Preliminary Results on the Estimation of Ground Water in Africa Using GRACE and Hydrological Models

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Abstract

Groundwater is a main source of fresh water in many parts of the world. Monitoring the global and regional groundwater resources is challenging nowadays because of the very scare and high cost in situ measurement networks, especially in Africa. Satellite gravimetry can be used in combination with land surface hydrological models (e.g., Global Land Data Assimilation System (GLDAS) and WaterGAP Global Hydrology Model (WGHM)) to infer groundwater storage behavior. Since 2002, the Gravity Recovery and Climate Experiment (GRACE) satellite mission provides estimation of the Earth's dynamic gravity field with unprecedented accuracy. Differences between monthly GRACE gravity field solutions give an estimation of the Terrestrial Water Storage (TWS) changes. The groundwater storage can be obtained using the available hydrological models by subtracting the surface water, soil moisture, snow, ice and canopy water from the TWS. GRACE data are available in terms of spherical harmonics expansion. However, GLDAS and WGHM hydrological models are available in the space domain as grids of 1° and 0.5°, respectively. For consistency, both GLDAS and WGHM are approximated in terms of spherical harmonic expansions to be comparable with the used GRACE data. In this paper, the groundwater storage in Africa is studied using GRCAE data (2003–2016) as well as GLDAS and WGHM models for the same time period. Inter annual variations is investigated from monthly groundwater time series.

Keywords

GLDAS · GRACE · Groundwater storage estimation · Terrestrial Water Storage (TWS) · WGHM

1 Introduction

Groundwater is an important part of the water cycle. In Africa, groundwater is considered as one of the major resources of fresh water. The total groundwater storage in Africa is estimated to be approximately 0.66 million km^3 (MacDonald et al. 2012). Not all of this groundwater storage is available for discharge, but it is estimated to be more than 100 times that of annual renewable freshwater resources in Africa. Groundwater resources are unequal distributed, while the largest found in the large aquifers in the North African countries like Libya, Algeria, Egypt and Sudan (MacDonald et al. 2012). Groundwater was normally monitored by traditional instruments, e.g. Ground Penetrating Radar (GPR), and nets of wireless sensors. However, global groundwater storage and its variability are difficultly monitored due to the lack of comprehensive global monitoring network with high cost and strong labor intensity (Jin and Feng 2013).

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The Gravity Recovery and Climate Experiment (GRACE) mission, provides an unprecedented opportunity to detect continental water-storage variations with a spatial resolution of about 300 km (half wavelength) and monthly temporal resolution. Tapley et al. (2004) and Wahr et al. (2004) provided early results on the application of the GRACE products for detecting hydrological signals in different major river basins (e.g., Amazon basin and Mississippi River). Although it has relatively low spatial and temporal resolutions, GRACE has the ability to sense the changes in total water storage in all levels; including groundwater, as well as surface water (Rodell et al. 2009).

GRACE has been widely used in numerous studies to retrieve water storage variations, both globally and regionally. For instance, Ramillien et al. (2004, 2005) investigated the continental water storage variations using the first 2 years data GRACE, and compared these changes with the output from four global hydrological models in different drainage basins of the world. It was possible to correlate large scale hydrological events with the estimated change in the gravity field for certain areas of the world at an accuracy of 9 mm equivalent water thickness.

Few GRACE applications have been carried out to study water storage variations over Africa. Crowley et al. (2006) estimated the TWS within the Congo Basin in Africa for the period from April 2002 up to May 2006. A total loss of about 280 km^3 of water was found over the period of study with a seasonal signal of 30 ± 6 mm of equivalent water thickness. Klees et al. (2007) compared monthly mean water storage variations inferred from GRACE in the upper Zambezi River (southern Africa) with the outputs of the LEW (Lumped Elementary Watershed) regional hydrological model. Rodell et al. (2009) studied groundwater depletion in India during the period from August 2002 to October 2008. They used the TWS change observed from GRACE as well as the simulated soil-water variations from GLDAS (Global Land Data Assimilation System). Their results showed that the groundwater depleted at a mean rate of 4.0 ± 1.0 cm/year equivalent water height. In this work, GRACE observations are used with the outputs from GLDAS hydrological model to study the groundwater storage variations in Africa during the period from January 2003 to December 2016. Comparison with the groundwater estimates from WGHM (WaterGAP Global Hydrology Model) is carried out.

2 Data Sources

2.1 Gravity Recovery and Climate Experiment (GRACE)

Since 2002, the Gravity Recovery and Climate Experiment (GRACE) satellite mission, sponsored by NASA and its German counterpart DLR, has been collecting gravimetric observations. One of the main products of the GRACE mission are the level-2 time-variable gravity fields (Flechtner 2007) which are monthly geopotential solutions released in terms of spherical harmonic coefficients. The latest Level-2 Release05 (RL05) monthly spherical harmonics coefficients provided by the Centre of Space Research (CSR) of the University of Texas at Austin (CSR, Bettadpur 2012) up to degree and order 60 are used for this study during the period from January 2003 up to December 2016 (except unavailable months, e.g., June 2015).

2.2 GLDAS Hydrological Model

The Global Land Data Assimilation System (GLDAS) project is led by scientists of the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA). GLDAS is a land surface simulation system which aims to ingest satellite- and ground-based observational data products in order to generate optimal fields of land surface state (e.g., soil moisture, snow, and surface temperature) and flux (e.g., evapotranspiration, sensible heat flux) products (Rodell et al. 2004). In this paper, GLDAS version-1 NOAH model with 1° resolution is used during the period from January 2003 to December 2016.

2.3 WaterGAP Global Hydrological Model (WGHM)

The WaterGAP Global Hydrology Model (WGHM) provides time series of monthly runoff (surface/subsurface runoff and groundwater recharge) and river discharge by using 724 globally distributed stations. All computations are done at a spatial resolution of $0.5° \times 0.5°$ covering all land areas with the exception of Antarctica and Greenland. The model has basically been developed to simulate variations of water storage components within the framework of water availability and water use assessment at the global scale over river basins (Döll et al. 2003; Güntner et al. 2007). In this paper we used the total groundwater storage from the WGHM model at $0.5° \times 0.5°$ spatial resolution for January 2003–December 2013 (no data are available after 2013) for comparison purposes.

3 Methodology

The Terrestrial water storage variations (Δ_{TWS}) observed by GRACE include a combined contribution of the modeled changes in soil moisture (Δ_{SM}), groundwater (Δ_{GW}), snow/ice water equivalent (Δ_{SWE}), and biomass ($\Delta_{biomass}$), i.e.,

$$\Delta_{TWS} = \Delta_{SM} + \Delta_{\mathrm{GW}} + \Delta_{\mathrm{SWE}} + \Delta_{biomass}. \qquad (1)$$

Because of the common warm weather in Africa, snow is uncommon (i.e., Δ_{SWE} nearly vanishes in Africa). Biomass water variation ($\Delta_{biomass}$) is negligible in most cases (Cazenave and Chen 2010). Accordingly, the non-negligible sources of the Terrestrial Water Storage variability (Δ_{TWS}) in Africa were assumed herein to be the soil moisture (Δ_{SM}) and the groundwater (Δ_{GW}) variations. Accordingly, the groundwater variation is computed as:

$$\Delta_{GW} = \Delta_{TWS} - \Delta_{\mathrm{SM}}. \qquad (2)$$

4 Estimation of TWS from GRACE

The terrestrial water storage (TWS) anomalies over the land can be related to changes in the Stokes coefficients, $\triangle C_{lm}$ and $\triangle S_{lm}$, for each month as (Wahr et al. 1998):

$$\Delta\sigma(\theta,\lambda) = \frac{a\,\rho_{av}}{3\,\rho_w}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\frac{2l+1}{1+k_l}W_l \times\left[\bar{P}_{lm}(\cos\theta)\left(\Delta C_{lm}\cos m\lambda + \Delta S_{lm}\sin m\lambda\right)\right], \qquad (3)$$

where $\Delta\sigma$ is the surface mass variability (which reflects the change in water storage), a is the earth's semi-major axis, ρ_{av} is the average density of the earth (5,517 kg/m^3), ρ_w is the density of the fresh water (1,000 kg/m^3), $\bar{P}_{lm}$ is the normalized associated Legendre functions with degree l and order m, k_l is the elastic love number of degree l, W_l corresponds to the Gaussian smoothing operator, θ is the co-latitude, λ is the eastward longitude, $\triangle C_{lm}$ and $\triangle S_{lm}$ are the monthly Stokes coefficient anomalies (Han and Wahr 1995). GRACE level-2 spherical harmonics solutions are provided by a number of institutes. In this work, GRACE CSR-RL05 solutions up to degree/order 60 are processed to infer TWS variations in Africa. The study area extends from 40.5°S latitude to 40.5°N and from 20.5°W longitude to 60.5°E.

GRACE CSR-RL05 solutions are also available up to degree/order 96. In order to study the effect of using a higher upper degree than 60, the TWS monthly anomaly in Africa during 2007 is computed from GRACE-CSR coefficients taking $N_{max} = 60$ and $N_{max} = 96$; Fig. 1. Figure 1 shows practically no differences. Thus, it can be concluded that using upper degree greater than 60 has *insignificant* influence on the geophysical signals.

The temporal mean, computed over the period of the study, has been removed from the monthly estimated GRACE fields. After removing the temporal mean, GRACE data are corrected for correlated errors by post-processing GRACE monthly solutions by applying a moving window filtering method according to Swenson and Wahr (2006). However, the window width used by Swenson and Wahr (2006) is not provided in the original paper, Duan et al. (2009) cited Swenson and Wahr's unpublished result of window width. Decorrelation filter is done for the spherical harmonics of order $m = 5$ and above, and the window width w depends on m in the following form:

$$w = \max\left(Ae^{-\frac{m}{k}} + 1, 5\right), \qquad (4)$$

where the function $max(x_1,x_2)$ selects the larger argument. Swenson and Wahr (2006) have empirically chosen $A = 30$ and $K = 10$ for the CSR RL02 data they used at the time, evidently based on a trial-and-error procedure. Here the same values of A and K are used.

Additionally, GRACE does not provide degree 1 coefficient changes C_{10}, C_{11}, and S_{11}, which represent variation of the earth's center of mass relative to the crust-fixed terrestrial reference frame (geocenter motion) (Chen et al. 1999; Chambers et al. 2004). The monthly degree 1 coefficients are used from (Swenson et al. 2008). The monthly C_{20} coefficients are replaced with the solutions from Satellite Laser Ranging (SLR) (Chen et al. 2004), because the native GRACE-C20 values have a larger uncertainty than the SLR-values.

The gravity field produced by GRACE satellite mission requires a smoothing operator to reduce the effects of the errors present in the short wavelength components. As the smoothing radius decreases, these errors manifest themselves in maps of surface mass variability as long, linear features generally oriented north to south (i.e., stripes). Then the spherical harmonic coefficients are smoothed with a Gaussian averaging kernel of 500 km radius, using the formula represented by Chambers (2006):

$$W_l = \left[-\frac{(lr/a)^2}{4\ln(2)}\right], \qquad (5)$$

where W_l is the smoothed value, and r is the smoothing radius.

Figure 2 shows the GRACE-derived TWS monthly mean difference and trend in Africa using a 500 km Gaussian smoothing. It shows that the maximum positive trend in Zambezi river basin in southern Africa. The maximum negative trend happened in Congo River basin in middle Africa. A negative trend happened in northern Africa.

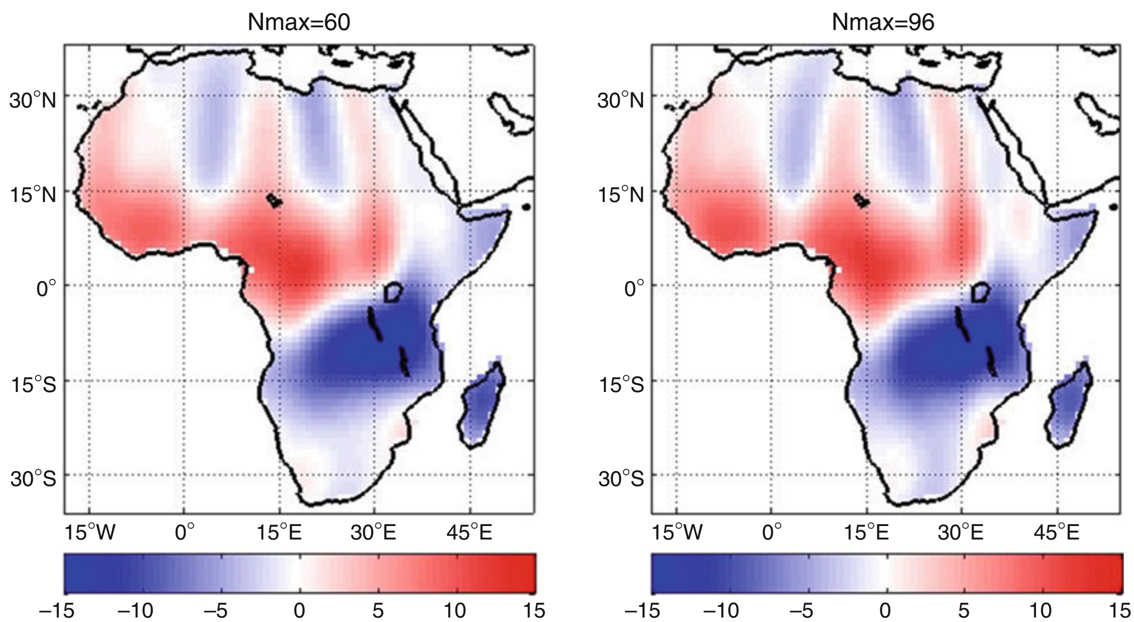

Fig. 1 The GRACE TWS monthly anomaly for 2007 using $N_{max} = 60$ and $N_{max} = 96$. Units in [mm]

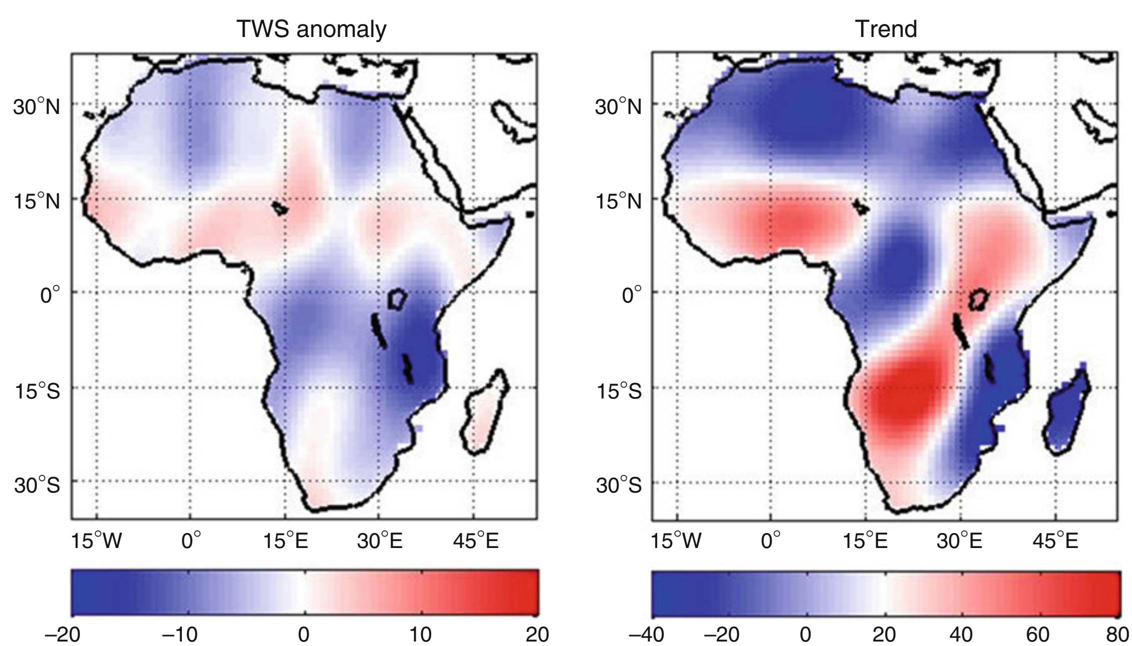

Fig. 2 The GRACE average monthly difference of TWS (*left panel*) and trend of TWS (*right panel*) from Jan. 2003 to Dec. 2016. Units in [mm]

5 Spherical Harmonic Analysis of the Hydrological Models

GRACE data are available in terms of spherical harmonics expansion. However, GLDAS and WGHM hydrological models are available in the space domain as grids of 1° and 0.5°, respectively. Accordingly, for fair comparisons, both GLDAS and WGHM are approximated in terms of spherical harmonic expansions to the same degree (i.e., 60) as the used GRACE data. Then, the same filtering process has been applied to the transformed GLDAS and WGHM (i.e., 500 km Gaussian smoothing filter and the decorrelation filter).

The estimation of the harmonic coefficients for both GLDAS and WGHM models is done using the Gauss-Legendre numerical integration harmonic analysis technique within an iterative approach (Abd-Elmotaal et al. 2014). In order to evaluate the performed spherical harmonics analysis, the estimated fields of GLDAS and WGHM, computed from their spherical harmonic expansions on a global grid of $1° \times 1°$, are compared to their original fields.

Figure 3 shows the original GLDAS field for January 2003, while Fig. 4 shows the approximated GLDAS filed for the same month computed from the spherical harmonic expansion. Figure 5 illustrates the difference between the original and the approximated GLDAS fields. Figure 5 demonstrates good approximation.

The soil moisture storage variation is estimated using the GLDAS NOAH (1° resolution) model by summing the four layers of soil moisture. Figure 6 shows the GLDAS soil moisture (monthly anomaly and trend) for Africa computed from the spherical harmonic analysis mentioned above. Figure 6 shows that the maximum signal occurs at Congo basin in middle Africa. The minimum signal happened in northern Africa.

6 Groundwater Estimation Using GRACE and GLDAS and Its Evaluation Using WGHM

We used GLDAS time series of soil moisture storage to isolate groundwater storage variations from the GRACE TWS anomalies (using Eq. (2)) by subtracting the GLDAS soil moisture storage (Δ_{SM}) from GRACE-TWS (Δ_{TWS}). Figure 7 represents the mean monthly variation of groundwater in Africa (*left panel*) as well as the trend over the time period (*right panel*). The maximum positive trend happened in Zambezi river basin in southern Africa. An increase in groundwater storage occurred in western Africa in Volta River basins while a negative variation happened in middle Africa in Congo River basin.

Figure 8 represents the time series of the averaged total (vertically-integrated) TWS over Zambezi river basin and estimates from the GRACE, GLDAS hydrological model and Groundwater (GRACE – GLDAS). It shows a small depletion at 2005 followed by a significant increasing trend from 2006 to 2010. The overall trend value of 16.60 + 1.1 mm/year is observed during the period of study.

In the view of the lack of in situ measurements, groundwater estimated directly from WGHM model is used to evaluate the GRACE-based groundwater variations. The disadvantage of the WGHM model is that it is only available up to December 2013. Figure 9 shows the WGHM groundwater monthly anomaly in Africa (*left panel*) and the trend over the time period (*right panel*) computed from the spherical harmonic expansion performed in Sect. 5. Comparing Figs. 7 and 9 illustrates the same positive trend in Volta River basin in western Africa. In addition, same strong negative signal appears in the western part of middle Africa, while almost zero signal appears in northern Africa. This proves that the used approach in the current paper to estimate the groundwater using GRACE and GLDAS is successful to a good extent.

7 Conclusion

In this paper, the groundwater variations in Africa are estimated and investigated from GRACE–GLDAS in the period of January 2003 to December 2016.

Figure 2 represents the mean monthly variation of TWS which comes from GRACE spherical harmonics, with the maximum signal occurs at Congo basin and zero signal in northern Africa. Figure 6 shows the mean monthly variation of soil moisture content which comes from GLDAS-NOAH model computed by its spherical harmonic expansion estimated by the Gauss-Legendre numerical integration harmonic analysis technique. Subtracting the soil moisture variation from total water storage variation gives the variation of the groundwater. Figure 7 represents the mean monthly variation of groundwater in Africa. An increase in groundwater storage occurred in western Africa in Niger and Volta River basins while a negative variation happened in middle Africa in Congo River basin. The results are then compared with the groundwater storage variation estimated from WGHM model. It shows similar results, which proved the success of the proposed developed approach. The proposed approach of using GRACE and GLDAS having the advantage of continuous data availability up to date. In contrast, WGHM is only available until December 2013.

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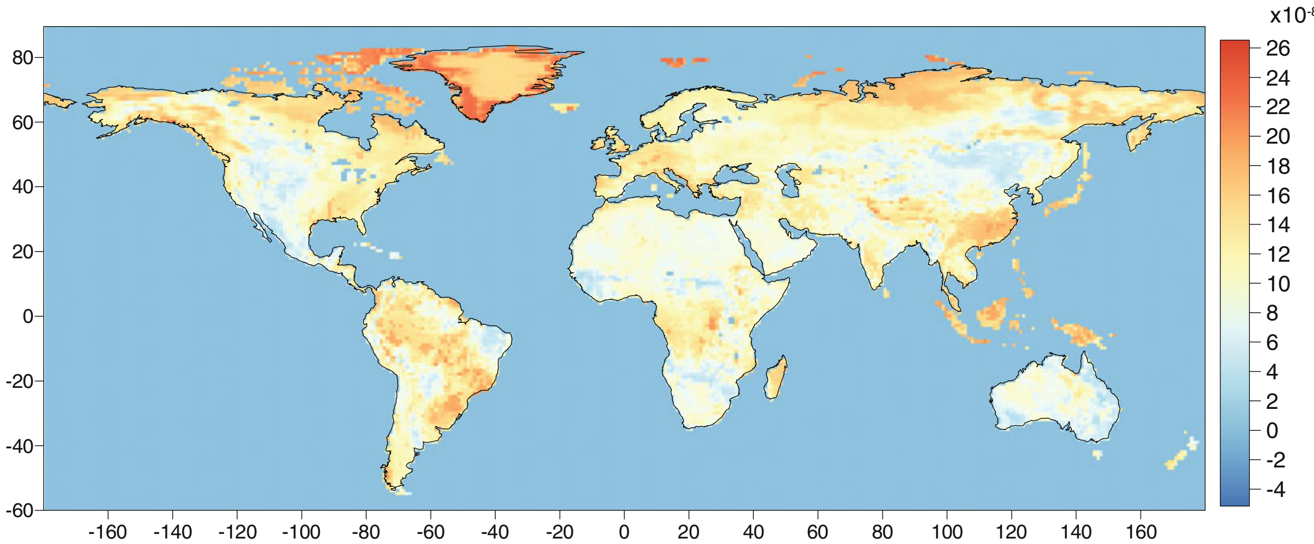

Fig. 3 The January 2003 original GLDAS. Units in [kg/m^2]

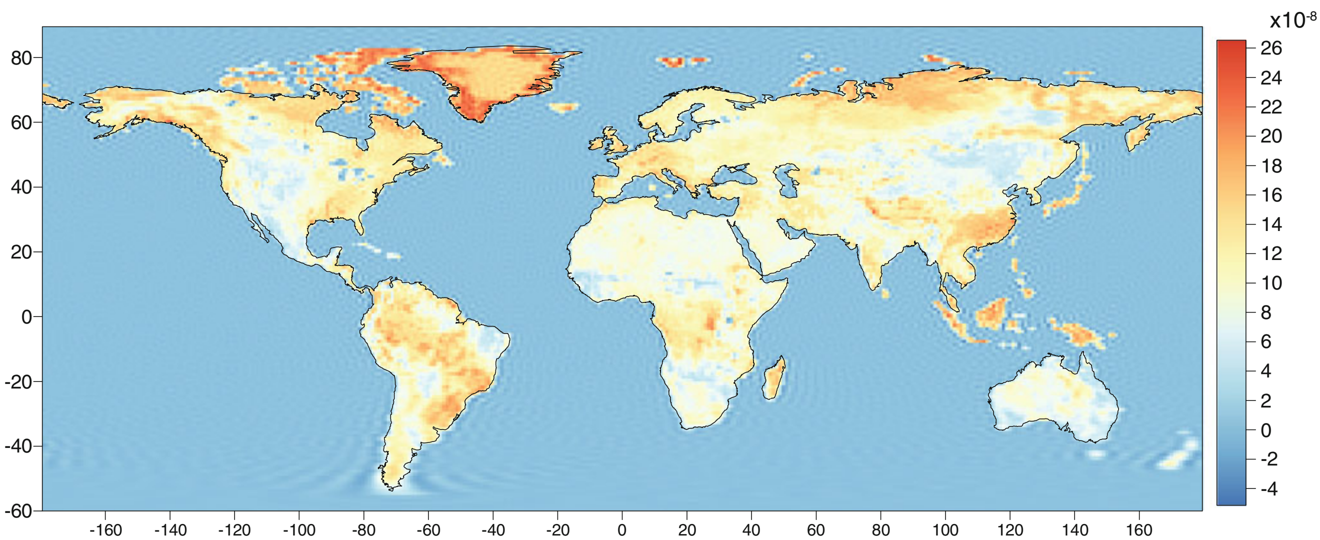

Fig. 4 The January 2003 approximated GLDAS computed from spherical harmonic expansion. Units in [kg/m^2]

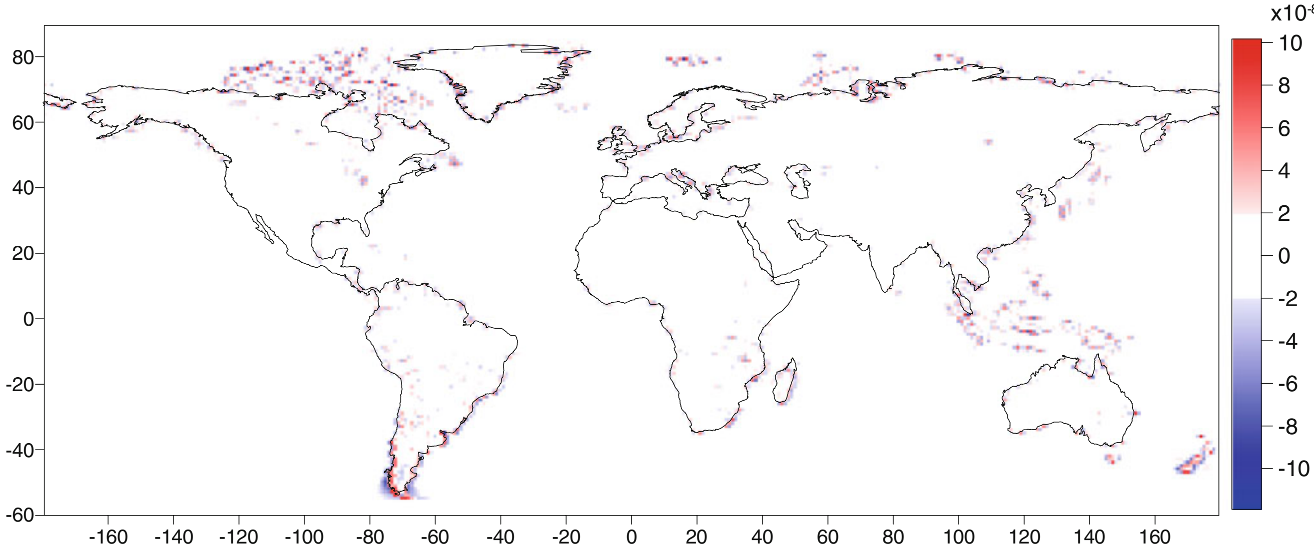

Fig. 5 The Difference between original GLDAS and approximated GLDAS by spherical harmonic expansion. Units in [kg/m^2]

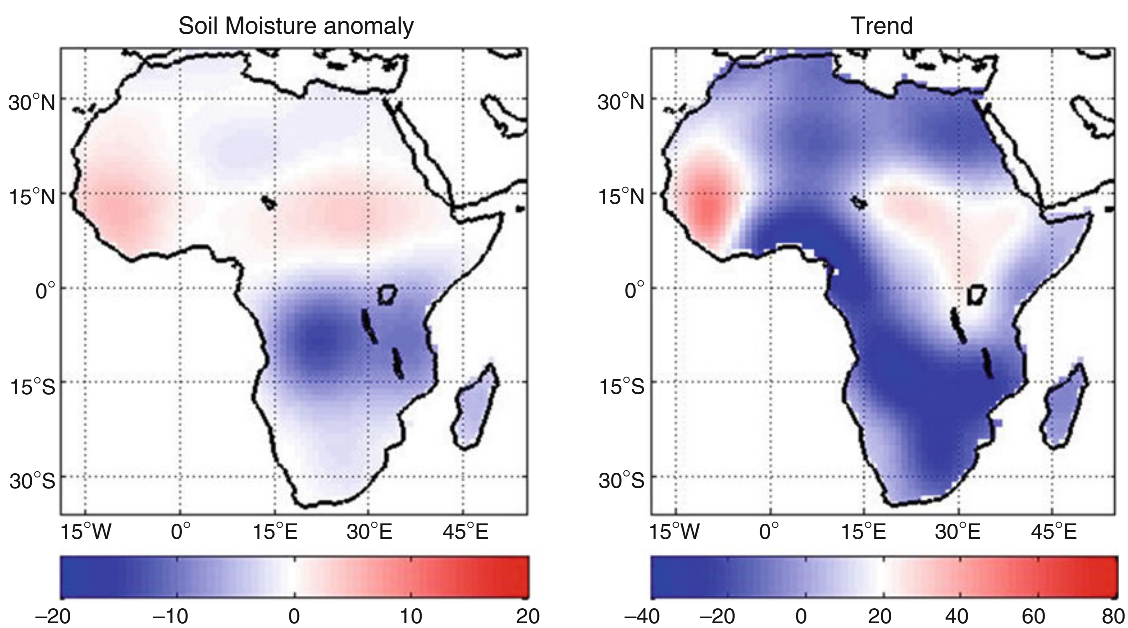

Fig. 6 The GLDAS average monthly difference of soil moisture (*left panel*) and trend of soil moisture (*right panel*) (both are computed from the spherical harmonic expansion) from Jan. 2003 to Dec. 2016. Units in [cm]

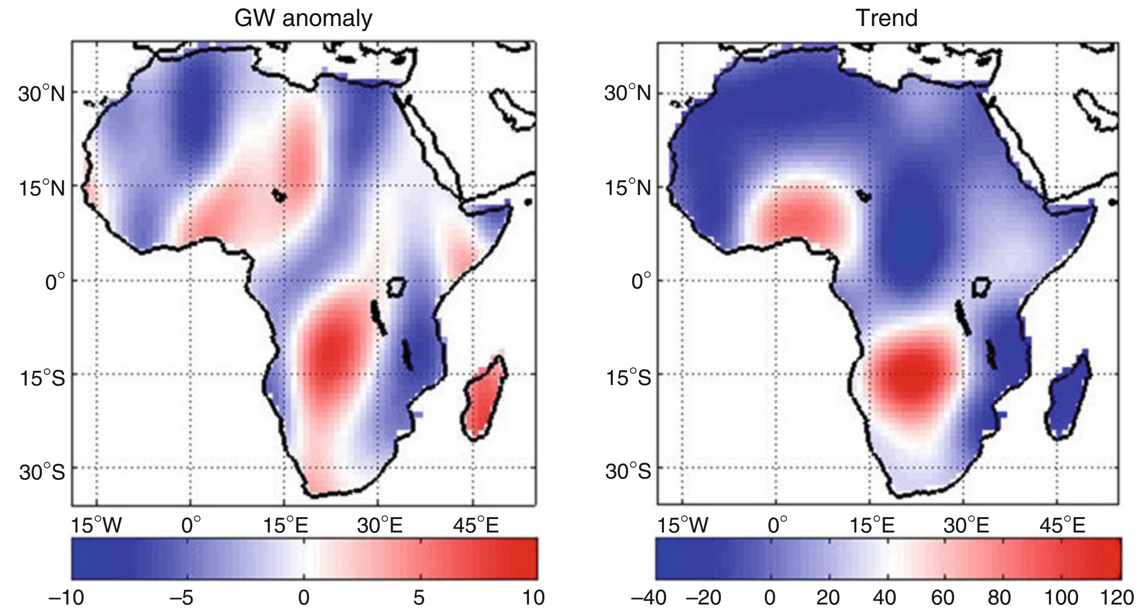

Fig. 7 The average monthly difference of groundwater (GW) (*left panel*) and trend (*right panel*) from Jan. 2003 to Dec. 2016 estimated using GRACE and GLDAS. Units in [cm]

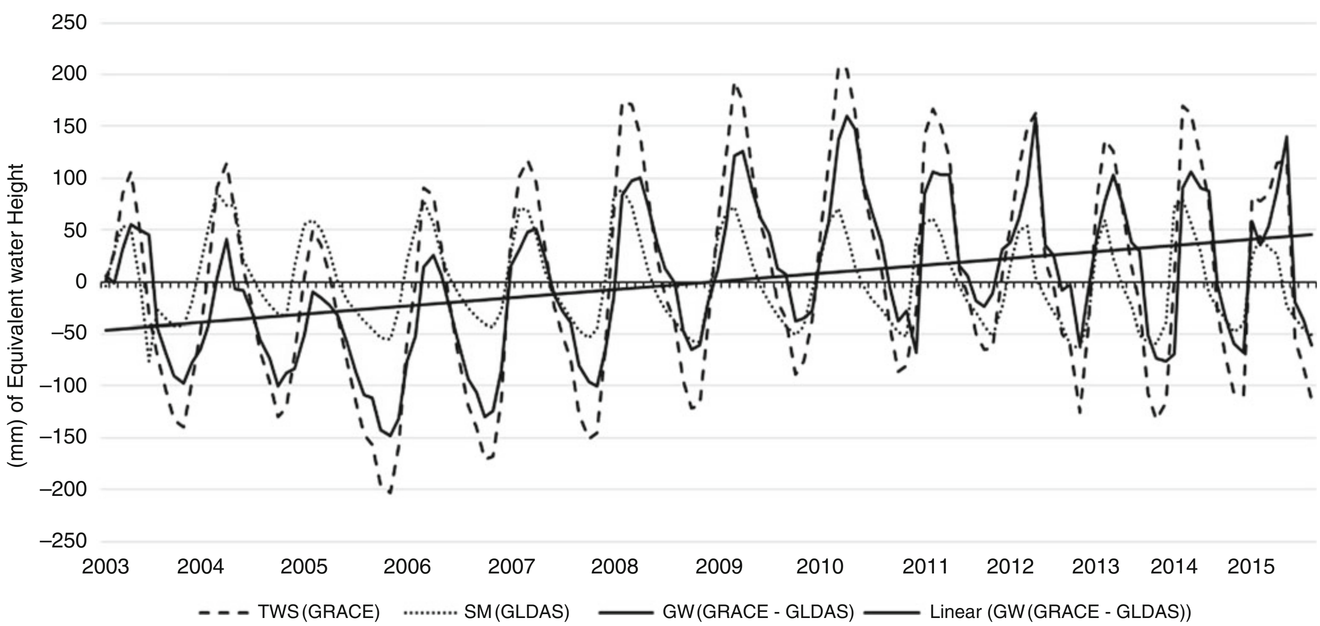

Fig. 8 The averaged TWS from GRACE, GW storage (GRACE - GLDAS), and GW trend for Zambezi river basin for the period from Jan 2003 to Sep 2015. Units in [cm]

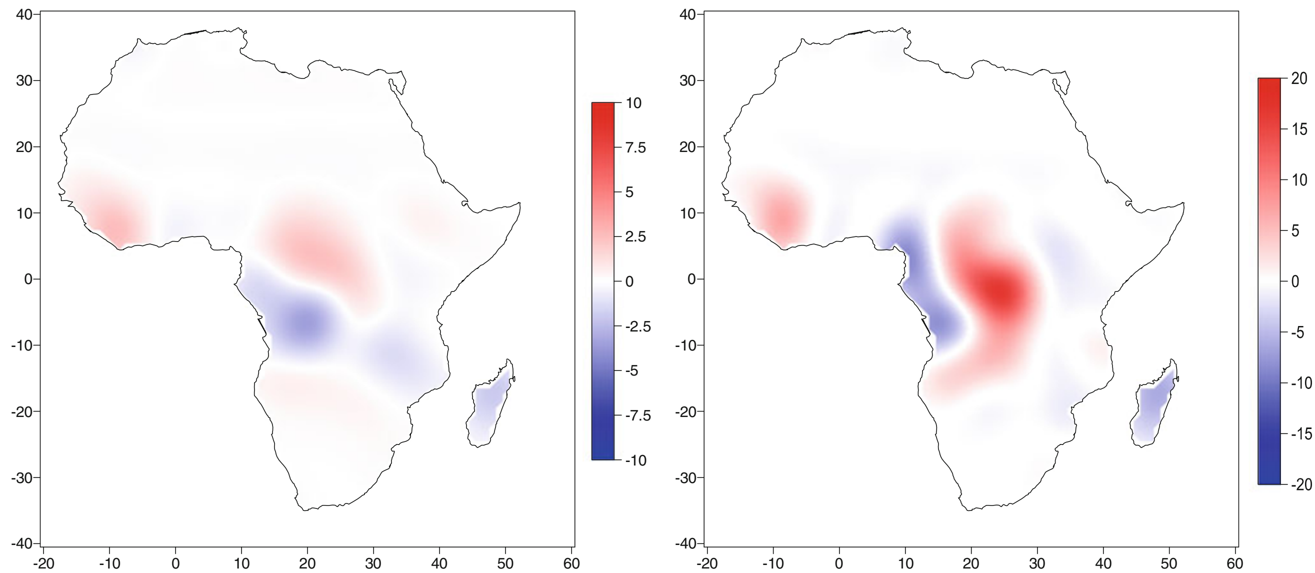

Fig. 9 The average monthly difference of groundwater from WGHM model (*left panel*) and trend (*right panel*) computed from spherical harmonic expansion from Jan. 2003 to Dec. 2013. Units in [cm]

References

Abd-Elmotaal HA, Seitz K, Abd-Elbaky M, Heck B (2014) Comparison among three harmonic analysis techniques on the sphere and the ellipsoid. J Appl Geod 8(1):1–20. https://doi.org/10.1515/jag-2013-0008

Bettadpur S (2012) UTCSR Level-2 processing standards document for level-2 product release 0005, GRACE 327-742, CSR Publ. GR-12-xx, Rev, 4, 16

Cazenave A, Chen J (2010) Time-variable gravity from space and present-day mass redistribution in the Earth system. Earth Planet Sci Lett 298(3):263–274. https://doi.org/10.1016/j.epsl.2010.07.035

Chambers DP (2006) Observing seasonal steric sea level variations with GRACE and satellite altimetry. J Geophys Res Oceans 111(C3). https://doi.org/10.1029/2005JC002914

Chambers DP, Wahr J, Nerem RS (2004) Preliminary observations of global ocean mass variations with GRACE. Geophys Res Lett 31(13). https://doi.org/10.1029/2004GL020461

Chen JL, Wilson CR, Eanes RJ, Nerem RS (1999) Geophysical interpretation of observed geocenter variations. J Geophys Res Solid Earth 104(B2):2683–2690

Chen JL, Wilson CR, Tapley BD, Ries JC (2004) Low degree gravitational changes from GRACE: validation and interpretation. Geophys Res Lett 31(22). https://doi.org/10.1029/2004GL021670

Crowley JW, Mitrovica JX, Bailey RC, Tamisiea ME, Davis JL (2006) Land water storage within the Congo Basin inferred from GRACE satellite gravity data. Geophys Res Lett 33(19). https://doi.org/10.1029/2006GL027070

Duan XJ, Guo JY, Shum CK, Van Der Wal W (2009) On the post-processing removal of correlated errors in GRACE temporal gravity field solutions. J Geod 83(11):1095–1106. https://doi.org/10.1007/s00190-009-0327-0

Döll P, Kaspar F, Lehner B (2003) A global hydrological model for deriving water availability indicators: model tuning and validation. J Hydrol 270(1):105–134. https://doi.org/10.1016/S0022-1694(02)00283-4

Flechtner F GFZ level-2 processing standards document for level-2 product release 0004 (Rev. 1.0, February 19, 2007)

Güntner A, Stuck J, Werth S, Döll P, Verzano K, Merz B (2007) A global analysis of temporal and spatial variations in continental water storage. Water Resour Res 43:W05416. https://doi.org/10.1029/2006WR005247

Han D, Wahr J (1995) The viscoelastic relaxation of a realistically stratified Earth and a further analysis of postglacial rebound. Geophys J Int 120(2):287–311. https://doi.org/10.1111/j.1365-246X.1995.tb01819.x

Jin S, Feng G (2013) Large-scale variations of global groundwater from satellite gravimetry and hydrological models, 2002–2012. Glob Planet Chang 106:20–30. https://doi.org/10.1016/j.gloplacha.2013.02.008

Klees R, Zapreeva EA, Winsemius HC, Savenije HHG (2007) Monthly mean water storage variations by the combination of GRACE and a regional hydrological model: application to the Zambezi River. In: Dynamic planet. Springer, Berlin, pp 488–495

MacDonald AM, Bonsor HC, Dochartaigh BÉÓ, Taylor RG (2012) Quantitative maps of groundwater resources in Africa. Environ Res Lett 7(2):024009. https://doi.org/10.1088/1748-9326/7/2/024009

Ramillien G, Cazenave A, Brunau O (2004) Global time variations of hydrological signals from GRACE satellite gravimetry. Geophys J Int 158(3):813–826. https://doi.org/10.1111/j.1365-246X.2004.02328.x

Ramillien G, Frappart F, Cazenave A, Güntner A (2005) Time variations of land water storage from an inversion of 2 years of GRACE geoids. Earth Planet Sci Lett 235(1):283–301. https://doi.org/10.1016/j.epsl.2005.04.005

Rodell M, Houser PR, Jambor UEA, Gottschalck J, Mitchell K, Meng CJ, Entin JK, Walker JP, Lohmann D, Toll D (2004) The global land data assimilation system. Bull Am Meteorol Soc 85(3):381–394. https://doi.org/10.1175/BAMS-85-3-381

Rodell M, Velicogna I, Famiglietti JS (2009) Satellite-based estimates of groundwater depletion in India. Nature 460(7258):999–1002. https://doi.org/10.1038/nature08238

Swenson S, Wahr J (2006) Post-processing removal of correlated errors in GRACE data. Geophys Res Lett 33(8). https://doi.org/10.1029/2005GL025285

Swenson S, Chambers DP, Wahr J (2008) Estimating geocenter variations from a combination of GRACE and ocean model output. J Geophys Res Solid Earth 113(B8). https://doi.org/10.1029/2007JB005338

Tapley BD, Bettadpur S, Watkins M, Reigber C (2004) The gravity recovery and climate experiment: mission overview and early results. Geophys Res Lett 31(9). https://doi.org/10.1029/2004GL019920

Wahr J, Molenaar M, Bryan F (1998) Time variability of the Earth's gravity field: hydrological and oceanic effects and their possible detection using GRACE. J Geophys Res Solid Earth 103(B12):30205–30229. https://doi.org/10.1029/98JB02844

Wahr J, Swenson S, Zlotnicki V, Velicogna I (2004) Time-variable gravity from GRACE: first results. Geophys Res Lett 31(11). https://doi.org/10.1029/2004GL019779