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Earth and Planetary Science Letters 235 (2005) 283–301

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Time variations of land water storage from an inversion of 2 years of GRACE geoids

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Received 1 December 2004; received in revised form 25 March 2005; accepted 5 April 2005
Available online 1 June 2005
Editor: V. Courtillot

Abstract

By delivering monthly maps of the gravity field, the GRACE project allows the determination of tiny time variations of the Earth's gravity and particularly the effects of fluid mass redistributions at the surface of the Earth. However, GRACE data represent vertically integrated gravity measurements, thus are the sum of all mass redistributions inside the Earth's system (atmosphere, oceans and continental water storage, plus solid Earth). In this paper, we apply a generalized least-squares inverse approach, previously developed by [1] [G. Ramillien, A. Cazenave, O. Brunau, Global time-variations of hydrological signals from GRACE satellite gravimetry, Geophys. J. Int. 158 (2004) 813–826.], to estimate, from the monthly GRACE geoids, continental water storage variations (and their associated uncertainties) over a 2-year time span (April 2002 to May 2004). Tests demonstrating the robustness of the method are presented, including the separation between liquid water reservoirs (surface waters + soil moisture + groundwaters) and snow pack contributions. Individual monthly solutions of total land water storage from GRACE, with a spatial resolution of ~660 km, are presented for the 2-year time span. We also derive the seasonal cycle map. We further estimate water volume changes over eight large river basins in the tropics and compare with model predictions. Finally, we attempt to estimate an average value of the evapotranspiration over each river basin, using the water balance equation which links temporal change in water volume to precipitation, evapotranspiration and runoff. Amplitudes of the GRACE-derived evapotranspiration are regionally consistent to the predictions of global hydrological models.

Keywords: GRACE satellite gravimetry; global hydrology; least-squares inversion

1. Introduction

In March 2002, a new generation of gravity missions was launched: the Gravity Recovery and Climate Experiment (GRACE) space mission [2,3]. The

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0012-821X/$ - see front matter
doi:10.1016/j.epsl.2005.04.005

objective of GRACE is to measure spatio-temporal variations of the gravity field with an unprecedented resolution and precision, over time scales ranging from a few months to several years. As gravity is an integral of mass, these spatio-temporal gravity variations represent horizontal mass redistributions only to the extent that they are assumed to be caused by surface loads. On time scales from months to decades, mass redistribution mainly occurs inside the surface fluid envelopes (oceans, atmosphere, ice caps, continental reservoirs) and is related to climate variability. The main application of GRACE is quantifying the terrestrial hydrological cycle through measurements of vertically-integrated water mass changes inside aquifers, soil, surface reservoirs and snow pack, with a precision of a few millimeters in terms of water height and a spatial resolution of ~400 km [4,5].

Until the launch of GRACE, no direct measurements of time-varying storage of snow, soil and underground waters were available globally. Therefore, the global distribution and spatio-temporal changes of land water mass were essentially estimated from modelling. The main motivation for developing global land surface models (LSMs) over the recent decades was to provide realistic temperature and humidity boundary conditions to atmospheric models developed for climate modelling. In effect, many land surface parameters exert a strong influence on water and energy surface fluxes and as a consequence on the atmosphere. Among these parameters, soil moisture and snow mass are important since they affect low-atmosphere state on both short and long (seasonal and inter-annual) time scales. Besides, land water storage and snow mass are themselves affected by atmospheric conditions and climate variability. In the recent years, a number of state-of-the-art LSMs have provided global gridded time series of soil water, underground water and snow mass, typically on a monthly basis and a geographical resolution of $\sim 1^\circ \times 1^\circ$ (among others, [6–11]). These global hydrological data sets are currently derived from model runs either in a coupled mode or in a stand alone mode forced by observations, in particular precipitation. Due to the lack of global information on soil water and snow depth, model validation is in general performed by comparing predicted runoff with in situ measurements in a number of river basins. Besides, international projects for inter-comparing the global hydrological models have been initiated in the recent years (e.g., PILPS [12]; GSWP1 [13]). However, these approaches remain limited and do not provide a global evaluation of the models accuracy. Thus, direct comparison of models outputs with independent observations, in particular the GRACE-based hydrological products, could be very instructive. However at present, such comparisons first serve to evaluate the precision of the GRACE products. Besides, they will provide the basis for future space data assimilation into the global hydrological models.

This paper presents results of monthly land water change over 2 years (from April 2002 to May 2004) from the GRACE geoids recently released by the GRACE project [2]. The method developed in this study differs from previously published GRACE results [3,14,15] in that it tries to separate mass signals from four different surface reservoirs (soil plus underground plus surface water reservoirs, snow pack, atmosphere and ocean) through an inverse modelling based on generalized least-squares adjustment [16]. The inverse approach which combines the GRACE observations with stochastic properties of the hydrological (or oceanic) signal significantly reduces the recovered land (or ocean) water signal compared to the direct conversion of geoid anomalies into water mass, because of noise reduction and elimination of unrelated signal (e.g., atmospheric noise).

2. The GRACE geoids

The data set recently provided to GRACE users by the GRACE project consists of monthly sets of spherical harmonic geoid coefficients (and associated uncertainties), up to degree and order 100, since April 2002. These coefficients derived from raw tracking measurements (GRACE consists of a pair of satellites whose mutual distance, absolute positions and velocities are continuously monitored) are currently computed by two groups: the Center for Space Research (CSR) in the USA and the GeoForschungs-Zentrum (GFZ) in Germany. The geoid coefficients are corrected for atmospheric loading and oceanic tides. An a priori model for the oceanic variability was also removed during the GRACE data processing. Therefore, temporal changes of the geoid coefficients