Remote Sensing of Environment 136 (2013) 89–98

Contents lists available at SciVerse ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Relating satellite gravimetry data to global soil moisture products via data harmonization and correlation analysis

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ARTICLE INFO

Article history:
Received 12 December 2012
Received in revised form 17 April 2013
Accepted 18 April 2013
Available online 25 May 2013

Keywords:
Soil moisture
Correlation analysis
Data harmonization
GRACE
WGHM
ASCAT

ABSTRACT

Due to limited in-situ data global soil moisture products should also be validated with respect to independent global data sets. Our study investigates possibilities and benefits of relating soil moisture products from remote sensing and hydrological modeling to information on total water storage change from satellite gravimetry. We use soil moisture data from the active satellite sensor ASCAT and the hydrological model WGHM as well as satellite gravity field observations from the GRACE mission. First we apply a data harmonization procedure to equalize the distinct data representations and formats of those data sets. Then we perform a correlation analysis. The results show correlations close to one between GRACE and soil moisture data specifically for humid and temperate regions. A comparison of correlation coefficients from different data pairs highlights that in arid environments total water storage from GRACE corresponds better to surface soil moisture captured by ASCAT than to total soil moisture from WGHM. In humid and temperate regimes the observation is reversed. Furthermore regions could be identified where the input data of the WGHM might be of low quality, producing higher correlations between ASCAT and GRACE than between ASCAT and WGHM. We therefore conclude that GRACE data can deliver valuable information for the quality assessment of soil moisture products and provide a link to their contribution to continental water storage.

1. Introduction

High-quality global or small-scale soil moisture products are of great interest to various sectors, dealing for example with agricultural development, disaster management (drought and flood forecast), or water supply (Bolten et al., 2010). Comprehensive and continuous measurements of soil moisture on site in direct contact with the medium are currently not available on global scale (Wang & Qu, 2009). Only some continental areas start to be well covered by The International Soil Moisture Network (www.ipf.tuwien.ac.at/insitu/). Therefore recent small-scale soil moisture maps are either derived indirectly from satellites or from the outputs of hydrological models. Examples of satellite sensors and models which are used for the generation of soil moisture maps are given in Table 1.

For creating or improving global data sets on soil moisture four main research targets can be identified:

1. Understanding the nature of soil moisture and associated processes
2. Understanding the nature of satellite data that are used to indicate soil moisture
3. Developing methods for the generation of soil moisture products based on this understanding
4. Developing methods for the validation of the generated soil moisture products and with it doing a quality assessment on Research Targets 1 to 3.

This study focuses on Research Target 4. Most commonly the validation of global soil moisture products is performed by choosing one or more local study sites where satellite or modeled data are compared against in-situ measurements. The lessons learnt from these local sites are then projected to larger regions. Major in-situ validation sites for AMSR-E are located in the United States. As part of the Soil Moisture Experiments (SMEX) they are situated for example in the Walnut Creek Watershed, Iowa (Cosh, 2004) and the little Washita river watershed, Oklahoma (Cosh et al., 2006). For ASCAT various studies have been done within Europe. An example is the extensive work of Brocca et al. (2011), comparing ASCAT and AMSR-E data with measurements of 17 in-situ stations in Italy, Spain, France, and Luxembourg. Another extensive study of Albergel et al. (2012) evaluates data from 200 stations, located in Africa, Australia, Europe, and the United States for ASCAT and SMOS. Specifically for the verification of SMOS data the field campaign “Surface Monitoring Of the Soil Reservoir EXperiment” (SMOSREX) has been established in Mauzac near Toulouse, France (De Rosnay et al., 2006). An example of respective validation studies on models is the work of Kato et al. (2007) comparing soil–water content of the three GLDAS land surface models NOAH, MOSAIC and CLM with globally

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http://dx.doi.org/10.1016/j.rse.2013.04.012

Table 1
Examples of satellite sensors and models, delivering data for global soil moisture maps.

Satellite sensors				Models		
Sensor	Satellite platform	Type	Operation time	Name	Type	Operation time
ASCAT (Advanced SCATterometer)	METOP	Active scatterometer (C-band)	2006–present	WGHM (WaterGAP Global Hydrology Model)	Hydrological water balance model	1901–present
AMSR-E (Advanced Microwave Scanning Radiometer for EOS)	AQUA	Passive radiometer (X-band and C-band)	2002–2011	GLDAS (Global Land Data Assimilation System)	Land surface model	1979–present
MIRAS (Microwave Imaging Radiometer using Aperture Synthesis)	SMOS	Passive radiometer (L-band)	2010–present	ERA-Interim (ECMWF global atmospheric reanalysis)	Atmospheric reanalysis	1989–present

distributed in-situ data from thirty field measurement stations from the Global Energy and Water Cycle Experiment (GEWEX).

Due to the sparse distribution of operating field measurement stations, the comparison of satellite or modeled data with in-situ data is limited to regional scales. Therefore comprehensive global validation studies are mainly done by the mutual comparison of different global soil moisture products, using various mathematical approaches such as statistical analysis (Dirmeyer et al., 2004), triple collocation method (Dorigo et al., 2010; Leroux et al., 2011; Scipal et al., 2008) or correlation analysis (Jeu et al., 2008; Reichle et al., 2004). Subject to those validation studies are mostly different remote sensing products from active and passive satellite sensors and various models providing hydrological information, as listed in Table 1.

Based on global validation studies of soil moisture products the following statements were for example made:

- High foliage density contaminates the microwave signal of soil moisture specifically for radiometers (Dirmeyer et al., 2004; Dorigo et al., 2010; Jeu et al., 2008; Scipal et al., 2008).
- Over dense forest no retrieval is possible, applying for both active and passive microwave data (Jeu et al., 2008).
- In desert areas microwave scatterometers are prone to volume scattering effects of dry sand and systematic surface roughness effects (Dorigo et al., 2010; Jeu et al., 2008; Scipal et al., 2008).
- Radio Frequency Interference artificially lowers soil moisture values (Jeu et al., 2008).
- Regions of snow and ice are susceptible to signal contamination for passive microwave sensors (Dirmeyer et al., 2004).
- Poor or absent snow-melt modeling degrades the quality of soil moisture products from models (Dirmeyer et al., 2004).

Furthermore information on data quality is used to produce merged global soil moisture products from different sensors (Liu et al., 2011, 2012) and to assimilate satellite soil moisture data into models (Dharssi et al., 2011; Draper et al., 2012; Reichle et al., 2013).

Reflecting on these results one can conclude that inter-comparisons of independent data sets on global scale have been helpful to identify and locate problems arising from the mapping of soil moisture from space or by modeling. In addition to direct comparisons with in-situ data they provide valuable information for global quality control.

Considering the fundamental importance of quality control for global soil moisture products and recognizing previous findings of inter-comparison studies, this paper investigates the possibilities and benefits of relating data from satellite gravimetry to global soil moisture products. Specifically satellite data from the GRACE (Gravity Recovery And Climate Experiment) mission are used. Those data have already been subject to several studies focusing on the quality control or calibration of model outputs in terms of total continental water storage (Güntner, 2008; Houborg et al., 2012; Mueller et al., 2011; Werth & Güntner, 2010; Werth et al., 2009). However, a specific analysis with respect to soil moisture data has not been performed yet. In our research we compare GRACE data against surface soil moisture products from ASCAT and total soil moisture and total water storage data from WGHM. For the comparison we perform a correlation analysis.

The comparison of GRACE data with global soil moisture products has some advantages. Firstly GRACE data are available on global scale from 2002 until present with a temporal resolution of one month. Secondly the derived information on changes in total water storage are based on the measurement of mass changes and are therefore totally independent of any other remote sensing technique or hydrological modeling method. Also the topographic complexity or land cover does not play any role for data quality (as it does for example for scatterometers).

Other characteristics of GRACE are rather challenging when it comes to the comparison with global soil moisture products. For example several assumptions have to be made in order to link changes in total water storage to changes in soil moisture, which are in fact two different kinds of parameters. Also GRACE data, which are usually provided in spherical harmonic coefficients, have to be corrected for signals related to the satellite's orbit characteristics and short-term mass changes using specific algorithms and filters (see Section 2.2). Consequently the soil moisture data have to be treated in the same way to achieve a harmonized representation of all data sets for the comparison. Relating soil moisture products to products from GRACE is therefore not straight forward.

Focusing on the integration of GRACE data into the validation of soil moisture products via correlation analysis this study addresses three main research questions:

1. Is the correlation of GRACE and soil moisture data feasible with respect to the harmonization steps:
   a. Conversion of soil moisture data into spherical harmonics
   b. Filtering
2. Can we observe in certain regions of the world correlations between the different data sets and with it identify where GRACE data may be useful for the understanding of soil moisture products?
3. What is the benefit of correlating GRACE data with soil moisture data sets?

For seeking the answers to those research questions the sections of this study are structured in the following way. In Section 2 on “Methodology” we first focus on the assumptions we make in order to link changes in total water storage to changes in soil moisture (Section 2.1). Afterwards we point out our approach for harmonizing soil moisture products and data from satellite gravimetry and describe the subsequent correlation analysis (Section 2.2). In Section 3 on “Materials” we introduce the data sets of GRACE, ASCAT and WGHM. In the fourth section we present the results of the correlation analysis with respect to the first two research questions. We demonstrate how correlation results are impacted if the input soil moisture products are converted into spherical harmonics and filtered using a standard Gauss-filter (Research Question 1). Furthermore we show world maps, highlighting the correlation coefficients for different data combinations for the time period September 2007 to August 2011 (Research Question 2). The correlation results and the benefits of relating GRACE data to soil moisture products (Research Question 3) are discussed in the fifth section. Finally we draw conclusions in the last section.