Atmospheric and Climate Sciences, 2022, 12, 635-647
https://www.scirp.org/journal/acs
ISSN Online: 2160-0422
ISSN Print: 2160-0414

Climate Change and Dynamics of the ITCZ on the Hydro-Climatic Regime of the Northern Ecosystems of the Gulf of Guinea: A Case of the Grand-Lahou Lagoon System

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How to cite this paper: Kone, K.J.-M., Kone, V., Yao, K.A. and Anoh, K.P. (2022) Climate Change and Dynamics of the ITCZ on the Hydro-Climatic Regime of the Northern Ecosystems of the Gulf of Guinea: A Case of the Grand-Lahou Lagoon System. *Atmospheric and Climate Sciences*, **12**, 635-647.
https://doi.org/10.4236/acs.2022.124036

Received: October 14, 2021
Accepted: September 10, 2022
Published: September 13, 2022

Abstract

Atmospheric dynamics and climatology in West Africa are strongly dominated by the latitudinal migration of the ITCZ which imposes directly or indirectly determinism on coastal ecosystems. Thus, the Grand-Lahou lagoon system and its watershed are influenced by the ITCZ, whose seasonal study made it possible to understand its mode of action first on climatic factors, then hydroclimatic, and finally hydrological in the context of global changes. The study of these factors showed a differentiated impact of its migration on the hydrological regime defining a new configuration of the lagoon system and beyond; the coastal ecosystems of the northern coast of the Gulf of Guinea irrigated by numerous fluvial inputs. Salinity, a hydrological parameter of critical ecosystem importance, combined with transparency and depth, has enabled the spatio-temporal description of hydrology. To do this, a series of monthly measurements (*in-situ*) for spatial coverage of 25 stations was tested. Long before that, the climatic and hydroclimatic parameters were obtained respectively at SODEXAM, the meteorological site earth.nullschool.net and ONADE. This study brought together the dynamics of the ITCZ and the hydrological system of the lagoon.

Keywords

Climate Change, Dynamics of the ITCZ, Hydro-Climatic Regime, Grand-Lahou Lagoon System, Coastal Ecosystems

1. Introduction

Resulting from the convection of the high pressures of the Saint Helena High

Pressure (south Atlantic monsoon) and the harmattan (north-east trade winds), the ITCZ is the fundamental key to climate variability in the intertropical belt and particularly in West Africa [1] [2]. According to [1] [2] [3], it is responsible for rainfall in Ivory Coast with two seasons in the coastal zone including a large (54% of annual precipitations) during its rise between May and July (GRS) and a small (16% of annual precipitation) during its return between October and November/December (SRS). It is characterized in the northernmost part of the country by a single season between May and November [4]. According to [5], the climatology of the Gulf of Guinea and the West African coast is now influenced by global warming. In the same vein, [6] cited by [7], show that the interannual variability of precipitation (1500 to 2000 mm/year) between 1948-1997 in the coastline shows a decreasing trend associated with a temporal shift in the maximum rainfall. Indeed, since the 1970s, there has been a decrease in GRS rainfall compared to an increase in SRS. Confirming the above, [8] shows that the rise in nearshore temperature would be notable with the thermal increase in the tropical ocean at 0.5˚C while [9], relates the changing seasons to rising temperatures. In Grand-Lahou, the years 2009, 2011, 2014, and 2016 recorded exceptional rainfall events in the watershed, causing river floods [10]. Annual maximums are observed in June (29.13 $m^3 \cdot s^{-1}$) and October (15.93 $m^3 \cdot s^{-1}$), respectively. The hydrological regime functions as a system characterized upstream by continental inputs and downstream by ocean inputs. In addition, the ocean is manifested in lagoons by the bi-daily tidal regime (of about 12 h 25 mn) with diurnal inequality with a range less than 1.5 m [11]. The tide, therefore, imposes a semi-diurnal rhythm on a number of parameters such as the direction and speed of currents, temperature, and salinity [11] [12]. In addition to these semi-diurnal variations, there are semi-synodic variations defined by the alternation of live and still-water [11]. The watershed of the lagoon system, with an area of 103,000 km^2, including 97,500 km^2 for Bandama located in the ITCZ swing zone, is characterized by three different climatic regimes [13]. A two-season tropical transition regime, an attenuated equatorial transition regime in the central part and an equatorial transition regime in the southern (coastal) zone with four seasons [11]. According to [12] [13] [14], Bandama accounts for about 60% of the total annual volume during the flood period (September-October) with an average flow of 1645 $m^3 \cdot s^{-1}$ for a contribution of 54.90% of inputs compared to 25 $m^3 \cdot s^{-1}$ in January and 45,10% of intakes during the stretch period. The Boubo, with an area of 5100 km^2; the Gô and the Krokoma River represent the forest component of the watershed [11] [12]. With an annual contribution of 6%, the Boubo regime is characterized by the duplication of the annual flood corresponding to the seasonal distribution of precipitation on the coast. The GRS contributes about 47.56% of the year-to-date for an average flow of 21.21 $m^3 \cdot s^{-1}$, therefore the highest. The smaller SRS (between September and November) recorded around 16 $m^3 \cdot s^{-1}$ with a total of 35.73% elapsed [12]. The Grand Lahou Lagoon (**Figure 1**), located between latitudes 5˚05' - 5˚15' and longitudes 4˚55' - 5˚25', with a length

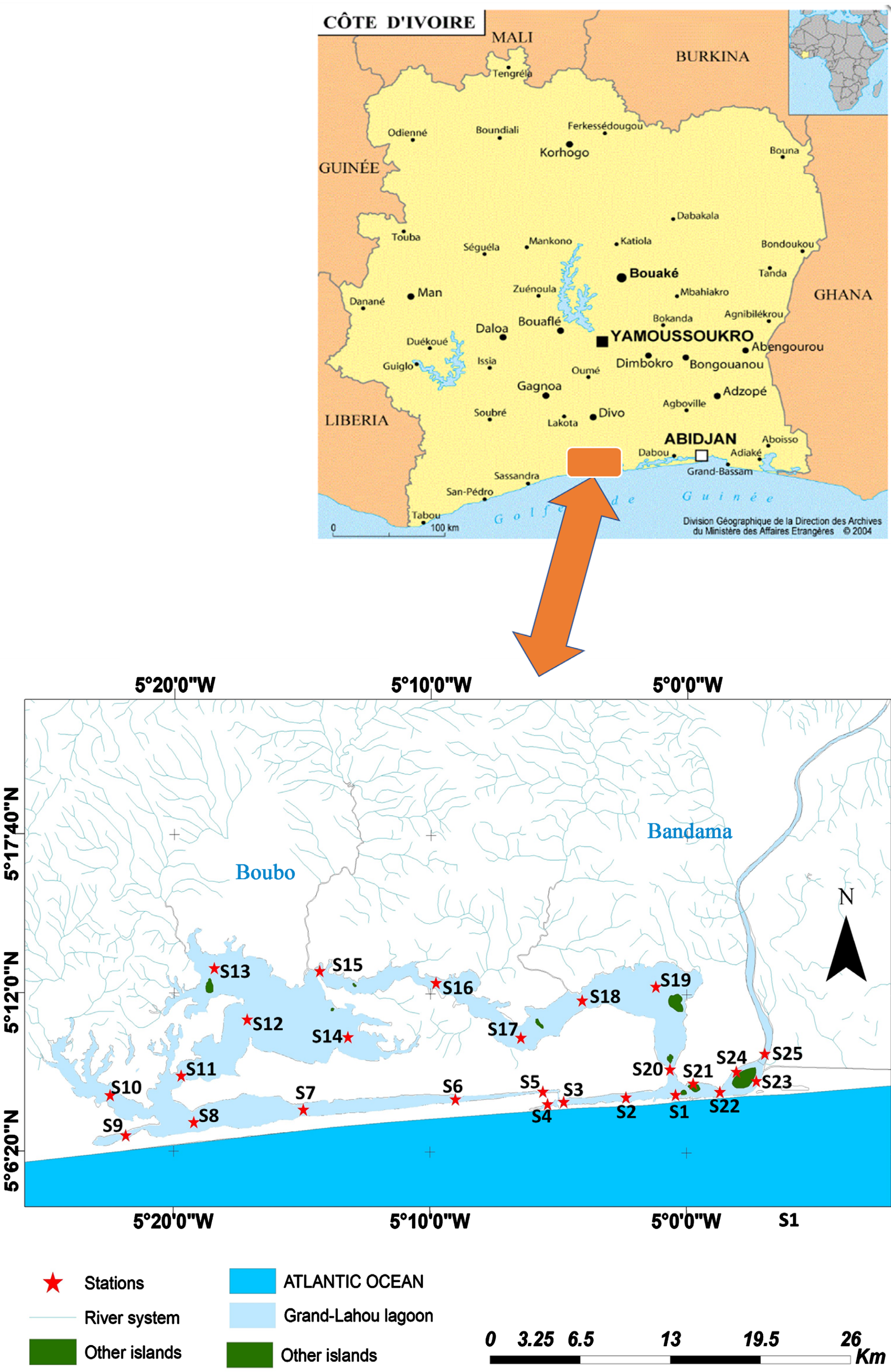


Figure 1. Presentation of the Grand-Lahou lagoon system.

of 50 km and an area of 190 km^2 [15], has benefited from numerous studies [16]-[23]. However, the dynamics of the ITCZ, fundamental in the climate of the watershed and its impact on the hydrological regime of the lagoon system, are still unknown, especially in the current context of global warming. Under these conditions of global environmental change, this study aims to establish a relationship between the migratory dynamics of the ITCZ on the hydrological regime of the lagoon system. The aim is to analyse its influence on the hydroclimatic variability of the watershed; to study the evolution of salinity in coastal zones and the tidal coefficient in opposition to that of lagoon salinity and associated parameters (transparency and depth).

2. Material and Methods

2.1. Experimentals Methods

SODEXAM (Société d'Exploitation et de Developpement Aeroportuaire Aaeronautique et Météorologique) enabled us to obtain precipitation data for Grand Lahou and Korhogo, while https://earth.nullschool.net/ provided climate parameters such as air temperature (At), relative humidity (Rh), atmospheric pressure (Ap), the direction and speed of air (Ad, As) per day at 5˚07N and 5˚00W. The ITCZ latitudinal migration at https://earth.nullschool.net/ was made in reference to [24] at longitude 28˚W. In this study, the choice was for the 10˚W meridian at the weekly scale where its variability is almost zero.

The Bandama and Boubo rivers debits come from ONADE (Office Nationale de l'Assainissement et du Drainage). These data were recorded with hourly resolution throughout the study period at the hydrological stations of Tiassalé and Babocon respectively. Transparency and salinity were observed over the duration of the campaign by a 25-station spatial coverage using a Secchi disk and a Hach HQ-40 multiparameter calibrated monthly prior to measurements. Specifically, salinity was measured at the surface; 0.50 meter below the air-water interface and 0.20 meter above the water-sediment interface. The depth was measured using an echo sounder. The use of a Garmin GPSMAP-78S GPS enabled the georeferencing of the stations throughout the study period.

2.2. Statistical Methods

The excel software allowed the statistical processing of the collected data. The analysis of the salinity distribution was carried out with the ARC-GIS 10.3 mapping software in order to understand the hydrological system resulting from the direct and/or indirect impact of the ITCZ. The [25] Stratification Index given by the following relationship provides an understanding of the variability of the vertical gradient and the mode of circulation of oceanic and continental water masses on a seasonal scale and according to the rate of movement of the ITCZ.

$$SI = \Delta S/Sg = Sb - Ss/Sg$$

Sb: *bottom salinity*;
Ss: *surface salinity*;
Sg: *average salinity*.

3. Results and Discussion

3.1. Results

3.1.1. Climate Variability

Figure 2 illustrates the latitudinal evolution of the ITCZ in comparison with climatic parameters on the one hand and hydroclimatic parameters on the other. In Figure 2(a), we have a phase inversion between the evolution of the ITCZ and the variation of the thermal field (At) of the air, the lagoon environment and the coastal ocean. The high temperatures are observed in the southern position of the ITCZ respectively between 0˚ - 4˚ in the period February-May (28˚C - 29˚C for the air-ocean matrices and 31˚C - 32˚C for the lagoon) and 2-8˚ between October-January (26˚C - 28˚C air-ocean and 29˚C - 31˚C for the lagoon). The thermal decrease is remarkable between June-September during its northernmost extension. The lowest temperatures (24˚C - 27˚C) are recorded between 13˚N - 15˚N latitude with lows in July-August for air and ocean (~24˚C - 25˚C)

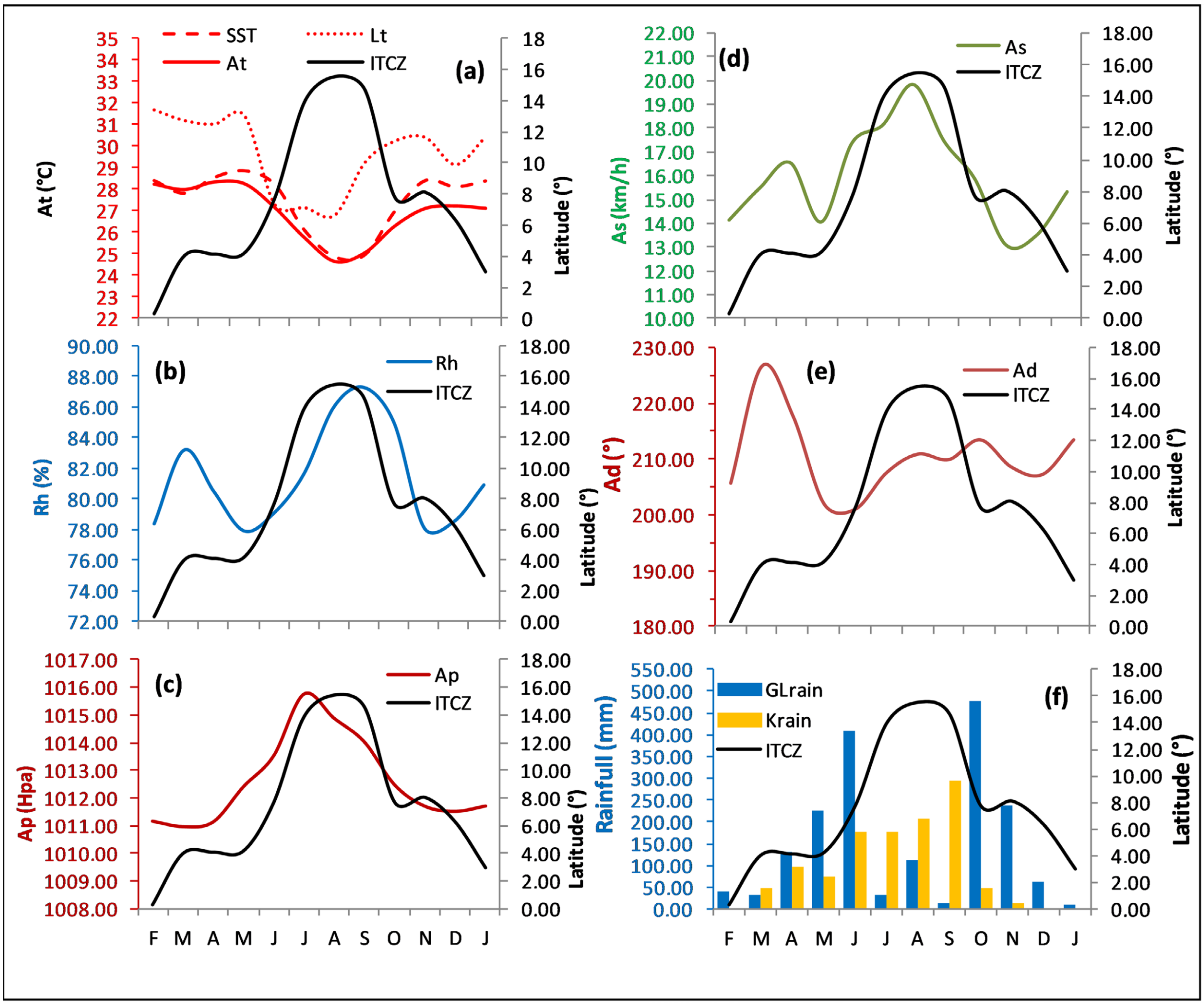


Figure 2. Comparative variability of climatic and hydroclimatic parameters at the annual scale. In (a), we have the variation between ITCZ and ocean, air and lagoon temperatures; with relative humidity in (b); atmospheric pressure in (c); air speed in (d); air direction in (e); precipitation in Grand-Lahou and Korhogo in (f).

and June-August for the lagoon (27˚C - 28˚C). Basically, the temperature in the lagoon is higher and more fluctuating compared to the other two matrices. If the thermal change is more or less sensitive in climate and oceanic environment and is rather abrupt in lagoon and promises a month in advance. This is the period that marks the point of balance between the rise of the ITCZ and the fall in temperatures. Relative humidity (Rh) and atmospheric pressure (Ap) are consistent with ITCZ (**Figure 2(b)** and **Figure 2(c)**). If the maximum ITCZ occurs between atmospheric pressure (June ~1016 Hpa) and relative humidity (September ~87%), it coincides with air speed around 20 $km \cdot h^{-1}$ (**Figure 2(d)**).

The change in air direction around Grand Lahou (**Figure 2(e)**) after the March maximum (210˚) coincident with relative humidity does not generally follow the ITCZ. It is below 210˚ after this period over the entire year. Rainfall in the lagoon system watershed follows the migration of ITCZ. Precipitation in Grand Lahou (YTD ~1787 mm) is consistent with the ITCZ's south-north and north-south migration in May-June (36% of annual precipitation) and October-November (40% of annual precipitation), respectively. In addition, the ITCZ records stationary phases coinciding with the high precipitation seasons of April-May and October-November. Between these two seasons is the intercrue (July-September) corresponding to the northern extension of the ITCZ. Precipitation at Korhogo (YTD ~1134 mm) symbolizing rainfall in the northern region (northern position of the ITCZ) is particularly high between June and September, which mark the annual peak (296.10 mm), preceding one month before the maximum rainfall at Grand-Lahou (October ~477.30 m).

3.1.2. Hydroclimatic and Hydrological Variability

Flows of Bandama and Boubo (**Figure 3(a)**) are correlated with precipitation patterns in the southern and northern positions of the ITCZ. Indeed, the change in the flow of the Boubo shows two peaks (June ~35.91 $m^3 \cdot s^{-1}$ and October ~43.19 $m^3 \cdot s^{-1}$) while that of the Bandama record a peak (September ~535.42 $m^3 \cdot s^{-1}$) thus reflect the bimodal precipitation regime at Grand-Lahou on the coast and unimodal in Korhogo.

These flows positively influence the depth of the lagoon system and negatively affect the transparency, which varies with the depth, particularly during periods of maximum flows and precipitation (**Figure 3(b)**).

The depth (Z) increases in June (~3.25 m) and October (~3.50 m). In these months the transparency is low with 0.80 m and 0.90 m. During the interval, the depth decreases (~3 m) in favor of the transparency (~1.30 m) which increases again. The tidal coefficient varies inversely with the ITCZ (**Figure 3(c)**), recording its minimum in August (~70), the period of maximum extension of the ITCZ; remaining in phase with thermal variations, and in phase with atmospheric pressure, relative humidity and air speed, and coastal precipitation. The salinity in the lagoon follows the same order of temporal variation with transparency with two minimums in June and October in relation to the migration of the ITCZ. However, the SSS does not record its annual minimum (33.8‰) in November. The implication of river inputs is so accentuated in lagoons that the mean haline variability is between 0‰ - 18‰ while it is between 33‰ - 35‰ in the coastal ocean.

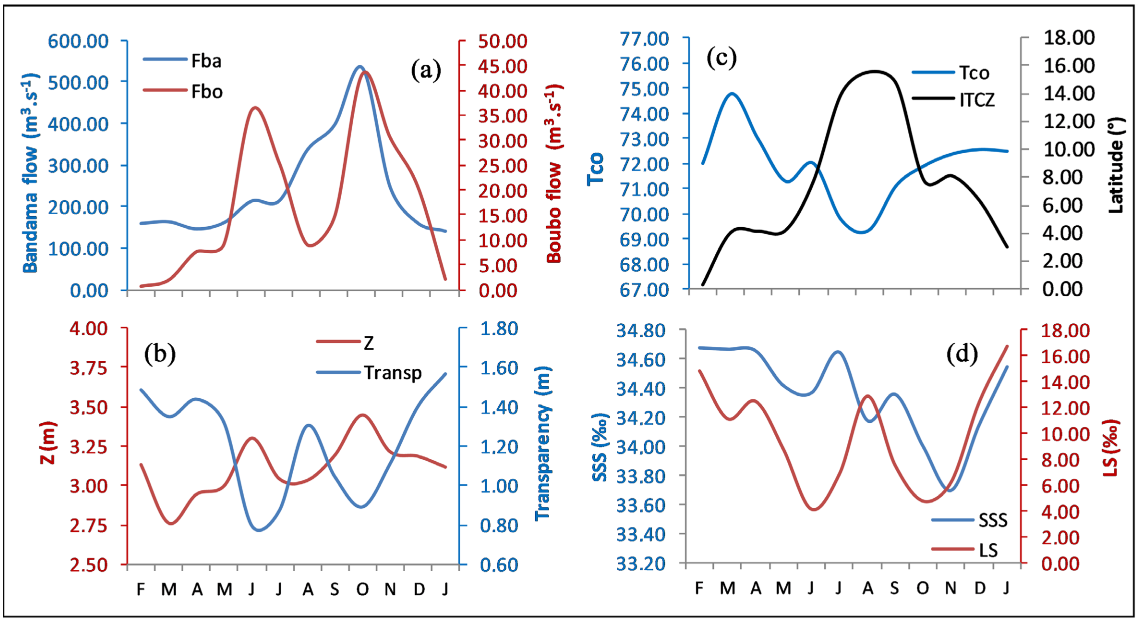
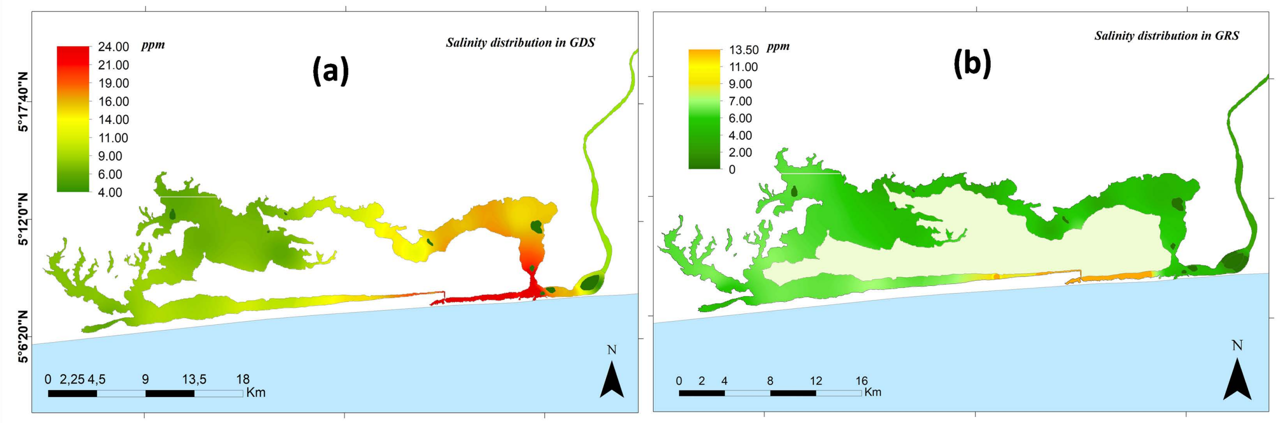


Figure 3. Comparative variation of Bandama and Boubo flows (a), depth (Z) and transparency (b), ITCZ and tidal coefficient (c), finally between salinities near the lagoon system and lagoon (d).

Figure 4 shows the spatial and seasonal distribution of salinity in the lagoon system. The Great Dry Season (GDS) between December and April (**Figure 4(a)**) and the July-August Intercrue (SDS) (**Figure 4(b)**) are associated with high salinity seasons, characterized by negative (decreasing) stratification between the Eastern Region (Lagoon-Ocean Trading Area) and Western Contained (GL12-GL15). During the freshet seasons (May-June and September-November) the lagoon environment records a sharp drop in salinity (**Figure 4(c)** and **Figure 4(d)**) respectively 6.48‰ and 6.20‰. The influence of continental inputs is therefore marked in the second freshet. Given the low bathymetry, there is a low positive gradient in the vertical profile outside the areas near the mouth, especially during floods (**Figure 4(e)**).



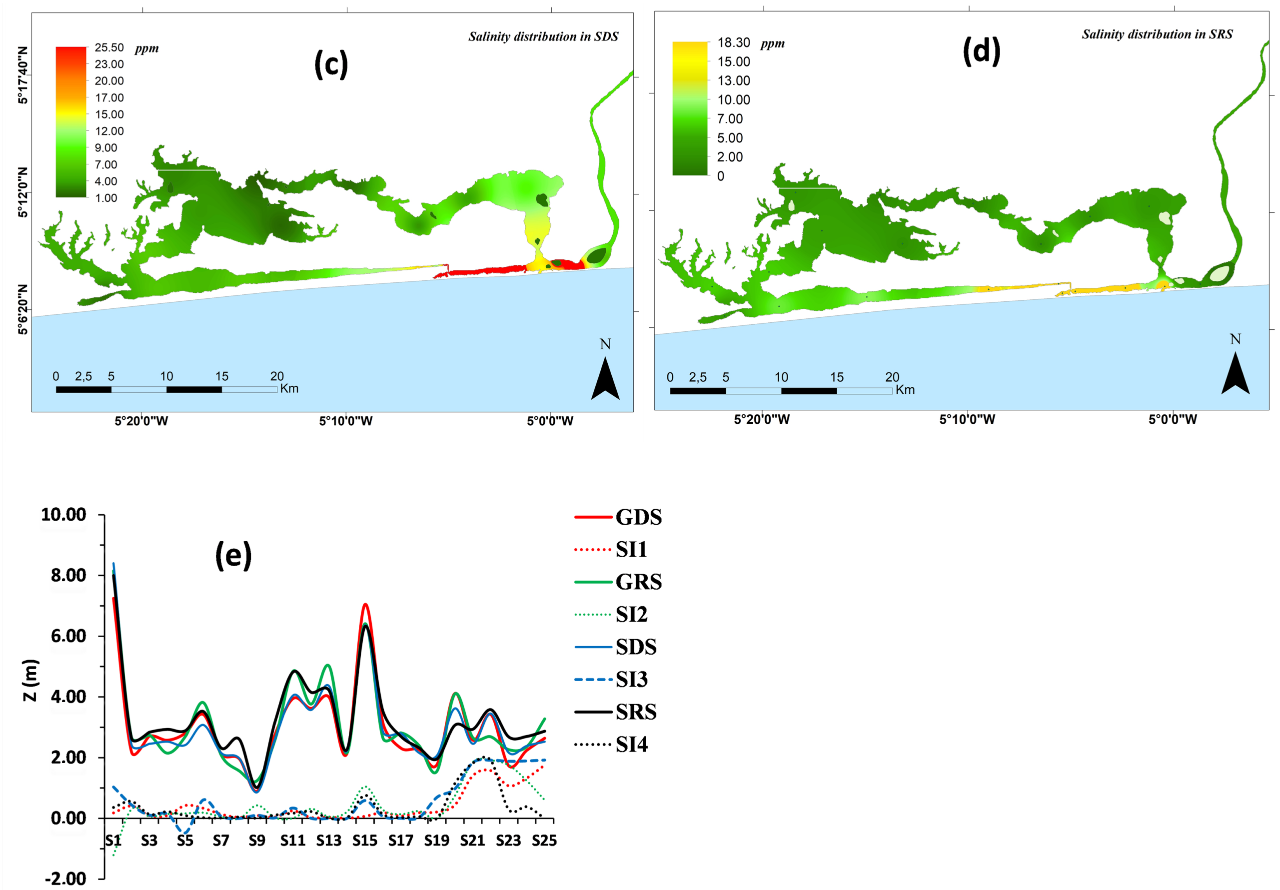


Figure 4. Seasonal distribution of salinity with in (a) the Great Dry Season (GDS) between December-April; (b) the Great Rain Season (GRS) between May-June; (c) the Short Dry Season (SDS) or inter-season between July-August and finally; (d) the Small Rain Season (SRS) associated with the flood of Bandama between September and November; (e) shows the spatial and seasonal variation in depth (Z) and Salinity Stratification Index (SI).

4. Discussion

Separating two different climate systems, the ITCZ determines by its annual migration, atmospheric dynamics, climatic and hydroclimatic characteristics in the watershed of the Grand-Lahou lagoon system as described by [3] [12] [26] This basic diagram is explained by a difference in the amount of movement to the advantage of the high pressures of the Saint Helena High Pressure promoting the northern progression of monsoon winds (ITCZ) at the origin of precipitation in the Guinean region between May and June (GRS); then in the Sudanese zone while it is in full operation on the coast. On the other hand, the loss of quantity of movement from September onwards translates into its return to a coastal environment (SRS). In addition, orbital parameters [27] [28] whose variation of the angle between the plane of the ecliptic and the declination of the Earth's equatorial bourrelé conditioning aphélie may influence the displacement of the high pressures of the Saint Helena's anticyclone. This dynamic would be favourable to the spatio-temporal variability of the motion quantities of each anticyclone. The land in aphelion predisposes a rise of the high pressures of the southern Atlantic, thus the West African monsoon, giving the illusion of a northern progression of the high pressures of the anticyclone of Saint Helena. Thus, the thermal field (ocean, air and lagoon), atmospheric pressure, relative humidity and air velocity; hydroclimatic factors such as rainfall and river flows are strongly influenced by ITCZ dynamics. It therefore gives its seasonal signal on the regime of the rivers that make up the watershed [12]. Moreover, the monsoon of West Africa between June and September cuts the meteorology of the coast, thus upsetting the climatic characteristics (decrease in temperature, increase in relative humidity, rise in atmospheric pressure, and rise in wind speed) and influence the temperature-salinity diagram of the lagoon environment. These climatic conditions, consistent with the work of [1] [2] [3] correspond to the influence of the monsoon on the Ivorian coast, while the northeast trade winds (harmattan) are pushed back in the extreme north. The West African monsoon thus remains the dominant component of atmospheric dynamics and climate variability of the watershed as is the case in West Africa. The wind rotational, weakly linked to this migration is explained by a change in the attraction of the Saharan depression without forgetting the influence of the position of the anticyclones at the origin of the trade winds maintaining the ITCZ and its ground trace (ICF) already observed by [29] and [2]. The change in the trajectory of air masses, sensitive but significant, induces rainfall translocation in the watershed. Other factors such as climate change could also explain the low correlation between air direction and ITCZ, which is fundamental to rainfall in the watershed. The water-deadbolt during the stabilization of the monsoon in the south, during the SDS (short dry season), does not seem to explain a simple coincidence of fact. Certainly taking place during a period of stabilization of the West African monsoon, the tide of dead water results from a perpendicularity between the axes of gravity (attractional) of the moon and the sun. It comes from our state of mind, the establishment of a relationship between the extension of the trade winds of the Saint Helena High Pressure as a result of the rise of the action centre of the High Pressure towards the equator and the aphelion corresponding to the boreal summer where the moon and the sun are geometrically perpendicular.

However, the upheaval in the rainfall pattern of the watershed, particularly in the nearshore region where SRS precipitation is more abundant, more or less significant precipitation between March and April is the hallmark of changes in ITCZ dynamics in recent years and is believed to be inherent in global warming. Moreover, the amplification of the dynamics in the very heterogeneous climate window, with extremely variable characteristics located between the monsoon nucleus and the harmattan, is strongly influenced by global warming. This factor appears to explain the stagnation and steady state of the ITCZ between March-May and October-November that led to the positive rainfall anomalies observed in March-April and the annual maximum in October-November contributing to the reversal of the lagoon and coastal hydrological system. The lagoon environment interacts over time with these different factors, influenced by the alternation of each climate system under the impulse of the respective action centers, their amount of movement and convective processes behind the governance and displacement of the ITCZ.

The importance of precipitation between October and November, initially due to the stagnation of the ITCZ around 7˚N, is also due to a change in the scale of interactions of the atmosphere/continent/ocean couple in the coastal zone; interface between these different matrices. More specifically, global warming causes OSH to rise above 30˚C in the Eastern Tropical Atlantic during February-March-April, resulting in significant evaporation followed by convection of moisture-laden air masses causing precipitation in March and April, while the ITCZ sits in a coastal environment. According to [30] [31], the interactions between monsoon flow and water vapour flow from oceanic sources affect precipitation in coastal regions. Thus, abnormal warming of the SST is the origin of low or very abundant precipitation in the coastal environment according to the dynamics at the base of the rainfall. Ultimately, the annual evolution of the thermal field suggests a seasonal change with a prolonged warm season, while rainfall declines two months earlier in March and April as described by [32]. Like temperature, rainfall, a key factor in climatology, imposes an unequivocal determinism on the hydrological variability of coastal lagoons and estuarine ecosystems. In the current state of our knowledge, the impact of jet currents and east waves do not really have a significant influence on the dynamics of ITCZ by trapping convection [33] [34]. This could only happen if the February-March-April period did not record any precipitation.

In the current context of changing the conventional pattern of coastal rainfall, the conjunction of the annual flood of Bandama (predominant in the hydrological system) with the second and increasing forest flood, seriously impacts the hydrological regime and distribution of salinity in lagoon environments. This situation would also be the cause of the decrease in salinity and the pattern of currents in the coastal zone. This process, which is the subject of the work of [35] [36] [37] [38] [39] allows us to understand the influence of ITCZ dynamics on precipitation variability in West Africa and their impact on the distribution of salinity in coastal ecosystems, in this case, the coastal ocean, estuaries, and lagoons, which could still undergo huge changes in the context of global warming.

5. Conclusion

The intertropical convergence zone is the fundamental key to the climate system in West Africa and more particularly the watershed of the Grand-Lahou lagoon. As a result, it influences the hydrological regime of tributary rivers, which today are strongly affected by climate change and its effect on the dynamics of ITCZ from both a structural and a dynamic point of view. Today, the real problem at the origin of the changes observed in the precipitation regime in the Ivory Coast, resides in the dynamics of the migration process of the ITCZ but especially the moisture load of the trade winds that feeds the convection. These changes have serious repercussions on the dynamics of the hydrological regime of all coastal ecosystems by giving a new configuration to the distribution of salinity and to a lesser degree the temperature; two environmental indicators of global warming, true tracers of the degree of impact on these sensitive ecosystems. The oceanic influence is less and less felt in the areas, especially the coastal environments exposed to river inputs. The monitoring of the West African monsoon and the ITCZ dynamics associated with it represent, in the context of global warming, the key issue for the management of increasingly vulnerable coastal ecosystems.

Acknowledgements

The authors express their thanks to Professor ATSE Boua Célestin; Dr. DJE Kouakou Bernard and Dr. KONE Djackaridja for the flow data of Bandama and Boubo. They also extend their thanks to the team at the meteo-oceanic site http://www.earth.nullschool.net for obtaining climate data. Special mention to the late Dr. KONE Yefanlan José-Matthieu for obtaining the multiparameter allowing the collection of lagoon salinity data.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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