Chapter

Continental Water Storage Changes Sensed by GRACE Satellite Gravimetry

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Abstract

Since its launch in March 2002, the Gravity Recovery And Climate Experiment (GRACE) mission has been mapping the time variations of the Earth's gravity field with a precision of 2–3 cm in terms of geoid height at the surface resolution of 300–400 km. The unprecedented precision of this twin satellite system enables to detect tiny changes of gravity that are due to the water mass variations inside the fluid envelops of our planet. Once they are corrected from known gravitational contributions of the atmosphere and the oceans, the monthly and (bi)weekly GRACE solutions reveal the continental water storage redistributions, and mainly the dominant seasonal cycle in the largest drainage river basins such as Amazon, Congo, Mississippi. The potential differences measured between the twin GRACE satellites represent the sum of integrated surface waters (lakes and rivers), soil moisture, snow, ice and groundwater. Once they are inverted for estimating surface water mass densities, GRACE solutions are also used to establish the long-term mass balance of the ice sheets impacted by global warming, for quantifying the interannual variations of the major aquifers, as well as for surveying the hydrological signatures of intense meteorological events lasting a few days such as tropical hurricanes. This chapter describes GRACE gravity products and the different data processings used for mapping continental water storage variations, it also presents the most remarkable results concerning global continental hydrology and climate changes.

Keywords: satellite gravimetry, geodesy, global hydrology, gravity field, continental water storage

1. Introduction

Water that is present in different forms in the Earth's system ensures the global transport of the solar heat in the oceans and atmosphere, and thus maintains life development. As it represents a precious resource, in particular for human activities, monitoring the water cycle from space remains important for its management and understanding climate change. Observation of the Earth from space, and the determination of its gravity fields in particular, provide precious information on the mass transfers in any part of the globe.

Global gravity field models are based on the theoretical expression of the variations of the geopotential V:

$$V(\lambda,\theta,r)=\frac{GM}{a_e}\sum_{n=0}^{\infty}\left(\frac{a_e}{r}\right)^{n+1}\sum_{m=0}^{n}P_{nm}(\sin\theta)(C_{nm}\cos m\lambda+S_{nm}\sin m\lambda) \qquad (1)$$

where λ and θ are the longitude and the latitude of the observation point respectively, r is the radial distance from the Earth's center to the point of observation, P_{nm} is the associate Legendre function of degree n and order m, a_e is the equatorial Earth's radius and the gravitational parameter is the product of the gravitational constant G with the total mass of the Earth M, so that $GM = 3.986004410 \cdot 10^{14} +/- 8 \cdot 10^{5}\ m^3/s^2$, according to IERS Standard. Space geodesy consists of determining the dimensionless Stokes coefficients C_{nm} and S_{nm} of the gravity field model as precisely as possible using combined satellite data and terrestrial gravity measurements on lands. As the satellite motion depends mainly on the gravitational field according to the Newton's law of attraction (~99% of the sensed gravity signal is from the solid Earth part), the only remote sensing technique to measure variations of water mass quantity is based on inversion of very precise satellite positions - with an accuracy of at least a few cm for detecting long wavelengths of the continental hydrology -, and/or satellite velocities [1].

Historically, long wavelengths of the gravity field time variations were determined using very precise Satellite Laser Ranging (SLR) data of 5900-km altitude LAGEOS 1–2 trajectories that reveal the movements of the center of mass of the Earth (or "geocenter") representing a few thousands of mm, and Earth's flatness due to seasonal mass exchange between the two hemispheres and the regular decrease due to post-glacial rebound occurring since 20 000 years [2] (**Figure 1**).

Since the beginning of the 21st century, a new generation of passive and quasi-polar Low-Earth-Orbit (LEO) satellites has been launched to improve the spatial resolution of global gravity field models: the CHAllenging Mini-satellite Payload (CHAMP, 2000–2010) mission operated by the DLR in Germany, and the Gravity field and steady-state Ocean Circulation Explorer (GOCE, 2009–2013) of ESA.

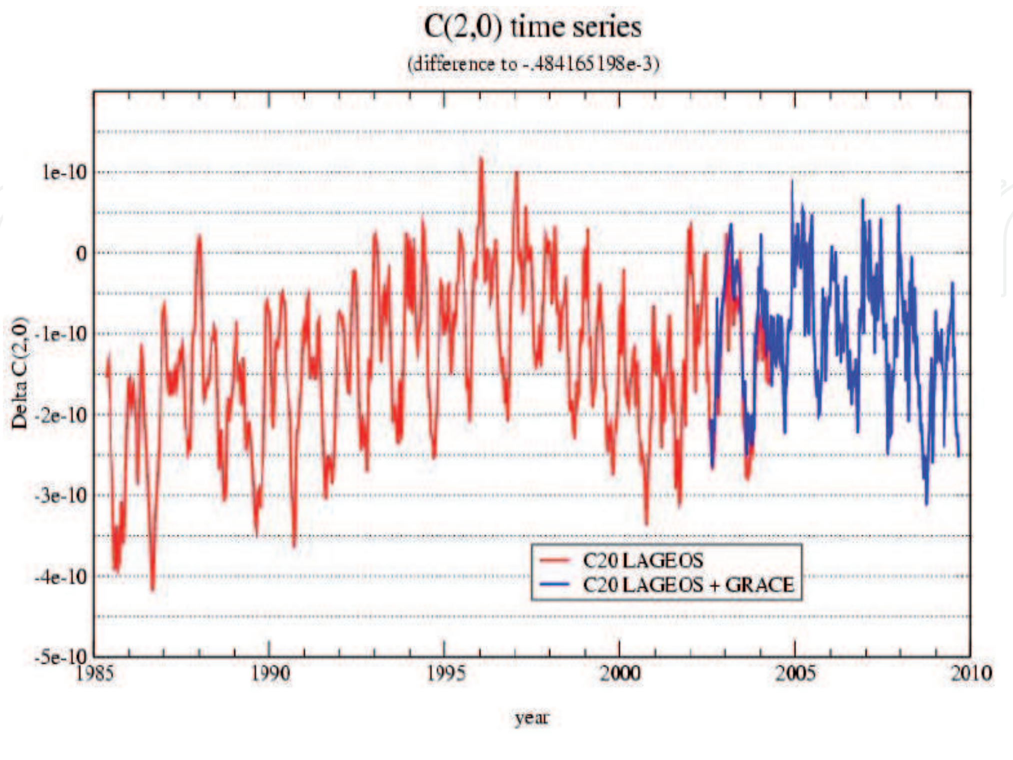

Figure 1.
Time variations of the C_{20} coefficient (representing Earth's flatness) determined by analysis of the LAGEOS 1 & 2 satellite telemetry (source: GRGS, Toulouse).

As the CHAMP mission represents its precursor, the main scientific objective of the Gravity Recovery And Climate Experiment (GRACE, 2002–2017) mission proposed by the American National Aeronautics and Space Administration (NASA) and the German Aerospace Center Deutsches Zentrum für Luft- und Raumfahrt (DLR), was to measure both static and time-varying gravity field acting in different regions of the world.

GRACE was the first mission to use the principle of two co-orbital identical satellites in pursuit, as initially proposed by [3] for estimating the spatial and temporal variations of the gravitational field which reflect mass changes in the Earth system over time scales ranging from months to a ten of years [4], so that GRACE observation represents the sum of the effects of all changes in mass which are radially integrated. In fact, GRACE observations are used to successfully survey the continental hydrology at different time scales (decanal, seasonal, rapid events) allowing to measure the climate change impacts in the Earth system, as for example, ice mass lost in Polar regions as a consequence of global warming [5].

2. GRACE mission orbit and its on-board instruments

The GRACE mission consists of two 0.5 ton satellites that followed each other at a distance of ~220 km, which were placed at a relatively low average altitude of around 450 km with a quasi-polar orbit inclination of 89.5 degrees to ensure a quasi-global coverage (**Figure 2**). The relative distance between the two satellites was measured with a accuracy of 1 $\mu m.s^{-1}$ by a radar telemeter operating at K-Band microwave Ranging (KBR) [4]. The inter-satellite distance depends of the gravitational acceleration changes that affect each GRACE satellite [6]. The A three-axis accelerometer that senses the dynamical effects as non-dissipative forces (the mean solar and Earth's radiation pressure, the atmospheric drag) is also placed on-board. Afterwards the non-gravitational effects are removed from the raw accelerations, the geopotential change along the track of the GRACE satellites is estimated from the residual perturbations in distance and inter-satellite distance changing rate. Changes of the observed inter-satellite distances reflect the variations of the Earth's gravity field related to topography and density heterogeneities.

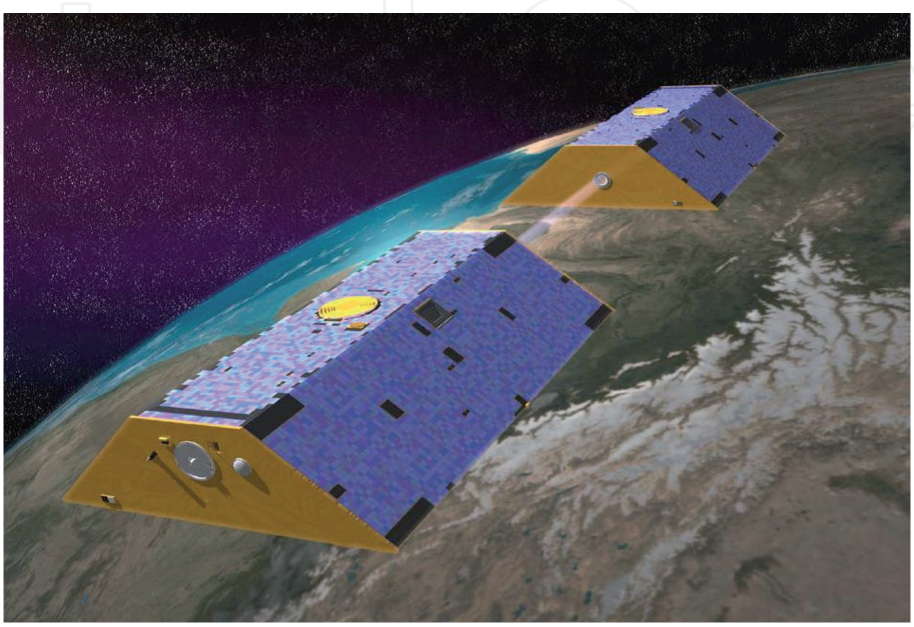

Figure 2.
Artistic view of the twin GRACE vehicles orbiting around the earth (source: NASA [7]).

The payload was composed of five instruments on-board, the satellite components of the GRACE mission are listed below [3]:

- The K-band ranging system (KBR) for inter-satellite distance an accuracy of 10 μm. It uses the phases of carrier electromagnetic waves in the K and Ka bands at frequencies of 26 and 32 GHz.

- The Ultra-Stable Oscillator (USO) for generating electromagnetic waves in the K-band for the KBR system at the desired frequency.

- The SuperSTAR accelerometers (ACC) for accurate measurement of the forces acting on each satellite along three axis.

- The Stellar Camera ASSEMBLY (SCA) for determining the orientation of the satellite relatively to the positions of fixed stars.

- The Black-Jack GPS receivers and Instrument Processing Unit for providing three coordinate components of the position and the ones of the velocity of each GRACE satellite in the geocentric reference frame.

3. GRACE data products

The three official processing centers forming the GRACE Science Data Center (GSDC), i.e. the Center for Space Research (CSR) in Austin, Texas, United States; the GeoFoschungsZentrum (GFZ) in Potsdam, Germany; the Jet Propulsion Laboratory (JPL) in Pasadena, California, United States, produce the Level-1B parameter products and the Level-2 solutions derived from measurements of the GRACE mission. Level-1B products are constituted by the processed positions and velocities, which were measured by the on-board GPS receivers, accelerometers and the accurate K-band measurements of the variations in distance between the two vehicles. Using these measurements, the monthly gravity field models or Level-2 products for continental hydrology are computed. These products are expressed by means of geoid heights and Equivalent-Water Heights (EWH). The latter products are distributed by the GFZ's Integrated System Data Center (ISDC, [8]), and the JPL's Physical Oceanography Distributive Active Data Center (PODAAC, [9]).

3.1 Spherical harmonics solutions

The Level-2 products are obtained using a dynamic approach, which relies on the Newtonian formulation of the satellite motion equation evaluated in an inertial reference frame having the origin at the Earth's center. The formulated solution is combined with a dedicated modeling of the gravitational and non-conservative forces, which act on the spacecrafts [6]. During the process of data reduction, the known gravitational contributions are removed from observations using a priori information from meteorological and global ocean circulation models as well as the non-gravitational forces that were measured by the on-board accelerometers [10, 11]. The residual values represent mainly the contribution of the continental hydrology and errors of the correcting models in the measured gravity field. More details about the pre-treatment of the GRACE data reduction can be found in [12]. These solutions are provided as monthly or weekly lists of Stokes coefficients, i.e. dimensionless Spherical Harmonic (SH) coefficients of the geopotential [13], up to degree and order 96 or less that correspond to a spatial resolution of 200–300 km [14–17]. The range of an ideal resolution for GRACE products for hydrology is discussed in [18]. While the correcting models represent a reasonable dealiasing of high-frequency changes, the errors due to tide modeling remain in the GRACE solutions, especially for diurnal S2 tides [18–22]. These SH solutions are affected by north–south striping, especially dominant in the tropical band where the coverage of the satellite is insufficient mainly because of three reasons including the sparsity of GRACE track sampling in the longitudinal direction due to the polar orbit plane; propagation of systematic errors from the correcting model acceleration [19–21]; and the numerical correlations generated by solving the underdetermined systems of normal equations for the high-degree Stokes coefficients [23]. Average of each Stokes coefficient C_{nm} and S_{nm} versus time is computed and removed to estimate the time anomalies for each monthly or weekly period. It is necessary to eliminate this noisy effect on the GRACE solutions, which are impacted by short North–South wavelength components. The monthly Stokes coefficients ΔC_{nm} and ΔS_{nm} that have been destriped by filtering have been used in very numerous studies on the evaluation of water storage on lands and the oceans [4, 24–32]. A simple strategy to attenuate the short-wavelength striping of the GRACE solutions consists of computing the weighted average of the solutions taken from the official centers for each period of time, and by considering the a posteriori uncertainty levels of the fitted Stokes coefficients to define these weights for combination [33].

Maps of water storage anomalies over lands directly based on [34] are:

$$\Delta\sigma(\lambda,\theta,t) = a_e \rho_w \sum_{n=0}^{\infty}\sum_{m=0}^{n} P_{nm}(\sin\theta)\frac{2n+1}{1+k_n}\left(\Delta C_{nm}(t)\cos m\lambda + \Delta S_{nm}(t)\sin m\lambda\right) \quad (2)$$

where $\Delta\sigma$ is the change in surface density (mass/area), ρ_w is the density of the water and k_n is the Love numbers [35]. The change of surface mass is usually expressed in meters of equivalent water thickness (EWH). All the mass anomalies derived from GRACE data were explicated as total water mass change.

3.2 Mascons and regional solutions

Other GRACE solutions can also be obtained by other research centers where different numerical approaches are used to reach temporal resolution of one day to one month in the form of SH coefficients (global approaches) or spatial grids (local or regional approaches). As alternative to the SH approach, which is based on frequency representation instead of pure spatial localization [36], other types of base functions are used to represent surface water mass densities, mass concentration elements or mascons. In this case, water mass anomalies are estimated in specified concentrated surfaces on the Earth's locations. The GRACE mascons have been proposed by several research groups such as Goddard Space Flight Center (GSFC) [37–41], Jet Propulsion Laboratory (JPL) [42, 43] and Center of Space Research (CSR) [44] at the University of Texas, Austin, where they are processed differently. As an instance, the 1° equatorial equivalent sampled mascons developed at CSR are computed by no temporal smoothing and regularization, as they are only based on GRACE information, whereas more recent mascons solutions are derived by using partial derivatives to relate KBRR observations to EWH to be determined [44]. In a second version, the mascons are related to the range rate or the range acceleration using SH that remain truncated at certain degrees and orders, as proposed by [38]. Mascons can also be estimated by post-processing of Level-2 GRACE SH solutions without a direct use of range rate observations (see examples in [44–47]). Global grids of mascons solutions can be easily downloaded from [48, 49] for CSR and JPL Releases 06, respectively. Note that these latter solutions need to be scaled by a gain factor that varies geographically. A sequential Kalman Filtering (KF) approach for estimating regional maps of water mass changes by progressive integration of daily along-track GRACE geopotential anomalies has been recently proposed by [1, 50]. This iterative Kalman filter procedure has been successfully applied to determine 2° x 2° surface water mass density solutions over continental regions instead of using the SH or mascons representation [51–53].

3.3 Spatial resolution and accuracy of the GRACE products on lands

The GRACE products contribute in continental hydrology research witn a novel information: the terrestrial water storage or integrated water content, i.e. the sum of the water contained in the column from the different hydrological reservoirs: surface water, soil water, groundwater and snow cover. An early study showed an expected measurement accuracy of a few millimeters of EWH in terms of surface density for a reference water density of 1000 kg/m^3, over areas of 400 km by 400 km, this work was based on Land Surface Models (LSM) outputs as soil moisture, evapotranspiration and run-off. It is expected that the presence of noise in the shorter wavelengths affects the TWS retrieval [34]. In addition, errors due to the spectra truncation increase as the area of the studied basin decrease. Based on LSM outputs and the expected accuracy of the GRACE land water solutions, it was proved that the changes in TWS could be detected by the GRACE system if they exceed 1.5 cm of EWH over an area of 200 000 km^2 [54]. The accuracy of the GRACE land water solutions was expected to be about 0.7 cm of EWH for a drainage area of 400 000 km^2 and 0.3 cm for a drainage basin of 4 million of km^2 [55].

Current GRACE Products have a spatial resolution of a few hundred kilometers (around 200 km for the mascons and for the regional solutions, and 330 km for the releases 03 and 05 for a typical degree of truncation of n = 60–90). Errors were estimated to be around 4 cm at the Equator, and decreasing to 1.5 cm in Polar regions due to denser GRACE satellite tracks coverage [56].

4. Continental hydrology assessment by GRACE observations

The GRACE mission has been observing mass changes in the Earth's body during 15 years, and since 2018 the new mission GRACE-FO continues this task. These satellite gravimetric missions have many applications as: to better understanding earthquake mechanism [57–60]; to quantify sea level rise [61, 62] and; to observe hydrological cycles [6, 63].

Analysis of the GRACE solutions consists of finding a set of time coefficients from SH or gridded solutions, so that the TWS anomalies for a given period can be decomposed into geographical coefficients:

$$\begin{aligned}\Delta\sigma(\lambda,\theta,t) = A(\lambda,\theta) + B(\lambda,\theta)t + C_1(\lambda,\theta)\sin(\omega t) + C_2(\lambda,\theta)\cos(\omega t)\\ + D_1(\lambda,\theta)\sin(\omega' t) + D_2(\lambda,\theta)\cos(\omega' t)\end{aligned} \quad (3)$$

With $\omega = 2\pi/T$ and $\omega' = 2\pi/T'$, considering $T = 1$ year and $T' = 1/2$ year, so that annual and semi-annual amplitudes C and D and phases φ and φ' are:

$$C = \sqrt{C_1^2 + C_2^2} \text{ and } D = \sqrt{D_1^2 + D_2^2} \quad (4)$$

$$\varphi = \tan^{-1}\frac{C_1}{C_2} \text{ and } \varphi' = \tan^{-1}\frac{D_1}{D_2} \tag{5}$$

These model coefficients A, B, C_1, C_2, D_1 and D_2 for GRACE variations are usually adjusted following the least square minimum criteria and then represented regionally or globally. The residuals from this relatively simple Eq. 3 of water mass variations represent intermediate wavelengths, short-term variations of unmodeled phenomena and possibly errors of the a priori correcting models (see Section 3.1).

4.1 Long term water mass variations, climate changes and irrigation

In particular, the linear trend, or equivalently the $B(\lambda,\theta)$ term, that is expressed in mm of EWH per year, corresponds to the increase if positive (or decrease when negative) of the water mass storage, and it can be interpreted in terms of long-term mass balance on the considered multi-year period.

A relatively complete synthesis of works on the evolution of the water storage in several parts of the world for 2002–2017 have recently presented [64] (**Figure 3**). The most important losses of mass are located on the ice shelves of Greenland and Antarctica, where ice storage is drastically melting at the highest rates (more than 200 Gt/y) due to the global warming and this can contribute to half of the sea level rise of about 0.3 mm/y.

In earlier studies based on SH and recently mascons solutions [47], analyzing these GRACE data has shown a continuous acceleration of the Greenland ice shelf melting.

Regions of important loss of water are revealed by GRACE such as the drought lasting up to 2007 in the southeast of Australia [48], in the North of India [62] as well as California [65]. Besides, continental waters are accumulating in other regions like in the endoheric Okavango delta in Africa [63].

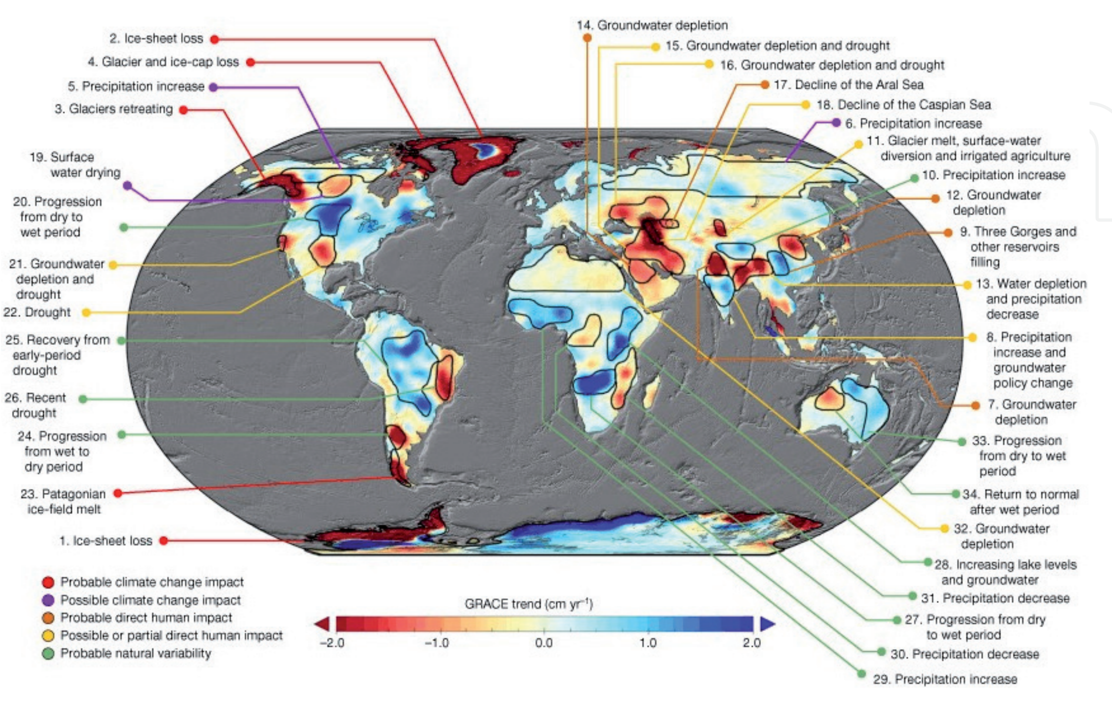

Figure 3.
Global map of the TWS trends and their climatic causes sorted by colors according to [64].

The same authors have validated the constant decrease of deep water of the North Sahara aquifer sensed by GRACE with in situ water table records from wells. The Level-2 solutions need to be combined with radar altimetry data and/or model outputs in lower thus wetter latitudes, so that GRACE solutions have been used to isolate the long-term evolution of groundwater over the entire Amazon basin [66].

4.2 Seasonal cycles in major drainage river basins

The fluctuations of TWS at annual and semi-annual scales reflect the effects of climatic phenomena varying seasonally as: rainfalls, snow, temperature, evapo-transpiration, river runoff, soil moisture, river discharge, groundwater and human activities. The knowledge of these periodical variations that are dominant in the large tropical basins is important to evaluate water resources. The seasonal signals estimated by GRACE are generally adjusted as described by C_1, C_2, D_1 and D_2 in Eq.

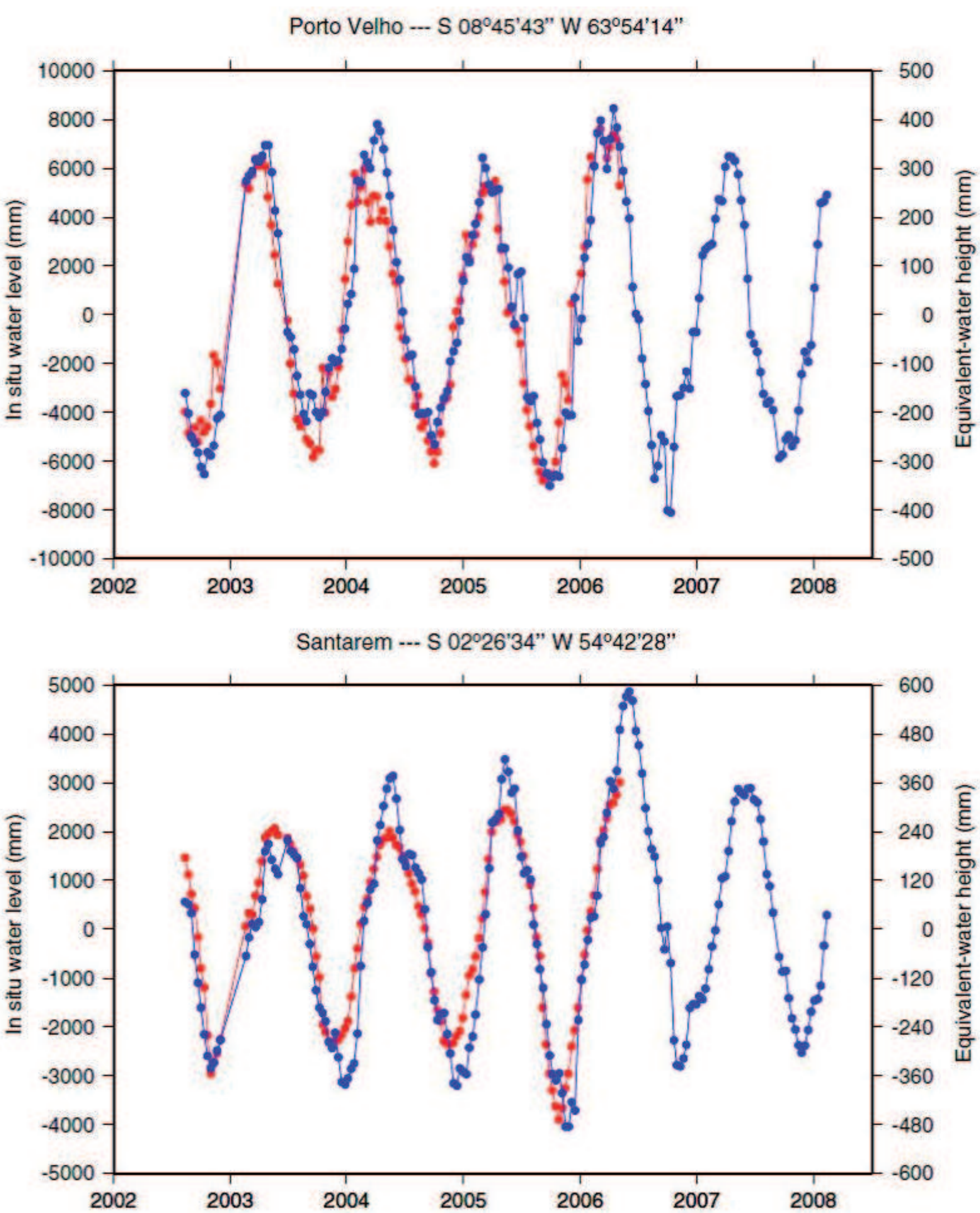

Figure 4.
Times series of in-situ observations of Agência national del Agua (red) and GRACE observations (blue) at the stations of Porto Velho and Santarem in the Amazon basin [28]. We can notice the high correlation of these dominant annual amplitudes.

3. These amplitudes and phases determined from GRACE solutions (Eqs. 4 and 5) allow to improve the understanding of water cycle.

For example, GRACE-based annual signals over the Amazon basin show a predominant annual amplitude in fall and in spring of hundreds of EWH at the basin scale [3] driven essentially by the rainfall seasonality [67]. A comparison of GRACE observed signals and in-situ measured are shown in **Figure 4**. A detailed study of the major tributaries in the Amazon river basin demonstrates that the rainfall variations generated surface water fluxes delayed by two months due to transfer processes [53].

In the African continent, GRACE solutions show that the stronger seasonal amplitudes are located in the Sahel latitudinal band and in the tropical Congo basin (**Figure 5**). An extended study based on Principal Analysis Components reveals a biannual or quadrennial water mass variations related to the West African monsoon [63]. The use of GRACE products also helps to conclude that dry season processes, in particular, evapotranspiration and the presence of vegetation, have an important role in the modeling of soil moisture in the Sahel region [66].

GRACE solutions have also been useful to observe snow cover variations in high latitude regions [68]. For Antarctica, seasonal analysis shows very variable TWS amplitudes in coastal areas with important snow accumulation rates because of oceanic humidity [69].

In the tropical and equatorial regions, GRACE products reveal that seasonal precipitations precede land water storage with a temporal lag of 2 months, however, seasonal cycle of surface temperature is out of phase with respect to TWS, whereas in cold and temperate regions seasonal phenomena are due to more complex

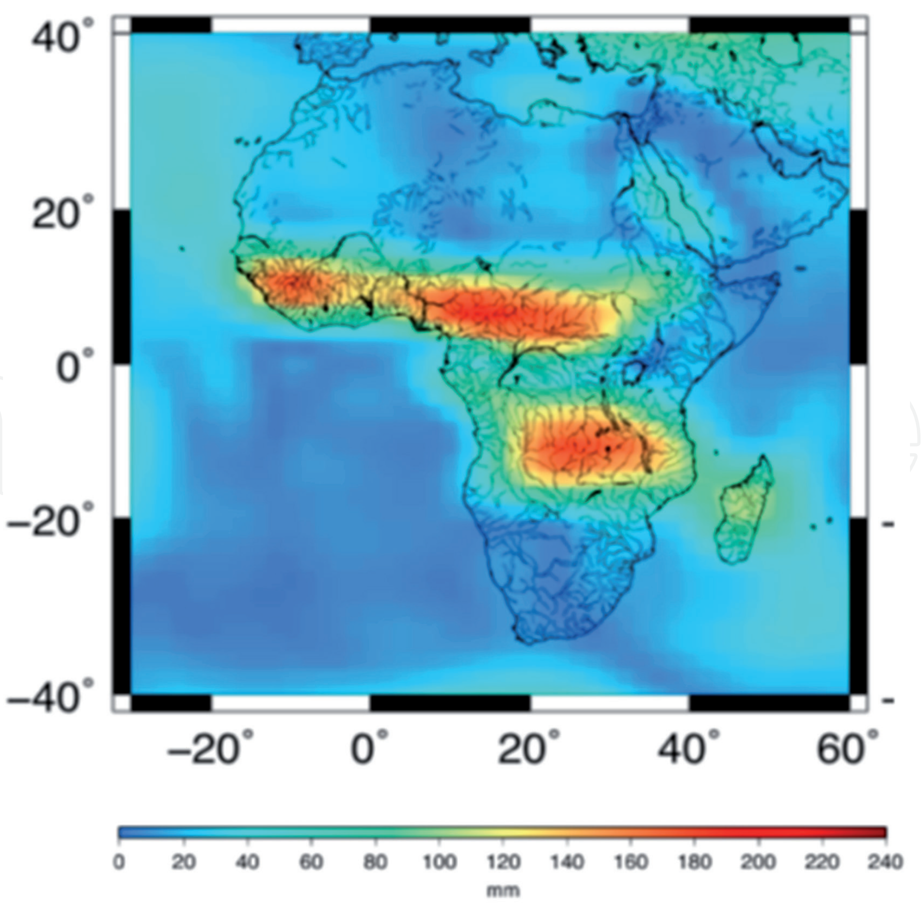

Figure 5.
Map of the seasonal amplitudes of the water mass changes adjusted by least squares adjustment of pure annual sinusoids at grid cells [$C\sin(\omega t+\varphi)$] using the 10-day regional solutions over Africa for the period 2003–2012 [70].

interactions [69]. There is also a significant contribution of river discharge in the spatial distribution of seasonal water storage with a dependency of climate [70].

Regional time variations of evapotranspiration rate - expressed in mm/yr. - can be also derived by integrating and solving the water mass balance equation, which relates TWS on land provided by GRACE, precipitation data from the Global Precipitation Climatology Centre, runoff given by a global land surface model and the unknown evapotranspiration to be determined [71].

4.3 Detection of extremes events

Gravimetric satellites missions also image the extreme climate events in the whole Earth system. Floods and droughts have been largely studied in different continents using the GRACE Level-2 products.

In the case of the Amazon basin, GRACE has revealed periods of extreme droughts and floods. During the 2005 drought, the TWS in the river and floodplains of the Amazon basin was 70% below its average for the 2003–2007 period [71]. However, in 2009 gravity measurements display an exceptional flood associated to La Niña event [26]. The maximum value of TWS in the entire Amazon basin was estimated at ~624 ± 32 Gt with respect to the mean value.

New detection approaches based on GRACE data are developed to identify drought episodes and their severity [72]. Advances in GRACE data treatment

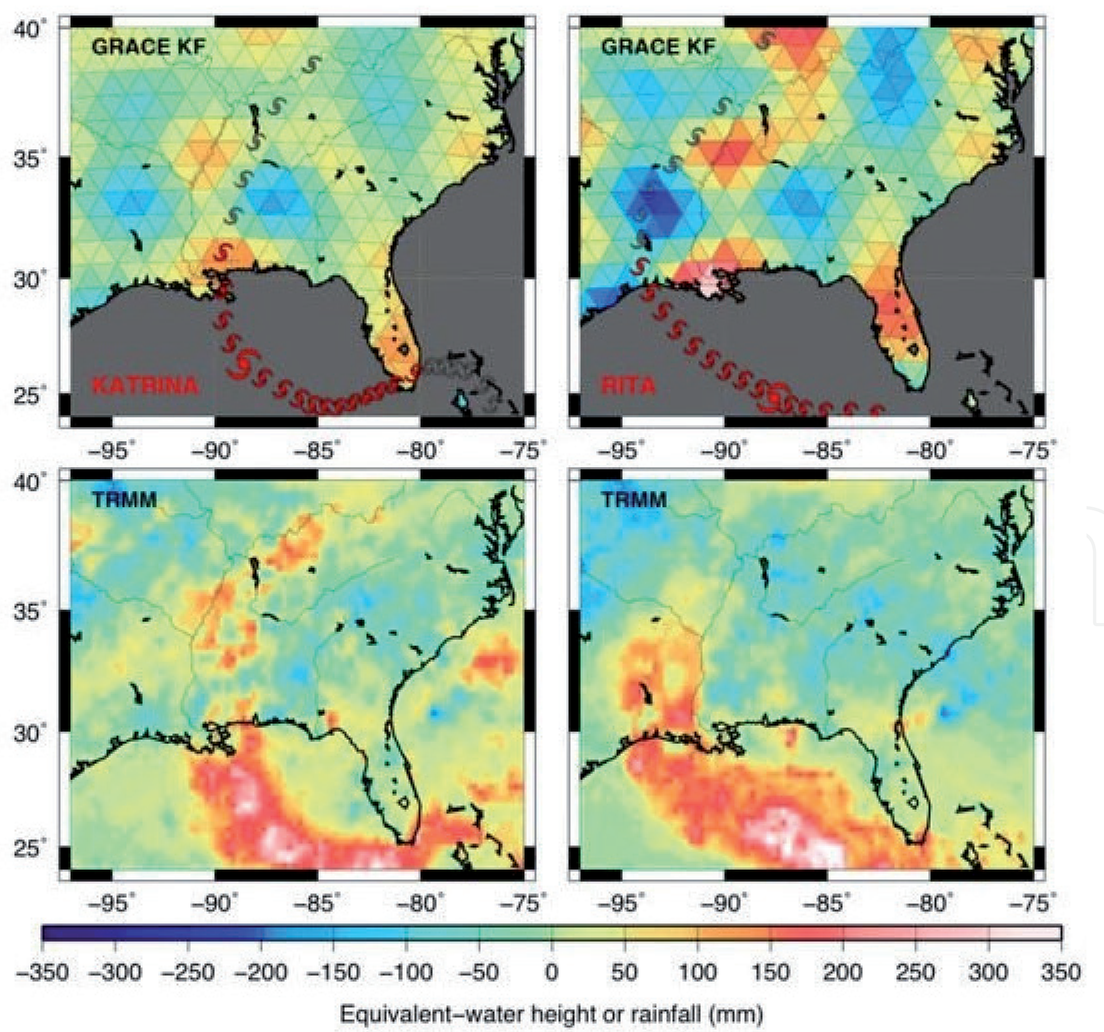

Figure 6.
Differences of weekly-averaged of GRACE solutions derived by the Kalman filter approach as proposed by [73], before and during the Katrina and Rita episodes (top); and comparison with the anomalies of TRMM precipitation for the same periods (bottom).

have allowed to improve spatial and temporal resolution, then rapid extremes events of several days has been observed [73]. One example is the most powerful depressions in late summer 2005 during the cyclonic season in the Gulf of Mexico and Louisiana, better known under the name of "Katrina" (23–31/08/2005), and followed by "Rita" (17–26/09/2005). The direct consequences of the passage of these hurricanes caused important rainfalls along their tracks, thus the significant storage and accumulation of water falling on land could be observed as water mass variations in the range of a few days. As shown in **Figure 6** the important rainfalls of Katrina located in the south of the Great Plains have produced river floods, and thus an important water accumulation is revealed by GRACE in the coastal region of New Orleans (up to 300 mm of EWH).

5. Conclusion

During its sixteen years of operation, the GRACE mission provided a novel source of information on variations of water mass on lands at unprecedented spatial and temporal resolutions. This mission offered an exceptional dataset for studying large-scale water mass redistributions, and for the very first time, the opportunity to monitor water changes in all the hydrological compartments and from regional to global scales. While spherical harmonics solutions were firstly used, regional and local approaches have already demonstrated the possible access to spatial (better localization of structures by construction) and temporal (through daily updates using Kalman filter strategies, e.g. see [73]) scales that were higher than those that were offered by global SH solutions. Additional bibliographic resources and useful information about GRACE can be found on the GRACE Tellus web site [74]. The GRACE mission ended in 2017, and later on a partnership between NASA and the German Research Centre for Geosciences (GFZ) decided to schedule GRACE Follow-On (GRACE-FO) mission to launch in 2018 in order to ensure the continuity of GRACE-type space gravimetry. By using a similar twin satellite configuration of the low-Earth and nearly polar orbit at 300–500 km altitude, the GRACE-FO mission is following its successful predecessor [75]. Additionally, it carries a demonstrator of laser system to measure the inter-satellite distance and velocity, and hence for an improved precision. It is promising for providing new perspectives in hydrology studies, such as refined long-term mass balance estimates of surface water storage and ice sheets. These new data that offer continuity with the previous GRACE observations will be of first interest for hydrology of global hydrological model calibration to constrain their operations through assimilation techniques.

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