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Evaluation of Terrestrial Total Water Height Variations over the Nile River Basin Based on Two Full-Years of GRACE-FO Gravity Field Monthly Solutions

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Abstract— *Gravity Recovery and Climate Experiment (GRACE) and its Follow-on (GRACE-FO) satellite missions could provide monthly gravity solutions representing the change in groundwater at both global and river basin scales. In this contribution, two full years of the sixth's release of GRACE-FO (RL06) decorrelation filtered (DDK1 – DDK8) products estimated by the three official GRACE science data centers; GFZ (the German Research Centre for Geosciences), JPL (NASA's Jet Propulsion Laboratory) and CSR (Centre for Space Research) will be used to evaluate the appropriate decorrelation filters (DDK1 – DDK8) for estimating the terrestrial total water storage (TWS) variations over the Nile River basin.*

The results expressed in units of equivalent water thickness show that when the mean temporal signal is included in the gravity products, the GRACE-FO (RL06) mean monthly solutions computed by the JPL center provide better TWS estimation in terms of standard deviations (STD) for the DDK1 – DDK6 of about 2.24 cm – 8.73 cm, respectively, with respect to the computed ones by the GFZ and CSR. When the mean temporal signal is removed the solutions by the JPL center provide improvements only for the DDK1 – DDK2, whereas the GRACE-FO (RL06) computed by the GFZ center surpasses those of both JPL and CSR centers for the DDK3 – DDK6 providing STD of about 3.91 cm – 5.32 cm, respectively. The CSR center provides the overall least STD of the equivalent water heights over the Nile basin for the DDK7 and DDK8.

Keywords— *GRACE-FO Gravity Mission, Nile River Basin, Total Water Storage.*

I. INTRODUCTION

The Nile River (NR) is considered as the longest river on the Earth with a length of about 6,695 km composing a river basin with an area of about 3,761,542 km^2. Its catchment area covers around a tenth of the area of Africa and is home to almost a quarter of the African population, for whom the river is the most important freshwater reservoir in the region. The NR passes through ten African countries that are called the Nile Basin countries: Egypt, Sudan, South Sudan, Ethiopia, Uganda, Kenya, Tanzania, DR Congo, Rwanda and Burundi. The NR basin (see Fig. 1) for some of these countries such as DR Congo forms only a very small part of their territory, while for other countries such as Egypt, Sudan, South Sudan, Burundi, Rwanda and Uganda, they are almost completely integrated into the Nile basin as a main water source.

The NR is originated from two main sources; namely the White Nile and the Blue Nile. The White Nile originates in the Great Lakes region in Central Africa, the farthest source is found in southern Rwanda and flows from northern Tanzania to Lake Victoria, to Uganda and then to southern Sudan. The Blue Nile begins in Lake Tana located in the Ethiopian heights and then flows to Sudan from the southeast. Both rivers meet at the Sudanese capital, Khartoum composing the main Nile River which flows along Egypt till it is divided into two main branches (Rashid and Damietta) forming the Nile Delta that drains into the Mediterranean Sea.

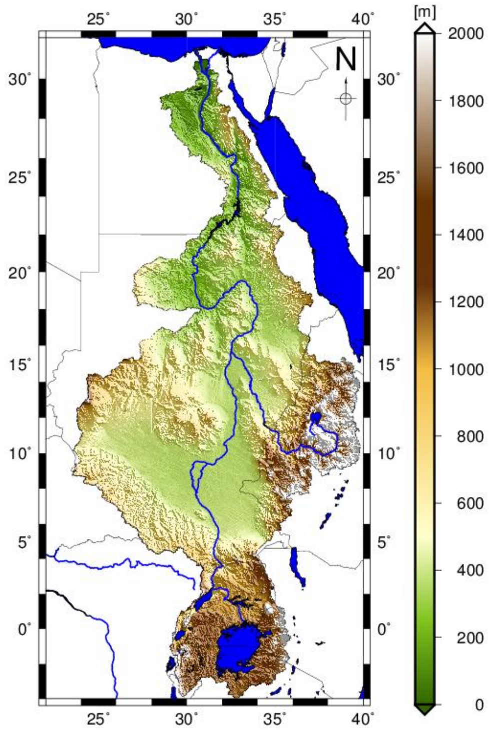

Fig. 1. The study area representing the Nile River basin in Africa showed on a topographic map [m].

It is quite important to investigate the change in terrestrial total water storage (TWS) of the NR basin because of the fact that the level of Lake Victoria, the main water source of the NR, is changing seasonally. These variations in the water heights are attributed more or less to the heavy rainfall over the lake and its tributaries and the evaporation process, respectively.

In the matter of fact, the in-situ observations are not well covered globally, in particular over the NR basin. This is due to the challenging issues such as the high cost, the time consuming and low resolution. Thanks to the Gravity Recovery and Climate Experiment (GRACE) mission [1] launched in the period between March 2002 and October

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2017, which could deliver a continuous sequence of monthly gravity field solutions and numerous model series. As a successive mission, the GRCAE Follow-On (GRACE-FO) mission [2] and [3] launched on 22 May 2018, continues providing accurate estimates of the mean and time-variable components of the gravity field and corresponding variations of the Earth's system, such as changes in atmosphere, ocean currents, solid and ocean tides, ice sheet as well as changes in terrestrial total water storage (TWS) from groundwater changes in deep aquifers till changes in soil moisture and surface water.

It should be mentioned here that determining high frequency temporal signals such as the TWS signal from GRACE-FO observations suffers from the same problems that faced GRACE satellite mission before mainly the temporal aliasing problem. The temporal aliasing errors (see e.g.[4] – [6]) are defined as errors that result from temporal under-sampling of geophysical signals which have period less than twice the (orbital) sampling period of GRACE-FO mission (i.e. one month) according to the Nyquist sampling theorem. In other words, the GRACE-FO mission provides 30-day solutions, within them there are alias-parts (e.g. hourly, daily, weekly, sub-monthly) of unrequired high-frequency mass variations of the TWS signal detected by GRACE-FO satellite mission. Therefore applying an appropriate smoothing approaches (i.e. filtering) would solve this temporal aliasing issue; however, this may led to the loss of some of the mass variations signal. Different smoothing techniques have been applied for the GRACE/GRACE-FO products, e.g. Gaussian filter ([7] and [8]) in addition to the decorrelation methods ([9] and [10]) or using an a priori synthetic model of the observation geometry (see [11] – [13]). The latter filters utilize error-covariance information.

The goal of this article is to investigate the performance of the decorrelation filters (DDK1 – DDK8) that were applied to reduce the associated noise of the GRACE-FO (RL06) products computed by three different centers (see sec. 2.1) and to evaluate which of them would provide better TWS estimates over the NR basin. The products will be compares in terms of standard deviations (STD) of the equivalent water heights (EWH) unit. In the following, the data and methodology used in this study are presented in Section 2. Section 3 provides the results regarding the comparison of the TWS variations derived from the three centers over the NR basin in spectral and spatial domain. Finally, a relevant conclusion is outlined in section 4.

II. DATA AND METHODOLOGY

A. GRACE-FO Data

Officially, there are three main centers that are responsible for producing the developed releases of the GRACE-FO products (monthly gravity solutions); namely GFZ (the German Research Centre for Geosciences), JPL (NASA's Jet Propulsion Laboratory) and CSR (Centre for Space Research) centers. These three centers were identified in the mission proposal as the GRACE Science Data System (SDS) and were considered as the official continuously releases monthly GRACE-FO geopotential gravity models. The GRACE-FO SDS is responsible for converting the raw data (Level 0) received from the GRACE-FO spacecraft scientific instrument into observations (Level 1), e.g., orbital data (positions, velocities and accelerations), satellite-to-satellite tracking observables (range, range-rate and range acceleration), star camera data for attitude determination and accelerometer data representing the sum of the non-gravitational accelerations. All these data are used in the gravity analysis procedure to derive the monthly gravity field spherical harmonic coefficients (SHC) which are known as Level 2 data. The gravity field products of GRACE-FO (RL06) are provided over approximately a month (30-day interval) (i.e. temporal monthly solutions) in two SHC degree and order (d/o) 60/60 and 96/96, which correspond to spatial resolution of 333 km and 208 km, respectively. In this article, the (RL06) products from the GFZ [14], JPL [15] and CSR [16] centers at d/o 96/96 are selected because they provide better spatial gravity field resolution with respect to (w.r.t) d/o 60/60. The GRACE_FO (RL06) is available for the period between June 2018 and July 2020, except for months July – August 2018.

B. Terrestrial Water Storage from GRACE-FO

In order to estimate the variations of the TWS from observations, the Level-2 data represented in monthly SHC from the de-correlated filters DDK 1 – DDK8 of GRACE-FO (RL06) are applied over the NR basin using the following formulae:

$$\mathrm{TWS}_{\mathrm{WM}(r,\varphi,\lambda)} = \mathrm{R}\,\frac{\rho}{3}\sum_{\mathrm{n}=0}^{\mathrm{N_{max}}}\left(\frac{2\mathrm{n}+1}{1+\mathrm{k_n}}\right)\sum_{\mathrm{m}=0}^{\mathrm{n}}\bar{\mathrm{P}}_{\mathrm{nm}}(\sin\varphi)\left(\Delta C_{\mathrm{nm}}\cos m\lambda+\Delta S_{\mathrm{nm}}\sin m\lambda\right), \quad (1)$$

where the subscript $_{\mathrm{WM}}$ stands for solutions with mean signal, r, φ, λ are spherical coordinates (distance to the geocenter, geodetic latitude and longitude, respectively) of a point, R is the mean radius of the Earth (applied in our study as 6387136.3 m), ρ is the average density of the Earth (5517 kg/m^3), k_n is the load love numbers, $\bar{P}_{nm}(\sin\,\varphi)$ is the fully normalized associated Legendre function, and n, m are degree and order of spherical harmonics, respectively, and N_{max} the maximum applied degree which is 96 in this article. The terms ΔC_{nm} and ΔS_{nm} are differences between the fully normalized spherical harmonic coefficients from the reference Eigen-6C4 Geopotential gravity model as

$$\Delta C_{nm} = (C_{nm})_{GRACE-FO} - (C_{nm})_{Eigen-6C4}, \quad (2)$$

$$\Delta S_{nm} = (S_{nm})_{GRACE-FO} - (S_{nm})_{Eigen-6C4}, \quad (3)$$

In order to compute the TWS variations excluding the effect of the mean temporal signal, the spherical harmonics represented in (1) have been re-produced after removing the mean temporal signal as:

$$\mathrm{TWS}_{\mathrm{WoM}(r,\phi,\lambda)} = \mathrm{R}\,\frac{\rho}{3}\sum_{\mathrm{n}=0}^{\mathrm{N_{max}}}\left(\frac{2\mathrm{n}+1}{1+\mathrm{k_n}}\right)\sum_{\mathrm{m}=0}^{\mathrm{n}}\bar{\mathrm{P}}_{\mathrm{nm}}(\sin\phi)\left(\bar{\mathrm{C}}_{\mathrm{nm}}\cos m\lambda+\bar{S}_{\mathrm{nm}}\sin m\lambda\right), \quad (4)$$

with

$$\bar{C}_{nm} = (C_{nm})_{GRACE-FO} - mean(C_{nm})_{GRACE-FO}, \quad (5)$$

$$\bar{S}_{nm} = (S_{nm})_{GRACE-FO} - mean(S_{nm})_{GRACE-FO}, \quad (6)$$

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where the subscript $_{WoM}$ stands for solutions without mean signal. In the following section, the results will be given in both representations, i.e. before (1) and after (4) removing the mean temporal signal of the spherical harmonic coefficients.

III. Results

First, the monthly solutions in terms of SHC of two full years (24 months) from June 2018 to July 2020 have been downloaded via the ICGEM webpage (http://icgem.gfz-potsdam.de/series) for each center (GFZ, JPL and CSR). The mean monthly TWS variations using 24 months of GRACE-FO (RL06) decorrelation filtered (DDK1 – DDK8) products are represented in Fig. 2 and Fig. 3, whereas the corresponding statistics are given in Table I and Table II, respectively. As shown in Fig. 2, the DDK1 provides the most smoothed gravity solution with STD of about 2.61 cm, 2.24 cm and 2.26 cm in EWH unit for the solutions computed by the GFZ, JPL and CSR, respectively, while the DDK8 provides the most noisy water height of about 12.09 cm, 12.14 cm and 12.06, respectively as indicated in Table I. This is already expected due to that DDK1 has a smoothing kernel radius which is corresponding to Gaussian radius of ≈1350 km (see Table II of [13]). The GRACE-FO (RL06) decorrelation filtered (DDK1 – DDK6) products estimated by the JPL center demonstrate better recovery of the mass variation signal showing a lower STD w.r.t. the products computed by the other two centers GFZ and CSR. The latter center shows the superiority of GRACE-FO (RL06) decorrelation filtered (DDK7 and DDK8) solutions w.r.t. those by the GFZ and JPL. As shown in Fig. 2, the mean temporal signal has an obvious impact on the recovery of the TWS signal, especially at Lake Victoria in the southern part of the NR basin and at Lake Tana in the eastern part.

TABLE I. Standard deviations of the terrestrial water storage over Nile River basin of GRACE-FO (RL06) gravity field products from GFZ, CSR and JPL centers. Mean temporal signal is not removed. Units are equivalent water heights [cm]. Grey cells stand for the least STD of each row.

S. No.	GRACE-FO (RL06) Products		
	GFZ	**JPL**	**CSR**
DDK1	2.618	2.243	2.268
DDK2	4.339	4.157	4.245
DDK3	6.414	6.165	6.619
DDK4	6.922	6.701	7.225
DDK5	8.092	8.042	8.286
DDK6	8.774	8.733	8.786
DDK7	10.727	10.882	10.604
DDK8	12.098	12.141	12.068

TABLE II. Standard deviations of the terrestrial water storage over Nile River basin of GRACE-FO (RL06) gravity field products from GFZ, CSR and JPL centers. Mean temporal signal is removed. Units are equivalent water heights [cm]. Grey cells stand for the least STD of each row.

S. No.	GRACE-FO (RL06) Products		
	GFZ	**JPL**	**CSR**
DDK1	2.566	2.514	2.678
DDK2	3.331	3.275	3.581
DDK3	3.911	4.120	4.486
DDK4	4.108	4.419	4.778
DDK5	4.871	5.4320	5.355
DDK6	5.322	6.035	5.610
DDK7	6.987	7.769	6.971
DDK8	12.098	12.141	12.068

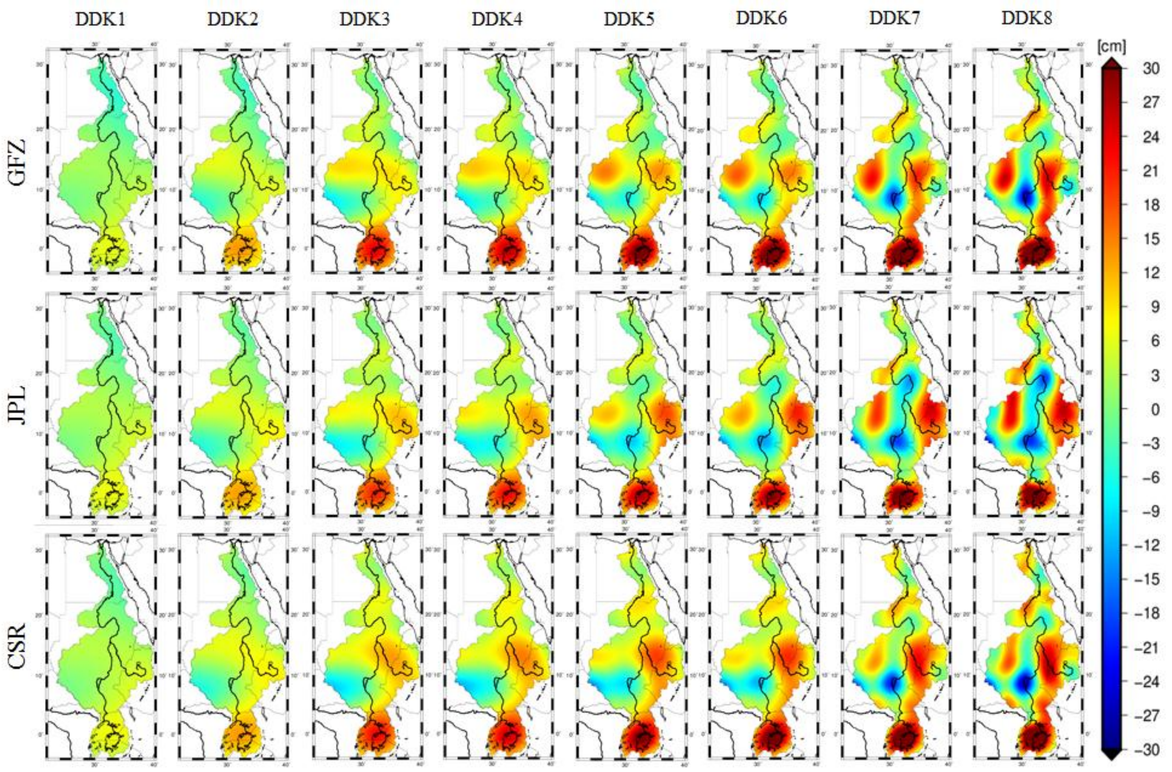

Fig. 2. Variations in TWS signals in terms of equivalent water heights [cm] determined over the Nile River basin from the GRACE-FO (RL06) gravity field products estimated by the GFZ, CSR and JPL centers. Mean signal is not removed regarding to (1).

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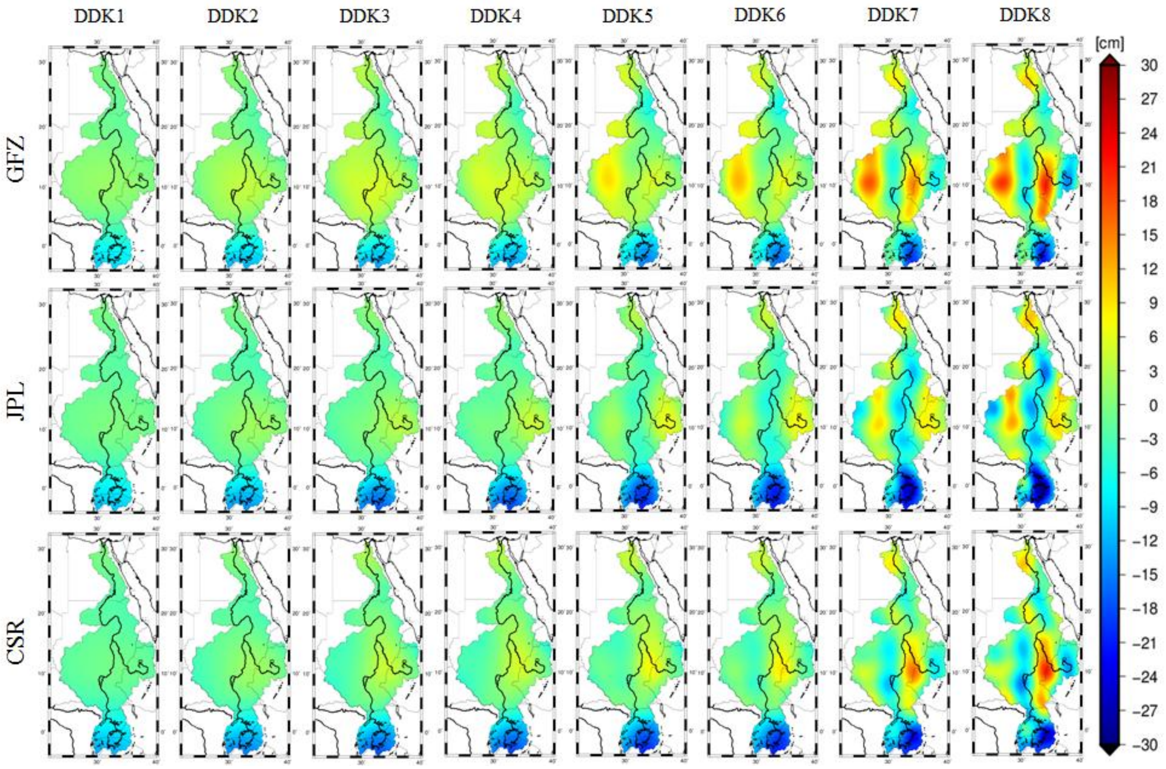

Fig. 3. Variations in TWS signals in terms of equivalent water heights [cm] determined over the Nile River basin from the GRACE-FO (RL06) gravity field products estimated by the GFZ, CSR and JPL centers. Mean signal is removed regarding to (4).

Therefore, it was quite important to investigate the TWS variations after removing the mean temporal signal applying (4). When the mean temporal signal is removed, the behavior of the TWS is totally changed as shown in Fig. 3. The GRACE-FO (RL06) decorrelation filtered (DDK3 – DDK6) products estimated by GFZ center show a better detection of the TWS and demonstrate the mass variations over the NR basin well w.r.t. the other two centers JPL and CSR. However the latter center provides a better estimation of the equivalent water heights considering the GRACE-FO (RL06) DDK7 and DDK8 w.r.t. the GFZ and JPL centers (see Tables I and II).

To sum up, the results shown in Fig. 2 and Fig. 3 show the superiority of DDK1 – DDK6 estimated by the JPL center when the mean temporal signal affect the mean monthly solutions. Whereas the GRACE-FO (RL06) decorrelation filtered (DDK3 – DDK6) products estimated by the GFZ center demonstrate a better detection of the TWS over the NR basin w.r.t. the other two centers JPL and CSR.

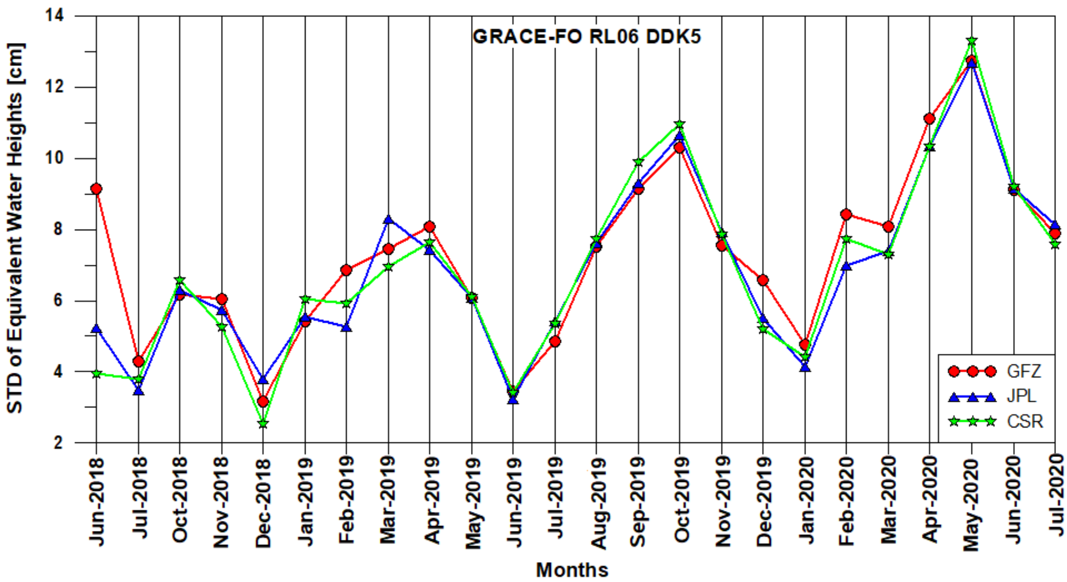

Fig. 4. Monthly TWS variations in terms of STD of equivalent water heights [cm] as derived from the 24 months of GRACE-FO (RL06) DDK5 products of the GFZ center.

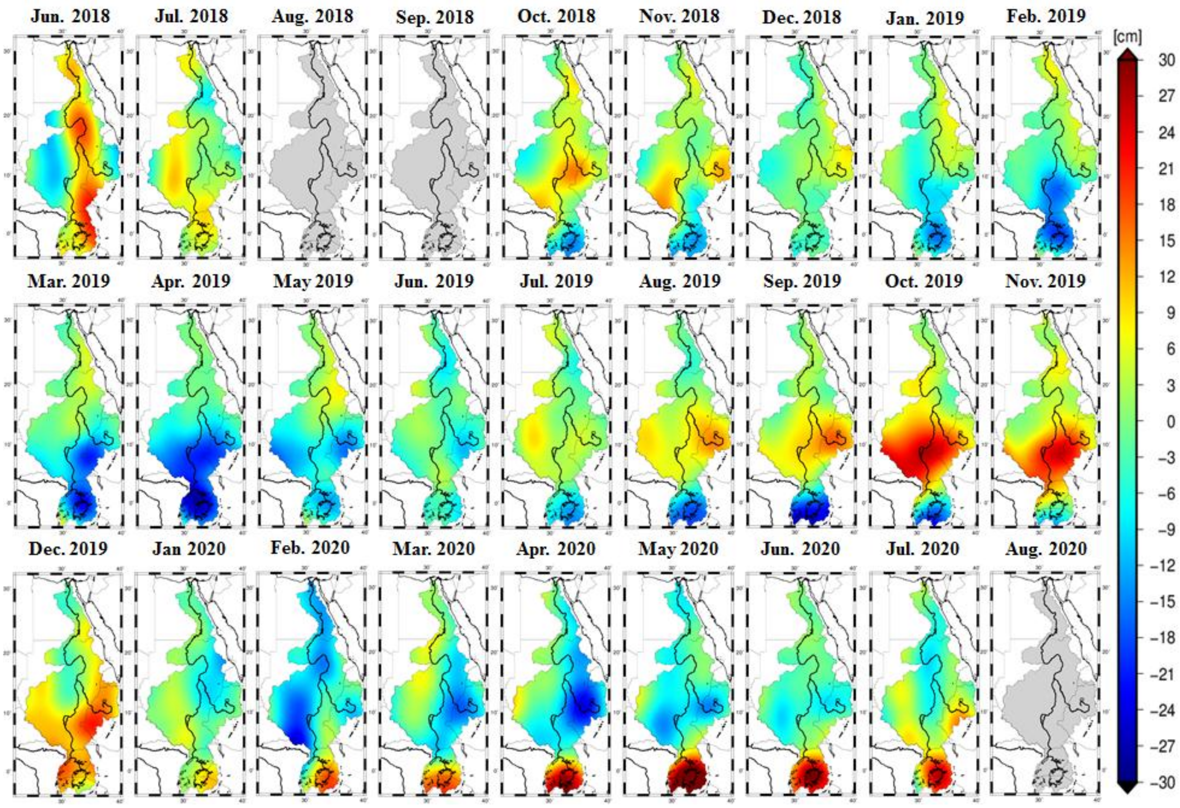

Fig. 5. Monthly total water storage in equivalent water heights [cm] as derived from the 24 months of GRACE-FO (RL06) DDK5 products of the GFZ center over the Nile River basin.

In order to examine the monthly TWS variations over the NR basin, two full years of GRACE-FO (RL06) DDK5 gravity products estimated from the GFZ center have been plotted spectrally in terms of STD of the TWS variations (see Fig. 4) and spatially as shown in Fig. 5. In Fig. 4 the peaks vary seasonally depending on the rainfall over the NR basin. The higher peaks appear between Septembers – Novembers. This may due to the rainfall over the southern and eastern parts of the NR basin which occurs in the summer season (from June to August). The effect can be clearly seen as a rise of equivalent water heights in the autumn season (from September to November). This can be obviously as higher rise regarding to charging of the TWS in the NR basin as seen in Fig. 5 (especially September 2019 – November 2019). In Whereas, the winter season (December – February) represents minimum of rainfall change, whose effect as discharging of TWS take place in the spring season (March – May) as shown in Fig. 5 (see e.g. April 2019 and April 2020).

IV. Conclusion

In this paper, different gravity field monthly solutions of the GRACE-FO (RL06) decorrelation filters (DDK1 – DDK8) estimated by the GFZ, JPL and CSR official centers have been evaluated over the Nile River basin.

First the mean monthly variations have been examined without removing the mean temporal signal. In this case, the GRACE-FO (RL06) products computed by the JPL center have provided better TWS estimation in terms of standard deviations (STD) for the DDK1 – DDK6 of about 2.24 cm – 8.73 cm, respectively, w.r.t. to the computed ones by the GFZ and CSR centers.

Second, the monthly variations have been evaluated after removing the mean temporal signal from the monthly solutions. In this case, the GRACE-FO (RL06) computed by the GFZ center surpasses those of both JPL and CSR centers for the DDK3 – DDK6 providing STD of about 3.91 cm – 5.32 cm, respectively. It has been found that the CSR center provides the overall least STD of the equivalent water heights over the Nile basin for the DDK7 and DDK8.

To examine the monthly mass variations over the NR basin, the TWS of two full years of GRACE-FO (RL06) DDK5 gravity product as derived from the GFZ center has been computed and plotted in the spectral as well as in spatial domain. Seasonal variations over the Nile River basin were clearly detected which are attributed to the seasonal rainfall over the southern and eastern parts of the Nile River basin. For the rainfall occurring in the summer season, its effect was seen in the autumn season (from September to November) as a rise of equivalent water heights. In the winter season (December – February), when minimum rainfall occurs, the effect of TWS variations was seen in the spring season (March – May). Finally, it is highly recommended to use the coming GRACE-FO products in order to extract more information about changing of the total water storage. This will help in assessing the evaluation given in this paper and will demonstrate the mass variations over the Nile River basin.

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