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Continuous wavelet analysis of rainfall fluctuations at interannual and decennial scales on the south-eastern part in the Democratic Republic of the Congo between 1940 and 1997

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ABSTRACT: Wavelet analysis was applied to the standardized rainfall time series in the south-eastern in the Democratic Republic of the Congo in order to determine periods of rainfall fluctuations in this region at interannual and decennial timescales and to assess the influence of regional or remote climate phenomena on the rainfall of that sector between 1940 and 1997. The local, the global and the scale-averaged wavelet power spectrum of the rainfall time series of that sector indicate an important fluctuation between practically 1960 and 1970. Wavelet coherence spectral analysis shows that the southern oscillation El Nino phenomenon, the Western Hemisphere Warm Pool, the Atlantic Ocean climate variability and the Indian Ocean dipole have a very weak influence on rainfall on this territory. Scale-averaged wavelet coherence in 2-16 years band is lower than 0.5 whatever the climate index considered. Other factors must also be considered in the study of rainfall variability in this study area.

KEYWORDS: climate index, wavelet analysis, coherence.

1 INTRODUCTION

Rainfall fluctuations are understudied in the Democratic Republic of the Congo (DRC) not only because of the lack weather data but also because probably of the water abundance in this area. The results of some climate variability studies carried out in western equatorial Africa and in the western part of the Congo basin are sometimes extended to the Democratic Republic of the Congo. However the DRC has his own rainfall characteristics and therefore can be studied independently of the other central African regions. Seasonal rainfall variability in Central Africa has been studied by some researchers. However a little is known about rainfall fluctuations at interannual and decennial timescales in the study area. A good knowledge of DRC climates and their variations over a long time period would help policymakers to take appropriate decisions on climate vulnerability. The understanding of climates in the region would also help the international community to apprehend the stakes of climate change in this intertropical space. The rainfall fluctuations are perceptible on certain areas in the Congo basin from which the DRC occupies the greatest part [1]. What are periods and timescales of these fluctuations in this region? Much more rainfall fluctuations influence also the population daily life and require to be studied in order to better understand the climate variability on this space.

Rainfall variability in Central Africa was subject of some rare investigations [1], [2], [3], [4]; the results of these investigations can be extended to certain zones in the study area. Certain studies carried out in Central Africa are more leaning on the seasonal rainfall variability [2], [3], other studies relative to the interannual rainfall variability in central Africa highlighted the rainfall seasonal dependence of remote connections [5], [6].

Balas et al. [3] showed that the interannual rainfall variability in the Congo basin is very complex and is due to several factors among which sea surface temperature anomalies of the Atlantic, Indian and Pacific Ocean, the El Nino southern oscillation and contrast between the Atlantic Ocean and the Indian Ocean. These factors vary seasonally and their influence on rainfall is seasonal. Farnsworth et al. [7] were interested by the broad scale factors of the rainfall variability in Central Africa and showed that central Africa is a very complex area with various factors influencing rainfall in each area seasonally.

In this article, we study the rainfall fluctuations on the south-eastern part of DRC on an interannual and decennial scale by continuous wavelet analysis. We first describe briefly in section 2.1 the study area in a context where the climate, the relief and the vegetation interact together. Data and wavelet analysis are briefly presented in section 2.2. Then we present in section 3 the results and their discussion and finally in section 4, a conclusion closes this study.

2 STUDY AREA AND METHODS

2.1 STUDY AREA

The interest area in this work corresponds to the south-eastern region in DRC. It is located coarsely between 5° and 14° of Southern latitude, and between 25° and 30° of eastern longitude.

Its climate is of $Aw4$ type in the classification of Köppen-Geiger in his northern part with an average temperature of 24°C and a rainfall of approximately 1600 mm [8]. This $Aw4$ zone is an area of wooded savanna with opened forests or an area of grassy savanna with dry forests [1], [9].

In that area, the climate is of Cw type with a temperature bordering 21°C; average altitude varies between 1130 m and 1300 m [8]. The average rainfall varies between 1000 mm and 1500 mm distributed over 125 days approximately [8]. Savannas of highlands or dry forests of the highlands cover this Cw zone [1]. The geographical coordinates of the weather stations of the sector are consigned in table 1 and represented in figure 1. The seasonal rainfall variation is represented on figure 1.

Table 1. Geographical station coordinates of the south-east DRC

Stations	Latitude	Longitude
Kalemie	5.883°S	29.183°E
Kamina	8.633°S	25.25°E
Kolwezi	10.717°S	25.45°E
Kongolo	5.35°S	27°E
Lubumbashi-Luano	11.667°S	27.483°E
Manono	7.283°S	27.433°E
Mitwaba-Shaba	8.65°S	27.333°E

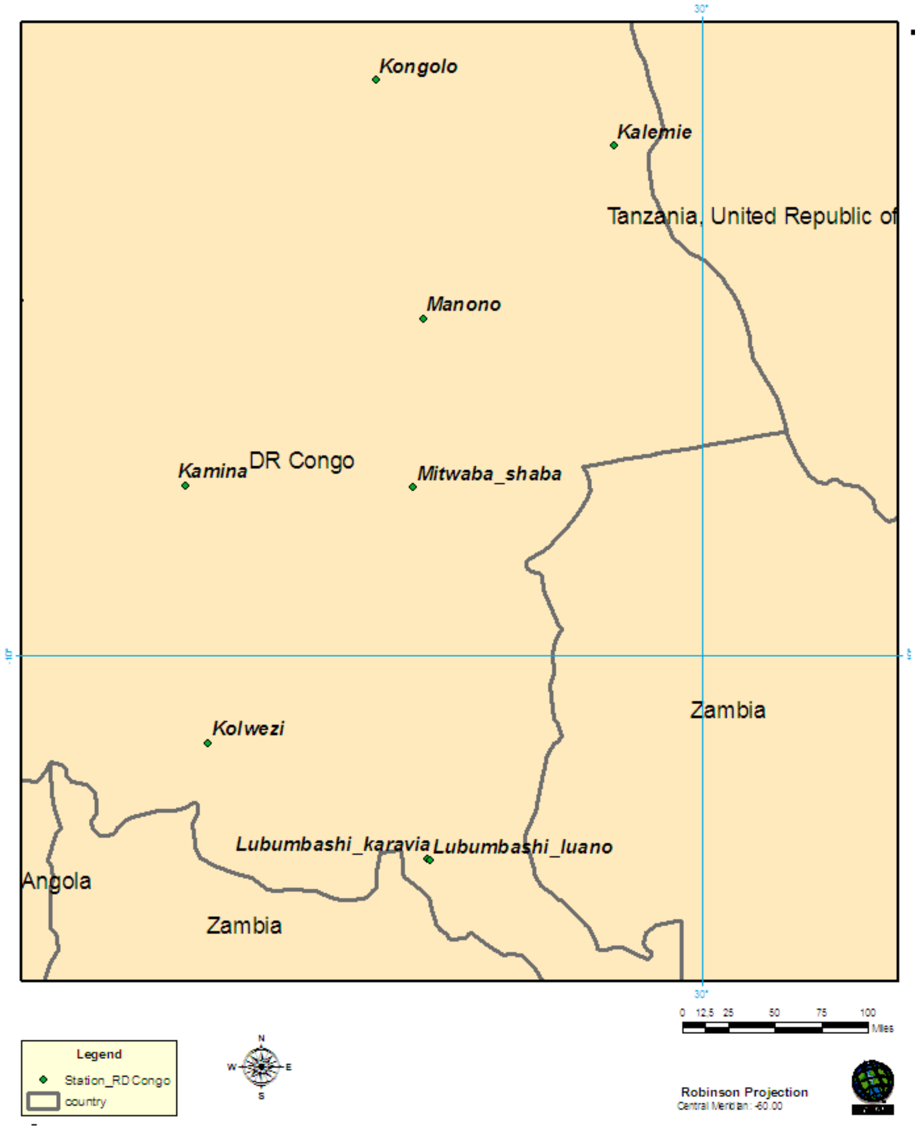


Fig. 1. Weather stations of study area

2.2 DATA

2.2.1 RAINFALL DATA AND CLIMATE INDICES

In this article we used rainfall data fields extracted from the gridded database of “Climatic Research Unit” (CRU), CRU TS 3.10, with a resolution of 0.5°×0.5°; they constitute a monthly data set retracing the rainfall temporal evolution on the globe except the polar zones over the period 1901-2009. The database is built, according to interpolation and homogenization methods, from more than 4000 weather stations distributed on all the ground where the missing data are estimated from the base period 1961-1990 [10].

The possible links between the rainfall fluctuations in our study zone and the regional or remote climate phenomena will be found by analyzing jointly some climate indices relating to the oscillations of the sea surface temperatures or sea level pressure of the Atlantic, Indian and Pacific oceans with the standardized rainfall time series on the south-eastern zone in the study area. Selected climate indices for our investigation are downloaded, except for the dipole of the Indian Ocean, from the site http: //www.esrl.noaa.gov/psd/data/climateindices/list/. These different indices are:

- the index of the Atlantic Multidecadal Oscillation (AMO) [11],
- the indexes of the Tropical Atlantic variability (Tropical North Atlantic (TNA)[12], Tropical South Atlantic (TSA)[12], Atlantic Meridional Mode (AMM) [12])

- the index of the North Atlantic Oscillation (NAO) [13], [14]
- the index of the dipole of the Indian Ocean or the Dipole Mode Index (DMI) [15], who is downloaded from the site:http://www.jamstec.go.jp/frcgc/research/d1/iod/DATA/dmi.monthly.txt
- some ENSO indexes (Southern Oscillation index (SOI) [16] , Nino 3.4 index [16], Trans Nino index (TNI)[17])
- the index of the Western Hemisphere Warm Pool (WHWP) [18],
- the St. Helena Island Climate Index (HIX) [19] that can be downloaded from the site http://www.io-warnemuende.de/en_hix-st-helena-island-climate-index.html

Hierarchical clustering on principal component analysis is applied to rainfall data of weather stations extracted from the CRU data base. The weather stations are thus sorted out in different groups and each group constitutes a study zone. The average series for each group is calculated and then standardized. The rainfall time series used in the wavelet analyses is a standardized time series.

The rainfall seasonal variation on the study zone is represented on figure 2. The standardized rainfall time series of this sector is represented on figure 3 and will be used as the rainfall time series.

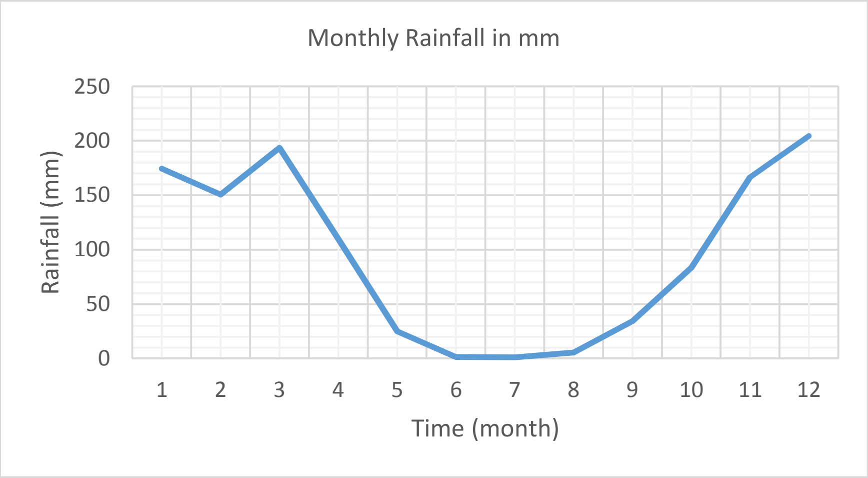


Fig. 2. Monthly rainfall in mm on the south-east in the study area

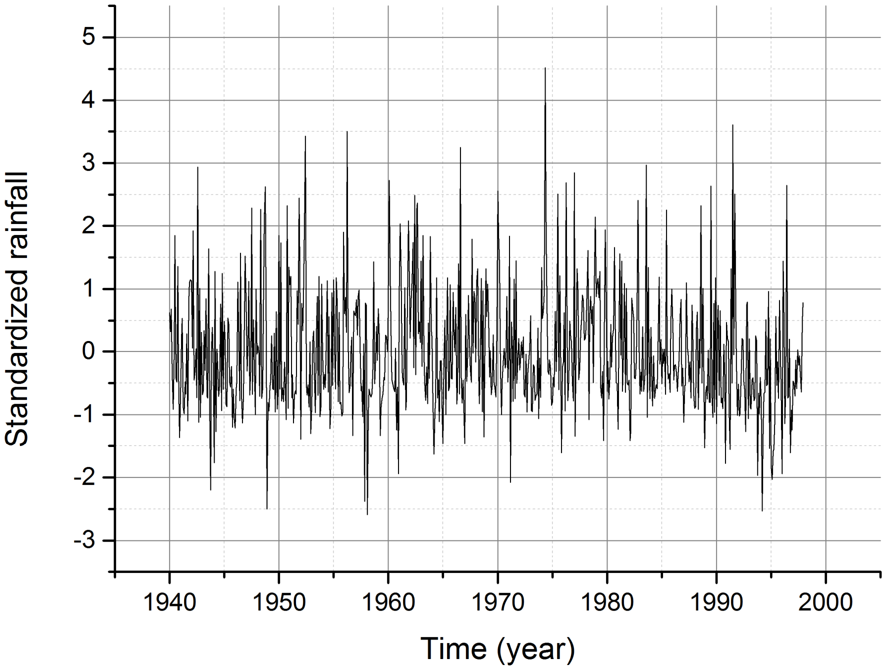


Fig. 3. Standardized rainfall of the study area

2.2.2 WAVELET ANALYSIS

Most climate time series are non-stationary and contain some intermittent localized oscillations. Wavelet analysis is an appropriate tool for analyzing such series. Wavelet analysis is used in this case for decomposing a time series in time and frequency components and may thus allow the extraction of the dominant modes of variability and transient aspects [20]. The frequencies present in a signal, peaks and fluctuations or energy bands covering certain time scales can be observed on the local wavelet power spectrum of a time series. The potential links between a climate signal and a regional or remote climate phenomenon can be established by using wavelet coherence analysis.

Instead of the functions sine and cosine used in the Fourier transform, the continuous wavelet analysis uses a wavelet function $\psi(t)$ of finite energy and zero mean.

The most used wavelet function in continuous wavelet analysis, Morlet wavelet, will be used in this article. It is defined as a plane wave damped by a Gaussian envelope of equation [20], [21].

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0 \eta} e^{-\eta^2/2}$$

where ω_0 is an adimensional frequency often taken equal to 6 in several analyses and $\eta = st$, s the wavelet scale used [22].

The continuous wavelet transform is applied like a pass band filter over the time series. The wavelet is stretched in time by varying its scale s and by normalizing it to have unit energy.

The continuous wavelet transform of a discrete time series $(X_n, n = 1,2,\dots,N)$ with a uniform temporal step δt is defined as the convolution of X_n with the scaled and translated version of $\psi_0(\eta)$. It is given by the relation [21], [22]:

$$W_n^X(s) = \sqrt{\frac{\delta t}{s}} \sum_{n'=1}^{N} X_{n'}\, \psi_0 \left[(n' - n) \frac{\delta t}{s} \right]$$

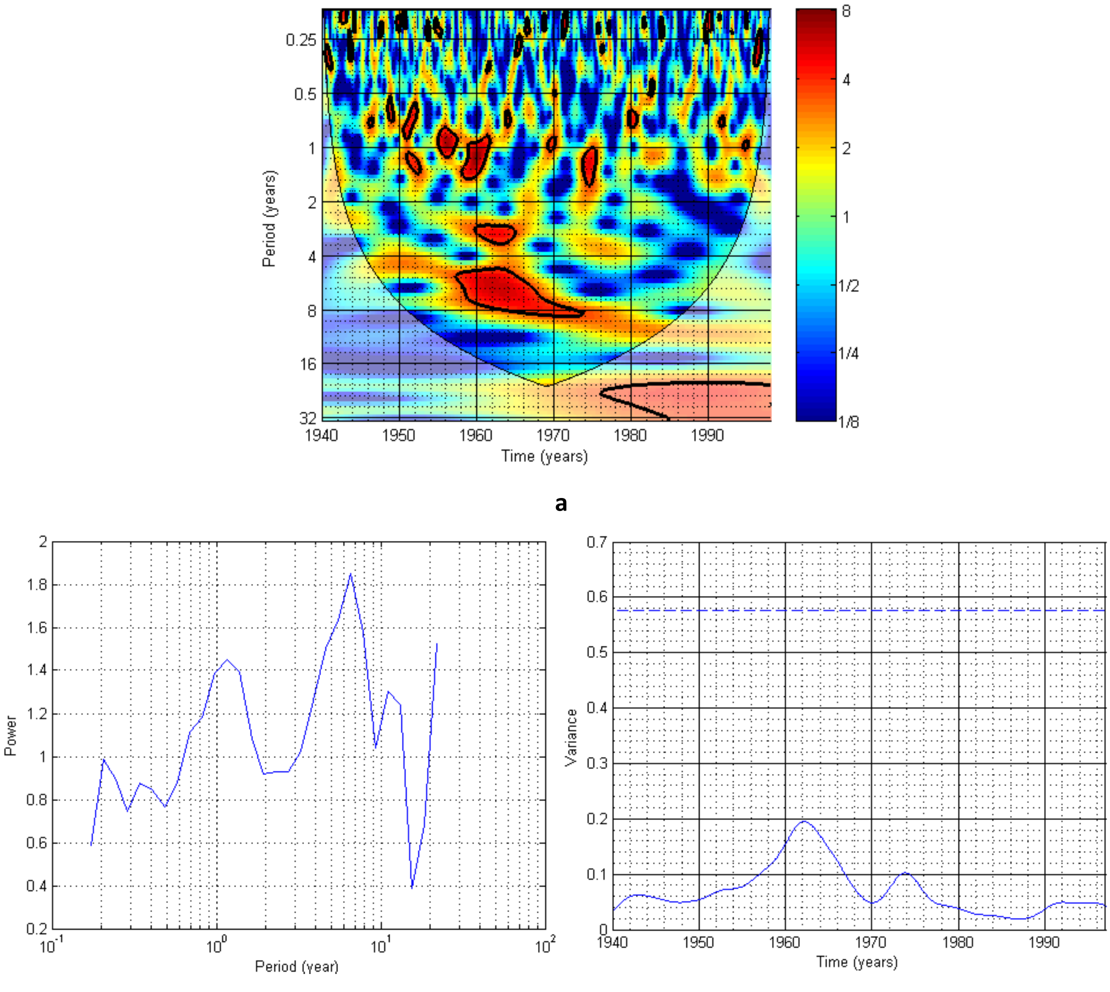
Wavelet analysis will be applied first to the standardized rainfall time series in the south- eastern region in DRC in the context of analyzing the wavelet power spectrum of a time series and secondly to the coherence between our standardized rainfall time series and a climate index representing the variability of a particular ocean in tropical region. Different concepts relative to wavelet power spectrum of a time series and wavelet coherence between two time series are defined in a submitted previous article entitled “Temperature fluctuations at interannual and decennial timescales on the eastern mountainous region in Democratic Republic of the Congo from period of 1940 to 1997”.

In order to differentiate false results from true positive results in wavelet analysis of climate data, one can use a statistical significance test based on a theoretical red noise [20] modeled by a first order autoregressive process. The most used significance tests in geophysical data wavelet analysis are Torrence and Compo test [21] extended to wavelet coherence by Grinsted et al. [22] by using the Monte Carlo methods and called “pointwise test” and Maraun et al. test [23] called “areawise test”. Results are accepted in this article with confidence levels superior or equal to 95%.

3 RESULTS AND DISCUSSIONS

3.1 RAINFALL FLUCTUATIONS IN THE SOUTH-EASTERN PART IN THE STUDY AREA

Rainfall fluctuations in the region present a band of strong power in the band of the periods ranging between 4 and 8 years, centered over 6.6 years as indicated by the local wavelet power spectrum and the global wavelet power spectrum (figure 4a, b)). The peaks of the rainfall fluctuations are observed at the following years: 1945, 1953, 1962, 1974, 1980, 1992 and 1996. Balas et al. [3], Nicholson S.E. and Dzefuli A. [5], Dzefuli A. and Nicholson S.E. [6], Farnworth et al. [7] studied the link between rainfall in central Africa and the oceanic and atmospheric climate phenomena during the rainy seasons and highlighted the wet years and the dry years which characterized the rainy seasons on this area. It is difficult to compare their results to ours since the studies undertaken on this geographical space refer to non-identical zones by their cutting and the timescales investigated are different.



a

b **c**

Fig. 4. Wavelet power spectrum of rainfall time series of the south-eastern region in the study area: a) Local wavelet power spectrum, b) Global wavelet power spectrum and c) Scale- averaged wavelet power spectrum

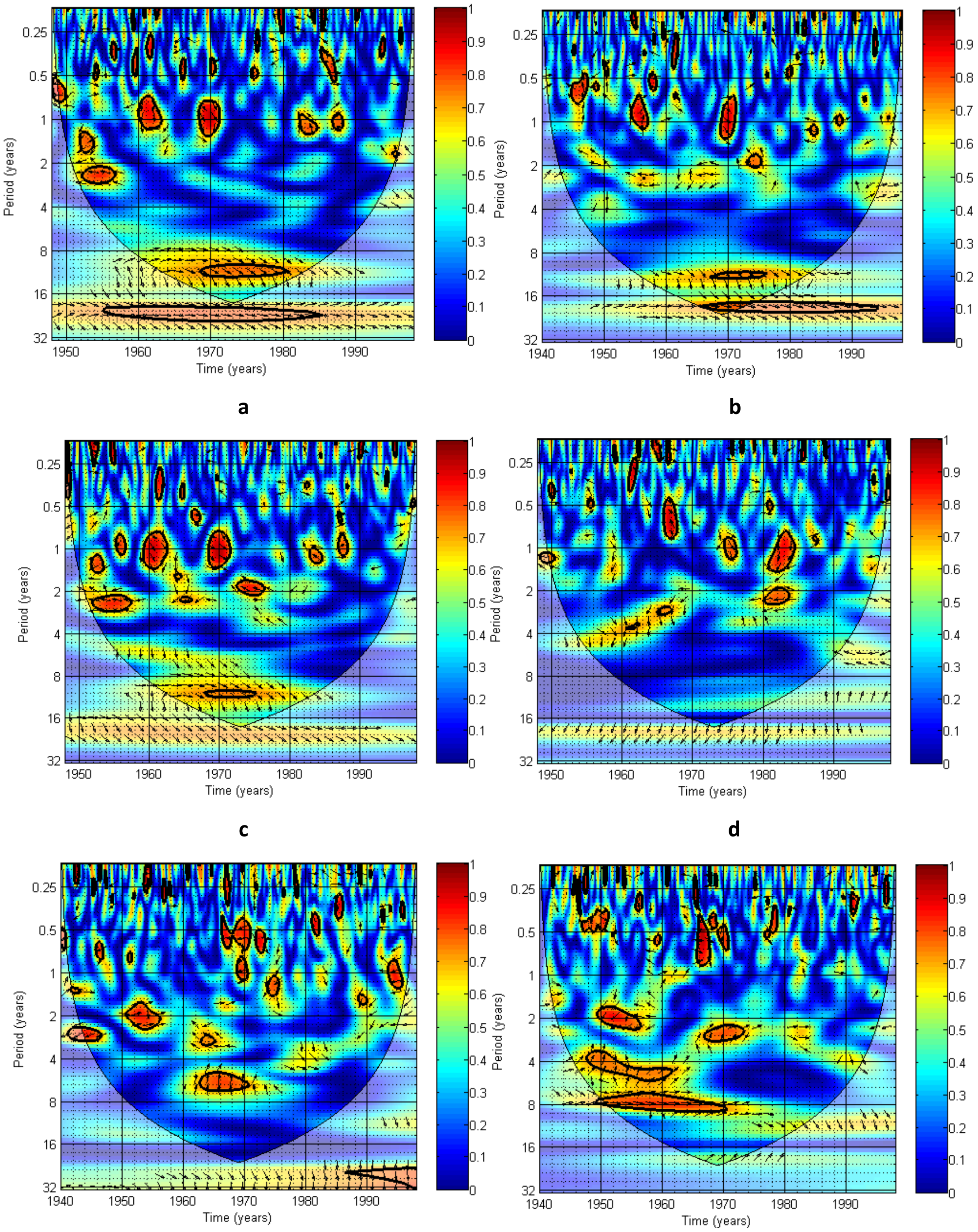
Whatever this region is characterized by low rainfall fluctuations, some variance peaks are observed (figure 4 c) and some maxima observed coincide with the El-Niño years (1957-58, 1965-66, 1972-73, 1982-83, 1986-87,1991-1992, 1997-1998) [16].

3.2 ATLANTIC OCEAN INFLUENCE ON RAINFALL

The anomalies of the sea surface temperatures of the Atlantic Ocean influence very slightly the rainfall on an interannual scale in the study area. The AMM, the AMO, the TNA and the TSA seem to covary slightly with rainfall on an interannual scale (figures 5 and 6). In 8-16 years band and beyond the cone of influence, coherence arises (figure 5 a, b, c and d). The AMO, the AMM and the TNA covary in the scale of 2-16 years in an almost similar way with rainfall in the study area. The coherence weighted in scale in this band reaches 0.48 (figure 7). The TSA and the rainfall seem to covary very slightly as well on an interannual scale as on a decennial scale. Average coherence is worth 0.23 roughly. The studied region is located far from Atlantic Ocean and the Atlantic Ocean influence diminishes towards the east [7].

The Southern Subtropical Atlantic Ocean has a strong influence on rainfall in the study area: in the 2-8 years band, some coherence bands are observed between the HIX and the rainfall. In the period between 1950 and 1980, rainfall and the HIX covaried in phase in the 4-8 years band (figure 5 f). As the southern subtropical Atlantic is governed by high atmospheric pressure and the DRC territory is located in the intertropical convergence zone which is a low pressure zone [19], the interaction between Southern subtropical Atlantic and rainfall in the south-eastern part in DRC is obvious.

The Northern Subtropical Atlantic Ocean has a weak influence on rainfall in the study area: in the 4-8 years band, two coherence bands are observed in the period 1960 – 1970 and around 1980 between the NAO and the rainfall (figures 5 e and 7). The influence of the NAO on rainfall seems to be weak as well on an interannual scale as on a decennial scale. Coherence is weak; it is equal to 0.32 in the band of 2-8 years and to 0.23 in the band of 8-16 years. The link between the NAO and the rainfall seems to be not obvious although the findings of Todd M.C. and Washington R. [23].



a

b

c

d

e

f

Fig. 5. Local wavelet coherence spectrum between the standardized rainfall time series over the south-eastern region of DRC and a) AMM, b) AMO, c) TNA, d) TSA, e) NAO and f) HIX.

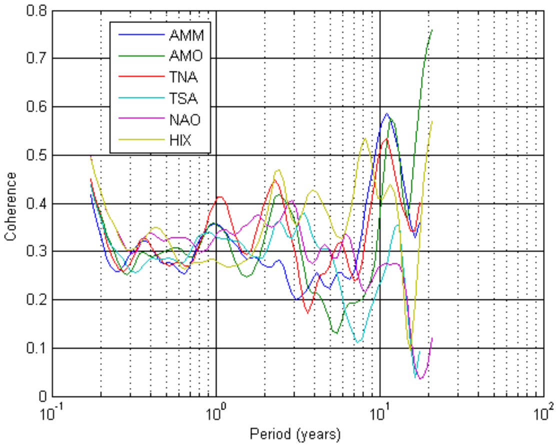


Fig. 6. Global wavelet coherence spectrum between the standardized rainfall time series over the south-eastern region of DRC and the AMM, AMO, TNA, TSA, NAO and HIX indices.

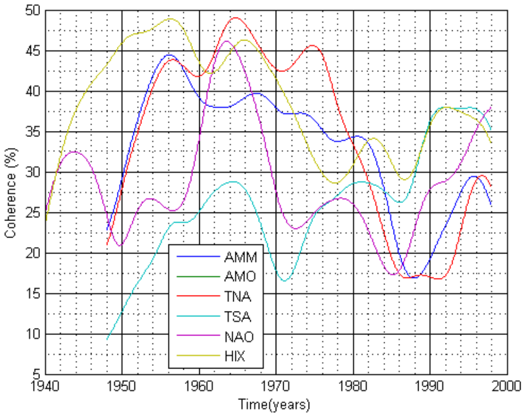
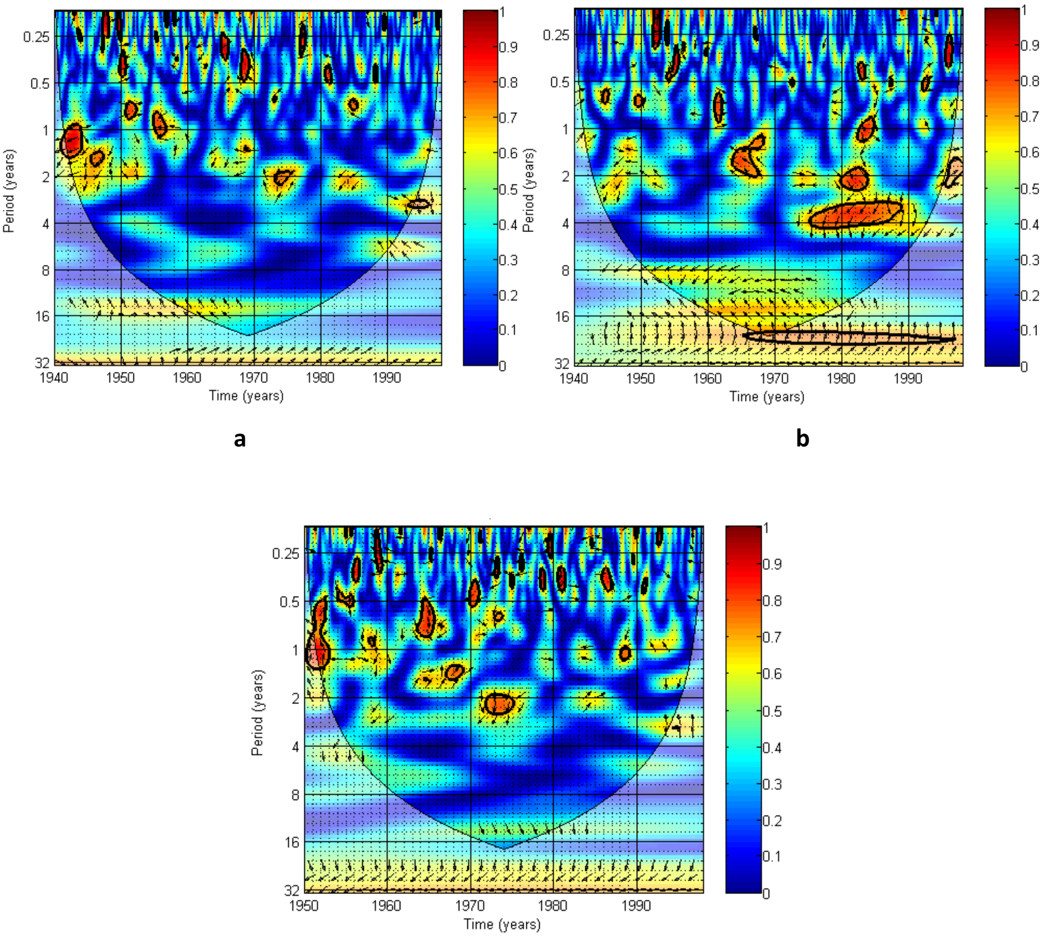


Fig. 7. Scale-averaged wavelet coherence between two series and averaged wavelet power spectrum of rainfall and Atlantic climate indices. The scale-averaged wavelet coherence spectrum is expressed in percentage as it gives us a timescale band contribution (here in 2-16 year band) to coherence.

The scale-averaged wavelet coherence between rainfall time series of this sector and each indice of Atlantic Ocean, except the NAO, reveals that some coherence peaks are observed in years of warm events in Tropical Atlantic Ocean [25]. In general, observed coherence between rainfall in the south-eastern region in DRC is inferior to 0.5.

3.3 ENSO INFLUENCE ON RAINFALL

The ENSO phenomenon and the rainfall covary very slightly as the figures 8 and 9 attest it; the peaks of covariation meet at the El-Nino years [16], [17] as illustrated in the figure 10. The different indices of the ENSO phenomenon used in this article and the rainfall in this sector have coherence less than 0.5. Although this coherence is low, its evolution with the El-Niño years suggests that the ENSO phenomenon interacts with rainfall in this region but other factors influencing climate must be considered.



a

b

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Fig. 8. Local wavelet coherence spectrum between the standardized rainfall time series over the south-eastern region of DRC and a) SOI, b) TNI and c) NINO 3.4

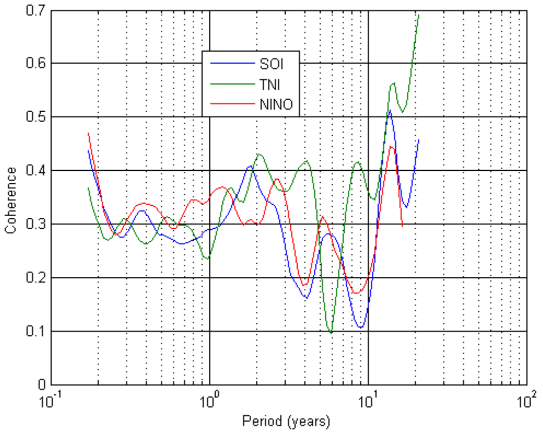


Fig. 9. Global wavelet coherence spectrum between the standardized rainfall time series over the south-eastern region of DRC and the SOI, the TNI and the NINO 3.4 indice.

Scaled-averaged wavelet coherence between rainfall and ENSO indice used shows some La-Nina or El-Niño years as years of minimum or maximum coherence (figure 10).

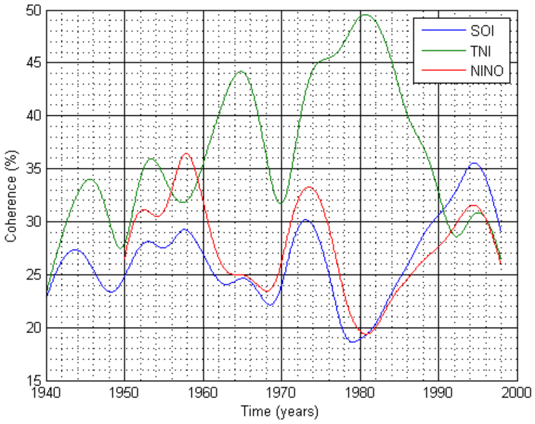
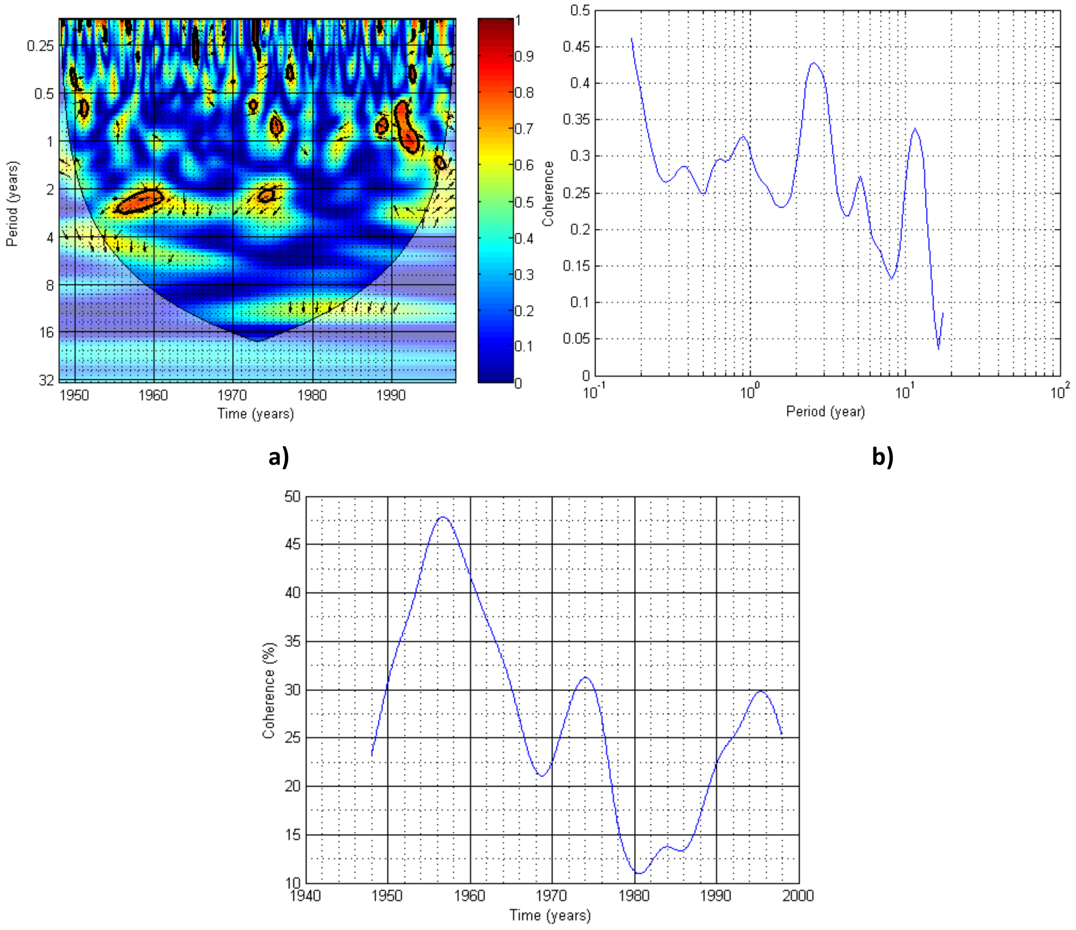


Fig. 10. Scale-averaged wavelet coherence between rainfall and ENSO indices (the SOI, the TNI and the NINO 3.4 indice). The scale-averaged wavelet coherence spectrum is expressed in percentage as it gives us a timescale band contribution (here in 2-16 year band) to coherence.

3.4 WHWP INFLUENCE ON RAINFALL

The WHWP and the rainfall covary slightly in the band of 2-8 years and 8-16 years as attested by the figure 13a. Average coherence in the 2-8 years band is equal to 0.28. Some coherence peaks are visible in the global coherence spectrum between rainfall in this study area and the WHWP (figure 11b). The covariance maxima are present in the years 1957, 1974, 1984 and 1996 which coincide with some warm event years occurred in the tropical Atlantic ocean as shown on figure 11c [25]. Some coherence maxima are present sometimes one year after an El-Niño event. The WHWP and the rainfall seem to vary together in phase opposition in 2-4 years band during the period interval 1960-1992 (figure 11c).



a)

b)

c)

Fig. 11. Wavelet coherence between rainfall and WHWP indice: a) Local wavelet coherence spectrum, b) Global wavelet coherence spectrum, c) Scale-averaged wavelet coherence. The scale-averaged wavelet coherence spectrum is expressed in percentage as it gives us a timescale band contribution (here in 2-8 year band) to coherence.

3.5 INDIAN OCEAN INFLUENCE ON RAINFALL

The Indian Ocean seems to influence the rainfall on an interannual scale in 2-4 years and 4-8 years bands as figure 12 attests it. Between 1955 and 1968, the rains and the DMI strongly covaried in the band of 4-8 years; local coherence being equal to 0.8 (figure 12). The years of high covariance coincide almost with the years of extreme events of the Indian Ocean dipole (1961, 1967, 1972, 1982, 1994 and 1997)(figure 13) [15]. In 2-8 years band, rainfall and DMI vary together almost in the same way from 1954 to 1968 (figure 12).

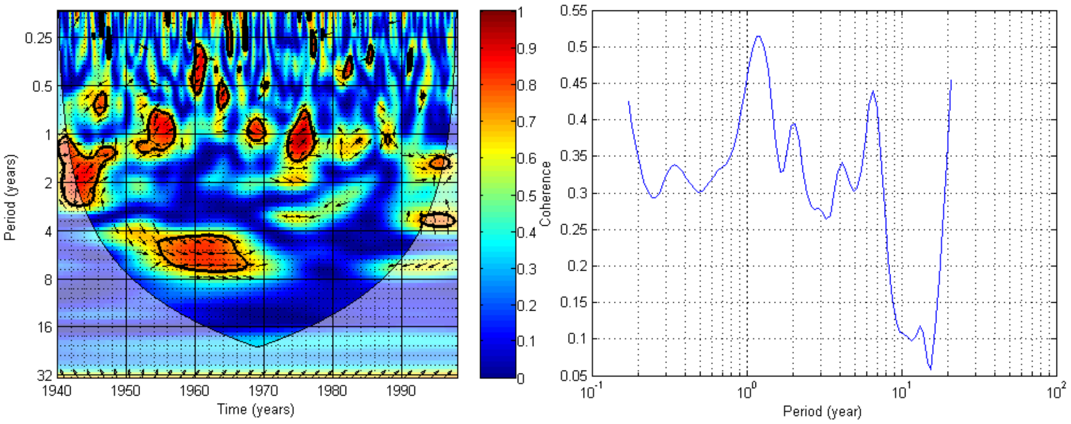


Fig. 12. Local(left) and global(right) wavelet coherence spectrum between the standardized rainfall time series over the south-eastern region of DRC and DMI

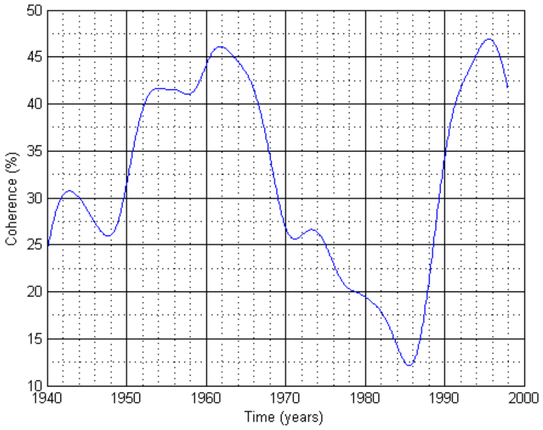


Fig. 13. Scale-averaged wavelet coherence between rainfall and DMI. The scale-averaged wavelet coherence spectrum is expressed in percentage as it gives us a timescale band contribution (here in 2-8 year band) to coherence.

All periods of coherence between rainfall and different regional or remote climate phenomena identified by different indices are given in table 2. Two periods in this table reflect the link of the ENSO phenomenon to rainfall in this sector in DRC (2 and 4 year period); other periods can be linked to the solar activity.

Table 2. Coherence peaks between rainfall and different indices used

BANDS	PEAKS OF COHERENCE										
	SOI	TNI	Nino 3.4	HIX	AMM	AMO	DMI	NAO	TNA	TSA	WHWP
2-8 years		2.3	2.8	2.3-2.5		2.6	2.0	3.1	2.3	2.5	2.6
	5.5	4.1		3.9			4.1		4.1	3.5	
			5.2				6.6	5.8			5.8
8-16 years		8.3		8.3-8.7	11.0	11.7		9.8	11.0		11.7
	14.7			12.4-13.1						13.1	

4 CONCLUSION

The rainfall fluctuations in the study area at interannual and decennial timescales are low. Some coherence peaks between sea surface temperatures and atmospheric phenomena over oceans and the rainfall coincide with some characteristic events of a particular Ocean: warm events in Tropical Atlantic, El-Niño years and Indian Ocean dipole years. The ENSO phenomenon is better reflected in scale-averaged wavelet coherence spectrum between rainfall and each ENSO indice used in this paper. The low coherence indicates that other factors must be considered in investigation of drivers of rainfall fluctuations at interannual and decennial timescales in this region.

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