**Modeling and the Uncertainty of Climate of the Volta Basin, West Africa.**

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**Abstract**

Owing to some debatable factors and/or the increased anthropogenic CO2 production over the last century, it is now commonly accepted that the earth’s climate will be affected in the foreseeable future globally as well as regionally. As for Africa, recent regional climate models have predicted significant seasonal changes of temperatures and precipitation for the coming century that will require regional adjustments of water resources management, particularly, for agriculture and household use. While the average citizen in West Africa may have the feeling that a warming trend with some extremes has affected the sub region several times during the last decade - also supported by meteorological measurements. It is still not clear whether such variations are just outliers in the observed hydro-meteorological time-series with it’s well-known stochastic nature, or whether they are just part of a long-term trend pattern that has already been ongoing over most of the last century. More uncertain are the projections made by many regional models for the West African area. To study the variability of stochastic hydrometeorological time-series various hydrometeorological data recorded over 1961-2005, namely (1) climatic data of monthly extremal precipitation at stations throughout the Volta basin and, (2) long-term monthly discharge series of Pwalugu river were used. While these results can somewhat be taken as indicators of some climate change that has been taking place in the basin recently, the abnormal weather conditions experienced here in the last decade may then also be explained more as an inter-decadal intermittency phenomenon than as a hint of a long-term climatic trend. Outputs of two well known downscaled models for the region, MM5 and REMO are compared and their corresponding hydrological dynamics compared with a water simulation model WASIM. MM5 and REMO overestimate rainfall for this selected time slice of 1,203 mm and 1,322 mm per annum, respectively, against the measured 1,101 mm per annum. MM5 overestimates the rainfall from April through July and September and underestimates for August and October. REMO, on the other hand, overestimates rainfall for February through April, July, October and November and underestimates for August. Although no coherent trends are found in the areas around the basin, interannual rainfall variability is more pronounced in the northern Volta as revealed by the projections.

*Keyword*: Climate, Modelling, Volta Basin, MM5, REMO.

**Introduction**

The International Union for Conservation of Nature (IUCN) discovered in their 2004 report “Reducing West Africa’s Vulnerability to Climate Impacts on Water Resources, Wetlands and Desertification” three main reasons why the changes in climate and hydrology need to be well understood and managed. These are: (1) the significant contribution of rainfed agriculture to the region’s economy, (2) the poor level of water control, and (3) the poor replenishment of reservoirs on which some countries sometimes depend heavily for the generation of hydropower and the electricity supply to industry and households. In general, the national economies of many West African states are directly affected by the variations in climate (IUCN, 2004).

The climate of West Africa, particularly in the Sahelian zone of which the Volta is part, has been undergoing recurrent variations of significant magnitude, particularly since the early 1970’s. According to the IUCN (2004), the region has experienced a marked decline in rainfall and hydrometric series around 1968-1972, with 1970 as a transitional year. The IUCN also found a decline in average rainfall before and after 1970 ranging from 15 % to over 30 % depending on the area. This situation resulted in a 200-km southward shift in isohyets. Average discharge in the region’s major rivers underwent concomitant and highly pronounced variations compared to rainfall values. An average decline in the range of 40-60 % in discharge has also been observed since the early 1970s.

Statistically, significant changes have been realized in the last century (Oguntunde et al., 2006). As the hydrological conditions in the Volta Basin have not been very favorable in the last decade, it has become necessary to give attention to water management strategies, as problems may arise if this situation continues or shifts into more water-stressful conditions as predicted by some climate model ensembles used by IPCC (2007) for the region. If the general agreement that hydrological conditions across the world are changing, then concepts on water management need to fit the changing situations. The growing number of reservoirs in the Volta Basin would need to be improved, and flexible methods of operations are required.

Major sources of water in the Volta River system and riparian countries consist of natural and induced rainfall (from cloud seeding from the northern part of the basin), rivers, streams, lakes, groundwater and artificial impounded water (dams, dug-outs and reservoirs). The estimation of direct discharge to the system is based on the assumption that discharge occurs when rainfall amounts and intensities surpass infiltration rates and subsurface saturation, balanced by actual evapotranspiration. Analyses of rainfall data from various stations within the Volta River system indicate that the months in which precipitation exceeds evapotranspiration are usually June, July, August, and September. The annual recharge for the river system ranges from 13.4 % to 16.2 % of the mean annual precipitation (Kasei, 2009).

Throughout the Volta Basin, over the past decades, dams and reservoirs have been constructed to mobilize water for agricultural and hydroelectricity purposes. The number of large and small dams continues to increase as the population grows. Increasing use of water and uncertainty in precipitation in the basin threatens present sustainable programs focused at water management. Several large dams have been constructed (e.g. Akosombo and Bagri) and some are still being constructed (e.g., Bui) in the Volta River system with the primary purpose of generating electricity. The damming of the Volta River at Akosombo lake covering an area of approximately 8,500 km2 is regarded as one of the largest man-made lakes in the world today . A smaller and shallower impoundment next to the Akosombo is the Kpong Head pond, covering an area of roughly 38 km2 at Kpong, 20 km downstream of Akosombo. Bui, which is north-west of Akosombo, is under construction and due in the not distant future. The riparian states of the Volta (e.g., Benin) depend on hydropower from dams built on other tributaries of the Volta, while many more like the Pouya (Natitingou) on the Yéripao are planned. The Fresh water needs of the inhabitants of the basin come from within the basin, and hence a supply shortfall like that in 2002 and 2003 could mean catastrophic consequences for the city water supply, e.g., in Burkina Faso, and severe energy crises in Ghana.

In recent times, there has been immense pressure on Burkina Faso to increase the number of dams in the Volta Basin to meet the country’s demand for fresh water. As a result, there are now an estimated 600 dams and 1,400 dugouts with a total storage potential of 4.7 km3, and about 10,484 wells of which 8,020 are in good condition (IUCN, 2004). The volume stored annually in these reservoirs is about 2.490 km3, which is about 25 % of total discharge. With respect to hydropower generation, 13 locations have been identified in the country, and 10 are located within the Volta Basin. A total of 125.9 GWh/yr is expected to be generated from these hydro-power stations. A recent survey by Department des Infrastructures et des resources Humaines (DIRH) indicates that several planned irrigation projects covering a total area of 1,045 ha will require about 65.3 million m3 water (IUCN, 2004).

**Study Area-Volta basin**

The Volta River Basin is located between latitudes 5oN and 14oN and longitudes 2oE and 5oW. It has a surface area of about 414,000 km2 covering areas in six riparian West African countries (Benin to the east, Burkina Faso to the north, Côte d'Ivoire to the west, Mali, Togo and Ghana to the south). The total basin population is estimated at a little over 14 million inhabitants, with an annual growth rate estimated at 2.9 % (Green Cross International, 2001). The hydrographical network of the basin is delineated into three main sub-catchments: the Mouhoun (Black Volta), the Nakambé (White Volta) and the Oti River.

According to Andreini (2000), the Volta Basin covers about 28 % of West Africa. The Sourou River is one of the trans-boundary rivers that crosses the border from Mali to Burkina Faso, but lately records little or no flow. Almost 66 % of the land surface of Burkina Faso is within the Volta Basin where the Black Volta (Monhoun) and White Volta (Nakambé) originate. The Black Volta stems from the southwest of Burkina Faso. In the south, it serves as the borders between Ghana and Burkina Faso and then further south between Ghana and Côte d'Ivoire. The White Volta originates from the northern part of Burkina Faso and also flows south-eastwards to Ghana. The Oti River flows along the border of Benin and Burkina Faso, crosses the northern part of Togo and passes along the border of Ghana and Togo before it reaches Lake Volta (Figure 1).



Figure 1: Volta River Basin of West Africa (Source: GLOWA Volta project)

**Overview of GCMs**

The climate models popularly used to derive or make projections into the future are the General Circulation Model (GCM). The GCM is basically a mathematical model based on the general circulation of the planetary atmosphere and ocean, which integrate the rotations of the sphere. According to Thorpe (2005), GCMs are among the best tools used for forecasting the weather, understanding the climate and projecting changes in climate.

Derived from the atmospheric global circulation models (AGCMs) and the atmosphere-ocean coupled GCMs (AOGCMs) are the HADCM, GFDL, CM2.X, ECHAM, among others, used for the study and simulation of the present climate and for the projections of the future climate. In the simulation of the hydrology of a watershed, credible input parameters of climate are essential for good results. Outputs of GCMs, however, have a spatial resolution of 250 km, offering only very coarse data for the study of small watersheds. According to Sintondji (2005) and Busche et al. (2005), GCMs have flaws for events of heavy rainfall in respect to their exceeding thresholds and frequencies. It is also evident that local or regional climates are influenced not only by the atmospheric processes, but are also greatly influenced by land-sea interaction, landuse and the topography, which is poorly presented by GCMs due to their coarse spatial resolutions (Storch et al. 1993)

Regional Climate Models (RCMs) have been derived from the coarse GCMs to much higher resolutions. The process of downscaling of GCMs to meso-scales or regional scales enables the downscaled regional climate model to adequately simulate the physical processes consistently with GCMs on a large scale (Mearns et al. 2004). Since parameters of landuse and topography are crucial in the efficiency of the RCMs, the higher the resolution of the RCMs, the better the simulation of the climate and ultimately, a better hydrological simulation is achieved. Some of the RCMs that have been popular in West Africa are REMO, MM5 and PRECIS.

***Application of Regional climate scenarios – MM5***

The regional climate model MM5 is a meso-scale model derived from the GCM-ECHAM4 recently developed for the assessments of the impacts of environmental and climate change on water resources on the Volta Basin of West Africa. The MM5 is a brain child of the cooperation of the Pennsylvania State University (PSU) and the National Center for Atmospheric Research (NCAR) of the USA. According to Grell et al. (1995), the MM5 (non-hydrostatic or hydrostatic available only in version 2) is designed with the initial and lateral boundary conditions of a region to simulate or predict meso-scale and regional-scale atmospheric circulation.

The GLOWA-Volta project (GVP) executed by the Center for Development Research (ZEF), Germany, run MM5 with the initial and lateral boundary conditions derived from the ECHAM4 runs of the time slice 1860-2100, and based on IPCC’s IS92a (assuming an annual increase in CO2 of 1 %, and doubling of CO2 in 90 years (May and Rockner, 2001; cited in Jung, 2006). Using future climate scenario and grided monthly observational dataset from the East Anglia Climate Research Unit (CRU), UK, the model was calibrated to 0.5o x 0.5o resolution. GVP further down-scaled the MM5 model for the Volta Basin to finer resolutions of 9 km x9 km, and for some watersheds within the basin to 3 km x3 km. Details of the setup, coupling and simulation are available in Kunstmann and Jung (2005) and Jung (2006).

A good agreement was reported between the ECHAM4-MM5 simulated climate and the CRU data sets for 1961-1990. According to Jung (2006), simulated temperature was slightly higher in the Sahara during the wet seasons and for the humid south during the dry season, while rainfall was generally comparable except for higher rainfall events that were underestimated. Between ECHAM4 and MM5, 1990-2000 simulations revealed that temperature was generally over estimated and rainfall under estimated by the latter even though the spatial representation was relatively good. However, the future simulations of the models were almost the same. Generally, MM5-Volta estimated an increase in rainfall in the Sahel zone (10-30 %), an increase mean annual rainfall of 44.7 mm (5.1 %) between 1990-2000 and 2030-2039, and a 1.2oC mean temperature rise (Jung, 2006).

GVP produced two 10-year simulated time slices of MM5 (1991-2000 and 2030-2039). For this section of the study, the 1991-2000 outputs were considered as the present climate and the time slice 2030-2039 as the future climate.

Changes in the hydrological cycle of a basin hinge largely on, among others, changes in climate. The 10-year time slices were used to represent three windows of the past, present and future conditions. Climatic inputs for the past are data obtained from the meteorological agencies of Ghana and Burkina Faso through the GLOWA Volta project for the period 1961-1970. The present and future climate conditions are outputs of the MM5-Volta after Jung (2006) and Kunstmann and Jung (2005); these are 1991-2000 and 2030-2039, respectively. For these analyses, the Pwalugu watershed (Savannah) represents the north of the basin and the Bui watershed (transition zone) represents the south.

***Application of Regional climate scenarios – REMO***

REMO is a hydrostatic regional climate model, initially developed at the Max-Planck-Institute for Meteorology (MPI) in Hamburg, Germany, on the foundation of the operational weather forecast model Europa-Modell of the German Weather Service (DWD) (Majewski 1991). According to Jacob et al. (2001) cited in Paeth (2005), the dynamical kernel is based on primitive equations with temperature, horizontal wind components, surface pressure, water vapor content and cloud water content as prognostic variables.

REMO simulations are driven according to Roeckner et al. (2003) by recent global coupled climate model simulations of ECHAM5/MPI-OM, which are known to be forced by enhanced greenhouse and sulphate aerosol conditions and are synonymous with the modelling approaches of the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC).

The simulation outputs used for this study are those produced and used in the GLOWA IMPETUS project whose focus was on western and northern Africa. The horizontal resolution is 0.5o, equivalent to about 55-km grid spacing at the equator, and 20 hybrids vertical levels are resolved. These levels follow the orography near the surface and correspond to pressure levels in the upper troposphere (Paeth, 2005).

The global climate model ECHAM4 (Roeckner et al. 1996) was adjusted to the 0.5o model grid scale of REMO to account for atmospheric processes like deep convection, cloud formation, convective rainfall, radiation and microphysics from the sub gridscale of ECHAM4. Similarly, land surface parameters such as soil characteristics, orography, vegetation, roughness length, and albedo are derived from the GTOPO30 and NOAA data sets (Hagemann et al. 1999) and partly modified according to the scenarios of land degradation. Underlying an idealized seasonal cycle over West Africa, the same daily interpolated surface parameters are prescribed each year using a model output statistics (MOS) system (Paeth, 2005).

The IMPETUS project made some changes to the default parameter of REMO to adapt to the tropical-subtropical West African region. The focus is on the key region of the West African monsoon system of which the Volta Basin is part. Some results of the adopted REMO correlated well with observed extreme climate year. For example, the driest years derived from simulated rainfall were 1981, 1983, 1990, 1992 and 1998, whereas 1979, 1984, 1988, 1989, and 1991 were characterized by abundant monsoon rainfall. Parker and Alexander (2002) basically confirm that the Climate Research Unit (CRU) time series data set reveals almost the same composite years.

**Results and Discussions**

Regional models share similar problems but differ in magnitude. Notable are MM5, MAR and REMO (Vizy and Cook, 2002; Gallée et al., (2004); Paeth et al., 2005). However, Schnitzler et al. (2001) suggest that integrating the interaction with vegetation cover and albedo considerably improves the simulation of rainfall over the Sahel in the global ECHAM4 model.

To assess the reliability of the MM5 and REMO future climate scenario for the evaluation of the impacts of climate change on water resources in the Volta Basin, the REMO-simulated and MM5-simulated mean rainfall for the time slice 1991-1997 obtained for the basin weather stations are compared to the mean observed rainfall for the same area and periods. This time slice was selected because it contained certified gauged meteorological data with minimal gaps. The results of the comparison for the Pwalugu catchment station, for example, show a good correlation between the observed and MM5-simulated and REMO-simulated monthly rainfall. Pearson correlation of gauged 1991-1997 and REMO 1991-1997 = 0.823; P-Value = 0.001; for gauged 1991-1997 and MM5 1991-1997 = 0.957; P-Value < 0.0001. On average, MM5 and REMO overestimate rainfall for this selected time slice of 1,203 mm and 1,322 mm per annum, respectively, against the measured1,101 mm per annum. MM5 overestimates the rainfall from April through July and September and underestimates for August and October. REMO, on the other hand, overestimates rainfall for February through April, July, October and November and underestimates for August. The strongest overestimation for MM5 is for the month of July, while for REMO, this is March and April (Figure 2).

Figure 2: MM5-simulated (mean over 7 years) and REMO-simulated (mean over 7 years) compared to observed (mean over 7 years) rainfall including standard deviation (error bars) of rainfall at Pwalugu (56,760 km2) catchment of the Volta Basin

Water balance dynamics

The Volta Basin’s water balance dynamics were simulated with the WaSiM-Volta model with daily climate inputs of historical data from the basin for the “past”; MM5-generated and REMO-generated climate series for the “present” and “future”. The resultant outputs were compared.

Considering the basin’s north-south transect in general, rainfall amounts have increased steadily from the past to the present and is projected to increase substantially in the north and marginally in the south by 2030-2039 according to MM5. A general decrease is projected by REMO under both IPCC’s scenarios A1B and B1 (Tables 1 and 2). The projected increase in precipitation by MM5 is largely due to the abnormally high projected precipitation for the period 2035-2039 (Figure 3), for which precipitation exceeds the previous period of 2030-2034 by over 500 mm over the two periods. REMO’s A1B and B1 scenarios also conflict on the sign of average annual precipitation for this period. While A1B projects a dryer period, B1 projects a relatively wetter period.

Table 1: Change in hydrology simulated using MM5 (1991-2000) and MM5 (2030-2039); REMO-A1B (1991-2000) and REMO-A1B (2001-2050); REMO-B1 (1991-2000) and REMO-B1 (2001-2050) for the north of the Volta Basin



Table 2: Change in hydrology simulated using MM5 (1991-2000) and MM5 (2030-2039); REMO-A1B (1991-2000) and REMO-A1B (2001-2050); REMO-B1 (1991-2000) and REMO-B1 (2001-2050) for the south of the Volta Basin

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The change in hydrology as simulated by WaSiM based on MM5 and the two scenarios of REMO have conflicting results (Tables 1 and 2). While MM5 projects an increase in precipitation between 1991-2000 and 2030-2039 by 10 % to 19 % for the basin, both REMO simulations project a reduction of between 4 % and 6 % between 1991-2000 and 2001-2050 for the north and a decline of 3 % to 19 % for the south. Discharge is expected to increase under MM5 by nearly 9 %, while a decrease between 2 % and 4 % is expected under REMO. The discrepancy in simulation between MM5 and REMO for the future may be due to extremely high projected precipitation of MM5 for the period 2036-2039 for which REMO does not project anything extraordinary (Figure 3). The only agreement between MM5 and REMO is in the area of soil water content change, where both scenarios show dry soils at the end of the seasons. These might be signs that drying soils maybe warnings of drought events

Several authors have suggested that the prevailing droughts during the second half of the 20th century were at least partly caused by land-cover changes in tropical and subtropical Africa (Zeng and Neelin 2000; Pielke 2001; Semazzi and Song 2001; Zeng et al. 2002). Texier et al. (2000) have shown that the African monsoon system is much more sensitive to low frequency changes in vegetation cover (Paeth et al., 2005), and hence evident in REMO simulations as they consider land-use changes.

Figure 3: MM5-simulated and REMO-simulated compared to observed (mean over 4 years) rainfall including standard deviation (over the period) and trend lines of rainfall at Pwalugu (56,760 km2) catchment of the Volta Basin

Under MM5 projections, total percentage discharge and surface flow are observed to increase at a steady rate in the north, which might be good for dugout and streams; the opposite is observed for the south even though the actual differences in amounts are not very large. This can be attributed to the wide variation of the increases in precipitation (Figure 4) within the highly heterogeneous basin. Interflow does not differ in percentages between the past and the present, but a significant reduction from 6.2 % (present) to 2 % (future) is expected for the north, and from 8 % to 1.8 % for the southern parts of the basin. Interflow, as already, is closely related to the drainage density of the river system, and so a decline in interflow will mean a reduction in the drainage density of the river network feeding into those catchments. Base flow is generally below 3 % of the total rainfall for both the past and the present, and will approach zero for the period of the future time slice. This phenomenon will further enhance the occurrence and frequency of low flows or drying of streams and ultimately have devastating consequences on ecosystems that depend on such water resources.



Figure 4: Exceedance probability of daily discharge simulated with MM5, REMO-A1B and REMO-B1 with annual average discharge of 338 mm, 523 mm and 1,200 mm, respectively, for the Pwalugu catchment of the Volta Basin for 2030-2039.

The results presented by REMO show nearly the opposite of the projections of MM5. Total annual discharge is expected to reduce between 2 % and 4 % for the northern part of the basin, with an increase of between 30 % and 35 % of potential evapotranspiration and an increase of about 3 % in actual evapotranspiration (Table 1). For the south of the basin, REMO’s A1B scenarios project a 3 % increase in discharge while the B1 scenarios project a 9 % decrease in discharge. Both scenarios, however, project between 8 % and 10 % increase in evapotranspiration. Potential evapotranspiration is expected to decrease under the A1B scenarios, but an increase of about 8 % is expected under the B1 scenarios.

By the estimations of MM5 outputs, average annual rainfall ranging from 1,133 mm (past) to 1,367 mm (future) representing 20 % increase in rainfall in the north results in 8.72 % increase in discharge, 1.48 % decrease in surface flow, and 10 % and 0.03 % increases in interflow and base flows, respectively. This scenario could be an indicator for extreme events of droughts and floods in the north. These projections seem to fit into the 2007-2009 rainfall patterns, when the basin experienced some extremes in rainfall accompanied with heavy floods. For the transition/south zones, a slight increase in the annual average of 1,239 mm (present) to 1,280 mm (future), results in 5 % increase in discharge with a slight decrease in surface runoff, 6 % increase in interflow, and 0.35 % decrease in base flows. It has already been established that with the use of MM5 projection many more days without rainfall are expected in the future compared to the past, which might result in low flow in streams. Consequently, rainfall amounts will generally increase across the basin, with the savannah zone generating a significant amount of the runoff of the basin (Figure 1) . This is however opposed by the projection of REMO as discussed earlier.

Although no coherent trends are found in the areas around the basin as reported by Peath et al. (2005), interannual rainfall variability is more pronounced in the northern Volta (Pwalugu) as revealed by the REMO protections (see Figure 5). The northern part of the basin is most vulnerable to these variations because it has a monomodal rainfall pattern compared to the south which has relatively higher rainfall amounts due to its bi-modal rainfall pattern. The SPI analysis conducted on projected precipitation based on REMO using IPCC’s A1B and B1 scenarios against the base period of 1961-2000 (Figure 5) shows both scenarios agreeing to a general drying trend for the future. With the exception of B1-scenario-based extreme dry year projections for 2016 (-2.5) and 2049 (2.1), the A1B scenario generally projects higher negative SPI values than B1 spanning the entire projection period and more profound for the period 2019 to 2047.



Figure 5: SPI characterization of REMO simulations for A1B and B1 scenarios for 2001-2050 for Pwalugu (north of Volta Basin) against base period of 1961-2000.

Table 3: Comparison of climate occurrences of past (1961-2005 gauged) with future (2006-2050 REMO’s A1B-simulated) for the Volta Basin



Both scenarios also agree on the few wet years that have been projected for the future. For instance, both REMO's A1B and B1 projections of 2008 and 2009 as very wet years have actually coincided with high rainfall and floods for the same years (official records). If these projections made in 2004 are anything to go by, then REMO’s projections of a blend of moderate and extreme dry years for the future should be given close attention in policy formulation. The SPI also indicates an increase in frequency of moderate to severe drought for the future (Table 3). MM5 does not have simulated outputs for 2008 and 2009 of the Volta Basin for validation.

**Conclusion**

The results from the comparison of the Volta Basin water balance dynamics, simulated with WaSiM-Volta model, using historical climate data from the basin for the “past”, and MM5- generated climate series for the “present” and the “future” with even durations of 10 years show that in the basin in general, from the north to the south, rainfall has increased steadily from the past to the present, and it is projected to increase substantially in the north and marginally in the south from 2030 to 2039. The WaSiM simulation using REMO data show a different trend of decrease in rainfall, and consequently decreases in almost all the discharge components of the periods 1961-2000 and 2001-2050. Analysis of climate data in the basin indicates that the months in which precipitation exceeds evapotranspiration are usually June, July, August and September. A comparison of wet and dry years shows that the ratio of direct runoff and base flow is at an average of 30 %, being high in the wet years with a sharp decline in the dry years. It is observed that total percentage discharge and surface flow have increased in the north, which might be good for dugouts and streams; the opposite is true for the south. The probability of daily average discharge falling below 1 mm is expected to increase from 0.47 in the “past” to 0.75 for the “future” time slice of 2030 to 2039 in the south of the basin, thus increasing the frequency of low flow occurrences. The annual recharge for the Volta River System ranges from 13.4 % to 16.2 % of the mean annual precipitation, and annual rainfall amounts from the simulations show an increase of between 5 % and 20 % for the highly heterogeneous basin. It is important to note, however, that REMO gives exactly opposite outputs to the scenario outputs of MM5.

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