Water Cycle and Climate Signals in Africa Observed by Satellite Gravimetry

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Abstract. The availability of hydrologic data is an important step for hydrological modeling and water resource management in the world. Unfortunately, the *in situ* observations with the right characteristics are very sparse globally, particularly in Africa. Understanding the climate variability of Africa and its prominent role as the heat engine of the global climate system is one of the key goals in climate research. Also, studies show that the time varying of terrestrial water storage contributes significantly to regional climate. In this paper, we have analyzed terrestrial water storage variations from GRACE satellite mission and from GLDAS model over the whole Africa for the period of August 2002 till April 2012. Amplitudes of water storage and rainfall data over some large river basins in Africa have been studied at seasonal and interannual scales. Comparison with the GLDAS model outputs is performed and discussed. Terrestrial Water Storage (TWS) estimates from GRACE and GLDAS show comparable patterns, however GRACE is better to detect interannual variation in water storage. Comparing TWS with rainfall data shows a phase lag of around one month between the maximum of the rainfall over a region and the maximum of TWS over the same region.

Keywords: Terrestrial water storage; Hydrological cycle; Africa

1. Introduction

Monitoring, understanding, and quantifying water cycle budget is of great importance in both continental and regional scales, especially in light of current global climate change. Global climate change affects water resources around the world in unknown ways. Climatic extremes (e.g. drought) are normal climatic occurrences in Africa. Awange et al. (2007) described how extensive droughts are a regular feature in parts of East Africa in the last few decades [1]. The absence of adapted measures of water resources may result in negative impact on human life. Pressure placed on water resources in the last few years is increased significantly due to population growth and economic development as well as political problems and wars between neighbouring countries. Monitoring the total water stored within river basins in Africa is crucial for growing population and agriculture. Performing *in-situ* measurements is very difficult in Africa because of its very high costs, especially in such poor countries in Africa, in addition to the lack of regional hydrological models describing the water cycle in Africa. Satellite remote sensing data may overcome current limitations.

The Gravity Recovery and Climate Experiment (GRACE) satellite mission provides unique observations of variations in the Earth's gravity field with monthly intervals and spatial resolution of several hundred km, theoretically reflecting the terrestrial water storage (TWS) variations in the land. Therefore, the using of global satellite data (e.g. GRACE) as well as global hydrological models (e.g. GLDAS) is of great importance for monitoring and understanding the water cycle in Africa. Studying the Total Water Storage (TWS) in some river basins in Africa (e.g. Volta River, Zambezi River, and Okavango River) is presented in this work. Seasonal and interannual scales of TWS variation will be studied as well as the effect of rainfall on TWS variation.

2. Satellite Gravimetry and Model

2.1. Gravimetric Data

Since mid-2002 the Gravity Recovery and Climate Experiment (GRACE) satellite mission has been collecting data about the Earth's gravity field over a large spatial scale. GRACE is currently measuring the Earth's mass redistributions with a spatial resolution of ~300 km (half wavelength) and monthly temporal resolution, which can be used to estimate water storage changes over an entire region or basin [2] [3].

Although it has relatively coarse spatial and temporal resolutions, GRACE has the advantage that it senses changes in water storage in all levels; including groundwater, as well as surface water [4]. TWS variations observed by GRACE include combined contributions of groundwater, soil water, surface water, snow, and ice. The climate of Africa is warm, so snow and ice are uncommon. GRACE represents unprecedented tool to address current research problems in hydrological modelling. For example, GRACE is used to estimate groundwater storage and depletion [4] [5], studying terrestrial water storage budget [6], monitoring water balance in lakes [e.g. 7] and river basins [e.g. 8], observing seasonal steric sea level variations [9], studying terrestrial water contributions to polar motion [10], and monitoring drought [11].

2.2. GLDAS Model Data

Fields of land surface states and fluxes were simulated by the Noah land surface model [12] driven by the Global Land Data Assimilation System [13]. The goal of the Global Land Data Assimilation System (GLDAS) is to ingest satellite- and ground-based observational data products, using advanced land surface modeling and data assimilation techniques, in order to generate optimal fields of land surface states and fluxes in near real time.

Each monthly GLDAS data consists of 25 variables. The data set covers from 60° S to 90° N of the world. From these files land surface state variables (soil moisture, snow water equivalent, canopy water storage) and land surface fluxes (precipitation, and evapotranspiration) are derived. The GLDAS soil moisture data has been used for global and regional studies. GLDAS soil moisture, snow water equivalent, and canopy water storage data can be used to isolate groundwater storage from the total water storage estimated by GRACE data [4].

3. Data Processing and Results

GRACE data is provided by different institutes. In this work we used GRACE RL04 spherical harmonics coefficients provided by the Centre of Space Research (CSR) of the University of Texas at Austin up to degree and order 60 from August 2002 up to April 2012. GRACE TWS anomalies are relative to the time mean of January 2003 to December 2006.

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After removing the temporal mean, GRACE observations are corrected for correlated errors by post-processing GRACE monthly solutions according to Swenson and Wahr (2006) [14]. Decorrelation is done with a filter width *w*=5 for spherical harmonics orders above 7 [15].

Additionally, the degree 1 coefficients (geocenter) is used from Swenson et al. (2008) [16], and the $C_{2,0}$ coefficients are substituted with measurements from Satellite Laser Ranging [17]. For spatial maps of TWS anomalies, the spherical harmonic coefficients are smoothed with a Gaussian averaging kernel of 300 km half width, and then mapped the data onto a regular 1° x 1° grid [3].

GRACE continuously provides monthly mean TWS anomalies, however in some months measurement is missing. For example, GRACE TWS data has missing values for June 2003, January 2011, and June 2011. These values can be linearly interpolated from the previous and following months [6]. We fit the time series using five terms: mean, annual sine and cosine, and semi-annual sine and cosine with $t=0$ at January 1st.

The GLDAS 1° by 1° monthly NOAH land surface model (i.e. GLDAS_NOAH10_M) that is distributed in Network Common Data Format (netCDF) files is used for this work. The time series is fitted using five terms: mean, annual sine and cosine, and semi-annual sine and cosine (the same way as GRACE data).

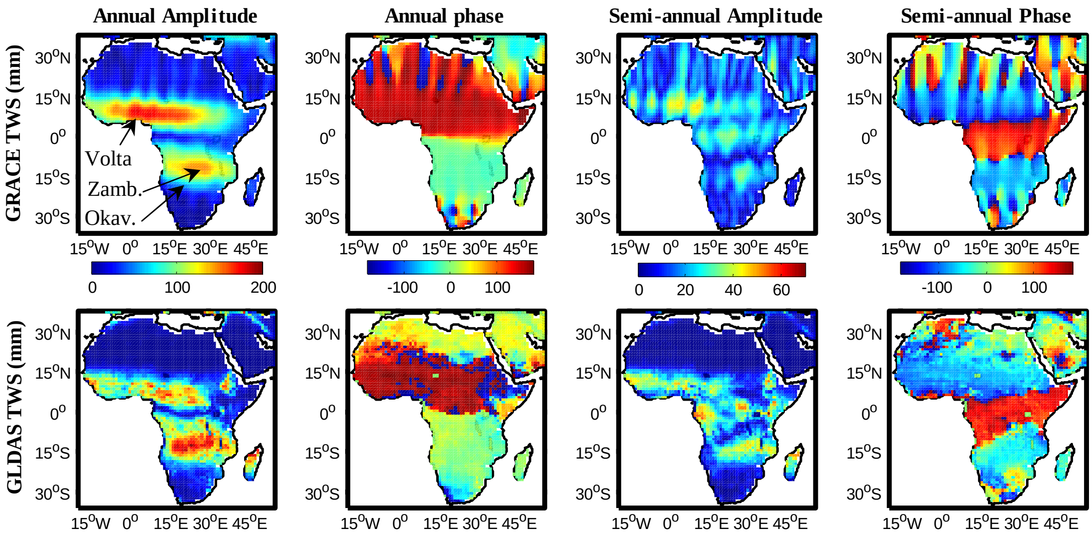

Figure 1. Amplitude A *(mm)* and phase φ *(degrees)* of annual and semiannual TWS in Africa from GRACE and GLDAS. Phase is calculated taking time $t=0$ at January 1st. Locations of rivers is shown in the first top left panel.

Figure (1) shows that during this time period, much of Africa above 15° N latitude as well as parts in east Africa experienced a noticeable lack of water storage. This is because most of these regions are arid and semiarid desert. The largest annual amplitude detected by GRACE occurs in the west part of Africa in regions of Volta River Basin with values reaching 170 mm. Another strong signal appears in parts of south central Africa in regions of Zambezi River Basin and Okavango River Basin with amplitudes approaching 150 mm. GLDAS model shows almost the same pattern as GRACE with one difference, that is the largest annual amplitude estimated by GLDAS occurs in the regions of Zambezi River Basin which approaching 180 mm while parts of central and western Africa shows a little weaker signal which reaches 100 mm. This difference may, conceptually, refer to that GRACE measures the total water storage (including groundwater and surface water) while GLDAS model can't estimate underground water storage.

Analysis of semiannual cycle is showing that GRACE and GLDAS are less comparable, (Figure 1). It shows that GLDAS model can't detect semiannual variability as well as GRACE. GRACE TWS shows semiannual variability in parts of northern Africa reaching the value of 20 mm. The largest semiannual amplitude signal detected by GRACE occurs in western Africa in regions of Volta River Basin which exceeding 40 mm.

Both sets of phase results, shown in Figure (1), show the annual cycle tends to be maximum in August above 0° latitude and in January below 0° latitude (i.e. in Summer). This is also clear from Figure (2) which is showing the seasonal cycle of GRACE TWS in the river basins which experienced the largest amplitude signals. It shows that the maximum TWS in regions of Volta River Basin occurs in September. The opposite occurs in regions of Zambezi and Okavango river basins in south central Africa with the maximum TWS in March and February respectively. Another river basin shown in figure (2) which is the Orange River Basin which lies in southern Africa. It has a very weak signal compared with the previous river basins. In addition, Figure (2) shows the seasonal cycle of TWS in parts of northern Africa (above 15° N latitude) which has a very weak signal.

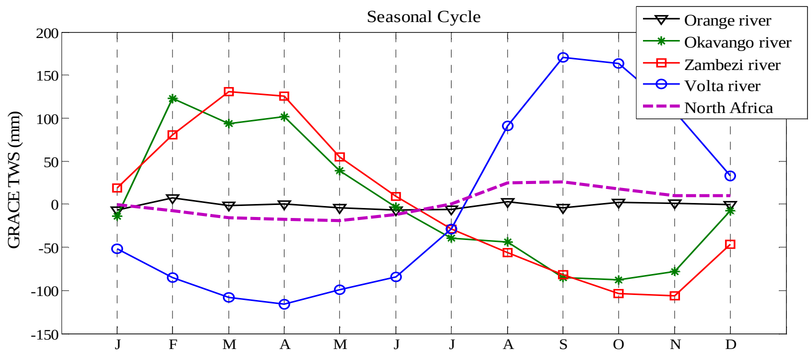

Figure 2. Seasonal cycle of GRACE TWS of some river basins in Africa

Figure (3) shows the time series of GRACE TWS in the same river basins along with the parts of northern Africa. It is easy to notice the large amplitude of Volta, Zambezi, and Okavango river basins compared the Orange River Basin. During this time period, all the three rivers experienced an increase in its TWS with values of 10.5 mm/yr, 17 mm/yr, and 20.4 mm/yr for Volta, Zambezi, and Okavango river basins respectively. It can be seen also that the TWS in northern Africa is interannually changing and it does not follow a clear trend in addition to its weak amplitude which is not exceeding 30 mm.

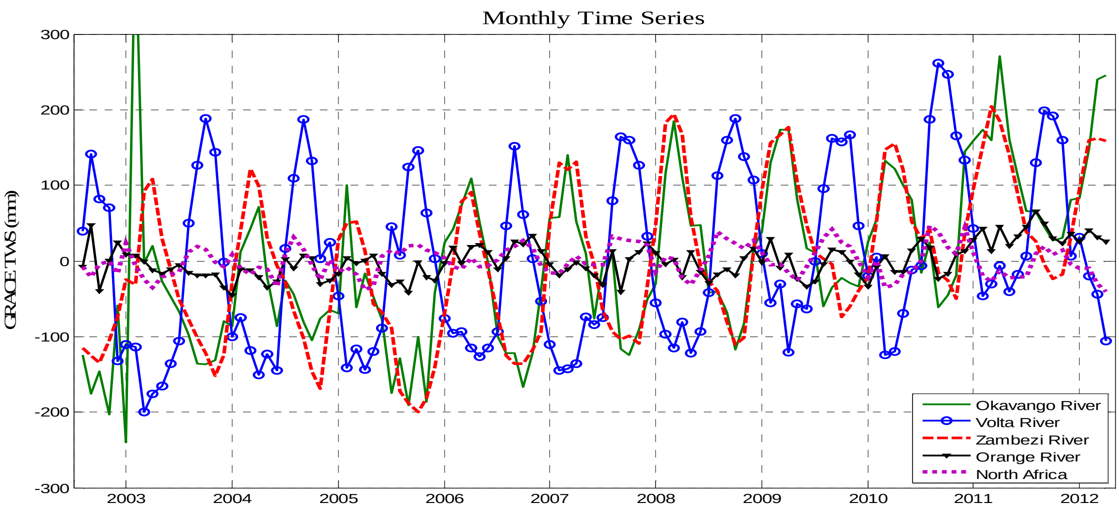

Figure 3. Monthly TWS of river basins in Africa as estimated by GRACE

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Figure (4) shows a comparison between GRACE TWS and the values of rainfall as estimated from GLDAS model. Both sets of amplitude show qualitative agreement with significant large signals in western Africa and south central Africa. While the annual phase shows that TWS is preceded by rainfall by about one month (i.e. a phase lag of around one month). This is also clear from figure (5) which shows the seasonal cycle of GRACE TWS and rainfall data over Volta, Zambezi, and Okavango river basins. It shows that the rainfall over Volta River Basin reaches its maximum in August while GRACE TWS is maximum in September (i.e. one month phase lag). Since both Zambezi and Okavango river basins are in the same region (south central Africa), so their rainfall seasonal cycle are almost the same, it reaches its maximum in January while GRACE TWS reaching maximum in March (i.e. two months phase lag) and February (i.e. one month phase lag) for Zambezi and Okavango river basins respectively.

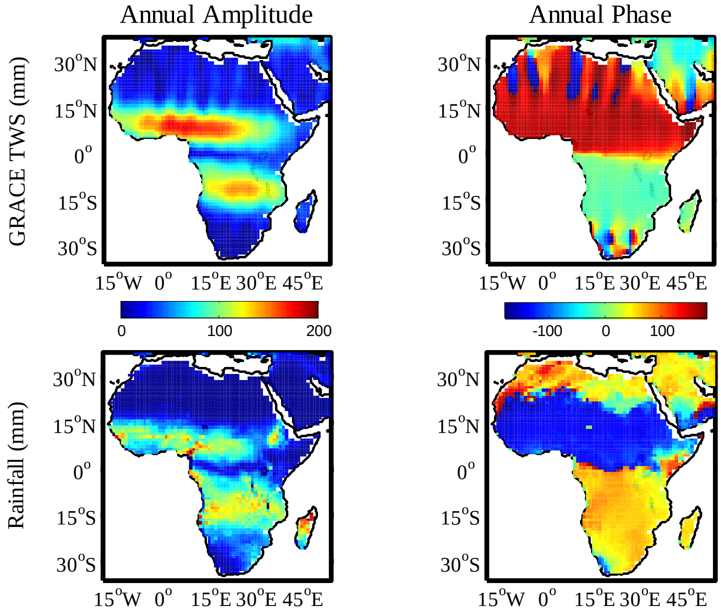

Figure 4. Comparison of annual amplitudes and phases of GRACE TWS and rainfall estimated from GLDAS. Phase is calculated taking time $t=0$ at January 1st.

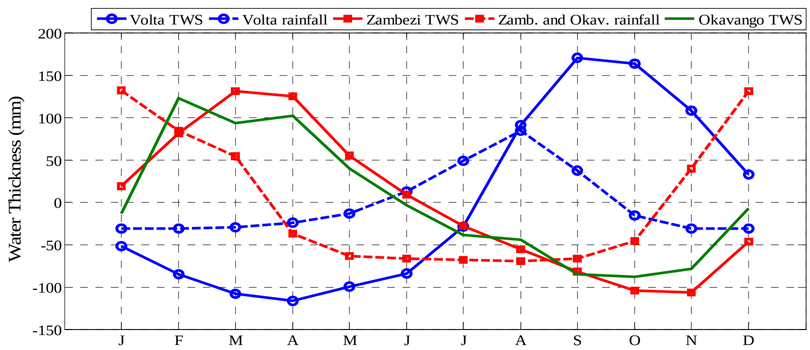

Figure 5. Seasonal cycle of GRACE TWS and rainfall data over Volta, Zambezi, and Okavango river basins.

4. Conclusions

In this work Total Water Storage (TWS) is estimated from GRACE observations and GLDAS model data for Africa. GRACE and GLDAS show the same pattern of estimating the amplitude and phase of TWS. However, GRACE is better in observing semiannual variations especially in regions suffering from a lack in water storage. Large annual amplitudes occur in regions of Volta River Basin in western

Africa and in regions of Zambezi and Okavango river basins in south central Africa. TWS tends to be maximum in summer. This will be in August and September above 0° latitude and in January and February below 0° latitude. Additionally, we found that TWS is preceded by rainfall by about one month (i.e. a phase lag of around one month).

References

[1] Awange J, Aluoch J, Ogallo L, Omulo M and Omondi P 2007. Frequency and severity of drought in the Lake Victoria region (Kenya) and its effects on food security. *Clim. Res.* **33**, 135-142.

[2] Tapley B, Bettadpur S, Watkins M and Reigber C 2004. The gravity recovery and climate experiment: mission overview and early results. *Geophys. Res. Lett.* **31**, L09607. doi: 10.1029/2004GL019920.

[3] Wahr J, Molenaar M and Bryan F 1998. Time-variability of the Earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE. *J. Geophys. Res.* **103** (32), 205–229, 1998.

[4] Rodell M, Velicogna I and Famiglietti J 2009. Satellite-based estimates of groundwater depletion in India. *Nature.* **460**, 999-1002, doi: 10.1038/nature08238.

[5] Rodell M, Chen J, Kato H, Famiglietti J, Nigro J and Wilson C 2006. Estimating groundwater storage changes in the Mississippi River basin (USA) using GRACE, (Springer-Verlag).

[6] Landerer F, Dickey J and Güntner A 2010. Terrestrial water budget of the Eurasian pan Arctic from GRACE satellite measurements during 2003–2009. *J. Geophys. Res.* **115**, D23115, doi: 10.1029/2010JD014584.

[7] Swenson S and Wahr J 2009. Monitoring the water balance of Lake Victoria, East Africa, from space. *J. of Hydrol.* vol. **370**, no. 1, pp. 163-176.

[8] Crowley J, Mitrovica J, Bailey R, Tamisiea M and Davis J 2006. Land water storage within the Congo Basin inferred from GRACE satellite gravity data. *Geophys. Res. Lett.* **33**, L19402, doi: 10.1029/2006GL027070.

[9] Chambers D 2006. Observing seasonal steric sea level variations with GRACE and satellite altimetry. *J. Geophys. Res.* **111**, C03010, doi: 10.1029/2005JC002914.

[10] Jin S, Hassan A and Feng G 2012. Assessment of terrestrial water contributions to polar motion from GRACE and hydrological models. *J. Geodyn.* **62**, 40-48, doi: 10.1016/j.jog. 2012.01.009.

[11] Yirdaw S, Snelgrove K and Agboma C 2008. GRACE satellite observations of terrestrial moisture changes for drought characterization in the Canadian Prairie. *J. Hydrol.* **356**, 84-92.

[12] Ek M, Mitchell K, Lin Y, Rogers E, Grunmann P, Koren V, Gayno G and Tarpley J 2003. Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model. *J. Geophys. Res.* **108** (D22), 8851, doi: 10.1029/2002JD003296.

[13] Rodell M, Houser P, Jambor U, Gottschalck J, Mitchell K, Meng C, Arsenault K, Cosgrove B, Radakovich J, Bosilovich M, Entin J, Walker J, Lohmann D and Toll D 2004. The Global Land Data Assimilation System, Bull. *Amer. Meteor. Soc.* **85**(3): 381-394.

[14] Swenson S and Wahr J 2006. Post-processing removal of correlated errors in GRACE data. *Geophys. Res. Lett.* **33**, L08402, doi: 10.1029/2005GL025285.

[15] Duan X, Guo J, Shum C and W. van der Wal 2009. On the postprocessing removal of correlated errors in GRACE temporal gravity field solutions, *J. Geod.* **83**, 1095–1106, doi: 10.1007/s00190-009-0327-0.

[16] Swenson S, Chambers D and Wahr J 2008. Estimating geocenter variations from a combination of GRACE and ocean model output. *J. Geophys. Res.* **113**, B08410, doi: 10.1029/2007 JB005338.

[17] Cheng M and Tapley B 2004. Variation's in the Earth's oblateness during the past 28 years. *J. Geophys. Res.* **109**, B09402, doi: 10.1029/2004JB003028.