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A multi-model climate response over tropical Africa at +2 °C

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ABSTRACT

The impact of a +2 °C global warming on temperature and precipitation over tropical Africa is examined, based on an ensemble of 12 regional climate model scenario simulations. These 12 scenarios are re-phased so that they all correspond to the same global warming of 2 °C with respect to pre-industrial conditions. The continental temperature increase is above the global average. If heat waves are defined with the same temperature threshold in the reference climate and in the scenario, their frequency increases by a factor of 10. When the temperature threshold is adapted to future conditions, there is still a slight increase in frequency. The average precipitation does not show a significant response, due to model-to-model spread. However two compensating phenomena occur, which are robust among the models: (a) the number of rain days decreases whereas the precipitation intensity increases, and (b) the rain season occurs later during the year with less precipitation in early summer and more precipitation in late summer. Simulated daily temperature and precipitation data are combined in two impact models, one for the hydrology of the Nile and Niger basins, one for the food security of the different countries. They show that the main feature of the climate change is not a continuous trend signal, but an alternation of dry and wet decadal to multidecadal episodes.

Practical implications

After the 21st Conference of Parties in Paris (2015), the political decisions will rely on a temperature threshold rather than on carbon emissions or concentrations. It is thus of great importance to associate a global temperature warming to potential local climate changes. This paper analyzes the consequences of a +2 °C global warming on tropical Africa, with a focus on Nile and Niger basins.

Even under such a moderate global warming, tropical Africa seems to bear serious consequences of climate change to which the region has to adapt to:

- In a warmer climate, the temperature elevation in tropical Africa is similar to the global temperature one (about 2 °C).
- Heat waves are expected to be more frequent, which implies possible impacts on human health.
- The change in rainfall is, on average, still uncertain, but in any case modest compared to the year-to-year variability.
- However, extreme precipitation is expected to increase. As a consequence, the risk of catastrophic floods in some sub-catchments of the Niger basin is likely to increase in most climate and land-use scenarios.
- On the other hand, crop water stress is projected to increase, and the irrigation requirement might therefore become frequent.

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The adaptation strategies will have to cope with decadal-scale fluctuating conditions rather than with persistent trends. The apparently weak average response of the hydrological cycle, masks an alternation of dry and wet periods, which contributes to increase the vulnerability of food production. This vulnerability appears to be stronger in the western part of the continent.

A +2 °C climate is not, on average, a climate widely different from the present one in tropical Africa. But this change concerns events for which a large vulnerability is already observed. The characteristics of climate change in this region underline the potential role of seasonal-to-decadal predictions in improving the efficiency of midterm adaptation measures and of emergency operations.

1. Introduction

Scientific progress, led by technical improvements in computing devices, has allowed at the end of the last century, the very important question of climate evolution under anthropic pressure to be addressed. This exploration has been conducted in two directions. Global atmosphere-ocean coupled models have explored the planetary-scale warming (e.g. Cubasch et al., 1992), whereas regional atmospheric models (e.g. Giorgi et al., 1992) have been used for "zooming in" the results of the global models on a particular area of the globe. It quickly appeared that the climate response of a single model was partly reflecting the choices of the scientific and numerical design of this particular model. Moreover, regional scenarios depend on both the global model used for driving and the choice of the regional model (Déqué et al., 2012). To overcome this, multi-model experiments have been designed by the scientific community, the most famous being the Coupled Model Intercomparison Projects (CMIPs) aka IPCC multi-model scenarios (e.g. IPCC, 2013). Within the regional modeling community, the common experiments were first targeted to Europe (Christensen et al., 2007) and North America (Mearns et al., 2009). Although individual regional simulations over Africa were available relatively early (e.g. Afiesimama et al., 2006) the first attempt to build a multi-model regional scenario for Africa was in the FP6-ENSEMBLES European project (van der Linden and Mitchell, 2009). As pointed out by Baron et al. (2005) global low-resolution scenarios can give some reliable information on temperature and precipitation. However some impact models were designed for smaller scale inputs and driving them with large scale results is likely to provide erroneous results. In ENSEMBLES, 11 regional models with a 50 km horizontal resolution were used on a domain 19.8°S to 35.2°N in latitude and 35.2°W to 31.2°E in longitude.

The international CORDEX (Coordinated Regional Climate Downscaling Experiment) project (Giorgi et al. 2009) aims at generalizing a multi-model RCM approach to 14 regions over the globe, Africa being a priority region. Compared to the earlier ENSEMBLES experiment, the CORDEX exercise is open to a larger number of RCMs (i.e. not limited to the partners of a European project), uses a larger domain (the whole African continent), a longer period (the whole 21st century) and more recent scenarios (IPCC AR5 instead of AR4). The first step of the project was to evaluate the capability of the RCMs to reproduce the observed climate, when driven by realistic lateral conditions (ERA-interim, Dee et al., 2011). The first 10 RCMs in the database were evaluated in Nikulin et al. (2012) and showed a reasonable reproduction of the major precipitation features of the continent, the common main drawback being a shift of the precipitation maximum earlier in the day than observed. This analysis was extended by Gbobaniyi et al. (2014) with a focus on West Africa. The second step of the CORDEX project was to downscale as many as possible global scenarios from IPCC-AR5 global simulations. Sylla et al. (2015) have recently analyzed the precipitation response in West Africa. The full list of publications related to CORDEX simulations over Africa is available at: http://www.csag.uct.ac.za/cordex-africa/cordex-africa-publications/.

A consequence of the multi-model approach is the spread between the results. A way to reduce this uncertainty is to exclude the fraction originating from the different climate sensitivities of the forcing GCMs from the analysis. The climate sensitivity of a model is the increase in global mean surface temperature in response to a given radiative forcing (e.g. doubling the GHG concentration). This has been done in the European FP7 project IMPACT2C by considering an asynchronous multi-model ensemble where in all driving simulations the mean global surface temperature (30-year average) is 2 °C above its pre-industrial value. Rather than considering an average for fixed time periods, e.g. 2021–2050 or 2071–2100 for all models, we consider 30-year periods based on an alternative criterion. The criterion is that, in the driving Atmosphere-Ocean General Circulation Models (AOGCM), the 30-year mean temperature increase is +2 °C over the globe. The new model-dependent periods start earlier with high climate sensitivity models than with low sensitivity ones. Further details about this methodology are described by Vautard et al. (2014). In this study, we focus on tropical (20°N–20°S) Africa with a set of 12 regional simulations from the CORDEX project. The goal is to translate a +2 °C warmer global climate in terms of temperature and precipitation distribution, independently of the period of the century when it could occur.

In Section 2, we describe in more detail the experiment and the models used. In Section 3, we examine the local temperature response, with a special examination of heat-wave frequency. In Section 4, we examine the local precipitation response, by splitting the frequency and the intensity signals. Section 5 is dedicated to the impact studies carried out in Africa during the IMPACT2C project with these climate models as an input. In Section 6, we discuss the +2 °C approach versus the traditional fixed time period. Conclusions are given in Section 7.

2. Models and experiments

Although the CORDEX archive and the IMPACT2C database (see Section 5) include scenarios RCP4.5, RCP8.5 and RCP2.6, we restrict the analysis here to RCP4.5, because the other two scenarios involve fewer regional climate models (RCMs). We use 7 AOGCM from the CMIP5 experiment, with the acronym of their institute in parentheses:

1. CNRM-CM5 (Météo-France)
2. EC-EARTH (ICHEC)
3. MPI-ESM-LR (MPI-M)
4. CanESM2 (CCCma)
5. MIROC5 (MIROC)
6. HadGEM2-ES (MOHC)
7. NorESM1-M (BCC)

Five RCMs have been driven by one or more of the above AOGCMs, with the acronym of their institute in parentheses:

1. ARPEGE (Météo-France)
2. HIRHAM (DMI)
3. RegCM (ENEA)
4. REMO (MPI-CSC)
5. RCA (SMHI)

These RCMs are some of those described in Nikulin et al. (2012). Their domain covers the whole African continent, with a 50 km

Table 1
Experiments available for an AOGCM (column) and an RCM (line) are marked by x.

	CNRM-CM5	EC-EARTH	MPI-ESM-LR	CanESM2	MIROC5	HADGEM2-ES	NorESM1-M
REMO		x	x				
RCA	x	x	x	x	x	x	x
ARPEGE	x						
HIRHAM		x					
RegCM	x						

horizontal resolution. We do not have all 35 possible AOGCM-RCM combinations, but only 12, as shown in Table 1. One can see that RCA has been driven by all AOGCMs, and that 3 AOGCMs have driven at least two RCMs. This is unfortunately insufficient to complete the matrix with an interpolation approach similar as that in Déqué et al. (2012), at least in a sufficiently convincing way. In the following we thus consider the average of the 12 simulations with equal weight. By doing this, we give a strong weight to the RCA model. But we will also examine the 12 individual responses as spatial averages, to check that the fact that more than one half of the scenarios use the same model RCA, does not bias the multi-model average toward an ‘‘RCA-like" response.

In order to focus on the tropical climate, and to avoid too large or too ‘‘zoomed out" charts, we restrict the analysis to the 20°N–20°S latitude interval, keeping only the land points in the statistics.

The simulations extend from 1950 to 2100, but we will keep two time intervals: 1971–2000 as a reference period, and an AOGCM-dependent period corresponding to time of the global +2 °C warming (Gobiet and Mendlik, 2014, personal communication):

1. CNRM-CM5 2043–2072
2. EC-EARTH 2042–2071
3. MPI-ESM-LR 2050–2079
4. CanESM2 2021–2050
5. MIROC5 2043–2072
6. HadGEM2-ES 2023–2052
7. NorESM1-M 2046–2075

In the following, we will compare the +2 °C time period with the reference period. We must keep in mind that the reference period does not reflect exactly the observed climate. Nikulin et al. (2012) have demonstrated that, when driven by almost perfect lateral boundary conditions the RCMs behave in a satisfactory way. Here, the RCMs are driven by imperfect boundary conditions. The analysis of the systematic errors in the simulations, and the attempts to reduce them by a statistical adjustment are out of the scope of the present study. Correcting reference and scenario simulations is, however, an important task in climate services. The difficulty in Africa is to have, for all variables to be considered, multidecadal homogeneous daily series of observations at a horizontal resolution comparable with that of the RCMs. In the present study, one can consider that we are comparing a reference climate (which is not necessarily the observed one at a given period) with another climate in warmer conditions. One should also have in mind that the +2 °C climate is warmer than our reference climate by only +1.54 °C. This is because ‘‘+2 °C" in IPCC language means +2 °C above the pre-industrial climate. This pre-industrial climate corresponds to 1880–1910. Our reference climate, based on 1971–2000 model statistics, is +0.46 °C above this estimated pre-industrial climate (see Vautard et al. 2014 and references therein).

3. Temperature response

In tropical regions, the annual cycle of temperature is less contrasted than in mid-latitude. For this reason, we consider here the response in annual mean. Table 2 shows the area average (20°N–20°S, land only) of the model response for each scenario. One can see that RCA scenarios offer a range of temperature increases from 1.5 °C with CNRM-CM5 to 2.2 °C with MIROC5. This justifies the fact that we can consider individual RCA simulations without the risk of biasing the mean response by a particular model. In addition, one can remark that RCA shows a weak warming with CNRM-CM5 driving, in agreement with ARPEGE and RegCM, and a stronger warming with EC-EARTH and MPI-ESM-LR, both in agreement with REMO. This shows the important role of the driving AOGCM in the continental-scale warming, which seems to be independent of the time of reaching +2 °C global warming. This role is confirmed by the last row in Table 2, which exhibits the AOGCM response over the same domain: CNRM-CM5 produces a temperature increase of 1.5 °C, whereas the increase is 2.0 °C for EC-EARTH and 2.4 °C for MPI-ESM-LR.

The spatial distribution of this warming could be displayed by the average of the 12 scenarios. But the information can be enriched by the 3rd, 6th and the 10th sorted values which correspond approximately to the percentiles 20%, 50% and 80% of the distribution of the 12 responses. Each percentile is calculated separately at each grid point. Fig. 1 shows the spatial distribution of the 3 percentiles. The median (50% percentile) shows a temperature elevation of about 2 °C (which is 0.46 °C above the global average in any of the driving AOGCMs), with higher values in Sahel, and, as expected, lower values near the coasts. The spread of the ensemble, as indicated by the 20% and 80% percentiles, shows that one could expect an elevation between 1.6 °C and 2.4 °C except in coastal regions. This result can be complemented by the annual cycle of the zonal means. Fig. 2 shows that the warming is larger at the beginning of the summer season: May for Northern Hemisphere (NH) and November for Southern Hemisphere (SH), with a stronger response in NH.

One important aspect in a warmer climate is the frequency of heat waves. The increase in extreme temperatures in a warmer

Table 2
Mean annual temperature difference (°C) between +2 °C and reference periods for individual model runs and for the driving GCM (last row).

	CNRM-CM5	EC-EARTH	MPI-ESM-LR	CanESM2	MIROC5	HADGEM2-ES	NorESM1-M
REMO		2.1	2.2				
RCA	1.5	2.1	2.2	1.9	2.2	1.8	2.0
ARPEGE	1.5						
HIRHAM		1.8					
RegCM	1.4						
GCM	1.5	2.0	2.4	1.7	1.9	1.8	1.8

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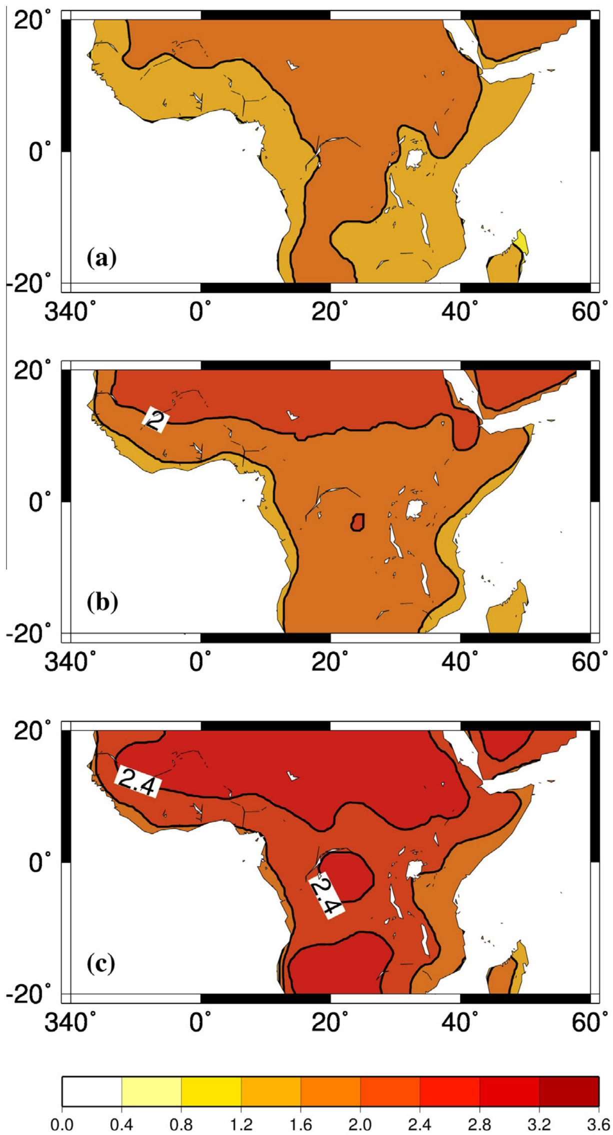

Fig. 1. Percentiles 20% (a), 50% (b) and 80% (c) of the mean annual temperature response; contour interval 0.4 °C.

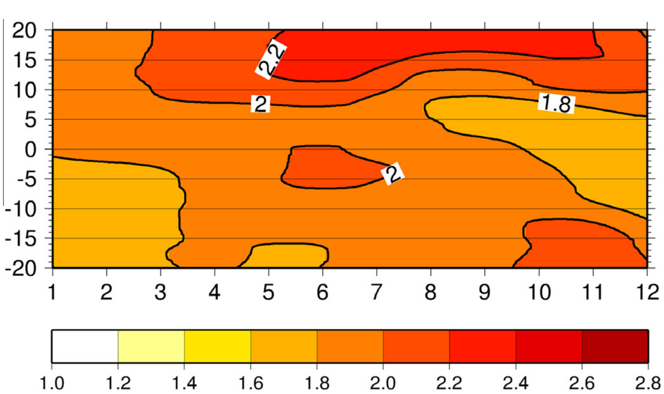

Fig. 2. Mean monthly zonal temperature response (°C) as a function of calendar month (x-axis) and latitude (y-axis); contour interval 0.2 °C.

climate has been widely described in the literature (e.g. Beniston et al. 2007; Fontaine et al., 2013), in particular after the 2003 hot summer in West Europe. Extreme warm temperatures may be associated with an increased human mortality (Gosling et al., 2009). A trend in extreme temperatures, more significant for the diurnal minimum than for the diurnal maximum, has been observed in West Africa during the second half of the 20th century, and the number of warm spells tends to increase (Ly et al., 2013).

There are different ways to define a heat wave (e.g. STARDEX, 2005). Here we define a heat wave as a sequence of at least 3 consecutive days above a temperature threshold HWT (the 90th percentile of the distribution, to reduce the effect of model systematic errors), as in Fontaine et al. (2013) or Russo et al. (2014). This threshold is calculated separately for each calendar month, each grid point, and each model simulation. If we count the days that belong to a heat wave in the reference simulations, the fraction varies from 2.8% to 3.3% according to the model, for the reference period.

When using the threshold HWT_{ref} of the reference period to count the heat wave days in the +2 °C scenarios, the number increases by 700% (RCA driven by HADGEM2-ES) to 1200% (RCA driven by EC-EARTH) on average in the whole domain (not shown). This means that if we apply the same threshold, we measure very different things in reference climates and in scenarios. The new threshold HWT_{scn} is 2.0 °C above HWT_{ref} on average. This difference is close to the difference in mean temperature (1.9 °C).

When using HWT_{scn} to count the heat wave days, the change is still positive with two exceptions, but its amplitude is much smaller (Table 3). This result emphasizes the need for adaptation to climate change: without any adaptation (i.e. considering that the same temperature threshold characterizes a heat wave in a warmer climate, because nothing has changed in the societal conditions) a rare and damaging phenomenon becomes much more frequent. Fig. 3 shows that the increase in number of heat wave days (taking into account a different HWT for reference and scenario) is not uniform in space and time. Its maximum is located between 10°S and 15°S and occurs in austral autumn.

4. Precipitation response

The temperature increase is expected to intensify the hydrological cycle but the distribution of the responses in precipitation is far from homogeneous over the globe (IPCC, 2013). Tropical Africa is not a place of large consensus among global or regional models which attempt to project the sign of precipitation change at the end of the 21st century, contrary to the Mediterranean basin for example where there is a strong drying signal. There are different aspects of precipitation change in a warmer climate. One is the risk of agricultural drought if the increase in potential evapotranspiration due to higher temperatures is not compensated by an increase in precipitation. Another one is the risk of floods if precipitation increases, or is concentrated in a few days separated by long dry periods. These questions are addressed in Section 5 with impact studies.

Precipitation in our tropical Africa domain concerns only a part of the year, namely the rain season. However, this period is not the same in different parts of the domain. In a first approach, we consider annual precipitation, to easily aggregate the different parts of the domain. Annual precipitation can be considered as a combination of a number of rain days and a mean rainfall intensity during these days. Table 4 shows that the number of rain days (with a threshold of 1 mm/day because models tend to produce a large number of days with small precipitation) decreases, except with ARPEGE. One can see that the driving GCM plays a role in this response: RCMs driven by CNRM-CM5 having a weak or positive response, whereas RCMs driven by EC-EARTH or MPI-ESM-LR have a stronger negative response. On the other hand, RCA exhibits responses with various amplitudes, showing that some RCMs do not impose a unique response whatever its forcing. Others like

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Table 3
Percentage of change in the number of heat wave days between +2 °C and reference periods for individual model runs. The two periods use their own threshold in the heat wave definition.

	CNRM-CM5	EC-EARTH	MPI-ESM-LR	CanESM2	MIROC5	HADGEM2-ES	NorESM1-M
REMO		5	8				
RCA	2	6	8	−5	7	1	−2
ARPEGE	3						
HIRHAM		2					
RegCM	1						

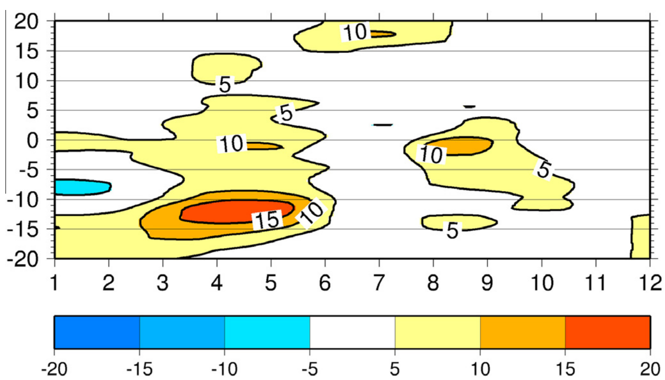

Fig. 3. As Fig. 2 but for the relative change of the number of heat wave days; see text for definition, the threshold HWT is increased in the +2 °C period; contour interval 5% (0% contour omitted).

REMO, however, seem to have a rather unique response in precipitation over tropical Africa and even flip the climate change signal of the forcing GCM (Saeed et al., 2013). Fig. 4b shows that the decrease in the number of rain days concerns the whole domain except the Somali Coast. However, the 80% percentile (Fig. 4c) indicates that this decrease is robust only in the southern part of the domain.

As mentioned above, a warmer climate intensifies the hydrological cycle through the Clausius-Clapeyron relation, and rain intensity (mm per day) is expected to increase. This is shown by Table 5, which exhibits an increase, expressed as a percentage of change relative to the reference intensity. Using a percentage rather than a raw value avoids giving too much weight to equatorial areas where annual precipitation is much larger than in semi-arid zones. If we spatially average raw differences rather than relative differences, we find an increase in the average daily rain intensity of wet days of 0.7 mm/day for RCA driven by MIROC5 and of 0.2 mm/day for RCA driven by HADGEM2-ES which are the two extreme values corresponding to Table 5 percentages. One can also notice that, contrary to temperature or number of rain days, the choice of the driving AOGCM does not seem to exert any influence on the change in intensity. RCA exhibits the two extreme situations (+3% and +11%) which supports the treatment of the 12 scenarios as equiprobable. Fig. 5b further supports this approach, the rainfall intensity increases everywhere. However, in the extreme North which is arid or semi-arid, the response is not robust: the percentiles 20% and 80% have an opposite sign. In addition, the denominator being small in this part of the domain, the two

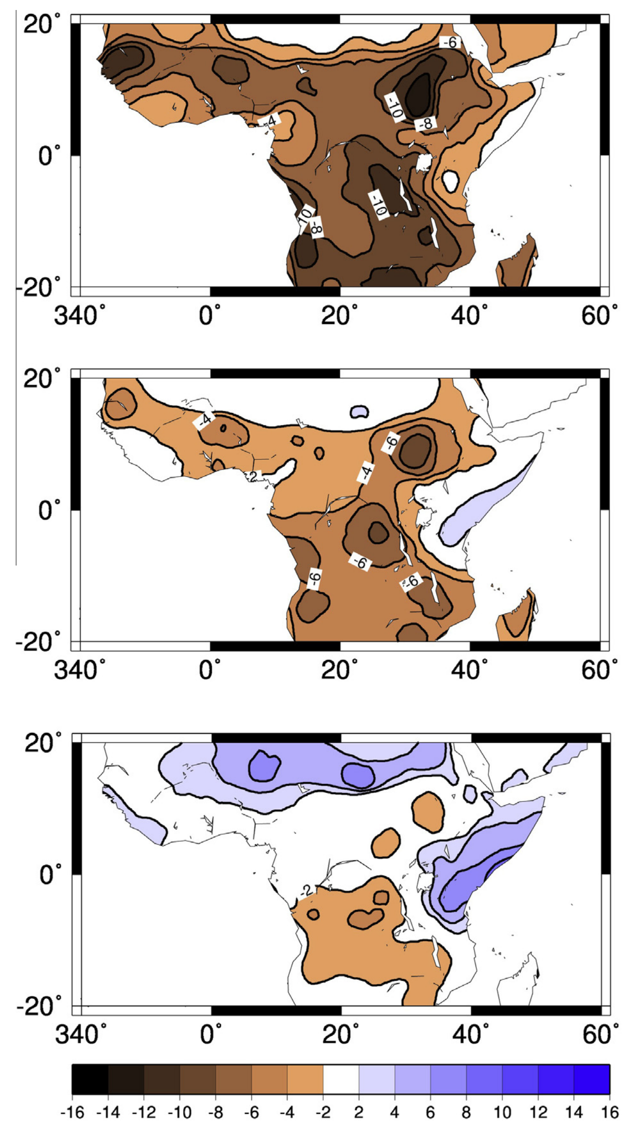

Fig. 4. Percentiles 20% (a), 50% (b) and 80% (c) of the relative change in precipitation days; contour interval 2% (0% contour omitted).

Table 4
Percentage of change in the number of rain days between +2 °C and reference periods for individual model runs.

	CNRM-CM5	EC-EARTH	MPI-ESM-LR	CanESM2	MIROC5	HADGEM2-ES	NorESM1-M
REMO		−6	−5				
RCA	0	−2	−5	−1	−2	−2	−2
ARPEGE	+3						
HIRHAM		−5					
RegCM	−1						

Table 5
As Table 4 for the rain intensity (%).

	CNRM-CM5	EC-EARTH	MPI-ESM-LR	CanESM2	MIROC5	HADGEM2-ES	NorESM1-M
REMO		8	7				
RCA	4	6	3	3	11	3	6
ARPEGE	5						
HIRHAM		7					
RegCM	6						

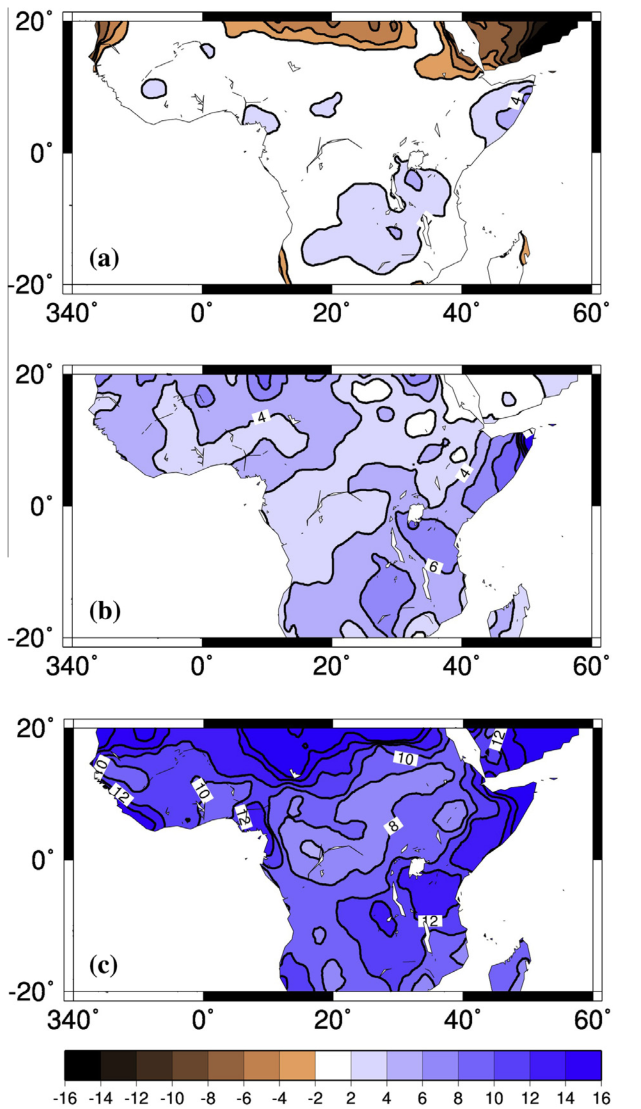

Fig. 5. Percentiles 20% (a), 50% (b) and 80% (c) of the relative change in precipitation intensity; contour interval 2% (0% contour omitted).

percentiles correspond to large responses in percentage, which is not the case if they are expressed in mm/day.

The annual precipitation response is thus the result of two compensating effects: fewer wet days with more precipitation per wet day. The net effect depends on the model: from −357 mm with REMO driven by MPI-ESM-LR to +607 mm with ARPEGE driven by CNRM-CM5. There are 6 positive and 6 negative responses. On average for the 12 models, the annual precipitation response is +100 mm, which corresponds to an increase by 1%. Given this weak value and the spread between the models, it is wise not to draw any conclusion about the net change. More interesting is the distribution in space and time (zonal and monthly means) of the net precipitation response. Fig. 6 shows clearly a shift of a couple of months of the rain season which starts later and finishes later. This is mostly visible for the NH and to a lesser extent for the SH. This lag is confirmed by the 20% and 80% percentiles (not shown) and therefore deemed to be robust.

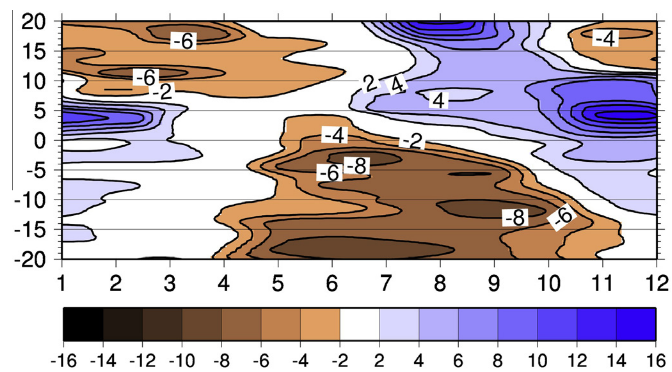

Fig. 6. Mean monthly zonal precipitation response (%) as a function of calendar month (x-axis) and latitude (y-axis); contour interval 2% (0% contour omitted).

5. Related impact studies

The daily data for temperature and precipitation used in the above sections have been stored on a public database: http://impact2c.dmi.dk/data/MODELS/WP3/AFRICA.

The domain covers the whole African continent on each RCM native grid. Together with the web-Atlas https://www.atlas.impact2c.eu/en/, this database is a climate service delivered by the IMPACT2C project and is freely available for use as an input for impact models. During the project IMPACT2C, the climate scenarios described in the previous sections have been used as an input for impact studies with a focus on Niger River and Nile River basins. For example, the Soil and Water Integrated Model (SWIM, Krysanova et al., 2014) has been used to investigate the impact of climate change on the frequency and magnitude of floods over the Niger River basin under different climate and land-use scenarios (Aich et al., 2016). Consistently with the results presented in the previous sections, the work of Aich et al. emphasizes the relatively higher increase of intense rainfall events with respect to annual means, which do not show significant trends in the study areas. As a consequence, the risk of catastrophic floods in the modeled sub-catchments of the Niger basin is likely to increase in most climate and land-use scenarios. The study of Aich et al. is focused on four sub-catchments of the river basin and stresses the need for broader regional studies, aimed framing adaptation measures under different land use and climatic settings in the area.

The RCP4.5 scenarios described in this paper have also been used as an input to the integrated tool Africa Risk View (ARV) for food security. This software was primarily developed by African Risk Capacity (ARC) to translate satellite-based rainfall information into near real-time estimates of drought response costs, by combining models on agricultural drought with data on vulnerable populations. It has been adapted to RCM output. More details at http://www.africanriskcapacity.org/fr/africa-risk-view/introduction.

The focus of this analysis is on agricultural drought, which is affected by rainfall anomalies on longer time scales than those affecting floods, analyzed with SWIM. The climate impact analysis conducted with ARV reflects the results described in Section 4 for the annual precipitation response, whereby the higher rainfall intensity is mostly compensated by the lower number of rainy days.

For the ARV study, rainfall and temperature data from the RCP4.5 scenarios described in the previous sections have been adopted as an input for the underlying crop model and then converted into an estimate of drought affected people by adopting a transfer function which reflects the current vulnerability of populations at the national scale. An example of the results obtained with ARV for the two river basins is reported in Fig. 7. The multi-model ensemble simulation of drought affected people along the whole 21st century shows large uncertainties. In the Nile basin (4 countries including Uganda, South Sudan, North Sudan and Ethiopia) weak negative trend is projected, along with a large uncertainty range, such that it is not advisable to draw conclusive recommendations concerning the long term tendency. On the other hand, the Niger Basin shows a sequence of decades with increased risk and decades with decreased risk. Together with the projection of a possible shift in the onset of the rainy season, suggests a potential role of seasonal-to-decadal predictions in improving the timeliness effectiveness of midterm adaptation measures and of emergency operations.

6. Discussion

In this paper, we follow the general approach of the IMPACT2C project of using variable 30-year periods according to the model climate sensitivity. Compared to the traditional approach of gathering different models according to years, there seems to be a loss of information, because no chronology is given for the phenomenon. In fact, a scenario is not a forecast; providing years like 2050 or 2100 refers to a calendar of hypothetical emissions, not to an actual calendar. On can consider that in the traditional approach, different models share the same global GHG concentration, whereas in the IMPACT2C approach, they share the same global temperature. To be more accurate, they share the same temperature increase; indeed, in the reference climate, because of modeling errors, different models have different global temperatures.

A relevant question is the dependence of the +2 °C approach on the emission scenario: would our results have been different if we had used an RCP8.5 or RCP2.6 scenario? The rate of climate change is an important issue for mitigation and/or adaptation policies (Watkiss et al., 2015). Unfortunately, we have fewer regional simulations available with those scenarios for Africa. A quick examination based on our available RCP8.5 scenarios suggests the answer is No. In Maule et al. (2016) a comprehensive study over Europe shows that the response is little dependent on the date when the +2 °C is reached. However they found a small trend, indicating that the later the global +2 °C delta is reached, the smaller the temperature response in Europe is obtained.

Our available regional scenarios in Africa allow us to look at this question with another approach. The 30-year period of the 12 scenarios are 2021–2050 for the earliest, and 2050–2071 for the latest (Section 2). On average, the +2 °C period is 2041–2070. We have recalculated the multimodel temperature and precipitation responses for this common period. The results are shown in Table 6. As expected, the mean response is almost the same for the +2 °C and the 2041–2070 period. One should expect the model spread to be reduced by the +2 °C period, because each driving AOGCM undergoes the same global warming, which is not true with the 2041–2070 period. We can see this effect for temperature, but the standard deviation is weakly reduced. This result may be explained by the fact that the local response depends much more on the choice of the model than on the choice of the period. If we average the 12 temperature responses over the whole tropical

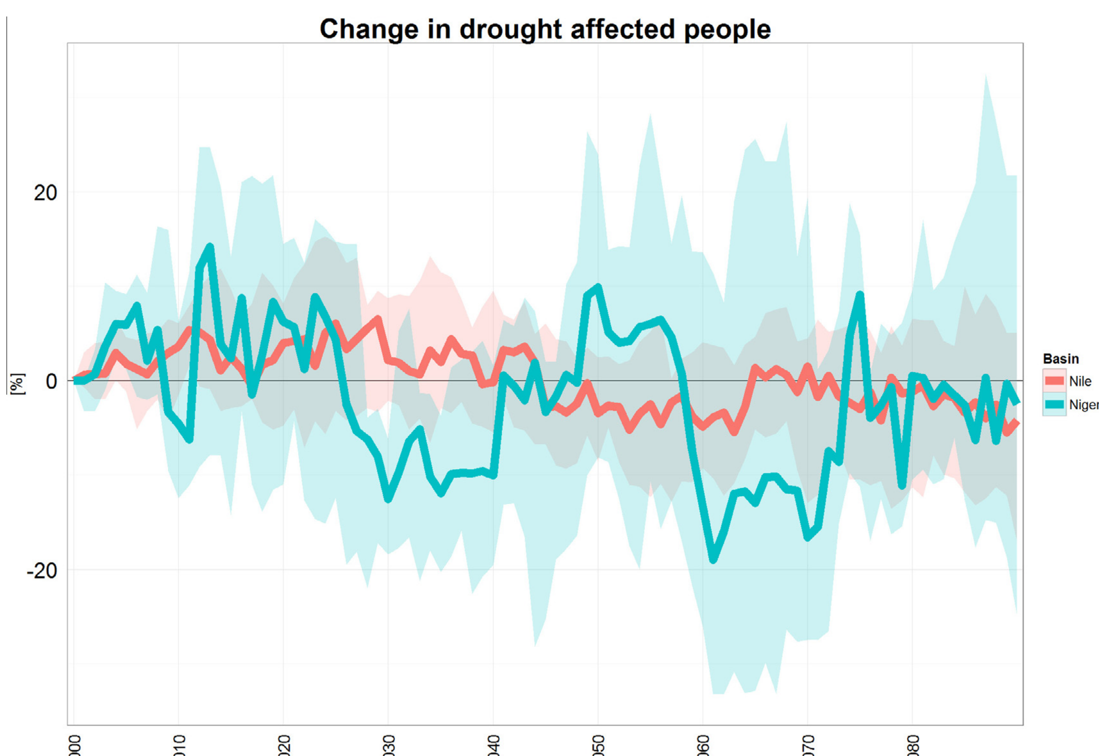

Fig. 7. Relative change (%) in drought-affected people in the Nile and Niger basins according to the different model runs. Thick lines represent the ensemble average and the shaded areas represent the mid-tercile range of the ensemble.

Table 6
Multi-model mean and spread (i.e. standard deviation) for temperature and precipitation responses with the IMPACT2C approach and with a common 2041–2070 period. These indices have been averaged over the whole tropical Africa.

	IMPACT2C mean	2041–2070 mean	IMPACT2C spread	2041–2070 spread
Temperature (°C)	1.90	1.92	0.32	0.35
Precipitation (mm/year)	8	6	77	75

Africa domain and sort them, the amplitude (maximum minus minimum response) is 0.8 °C for IMPACT2C and 1.0 °C for 2041–2070. This approach, although statistically less robust, better illustrates the reduction in model spread. For precipitation, Table 6 shows a small increase in standard deviation with the IMPACT2C approach. As indicated in Section 5 and shown in Fig. 7, the precipitation response along the 21st century is a succession of positive and negative values, not a regular trend. If we look at the models individually, there is no consistency between the positive and negative phases. So the spread between the model responses does not depend on the fact that the 30-year periods are synchronous or not. As far as precipitation is concerned, the IMPACT2C approach does not allow to reduce the model uncertainty.

7. Conclusion

Twelve regional simulations out of the CORDEX ensemble have been analyzed in tropical Africa, as far as above surface temperature and precipitation are concerned. Rather than the traditional 2071–2100 versus 1971–2000 aggregation of the model statistics, we have considered different time periods for the scenario, so that in each RCM, the global background warming is +2 °C with respect to pre-industrial temperature. With respect to our 1971–2000 reference period, the warming is slightly above 1.5 °C. The first result is the homogeneity of our sample: although more than one half of the scenarios use the same RCM, the individual responses do not characterize the corresponding RCM, and even in some cases reflect the choice of the GCM. As far as mean temperature is concerned, the response is, on average, above the global one. A heat wave index has been defined with the 90th percentile of each model. If the threshold used in the reference climate is kept in the +2 °C climate, the heat wave frequency is increased by 700–1200% according to the model, which shows that a +2 °C warming is of the same magnitude as the day-to-day variability of temperature. Adapting the threshold to a warmer climate still leads to an increase (about 5%) in the heat wave frequency. The precipitation response is weak and model dependent. If we decompose the annual precipitation as a product of the number of rainy days by the rainfall intensity, it appears that the former decreases whereas the latter increases. The fact that intensity increases, is in agreement with thermodynamics laws. Another compensation phenomenon is observed when the annual cycle of precipitation change is examined: precipitation decreases in early summer and increases in late summer. Thus, stating that precipitation will not change in tropical Africa is too coarse a simplification.

In impact models, precipitation and temperature distributions are combined in a non-linear way to produce river discharge and available soil moisture. In the IMPACT2C project, we have used one hydrological model (SWIM) and one food security model (ARV). SWIM shows that the risk of catastrophic floods in the modeled sub-catchments of the Niger Basin is likely to increase. ARV shows a stronger increase in vulnerability in West Africa and Niger basin than in other parts of the region. However, most changes occur as decadal scale fluctuations rather than as a linear centennial trend. As a consequence, the spread of the models, except for temperature, is not reduced by considering a common +2 °C period for each of them.

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