MONITORING MASS CHANGES IN THE VOLTA RIVER BASIN USING GRACE SATELLITE GRAVITY AND TRMM PRECIPITATION

Mudanças em massa na bacia hidrográfica do Rio Volta empregando-se os satélites GRACE e TRMM

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ABSTRACT

GRACE satellite gravity data was used to estimate mass changes within the Volta River basin in West African for the period of January, 2005 to December, 2010. We also used the precipitation data from the Tropical Rainfall Measurement Mission (TRMM) to determine relative contributions source to the seasonal hydrological balance within the Volta River basin. We found out that the seasonal mass change tends to be detected by GRACE for periods from 1 month in the south to 4 months in the north of the basin after the rainfall events. The results suggested a significant gain in water storage in the basin at reference epoch 2007.5 and a dominant annual cycle for the period under consideration for both in the mass changes and rainfall time series. However, there was a low correlation between mass changes and rainfall implying that there must be other processes which cause mass changes without rainfall in the upstream of the Volta River basin.

Keywords: Equivalent Water Thickness; Mass Transport; Water Storage.

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RESUMO

Dados da missão *Gravity Recovery and Climate Exchange* (GRACE) são usados para estimar mudanças em massa na bacia hidrográfica do Rio Volta na Africa Ocidental entre o período de janeiro de 2005 a dezembro de 2010. Empregou-se também os dados de precipitação do satélite *Tropical Rainfall Measurement Mission* (TRMM) para determinar a fonte de contribuições em relação ao balanço hidrológico sazonal na bacia do Rio Volta. Os resultados mostram que a mudança de massa sazonal tende a ser detectada pelos satélites da missão GRACE a partir de 1 mês, no sul e de 4 meses no norte da bacia após a precipitação. Os resultados sugerem um ganho significativo no armazenamento d'água na bacia para a época de referência 2007,5 e um ciclo anual predominante para o período considerado para mudanças em massa e precipitação. No entanto, notou-se uma baixa correlação entre as alterações da massa e precipitação o que implica que deve haver outros processos que causam mudanças em massa sem ocorrer precipitação para o montante da bacia do Rio Volta.

Palavras-chave: Equivalente à Lâmina D'água; Transporte de Massa; Armazenamento D'água.

1. INTRODUCTION

Since 17 March 2002, the Gravity Recovery and Climate Experiment (GRACE) twin satellites have been used to monitor the gravity field of Earth in the space and time domains. Wahr *et al.* (1998) reported that the largest-amplitude and most varied time-dependent signals are related to water storage variability on land. Ramillien *et al.* (2008a) concluded that GRACE satellite gravimetry offers a very interesting alternative remote sensing technique to measure changes in total water storage over continental areas. This includes ice, snow, surface waters, soil moisture and groundwater. The measurements cannot distinguish between these stores, but can only recover the sum. However, the distribution of the locations of Earth's freshwater shows that the percentage of superficial water is very small (~ 1.3%) and we could consider that the main variations of the water storage are associated with groundwater storage (~ 30.1%).

Data of the GRACE satellite mission have been extensively applied to the study of the stored water changes. Recent publications suggest that water storage losses have occurred in central and south Asian (TANGDAMRONGSUB *et al.*, 2011). The water storage changes from GRACE show decreasing trends in these regions. Lenk (2012) found that decreasing trends of terrestrial water storage changes observed by GRACE in the southern part of central Anatolia, Turkey, were largely explained by the decreasing trends of groundwater variations which were confirmed by *in situ* well groundwater level data. Crowley *et al.* (2006) estimated the water storage within the Congo Basin, Africa, and their results exhibit significant long-term trends yielding a total loss of 280 km^3 of water over the fifty months of data.

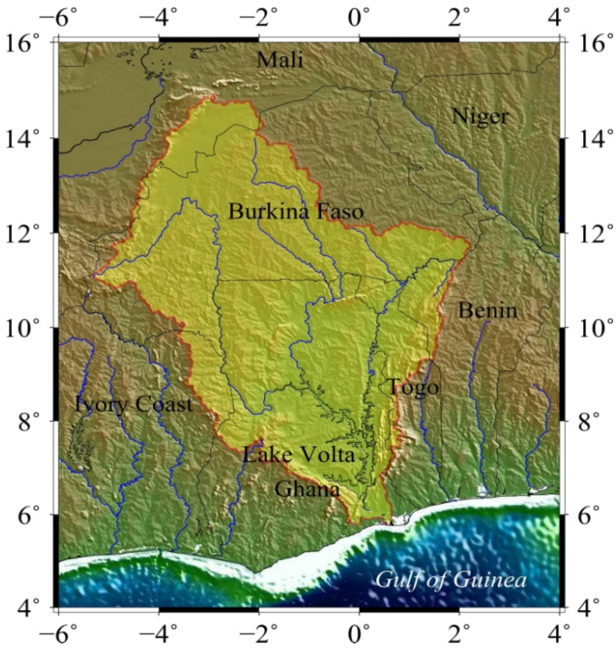
Over West Africa, only a few GRACE applications have been carried out with emphasis in the Niger River basin and Sahel region (*e.g.*, GRIPPA *et al.*, 2011 and HINDERER *et al.*, 2011) and in basins in Sub-Saharan Africa (XIE *et al.*, 2012). Other studies in a global scale also mentioned the Niger River basin, for example, Ramillien *et al.* (2008b) and Syed *et al.* (2008). Grippa *et al.* (2011) results revealed that GRACE data is able to reproduce the water storage inter-annual variability over the Sahel. Xie *et al.* (2012) have used seven years of GRACE data to calibrate a semi-distributed regional scale hydrological model Soil and Water Assessment Tool (SWAT). Their results showed that the simulated total water storage variations tend to have less agreement with the GRACE data in arid and equatorial humid regions. To the best of our knowledge there are no results in the literature regarding the mass changes in the Volta River basin, West African, using time-variable gravity fields from GRACE and precipitation data from the Tropical Rainfall Measurement Mission (TRMM).

Some 20 million people in the countries of Ghana, Burkina Faso, Mali, Benin, Togo and Ivory Coast (*Côte d'Ivoire*) make their homes within the river's basin shown in Figure 1. The river is highly depended upon by these countries for the purposes of irrigation, hydro-energy, industrial, and domestic usage. The most significant hydrological structure within the basin is the Akosombo Dam which holds back both the water of the White Volta, Black Volta and the Oti River for the generation of hydro-electric power. The dam forms the largest man-made lake in the world, the Volta Lake of a surface area of 8,500 km^2 which lies entirely within Ghana.

The total of surface area of Volta Basin is about the 407,093 km^2 and for that reason; the climate, soils and vegetation are largely variable in different regions. Rainfall is extremely low in the north and the south, increasing gradually to high values in the mid-section of the basin. Most streams within the basin are ephemeral; it is thus extremely difficult to find potable water in most parts of the basin during the dry season. Water storage changes are of particular importance in areas with arid or semi-arid climates within the Volta River basin. Information on the spatial and temporal behavior of terrestrial water storage is crucial for the management of local, regional and global water resources. In monitoring water storage traditionally, large amount of *in-situ* data from different points is required. GRACE however provides data over the entire basin without the need for ground data making it an ideal tool for this study (*cf.* DEUS *et al.*, 2011 and MILZOW *et al.*, 2011).

The aim of the present work is to compare the temporal variations of GRACE-derived mass changes expressed as equivalent water thickness (EWT) and TRMM precipitation data over the Volta River basin. Hence the Stokes coefficients of monthly Earth's gravity solutions are applied; the gravity changes over Volta River basin are analyzed during 2005–2010. We also characterize the water storage variability in the Volta River basin to provide a guide for water management. The results showed an increase in the stored water. It is clearly depicted in the mass changes as well as the clearly seasonal and inter-annual changes. However, it seems that mass changes for the period were not caused by rainfall only. There must be some other processes involved which cause mass changes without rainfall.

Figure 1 – The Volta River and its Catchment Area (the red line is the main water divide of the hydrographic basin).



2. DATA AND PROCESSING

2.1 Mass changes from GRACE

Changes in the Stokes coefficients can be used to calculate changes in the geoid at a point with co-latitude ϑ and longitude λ. To convert variations of the geoid in equivalent water thickness (EWT) we used a filtering technique proposed by Wahr *et al.* (1998) which is based on the following assumptions:

- The mass variations in the water stored occur almost entirely within a thin layer of 1 km thick closer to the surface of the Earth. The density anomaly is concentrated within this thin layer.
- The deformation within the solid Earth due to mass at the surface can be represented in terms of load Love numbers.
- The density of the water is constant, so mass variations are associated to changes in the height of water layer.

Under the above assumptions, the EWT can be expressed as (WAHR *et al.*, 1998):

$$h(t) = R\sum_{n=2}^{n_{\max}}\sum_{m=0}^{n}\bar{P}_{n,m}(\cos\vartheta)\left[\Delta\tilde{C}_{n,m}(t)\cos m\lambda + \Delta\tilde{S}_{n,m}(t)\sin m\lambda\right], \quad (1)$$

at a given month t, where $\bar{P}_{n,m}$ is the normalized associated Legendre functions of degree n and order m, R is the mean radius of the Earth. $\Delta\tilde{C}_{n,m}$ and $\Delta\tilde{S}_{n,m}$ are the residual surface density coefficients obtained from the following relation (WAHR *et al.*, 1998):

$$\begin{pmatrix}\Delta\tilde{C}_{n,m}\\ \Delta\tilde{S}_{n,m}\end{pmatrix}_i = \frac{\rho_e}{3\rho_w}\frac{2n+1}{1+k_n}\begin{pmatrix}\Delta\bar{C}_{n,m}\\ \Delta\bar{S}_{n,m}\end{pmatrix}_i, \quad (2)$$

of the *i*-th monthly solution, where ρ_e is the average density of the Earth, ρ_w is the density of the water, and k_n is the load Love number for degree n. Note that the equation (2) defines a simple filter that allows converting the variations of the geoid in EWT (usually expressed in mm).

The residual Stokes's coefficients, $\Delta\bar{C}_{n,m}(t)$ and $\Delta\bar{S}_{n,m}(t)$ are defined by:

$$\begin{pmatrix}\Delta\bar{C}_{n,m}\\ \Delta\bar{S}_{n,m}\end{pmatrix}_i = \begin{pmatrix}\bar{C}_{n,m}\\ \bar{S}_{n,m}\end{pmatrix}_i - \frac{1}{N}\sum_{j=1}^{N}\begin{pmatrix}\bar{C}_{n,m}\\ \bar{S}_{n,m}\end{pmatrix}_j, \quad (3)$$

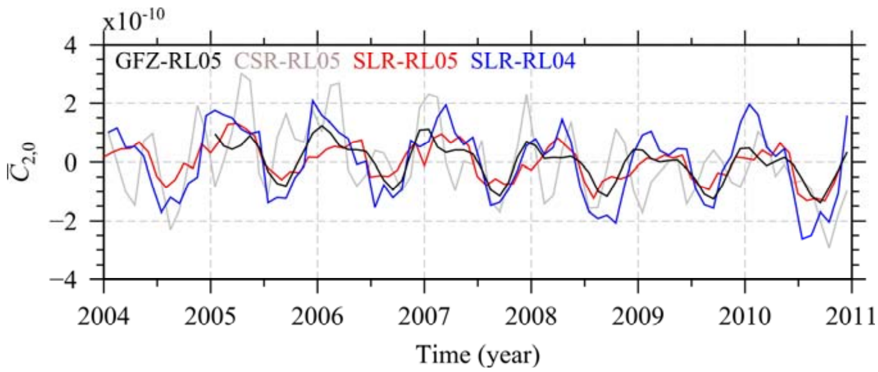
where the long-term value of $\bar{C}_{n,m}$ and $\bar{S}_{n,m}$, Stoke's coefficients, is removed. *N* is the total number of monthly solutions. The reason for removing the mean field is that it is dominated by the static density distribution inside the solid Earth. Removing the static field means that all contribution from the means stored water is also removed. Thus, only the time-variable component of the water storage can be recovered.

2.2 GRACE data set

The GRACE observations are processed at the Center for Space Research (CSR) at the University of Texas, Jet Propulsion Laboratory (JPL), the *GeoForschungsZentrum* (GFZ), *Centre National d'Études Spatiales* (CNES) and Delft institute of Earth Observation, Space systems (DEOS) at Delft University of Technology and a few others institutions. However, each center follows different data processing methodologies, which may cause some differences in monthly sets of Stokes's coefficients (KLEES *et al.*, 2008). The final results, known as Level 2 (L2) products, are the monthly geopotential solutions expressed in terms of spherical harmonic expansion, *cf.* Duan *et al.* (2009), which are widely used to study mass changes on the surface of the Earth. Each monthly Stokes's coefficients data set was referenced to the individual long term mean to derive residual time-variable quantities.

The data for this study include $N = 72$ GFZ release 05 (GFZ-RL05) GRACE monthly solutions, *cf.* Dahle *et al.* (2012) for details, covering the time period from January 2005 to December 2010. These set of coefficients are complete up to a degree and order of 90 and they are available at: http://icgem.gfz-potsdam.de/ICGEM/shms/monthly/gfz-rl05/. We limit the development in series up to degree and order 60, this limit ($n = 60$) fixes spatial resolution at approximately 334 km ($\rho = \frac{\pi}{n} R$). In contrast to RL04, the RL05's values are much closer to Satellite Laser Ranging (SLR) derived values, see Figure 2 for comparison. Because $C_{2,0}$ is affected by large tide-like aliases, it is necessary to replace $C_{2,0}$ with an independent estimate from SLR (CSR's approach for RL05). However, other option is to constrain $C_{2,0}$ to an *a priori* model during the gravity field solution process (GFZ's approach for RL05). Either approach achieves the same thing, which is to avoid the errors in $C_{2,0}$. For additional information we recommend Cheng and Tapley (2004), Cheng and Ries (2012), Bettadpur *et al.* (2012) and Dahle *et al.* (2012).

Figure 2 – Time series of $\overline{C}_{2,0}$ from SLR (RL04 and RL05) and GRACE (GFZ-RL05 and CSR-RL05). The respective mean values were subtracted for the four time series.

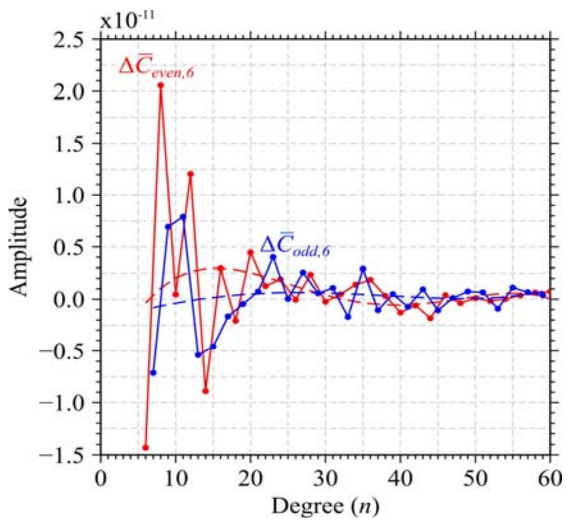


2.3 Post-processing of GFZ-RL05's coefficients

The maps of equivalent water thickness calculated with this methodology describe present linear features in north-south direction called as "stripes". The presence of these stripes indicates a high degree of spatial correlation in the GRACE errors in short wavelength components (high frequencies). Striping is the largest problem in GRACE solutions and according to Awange *et al.* (2009), there remains some conjecture as to the exact cause of the striping. However, in agreement with Swenson and Wahr (2006) and Schrama and Visser (2006) it is thought to be mostly due to weight being placed on the along-track K-band ranging (KBR) data coupled with inaccurate de-aliasing models and the mission configuration.

These systematic errors show a different tendency between *odd* and *even* degree coefficients for the same order. To obtain coherent results it is necessary to remove stripes using a post-processing method to reduce correlated error with a minimal impact in the real signal. Several methods have been used to remove stripes and noise of high frequency of GRACE data. These correlations can be reduced using either an empirical method based on a polynomial fit (SWENSON; WAHR, 2006) or an *a priori* synthetic model of the observation geometry (KUSCHE, 2007). In this study the polynomial fit scheme filter suggested by Chen *et al.* (2007) was applied to residual Stokes's coefficients. For residual Stokes's coefficients with orders 6 and above, a least square fit degree 4 polynomial was removed from even and odd degree coefficient pairs (CHEN *et al.*, 2010). For example, for Stokes's coefficients of order 6, we fit a degree 4 polynomial to the even degree pair (*e.g.*, $\Delta\overline{C}_{6,6}$, $\Delta\overline{C}_{8,6}$, …, $\Delta\overline{C}_{60,6}$) and remove the polynomial fit from the coefficients as shown in the Figure 3. The same process holds the odd degree pair (*e.g.*, $\Delta\overline{C}_{7,6}$, $\Delta\overline{C}_{9,6}$, …, $\Delta\overline{C}_{59,6}$). Chen *et al.* (2010) call this procedure the de-correlation filter, here after abbreviated as *P*4*M*6.

Figure 3 – Residual Stokes's coefficients $\Delta\overline{C}_{n,m}$ as function of degree n and order $m = 6$.



Note: The coefficients was plotted separately for coefficients with degree even (red solid curve) and degree odd (blue solid curve). The *P4M6* filter for the degree even (red dashed curve) and odd (blue dashed curve) and order 6.

After *P4M6* filtering, a Gaussian low-pass filter was applied to further suppress the 72 remaining short-wavelength errors. Given the averaging or smoothing radius r, the Gaussian smoothing operator W for a degree n is defined by a recursive relation (WAHR *et al.*, 1998):

$$W_0 = \frac{1}{2\pi}, \quad W_1 = \frac{1}{2\pi}\left(\frac{1+e^{-2b}}{1-e^{-2b}} - \frac{1}{b}\right), \quad W_{n+1} = -\frac{2n+1}{b}W_n + W_{n-1}\,, \tag{4}$$

where the parameter b, given the half-height length, is:

$$b = \frac{\ln(2)}{1-\cos(\frac{r}{R})}. \tag{5}$$

Following Ramillien *et al.* (2005) the choice of the r is a good compromise between spatial resolution and effect of noise. The selection of a smoothing radius of 300 km is also a compromise in that it removes the striping effects, but still allows to study sub-basin changes.

2.4 The terrestrial hydrological water balance

It is well known that the water budget methods are based on the principle of conservation of mass applied to some part of the hydrologic cycle, *cf.* Brutsaert (2008). Over a land-surface of area Ω, the mean evaporation rate, *E*, can be expressed in terms of the water balance equation as follows (BRUTSAERT 2008, p. 142):

$$E(t) = P(t) - Q(t) - \frac{dW(t)}{dt}\,, \tag{6}$$

where *P* is the areal mean rate of precipitation; *Q* is the mean net surface runoff rate per unit area from the basin (assumed to include both the surface and the groundwater runoff of the area); and *W* is the water volume stored per unit area.

If we integrate the both sides of the (6) as:

$$W(t) = \int_{t_1}^{t} [P(t) - Q(t) - E(t)]dt\,, \tag{7}$$

we can compare the GRACE-derived equivalent water thickness with the right hand side of (7) where t_1 and t are the first day and the last days of the month. However, Ogawa *et al.* (2011) reported that a linear trend in $P(t)$, $Q(t)$, and $E(t)$ implies, after the integration as in (7), in a quadratic term in $W(t)$. Crowley *et al.* (2007) after separated the quantities in the (7) into constant, linear, quadratic, and seasonal terms found a good agreement between water volume stored anomalies from GRACE and the integrated precipitation anomalies within the Amazon Basin, South American and Congo Basin, Africa. We apply the same approach to detect the mass changes over Volta Basin at annual and inter-annual time scales.

2.5 Precipitation data

In this paper we used the global monthly accumulated rain grids supplied by the Tropical Rainfall Measuring Mission (TRMM) as Level-3 V7 products, more specifically the TRMM 3B43. TRMM is a joint satellite mission of Goddard Space Flight Centre (GSFC), from National Aeronautics and Space Administration (NASA), and the Japan Aerospace Exploration Agency (JAXA). Since the end of 1997, the TRMM provides monthly rainfall rates for the tropical and subtropical regions. Owing to the availability of the GRACE products (CFZ-RL05) at the time of the study, the used time period is limited to January 2005 to December 2010 (total 72 grids) with 0.25°x0.25° of spatial resolution available at: http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=TRMM_L3_comp.

The precipitation data was also filtered, as EWT derived from GRACE, by applying a Gaussian filter (smoothing 300 km). It was necessary for a direct comparison with GRACE water storage changes. Following Wahr *et al.* (1998), in spatial representation the Gaussian smooth is defined by:

$$W(\psi) = \frac{b}{2\pi} \frac{e^{-b(1-\cos\psi)}}{1-e^{-2b}}, \tag{8}$$

where ψ is the spherical distance between the points (the center of the study area and each grid point). We decided use 300 km for the smoothing radius because the study area is relative small in longitude (10°).

3. RESULTS AND DISCUSSIONS

The GRACE-derived EWT were compared with rainfall data at the Volta River basin in West African to assess mass changes expressed as water storage changes and detect its mechanisms. To discuss seasonal or inter-annual changes, the time-series of EWT and precipitation at a given grid point was analyzed using the following expression:

$$y(t) = a_0 + a_1(t-t_0) + a_2(t-t_0)^2 + \sum_{k=1}^{2}[b_k\cos(k\omega t) + c_k\sin(k\omega t)], \tag{9}$$

where t is a given time point expressed by years from a reference epoch; $y(t)$ is the original input series; ω is the frequency ($\omega = 2\pi/T$, where T is the period, one year in our analyses); *k* represents the rank of the harmonics (*k* = 1 corresponds to the fundamental component). The magnitude and phase of the selected harmonic component are calculated by $A_k = \sqrt{b_k^2 + c_k^2}$ and $\Phi_k = \arctan(c_k / b_k)$, respectively. The coefficient a_1 represents an instantaneous trend at the epoch t_0, here $t_0 = 2007.5$, *i.e.*, the mid-point of our time span. The terms a_0 and a_2 are the offset depending on the start point of the time series and the acceleration/deceleration (OGAWA *et al.*, 2011), respectively.

The Figure 4 shows the inter-annual changes in EWT and rainfall in mm per year (mm/yr). The largest EWT rates were found at Volta Lake. The trend indicates a mass increase over Volta River basin (up to 30 mm/yr in the Volta Lake). In addition, the rates of rainfall were low 3 mm/yr at Lake Volta. Therefore, the positive rate of GRACE-derived EWT is most likely caused by the water impoundment at the Volta Lake. For the EWT the trend reached the maximal values in the south, while in the north values were relative small. Furthermore, it seems the northern parts experiences more drier periods relative to the southern parts. It makes sense if we take into account that the annual rainfall varies greatly across the basin, from 1,500 mm in the south to 400 mm in the north.

Figure 4 – Inter-annual trends in EWT (left) and rainfall (right) in mm/yr for the period from 2005 to 2010 and the reference epoch is 2007.5.

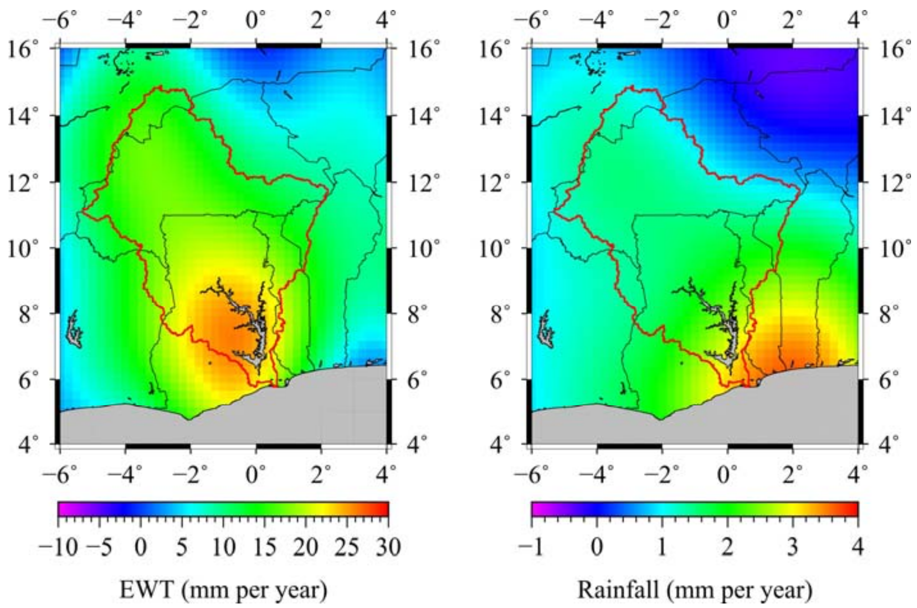
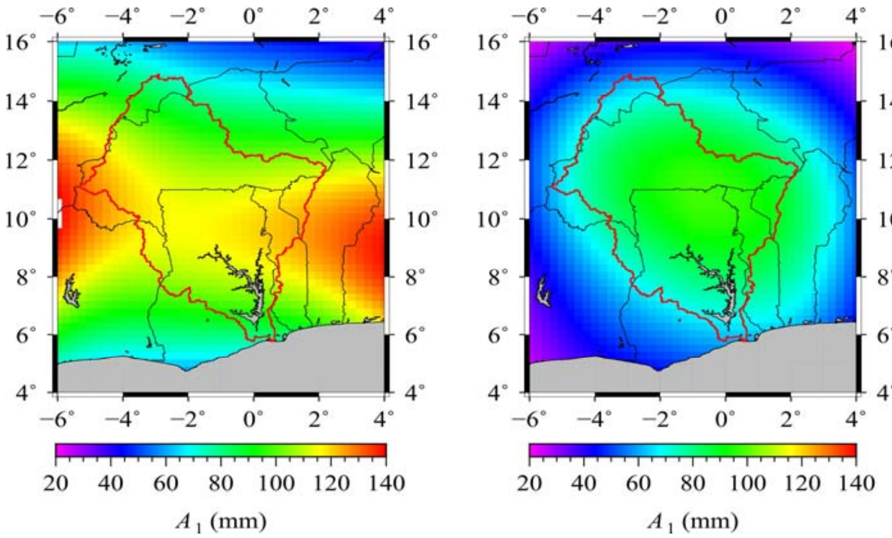


Figure 5 illustrates the amplitude A_1 (the annual signal) for EWT (left) and the rainfall (right) as well. The amplitudes of the annual signal of the EWT and the rainfall show quite similarities. The spatial distribution of the amplitude is dominated in the tropical transition zone by larges amplitudes in the EWT. This tropical transition zone is characterized with two rainfall seasons close to each other. Furthermore, for the entire study area, the correlation coefficient between the EWT annual amplitudes and the rainfall annual amplitudes was about the 0.63. This means that, at the annual scale, the precipitation can explain about the 63% of the EWT variations, *i.e.*, the EWT are not only caused by the occurrence of rainfall. However, if we look at the relation (7) we can see that only a small portion of precipitation accumulates in the region. Part of the water from rainfall evaporates and runs-off into the rivers and lakes. There must be some other processes involved, such as, mass transport from one region to another, which cause mass changes without rainfall.

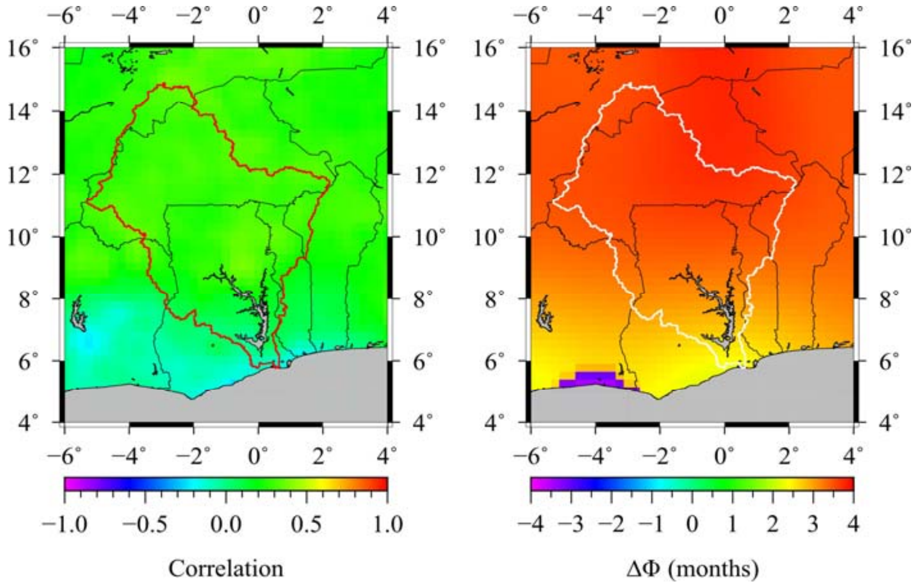
Figure 5 – The amplitude of the annual signal in mm are shown in panels where the left one for the EWT and in the right one for the rainfall.



To determine the relationship between both data sets, linear correlation coefficients were assessed at the seasonal scale. This was obtained by computing the correlation coefficient between the time series of EWT and rainfall for every grid point. We removed the constant a_0, linear a_1 and quadratic a_2 terms, *cf.* the expression (9), in both time series (EWT and rainfall) for each grid point. The results for the correlation coefficients are illustrated in Figure 6 (left). It can be recognized that for the tropical climate zone very similar correlation coefficients (around 0.3) are present. The mean value accounts for approximately 0.2, which indicates a low correlation. A possible explanation for the low correlation coefficient is that the both signal are not in phase indicating an offset in time or the influence of one variable may be spread over several observations of the other variable.

Rieser *et al.* (2010) reported that precipitation generally precedes EWT, and it takes some time until the accumulated water from precipitation is monitored as gravity change by GRACE. However, instead of using cross correlation function to determine the phase difference between the annual signals, we can use the differencing the phases obtained for each data set separately (*ibid*). In Figure 6 (right), the phase differences between EWT and rainfall ($\Phi_{EWT} - \Phi_{rainfall}$) are illustrated for the annual signals for each grid point. In the study area, rainfall appears approximately 1 to 4 months (from the south to north) before mass changes be detected by GRACE. This means that a rainfall event has occurred and then it takes between 1 to 4 months for the water mass be detected by GRACE mission.

Figure 6 – Correlation coefficients (left) of EWT and rainfall, phase differences (right) between EWT changes and rainfall.



Note: Positive values for phase differences (right) mean that the rainfall time series precede EWT time series and vice versa for negative phase differences.

4. CONCLUSION

We have assessed the water storage changes over the Volta River basin, West African to detected mass changes and its mechanisms. To achieve this goal, we have used the GRACE monthly gravity field solutions in the form of Stokes's coefficients and compared with precipitation data from TRMM grids. The comparison between terrestrial water storage changes and precipitation allowed the identification of the processes that need to be taken into account to understand mass changes over the study area. We found that the EWT in the Volta River basin increased over the period under consideration (January 2005 to December 2010 at a specific epoch 2007.5) from 20 mm/yr in the south part of the basin to 10 mm/yr in the north part. The analysis of seasonal variations revealed that mass changes are preceded by rainfall by about one month in the south of the basin while in the north about the four months. Future work should benefit greatly by using *in-situ* hydrology observations (*e.g.*, river level, river flow, soil moisture, etc.) to detect mass transport over Volta River basin.

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