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Characterization of spatio-temporal patterns for various GRACE- and GLDAS-born estimates for changes of global terrestrial water storage

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ABSTRACT

Since the launch in March 2002, the Gravity Recovery and Climate Experiment (GRACE) satellite mission has provided us with a new method to estimate terrestrial water storage (TWS) variations by measuring earth gravity change with unprecedented accuracy. Thus far, a number of standardized GRACE-born TWS products are published by different international research teams. However, no characterization of spatio-temporal patterns for different GRACE hydrology products from the global perspective could be found. It is still a big challenge for the science community to identify the reliable global measurement of TWS anomalies due to our limited knowledge on the true value. Hence, it is urgently necessary to evaluate the uncertainty for various global estimates of the GRACE-born TWS changes by a number of international research organizations. Toward this end, this article presents an in-depth analysis for various GRACE-born and GLDAS-based estimates for changes of global terrestrial water storage. The work characterizes the inter-annual and intra-annual variability, probability density variations, and spatial patterns among different GRACE-born TWS estimates over six major continents, and compares them with results from GLDAS simulations. The underlying causes of inconsistency between GRACE- and GLDAS-born TWS estimates are thoroughly analyzed with an aim to improve our current knowledge in monitoring global TWS change. With a comprehensive consideration of the advantages and disadvantages among GRACE- and GLDAS-born TWS anomalies, a summary is thereafter recommended as a rapid reference for scientists, end-users, and policy-makers in the practices of global TWS change research. To our best knowledge, this work is the first attempt to characterize difference and uncertainty among various GRACE-born terrestrial water storage changes over the major continents estimated by a number of international research organizations. The results can provide beneficial reference to usage of different GRACE hydrology products to study TWS changes in different regions of the world.

1. Introduction

Terrestrial water storage (TWS) plays an essential role within the global water cycle and on climate (Famiglietti, 2004), and it is one of the extremely important resources related to economic and societal development. Monitoring and accurate estimate of TWS variations is fundamental to watch and predict droughts, floods and other natural hazards under the condition of global climate change. However, cost of intensive and expensive labor and materials have seriously hindered the development of networks to measure TWS changes, especially at continental and global scales.

Satellite observations of time-variable gravity from the Gravity Recovery and Climate Experiment (GRACE) mission provided new approaches for TWS measurements with unprecedented accuracy (Tapley et al., 2004). Till far, GRACE-born products have been increasingly used for a wide variety of purposes on hydrology and water resources (Ramillien et al., 2008; Schmidt et al., 2008). Some examples include evaluating hydrological fluxes such as evapotranspiration (Rodell et al., 2004a; Ramillien et al., 2006; Rodell et al., 2011), estimating rates of groundwater depletion (Swenson et al., 2008b; Fukuda et al., 2009; Rodell et al., 2009) and improving parameter estimation in land surface models (Yirdaw et al., 2009; Lo et al., 2010).

TWS changes can be accurately derived from the terrestrial gravity field variations measured by the GRACE satellite mission. Nevertheless, the retrieval is not straightforward, and different processing methods will result in different estimates of the GRACE-born TWS products. Although a considerable number of studies have been carried out widely to investigate TWS changes over different parts of the globe using the GRACE-born data, only a few GRACE studies have been implemented at continental or global scales (Ramillien et al., 2004; Wahr et al., 2004; Schmidt et al., 2006; Grippa et al., 2011). Moreover, as a key point, no

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Table 1
The GRACE-born estimates of global TWS change.

Product name	Institute	Countries involved	Reference or/and sponsorship	Spatial grid	Spatial resolution	Temporal resolution
JPL-GRACE Tellus	NASA Jet Propulsion Laboratory	USA	Swenson and Wahr (2006)	$1° \times 1°$	300 km	1 month
DEOSS DMT V 1b	Delft University of Technology, Wuhan University	Netherlands, China	Klees et al. (2008) Liu et al. (2010)	$0.5° \times 0.5°$	200 km	1 month
CNES-GRGS V 2	Space Geodesy Research Group	France	Bruinsma et al. (2010)	$1° \times 1°$	400 km	10 days
CU, Boulder	The University of Colorado	USA	Swenson and Wahr (2002, 2006), Swenson et al. (2008a)	$1° \times 1°$	300 km	1 month

assessment on the reliability or uncertainty for various global estimates of the GRACE-born TWS changes by a number of international research organizations has been found so far. This seriously limits further in-depth utilization of the global GRACE-born products in hydrology. With this regard in mind, the study hereby strives to answer how reliable different estimates of GRACE-born TWS change are in different continents, through a comprehensive inter-comparison with a variety of estimates from the GRACE and Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004b). This is because we are unable to identify the true value of global TWS currently. Meanwhile, the inter-annual and intra-annual variability of different global GRACE-born and GLDAS-born TWS estimates are detected. The findings from this study can significantly contribute to identify reliable estimates of global GRACE-born TWS in different continents, and boost our current skills in monitoring global TWS change under the climate change conditions using the state-of-the-art GRACE technology.

2. Data and method

2.1. Estimates of TWS changes by different GRACE-born products

Four different GRACE hydrology products (Table 1) employed in this study are briefly described below.

(1) The monthly land water solutions from the GRACE Tellus website (http://gracetellus.jpl.nasa.gov/data/gracemonthlymassgridsland/) by the NASA Jet Propulsion Laboratory (JPL) with a spatial resolution of $1° \times 1°$ are available from April 2002 to November 2011. These monthly GRACE gravity models are based on the U. Texas Center for Space Research RL version 4.0 gravity field coefficients (land grid version "ss201008") truncated at degree 60 (Swenson and Wahr, 2006). The degree 2 order 0 coefficients observed by GRACE showed unreasonable variability, so were replaced with values derived from Satellite Laser Ranging (SLR) (Cheng and Tapley, 2004). The degree 1 coefficients are those derived by Swenson et al. (2008a) due to GRACE's inability to provide degree 1 coefficients which represent geocenter motion (Chen et al., 2005a). The GRACE mass anomalies were further corrected for the postglacial rebound contributions generated by the high-latitude Pleistocene deglaciation according to the model of Paulson et al. (2007). A destriping filter was applied to the data to reduce the anisotropic noise, which manifests itself as strong north–south stripes (Swenson and Wahr, 2006). After destriping, the signal was further smoothed using a 300 km wide Gaussian filter to reduce high degree measurement errors (Swenson and Wahr, 2002). The scaling coefficients provided for each 1° bin of the GRACE gridded data are used to compensate bias and leakage and restore much of the energy removed by truncation, destriping and Gaussian smoothing processes (Swenson and Wahr, 2006).

(2) The DEOS Mass Transport Model (DMT) monthly solutions by the University of Delft (http://www.lr.tudelft.nl) are also based on the decomposition into spherical harmonic coefficients but to degree and order 120 (Liu et al., 2010). The data is available from February 2003 to August 2010. Computation of purely dynamic orbits of GRACE satellites and monthly solutions with corresponding covariance matrices are executed iteratively, as described in detail by Liu (2008). The series of monthly solutions is post-processed by applying statistically optimal Wiener filters based on full signal and noise covariance matrices. The signal variances and solutions are computed iteratively, according to the schemes addressed by Klees et al. (2008). Each monthly solution is further transformed into an equivalent water layer thickness with units of meter as a function of latitude and longitude in spherical coordinates according to the method described by Wahr et al. (1998).

(3) The GRGS-EIGEN-GL04 10 day models released by the Centre National d'Études Spatiales (CNES) available from August 2002 to July 2011 are computed based on the GRACE GPS and K band range rate (KBRR) data and LAGEOS-1/2 SLR data (http://grgs.obs-mip.fr/index.php/fre/Donnees-scientifiques/Champ-de-gravite/grace) (Bruinsma et al., 2010). These gravity fields consist of a set of normalized spherical harmonic coefficients from degree 2 up to degree and order 50 applying a stabilization method without additional filtering. Unlike land grid version "ss201008" monthly data, GRGS products do not require additional filtering, hence no scaling factor is applied for the GRGS data (Ramillien et al., 2008; Tregoning et al., 2008). The 10 day GRGS solutions were converted to a monthly time series by taking the average values in order to directly compare them with other GRACE solutions employed in our study.

(4) The error-corrected mass anomalies from the University of Colorado (CU) real-time GRACE website (http://geoid.colorado.edu/grace/grace.php) spans from June 2002 to November 2009. Gravity fields used at this site are truncated at degree 70. From each monthly solution, a time-mean field is removed to obtain the TWS anomaly. The gravity field data are expressed in units of millimeters of equivalent water thickness using relationship between changes in the geopotential and changes in the associated surface-mass density. After the data are converted to mass

Table 2
Land Surface Models in GLDAS.

Model acronym	Institute	Countries involved	Spatial grid	Reference
CLM 2.0	The National Center for Atmospheric Research (NCAR)	USA	$1° \times 1°$	Bonan et al. (2002), Dai et al. (2003)
MOSAIC v3	The National Aeronautics and Space Administration (NASA)	USA	$1° \times 1°$	Koster and Suarez (1996)
NOAH 2.7	The National Oceanic and Atmospheric Administration (NOAA)	USA	$1° \times 1°$	Chen et al. (1996), Koren et al. (1999), Ek et al. (2003)
VIC 4.0.4	University of Washington (UW)	USA	$1° \times 1°$	Liang et al. (1994)