel along the diagonal of the West Africa domain under 2 °C global warming. This is in line with the finding of Adeniyi (2017), who found precipitation changes in West Africa to be SW–NE oriented in response to changes in the Atlantic sea surface temperature. The spatial pattern and magnitude of projected precipitation change signal under GWL of 2 °C are comparable with the projection from the large ensemble under RCP 8.5 in Nikulin et al. (2018). Precipitation is expected to reduce at the south-central coastal area (Figure 9(a)). Intensification of wetness is projected over the ocean and eastern Sahel, but dryness in other areas with 3 °C GWL (Figure 9(b) and 9(c)). Runoff is expected to increase on the ocean, Sahara and part of Sahel, under 2 °C GWL, while it is projected to reduce at the Guinea Coast and Savannah (Figure 9(d)). Increased GWL up to 3 °C is expected to reduce runoff generally over West Africa except at

Figure 8 | The OND RCP 8.5 projected changes (mm/day) in water balance components in response to 2 °C and 3 °C GWLs. Response to 2 °C GWL are in column 1 (a, d, g, j), the projected changes under 3 °C GWL are in column 2 (b, e, h, k), while the difference between the projected changes under 3 °C and 2 °C GWLs are in column 3 (c, f, i, l). Stippling indicates significant change at 5% level.

Downloaded from http://iwaponline.com/jwcc/article-pdf/12/5/1654/924368/jwc0121654.pdf by guest
10–15°N (Figure 9(e) and 9(f)). Evapotranspiration would increase over ocean towards the Sahel along the diagonal of the West Africa domain in SW–NE orientation, similar to precipitation increase, but with more spatial spread under 2°C GWL (Figure 9(a) and 9(g)). Under 3°C GWL, there would be intensified increase in evapotranspiration over ocean and Sahel, but reduction over central southern land areas (Figure 9(h) and 9(i)). Storage change is projected to reduce all over the West Africa domain under 2°C GWL except for isolated increase over the Sahel and south-western ocean area (Figure 9(j)). The 3°C GWL would intensify expected change signal under 2°C GWL. It would intensify reduction at the areas of reduced storage change on ocean and intensify increase at areas of increased storage change on ocean, Sahel and Sahara (Figure 9(k) and 9(l)).

Annual projected water balance components under GWL 2 and 3 °C based on RCP 8.5

Annual responses of water balance components to GWLs of 2 and 3 °C under RCP 8.5 are shown in Figure 10. The 2 °C GWL would lead to an increase in annual precipitation towards the Sahel and part of the Sahara on SW–NE orientation from the south-western ocean area of the West Africa
domain. It would also lead to wetness at the coast below 0°N and reduction at every other area of the West Africa domain (Figure 10(a)). The 3 °C warming would intensify the precipitation increase in areas with increased precipitation and also intensify dryness in areas of dryness (Figure 10(b) and 10(c)). Runoff would reduce on an annual basis everywhere as a result of 2 °C GWL, except for isolated increase at the southern coast (Figure 10(d)). Increase in runoff would intensify at the southern land areas, while reduction would intensify in other areas, under 3 °C GWL (Figure 10(e) and 10(f)). Evapotranspiration is projected to increase over ocean including the Mediterranean and over land along SW–NE diagonal of the West Africa domain to eastern Sahel. It would also increase at coastal areas below 0°, under 2 °C GWL (Figure 10(g)). The 3 °C GWL would intensify evapotranspiration in areas with evapotranspiration increase and intensify reduction in areas with reduced evapotranspiration under 2 °C GWL (Figure 10(h) and 10(i)). Storage change under 2 °C GWL would increase on an annual basis from the south-western ocean area of the West Africa domain (Figure 10(j), 0°N, 25°W) and at the coast below 0°N (Figure 10(j)). Storage change is expected to reduce at the Sahara under 3 °C GWL and intensify in areas of increased

Figure 10 | Annual RCP 8.5 projected changes (mm day⁻¹) in water balance components in response to 2 °C and 3 °C GWLs. Responses to 2 °C GWL are in column 1 (a, d, g, j), the projected changes under 3 °C GWL are in column 2 (b, e, h, k), while the difference between the projected changes under 3 °C and 2 °C GWLs are in column 3 (c, f, i, l). Stippling indicates significant change at 5% level.
storage change under 2°C GWL (Figure 10(k) and 10(l)). Clearer change signals are simulated in RCP 8.5. Global warming of 2°C impacts negatively on central and southern Nigeria and some other countries at the Guinea Coast as a result of the orientation (SW–NE) of precipitation increase from the ocean (−5 to 10°N, 15 to 25°W) to the Sahel.

**Uncertainty in the projected water balance components**

Uncertainty in the projected water balance components is considered during the planting season (AMJJAS), when the population depends mostly on precipitation. There is no significant difference in the projected changes in precipitation under RCPs 4.5 and 8.5 at 2°C GWL across all regions. Uncertainty is higher in projected precipitation changes at the Sahel (Figure 11(a)), while the least uncertainty is at the Guinea Coast. At 3°C GWL, the projected changes under RCP 8.5 are significantly different from RCP 4.5 projected changes at the Guinea Coast and Savannah. Differences between projected changes at 3°C and 2°C GWLs are significantly higher under RCP 8.5 than RCP 4.5 across all regions, with higher uncertainty at the Sahel. Uncertainty is higher in projected precipitation changes at the Sahel under both GWLs and RCPs.
At 2 °C GWL, there is no significant difference in the projected changes in runoff from both RCPs (Figure 11(b)) across all regions. Projected changes are significantly higher at the Guinea Coast. There is higher uncertainty in projected runoff at the Sahel. Differences between projected changes at 3 °C and 2 °C GWLs are significantly higher under RCP 8.5 than RCP 4.5 at the Guinea Coast and Savannah with higher uncertainty at the Savannah and Sahel. Uncertainties in projected runoff are also higher at the Sahel for both RCPs and GWLs (Figure 11(b)).

There are generally higher uncertainties in runoff than precipitation at both GWLs across all regions and there is no significant difference in projected evapotranspiration under both RCPs at 2 °C GWL. However, at 3 °C, projected change in evapotranspiration is higher at Savannah and Sahel under RCP 8.5 than RCP 4.5. Differences between projected changes at 3 °C and 2 °C GWLs are significantly higher under RCP 8.5 than RCP 4.5 across all regions (Figure 12(a)). Sahel projections have higher uncertainty in evapotranspiration.

Projected changes in storage change show no significant difference across all regions, RCPs and GWLs. More uncertainty exists in projected changes in storage change at the Sahel (Figure 12(b)).

Figure 12 | Same as Figure 11 but for evapotranspiration and storage change.
Robustness of projected changes is highest in precipitation followed by storage change, while the least robustness is in evapotranspiration.

CONCLUSION

This paper analyses the state of precipitation, evapotranspiration, runoff and storage change over West Africa at 2 and 3 °C GWLs based on RCPs 4.5 and 8.5. The two RCPs and three seasons (pre-planting, JFM; planting, AMJJAS; and post-planting, OND) at the same GWL, generally agree on the projected changes in the water balance components except for difference in spatial coverage of some change signals and runoff. West Africa would be drier at 2 °C GWL except for a precipitation increase at the south-western ocean area of the West Africa domain towards the Sahel with SW–NE orientation. This would intensify under a warmer world of 3 °C GWL. Evapotranspiration would reduce over the Sahara in all seasons and at Guinea Coast and Savannah during the pre- and post-planting seasons. However, it would increase at 2 °C GWL and intensify at 3 °C GWL over the ocean, central and eastern Sahel. The same areas with projected precipitation increase are also having increased evapotranspiration and vice versa. This could be explained as the production of atmospheric moisture for cloud formation and subsequent precipitation by evapotranspiration. Evapotranspiration reduction during pre- and post-planting seasons shows the overall reduction in evapotranspiration and available moisture in the atmosphere for cloud formation. At some coastal areas and a little inland, under 2 °C GWL, water storage change is projected to increase but reduce at 3 °C GWL as a result of increased evapotranspiration. However, at 3 °C GWL, storage change would increase at the northern coast, Sahara and Sahel during the planting season in order to make closure of the water balance equation possible. Runoff would increase over the ocean, Sahara and part of Sahel and reduce in Guinea Coast and Savannah under 2 °C GWL, but reduce under a warmer world with isolated increase during the planting season. This could result from intensified increased rate of evapotranspiration. The areas that are particularly affected by warming, such as south-western Nigeria, Senegal, Liberia, Burkina Faso and the whole Sahel, need adequate adaptation strategies against the subsequent consequences of warming. At south-western Nigeria and Senegal, warming of 3 °C would cause excessive dryness, reduction in runoff, evapotranspiration and storage change. Policy strategies to relieve the environment of dryness should be put in place in those areas. On the other hand, Liberia, Burkina Faso and other areas in Sahel would experience excessive rainfall very soon, so strategies against inevitable flooding occurrences should be put in place in those areas.

Early onset is projected for Burkina Faso, Ghana, Ivory Coast, Togo, Benin, eastern Niger and northern Chad, while false onset is projected for central Nigeria and Ghana. The false onset may affect crops negatively if a proper adaptation strategy is not in place. The farmers in central Nigeria and Ghana should be aware of the looming false rainfall onset beginning from the 2020s. This corroborates the findings of Adeniyi (2016), who reported that false rainfall onset should be expected at the central Guinea Coast, which includes these areas. Precipitation change signals in the three seasons reveal a shift in the rainfall season at southern Chad. Extension of the rainfall season is projected at southern Niger, with increased precipitation in all the three seasons considered, with respect to climatology. Global warming of 2 °C impacts negatively on central and southern Nigeria and other countries at the Guinea Coast and Savannah as a result of the SW–NE orientation of precipitation increase from the ocean (−5 to 10°N, 15 to 25°W) to the Sahel.

Robustness of projected changes is highest in precipitation followed by storage change, while the least robustness is in evapotranspiration. Uncertainty is generally higher at the Sahel.

ACKNOWLEDGEMENTS

The author is grateful to the modelling group at the Swedish Meteorological and Hydrological Institute (SMHI) Rossby Centre, for the release of RCA4 downscaled CMIP5 output. The author also acknowledges the coordinators of CMIP5 and CORDEX for the release of the model output. This work was carried out at the Abdus-Salam International Centre for Theoretical Physics, Trieste, Italy.
Observational datasets from Climate Research Unit at the University of East Anglia are used for evaluation together with ERA5 reanalysis data released by Copernicus Climate Change Service (https://cds.climate.copernicus.eu/cdsapp#!/home). There is no conflict of interest with regard to this paper.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories. https://esg-dn1.lns.cliu.se/search/cordex/ https://cds.climate.copernicus.eu/cdsapp#!/home https://catalogue.ceda.ac.uk/uuid/b2f81914257c4188b181a4d8b0a46bff.

REFERENCES


Skiliris, N., Zika, J. D., Josey, S. A. & Marsh, R. 2016 Global water cycle amplying at less than the Clausius-Clapeyron rate. Scientific Reports 6, 38752. doi:10.1038/srep38752.

Scenarios for Europe From the Rossby Centre Regional Climate Model RCA4. Technical report 116, Climate research-Rossby Centre.


First received 15 April 2020; accepted in revised form 3 September 2020. Available online 28 October 2020