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Agriculture in West Africa in the Twenty-first Century: climate change and impacts scenarios, and potential for adaptation

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Abstract

West Africa is known to be particularly vulnerable to climate change due to high climate variability, high reliance on rain-fed agriculture and limited economic and institutional capacity to respond to climate variability and change. In this context, better knowledge of how climate will change in West Africa and how such changes will impact crop productivity is crucial to inform policies that may counteract the adverse effects. This review paper provides a comprehensive overview of climate change impacts on agriculture in West Africa based on the recent scientific literature. West Africa is nowadays experiencing a rapid climate change, characterized by a widespread warming, a recovery of the monsoonal precipitation, and an increase in the occurrence of climate extremes. The observed climate tendencies are also projected to continue in the 21st century under moderate and high emission scenarios, although large uncertainties still affect simulations of the future West African climate, especially regarding the summer precipitation. However, despite diverging future projections of the monsoonal rainfall, which is essential for rain-fed agriculture, a robust evidence of yield loss in West Africa emerges. This yield loss is mainly driven by increased mean temperature while potential wetter or drier conditions as well as elevated CO₂ concentrations can modulate this effect. Potential for adaptation is illustrated for major crops in West Africa through a selection of studies based on process-based crop models to adjust cropping systems (change in varieties, sowing dates and density, irrigation, fertilizer management) to future climate. Results of the cited studies are crop and region specific and no clear conclusions can be made regarding the most effective adaptation options difficult. Further efforts are needed to improve modelling of the monsoon system and to better quantify the uncertainty in its changes under a warmer climate, the response of the crops to such changes and in the potential for adaptation.

Keywords: West African monsoon, climate change, impacts, adaptation, agriculture

1 **1. Introduction**

2 Climate has a strong influence on agriculture, considered as the most weather-dependent of all
3 human activities (Hansen 2002) with impacts on food security (Schmidhuber and Tubiello
4 2007). Both variability and change in climate affect food production availability, stability of
5 food supplies, food utilization, access to food and food prices everywhere in the world
6 (Schmidhuber and Tubiello 2007). It is especially true in Sub-Saharan Africa which is known
7 to be particularly vulnerable to climate change due to a combination of naturally high levels of
8 climate variability, high reliance on rain-fed agriculture and limited economic and institutional
9 capacity to cope with and adapt to climate variability and change (Roudier et al. 2011; Müller
10 et al. 2011; Challinor et al. 2007). Indeed, under its current climate Sub-Saharan Africa is
11 already facing recurrent food crises and water scarcity triggered or exacerbated by climate
12 variability and extreme events such as droughts, excessive rains and floods which affect
13 agricultural productivity and hence rural household food security (Haile 2005; Dilley et al.
14 2005). This chronic food insecurity may even increase in the future since the food demand is
15 expected to be multiplied by more than five in Africa by 2050 (Collomb 1999).

16 Climate change and its impact on food security is an additional strain on the agriculture sector
17 in Africa. The last Intergovernmental Panel on Climate Change (IPCC 2014) highlighted that:
18 “warming of the climate system is unequivocal, and since the 1950s, many of the observed
19 changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed,
20 the amounts of snow and ice have diminished, and sea level has risen. Changes in many extreme
21 weather and climate events have been observed since about 1950. Recent climate changes have
22 had widespread impacts on human and natural systems”. Moreover, “continued emission of
23 greenhouse gases will cause further warming and long-lasting changes in all components of the
24 climate system, increasing the likelihood of severe, pervasive and irreversible impacts for
25 people and ecosystems”. In this context, crop productivity, which is directly tied to climate
26 variability, appears particularly exposed to current and future climate change impacts. Indeed,
27 “many studies covering a wide range of regions and crops shows that negative impacts of
28 climate change on crop yields have been more common than positive impacts”. Moreover,
29 “rural areas are expected to experience major impacts”, and “all aspects of food security are
30 potentially affected by climate change, including food production, access, use and price
31 stability”. At the turn of the 21st century, West Africa has been identified among the primary
32 observed climate change hot-spots, and among the most persistent and early emerging
33 prominent hot-spots foreseen for the 21st century, because of the observed and projected
34 widespread increase in mean temperature and extreme hot-season occurrence (Turco et al.
35 2015). Given the particularly strong deep connection between crop production and climate
36 variability in West Africa since agriculture is mostly rain-fed and crop management (use of
37 fertilizers and pesticides combined with modern cultivars) remains low (Dingkuhn et al. 2006),
38 the detected sensitivity to recent and future climate change makes the region a hotspot even in
39 terms of food production and security.

40 In the context described above, better knowledge of how climate will change in West Africa
41 and how such changes will impact crop productivity is crucial to inform policies that may
42 counteract the adverse effects. Furthermore, the ability to identify the most suitable crop
43 varieties and practices with the most robust characteristics for withstanding climate change, is
44 crucial for formulating adaptation strategies in this region where farmers are already able to
45 select adapted varieties (e.g. late or early millet) or to adapt their practices (e.g. delayed or early

1 sowing) to a changed environment (Dingkuhn et al. 2006). However, although there is a
2 growing literature on the impact of climate change on crop productivity in Africa, there are
3 large uncertainties in climate change projections, in the response of crops to such changes and
4 in the adaptation of agricultural systems to future climate conditions (Roudier et al. 2011,
5 Challinor et al. 2007). Thus this paper provides a comprehensive overview of climate change
6 impacts on agriculture in West Africa based on the recent scientific literature.

7 This review is based on a wide review of the literature on climate variability and change in
8 West Africa and associated impacts on crop productivity. Given the sensitivity of the topic, the
9 available literature is vast (more than 200 papers are cited in the references), the review
10 presented here does not claim to be exhaustive and certainly misses many studies. However, an
11 effort has been done to present a selection of the most important results, with a special attention
12 to the recent studies. Moreover, the extensive and coordinated discussion of the crop
13 productivity problem and the related climate dynamics aspects represents the noticeable novelty
14 of this review. Section 2 of this review paper provides observed evidences of climate change in
15 West Africa and gives some robust features about expected changes in the next decades. Section
16 3 investigates how such climate changes affect crop production as well as potential for
17 adaptation for the major crops in West Africa. Each section attempts to stress the most robust
18 results in the screened literature but, more importantly, includes a discussion about limitations
19 and uncertainties. The reader is invited to read the cited papers for more details on any specific
20 aspects discussed in this review.

22 **2. Climate change scenarios**

23 **2.1 West African climate and monsoon dynamics**

24 The West African climate is deeply tied to the West African monsoon (WAM) system, which
25 develops in May over the Guinean coast (~5-10°N), reaches the maturity in August in the Sahel
26 (~10-15°N), and finally retreats to the coast in October (Sultan and Janicot 2003; Cook 2015),
27 concentrating in this period more than 70% of the annual precipitation in the region (CLIVAR
28 2015). The monsoonal rainfall is a key element of the regional climate, especially in the
29 semiarid Sahel, where vegetation is highly sensitive to precipitation variability, at time scales
30 from intraseasonal to interannual (Philippon et al. 2007; Martiny et al. 2010; Taylor et al. 2011).
31 Moreover, the atmospheric circulation characterizing the monsoonal system is associated with
32 mineral dust emission (Bou Karam et al. 2007; Wang et al. 2015) and thermal anomalies
33 (Guichard et al. 2009; Fontaine et al. 2013) in the region.

34 The WAM is the response to the land-sea thermal contrast triggered by the seasonal cycle of
35 the insolation at the surface, which favors the inland penetration of the deep convection
36 associated with the intertropical convergence zone (ITCZ) (Thorncroft et al. 2011). In the lower
37 troposphere, the atmospheric circulation is characterized by a southwesterly moist flow from
38 the Gulf of Guinea, contrasting a dry northeasterly flow crossing the Sahara desert. This
39 intertropical front can be regarded as the northern boundary of the WAM, and at the peak of
40 the monsoonal season it is displaced around 20°N (Issa Lele and Lamb 2010). In the mid
41 troposphere, the circulation is dominated around 12°N by the African easterly jet, originated by
42 the meridional thermal gradient between the vegetated Guinean coast and the Sahara desert
43 (Thorncroft and Blackburn 1999). The African easterly jet is the wave guide for synoptic
44 disturbances propagating westward along the Guinean coast and the Sahelian belt, known as

1 African easterly waves (Poan et al. 2015). These disturbances are particularly important in
2 triggering the monsoonal precipitation through the initiation and organization of mesoscale
3 convective systems and squall lines during the monsoonal season (Cretat et al. 2015). The
4 annual evolution of the WAM thermodynamic features (moisture fluxes and convergence), and
5 of the associated rainfall distribution, is strongly impacted by the emergence of the Atlantic
6 cold tongue, and the installation of the Saharan heat low. The Atlantic cold tongue is a cold
7 pool which characterizes the equatorial eastern Atlantic Ocean from boreal spring to early
8 summer, and its variability influences the timing of the monsoon onset over the Guinean coast
9 and the intensity of the inland precipitation (Druyan and Fulakeza 2015). The Saharan heat low
10 is a lower tropospheric thermal depression over the Sahara desert west of 10°E, developing in
11 response to the surface heating over West Africa in boreal summer (Lavaysse et al. 2009). The
12 Saharan heat low onset is closely linked to the WAM onset in late June, and its variability
13 modulates the longitudinal distribution of the monsoonal precipitation in the Sahel, being strong
14 Saharan heat low phases associated with wet/dry anomalies in eastern/western Sahel (Lavaysse
15 et al. 2010).

16 **2.2 Multi-time scales variability**

17 In the 20th century, the West African climate has been characterized by the variability of the
18 WAM, showing a succession of long lasting wet and dry periods. This climate variability has
19 been particularly relevant in the Sahel, where a large scale drought during the 70s-80s has been
20 followed by a partial recovery of precipitation at the turn of the 21st century (Trenberth et al.
21 2007). The main driver of the WAM variability at time scales from intraseasonal to
22 multidecadal is the global ocean sea surface temperature (SST) (Rodriguez-Fonseca et al. 2015;
23 Pomposi et al. 2015).

24 The observed 40-day variability of the WAM is mainly related to SST anomalies in the Indian
25 Ocean associated with the Madden-Julian oscillation, which trigger convection disturbances
26 travelling along the Equator and modulating the WAM precipitation (Pohl et al. 2009; Mohino
27 et al. 2012).

28 The SST variability in the Tropical Atlantic is the main driver of the monsoonal circulation at
29 the interannual time scales, through the land-sea thermal gradient which influences the
30 meridional displacement of the precipitation belt, with the strongest impact on the Guinean
31 coast (Polo et al. 2008; Losada et al. 2010). The Mediterranean Sea plays a role in modulating
32 the interannual variability of the monsoonal precipitation over the Sahel, by feeding the
33 convergence over the Sahel with moisture transported across Sahara (Fontaine et al. 2010;
34 Gaetani et al. 2010). The WAM interannual variability is also remotely influenced by the SST
35 variability in the Tropical Indian/Pacific Oceans, which may induce stationary waves
36 propagating along the Equator and interacting over the Sahel (Rowell, 2001; Mohino et al
37 2011b). These regional and remote connections are not stationary and are modulated at decadal
38 and multidecadal time scales (Fontaine et al. 2011a).

39 The multidecadal variability of the WAM dynamics results from the combination of diverse
40 low frequency global ocean signals (Mohino et al. 2011a). On the one hand, the warming of the
41 Tropical Ocean, associated with global warming and positive phases of the interdecadal Pacific
42 oscillation, favors dry conditions in the Sahel, through the inhibition of the tropical convection
43 (Bader and Latif 2003; Villamayor and Mohino 2015). On the other hand, positive phases of
44 the Atlantic multidecadal variability, by displacing northward the ITCZ, favor precipitation in

1 the Sahel (Zhang and Delworth 2006; Ting et al. 2009). The severe drought that affected the
2 Sahel during the 70s-80s has been attributed to a negative Atlantic multidecadal variability
3 phase, concomitant with a positive interdecadal Pacific oscillation phase, in a global warming
4 context (Mohino et al. 2011a).

5 Other than to the SST forcing, the West African climate is highly sensitive to land surface
6 conditions and processes. Vegetation-associated land surface processes have in West Africa the
7 largest climate impact worldwide, especially in summer (Ma et al. 2013), and the Sahel shows
8 the strongest soil moisture/climate coupling (Koster et al. 2006). In this context, it has been
9 shown that the vegetation degradation has a role in the drought events in the Sahel, through the
10 increase in albedo and the reduction of evaporation, leading to reduced net radiation and
11 inhibited convection, respectively, which in turn weaken the monsoonal circulation (Xue et al.
12 2004).

13 **2.3 Modelling the West African climate**

14 In the last 15 years, a big effort has been made to understand climate variability and change in
15 West Africa. The African Monsoon Multidisciplinary Analysis program (AMMA; [http://amma-
16 international.org/](http://amma-international.org/)), launched in 2002 and involving a number of research institutions in the
17 international scientific community, was the first large scale coordinated program aiming to
18 improve the understanding of the WAM system and its influence on the physical, chemical and
19 biological environment, regionally and globally. The AMMA community is still active to
20 provide the underpinning science to assess the impacts of WAM variability on health, water
21 resources, food security and demography in the West African countries, and to define and
22 implement monitoring and prediction strategies (Redelsperger et al. 2006). Specifically
23 addressed to climate modelling issues, the West African Monsoon Modelling and Evaluation
24 project (WAMME) (Druryan et al. 2010) is an initiative designed to evaluate the performance
25 of global and regional climate models (GCMs and RCMs, respectively) in simulating the WAM
26 dynamics and associated precipitation.

27 In the context of the Coupled Model Intercomparison Project Phase 3 and 5 (CMIP3 (Meehl et
28 al. 2007) and CMIP5 (Taylor et al. 2012), respectively), a World Climate Research Programme
29 (WCRP, <http://www.wcrp-climate.org/>) standard experimental protocol for studying the output
30 of coupled atmosphere-ocean GCMs, climate variability in West Africa is extensively studied,
31 with promising but still unsatisfying results. Specifically, state-of-the-art climate models in both
32 CMIP3 and CMIP5 exercises show low skill in simulating the observed WAM variability
33 (amplitude, phases and trends), and sizable uncertainties affect projections in the 21st century,
34 ranging from dry to wet conditions in the Sahel (Biasutti, 2013). Although coupled models
35 generally well reproduce the relationship between the regional atmospheric circulation and the
36 monsoonal precipitation, during both the 20th and the 21st century, the same models show
37 discrepancies in future projections (Biasutti et al. 2009). Therefore, model shortcomings can be
38 firstly related to the ability in reproducing the large scale mechanisms which influence the
39 regional atmospheric circulation, and especially the teleconnections with the global SST
40 teleconnections (Biasutti et al. 2009; Rowell 2013). An important source of uncertainty in the
41 modelling of climate change in West Africa is also the model responses to the direct and indirect
42 CO₂ radiative forcing in the atmosphere: the former rapidly warms the continental surface,
43 inducing a positive response in the WAM precipitation; the latter slowly warms the ocean
44 surface, inducing dry conditions (Giannini 2010). It has been shown that wet and dry model

1 biases over West Africa may be related to an unbalanced model response to the direct and
2 indirect CO₂ forcing (Gaetani et al. 2016). At a regional scale, limitations in the model
3 representation of SST in the Tropical Atlantic (Roehrig et al. 2013), surface heat fluxes (Xue et
4 al. 2010), vegetation feedback (Kucharski et al. 2013), land use (Bamba Sylla et al. 2016) and
5 mineral dust atmospheric concentration (Tompkins et al. 2005) are sources of incorrect
6 simulations of the temporal and spatial variability of the WAM precipitation. Finally, the coarse
7 resolution typical of GCMs limits the model ability to simulate the intense and organized
8 convection characterizing the WAM (Vellinga 2015). The assessment of model performances
9 is critical to understand the sources of errors and limit uncertainties, but an overall and objective
10 evaluation is a particularly difficult task, because results may differ depending on the specific
11 variable analyzed and the metrics used. In the CMIP5 archive, a discrimination in the model
12 performances for the historical climate may be achieved, but uncertainty in the projections is
13 not reduced when skillful models are selected (Rowell et al. 2016). This suggests that the
14 underlying assumption relating the model shortcomings in simulating past, present and future
15 climate in West Africa is incorrect, being the assumption that the same modelled processes lead
16 to errors in the simulation of the historical climate and uncertainty in projected change (Rowell
17 et al. 2016). Therefore, further research, based on the understanding of the mechanisms that
18 drive the errors and uncertainty in projected changes, is needed to discriminate model
19 performances.

20 In the CMIP5 exercise, a specific effort had been devoted to climate prediction at decadal time
21 scales (10-to-30 years), which is recognized as a key planning horizon in a socioeconomic
22 perspective (Doblas-Reyes et al. 2013). Results demonstrate that the WAM variability at
23 decadal time scales is influenced by both the global SST natural variability and the green-house
24 gases (GHG) external forcing, and the prediction skill is highly model dependent (Gaetani and
25 Mohino, 2013; Martin and Thorncroft 2014; Otero et al. 2015). Specifically, highest skill
26 models are characterized by the ability in reproducing the WAM connection with, primarily,
27 the Atlantic multidecadal variability (Gaetani and Mohino 2013) and, secondly, with the
28 relative SST difference between the subtropical North Atlantic and the tropics and
29 Mediterranean SST (Martin and Thorncroft 2014).

30 In the framework of the Coordinated Regional Climate Downscaling Experiment (CORDEX,
31 <http://www.cordex.org/>), a WCRP initiative for the assessment and comparison of RCM skills
32 in diverse regions, CORDEX-Africa provides a set of state-of-the-art simulations and
33 predictions for the West African climate at high resolution (Nikulin et al. 2012). The availability
34 of reliable climate simulations at high spatial-temporal resolution is crucial for a robust
35 assessment of climate impacts at regional scale, and the CORDEX-Africa exercise shows
36 encouraging results for West Africa. The dynamical downscaling of GCMs, operated at higher
37 resolution by the RCMs, leads to improvements in the simulation of the atmospheric circulation,
38 temperature and precipitation climatology, as well as the occurrence of wet and dry spells, the
39 frequency of heavy rain events, and the drought geographical distribution (Laprise et al. 2013;
40 Bucchignani et al. 2015; Buontempo et al. 2015; Diasso and Abiodun 2015; Dosio et al. 2015),
41 although the biases in the lateral boundary conditions provided by the driving GCMs may
42 significantly affect the RCMs outputs (Laprise et al. 2013; Dosio et al. 2015). Being the GCM
43 biases more pronounced over the Tropical Atlantic, the RCM performances are in general better
44 over the Sahel than in the Guinean coast, which is more influenced by the local SST variability
45 (Paxian et al. 2016). Uncertainties in the simulation of daily precipitation are also observed,
46 mainly related to the diverse convection schemes utilized in the CORDEX-Africa models

1 (Klutse et al. 2016). However, the spread in the individual model performances is substantially
2 improved when the ensemble mean is computed (Klutse et al. 2016).

3 **2.4 Recent climate change**

4 After the devastating drought of the 70s-80s, West Africa is nowadays experiencing a partial
5 recovery of precipitation, with a coherent increase in the annual rainfall in the Sahel (29 to 43
6 mm/year per decade in the period 1983-2010) (Maidment et al. 2015). This recovery is
7 characterized by a modification of the seasonal cycle, showing a delay of the monsoon retreat
8 in the Sahel (2 day/decade in the period 1983-2010) (Sanogo et al. 2015), and by a change in
9 the rainfall regime, showing a decrease in the number of rainy days and an increase in the
10 proportion of annual rainfall associated with extreme events (17% in the period 1970-1990 and
11 21% in the period 2001-2010) (Panthou 2014). This precipitation recovery is accompanied by
12 a stable rainfall/vegetation trend (Hoscilo et al. 2015). The recent climate change is also
13 characterized by modifications in terms of atmospheric circulation and surface temperature.
14 The meridional overturning cell associated with the monsoonal circulation is shifted $\sim 1^\circ$
15 northward, with changes in the convection belt in West Africa and the subsidence over the
16 Mediterranean region (Fontaine et al. 2011b). Moreover, an amplified warming of the Sahara
17 desert is detected (Cook and Vizzy 2015), and the Saharan heat low shows an intensification
18 (Lavaysse et al. 2015) with reduced desert dust emission in summer (Wang et al. 2015). The
19 origin of this climate change signal in the Sahara region has been related to the direct radiative
20 forcing of the increased CO_2 concentration (Gaetani et al. 2016) and to an augmented moisture
21 availability in the lower troposphere over the desert, triggering a water vapor-temperature
22 feedback (Evan et al. 2015). The changes in the regional atmospheric dynamics accompanies
23 positive temperature anomalies and extremes in spring and summer in the Sahel (Fontaine et
24 al. 2013; Russo et al. 2016). Using a network of 90 in-situ observations in West Africa, Moron
25 et al. (2016) found that the linear trends of annual mean maximum and minimum temperature
26 equal respectively $+0.021^\circ\text{C/yr}$ and $+0.028^\circ\text{C/yr}$.

27 The debate on the origin of the recent precipitation recovery in West Africa and the associated
28 modifications in the regional atmospheric dynamics is open and heated, and the positions may
29 be conveyed into two main arguments. On the one hand, the recovery is ascribed to the
30 northward migration of the ITCZ in response to the SST warming at end of the 20th century,
31 which was stronger in the Northern Hemisphere than in Global Tropical Ocean (Park et al.
32 2014). A role of the warming of the subtropical North Atlantic in providing the moisture to feed
33 the monsoonal system has been identified (Giannini et al. 2013). On the other hand, a dominant
34 role of the direct GHG radiative forcing is hypothesized, acting by warming the surface and
35 increasing evaporation over the continental surface (Dong and Sutton 2015).

36 **2.5 Future Projections**

37 In the CMIP5 exercise, a positive trend in the WAM precipitation results from the multi-model
38 mean in the 21st century, though the individual model projections are characterized by a large
39 spread (Biasutti 2013). Indeed, about 50% of the model runs in the CMIP5 archive shows a
40 robust positive trend, about 25% shows a robust decreasing trend, while the trend is negligible
41 in the remaining 25% (Biasutti 2013). In the models predicting wet conditions, these are related
42 to the direct radiative effect of the increase in GHG concentration, leading to local increased
43 evaporation and vertical instability (Hoerling et al. 2006; Giannini 2010). On the contrary,
44 models projecting dry conditions simulate reduced moisture transport and deep convection over

1 land as a response to the global ocean warming, which heats the troposphere and imposes
2 stability (Held et al. 2005, Caminade and Terray 2010). Therefore, the competition between the
3 response of the land-atmosphere system to the local GHG radiative forcing, and the response
4 mediated through the warming of the global SST, emerges as a key component of the West
5 African climate change (Bony et al. 2013, Gaetani et al. 2016), and understanding the relative
6 impact of these two diverse forcings represents a task of primary importance for the climate
7 modelling community.

8 The future projection in precipitation simulated by climate models in the 21st century is not
9 spatially homogeneous over the Sahel. Indeed, future wet conditions in central-eastern Sahel
10 (east of approximately 0°E) contrast with dry anomalies over western Sahel (west of
11 approximately 0°E), and these sub-regional trends are more robust than the trend simulated in
12 the extended Sahelian belt (Monerie et al. 2012; 2013; Biasutti 2013). The rainfall excess
13 expected in central-eastern Sahel is mainly linked to a strengthening and northward shift of the
14 meridional overturning circulation over West Africa, reinforcing the monsoonal flow, with a
15 feedback in the lower levels from the increased temperature and evaporation associated with
16 the GHG radiative forcing (Monerie et al. 2012). The projected dry spot over western Sahel is
17 associated with a reinforcement of the African easterly jet and modifications in the overturning
18 zonal circulation connecting the Indian and Atlantic Oceans, which result in anomalous
19 subsidence on its descending branch over subtropical North Atlantic (Monerie et al. 2012).
20 Moreover, this east-west anomaly dipole in precipitation is consistent with the recently
21 observed long term intensification of the Saharan heat low (Lavaysse et al. 2015). The projected
22 rainfall trends result to be gradually enhanced and extended in future scenarios with a global
23 warming of 2-to-4 °C and beyond, showing an approximately linear amplification with no
24 tipping points being reached (James and Washington 2013; James et al. 2014). The 21st century
25 evolution of the WAM precipitation simulated by a subset of the CMIP5 models is illustrated
26 in Figure 1.

27 The WAM seasonal cycle is also affected by climate change in the 21st century. The projected
28 precipitation increase in the central-eastern Sahel is characterized by a robust increase of the
29 rainfall amounts in September-October (70% of the CMIP5 model runs; Biasutti 2013). This
30 results in a delay of the monsoon withdrawal, with a lengthening of the monsoon season
31 (Monerie et al. 2016). The moisture transport dominates the water budget change in September,
32 while the local recycling role is prominent in October (Monerie et al. 2016). Conversely, the
33 drying of the western Sahel appears to be concentrated in June-July in 80% of the CMIP5 model
34 runs (Biasutti 2013). The future modifications in the WAM seasonal cycle are accompanied by
35 coherent changes in the African easterly wave activity, showing a reduction in late spring and
36 early summer and a large increase between July and October, although large differences exists
37 in African easterly wave projections between high- and low-resolution models (Martin and
38 Thorncroft 2015; Skinner and Diffenbaugh 2014).

39 In contrast to the uncertainties affecting the future projection of the West African rainfall, a
40 broad consensus characterizes the model simulations of the surface temperature for the 21st
41 century. The future change in the monsoonal regime will be accompanied by a general warming
42 of the African continent, with a maximum over the Sahara desert, ranging between 3 and 7 °C,
43 depending on the model and the emission scenario (Monerie et al. 2012; Dike et al. 2015).
44 Boreal winter in West Africa will be also affected by a 2-3 °C warming, with the strongest
45 anomalies over the Guinea coast (Dike et al. 2015).

1 High resolution RCMs provide a detailed description of the future climate change in West
2 Africa, generally agreeing with GCMs on the temperature projection in the region. A robust
3 warming is predicted throughout the twenty-first century, although even large differences (more
4 than 1 °C) with the driving GCMs exist locally (Laprise et al. 2013; Dosio and Panitz 2016).
5 This will be accompanied, in the mid-twenty-first-century, by an increase in the number of heat
6 wave days, by 20-120 days per year over the Sahel, by 20-60 days over western Sahara, and by
7 5-40 days over eastern Sahara (Vizy and Cook 2012). Moreover, half of the CORDEX-Africa
8 projections suggest that heat waves that are unusual under present climate conditions in West
9 Africa, will occur on a regular basis by 2040 under high emission scenarios (Russo et al. 2016).
10 Finally, in the mid-twenty-first-century, daily maximum and minimum temperatures are
11 projected to increase, and the daily diurnal temperature range to decrease, by 0.3-1.2 °C during
12 boreal spring and fall over West Africa, and by 0.5-1.5 °C during boreal summer over the Sahel
13 (Vizy and Cook 2012).

14 The number of dry days is predicted to decrease by 3%-7% over central Africa in spring and
15 over eastern Sahel in summer. Conversely, the occurrence of extreme wet days will increase
16 over West Africa by 40%-60% (1-4 days) and the southern Sahel by 50%-90% (1-4 days),
17 uniformly during boreal summer. The associated changes in extreme wet rainfall intensity show
18 a regional response, including a 30%-70% decrease over northern Niger and northeastern Mali,
19 and a 10%-25% increase over Senegal, southern Mali, Burkina Faso, northern Nigeria, and
20 southern Chad (Vizy and Cook 2012). However, future RCM rainfall projections are affected
21 by large uncertainties. On the one hand, RCMs tend to inherit the biases of the driving GCMs,
22 so that a RCM downscaling several GCMs reproduces the inter-GCM spread, though with a
23 reduced amplitude (Buontempo et al. 2015; Dosio and Panitz 2016). On the other hand, a RCM
24 may project its own trend regardless the inter-model spread of the driving GCMs, due to the
25 differences in the specific physical formulation of RCMs and GCMs (Laprise et al. 2013;
26 Buontempo et al. 2015; Saini et al. 2015).

27 Finally, it has been recently pointed out that the projected modification in the atmospheric
28 dynamics over North Africa may impact the Saharan dust emission and atmospheric
29 concentration, leading to a significant negative trend in the 21st century (Evan et al. 2016).
30 Other than on human health in the region, expected to be benefitted, the reduction in dust
31 concentration may have a positive feedback on the monsoonal precipitation, through a reduction
32 in the associated surface cooling and lower troposphere heating, favoring atmospheric
33 instability (Yoshioka et al. 2007; Ji et al. 2016).

34

35 **3. The impact on crop yield and potential for adaptation**

36 **3.1 Predicting crop yield from GCM simulations**

37 *Crop models*

38 Predicting the potential impacts of climate change on crop yields requires a model of how crops
39 respond to future conditions induced by anthropogenic climate change, such as: warmer
40 temperatures, more frequent extreme temperatures, possible changes in rainfall mean,
41 seasonality spatial and temporal distribution. In addition, there is a direct impact of atmospheric
42 composition on crops with elevated levels of carbon dioxide acting to increase crop yields
43 through the stimulation of photosynthesis and reduction of drought stress (Tubiello et al. 2007;

1 Leakey 2009) while elevated levels of atmospheric ozone which are expected in developing
2 countries like Africa (Royal Society 2008) can lead to yield losses (Van Dingenen et al. 2008).
3 Crop models typically simulate the response of the crop to variability and change in weather
4 and climate related to temperature, precipitation and radiation, and atmospheric CO₂
5 concentration (Ewert et al. 2015). There are numerous crop models with different levels of
6 sophistication (di Paola et al. 2016) and several reviews can be found in the literature,
7 describing the concepts and limitations (see for instance di Paola et al. 2016; Ewert et al. 2015;
8 Affholder et al. 2012; White et al. 2011; Boote et al. 1996). Crop models can be roughly divided
9 into two categories: statistical models trained on historical yields and some simplified
10 measurements of weather, such as growing season average temperature and precipitation
11 (Lobell and Burke 2009) and process-based crop models which simulate explicitly the main
12 processes of crop growth and development (see for instance Ewert et al. 2015). Table 1 shows
13 a selection of models that have been used to assess the impact of climate change on yields of
14 various crops in West Africa. If the use of process-based models for climate change impact and
15 risk assessment studies has become increasingly important (Tubiello and Ewert 2002; Challinor
16 et al. 2009; White et al. 2011; Rötter et al. 2012 and Angulo et al. 2013b; Ewert et al. 2015)
17 since they are able to simulate impacts of climate, CO₂ concentrations on bio-physical processes
18 (e.g. phenology, photosynthesis, respiration, transpiration and soil evaporation) and other
19 production constraints such as N limitations, these models require extensive input data on
20 cultivar, management, and soil conditions as well as calibration and validation data that are
21 often unavailable in Africa (Lobell and Burke 2010). Even in the presence of such data these
22 models can be very difficult to calibrate because of a large numbers of uncertain parameters
23 (Iizumi et al. 2009; Tao et al. 2009). Furthermore, research effort in crop modelling has focused
24 on the world's major food crops such as wheat, maize, rice and sorghum and the simulation of
25 crops common in African farming systems (sorghum, millets, yam) is less well developed as
26 well as simulations of crops grown as intercrops across Africa (White et al. 2011; Challinor et
27 al. 2007). Ensemble modelling including a variety of crop models is thus highly recommended
28 to enable a quantification of the uncertainty (Challinor et al. 2009). In this context, extensive
29 model intercomparisons such as the ones conducted throughout the Agricultural Model
30 Intercomparison and Improvement Project (AgMIP; www.agmip.org/; Rosenweig et al. 2014),
31 which includes Sub-Saharan Africa as one of the target region (Adiku et al. 2015), are likely to
32 improve substantially the characterization of the threat of crop yield losses and food insecurity
33 due to climate change.

34 *Link with climate*

35 The use of climate projections from GCMs to force crop models is challenging and raises
36 several important issues. First, combining GCMs and process-based crop models raises a scale
37 mismatch since climate models typically operate on spatial scales much larger than the
38 processes governing the yields at the plot scale and most factors affecting crops such as soil
39 properties and farming practices (Challinor et al. 2009; Baron et al 2005). To overcome this
40 issue, climate data can be downscaled to the scale of a crop model with two types of
41 downscaling approaches that can be sometimes combined (see for instance Zorita and von
42 Storch 1999). Statistical downscaling relies on the use of empirical relationships between
43 mesoscale and local climate observed variables to relate GCM output to local climate (Zorita
44 and von Storch 1999). An alternative approach is the use of dynamical downscaling which
45 offers a self-consistent approach that captures fine-scale topographic features and coastal

1 boundaries by using regional climate models (RCMs) with a fine resolution (approximately 10–
2 50 km) nested in the GCM (Paeth et al 2011, Glotter et al 2014). The use of dynamical
3 downscaling in long-range climate projections has recently increased with the growth of
4 computing resources and large simulations databases of downscaled climate outputs are
5 available for intercomparison and impacts assessment (Glotter et al. 2014). For instance the
6 international Coordinated Regional Climate Downscaling Experiment Africa (CORDEX
7 Africa) simulations are now publicly available and used in the literature, including a
8 downscaled subset of GCMs simulations with different RCMs (Diallo et al. 2016). However,
9 although it can improve weather and climate variability (Feser et al 2011, Gutmann et al 2012)
10 as well as crop yield projections (e.g. Mearns et al 1999, Mearns et al 2001, Adams et al 2003,
11 Tsvetsinskaya et al 2003), it is important to keep in mind that downscaling is an additional
12 source of errors and uncertainties to crop yield projections. For example, when different RCMs
13 were used to downscale atmospheric re-analyses to force the SARRA-H crop model in Senegal,
14 Oettli et al (2011), large differences were found in the simulated sorghum yields depending on
15 the RCM used. More recently, Ramarohetra et al. (2015) conducted a sensitivity analysis of the
16 WRF model and found that a change in the physical parameterizations of a single RCM as well
17 as internal variability of the RCM can lead to major changes in the simulation of crop yields of
18 millet and maize in West Africa. As alternative to downscaling, the use of large-area crop
19 modelling has grown in recent years (Challinor et al. 2009; Tao et al. 2009; Challinor et al.
20 2004). This approach offers the possibility of using the outputs from climate models directly in
21 a process-based way, suppressing the needs for downscaling, has grown in the literature
22 (Challinor et al. 2009; Challinor et al. 2004). Several models have been used in West Africa
23 like the GLAM model used to simulate groundnut (Parkes et al. 2015) or LPJ-ml (Müller et al.
24 2010) and ORCHIDEE (Berg et al. 2011; 2013) which are part of Earth System vegetation
25 models in which they account for tropical croplands.

26 The second issue raised by the use of GCM for assessing climate impacts is that climate models
27 show significant biases in simulating current climate with sometimes insufficient skill for GCM
28 outputs to be used directly as inputs for impact models without prior bias correction (Semenov
29 and Barrow 1997). If bias-correction is often included into statistical downscaling, the skill of
30 representing the present-day climate can be very low using regional downscaling (Oettli et al.
31 2011). Since impact models ultimately rely on the accuracy of climate input data (Berg et al
32 2010), the errors inevitably propagated into the combined climate/crop modelling (Ramarohetra
33 et al. 2015; Glotter et al. 2014 ; Oettli et al. 2011). For instance, using two RCMs and the
34 DSSAT-CERES-maize crop model over the United States, Glotter et al (2014) showed that
35 although the RCMs correct some GCM biases related to fine-scale geographic features, the use
36 of a RCM cannot compensate for broad-scale systematic errors that dominate the errors for
37 simulated maize yields. Moreover, Ramirez-Villegas et al. (2013) suggested that the use of raw
38 GCM outputs can even affect the estimation of the climate change impact on crop yields by
39 significantly under- or overestimate cropping system sensitivity by 2.5–7.5% for precipitation-
40 driven areas and 1.3–23% for temperature-driven areas. Thus, careful evaluation of climate
41 models using regional key drivers of crop yields (Berg et al. 2010; Ramirez-Villegas et al. 2013;
42 Guan et al. 2015) is needed to make the best use of climate change simulations for impact
43 research. Large errors have been found in the simulation of the West African monsoon rainfall
44 by climate models which usually suffer from too much drizzle and a large bias in rainfall
45 frequency, large errors in simulating seasonal rainfall as well as an underestimation of the
46 interannual variability which can subsequently bias simulated crop yield (Guan et al. 2015;

1 Ramirez-Villegas et al. 2013; Berg et al. 2010; Baron et al. 2005). Significant biases have also
2 been found CMIP5 simulations for mean temperature and diurnal temperature ranges in West
3 Africa (Ramirez-Villegas et al. 2013). To overcome this issue, climate impact studies generally
4 require some level of climate data bias correction. The simplest correction method is the delta
5 method used by Müller et al. (2010) or Sultan et al. (2013) which consists to add a computed
6 mean annual anomaly between future and current simulated climates of a given GCM to a
7 current observation-based dataset. Promising results are obtained by Oettli et al. (2011) when
8 applying a more complex bias correction technique (Michelangeli et al. 2009) to climate model
9 outputs. In particular the authors showed that means and standard deviations of simulated yields
10 of sorghum in Senegal are much more realistic with bias corrected climate variables than those
11 using raw climate models outputs.

12 Another important issue which has already been discussed in section 2 is the large plausible
13 range of future climate changes at the regional scale of West Africa. Although there are some
14 robust features in climate change scenarios in the region (see section 2), there is a wide spread
15 in current climate model projections of regional rainfall changes over West Africa, especially
16 with respect to summertime rainfall totals (Druyan 2011) which are crucial for yields of staple
17 food crops in West Africa (Guan et al. 2015; Berg et al. 2010). Up to now, using the largest
18 number of GCMs from the CMIP5 ensemble of around 36 GCMs remains the best way to
19 represent the range of climate futures in impact assessment. Knox et al. (2012) showed that
20 increasing the number of climate models used to force crop models reduces the median range
21 and outliers about the mean change in future yields. Important biases or underestimation of
22 uncertainties can be expected from climate impact assessments based on subsets of CMIP
23 datasets, and similarly from downscaled or bias-corrected datasets (like CORDEX) which are
24 based on a restricted subset of GCMs. This point is illustrated by McSweeney and Jones (2016)
25 who investigated how well the widely used Inter-Sectoral Impact Model Inter-comparison
26 Project (ISI-MIP) subset of five CMIP5 models (see for instance Adiku et al. 2015) represent
27 the plausible range of future climate changes. They found that the fraction of the full range of
28 future projections captured by the ISI-MIP subset is sometimes very low depending on the
29 variable, the season and the region especially for summer rainfall and temperatures in the
30 Western part of West Africa (McSweeney and Jones 2016).

52 **3.2 Assessing climate impacts**

53 *The overall signal*

54 Although there is a growing literature on the impact of climate change on crop productivity in
55 tropical regions, it is difficult to provide a consistent assessment of future yield changes because
56 of large uncertainties in regional climate change projections, in the response of crops to
57 environmental change (rainfall, temperature, CO₂ concentration), in the coupling between
58 climate models and crop productivity functions, and in the adaptation of agricultural systems to
59 progressive climate change (Roudier et al 2011, Challinor et al 2007). These uncertainties result
60 in a large spread of crop yield projections indicating a low confidence in future yield
61 projections. As an example of the diversity of yield scenarios that have been produced, Roudier
62 et al. (2011) found that the response of crop yield to climate in change in West Africa can vary
63 from -50% to +90% in a selection of 16 publications. This range is even larger in the review
64 made by Müller et al. (2011) which showed that projected impacts relative to current African

1 production levels range from -100% to +168%. This range reflects the variety of regions, crops,
2 climate scenarios and models and crop models chosen in the studies.

3 To identify the main sources of uncertainty and establish robust estimates of the aggregate
4 effects of climate change on crop yields, meta-analyses were conducted at the global scale by
5 Challinor et al. (2014) to contribute to the food security and food production systems chapter
6 of the Fifth Assessment Report (AR5) of the IPCC and at the regional scale, including West
7 Africa (Knox et al. 2012, Roudier et al. 2011). Meta-analyses that combine and compare results
8 from numerous studies are widely used in epidemiology and medicine and can be a useful way
9 of summarizing the range of projected outcomes in the literature and assessing consensus. The
10 meta-analysis conducted by Challinor et al. (2014) used a data set of more than 1,700 published
11 simulations to evaluate yield impacts of climate change and adaptation which is the largest pool
12 of data from diverse modelling studies ever used for a global synthesis of this kind (Rotter
13 2014). The meta-analyses published by Knox et al. (2012) and Roudier et al. (2011) are based
14 on a smaller data set (1144 and 347 published simulations respectively) but concern specific
15 regions: Asia and Africa in database compiled by Knox et al (2012) and only West Africa in
16 the database compiled by Roudier et al. (2011). These latter two meta-analyses also include the
17 response of relevant crops in Africa (maize, sorghum, millet, rice, cotton, cassava, groundnut,
18 yam) while the meta-analysis conducted by Challinor et al. (2014) includes only major crops
19 such as maize, rice and wheat; maize and rice being the only crops of the study grown in West
20 Africa. Interestingly, while there are all based on different approaches and different samples,
21 the three studies came out with similar conclusions on how climate change will affect crop yield
22 in West Africa and how this response varies across the different assumptions and
23 methodological choices. While the magnitude of the response of crop yield to climate warming
24 scenarios varies considerably in the simulations reported by Challinor et al. (2014), Knox et al.
25 (2012) and Roudier et al. (2011), the sign of the change is mostly negative with a mean yield
26 reduction of -8% was identified in all Africa (Knox et al. 2012) and -11% in West Africa
27 (Roudier et al. 2014). Maize was found to be the most affected crop in West Africa and in the
28 Sahel by Knox et al. (2012). Without adaptation, the mean response of major crops (mostly
29 maize and rice) to climate change depicted by Challinor et al. (2014) in tropical regions is a
30 yield reduction. This robust yield loss is already significant at moderate levels of local warming
31 (+2°C) but is more consensual and stronger in the second half of the century when the additional
32 radiative forcing is amplified. If this negative impact on crop yield was already depicted in the
33 previous IPCC report, it suggested such yield loss would only occur when exceeding 3 to 4 °C
34 local warming which might be due to an overestimation in previous studies of the yield benefits
35 of enhanced atmospheric CO₂ (Rotter 2014).

36 Such robust evidence of future yield loss in West Africa also confirmed in previous review of
37 the literature (Muller et al. 2011; Kotir 2010; Challinor et al. 2007) can be surprising in regards
38 to the diverging projections in a warmer climate of summer monsoon rainfall. This is because
39 of the adverse role of higher temperatures in shortening the crop cycle duration and increasing
40 evapotranspiration demand and thus reducing crop yields, irrespective of rainfall changes
41 (Sultan et al. 2013; Berg et al. 2013, Roudier et al. 2011, Schlenker and Lobell 2010). Potential
42 wetter conditions or elevated CO₂ concentrations hardly counteract the adverse effect of higher
43 temperatures (Sultan et al. 2014) while dryer conditions can strongly amplify the yield losses
44 (Sultan et al. 2014; 2013; Roudier et al. 2011; Schlenker and Lobell 2010).

45 *Crop model differences*

1 The response of the crop to climate change is subject to uncertainty that can arise from several
2 sources (Challinor et al 2009). In particular, significant differences were found in yield response
3 from process-based versus statistical models. Knox et al. (2012) and Roudier et al. (2011) both
4 found that the dispersion around the mean is greater using process-based crop models.
5 Furthermore, Challinor et al. (2014) found that statistical models predict a greater negative
6 impact of climate on crop yields. The review of Müller et al. (2011) based on recent climate
7 change impact assessments (14 quantitative, six qualitative) in Africa also stressed this larger
8 dispersion with projected impacts relative to current production levels range from -84% to
9 +62% in process-based and from -57% to +30% in statistical assessments. The larger
10 dispersion of process-based crop models can be induced by the fact that they incorporate more
11 complex factors in the yield response to climate change (CO₂ effect, rainfall distribution,
12 extreme temperatures) but also that the lack of sufficient data for accurate calibration and
13 validation (Lobell and Burke 2010, Lobell et al. 2011) and site specific parametrization of the
14 crop management options and cultivars (Müller et al. 2011) in developing countries such in as
15 Africa increase uncertainty in the crop response. More recently, systematic intercomparison
16 studies of climate change impacts in West Africa were conducted using five process-based crop
17 models (EPIC, GEPIC, LPJ-GUESS, pDSSAT and PEGASUS; see Deryng 2015) and two
18 process-based crop models (DSSAT and APSIM in Adiku et al. 2015; SARRA-H and APSIM
19 in Sultan et al. 2014) using the same forcing climate datasets. They all found a general
20 agreement in the sign of the crop yield response to climate change scenarios while the amplitude
21 of the impact varied strongly across models and simulated crops.

22 *Regional differences*

23 Important regional differences have been found in the response of crop yield to climate change.
24 Roudier et al. (2011) found that cropped areas in the Soudano-Sahelian zone are likely to be
25 more affected by climate change than those located in the Guinean zone. This difference can be
26 explained by the projections of future climate in Africa which show a greater warming over
27 continental Africa (particularly in the Sahel and Sahara) while the temperatures of the Guinean
28 zone, which are influenced by the Atlantic Ocean, are expected to increase more slowly.

29 Using simulations of nine bias-corrected CMIP5 climate models and two crop models
30 (SARRA-H and APSIM), Sultan et al. (2014) found a West-East dipole in the impacts of crop
31 yield to climate change in West Africa. Indeed, in broad agreement with the full CMIP5
32 ensemble, their subset of bias-corrected climate models depicted a robust change in rainfall in
33 West Africa with less rain in the Western part of the Sahel (Senegal, South-West Mali) and
34 more rain in Central Sahel (Burkina Faso, South-West Niger) in the decades of 2031–2060
35 compared to a baseline of 1961–1990. In response to such climate change, but without
36 accounting for direct crop responses to CO₂, mean crop yield of sorghum decreases by about
37 16–20% and year-to-year variability increases in the Western part of the Sahel, while the eastern
38 domain sees much milder impacts. This West-East dipole is confirmed by the study of Deryng
39 (2015) which uses a set of five global climate models and six different global gridded crop
40 models to assess climate change impacts on crop productivity in semi-arid croplands by the
41 2030s under the RCP 8.5 scenario. Without including the effect of elevated CO₂ on crop
42 photosynthesis and water demand, the author shows in Senegal, where three over five GCMs
43 simulate drier conditions a median decrease of rainfed crop (-8.5±9.9%) while in the Eastern
44 part of West Africa in Burkina Faso, where four of the five GCMs simulate wetter conditions,
45 the results show a slight decrease (-3.9±4.3%). This dipole was also found in the study of Adiku

1 et al. (2015) which used DSSAT and APSIM to simulate climate change impacts on crop yields
2 in two locations in Niore (Senegal) and Navrongo (Ghana). The effect of climate change was
3 higher in the Senegalese site than in the one in Ghana using both crop simulation models.

4 *The effect of elevated CO₂*

5 If rising atmospheric CO₂ concentrations directly contributes to climate change, it has the
6 potential to increase crop water productivity by enhancing photosynthesis and reducing leaf-
7 level transpiration of plants (Deryng et al. 2016, Tubiello et al. 2007; Leakey 2009). Significant
8 increases of crop yield due to elevated levels of CO₂ have been reported in experiments for
9 different crops (Kimball et al. 1983; 2002) and most of the recent modelling studies simulate
10 the effect of elevated CO₂ (Deryng et al. 2016). However, there is an ongoing debate about the
11 extent of impacts of CO₂ fertilization on crop yields in observations and models (Long et al.
12 2006; Ainsworth et al. 2008), especially in Africa where few field observations are unavailable
13 to validate and further improve the models. In particular there is no free air carbon dioxide
14 enrichment (FACE) experiments in Africa. Yet, the impact of higher atmospheric CO₂
15 concentration is a major source of uncertainty in crop yield projections (Soussana et al. 2010;
16 Roudier et al. 2011). For instance, by conducting a systematic comparison between yield
17 response to climate change with, or without, CO₂ fertilization effect, Müller et al. (2010) found
18 a yield increase of 8% in Africa (percent change in 2046–2055 relative to 1996–2005) with full
19 CO₂ fertilization, and a yield loss of –8% without the CO₂ effect. More recently, Deryng (2015)
20 found that simulated median yield of rain-fed crops in six countries of semi-arid areas
21 (including Senegal and Burkina Faso in West Africa) increases by 4.7±9.6% when including
22 the effects of both climate change and elevated CO₂ concentrations while median yield
23 decreases by 4.5±7.3% when excluding the effects of elevated CO₂ concentrations. Sultan et
24 al. (2014) also found that CO₂ fertilization would significantly reduce the negative climate
25 impacts, increasing sorghum yields on average by 10%, and drier regions would have the
26 largest benefits. However, other studies show lower differences between full and no CO₂
27 fertilization scenarios (Berg et al. 2013). Overall most studies conclude that benefits of
28 elevated CO₂ will be greater for C3 crops (e.g. soybean, groundnut) which are likely to
29 accumulate more biomass and for C4 crops in arid regions through increased water use
30 efficiency (Deryng et al. 2016; Sultan et al. 2014; Berg et al. 2013). However, while
31 showing benefits of higher CO₂ concentrations on water crop productivity, Deryng (2015)
32 and Sultan et al. (2014) both show that it partially offsets the impacts from climate changes
33 especially in the Western part of Africa where yield losses are expected even after
34 accounting for CO₂ fertilization effect. Deryng (2015) found a decrease of crop yield of
35 groundnut, millet, sorghum and maize in Senegal by the 2030s even when including the effects
36 of CO₂. The author also found a slight increase of crop yield of millet and sorghum in Burkina
37 Faso when including CO₂ but yield of groundnut and maize decreases. Moreover, even if we
38 can expect benefits from increasing CO₂ on crop productivity, nutritional value may
39 nevertheless be compromised (Muller et al. 2014). Indeed, a meta-analysis conducted by Myers
40 et al. (2014) demonstrated that CO₂ fertilization is likely to have adverse effects on the
41 nutritional value of many key food crops by reducing the concentrations of essential minerals
42 and protein with potential serious consequences in food security (Muller et al. 2014).

43 **3.3 Adaptation studies**

45 Despite large uncertainty, there is a robust conclusion from the above section: agriculture in
46 West Africa is at risk to be negatively affected by climate change. These potential adverse
47 negative climatic changes effects are superimposed on top of high natural variability in seasonal

1 rainfall, which historically has produced large inter-annual variations in rainfall and prolonged
2 droughts (Giannini et al. 2008) and the recent increase in rainfall intensity and extreme heavy-
3 rainfall events (Panthou et al. 2014). Both climate variability and trend pose a challenge for the
4 primarily rain-fed agriculture systems in West Africa. Since the 1970's, the largest food crises
5 in Africa that required large-scale external food aid (1974, 1984/1985, 1992 and 2002) have
6 been attributed fully or partially to extreme weather events (Dilley et al. 2005). Thus, any
7 successful adaptations should be able to cope with the short-term climate variability as well as
8 reduce the negative impacts of climate change in the long term (Lobell 2014; Saba et al. 2013).
9 Hertel and Lobell (2014) distinguished between three categories of adaptation: (i) adaptation
10 options based on current technology which can also identified as autonomous adaptation, (ii)
11 adaptation involving a new technologies and (iii) adaptations involving the institutional
12 environment within which the producer is operating such as markets and policy and resulting
13 from planned adaptation. Adjustments in planting and harvesting dates, varieties of crops to be
14 grown (including combination between crops and cultivars as intercrop or the use of existing
15 varieties more resistant to climate-induced stress), increase planting density and/or fertilizers
16 use, use of crop residue as mulch are examples of options already available to farmers in West
17 Africa to adapt to climate variability and change. Breeding more resilient crop varieties (Rotter
18 et al. 2015), advanced breeding methods including more effective root system size, dehydrin
19 genes, phenotyping (Amelework et al. 2015; Setter 2012; Araus et al. 2012; Valdez et al. 2012);
20 innovating water harvesting techniques (Rockström and Falkenmark 2015; Lebel et al. 2015)
21 belong to the second category of adaptation options. In the third category defined by Hertel and
22 Lobell (2014), fertilizer subsidies, crop insurances (Berg et al. 2009), credits, climate services
23 (access and use of weather and seasonal forecasts; Sultan et al. 2010; Roudier et al. 2016; 2014;
24 2012) are such important changes in the institutional and market environment of West Africa
25 that would affect producer decisions. Assessing various possible adaptation options and their
26 uncertainties is crucial for optimal prioritization of adaptation investments for supporting
27 adaptation strategies in West Africa that may counteract the adverse effects of climate change.
28 However, pointing out the most promising adaptation options remain challenging since there is
29 a large scatter of possible results across locations and situations, indicating the need for a more
30 contextual approach on regional and local scales (Challinor et al. 2014). We will thus give some
31 examples of some recent studies who quantified the potential of adaptation for major crops in
32 West Africa showing sometimes apparent contradictory and crop-specific results.

33 *Millet and sorghum*

34 These two crops are among the main staple crops of sub-Saharan West Africa (64% of the total
35 cereal production in 2000; FAOSTAT data). On-farm surveys have shown the dominance of
36 traditional cultivars of sorghum and millet characterized by a strong sensitivity to photoperiod
37 (Traoré et al. 2011). Photoperiod sensitivity would likely present some advantages in the event
38 of future change in the timing of the rainy season. Indeed, it allows for flowering at the end of
39 the rainy season for a wide range of planting dates and avoids incomplete grain filling, a
40 problem for late maturing varieties faced with water shortage at the end of the rainy season
41 (Dingkuhn et al. 2006). Furthermore, Sultan et al. (2013) found that traditional photoperiod-
42 sensitive cultivars are less affected by temperature increase since the photoperiod limits the
43 reduction of the crop duration. On the opposite, adverse impacts of climate change have been
44 found to be the lowest on mean yield and yield variability for photoperiod-insensitive cultivars,
45 as their short and nearly fixed growth cycle appears to be more resilient to the seasonality shift
46 of the monsoon, thus suggesting shorter season varieties could be considered a potential
47 adaptation to ongoing climate changes (Sultan et al. 2014). This result is consistent with the

1 study from Kouressy et al. (2008), which demonstrated that potentially high-yielding and
2 photoperiod-insensitive cultivars display an advantage where the rainy season is short.
3 Modelling studies (Turner and Rao 2013; Sultan et al. 2014) suggest that while increasing
4 fertilizer inputs and restoring nutrients imbalance in low-input, smallholder, sorghum
5 farmers of Africa would increase overall food production and have fundamental benefits
6 increasing food security (Vitousek et al 2009), the trade-off is that it would increase the
7 sensitivity of those systems to climate variability and increase adverse impacts of climate
8 change.

9 Several studies also investigated new technologies for mitigating the adverse impacts of climate
10 change on millet and sorghum production. Adiku et al. (2015) used two crop models DSSAT
11 and APSIM to simulate millet cultivars adapted to future climate conditions. They found
12 positive effects on crop yield whereas the benefits depend on the location, the crop and the
13 climate model used for the simulation. Sultan et al. (2013) also found advantages of breeding
14 varieties with higher thermal requirements which can partly counteract the shortening of crop-
15 cycle duration in a warmer climate. Guan et al. (2016) used two crop models APSIM and
16 SARRA-H to assess five possible and realistic adaptation options for the production of
17 sorghum (late sowing, increase planting density and fertilizer use, increasing cultivars'
18 thermal time requirement, water harvesting, and increase resilience to heat stress during the
19 flowering period). They found that most proposed adaptation options are not more
20 beneficial in the future than in the historical climate so that they do not really reduce the
21 climate change impacts. Increased temperature resilience during grain number formation
22 period is the main adaptation that emerges from this study.

23 *Maize*

24 Maize is the most important staple food and accounts for nearly 20% of total calorie intake in
25 sub-Saharan Africa (SSA) (FAOSTAT data). In their meta-analysis, Challinor et al. (2014)
26 compared the effect of climate change on maize yields in the Tropics with and without
27 adaptation; adaptation options including changes in planting dates, fertilizer use, irrigation,
28 cultivar or other agronomic options. They concluded that in contrast to what has been published
29 for wheat and rice in the temperate latitudes, there is no effect of adaptation in the Tropics and
30 little evidence for the potential to avoid yield loss in maize yield since the varieties of crop
31 grown are already adapted to high temperatures. Similar results were also found by Deryng et
32 al. (2011) who reported substantial yield losses in developing countries located in the Tropics
33 for maize even after allowing for adjustment of planting dates and varieties grown. Using
34 simulations from the GEPIC model in Sub-Saharan Africa, Folberth et al. (2014) investigated
35 different intensification options for growing maize under climate change. They found that
36 intensive cultivation is predicted to result in lower yields under future climate conditions and
37 increased soil erosion while eco-intensification shows better yields. However, yield losses are
38 simulated in all management scenarios towards the end of the century suggesting a limited
39 effect of eco-intensification as a sole means of adapting agriculture to climate change. Finally,
40 promising results of rainfall harvesting have been found by Lebel et al. (2015) which found that
41 applying this technique to maize cultivation across Africa could mitigate 31 % of yield losses
42 attributable to water stress and increase maize yields by 14–50 % on average under the projected
43 climatic conditions of the 2050s.

44 *Groundnut and Yam*

1 Groundnut is an important crop for Nigeria, southern Mali, Ivory Coast, Burkina Faso, Ghana
2 and Senegal. Parkes et al. (2015) investigated the benefits of breeding cultivars of groundnuts
3 with heat and water stress resistance as well as the potential of marine cloud brightening to
4 reduce the rate of crop failures in West Africa using the GLAM model. The authors found that
5 climate change will increase mean yields of groundnut and reduce the risk of crop failure in
6 West Africa. This projected increase in yields is due to the carbon dioxide fertilization effect
7 also to increased seasonal rainfall in the unique GCM simulation used in this study. Parkes et
8 al. (2015) investigated the benefits of breeding cultivars of groundnuts with heat and water
9 stress resistance as well as the potential of marine cloud brightening to reduce the rate of crop
10 failures in West Africa. They found that water stress, rather than heat stress, is the main cause
11 of crop failure in current and future climate and also demonstrated a positive impact of marine
12 cloud brightening.

13 Yam is the second most important crop in Africa in terms of production after cassava.
14 Srivastava et al. (2015) simulated the advantages of specific adaptation strategies using the
15 EPIC model. They found that changing solely sowing date may be less effective in reducing
16 adverse climatic effects than adopting late maturing cultivars. Yet, combining different options
17 such as coupling irrigation and fertilizer application with late maturing cultivars, highest
18 increase in the yields could be realized.

19 *Cassava*

20 Using the EcoCrop model to investigate the response of important staple food crops for Africa
21 including maize, millets, sorghum, banana, and beans to climate projections by 2030, Jarvis et
22 al. (2012) found that cassava reacted very well to the predicted future climate conditions
23 compared to other crops. Whilst most simulated crops in Africa were predicted to experience
24 decreases in overall suitability in Africa, cassava always outperformed or (in the worst case)
25 equaled the average and appeared as a highly resilient staple crop. Crop improvements towards
26 greater drought tolerance and heat tolerance in localized pockets of West Africa and the Sahel
27 could bring some additional benefits.

28

29 **4. Summary and conclusions**

30 In this paper, an extensive review of the recent literature on the West African climate and
31 impacts is used to draw a general picture of the main features of the regional climate, the
32 associated observed variability, the future change as well as expected impacts and potential for
33 adaptation in the agriculture sector.

34 The dominant role of the WAM in determining the regional climate is highlighted, and the
35 importance of the global SST in driving the multi-time scales variability is described
36 (Rodriguez-Fonseca et al. 2015). In particular, the relationship of the WAM precipitation
37 variability with the tropical ocean SST at the interannual time scales (Rowell, 2001; Polo et al.
38 2008; Losada et al. 2010; Mohino et al. 2011b), and with the extratropical ocean SST at
39 multidecadal time scales (Zhang and Delworth 2006; Ting et al. 2009; Mohino et al. 2011a;
40 Villamayor and Mohino 2015), is illustrated. The long lasting wet phase characterizing the
41 Sahelian precipitation in the 20th century up to the 70s, and the following severe drought
42 affecting the Sahel culminating in the 80s, have been related principally to the SST variability
43 associated with the Atlantic multidecadal variability (Mohino et al. 2011a). At the turn of the
44 21st century, the Sahel experienced a slight recovery of precipitation (Panthou 2014; Maidment

1 et al. 2015; Sanogo et al. 2015), but the attribution of this recovery is still debated. On the one
2 hand, it is attributed to the differential warming between extratropical and tropical SST in the
3 Northern Hemisphere, favoring the northward displacement of the ITCZ (Park et al. 2014). On
4 the other hand, the recovery is attributed to the regional radiative warming produced by the CO₂
5 direct forcing, inducing a thermodynamic feedback on the monsoon system (Dong and Sutton
6 2015). The rainfall recovery has been characterized by a modification of the precipitation
7 regime, with higher intensity rainfall events concentrated in less rainy days (Panthou 2014).
8 Moreover, a widespread warming of the North African subcontinent, and an increase in the
9 occurrence of climate extremes, such as heat waves and hot summers, has been observed
10 (Fontaine et al. 2013; Moron et al. 2016).

11 The same tendencies in temperature, precipitation and climate extremes are projected in the
12 21st century, in all the moderate-to-high emission scenarios, with the amplitude of the climate
13 change signal growing proportionally with the projected global warming. The intensification of
14 the hydrological cycle in the recent decades and in future projections has also been detected in
15 in the world's dry and wet regions, leading to an increased risk of flooding in dry regions as the
16 climate warms (Donat et al. 2016). However, the future projections of the West African climate
17 are affected by large uncertainties, especially regarding the monsoonal precipitation. Indeed,
18 although around 50% of the CMIP5 GCMs agrees on the future positive trend, around 25% of
19 the models project the opposite situation, weakening the prevision (Biasutti 2013). The origin
20 of this uncertainties is twofold. On the one hand, the biases characterizing the SST simulated
21 by the atmosphere-ocean climate models, which affect the mechanisms driving the multidecadal
22 variability of the WAM system (Rowell 2013; Roehrig et al. 2013). On the other hand, the
23 diverse sensitivity of climate models to the effect of the projected increase in CO₂ concentration,
24 which induces wet anomalies through the direct radiative warming of the surface at the regional
25 scale, but at the same time inhibits the precipitation when the radiative forcing is mediated by
26 the global SST warming (Bony et al. 2013; Gaetani et al. 2016). Climate modelling of West
27 Africa at the regional scale show promising improvements of the GCM performances, although
28 large uncertainties still persist. Firstly, RCMs are inevitably affected by the biases of the driving
29 GCMs (Dosio et al. 2015). Secondly, RCMs experiments show high sensitivity to the physical
30 parametrization, especially regarding convection (Klutse et al. 2016), which is crucial for the
31 simulation of the monsoonal rainfall. Therefore, the climate modelling community is pushed
32 for a further effort to improve the modelling of West African climate, in the direction of both
33 understanding the physical mechanisms and reducing the climate model shortcomings.

34 There are many complex processes that drive the response of crop yield to such climate changes.
35 These processes can act in a competing way as we can expect from the role of increased
36 atmospheric CO₂ concentration which increase crop yield while warmer mean temperatures are
37 likely to lead to crop yield losses. Such processes can interact together and their importance
38 might depend on the region, the scale and the crop. The complexity of the risk posed by climate
39 change and possible adaptation strategies have called for a number of climate change
40 assessment studies especially in Africa where this risk can severely affect food security and
41 impede development. Despite a large uncertainty in the published results and diverging future
42 projections of summer monsoon rainfall which is key for rain-fed agriculture, a robust evidence
43 of yield loss in West Africa emerges from these studies. This yield loss is mainly driven by
44 increased mean temperature while potential wetter conditions as predicted in Central Sahel or
45 elevated CO₂ concentrations for C3 crops and C4 crops in the arid zones of the Sahel can partly
46 or totally counteract this effect. On the opposite, yield losses will be the highest for C4 crops in

1 the Soudano-Sahelian zones and in areas where rainfall is expected to decrease like in the
2 Western part of the Sahel. Identifying the most promising adaptation options is even more
3 uncertain since uncertainty about climate impacts is then cumulated with uncertainty about the
4 effectiveness of adaptations. Most adaptation options illustrated in this review are implemented
5 in process-based crop models to adjust cropping systems (change in varieties, sowing dates and
6 density, irrigation, fertilizer management) to future climate. Results of the cited studies are crop
7 and region specific and no clear conclusions can be made regarding the most effective
8 adaptation options.

9 Although substantial progress has been made in the assessment of the effect of climate change
10 on crop yield and potential for adaptation in West Africa, large gaps still exist. Important
11 processes like the effect of heat stress or ozone are missing in crop models (Ewert et al. 2015),
12 most effort on model development and intercomparison are biased towards major crops in
13 temperate regions and the African region generally suffers from a lack of sufficient data for
14 accurate calibration and validation of crop models (Lobell and Burke 2010). Furthermore,
15 specific crop management options and cultivars of low intensive systems as mainly found in
16 West Africa (mulching, species mixtures, intercropping and reduced tillage technologies) are
17 not well represented in crop models (Ewert et al. 2015; Hertel and Lobell 2013). If recent
18 progress has been made to quantify the potential for adaptation in integrated assessment and
19 modelling approaches linking biophysical and economic models (Ewert et al. 2015; Patt et al.
20 2010), these approaches are built on assumptions which are more appropriate for the high
21 income and developed countries with high adaptive capacity. Hertel and Lobell (2013)
22 concludes that they present a risk to underestimate the impacts of climate change in the Tropics
23 and a risk of overstating the efficiency of adaptations in regions like Sub-Saharan Africa.

24 As suggested by Challinor et al. (2009), an objective quantification of impacts uncertainty is a
25 necessary step to go beyond syntheses or meta-analyses of published studies with large
26 heterogeneity resulting from inherently uncoordinated studies. Large ensemble of climate
27 simulations, downscaling techniques and crop simulation ensembles including different
28 modelling approaches and sensitivity analyses are necessary for improved understanding of
29 how climate uncertainties and errors propagate into impact estimates, a better quantification of
30 crop model uncertainty as well as a better quantification of downscaling and bias-correction
31 uncertainty (Ramirez-Villegas et al. 2013). In this respect, coordinated efforts such as the
32 AgMIP initiative which aims to improve agricultural models including biophysical and socio-
33 economic approaches at various scales and develop common protocols to systematize
34 modelling for the assessment of climate change impacts on crop production represents a
35 promising way towards more robust results (Rotter 2014). While they are crucially lacking in
36 Sub-Saharan Africa, observations are also a key to go forward in the quantification of
37 uncertainty and possible reduction of its range. Most modelling work on climate impacts
38 assessment needs quality data to validate and bias-correct climate simulations, calibrate,
39 validate and force crop models or evaluate cropping systems adaptation. Improvement of
40 quality, accessibility of data (including weather, soil, on-farm and experimental crop data,
41 socio-economic data) as well as support for maintaining data over time and collecting long-
42 term time series is of high importance in Sub-Saharan Africa. Finally, if there is evidence that
43 farmers and farming systems are highly resilient to environmental changes, adaptation to
44 climate change needs to be supported and facilitated by governmental, institutional and macro-
45 economic conditions (Challinor et al. 2007). Adaptation to climate change cannot be achieved
46 without a considerable institutional and political commitments for technical support or access

1 to credit for instance (Thornton et al. 2005) and many of institutional, economic, informational,
2 and social constraints are still ignored in modelling approaches of adaptation (Hertel and Lobell
3 2013) which need to better account for both the biophysical and socio-economic determinants
4 and specificities of agricultural systems in Africa.

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7 All authors listed have made substantial, direct and intellectual contribution to the work, and
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17 **Conflict of Interest Statement**

18 The authors declare that the research was conducted in the absence of any commercial or
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21 **References**

- 22 Adams, R.M., McCarl, B.A., and Mearns, L.O. (2003). The effects of spatial scale of climate
23 scenarios on economic assessments: an example from US agriculture. *Clim. Change* **60**, 131–
24 148.
- 25 Adejuwon, J.O. (2006). Food crop production in Nigeria. II. Potential effects of climate change,
26 *Climate Research* **32**, 229–245.
- 27 Adiku, S.G.K., MacCarthy, D.S., Hathie, I., Diancoumba M., Freduah, B.S., Amikuzuno, J., et
28 al. (2015). Climate Change Impacts on West African Agriculture: An Integrated Regional
29 Assessment (CIWARA), Handbook of Climate Change and Agroecosystems The Agricultural
30 Model Intercomparison and Improvement Project (AgMIP) Integrated Crop and Economic
31 Assessments — Joint Publication with American Society of Agronomy, Crop Science Society
32 of America, and Soil, Edition: ICP Series on Climate Change Impacts, Adaptation, and
33 Mitigation. Volume 3, Chapter: chapter 2, Publisher: Imperial College Press, Editors: Cynthia
34 Rosenzweig (Columbia University, USA, Daniel Hillel (Columbia University USA), pp.25-73.
- 35 Affholder, F., Tiftonell, P., Corbeels, M., Roux, S., Motisi, N., Tixier, P., and Wery, J. (2012).
36 Ad Hoc Modeling in Agronomy: What Have We Learned in the Last 15 Years? *Agron. J.* **104**,
37 735–748.
- 38 Ainsworth, E.A., Leakey, A.D.B., Ort, D.R., Long, S.P. (2008). FACE-ing the facts:
39 Inconsistencies and interdependence among field, chamber and modeling studies of elevated

- 1 [CO₂] impacts on crop yield and food supply. *New Phytologist* 179, 5-9.
- 2 Amelework, B., Shimelis, H., Tongoona, P., & Laing, M. (2015). Physiological mechanisms of
3 drought tolerance in sorghum, genetic basis and breeding methods: A review. *African Journal*
4 *of Agricultural Research* 10, 3029-3040.
- 5 Angulo, C., Rötter, R.P., Trnka, M., Pirttioja, N., Gaiser, T., Hlavinka, P., and Ewert, F. (2013).
6 Characteristic ‘fingerprints’ of crop model responses to weather input data at different spatial
7 resolutions. *Eur. J. Agron.* 49, 104–114.
- 8 Araus, J.L., Serret, M.D., Edmeades, G. (2012). Phenotyping maize for adaptation to drought,
9 *Frontiers in Physiology* 3, doi=10.3389/fphys.2012.00305
- 10 Bader J, Latif M (2003). The impact of decadal-scale Indian Ocean sea surface temperature
11 anomalies on Sahelian rainfall and the North Atlantic Oscillation. *Geophys Res Lett* 30, 1–4,
12 doi:10.1029/2003GL018426.
- 13 Bamba Sylla M., Jeremy S. Pal, Guiling L. Wang, and Peter J. Lawrence (2016). Impact of land
14 cover characterization on regional climate modelling over West Africa. *Clim Dyn* 46, 637–650,
15 DOI 10.1007/s00382-015-2603-4.
- 16 Baron, C., Sultan, B., Balme, M., Sarr, B., Traore, S., Lebel, T., et al. (2005). From GCM grid
17 cell to agricultural plot: scale issues affecting modelling of climate impacts. *Philos Trans R Soc*
18 *Lond, B* 360, 2095–2108.
- 19 Ben Mohamed, A., Vanduivenbooden, N., and Abdousallam, S. (2002). Impact of climate
20 change on agricultural production in the Sahel—Part 1. Methodological approach and case study
21 for millet in Niger. *Climatic Change* 54, 327–348.
- 22 Berg, A., de Noblet-Ducoudre, N., Sultan, B., Lengaigne, M., Guimberteau, M. (2013).
23 Projections of climate change impacts on potential C4 crop productivity over tropical regions.
24 *Agricultural and Forest Meteorology* 170, 89-102.
- 25 Berg, A., Quirion, P., Sultan, B. (2009). Weather-Index Drought Insurance in Burkina-Faso:
26 Assessment of Its Potential Interest to Farmers. *Weather Climate and Society* 1, 71-84.
- 27 Berg, A., Sultan, B., and de Noblet, N. (2011). Including tropical croplands in a terrestrial
28 biosphere model: Application to West Africa. *Climatic Change* 104, 755–782.
- 29 Berg, A., Sultan, B., and de Noblet-Ducoudre, N. (2010). What are the dominant features of
30 rainfall leading to realistic large-scale crop yield simulations in West Africa? *Geophysical*
31 *Research Letters* 2010;37.
- 32 Biasutti M. (2013). Forced Sahel rainfall trends in the CMIP5 archive. *J Geophys Res Atmos*
33 118, 1613–1623, doi:10.1002/jgrd.50206.
- 34 Biasutti M., Sobel A.H., Camargo S.J. (2009). The role of the Sahara low in summertime Sahel
35 rainfall variability and change in the CMIP3 models. *J Clim* 22, 5755–5771,
36 doi:10.1175/2009JCLI2969.1.
- 37 Bony S., Bellon G., Klocke D., Sherwood S., Fermepin S., Denvil S. (2013). Robust direct
38 effect of carbon dioxide on tropical circulation and regional precipitation. *Nat Geosci* 6, 447–
39 451. doi:10.1038/ngeo1799.
- 40 Boote, K.J., Jones, J.W., and Pickering, N.B. (1996). Potential uses and limitations of crop
41 models. *Agron J* 88, 704–716.

1 Bou Karam, D., C. Flamant, P. Knippertz, O. Reitebuch, J. Pelon, M. Chong, and A. Dabas
2 (2007). Dust emissions over the Sahel associated with the West African monsoon intertropical
3 discontinuity region: A representative case-study. *Q. J. R. M. S.*, 134, 621–634.

4 Bucchignani E., P. Mercogliano, G. Rianna and H.-J. Panitzc (2015). Analysis of ERA-
5 Interim-driven COSMO-CLM simulations over Middle East – North Africa domain at different
6 spatial resolutions. *Int. J. Climatol.* DOI: 10.1002/joc.4559.

7 Buontempo C., Camilla Mathison, Richard Jones, Karina Williams, Changgui Wang, Carol
8 McSweeney (2015). An ensemble climate projection for Africa. *Clim Dyn* 44, 2097–2118,
9 DOI: 10.1007/s00382-014-2286-2.

10 Butt, T., McCarl, B., Angerer, J., Dyke, P., and Stuth, J. (2005). The economic and food
11 security implications of climate change in Mali, *Climatic Change* 68, 355–378.

12 Caminade C, Terray L (2010). Twentieth century sahel rainfall variability as simulated by the
13 ARPEGE AGCM, and future changes. *Clim Dyn* 35, 75–94. doi:10.1007/s00382-009-0545-4.

14 Challinor, A. J., and Wheeler, T. R. (2008). Crop yield reduction in the tropics under climate
15 change: processes and uncertainties. *Agric. For. Meteorol* 148, 343-356.

16 Challinor, A., Wheeler, T., Garforth, C., Craufurd, P., Kassam, A. (2007). Assessing the
17 vulnerability of food crop systems in Africa to climate change. *Climatic Change* 83, 381-399.

18 Challinor, A.J., Ewert, F., Arnold, S., Simelton, E. and Fraser, E. (2009). Crops and climate
19 change: progress, trends, and challenges in simulating impacts and informing adaptation. *J.*
20 *Exp. Bot.* 60, 2775-2789.

21 Challinor, A.J., Slingo, J.M., Craufurd, P.Q., Grimes, I.F. (2004). Design and optimisation of a
22 large-area process-based model for annual crops. *Agricultural and Forest Meteorology* 124,
23 99–120.

24 Challinor, A.J., Watson, J., Lobell, D. B., Howden, S. M., Smith, D. R., and Chhetri, N. (2014).
25 A meta- analysis of crop yield under climate change and adaptation. *Nature Climate Change* 4,
26 287–291.

27 CLIVAR Exchanges No. 66, Vol. 19, No. 1, Jan 2015: Special Issue on Monsoons: Advancing
28 understanding of monsoon variability and improving prediction.

29 Cook, K. H. (2015). Role of inertial instability in the West African monsoon jump. *J. Geophys.*
30 *Res. Atmos.*, 120, 3085–3102, doi:10.1002/2014JD022579.

31 Cook K.H., Vizy E.K. (2015). Detection and analysis of an amplified warming of the Sahara
32 desert. *J Clim* 28, 6560–6580. doi:10.1175/JCLI-D-14-00230.1.

33 Cretat J., Edward K. Vizy, and Kerry H. Cook (2015). The relationship between African
34 easterly waves and daily rainfall over West Africa: observations and regional climate
35 simulations. *Clim Dyn* 44, 385–404, DOI 10.1007/s00382-014-2120-x.

36 Deryng, D. (2015) *Climate change impacts on crop productivity in global semi-arid areas and*
37 *selected semi-arid economies*, Small Grant Programme Working Paper, Overseas Development
38 Institute (ODI), London, [http://prise.odi.org/research/small-grants-programme-climate-](http://prise.odi.org/research/small-grants-programme-climate-change-impacts-on-crop-productivity-in-global-semi-arid-areas-and-selected-semi-arid-economies/)
39 [change-impacts-on-crop-productivity-in-global-semi-arid-](http://prise.odi.org/research/small-grants-programme-climate-change-impacts-on-crop-productivity-in-global-semi-arid-areas-and-selected-semi-arid-economies/)
40 [economies/](http://prise.odi.org/research/small-grants-programme-climate-change-impacts-on-crop-productivity-in-global-semi-arid-areas-and-selected-semi-arid-economies/)

- 1 Deryng, D., Elliott, J., Folberth, C., Müller, C., Pugh, T.A.M., Boote, K.J., et al. (2016).
2 Regional disparities in the beneficial effects of rising CO₂ concentrations on crop water
3 productivity. *Nature Climate Change*, 2016; doi: 10.1038/nclimate2995.
- 4 Deryng, D., Sacks, W.J., Barford, C.C., and Ramankutty, N. (2011). Simulating the effects of
5 climate and agricultural management practices on global crop yield, *Glob. Biogeochem. Cycles*
6 25, doi:201110.1029/2009GB003765)
- 7 Di Paola, A., Valentini, R., and Santini, M. (2016). An overview of available crop growth and
8 yield models for studies and assessments in agriculture. *J Sci Food Agric* 96, 709–714.
- 9 Diallo, I., Giorgi, F., Deme, A., Tall, M., Mariotti, L., and Gaye, A.T. (2016). Projected changes
10 of summer monsoon extremes and hydroclimatic regimes over West Africa for the twenty-first
11 century. *Climate Dynamics*, 1-24, doi: 10.1007/s00382-016-3052-4
- 12 Diasso U., and Babatunde J. A. (2015). Drought modes in West Africa and how well CORDEX
13 RCMs simulate them. *Theor Appl Climatol*, DOI: 10.1007/s00704-015-1705-6.
- 14 Dike, V. N., Shimizu, M. H., Diallo, M., Lin, Z., Nwofor, O. K. and Chineke, T. C. (2015).
15 Modelling present and future African climate using CMIP5 scenarios in HadGEM2-ES. *Int. J.*
16 *Climatol*, 35, 1784–1799. doi:10.1002/joc.4084.
- 17 Dilley, M., Chen, R.S., Deichmann, U., Lerner-Lam, A.L. and Arnold, M. (2005). *Natural*
18 *disaster hotspots: a global risk analysis*. Disaster Risk Management Series No.5. Washington,
19 DC: The World Bank.
- 20 Dingkuhn, M., Singh, B.B., Clerget, B., Chantreau, J., and Sultan B. (2006) Past, present and
21 future criteria to breed crops for water-limited environments in West Africa *Agric. Water*
22 *Manag.* 80, 241–61.
- 23 Doblus-Reyes F., and Coauthors (2013). Initialized near-term regional climate change
24 prediction. *Nature Commun.*, 4, 1715, doi:10.1038/ncomms2704.
- 25 Donat, M. G., Lowry, A. L., Alexander, L. V., Ogorman, P. A., and Maher, N. (2016). More
26 extreme precipitation in the world's dry and wet regions. *Nature Clim. Change* 6, 508-513.
- 27 Dong, B., and R. Sutton (2015). Dominant role of greenhouse-gas forcing in the recovery of
28 Sahel rainfall. *Nat. Clim. Change*, 5, 757-760.
- 29 Dosio A. and Hans-Jürgen Panitz (2016). Climate change projections for CORDEX-Africa
30 with COSMO-CLM regional climate model and differences with the driving global climate
31 models. *Clim Dyn* 46, 1599–1625, DOI: 10.1007/s00382-015-2664-4.
- 32 Dosio A., H.J. Panitz, M. Schubert-Frisius, D. Lüthi (2015). Dynamical downscaling of CMIP5
33 global circulation models over CORDEX-Africa with COSMO-CLM: evaluation over the
34 present climate and analysis of the added value. *Clim Dyn* 44:2637–2661, DOI
35 10.1007/s00382-014-2262-x.
- 36 Druyan, L.M. (2010). Studies of 21st-century precipitation trends over West Africa,
37 *International Journal of Climatology* (2010) Online

- 1 Druyan L.M. and M. Fulakeza (2015). The impact of the Atlantic cold tongue on West African
2 monsoon onset in regional model simulations for 1998–2002. *Int. J. Climatol.* 35: 275–287,
3 DOI: 10.1002/joc.3980.
- 4 Evan A.T., C. Flamant, M. Gaetani, F. Guichard (2016). The Past, Present and Future of African
5 Dust. *Nature*, 531, 493-495, doi:10.1038/nature17149.
- 6 Evan A.T., Flamant C., Lavaysse C., Kocha C., Saci A. (2015). Water vapor-forced greenhouse
7 warming over the Sahara desert and the recent recovery from the Sahelian drought. *J Clim*
8 28:108–123. doi:10.1175/JCLI-D-14-00039.1.
- 9 Ewert, F., Rötter, R.P., Bindi, M., Webber, H., Trnka, M., Kersebaum, K.C., et al. (2015). Crop
10 modelling for integrated assessment of risk to food production from climate change.
11 *Environmental Modelling & Software* 72, 287-303.
- 12 FAOSTAT (2012). Statistical Database (Rome: Food and Agricultural Organization of the UN)
13 <http://faostat.fao.org> (Accessed on 20 September 2012)
- 14 Feser, F., Rockel, B., von Storch, H., Winterfeldt, J. and Zahn, M. (2011). Regional climate
15 models add value to global model data: a review and selected examples. *Bull. Am. Meteorol.*
16 *Soc.* **92**, 1181–92.
- 17 Fischer, G., Shah, M., Tubiello, F.N., and van Velhuizen, H. (2005). Socio-economic and
18 climate change impacts on agriculture: an integrated assessment, 1990–2080, *Philosophical*
19 *Transactions on Royal Society B* 360, 2067–2083.
- 20 Folberth C., Yang, H., Gaiser, T., Liu, J., Wang, X., Williams, J. and Schulin, R. (2014). Effects
21 of ecological and conventional agricultural intensification practices on maize yields in sub-
22 Saharan Africa under potential climate change. *Environmental Research Letters*, 9, 4.
- 23 Fontaine, B., M. Gaetani, A. Ullmann, and P. Roucou (2011a), Time evolution of observed
24 July–September sea surface temperature-Sahel climate teleconnection with removed quasi-
25 global effect (1900–2008), *J. Geophys. Res.*, 116, D04105, doi:10.1029/2010JD014843.
- 26 Fontaine, B., J. Garcia-Serrano, P. Roucou, B. Rodríguez-Fonseca, T. Losada, F. Chauvin, S.
27 Gervois, S. Sivarajan, P. Ruti, S. Janicot (2009), Impacts of warm and cold situations in the
28 Mediterranean basins on the West African monsoon: Observed connection patterns (1979–
29 2006) and climate simulations, *Clim. Dyn.*, 35, 95–114, doi:10.1007/s00382-009-0599-3.
- 30 Fontaine, B., S. Janicot, and P.-A. Monerie (2013), Recent changes in air temperature, heat
31 waves occurrences, and atmospheric circulation in Northern Africa, *J. Geophys. Res. Atmos.*,
32 118, 8536–8552, doi:10.1002/jgrd.50667.
- 33 Fontaine B., P. Roucou, M. Gaetani, R. Marteau (2011b). Recent changes in precipitation, ITCZ
34 convection and northern tropical circulation over North Africa (1979-2007). *International*
35 *Journal of Climatology*, 31, 633-648, doi: 10.1002/joc.2108.
- 36 Gaetani M., C. Flamant, S. Bastin, S. Janicot, C. Lavaysse, F. Hourdin, P. Braconnot, S. Bony
37 (2016). West African Monsoon dynamics and precipitation: the competition between global
38 SST warming and CO₂ increase in CMIP5 idealized simulations. *Climate Dynamics*, doi:
39 10.1007/s00382-016-3146-z.
- 40 Gaetani, M., B. Fontaine, P. Roucou, and M. Baldi (2010), Influence of the Mediterranean Sea
41 on the West African Monsoon: Intraseasonal variability in numerical simulations, *J. Geophys.*
42 *Res.*, 115, D24115, doi:10.1029/2010JD014436.

- 1 Gaetani, M., and E. Mohino (2013). Decadal prediction of the Sahelian precipitation in CMIP5
2 simulations. *J. Climate*, 26, 7708–7719, doi:10.1175/JCLI-D-12-00635.1.
- 3 Gaiser, T., Judex, M., Hiepe, C., and Kuhn, A. (2010). Regional simulation of maize production
4 in tropical savannah fallow systems as affected by fallow availability. *Agric Syst* 103, 656–665.
- 5 Gerardeaux, E., Sultan, B., Palai, O., Guiziou, C., Oettli, P., and Naudin, K. (2013). Positive
6 effect of climate change on cotton in 2050 by CO₂ enrichment and conservation agriculture in
7 Cameroon. *Agronomy For Sustainable Development* 33, 485-495.
- 8 Giannini A. (2010). Mechanisms of climate change in the Semiarid African Sahel: the local
9 view. *J Clim* 23:743–756. doi:10.1175/2009JCLI3123.1.
- 10 Giannini, A., Biasutti, M., Held, I.M., and Sobel, A.H. (2008). A global perspective on African
11 climate. *Clim. Change* 90, 359–383.
- 12 Giannini, A., S. Salack, T. Lodoun, A. Ali, A.T. Gaye and O. Ndiaye (2013). A unifying view
13 of climate change in the Sahel linking intra-seasonal, interannual and longer time scales.
14 *Environ. Res. Lett.*, 8, 024010.
- 15 Glotter, M., Elliott, J., McInerney, D., Best, N., Foster, I., and Moyer, E.J. (2014). Evaluating
16 the utility of dynamical downscaling in agricultural impacts projections *Proc. Natl Acad. Sci.*
17 *USA* **111**, 8776–81.
- 18 Guan, K., Sultan, B., Biasutti, M., Baron, C., Lobell, D.B. (2015). What aspects of future
19 rainfall changes matter for crop yields in West Africa? *Geophysical Research Letters* 42, 8001-
20 8010.
- 21 Guan, K., Sultan, B., Biasutti, M., Baron, C., Lobell, D.B. (2016). Assessing climate adaptation
22 options and uncertainties for cereal systems in West Africa *Agric. For. Meteorol.* in press.
- 23 Gutmann, E.D., Rasmussen, R.M., Liu, C., Ikeda, K, Gochis, D J, Clark, M P, Dudhia, J and
24 Thompson, G (2012) A comparison of statistical and dynamical downscaling of winter
25 precipitation over complex terrain *J. Clim.* **25** 262–281.
- 26 Guichard, F., L. Kergoat, E. Mougin, F. Timouk, F. Baup, P. Hiernaux, and F. Lavenu (2009),
27 Surface thermodynamics and radiative budget in the Sahelian Gourma: Seasonal and diurnal
28 cycles, *J. Hydrol.*, 375, 161–177, doi:10.1016/j.jhydrol.2008.09.007.
- 29 Haile, M. (2005). Weather patterns, food security and humanitarian response in sub-Saharan
30 Africa. *Philosophical Transactions of the Royal Society B* 360, 2169-2182.
- 31 Hansen, J. W. (2002). Realizing the potential benefits of climate prediction to agriculture:
32 issues, approaches, challenges. *Agric. Syst.* 74, 309–330.
- 33 Held I.M., Delworth T.L., Lu J., Findell K.L., Knutson T.R. (2005) Simulation of Sahel drought
34 in the 20th and 21st centuries. *Proc Natl Acad Sci USA* 102:17891–17896.
35 doi:10.1073/pnas.0509057102.
- 36 Hertel, T.W. and Lobell, D.B. (2014). Agricultural Adaptation to Climate Change in Rich and
37 Poor Countries: Current Modeling Practice and Potential for Empirical Contributions, *Energy*
38 *Economics*, <http://dx.doi.org/10.1016/j.eneco.2014.04.014>
- 39 Hoerling M, Hurrell J, Eischeid J, Phillips A (2006) Detection and attribution of twentieth-
40 century northern and southern African rainfall change. *J Clim* 19:3989–4008.
41 doi:10.1175/JCLI3842.1.

1 Hoscilo A., H. Balzter, E. Bartholomé, M. Boschetti, P. A. Brivio, A. Brink, M. Clerici and J.
2 F. Pekel (2015). A conceptual model for assessing rainfall and vegetation trends in sub-Saharan
3 Africa from satellite data. *Int. J. Climatol.* 35, 3582–3592, DOI: 10.1002/joc.4231.

4 Iizumi, T., Yokozawa, M., and Nishimori, M. (2009). Parameter estimation and uncertainty
5 analysis of a large-scale crop model for paddy rice: application of a Bayesian approach.
6 *Agricultural and Forest Meteorology* 149, 333–348.

7 IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II
8 and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core
9 Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

10 IPCC 2014, Climate Change 2014: Impacts, Adaptation, and Vulnerability. Working Group II.
11 (Cambridge, UK: Cambridge University Press)

12 Issa Lele M. and Peter J. Lamb (2010). Variability of the Intertropical Front (ITF) and Rainfall
13 over the West African Sudan–Sahel Zone. *Journal of Climate*, DOI: 10.1175/2010JCLI3277.1.

14 James, R., and R. Washington (2013). Changes in African temperature and precipitation
15 associated with degrees of global warming. *Climatic Change*, 117, 859–872, doi:
16 10.1007/s10584-012-0581-7.

17 James R., R. Washington, and D.P. Rowell (2014). African Climate Change Uncertainty in
18 Perturbed Physics Ensembles: Implications of Global Warming to 4°C and Beyond. *Journal of*
19 *Climate* 27, 12, 4677-4692.

20 Jarvis, A., Ramirez-Villegas, J., Herrera Campo, B.V., and Navarro-Racines C. (2012). Is
21 Cassava the Answer to African Climate Change Adaptation? *Tropical Plant Biology* 5, 9-29.

22 Ji Z., G. Wang, J.S. Pal, M. Yu (2016). Potential climate effect of mineral aerosols over West
23 Africa. Part I: model validation and contemporary climate evaluation. *Clim Dyn* 46, 1223–
24 1239, DOI 10.1007/s00382-015-2641-y.

25 Jones, P.G., Thornton, P.K. (2003). The potential impacts of climate change on maize
26 production in Africa and Latin America in 2055, *Global Environmental Change* 13, 51–59.

27 Kimball, B.A. (1983) Carbon dioxide and agricultural yield: an assemblage and analysis of 430
28 prior observations. *Agronomy Journal* 75, 779-788.

29 Kimball, B.A., Kobayashi, K., and Bindi, M. (2002). Responses of agricultural crops to free-
30 air CO₂ enrichment. *Advances in Agronomy* 77, 293-368.

31 Klutse N. A. B. et al. (2016). Daily characteristics of West African summer monsoon
32 precipitation in CORDEX simulations. *Theor Appl Climatol* 123, 369–386 DOI
33 10.1007/s00704-014-1352-3.

34 Knox, J., Hess, T., Daccache, A., and Wheeler, T. (2012). Climate change impacts on crop
35 productivity in Africa and South Asia. *Environ. Res. Lett.* 7, 034032.

36 Koster, R. D., and Coauthors (2006). GLACE: The Global Land–Atmosphere Coupling
37 Experiment. Part I: Overview. *J. Hydrometeor.*, 7, 590–610, doi:10.1175/JHM510.1.

38 Kotir, J.H. (2010). Climate change and variability in Sub-Saharan Africa: a review of current
39 and future trends and impacts on agriculture and food security, *Environ Dev Sustain* 13, 587–
40 605.

- 1 Kouressy, M., Dingkuhn, M., Vaxsmann, M. and Heinemann, A.B. (2008). Adaptation to
2 diverse semi-arid environments of sorghum genotypes having different plant type and
3 sensitivity to photoperiod. *Agric. For. Meteorol.* 148, 357–71.
- 4 Kucharski F., N. Zeng, E. Kalnay (2013). A further assessment of vegetation feedback on
5 decadal Sahel rainfall variability. *Clim Dyn* 40,1453–1466, DOI 10.1007/s00382-012-1397-x.
- 6 Laprise R., L. Hernandez-Diaz, K. Tete, L. Sushama, L. Separovic, A. Martynov, K. Winger,
7 M. Valin (2013): Climate projections over CORDEX Africa domain using the fifth-generation
8 Canadian Regional Climate Model (CRCM5). *Clim Dyn* 41, 3219–3246 DOI 10.1007/s00382-
9 012-1651-2.
- 10 Lavaysse C., C. Flamant, A.T. Evan, S. Janicot, M. Gaetani (2015). Recent climatological trend
11 of the Saharan Heat Low and its impact on the West African climate. *Climate Dynamics*, doi:
12 10.1007/s00382-015-2847-z.
- 13 Lavaysse, C., C. Flamant, S. Janicot, D. J. Parker, J. P. Lafore, B. Sultan, and J. Pelon (2009),
14 Seasonal evolution of the West African heat low: A climatological perspective, *Clim. Dyn.*, 33,
15 313–330, doi:10.1007/s00382-009-0553-4.
- 16 Lavaysse, C., C. Flamant, and S. Janicot (2010), Regional-scale convection patterns during
17 strong and weak phases of the Saharan heat low, *Atmos. Sci. Lett.*, 11, 255–264,
18 doi:10.1002/asl.284.
- 19 Leakey, A.D.B. (2009). Rising atmospheric carbon dioxide concentration and the future of C4
20 crops for food and fuel. *Proceedings of Royal Society B* 276, 2333–2343.
- 21 Lebel, S., Fleskens, L., Forster, P. M., Jackson, L. S., Lorenz, S. (2015). Evaluation of In Situ
22 Rainwater Harvesting as an Adaptation Strategy to Climate Change for Maize Production in
23 Rainfed Africa. *Water Resources Management* 29, 4803-4816.
- 24 Liu, J., Fritz, S., van Wesenbeeck, C.F.A., Fuchs, M., You, L., Obersteiner, M., and Yang, H.
25 (2008). A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan
26 Africa in the context of global change. *Global and Planetary Change* 64, 222–235.
- 27 Lobell, D.B. (2014). Climate change adaptation in crop production: Beware of illusions. *Glob.*
28 *Food Sec.* 3, 72–76.
- 29 Lobell, D.B., and Burke, M.B. (2010). On the use of statistical models to predict crop yield
30 responses to climate change. *Agric. For. Meteorol.* 150, 1443–52.
- 31 Lobell, D.B., Bänziger, M., Magorokosho, C., and Vivek, B. (2011). Nonlinear heat effects on
32 African maize as evidenced by historical yield trials. *Nature Clim. Change* 1, 142–45.
- 33 Lobell, D.B., Burke, M.B. (Eds.) (2009). *Climate Change and Food Security: Adapting*
34 *Agriculture to a Warmer World*. Springer.
- 35 Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P., and Naylor, R.L.
36 (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science*, 319,
37 607–610.
- 38 Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Morgan, P.B. (2006). Food for thought: lower-
39 than-expected crop yield stimulation with rising CO₂ concentrations. *Science* 312, 1918-1921.
- 40 Losada, T., B. Rodríguez-Fonseca, S. Janicot, S.Gervois, F.Chauvin, and P. Ruti (2010). A
41 multi-model approach to the Atlantic equatorial mode: Impact on the West African monsoon.
42 *Climate Dyn.*, 35, 29–43, doi:10.1007/s00382-009-0625-5.

1 Ma, H., H. Xiao, C. Mechoso, and Y. Xue, 2013: Sensitivity of global tropical climate to land
2 surface processes: Mean state and interannual variability. *J. Climate*, 26, 1818–1837,
3 doi:10.1175/JCLI-D-12-00142.1.

4 Maidment, R. I., R. P. Allan, and E. Black (2015): Recent observed and simulated changes in
5 precipitation over Africa, *Geophys. Res. Lett.*, 42, 8155–8164, doi:10.1002/2015GL065765.

6 Martin E.R., and C.D. Thorncroft, 2014: Sahel rainfall in multimodel CMIP5 decadal hindcasts.
7 *Geophys. Res. Lett.*, 41, 2169–2175, doi:10.1002/2014GL059338.

8 Martin E.R. and C. Thorncroft, 2015: Representation of African Easterly Waves in CMIP5
9 Models. *Journal of Climate*, DOI: 10.1175/JCLI-D-15-0145.1.

10 Martiny, N., Philippon, N., Richard, Y., Camberlin, P., Reason, C. (2010). Predictability of
11 NDVI in semi-arid African regions. *Theor. Appl. Climatol.* 100, 467–484.

12 McSweeney, C.F. and Jones, R.G. (2016)? How representative is the spread of climate
13 projections from the 5 CMIP5 GCMs used in ISI-MIP? *Climate Services* 1, 24–29.

14 Mearns, L.O., Easterling, W., Hays, C., and Marx, D. (2001). Comparison of agricultural
15 impacts of climate change calculated from high and low resolution climate change scenarios: I.
16 The uncertainty due to spatial scale. *Clim. Change* 51,131–172.

17 Mearns, L.O., Mavromatis, T., Tsvetsinskaya, E., Hays, C. and Easterling, W. (1999)
18 Comparative responses of EPIC and CERES crop models to high and low spatial resolution
19 climate change scenarios. *J. Geophys. Res.* 104, 6623–6646.

20 Meehl G.A., Covey C., Taylor K.E., Delworth T., Stouffer R.J., Latif M., McAvaney B.,
21 Mitchell J.F.B. (2007) THE WCRP CMIP3 multimodel dataset: a new era in climate change
22 research. *Bull Am Meteorol Soc* 88:1383–1394. doi:10.1175/BAMS-88-9-1383.

23 Michelangeli, P.A., Vrac, M., and Loukos, H. (2009). Probabilistic downscaling approaches:
24 application to wind cumulative distribution functions. *Geophys. Res. Lett.* 36, L11708.

25 Mohino, E., S. Janicot, and J. Bader, 2011a: Sahelian rainfall and decadal to multidecadal SST
26 variability. *Climate Dyn.*, 37, 419–440, doi:10.1007/s00382-010-0867-2.

27 Mohino, E., S. Janicot, H. Douville, and L. Z. X. Li, 2012: Impact of the Indian part of the
28 summer MJO on West Africa using nudged climate simulations. *Climate Dyn.*, 38, 2319–2334,
29 doi:10.1007/s00382-011-1206-y.

30 Mohino, B. Rodríguez-Fonseca, C. R. Mechoso, S. Gervois, P. Ruti, and F. Chauvin, 2011b:
31 Impacts of the tropical Pacific/Indian Oceans on the seasonal cycle of the West African
32 monsoon. *J. Climate*, 24, 3878–3891, doi:10.1175/2011JCLI3988.1.

33 Monerie P.A., Michela Biasutti and Pascal Roucou (2016). On the projected increase of Sahel
34 rainfall during the late rainy season. *Int. J. Climatol.* DOI: 10.1002/joc.4638.

35 Monerie PA, Fontaine B, Roucou P (2012) Expected future changes in the African monsoon
36 between 2030 and 2070 using some CMIP3 and CMIP5 models under a medium-low RCP
37 scenario. *J Geophys Res Atmos* 117:1–12. doi:10.1029/2012JD017510.

38 Monerie PA, Roucou P, Fontaine B (2013) Mid-century effects of climate change on African
39 monsoon dynamics using the A1B emission scenario. *Int J Climatol* 33:881–896.
40 doi:10.1002/joc.3476.

1 Moron, V., B. Oueslati, B. Pohl, S. Rome, and S. Janicot (2016). Trends of mean temperatures
2 and warm extremes in northern tropical Africa (1961–2014) from observed and PPCA-
3 reconstructed time series, *J. Geophys. Res. Atmos.*, 121, doi:10.1002/2015JD024303.

4 Müller, C., Bondeau, A., Popp, A., Waha, K., and Fader, M. (2010). *Climate change impacts*
5 *on agricultural yields*. Background note to the World Development Report 2010, Potsdam
6 Institute for Climate Impact Research, Potsdam.

7 Müller, C., Elliott, J., and Levermann, A. (2014). Fertilizing hidden hunger, *Nature Climate*
8 *Change* 4, 540–541.

9 Myers, S.S., Zanobetti, A., Kloog, I., Huybers, P., Leakey, A.D.B., Bloom, A.J. et al. (2014)
10 Increasing CO₂ threatens human nutrition. *Nature* 510, 139–142.

11 Nelson, G.C., Rosegrant, M., Koo, J., Robertson, R., Sulser, T., Zhu, T., et al. (2009) Climate
12 Change: Impact on Agriculture and Costs of Adaptation, *International Food Policy Research*
13 *Institute*, Washington, DC (2009).

14 Nikulin, G., and Coauthors, 2012: Precipitation climatology in an ensemble of CORDEX-
15 Africa regional climate simulations. *J. Climate*, 25, 6057–6078, doi:10.1175/JCLI-D-11-
16 00375.1.

17 Oettli, P., Sultan, B., Baron, C. and Vrac, M. (2011) Are regional climate models relevant for
18 crop yield prediction in West Africa? *Environ. Res. Lett.* **6**, 014008.

19 Otero N., E. Mohino, M. Gaetani, 2015: Decadal prediction of Sahel rainfall using dynamics-
20 based indices. *Climate Dynamics*, doi: 10.1007/s00382-015-2738-3.

21 Paeth, H., Capo-Chichi, A., and Endlicher, W. (2008). Climate Change and food security in
22 tropical West Africa: a dynamic-statistical modelling approach. *Erdkunde*, 62, 101–115.

23 Paeth, H., Hall, N.M.J., Gaertner, M.A., Dominguez Alonso, M., Moumouni, S., Polcher, J., et
24 al. (2011). Progress in regional downscaling of West African precipitation. *Atmospheric*
25 *Science Letters* 12, 75–82.

26 Panthou, G., Vischel, T., and Lebel, T. (2014). Recent trends in the regime of extreme rainfall
27 in the Central Sahel. *Int. J. Climatol.* 34, 3998–4006.

28 Park J.Y., Jurgen Bader, Daniela Matei, 2014: Northern-hemispheric differential warming is
29 the key to understanding the discrepancies in the projected Sahel rainfall. *Nature*
30 *Communications*, 6:5985, DOI: 10.1038/ncomms6985.

31 Parkes, B., Challinor, A.J., and Nicklin, K. (2015). Crop failure rates in a geoengineered
32 climate: impact of climate change and marine cloud brightening, *Environmental Research*
33 *Letters*, 10, 8.

34 Parry, M.L., Rosenzweig, C., Iglesias, A.M., and Livermore, G.F (2004). Effects of climate
35 change on global food production under SRES emissions and socio-economic scenarios. *Global*
36 *Environmental Change* 14, 53–67.

37 Patt, A.G., van Vuuren, D.P., Berkhout, F., Aaheim, A., Hof, A.F., Isaac, M., and Mechler, R.
38 (2010). Adaptation in integrated assessment modeling: where do we stand? *Clim. Change* 99,
39 383–402.

40 Paxian, A., et al. (2016), Bias reduction in decadal predictions of West African monsoon rainfall
41 using regional climate models, *J. Geophys. Res. Atmos.*, 121, 1715–1735, doi:
42 10.1002/2015JD024143.

- 1 Philippon, N., Jarlan, L., Martiny, N., Camberlin, P., Mougou, E. (2007) Characterization of the
2 interannual and intraseasonal variability of West African vegetation between 1982 and 2002 by
3 means of NOAA AVHRR NDVI data. *J. Clim.* 20, 1202–1218.
- 4 Poan D.E., J.P. Lafore, R. Roehrig and F. Couvreur (2015) Internal processes within the
5 African Easterly Wave system, *Q. J. R. Meteorol. Soc.* 141: 1121–1136, DOI:10.1002/qj.2420.
- 6 Pohl B., S. Janicot, B. Fontaine, R. Marteau (2009) Implication of the Madden-Julian
7 Oscillation in the 40-day variability of the West African monsoon. *Journal of Climate*, 22, 3769-
8 3785. doi:10.1175/2009JCLI2805.1.
- 9 Polo, I., B. Rodríguez-Fonseca, T. Losada, and J. García-Serrano, 2008: Tropical Atlantic
10 variability modes (1979–2002). Part I: Time-evolving SST modes related to West African
11 rainfall. *J. Climate*, 21, 6457–6475, doi:10.1175/2008JCLI2607.1.
- 12 Pomposi C., Y. Kushnir, A. Giannini (2015). Moisture budget analysis of SST-driven decadal
13 Sahel precipitation variability in the twentieth century. *Clim Dyn* 44, 3303–3321.
- 14 Ramarohetra, J., Pohl, B. and Sultan, B. (2015) Errors and uncertainties introduced by a
15 regional climate model in climate impact assessments: example of crop yield simulations in
16 West Africa. *Environmental Research Letters* 10, 12.
- 17 Ramirez-Villegas, J., Challinor, A.J., Thornton, P.K., and Jarvis, A. (2013). Implications of
18 regional improvement in global climate models for agricultural impact research. *Environmental*
19 *Research Letters*, 8-2.
- 20 Redelsperger, J.-L., C. D. Thorncroft, A. Diedhiou, T. Lebel, D. J. Parker, and J. Polcher, 2006:
21 African Monsoon Multidisciplinary Analysis: An international research project and field
22 campaign. *Bull. Amer. Meteor. Soc.*, 87, 1739–1746, doi:10.1175/BAMS-87-12-1739.
- 23 Rezaei, E.E., Gaiser, T., Siebert, S., Sultan, B., and Ewert, F. (2014). Combined impacts of
24 climate and nutrient fertilization on yields of pearl millet in Niger. *European Journal of*
25 *Agronomy* 55, 77-88.
- 26 Rockström, J., and Falkenmark, M. (2015). Increase water harvesting in Africa. *Nature* 8–10.
- 27 Rodríguez-Fonseca, B. et al. (2015), Variability and Predictability of West African Droughts:
28 A Review on the Role of Sea Surface Temperature Anomalies, *J. Clim.*, 28, 4034–4060,
29 doi:10.1175/JCLI-D-14-00130.1.
- 30 Roehrig R, Bouniol D, Guichard F, Hourdin FD, Redelsperger JL (2013) The present and future
31 of the west african monsoon: a process-oriented assessment of CMIP5 simulations along the
32 AMMA transect. *J Clim* 26:6471–6505. doi:10.1175/JCLI-D-12-00505.1.
- 33 Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A. et al. (2014).
34 Assessing agricultural risks of climate change in the 21st century in a global gridded crop model
35 intercomparison. *Proc Nat Acad Sci USA* 111, 3268–3273.
- 36 Rötter, R.P. (2014). Agricultural Impacts: Robust uncertainty, *Nature Climate Change* 4, 252-
37 252.
- 38 Rötter, R.P., Höhn, J.G., and Fronzek, S. (2012). Projections of climate change impacts on crop
39 production: a global and a Nordic perspective. *Acta Agric. Scand. Sect. A Anim. Sci.* 62, 166–
40 180
- 41 Rötter, R.P., Tao, F., Höhn, J. G., and Palosuo, T. (2015). Use of crop simulation modelling to
42 aid ideotype design of future cereal cultivars. *J. Exp. Bot.* 66, 3463-3476.

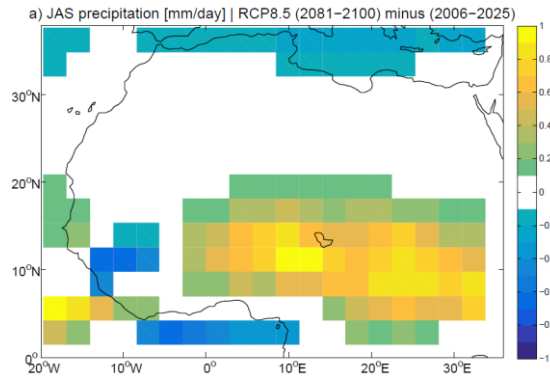
- 1 Roudier, P., Alhassane, A., Baron, C., Louvet, S., and Sultan, B. (2016) Assessing the benefits
2 of weather and seasonal forecasts to millet growers in Niger. *Agricultural and Forest*
3 *Meteorology* 223, 168–180.
- 4 Roudier, P., Muller, B., d’Aquino, P., Roncoli, C., Soumaré, M.A., Batté, L., et al. (2014). The
5 role of climate forecasts in smallholder agriculture: Lessons from participatory research in two
6 communities in Senegal. *Climate Risk Management* 2, 42-55.
- 7 Roudier, P., Sultan, B., Quirion, P., Baron, C., Alhassane, A., Traore, S.B., et al. (2012). An
8 ex-ante evaluation of the use of seasonal climate forecasts for millet growers in SW Niger.
9 *International Journal of Climatology* 32, 759-771.
- 10 Roudier, P., Sultan, S., Quirion, P., and Berg, A. (2011). The impact of future climate change
11 on West African crop yields: what does the recent literature say? *Glob. Environ. Change* 21,
12 1073–83.
- 13 Royal Society (2008). Ground-level ozone in the 21st century: future trends, impacts and policy
14 implications. *RS Policy document* 15/08. ISBN: 978085403–7131
- 15 Rowell, D. P., 2001: Teleconnections between the tropical Pacific and the Sahel. *Quart. J. Roy.*
16 *Meteor. Soc.*, 127, 1683–1706, doi:10.1002/ qj.49712757512.
- 17 Rowell D.P. (2013) Simulating SST teleconnections to Africa: what is the state of the art? *J*
18 *Clim* 26:5397–5418. doi:10.1175/JCLI-D-12-00761.1.
- 19 Rowell D.P., Catherine A. Senior, Michael Vellinga, Richard J. Graham (2016). Can climate
20 projection uncertainty be constrained over Africa using metrics of contemporary performance?
21 *Climatic Change* 134:621–633 DOI 10.1007/s10584-015-1554-4.
- 22 Russo S., Andrea F Marchese, J Sillmann and Giuseppina Immé (2016). When will unusual
23 heat waves become normal in a warming Africa? *Environ. Res. Lett.* 11 054016,
24 doi:10.1088/1748-9326/11/5/054016.
- 25 Saba, A., Biasutti, M., Gerrard, M.B., and Lobell, D.B. (2013). Getting Ahead of the Curve:
26 Supporting Adaptation to Long-term Climate Change and Short-term Climate Variability Alike.
27 *Carbon & Climate Law Review* 7, 3–24.
- 28 Saini, R., G. Wang, M. Yu, and J. Kim (2015), Comparison of RCM and GCM projections of
29 boreal summer precipitation over Africa, *J. Geophys. Res. Atmos.*, 120, 3679–3699,
30 doi:10.1002/2014JD022599.
- 31 Salack, S. (2006). *Impacts des changements climatiques sur la production du mil et du sorgho*
32 *dans les sites pilotes du plateau central, de Tahoua et de Fakara*, CILSS, Niamey, Niger.
- 33 Sanogo S., A.H. Fink, J.A. Omotosho, A. Ba, R. Redl and V. Ermert (2015). Spatio-temporal
34 characteristics of the recent rainfall recovery in West Africa. *Int. J. Climatol.* 35, 4589–4605
35 DOI: 10.1002/joc.4309.
- 36 Schlenker, W., Lobell, D.B. (2010). Robust negative impacts of climate change on African
37 agriculture. *Environmental Research Letters* 5, 1-8.
- 38 Schmidhuber, J. and Tubiello, F.N. (2007). Global food security under climate change. *Proc.*
39 *Natl Acad. Sci. USA* 104, 19703–19708.
- 40 Semenov, M.A., and Barrow, E.M. (1997). Use of a stochastic weather generator in the
41 development of climate change scenarios. *Clim Change* 35, 397–414.

- 1 Setter, T.L. (2012) Analysis of Constituents for Phenotyping Drought Tolerance in Crop
2 Improvement. *Front. Physiol.* 3, doi: 10.3389/fphys.2012.00180.
- 3 Skinner C.B. and N.S. Diffenbaugh (2014). Projected changes in African easterly wave
4 intensity and track in response to greenhouse forcing. *PNAS*, 111, 6882–6887.
- 5 Smith, J.B., Huq, S., Lenhart, S., Mata, L.J., Nemesova, I., and Toure, S. (1996). *Vulnerability
6 and Adaptation to Climate Change: Interim Results from the U.S. Country Studies Program*,
7 Kluwer Academic Publishers.
- 8 Soussana, J.F., Graux, A.I., and Tubiello, F.N. (2010). Improving the use of modelling for
9 projections of climate change impacts on crops and pastures. *Journal of Experimental Botany*
10 2217–2228.
- 11 Srivastava, A.K., Gaiser, T., and Ewert, F. (2015). Climate change impact and potential
12 adaptation strategies under alternate climate scenarios for yam production in the sub-humid
13 savannah zone of West Africa. *Mitigation and Adaptation Strategies for Global Change*, 1-14.
- 14 Sultan B, Guan K, Kouressy M, Biasutti M, Piani C, Hammer GL, et al. Robust features of
15 future climate change impacts on sorghum yields in West Africa. *Environmental Research
16 Letters* 2014;9.
- 17 Sultan, B., Barbier, B., Fortilus, J., Mbaye, S.M., Leclerc, G. (2010) Estimating the Potential
18 Economic Value of Seasonal Forecasts in West Africa: A Long-Term Ex-Ante Assessment in
19 Senegal. *Weather Climate and Society* 2, 69-87.
- 20 Sultan, B., Guan, K., Kouressy, M., Biasutti, M., Piani, C., Hammer, G.L., et al. (2014). Robust
21 features of future climate change impacts on sorghum yields in West Africa. *Environmental
22 Research Letters* 2014;9.
- 23 Sultan, B., and S. Janicot, 2003: The West African monsoon dynamics. Part II: The “preonset”
24 and “onset” of the summer monsoon. *J. Climate*, 16, 3407–3427, doi:10.1175/1520-
25 0442(2003)016,3407:TWAMDP.2.0.CO;2.
- 26 Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., et al. (2013).
27 Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian
28 savannas of West Africa. *Environmental Research Letters* 2013;8.
- 29 Tao, F., Yokozawa, M., and Zhang, Z. (2009). Modelling the impacts of weather and climate
30 variability on crop productivity over a large area: a new process-based model development,
31 optimization, and uncertainties analysis. *Agricultural and Forest Meteorology* 149, 831–850.
- 32 Taylor, C.M. et al. (2011) New perspectives on land-atmosphere feedbacks from the African
33 Monsoon Multidisciplinary Analysis. *Atmos. Sci. Lett.* 12, 38–44.
- 34 Taylor K.E., Stouffer R.J., Meehl G.A. (2012) An overview of CMIP5 and the experiment
35 design. *Bull Am Meteorol Soc* 93:485–498. doi:10.1175/BAMS-D-11-00094.1.
- 36 Tingem, M., and Rivington, M. (2009). Adaptation for crop agriculture to climate change in
37 Cameroon: turning on the heat, *Mitigation and Adaptation Strategies for Global Change* 14,
38 153–168.
- 39 Thorncroft C.D., Blackburn M. (1999) Maintenance of the African easterly jet. *Q J R Meteorol
40 Soc* 125:763–786. doi:10.1002/qj.49712555502.

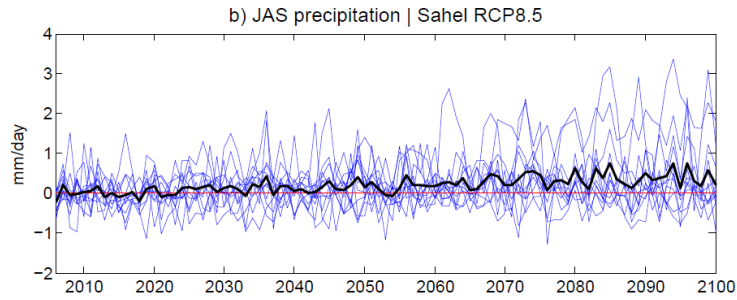
- 1 Thorncroft C.D., H. Nguyen, C. Zhang and P. Peyrille (2011) Annual cycle of the West African
2 monsoon: regional circulations and associated water vapour transport. *Q. J. R. Meteorol. Soc.*
3 137, 129–147.
- 4 Ting M., Kushnir Y., Seager R., Li C. (2009) Forced and internal twentieth-century SST trends
5 in the North Atlantic. *J Clim* 22:1469–1481. doi:10.1175/2008JCLI2561.1.
- 6 Tompkins, A. M., C. Cardinali, J.-J. Morcrette, and M. Rodwell (2005), Influence of aerosol
7 climatology on forecasts of the African Easterly Jet, *Geophys. Res. Lett.*, 32, L10801,
8 doi:10.1029/2004GL022189.
- 9 Traore, S.B., Alhassane, A., Muller, B., Kouressy, M., Some, L., Sultan, B., et al. (2011).
10 Characterizing and modeling the diversity of cropping situations under climatic constraints in
11 West Africa. *Atmospheric Science Letters* 12, 89-95.
- 12 Trenberth, K.E., P.D. Jones, P. Ambenje, R. Bojariu, D. Easterling, A. Klein Tank, D. Parker,
13 F. Rahimzadeh, J.A. Renwick, M. Rusticucci, B. Soden and P. Zhai, 2007: Observations:
14 Surface and Atmospheric Climate Change. In: *Climate Change 2007: The Physical Science*
15 *Basis. Contribution of Working Group I to the Fourth Assessment Report of the*
16 *Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M.
17 Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press,
18 Cambridge, United Kingdom and New York, NY, USA.
- 19 Tsvetsinskaya, E.A., Mearns, L.O., Mavromatis, T., Gao, W., McDaniel, L., and Downton, M.
20 W. (2003). The Effect of spatial scale of climatic change scenarios on simulated maize, winter
21 wheat, and rice production in the southeastern United States. *Clim. Change* 60, 37–72.
- 22 Tubiello, F.N., and Ewert, F. (2002). Simulating the effects of elevated CO₂ on crops:
23 approaches and applications for climate change. *Eur. J. Agron.* 18, 57–74.
- 24 Tubiello, F.N., Soussana, J.F., Howden, M. (2007). Crop and pasture response to climate
25 change, *Proc. Natl Acad. Sci. USA* 104, 19686–19690.
- 26 Turco, M., E. Palazzi, J.von Hardenberg, and A. Provenzale (2015), Observed climate change
27 hotspots. *Geophys. Res. Lett.*, 42, 3521–3528. doi: 10.1002/2015GL063891.
- 28 Turner, N.C. and Rao, K. (2013). Simulation analysis of factors affecting sorghum yield at
29 selected sites in eastern and southern Africa, with emphasis on increasing temperatures, *Agric.*
30 *Syst.* 121, 53–62.
- 31 Vadez, V., Hash, T., Bidinger, F. and Kholova, J. (2012) Phenotyping pearl millet for adaptation
32 to drought. *Front. Physiol.* 3, doi: 10.3389/fphys.2012.00386
- 33 Van Dingenen, R., Dentener, F.J., Raes, F., Krol, M.C., Emberson, L., Cofala, J. (2008). The
34 global impact of ozone on agricultural crop yields under current and future air quality
35 legislation. *Atmospheric Environment* 43, 604-618.
- 36 Vanduivenbooden, N., Abdousallam, S., and Ben Mohamed, A. (2002). Impact of climate
37 change on agricultural production in the Sahel—Part 2. Case study for groundnut and cowpea
38 in Niger. *Climatic Change* 54, 349–368.
- 39 van Vuuren D.P, et al. (2011) The representative concentration pathways: an overview.
40 *Climatic Change* 109, 5-31, DOI 10.1007/s10584-011-0148-z.
- 41 Vellinga, M., M. Roberts, P. L. Vidale, M. S. Mizieliński, M.-E. Demory, R. Schiemann, J.
42 Strachan, and C. Bain (2015), Sahel decadal rainfall variability and the role of model horizontal
43 resolution, *Geophys. Res. Lett.*, 42, doi:10.1002/2015GL066690.

- 1 Villamayor J, Mohino E (2015) Robust Sahel drought due to the Interdecadal Pacific Oscillation
2 in CMIP5 simulations. *Geophys Res Lett* 42:1214–1222. doi:10.1002/2014GL02473.
- 3 Vitousek P.M. et al. (2009). Nutrient imbalances in agricultural development, *Science* 324,
4 1519–1520.
- 5 Vizzy E.K. and Kerry H. Cook (2012) Mid-Twenty-First-Century Changes in Extreme Events
6 over Northern and Tropical Africa. *Journal of Climate* 25, 17, 5748-5767.
- 7 Wang, W., A. Evan, C. Flamant, and C. Lavaysse (2015), On the Decadal Scale Correlation
8 between African Dust and Sahel Rainfall: the Role of Saharan Heat Low-Forced Winds, *Sci.*
9 *Adv.*, 1, e1500646.
- 10 White, J.W., Hoogenboom, G., Kimball, B.A., and Wall G.W. (2011). Methodologies for
11 simulating impacts of climate change on crop production. *Field Crop. Res.* 124, 357–368.
- 12 Xue, Y., and Coauthors, 2004: The Sahelian climate. *Vegetation, Water, Humans and the*
13 *Climate*, P. Kabat et al., Eds., Springer-Verlag, 59–77.
- 14 Xue Y. et al (2010) Intercomparison and analyses of the climatology of the West African
15 Monsoon in the West African Monsoon Modeling and Evaluation project (WAMME) first
16 model intercomparison experiment. *Clim Dyn* 35:3–27. doi:10.1007/s00382-010-0778-2
- 17 Yoshioka M., N.M. Mahowald, A.J. Conley, W.D. Collins, D.W. Fillmore, C.S. Zender, D.B.
18 Coleman (2007) Impact of Desert Dust Radiative Forcing on Sahel Precipitation: Relative
19 Importance of Dust Compared to Sea Surface Temperature Variations, Vegetation Changes,
20 and Greenhouse Gas Warming. *Journal of Climate*, DOI: 10.1175/JCLI4056.1.
- 21 Zhang R., Delworth T.L. (2006) Impact of Atlantic multidecadal oscillations on India/Sahel
22 rainfall and Atlantic hurricanes. *Geophys Res Lett* 33:L17712. doi:10.1029/2006GL026267.
- 23 Zorita, E., and von Storch, H. (1999). The analog method—a simple statistical downscaling
24 technique: comparison with more complicated methods. *Journal of Climate* 12, 2474–2489.
- 25

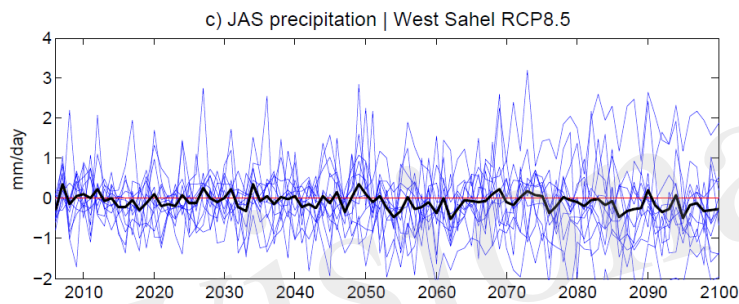
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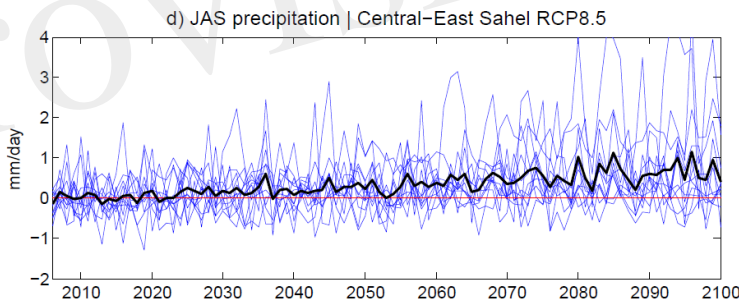
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5 Figure 1: WAM precipitation evolution in the 21st century, simulated by 12 CMIP5 models in
 6 the RCP8.5 scenario (van Vuuren et al. 2011). (a) Projected change in multi-model mean of the
 7 July-to-September (JAS) precipitation [mm/day] at the end of the 21st century (2081-2100),
 8 represented by computing the difference with the period 2006-2025. Significance is estimated
 9 through a Student's t-test at 90% level of confidence. Time series of the WAM precipitation
 10 averaged in (b) Sahel [15°W-30°E, 7-20°N], (c) western Sahel (west of 5°W) and (d) central-
 11 eastern Sahel (east of 5°E). The 21st century anomalies are computed regarding the period
 12 2006-2015. The models analysed are: BCC-CSM1-1, CanESM2, CCSM4, CNRM-CM5,
 13 FGOALS-g2, HadGEM2-CC, IPSL-CM5A-LR, IPSL-CM5B-LR, MIROC5, MPI-ESM-LR,
 14 MPI-ESM-MR, MRI-CGCM3. For data availability and accessibility, the reader may refer to
 15 the CMIP5 web portal at <http://cmip-pcmdi.llnl.gov/cmip5/availability.html>.

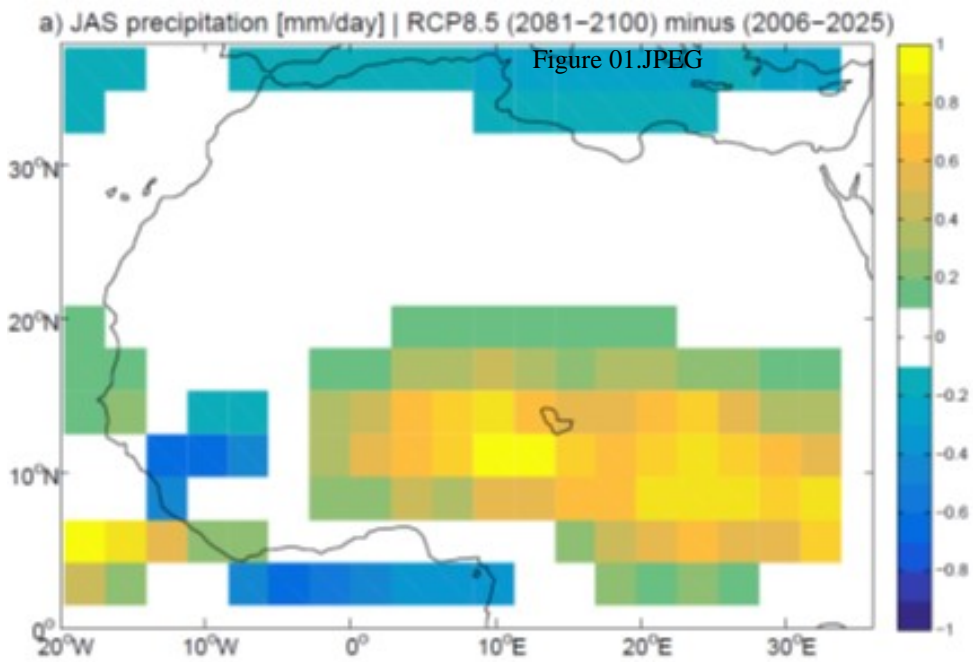
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Crop model	Area	Crop	Reference
EPIC	Nigeria	Cassava, maize, millet, rice, sorghum	<i>Adejuwon (2006)</i>
Empirical	Niger	Millet	<i>Ben Mohamed et al. (2002)</i>
EPIC + PHYGROW + NUTBAL	Mali	Cotton, cowpea, groundnut, maize, millet, sorghum	<i>Butt et al. (2005)</i>
AEZ + BLS	Sub-Saharan Africa	Global	<i>Fischer et al. (2005)</i>
IMPACT + DSSAT	Sub-Saharan Africa	Global, maize, millet, rice, sorghum, wheat, soybean, groundnut	<i>Nelson et al. (2009)</i>
CERES – maize	West Africa	Maize	<i>Jones and Thornton (2003)</i>
CERES – maize + Empirical	Niger, Nigeria, Mali, Guinea, Ivory Coast, Cameroun	Maize	<i>Lobell and Burke (2010)</i>
GEPIC	Sub-Saharan Africa, West Africa	Global, cassava, maize, millet, rice, sorghum, wheat	<i>Liu et al. (2008)</i>
Empirical	West Africa	Cassava, groundnut, maize, millet, rice, sorghum, wheat, yams	<i>Lobell et al. (2008)</i>
LPJmL	West Africa	Global	<i>Müller et al. (2010)</i>
MOS (empirical)	Benin	Beans, cassava, cotton, groundnut, maize, rice, sorghum, yams	<i>Paeth et al. (2008)</i>
Empirical + BLS	West Africa	Global	<i>Parry et al. (2004)</i>
DSSAT	Niger, Burkina Faso	Millet (two cultivars), sorghum	<i>Salack (2006)</i>
Empirical	West Africa	Cassava, groundnut, maize, millet, sorghum	<i>Schlenker and Lobell (2010)</i>
DSSAT	Gambia	Groundnut, maize, millet late, millet early	<i>Smith et al. (1996)</i>
Cropsyst	Cameroon	Bambara nut, groundnut, maize, sorghum, soybean	<i>Tingem and Rivington (2009)</i>
Empirical	Niger	Cowpea, groundnut	<i>Vanduivenbooden et al. (2002)</i>
SARRA-H + APSIM	West Africa	Sorghum (two cultivars)	<i>Sultan et al. (2014)</i>
SARRA-H	West Africa	Millet (three cultivars), Sorghum (three cultivars)	<i>Sultan et al. (2013)</i>
CROPGRO	Cameroon	Cotton	<i>Gerardeaux et al. (2013)</i>
EPIC + GEPIC + LPJ-GUESS + pDSSAT + PEGASUS	Burkina Faso, Senegal	Maize, Wheat, Soybean, Rice, Millet, Sorghum, Sugarcane, Beans, Cassava, Cotton, Sunflower, Groundnut	<i>Deryng (2015)</i>
SARRA-H + EPIC	Niger, Benin	Maize, Millet	<i>Ramarohetra et al. (2015)</i>
DSSAT	Niger	Millet	<i>Rezai et al. (2015)</i>
EPIC	Benin	Yam (early and late cultivars)	<i>Srivastava et al. (2015)</i>
EPIC	Benin	Maize	<i>Gaiser et al. (2010)</i>
ORCHIDEE	West Africa	C4 crop	<i>Berg et al. (2013)</i>
GLAM	West Africa	Groundnut	<i>Parkes et al. (2015)</i>
GEPIC	Sub-Saharan Africa	Maize	<i>Folberth et al. (2014)</i>
DSSAT + APSIM	Senegal, Ghana	Maize, Millet, Peanut	<i>Adiku et al. (2015)</i>
EcoCrop	Africa	maize, millets, sorghum, banana, and beans	<i>Jarvis et al. (2012)</i>

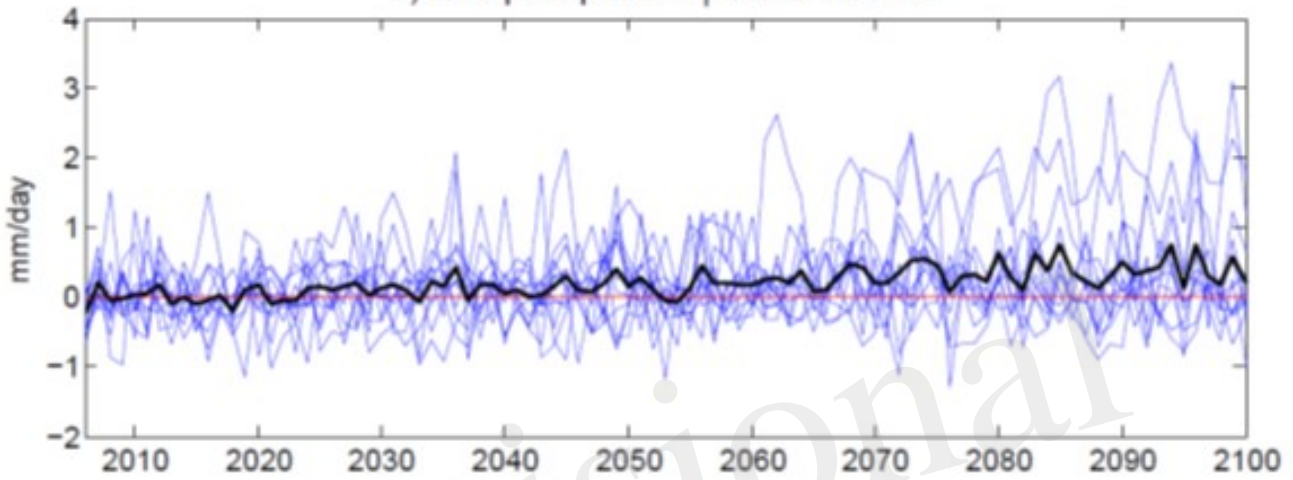
1 **Table 1 :** A selection of crop models (including combination between crop models) that have
2 been used to assess the impact of climate change on yields of various crops in West Africa in
3 the recent scientific literature.

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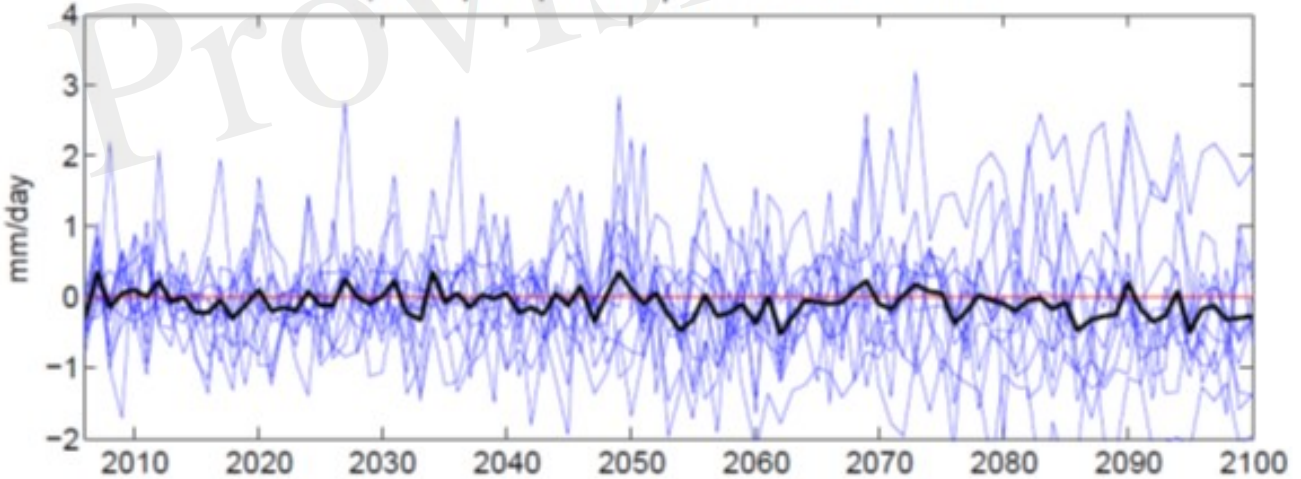
Provisional



b) JAS precipitation | Sahel RCP8.5



c) JAS precipitation | West Sahel RCP8.5



d) JAS precipitation | Central-East Sahel RCP8.5

