

Climate and river runoff changes in West and Central Africa: past variability and prediction of water resources for the 21st century.

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Abstract

The aim of this study is first to show how climate and river runoff have changed over the last century in West and Central Africa, and secondly from this knowledge, in combination with river modelling, to predict the water resources for the 21st century for 328 river basins of West and Central Africa, obtained from the FRIEND-AOC database (UNESCO IHP).

The GR2M rainfall-runoff conceptual model is calibrated and validated for each runoff series at a monthly time step. Rainfall are calculated from an IRD monthly gridded database, available on a website, PE are calculated from the CRU database. The reservoir height is taken as the Water Holding Capacity, given by the FAO soil Map of the World. All data are averaged for half degree squares. We simulate future runoff using rainfall and PE data derived from the HadCM3 2001 GCM outputs, SRES-A2 scenario, according to an original procedure for estimating "realistic" rainfall and PE values from the GCM outputs.

The results are presented for 3 time horizons: 2020, 2050 and 2080. In 2020 and 2050 one observe an important variability over West Africa, except over three regions: the North-West (Senegal-Guinea-Mauritania) and the North of the Congolese basin, where runoff decreases as soon as the 2020 horizon; and the Chari basin where runoff increases. In 2080 runoff decreases everywhere in West and Central Africa, except over the Chari basin. The seasonal runoff dynamic, and particularly the flood peak occurrence, might be also modified by the forthcoming climatic fluctuations predicted by the HadCM3 GCM.

The bias due to the use of a single GCM and a single scenario of greenhouse gases emission variability output data set is discussed, and we present a comparison between 4 GCM outputs over West Africa.

Key words: Climate, Runoff, West and Central Africa, Climatic variability, River modelling, Water resources, GCM, HadCM3, FRIEND-AOC

Introduction

The climate of West and Central Africa (WCA) has varied very strongly during the 20th century. A rainfall diminution has occurred abruptly over the region, around 1970 in West Africa, and later on, in the mid-1970s or at the beginning of the 1980s in Central Africa (Paturel *et al.*, 1998; Hulme *et al.*, 2001; Mahe *et al.*, 2001; L'Hôte *et al.*, 2002). The impact of this rainfall diminution on runoff has been very quick but quite different according to the sub-areas (Mahe and Olivry, 1999; Mahe, 2006). Except over the Sahel, where runoff increased since the 1970s due to land degradation (Mahe *et al.*, 2005), runoff decreased over all other basins in WCA. This decrease is much stronger in West Africa than in Central Africa, where for some rivers no long term change is observed.

The figure 1 shows that the variability of runoff is different in each of the 4 main regions of West and Central Africa. The Congo river runoff has been increasing from the beginning of the century up to the early 1960s, then decreased to reach in the 1990s the same level than in the 1910s. The equatorial rivers runoff do not seem to follow a long term trend over the

observed period (1930s to 1990s), but show an important interannual variability with very low values in the 1980s. Differently from the Congo basin, the runoff increased again since the end of the 1980s. The runoff of humid tropical rivers (eg. Senegal, Niger, Volta, Chari), also show a high interannual variability, but is characterized by an intense decrease since 1970, which led to exceptionally low flows values since the mid 1970s, never observed before. Finally, the Sahelian river runoff is increasing since the beginning of the 1970s, despite the rainfall decrease which is still going on over the area (L'Hôte *et al.*, 2002; 2003), this being significantly correlated with the increase of the land degradation (Seguis *et al.*, 2004; Mahe *et al.*, 2005).

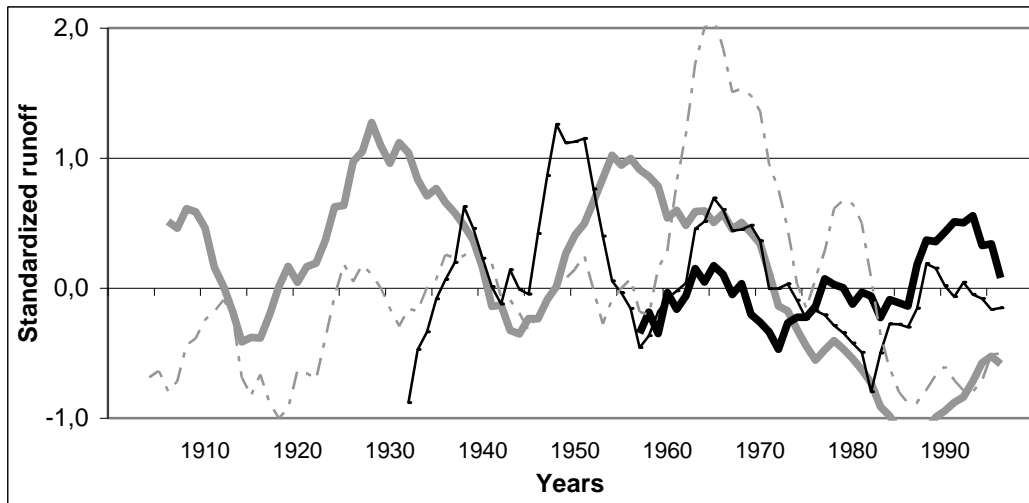


Figure 1: runoff interannual variability over West and Central Africa, according to four main climatic areas: the Congo river basin at the Brazzaville station (3 000 000 km²)(dashed line); the equatorial rivers (in Gabon, Congo, South Cameroon)(thin black line); the tropical rivers in humid area (more than 750 mm of annual rainfall)(thick grey line); the Sahelian rivers (annual rainfall between 250 and 750 mm)(thick black line).

According to IPCC (2001, 2003) most of the GCMs outputs projected that rainfall might continue to decrease during the 21st century over most of the West Africa, and especially over the western part of West Africa (Senegal/Mauritania).

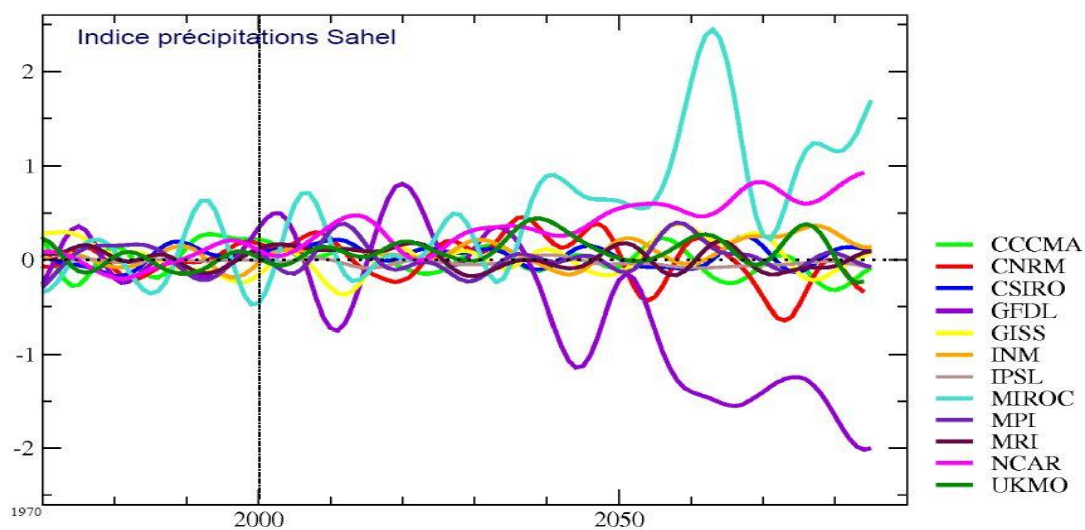


Figure 2: Low-frequency signals extracted by digital filtering (10-year cut-off) of the Sahel JJAS rainfall index, for the SRES-A2 scenario of the 12 selected IPCC4 coupled models. The anomalies are displayed relatively to the 1971-2000 climatology of the model (in mm/day) (Joly *et al.*, 2007).

The recent new release of IPCC projected climate change (2007)(figure 2) shows quite no change for the global Sahel rainfall during the century. Looking at the projected map on the same report one can observe local variability, and for instance, rainfall are still projected to decrease over the Senegal/Mauritania area, while in Central Africa a slight increase is projected.

In this region of the world, where the majority of the population lives in rural areas and depends on rainfed agriculture for its subsistence, everyone is interested in the climate projections for the 21st century, and what will be the rainfall and runoff changes. According to IPCC (2007) by 2080, an increase of 5 to 8% of arid and semi-arid land in Africa is projected under a range of climate scenarios (*high confidence*).

The purpose of this study is to use rainfall and PE projections for the 21st century, according to GCM outputs, to run a rainfall-runoff model, previously calibrated on observed data, to simulate future runoff.

Data and Methods

The studied area is the West and Central Africa, where ORSTOM (Office de la Recherche Scientifique et Technique Outre-Mer), now IRD (Institut de Recherche pour le Développement), has developed in the past the hydrological networks of many countries, creating more than 1000 river basins gauging stations. From that network, we studied 328 basins, among those presented on the map of the river basins of WCA (figure 3, Dieulin, 2007) which sizes range between 100 and 1 300 000 km². All the well known great rivers of the region are studied like the Senegal, Niger, Volta, Logone-Chari, Ogooue and Congo basins.



Figure 3: The study area: the map of river basins in West and Central Africa (Dieulin, 2007).

The model used is a conceptual rainfall-runoff one: GR2M, a single reservoir model developed by Cemagref (Paturol *et al.*, 1995, Mouelhi *et al.*, 2006)). It runs a monthly time step hydrological balance. The variables used are: precipitations (P), evapotranspiration (PE),

runoff (Q) and soil water holding capacity (SWHC), taken as the height of the reservoir (figure 4).

The model is calibrated with two parameters, linked to direct runoff Q_r (X_1 (α)) and lagged runoff Q_l (X_2 (β)).

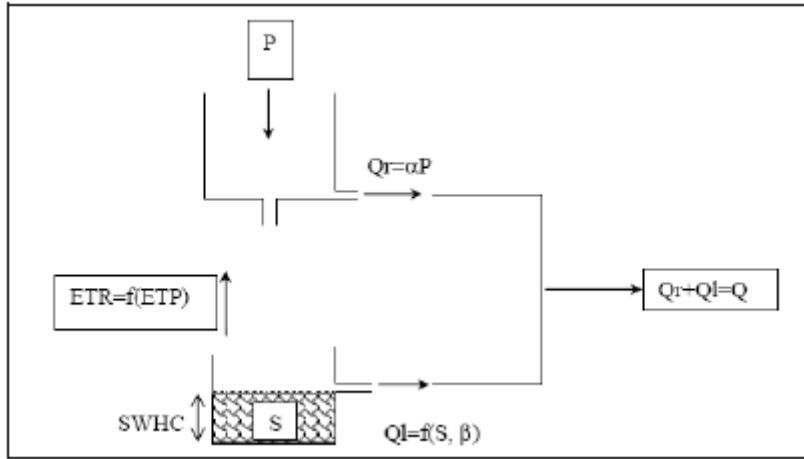


Figure 4: GR2M - Global Runoff 2 parameters Monthly hydrological model (Paturel *et al.*, 2003). ETR=Actual PE= Potential Evaporation. S is equivalent to the Soil Water Holding Capacity (SWHC), and fixed in time.

Interception (U) is removed as follows:

$$U = \frac{P' \times ETP'}{(\sqrt{P'} + \sqrt{ETP'})^2}$$

The optimization is done by a combined Rosenbock-Simplex procedure.

The performance of the river modelling is estimated by the Nash criterion between -1 and 1 (best), combination between observed and calculated runoff:

$$Nash = 100 \times \left(1 - \frac{\sum_i (e_{OBS}^i - e_{CALC}^i)^2}{\sum_i (e_{OBS}^i - \bar{e}_{OBS})^2} \right)$$

The raw rainfall values issued from the GCM outputs are not realistic ones over West Africa (Casenave, 2004; IPCC, 2001).

We defined two methods for the construction of rainfall monthly time series for the future:

Horizon scenario and Anomaly scenario (Ardoin *et al.*, 2005).

Horizon Scenario:

$$Var_{GCM} = \frac{\overline{X_{GCM,horiz}} - \overline{X_{GCM,ref}}}{\overline{X_{GCM,ref}}} \times 100 \quad \boxed{X_{SCEN-Horiz} = X_{FICT} \times Var_{GCM}}$$

Anomaly Scenario:

$$Ano = \frac{X_{GCM} - \overline{X_{GCM}}}{\sigma_{GCM}} \quad \boxed{X_{SCEN-Ano} = (Ano \times \sigma_{CRU}) + \overline{X_{CRU}}}$$

Where in the Horizon scenario a fictitious time series is combined with the variability of rainfall issued from the GCM outputs, as the absolute values from GCM are unrealistic. And

in the Anomaly scenario the anomaly issued from the GCM outputs is combined with the standard deviation from the CRU rainfall data.

We study 328 river basins (figure 3), which are spread all over the major great river basins of WCA.

The sizes of the basins range between 100 and 1 300 000 km² (figure 5). This figure shows that half of the basins studied have a surface less than 11 000 km². The average length of the observed time series is about 31 years. The choice of the years for the calibration is driven by previous results (Ardoin *et al.*, 2005; Paturel *et al.*, 2003): 1971-1987 for calibration, and 1988-1995 for validation.

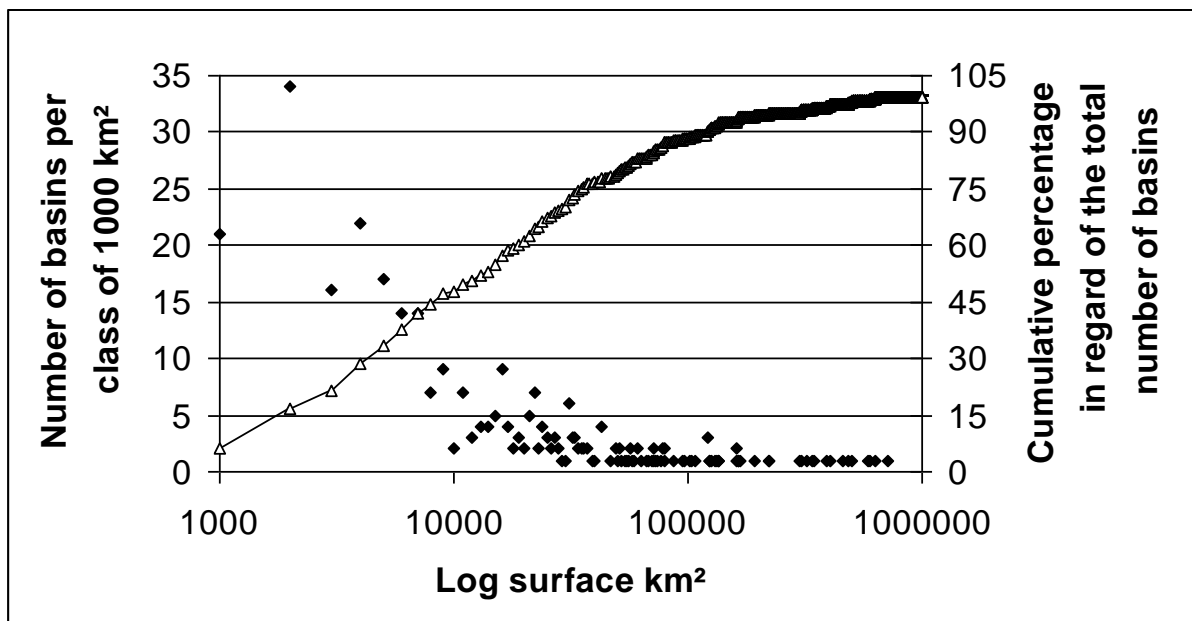


Figure 5: Number of basins per class of 1000 km² (the two basins over 1 million km² are not represented – Onitsha and Lokodja, Niger river basin in Nigeria- for the clarity of the graph). The right Y axis shows the cumulative percentage of number of basins.

Because of the significant pluviometric discontinuity around 1970 in the WCA rainfall time series, separating a previous humid period and the actual drought period, we choose to calibrate and validate the model only for years after 1970. This choice is also supported by the projections of the 21st century future rainfall from GCM outputs (Casenave, 2004; Ardoin *et al.*, 2005), on the basis of the IPCC (2001) outputs, according to which rainfall should still decrease over West Africa in the decades to come, and should not much change or slightly increase in some parts of Central Africa. It seems thus more realistic to use time series after the pluviometric break of 1970 in the region. Previous tests also showed that the calibration over the years after 1970 gives better results for simulation whatever the period considered.

Results

The Nash criterion reaches good values for the majority of basins, either in calibration (1971-1987) or in validation (1988-1995), and either in West or Central Africa (figures 6 and 7).

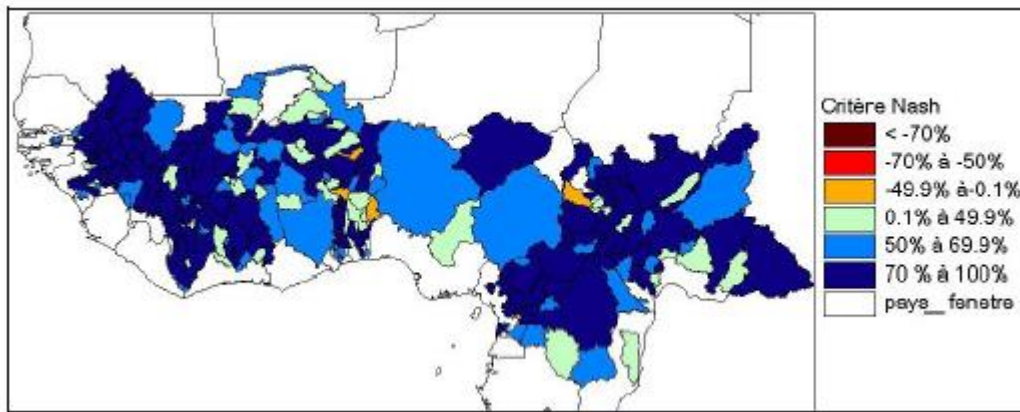


Figure 6: Nash criterion for calibration procedure over the 1971 – 1987 period

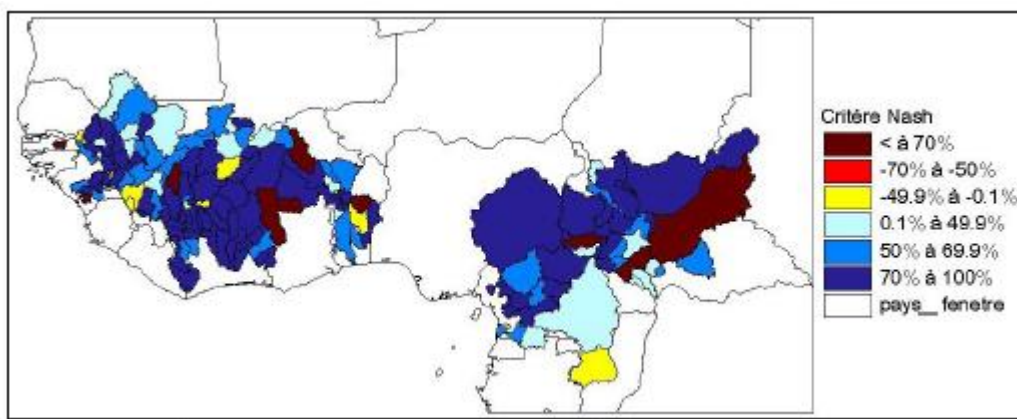


Figure 7: Nash criterion for validation procedure over the 1988 – 1995 period.

Due to time series length not homogeneous, some river basins are used only for the calibration procedure. The lowest quality results, either in calibration or in validation, correspond mainly to two groups of basins: very large river basins and Sahelian basins. For the very large basins, the monthly time step is not adapted to the response time of the basin to rainfall: the flood takes more than one month to reach the station from the region of maximum rainfall, either because of the very long distance, or because of flood plains along the river course which slow the discharges. For Sahelian basins, the bad results come from the changes observed in the surface runoff processes since the beginning of the drought. The hydrological model, using fixed SWHC in time, is not designed to take into account changes in land-use, which explains the bad results. Mahe *et al.* (2005) showed that for this region better results are obtained when using a time varying SWHC rather than a fixed one, which is the usual case in river modelling, because of lack of data.

The Nash values are compared to 3 variables: the length of the time series for calibration, the basin surface and the date observations start (figure 8). No strong relationships can be observed between all these variables and the Nash values. Nevertheless two observations can be pointed out: i) Nash values tend to slightly increase together with the basin surface (between 0 and 30 000 km²); ii) Nash values are systematically over 50% for river basins which time series begin before 1950 (which are supposedly also the longest ones). For this last point, knowing that the calibration and validation tests are done after 1970, this might be linked either with a better data quality for “synoptic” stations, or with the size of the basins, as the longest time series often correspond to large scale basins.

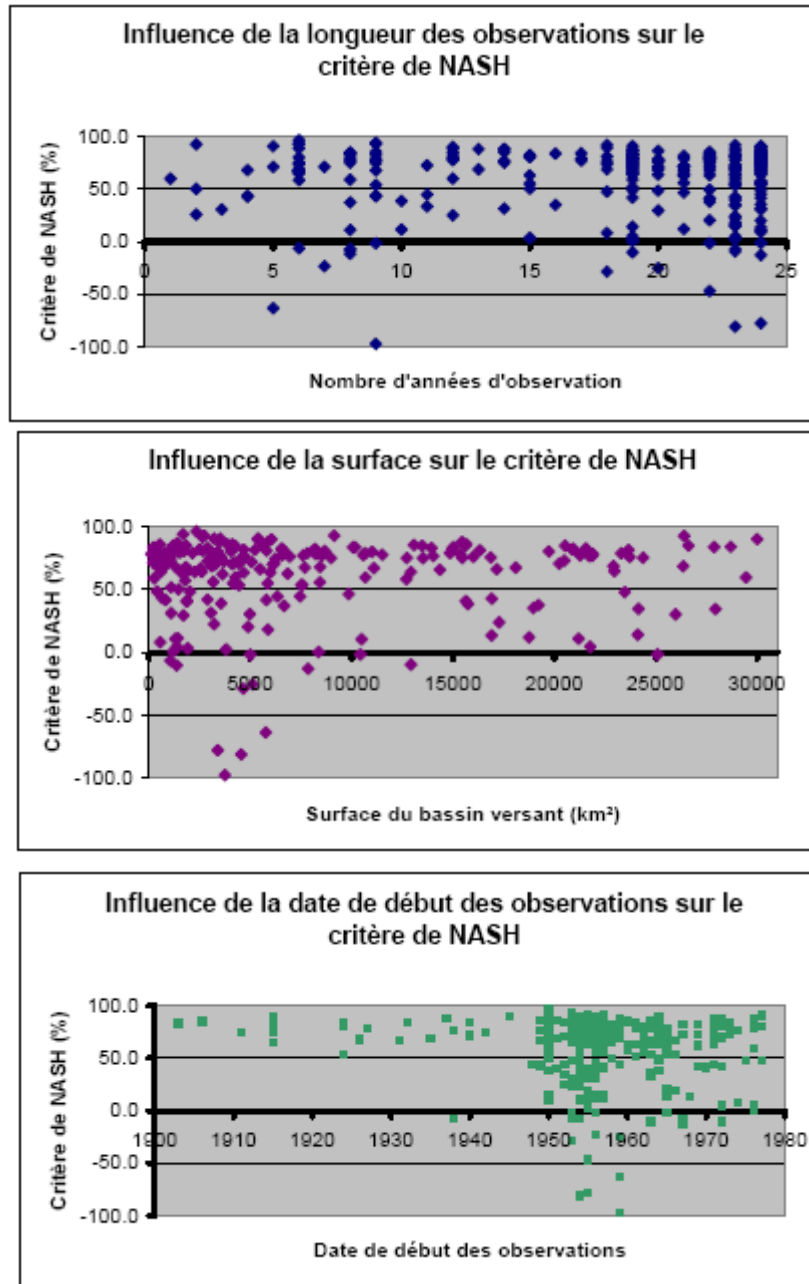


Figure 8: Relationship between the Nash value for calibration and the length of the time series (top), the surface of the basin (middle) and the date of the beginning of records (bottom).

Climate scenarios

The rainfall fields outputs of four GCMs have been compared for the region (figure 9) (Ardoin *et al.*, 2006) over past periods. The four GCMs reproduce quite well the main features of the rainfall fields at the global scale. But the interannual averaged rainfall amounts are not well reproduced at the sub-regional scale. The HadCM3 GCM, that we use in this study, is particularly optimistic for the regional rainfall (except for the Senegal/Mauritania area), and overestimates rainfall in regard to the three other GCMs.

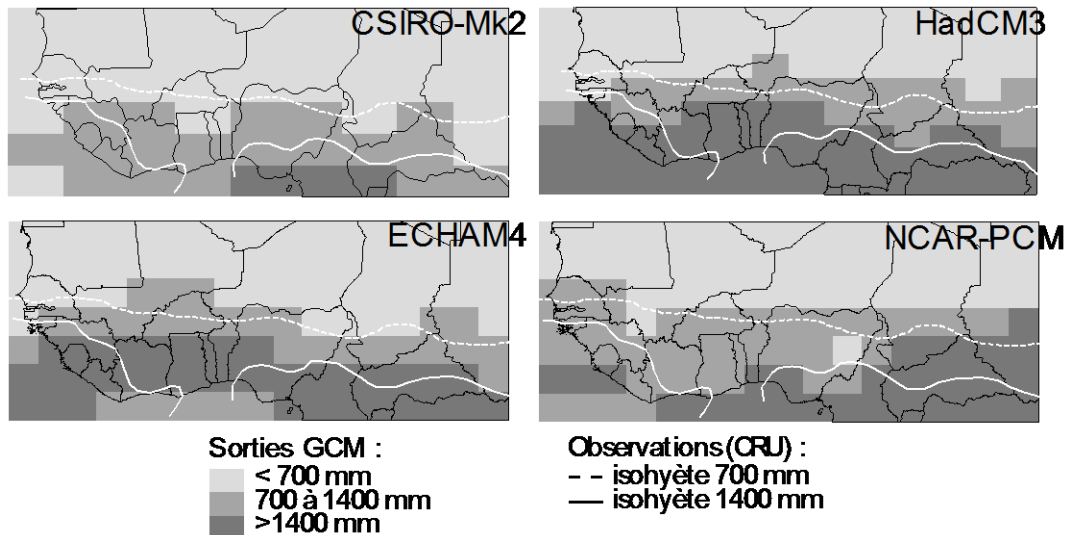


Figure 9: Annual rainfall isohyets 700 mm and 1400 mm (after 1969–1998 CRU data) and annual average projected rainfall after: CSIRO-Mk2 (1961–1998), ECHAM4 (1990–1998), HadCM3 (1950–1998) and NCAR-PCM (1981–1998) (Ardoin *et al.*, 2006).

The application of future rainfall and PE scenarios from HadCM3 outputs to the GR2M model, for each river basin, are represented following 3 time horizons: 2020, 2050 and 2080, in regard of the 1966-1995 average period. Three types of evolutions are projected (figure 10 and 9): i) an increase of runoff, mainly over the Lake Chad basin; ii) a decrease of runoff, over the Sangha basin (subcatchment of the Congo basin); iii) fluctuations over West African basins and in Central South basins (a slight increase followed by a decrease).

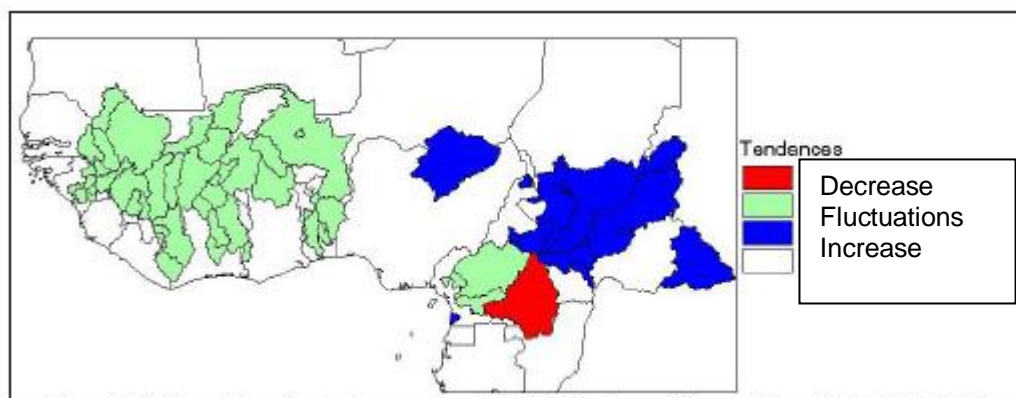


Figure 10: Schematic runoff tendencies for the 21st century in regard of the 1966-1995 period, after the HadCM3, A2 outputs.

Runoff is projected to vary differently in West and in Central Africa: mainly a decrease in West Africa and an increase around the Chad basin. But at the basin level, there are many local discrepancies which can not be explained by simple variables like those seen on figure 8. Except over the Sangha basin, where runoff are projected to decrease constantly, over West and Central Africa runoff are projected to increase at the horizons 2020 and 2050 (figure 11). It is only at the horizon 2080 that runoff is projected to dramatically decrease over most of West Africa, while it is still increasing over Central Africa. These variations of runoff are similar to that of rainfall: a majority of GCMs projections show a continuous decrease of rainfall over the western part of West Africa during the 21st century.

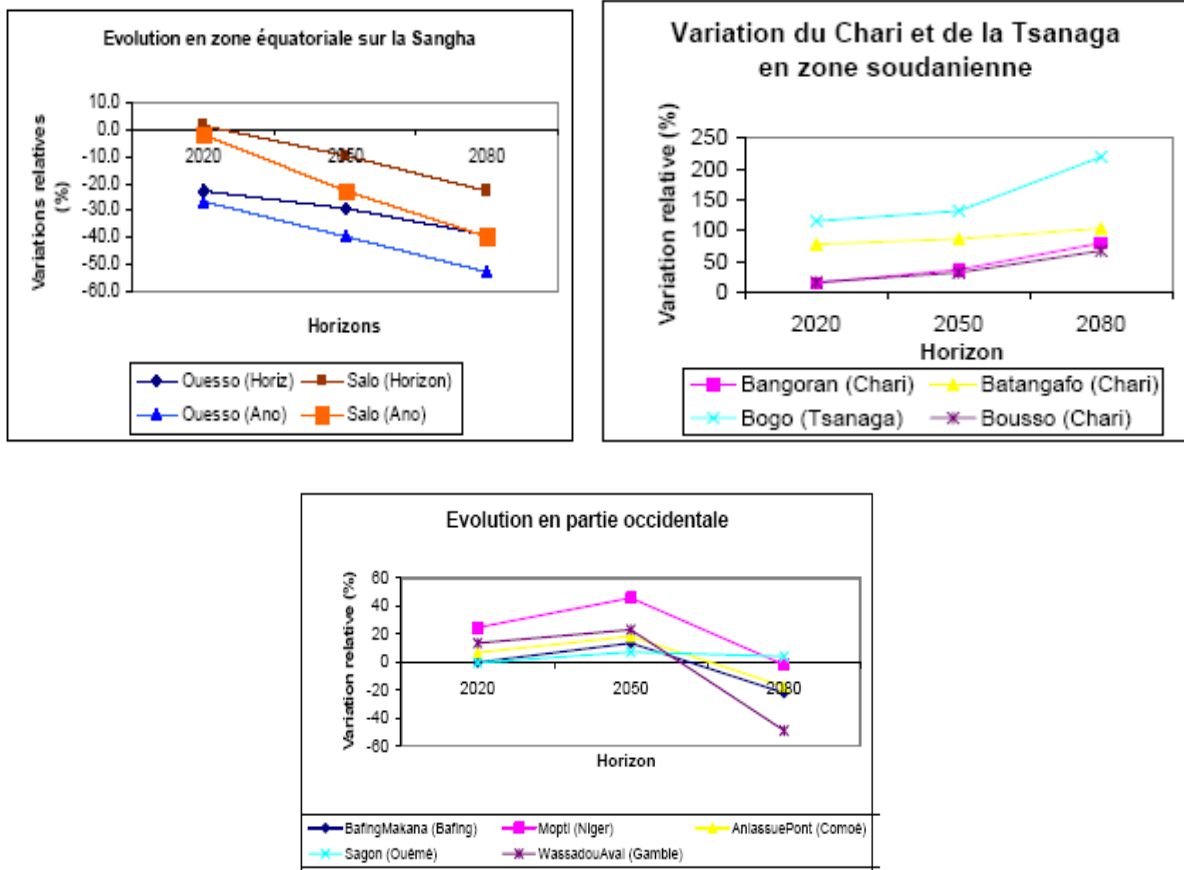


Figure 11: Examples of projected runoff fluctuations over West and Central Africa during the 21st century, from HadCM3 GCM outputs, SRES-A2 scenario: Equatorial area-Sangha basin (top left); Central African tropical humid area –Chari and Tsanaga basins (top right); West Africa (bottom).

Seasonality change

The monthly river regimes are awaited to be also modified (figure 12). Monthly maximum runoff decrease or increase, depending on the river basin (Lake Chad basin or elsewhere), and are often awaited to occur sooner in the season (Niger and Chad basins).

Impact of temperature increase

The rainfall decrease projected for the 21st century over WAC is not very strong. But the runoff decrease awaited is much more amplified. This is due in the model to an increase of PE related to the temperature increase. This is also due to the change in the non-linear rainfall/runoff relationship, which led after 1970 to a runoff decrease of minus 30 to 60% in humid tropical rivers, while rainfall decreased by only 10 to 20% (Mahe and Olivry, 1999). As rainfall is not projected to increase in WAC, rainfall/runoff relationships are not awaited to change from actual ones.

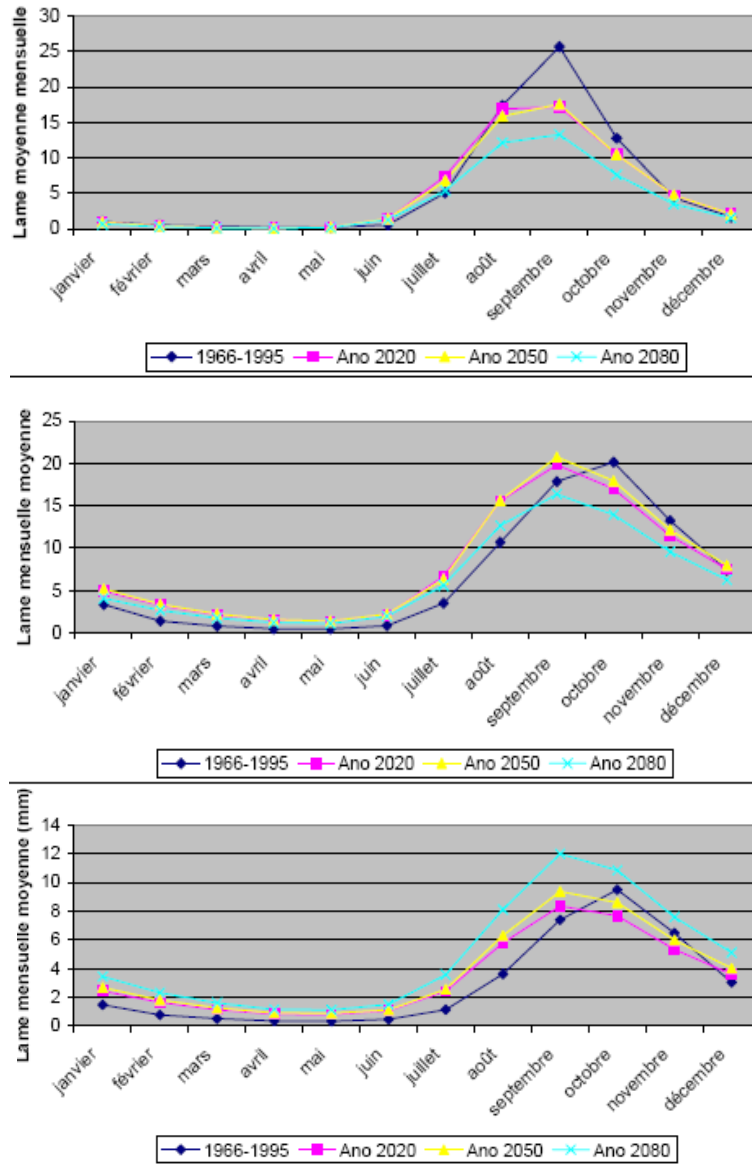


Figure 12: Projected changes in the seasonality of monthly river regime over West and Central Africa during the 21st century, from HadCM3 GCM outputs, SRES-A2 scenario, from top to bottom over Senegal, Niger and Chad basins.

Conclusion

GCMs outputs for the 21st century over West and Central Africa show a global temperature increase, and rainfall changes according to the areas: increase over Central Africa, and slight increase then decrease over most of West Africa. Runoff changes linked to this projected climate change are studied through rainfall/runoff modelling for 328 river basins. The GR2M hydrological model is calibrated and validated for the observed times series for each of the basins. Then the GCM outputs are processed according to two different methods to create two scenarios before being applied to the hydrological model.

The projected runoff variations up to the horizon 2080 show three main regions, although within each area there are many local discrepancies. In West Africa runoff is projected to slightly increase up to the horizon 2050, then to decrease at the horizon 2080. In Central Africa, over the Chad basin runoff is projected to increase up to the horizon 2080, while over the Equatorial Sangha basin runoff is projected to decrease during the whole 21st century.

The seasonality of the river regimes might also change, with often a peak flood occurring one month sooner over many river basins. The increase of temperature will also have a great effect on runoff because of the increase of PE, which will counter the slight increase of rainfall projected over some areas.

The HadCM3 GCM outputs correspond to the SRES-A2 scenario, on the basis of the 2001 run for the IPCC assessment. Three other GCMs outputs CSIRO-Mk2, ECHAM4 and NCAR-PCM are compared to the HadCM3 outputs. This shows that the HadCM3 projection of rainfall during the 21st century is more optimistic for West and Central Africa than the three other GCMs' projections, except over the Senegal/Mauritania area. Thus the runoff decrease over West Africa simulated by the GR2M model, on the basis of rainfall and PE projections for the 21st century from the HadCM3 model, might well be underestimated in regard to most of other GCMs outputs.

This study is to be updated with 2007 IPCC run and multi-model approach. A first look at the rainfall projections over Africa from IPCC 2007 results show that rainfall in West Africa, including Sahel, are not awaited to change much from the actual situation, even until the end of the 2090s. Locally a slight increase is projected over Central Africa, while a decrease is still projected over Senegal/Mauritania.

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