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Efficient basin scale filtering of GRACE satellite products

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A B S T R A C T

The Gravity Recovery And Climate Experiment (GRACE) satellite mission provides time-variable gravity fields that are commonly used to study regional and global terrestrial total water storage (TWS) changes. These estimates are superimposed by different error sources such as the north–south stripes in the spatial domain and spectral/spatial leakage errors, which should be reduced before use in hydrological applications. Although different filtering methods have been developed to mitigate these errors, their performances are known to vary between regions. In this study, a Kernel Fourier Integration (KeFIn) filter is proposed, which can significantly decrease leakage errors over (small) river basins through a two-step post-processing algorithm. The first step mitigates the measurement noise and the aliasing of unmodelled high-frequency mass variations, and the second step contains an efficient kernel to decrease the leakage errors. To evaluate its performance, the KeFIn filter is compared with commonly used filters based on (i) basin/gridded scaling factors and (ii) ordinary basin averaging kernels. Two test scenarios are considered that include synthetic data with properties similar to GRACE TWS estimates within 43 globally distributed river basins of various sizes and application of the filters on real GRACE data. The KeFIn filter is assessed against water flux observations through the water balance equations as well as in-situ measurements. Results of both tests indicate a remarkable improvement after applying the KeFIn filter with leakage errors reduced in 34 out of the 43 assessed river basins and an average improvement of about 23.38% in leakage error reduction compared to other filters applied in this study.

1. Introduction

Since 2002, the Gravity Recovery And Climate Experiment (GRACE) satellite mission has been providing time-variable global gravity field solutions (Tapley et al., 2004). These variations are primarily caused by temporal changes in the gravity field due to changes in hydrology, ice masses of the cryosphere, or surface deformation, e.g., glacial isostatic adjustment (GIA). Within a temporal and spatial resolution of respectively one day to one month and a few hundred kilometers, GRACE products have proved to be very useful for various geophysical and hydrological studies (see, e.g., Kusche et al., 2012; Wouters et al., 2014, for applications). In particular, the so-called level 2 (L2) time-variable gravity fields are widely used to quantify global (e.g., Eicker et al., 2016; Kusche et al., 2016; Rodell et al., 2004) and regional (e.g., Awange et al., 2014; Chen et al., 2009; Khaki et al., 2017a,b; Munier et al., 2014) terrestrial total water storage (TWS) changes, i.e., the sum of changes in surface and sub-surface water storage compartments. GRACE products are also applied to estimate changes of the terrestrial water cycle (e.g., Eicker et al., 2016; Ogawa et al., 2011) or to validate the water cycle in atmospheric reanalyses (e.g., Forootan et al., 2017; Kusche et al., 2016; Springer et al., 2014). Combined with information observed from other monitoring techniques (e.g., GPS and satellite altimetry) or simulations by land surface models, L2 products are applied to estimate surface (e.g., lakes and rivers) and sub-surface(e.g., soil moisture and groundwater) storage changes at (river) basin scales (e.g., Famiglietti and Rodell, 2013; Forootan et al., 2014; Longuevergne et al., 2010; Syed et al., 2005).

GRACE L2 products are provided in terms of potential spherical harmonic coefficients, e.g., up to degree and order 60 or 90, which mainly represent the large- to medium-scale (e.g., few hundred km) time-variable gravity changes. However, the L2 potential coefficients contain different types of errors. A part of these errors is related to

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colored/correlated noise due to the anisotropic spatial sampling of the mission, instrumental noise (K-band ranging system, GPS, and the accelerometer observations and star cameras), and temporal aliasing caused by the incomplete reduction of short-term mass variations by models (Dobslaw et al., 2016; Forootan et al., 2013, 2014a). These errors are manifested as north–south striping patterns in the spatial domain (e.g., gridded TWS products). The application of smoothing techniques with the primary aim of removing the stripes can lead to spatial leakages. The spatial averaging introduced by the smoothing kernels such as the Gaussian Kernel in Jekeli (1981) or non-Gaussian Kernels in Kusche (2007), results in spatial interference of mass anomalies. These leakage errors do not allow for perfect separation of gravity anomalies, e.g., between land and oceans, and limit the detection of small-scale hydrological signals. The accuracy of GRACE TWS estimation is very important for hydrological applications especially at the basin scale, e.g., to interpret redistribution of water storage or to indicate drought and flood patterns (e.g., Awange et al., 2016; Longuevergne et al., 2010; Yeh et al., 2006). Therefore, better post-processing of GRACE data must be applied to improve consistencies between various types of products that are usually used for studying the water cycle (e.g., Eicker et al., 2016).

Different filtering methods have been proposed to reduce north–-south striping errors, such as the isotropic Gaussian filter (Jekeli, 1981) and anisotropic filters (e.g., Klees et al., 2008; Kusche, 2007; Swenson and Wahr, 2006). A comprehensive review on filtering techniques has been done e.g., by Frappart et al. (2016). The isotropic Gaussian filter Jekeli (1981) is a degree-dependent filter in the spectral domain and bell-shaped filter in the spatial domain. Anisotropic filters, on the other hand, are introduced to deal with the correlated errors between the coefficients of L2 products (e.g., different marginal shapes in the north–south and the east–west directions). In general, filtering techniques that spatially smooth the L2 signal contents (e.g., Kusche et al., 2009; Wahr et al., 2006) down-weight L2's higher degree and order potential coefficients. Although these filters reduce noises, their main problem is that they also attenuate the signals. In addition, the application of filtering moves gravity anomalies from one region to another region. Generally speaking, after applying a smoothing kernel some parts of the signals inside an area of interest leak out from it or alternatively signals from outside leak into the area of interest (e.g., Baur et al., 2009; Chen et al., 2007). These issues become more critical for basin-scale studies, especially where the sizes of the basins are small in comparison to the spatial resolution of GRACE (e.g., Longuevergne et al., 2010; Yeh et al., 2006).

Several methods have been put forward to mitigate spatial leakage effects in TWS estimations from L2 products. These methods can largely be categorised into the following three groups (i) those that numerically estimate the leakages (leakage in and out) using the averaging kernels (e.g., Baur et al., 2009; Longuevergne et al., 2010; Seo and Wilson, 2005), (ii) those that are based on scaling factors derived from synthetic data (e.g., Landerer and Swenson, 2012; Long et al., 2015), and (iii) those that use inversion for simultaneous signal separation and leakage reduction (e.g., Forootan et al., 2014; Frappart et al., 2011, 2016; Wouters and Schrama, 2007). From the first group, Swenson and Wahr (2002) developed an isotropic kernel using a Lagrange multiplier filter to best balance signal and leakage errors over a basin of interest. A non-isotropic Gaussian filter proposed by Han et al. (2005) to improve spatial resolution during the filtering process also belongs to this group. In another effort, Harig and Simons (2015) used Slepian-function analysis to decrease leakage effects in Antarctica by maximizing signal energy concentration within the area of interest. The second category uses synthetic data, e.g., from land surface models (LSMs) or hydrological fluxes to derive scaling factors that can be multiplied by GRACE filtered products to recover the lost signals. In this approach, efforts are focused on the application of the same filtering techniques to the synthetic data (that is close enough to the signal contents of GRACE products). Basin-averaged or gridded scale factors are usually estimated as the solution of a least squares adjustment that compares data before and after application of the filter. Landerer and Swenson (2012) estimated gridded scaling factors for GRACE TWS anomalies to restore the signals lost after applying a regular smoothing filter (a Gaussian smoothing kernel). A similar study that uses a different spatial scale (basin averages) has been performed by Long et al. (2015) who estimated scale factors using a global hydrological model over the Yangtze River Basin in China. A possible drawback of this approach is its dependency on the reliability of the hydrological model used to estimate the desired scale factors. The inversion techniques in (iii) also require a prior information about mass changes within different storage compartments. The dependency of final signal separation results on these information has not been reported yet.

To address the above problems arising from the application of filtering methods, the present study proposes a new filtering method, Kernel Fourier Integration (KeFIn), which is designed to reduce both types of above-mentioned errors using a two-step algorithm. In the first step, the advantages of image processing techniques such as motion filters (e.g., Hichri et al., 2012; Zhang et al., 2009) are exploited to reduce the measurement noise and aliasing of unmodelled high-frequency mass variations. This attempt is designed to keep as much of the higher frequency information as possible. It should be mentioned here that, although the proposed KeFIn filter has less effect on high-frequency signals compared to the existing methods, some signal inferences still exist mainly due to the truncation of degree and order in L2 products. In the second step of the KeFIn filter, the leakage problem is mitigated using an anisotropic kernel to isolate the signals in the basin of interest. The main idea of this step is to combine the Fourier transform and basin kernel functions to increase the strength of the attenuated signals. It will be shown in the following that the KeFIn filter is suited to deal with basins of various shapes and sizes.

The primary objectives of this study is developing a filter for (i) dealing with colored/correlated noise of high-frequency mass variations (i.e., stripes); and (ii) reducing basin scale spatial leakage errors for hydrological applications. These objectives are addressed by introducing novel methodologies discussed in Sections 3.1.1 and 3.1.2, respectively. The performance of the introduced filtering method (KeFIn) in terms of leakage reduction is compared with commonly used methods that deal with leakage problem from the basin averaging kernel and the model-based scaling factor groups. For this purpose, both real and synthetic data sets are employed. The purpose of using synthetic data is to provide a more accurate evaluation of the newly proposed method in comparison to existing methods (e.g., Chen et al., 2009; Seo and Wilson, 2005). Therefore, we generate synthetic data in 43 globally distributed basins and use them to examine the performance of the proposed KeFIn and other commonly used filters. These filters are further assessed using water flux observations in the context of the water balance equation (see Eq. (1) in Section 2.3), as well as by comparisons with in-situ measurements.

2. Data

2.1. GRACE

Monthly GRACE L2 products along with their full error information are computed at the Technical University of Graz known as the ITSG-Grace2014 gravity field models (Mayer-Gürr et al., 2014). We use these products and their full covariance errors up to degree and order 60 covering the period 2002–2013 (https://www.tugraz.at/institute/ifg/downloads/gravity-field-models/itsg-grace2014). Degree 1 coefficients are replaced with those estimated by Swenson et al. (2008) to account for the movement of the Earth's center of mass. Degree 2 and order 0 (C20) coefficients are replaced by those from Satellite Laser Ranging solutions owing to unquantified large uncertainties in this term (e.g., Chen et al., 2007). We also account for the post-glacial rebound by incorporating the corrections provided by Geruo et al. (2013). The L2