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Time-variable gravity from space and present-day mass redistribution in the Earth system

Anny Cazenave [a], Jianli Chen [b,*]

[a] LEGOS-CNES, Toulouse, France
[b] CSR, University of Texas, Austin, USA

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ABSTRACT

Since 2002, the US–German GRACE (Gravity Recovery and Climate Experiment) mission has been providing a precise survey of Earth's time-variable gravity field, with unprecedented temporal and spatial sampling. GRACE time-variable gravity fields provide a means of measuring temporal and spatial variations of mass redistribution within the Earth system. The GRACE mission has launched a new era in studying a series of geophysical problems ranging from deep Earth structure to tracking mass redistribution on and near the surface of the Earth. GRACE has greatly improved understanding of mass redistribution in various compartments of the climate system (atmosphere, oceans, terrestrial water, and cryosphere). In this review, we use examples to show how GRACE has fundamentally enriched a number of fields, including (but not limited to) the global water cycle and land hydrology, mass balance of polar ice sheets and mountain glaciers, ocean mass and global sea level change, and solid Earth geophysics.

1. Introduction and historical background

Observing the Earth from space over the past 50 years has resulted in spectacular advances in various areas of the geosciences. This is the case, in particular, for measuring the precise shape of the Earth and its broad scale internal structure from detailed measurement of the planet's gravity field. Since the early 1970s, tracking the orbits of tens of satellites at different altitudes and orbit inclinations has gradually improved knowledge of Earth's average (static) gravity field. Traditionally, gravity field recovery from tracking data has been an iterative approach, which compares a numerically integrated orbit from an initial gravity field and other force models with observations of the satellite motion (usually from ground-based stations). Accumulation of decades of tracking data from a large number of geodetic satellites in different orbital configurations led to a succession of gravity field solutions of increased precision and resolution. Moreover the combination of these 'satellite only' solutions with surface measurements and altimetry-based gravity anomalies (from ocean geoid height measurements) has provided global gravity fields solutions of ever better quality and resolution. Fig. 1 shows a map of the static gravity field from one of the most recent solutions, the Earth Gravity Model 2008 (EGM08) (Pavlis et al., 2008).

During the 1980s and 1990s, continuous improvements in space techniques and improved modeling of satellites orbits enabled a new field of space geodesy: observation of temporal variations of the Earth's gravity field due to mass redistribution within and among the various elements of the Earth system. Classically Earth's gravity field (or equivalently the geoid, an equipotential surface of the Earth gravity field that coincides with mean sea level) is represented by a series of coefficients C_{nm}, S_{nm} (known as Stokes Coefficients of a spherical harmonic representation) up to a given degree n and order m as (e.g., Heiskanen and Moritz, 1967),

$$H(\theta,\phi) = R_e \sum_{n=0}^{\infty} \sum_{m=0}^{n} \tilde{P}_{nm}(\cos\theta) \times [C_{nm}\cos(m\phi) + S_{nm}\sin(m\phi)] \quad (1)$$

H is geoid height change at the mean surface at location θ (colatitude), ϕ (longitude). R_e is mean radius of the Earth, and P_{nm} is normalized Legendre polynomial. Degree n is related to wavelength w (in km) through the relationship $w = 40000/n$. The very first terms of Eq. (1) (i.e., the low degree or long wavelength components) can be directly interpreted in terms of physical properties of the planet (e.g., the degree 2 order 0 term represents the dynamical flattening of the Earth; the degree 2, order 1 term describes the position of the axis of rotation on Earth's surface, etc.).

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* Corresponding author. Center for Space Research, University of Texas at Austin, 3925 West Braker Lane, Suite 200, Austin, TX 78759-5321, USA. Tel.: +1 512 232 6218; fax: +1 512 471 3570.
E-mail address: chen@csr.utexas.edu (J. Chen).

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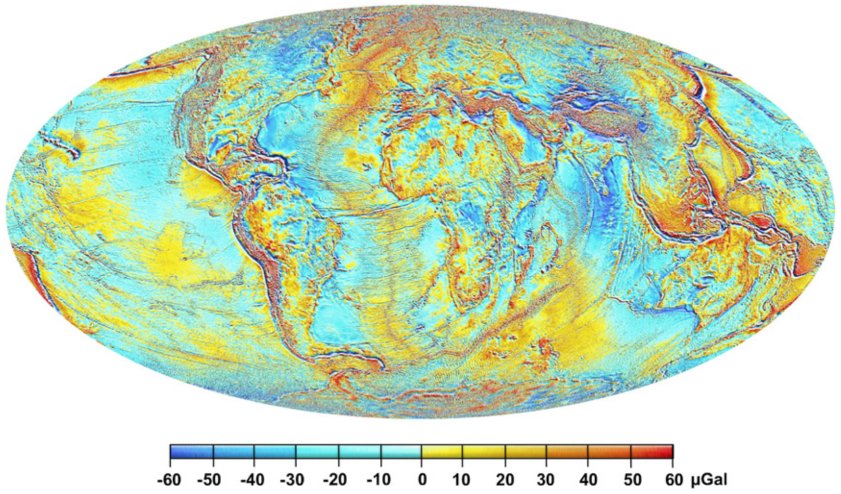


Fig. 1. The static (average) component of Earth's gravity field (EGM08 model, from Pavlis et al., 2008). The figure shows gravity anomalies in mGal.
Source: Bureau Gravimetrique International.

A secular decrease of Earth's flattening (the degree 2, order 0 term) was discovered by precise analysis of the Lageos laser satellites (Yoder et al., 1983; Cox and Chao, 2002), and attributed to post-glacial rebound (PGR) (the viscoelastic response of the crust and mantle to melting of the large ice sheets that covered part of the northern hemisphere during the last ice age). Seasonal variations of the low degree terms of the Earth's gravity field expansion (up to ~degree 6) have been detected from analysis of satellite orbital perturbations (Cheng and Tapley, 1999, 2004; Chen et al., 1999). These variations were attributed to seasonal transfer of air mass inside the atmosphere as well as annual fluctuations of snow and land water storage (e.g., Chen et al., 1999; Cazenave et al., 1999). However until the advent of the GRACE mission (Dickey et al., 1997; Wahr et al., 1998), temporal changes of only the longest-wavelength (lowest degree) harmonic coefficients could be monitored from orbital perturbations. This approach indeed limited effective spatial resolution to several thousand km, because large uncertainty in higher degree coefficients prevented detection of any time-varying signal. The unprecedented precision and spatial resolution (around 400 km) of the GRACE mission, launched in 2002, have therefore revolutionized the understanding of many components of the Earth system that exchange or redistribute mass at a variety of time scales. Examples include the continental water cycle and related climate variability, ice sheets, glaciers and contributions to sea level rise, water mass redistribution within and among ocean basins, and tectonic processes.

Section 2 describes the GRACE mission and its time-variable gravity measurements. Applications to continental hydrology are discussed in Section 3. Sections 4 and 5 present GRACE results on the mass balance of the Greenland and Antarctic ice sheets as well as on glaciers. Oceanic applications of GRACE are summarized in Section 6. Section 7 provides examples of solid Earth applications. Some concluding remarks are presented in Section 8.

2. Satellite gravity measurements from GRACE

The GRACE mission is jointly sponsored by NASA and DLR (German Aerospace Center) under the NASA Earth System Science Pathfinder Program (Tapley et al., 2004). GRACE was launched on March 17, 2002, with a design lifetime of 5 years. Now well past this milestone and still producing excellent data, the GRACE mission has been extended through 2012, promising to extend the data set beyond a full decade. GRACE utilizes a state-of-the-art technique to observe variations of Earth's gravity by tracking the inter-satellite range and range-rate between two coplanar, low altitude satellites (GRACE A and B, see Fig. 2) via a K-band ranging (KBR) system, which measures the distance between the two satellites at micron meter level accuracy using carrier phase measurements in the K (26 GHz) and Ka (32 GHz) frequencies (Thomas, 1999). In addition, each satellite is equipped with a SuperSTAR Accelerometer, GPS receiver/antenna, Star Cameras, and Laser Retro Reflectors to complement the science instruments.

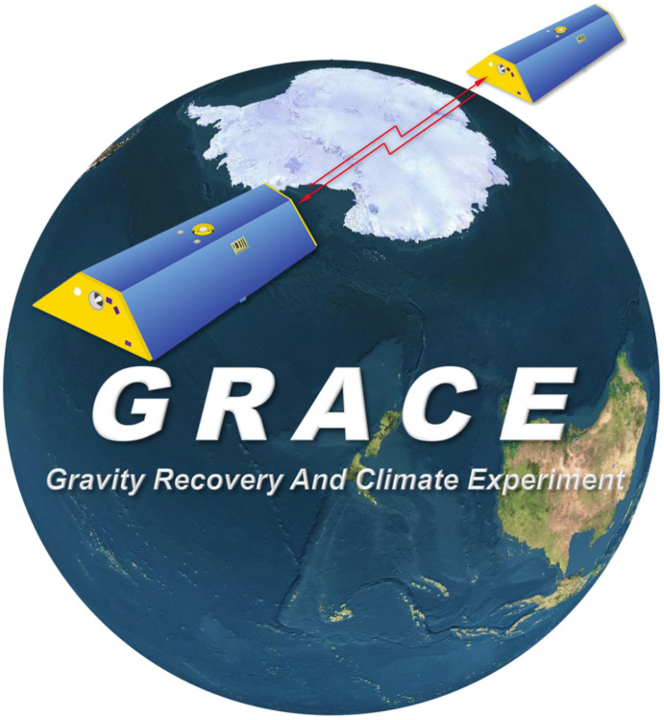


Fig. 2. The Gravity Recovery and Climate Experiment (GRACE) is a twin satellite mission orbiting the Earth at an initial altitude of about 500 km in a polar orbit (89° inclination), and 220 km apart. GRACE was launched on March 17, 2002, with a designed lifetime of 5 years. Now entering its 8th year the GRACE mission has been extended to 2012 or beyond. GRACE utilizes a state-of-the-art technique to observe variations of Earth's gravity by tracking the inter-satellite range and range-rate between two coplanar, low altitude satellites via a K-band ranging (KBR) system. In addition, each satellite is equipped with a SuperSTAR Accelerometer, GPS receiver/antenna, Star Cameras, and Laser Retro Reflectors to complement the science instruments. The GRACE Science Data System uses the range and range-rate data, along with ancillary data, to estimate a new gravity field every month, which can be used to study mass redistribution within the Earth system.
Source: NASA/CSR.

The GRACE Science Data System uses the range and range-rate data, along with ancillary data, to estimate a new gravity field every month, in the form of corrections to a well-defined background gravity model used in the data processing procedure (Bettadpur, 2007). The monthly sampling rate has been selected in order to accumulate sufficient observations to provide spatial resolution of about 400 km. Generally there is a trade-off in selecting the temporal sampling interval. Accumulating data over longer time intervals increases spatial resolution, but decreases temporal resolution.

Monthly GRACE global gravity solutions are provided by three GRACE data processing centers of the Science Data System (SDS), including the Center for Space Research (CSR) at the University of Texas at Austin, the Geoforschungszentrum (GFZ) in Potsdam, and the NASA Jet Propulsion Laboratory (JPL). GRACE solutions are distributed by the NASA PODAAC (http://podaac.jpl.nasa.gov/grace/). Other groups (external to SDS) that also provide GRACE solutions include the Goddard Space Flight Center (NASA, Rowlands et al., 2002), the Delft Institute of Earth Observation and Space Systems (DEOS; Klees et al., 2008), the Groupe de Recherche de Geodesie Spatiale (GRGS, Lemoine et al., 2007), the Institute of Theoretical Geodesy (ITG) at the University of Bonn (Eicker, 2008), and others. Some of these groups provide alternative sampling rates, for example once every 10 days. GRACE temporal solutions are generally expressed in the form of spherical harmonic coefficients of the geoid, up to some maximum degree (typically between 60 and 100, corresponding to wavelengths of ~400 to 700 km). These solutions are obtained through a 'dynamical approach' (see for example Schmidt et al., 2008 for details). Atmospheric and barotropic oceanic mass redistribution, and tidal effects are removed during the GRACE data processing using atmospheric reanalyses and ocean circulation and tides models (e.g., Bettadpur, 2007; Flechtner, 2007). Slight differences in data processing methods and post-processing strategies lead to some differences in the various solutions. Since the beginning of the mission, different GRACE solutions have been released by the SDS groups. Each release has included reprocessed data from the beginning of the mission, showing greatly improved quality over time. GRACE geoid data are further expressed in surface mass change (usually in equivalent water height) assuming that mass redistribution occurs in thin surface layers compared to the Earth's dimensions (Swenson and Wahr, 2002).

Assessing the errors of GRACE monthly solutions is a major challenge. Two categories of errors are recognized (e.g., Schmidt et al., 2008; Chambers, 2006): (1) errors introduced by data processing (errors of GRACE measurements and models used to remove other geophysical signals) and (2) post-processing errors (e.g., spatial smoothing of the GRACE solutions to remove high-frequency noise and leakage errors due to signal contamination from regions outside the studied area). Among errors in category (1), correlated errors due to unmodeled effects and contamination of other geophysical signals during data processing are highly problematic. Because of the limited spatio-temporal sampling provided by the GRACE satellites, these errors are aliased into the estimated spherical harmonic coefficients, giving rise to north–south stripes evident in GRACE geoid maps. To reduce this organized spatial noise different smoothing methods have been proposed (e.g., Swenson and Wahr, 2002; Swenson et al., 2003; Han et al., 2005; Chen et al., 2006d; Swenson and Wahr, 2006). The use of such spatial filters or smoothing methods (category 2 errors) significantly affects GRACE estimates of surface mass change by reducing signal amplitude at the higher degrees and orders suppressed by these filters. Another post-processing error arises from the limited range of spherical harmonics used in the solution. This results in contamination from surrounding regions ('leakage'). The GRACE orbital configuration (altitude and inter-satellite distance) and the need for spatial filtering are the main limitations to spatial resolution, estimated to be on the order of 300–400 km (Wahr et al., 2004; Wahr et al., 2006; Chen et al., 2006a, b; Schmidt et al., 2008).

In addition to spherical harmonic solutions, an alternative approach is to use the range-rate and other data to directly estimate surface mass changes represented as point or concentrated masses (the 'mascon' approach) (Lemoine et al., 2005; Luthcke, et al., 2006; Klees et al., 2008). In principle, mascon solutions can improve the spatial resolution but are dependent to some extent on applied constraints and imposed correlations among regional mass changes (Luthcke, et al., 2006; Luthcke et al., 2008a,b). Forward modeling is another approach that can increase the effective spatial resolution of GRACE estimates, and has been successfully applied in a series of studies of regional and continental scale ice mass change (Chen et al., 2006a,b, 2008, 2009a,b; Wouters et al., 2008). The purpose of this method is to construct a mass rate map using geographical and other information to locate concentrated mass changes that agree with the GRACE-observed mass rate map, and are unbiased because they are subjected to the same data processing procedures applied to GRACE data.

3. Hydrological applications

The global water cycle that exchanges water among oceans, atmosphere and land (Fig. 3), plays a key role in the physical and chemical processes that influence Earth's climate and its change over time. Water mass redistribution and state transformations (e.g., precipitation, evapotranspiration, and snow/ice melting) alter heating and cooling of Earth's surface and atmosphere, and in turn, affect global atmospheric and oceanic circulation, and eventually precipitation and evapotranspiration patterns. There is increasing evidence that Earth's climate system is experiencing significant changes with observable consequences for a variety of processes (IPCC, 2007). There is evidence of changes in intensity of climate events, such as El Niño and La Niña, extreme droughts and floods, severe winter and summer storms, and large hurricanes (IPCC, 2007). Improved monitoring and understanding of the global water cycle provides critical information to better understand Earth's climate and ecosystems.

Terrestrial water storage (TWS) change, as a major component of the global water cycle, reflects changes in water stored in soil, snow over land, and groundwater reservoirs, and is closely connected to accumulated precipitation (P), evaporation (E), surface and subsurface runoff (Q) within a given area or basin, through the water balance equation relating a change in water storage (dS) in unit time (dt),

$$\frac{dS_l}{dt} = P_l - E_l - Q \tag{2}$$

and over the oceans,

$$\frac{dS_o}{dt} = P_o - E_o + Q \tag{3}$$

in which subscripts l and o refer to land and ocean, respectively. For many land areas, TWS is virtually a measure of total water content in

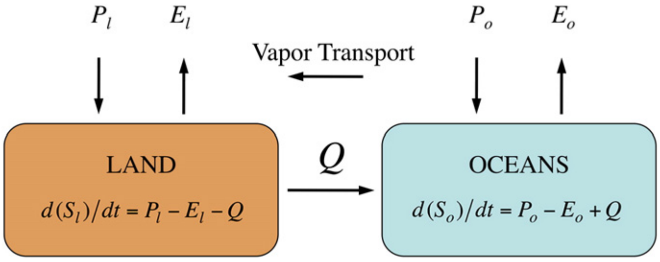


Fig. 3. Schematic diagram of the global water cycle. S_l and S_o are terrestrial and ocean water storage; P_l and P_o are precipitation on land and ocean; E_l and E_o are evaporation on land and ocean; Q is runoff and t is time (see Seo et al., 2008, 2009 for details).

surface stores, soil layers, ice (including snow), groundwater reservoirs and biomass (which is negligible in most cases), and is also a good indicator of abnormal climate conditions, such as droughts and floods. S_l can be expressed as,

$$S_l = S_{soil} + S_{groundwater} + S_{ice} + S_{biomass}. \quad (4)$$

Accurately quantified TWS change (with respect to the mean TWS over a certain period of time) provides a key measure of the continental water cycle and available water resources in a given region or river basin. However, estimating TWS change is difficult because limited observations (especially for groundwater and soil moisture) are available, and often are simply non-existent (e.g., Rodell and Famiglietti, 1999, Shiklomanov et al., 2002) at basin or smaller scales.

Global and regional hydrological models developed for climate research purposes provide an alternative to inadequate or non-existent in situ measurements. These models compute the water and energy balance at Earth's surface, yielding time variations of water storage in response to boundary conditions imposed by near-surface atmospheric observations. Required atmospheric data include atmospheric state (temperature, humidity and wind) and incident water and energy fluxes from the atmosphere (precipitation and radiation). These are estimated from syntheses of observational analyses and atmospheric model “reanalyses” in which a model is driven in “stand-alone” mode (forced by observations). Alternatively, surface hydrologic variation can be simulated by an atmospheric general circulation model run in “coupled” mode. Global hydrological models were not designed to estimate water storage on land, but rather to calculate fluxes from land to atmosphere for the purpose of climate modeling. This distinction is important, because a model can perform well at calculating fluxes, yet make large errors in computed quantities such as long-term trends in storage. Such a disparity in performance is possible because storage change is a small difference between two large terms representing input (P_l) and output ($E_l + Q$).

GRACE is generally regarded as providing revolutionary advances in measuring global TWS change from space, despite its limited spatial resolution. Note that GRACE measures vertically-integrated water storage change and cannot separate contributions from individual stores (i.e. surface water reservoirs, soil, ice and groundwater) without other independent data (Eq. (4) and Fig. 4).

In recent years, GRACE data have been successfully applied to the study of global and basin-scale TWS changes. Early studies focused on the seasonal cycle and showed good agreement with global hydrological models (e.g., Wahr et al., 2004; Tapley et al., 2004; Chen et al., 2005a; Ramillien et al., 2005; Schmidt et al., 2006; Syed et al. 2005, 2008; Winsemius et al., 2006; Yamamoto et al., 2007). Fig. 5 shows mean TWS evolution since 2002 over a few selected river basins estimated from GRACE (using CSR RL04 solutions) and simulated by the hydrological model GLDAS (Global Land Data Assimilating System, Rodell et al., 2004), which does not include the simulation of groundwater and surface water stocks. In general hydrological models perform well at seasonal time scales (in most basins, the seasonal signal is the dominant contribution, accounting for 70–80% of the total signal). However, in the Amazon basin (Fig. 5a) surface water and groundwater stocks, which are absent from GLDAS estimates, can contribute significantly to TWS change and are likely responsible for the large discrepancy between GRACE observations and GLDAS estimates (Chen et al., 2009b). As discussed by Guentner (2008), the various comparisons performed so far show that for the annual cycle, the differences between hydrological models are the same order of magnitude as GRACE errors. However hydrological model–GRACE comparisons also highlight the spatial resolution limits of GRACE when considering small basins (<1 million km^2). The study by Klees et al. (2008) investigated different global (spherical harmonic) and regional (mascon–GRACE solutions) from various processing centers over a large number of river basins and found no consistently better performance from one solution type or the other, and no relation between accuracy and size of the basin (>1 million km^2). They estimated current accuracy of monthly GRACE solutions to ~2 cm equivalent water layer over river basins exceeding 1 million km^2.

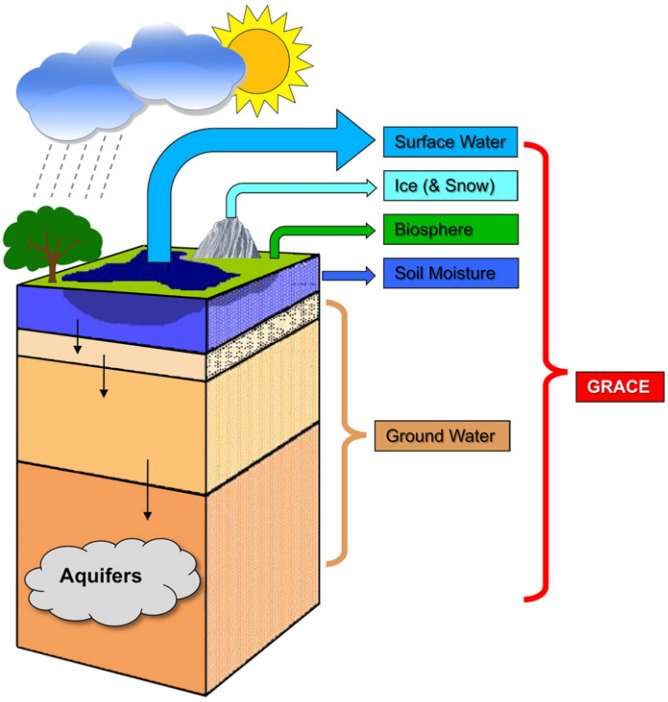


Fig. 4. Schematic diagram of integrated water storage as measured by GRACE.

Now exceeding 7 years in length, the GRACE time series provides some measure of interannual variability in TWS. Over the Amazon basin, Chen et al. (2009b) detected the signature of an extreme drought event in 2005 in the Amazon basin, apparently connected to rainfall deficits in prior years, the 2002–2003 El Nino event, and abnormal warming of the northern tropical Atlantic Ocean (see also Xavier et al., 2010). In the East African Lakes region, Swenson and Wahr (2009) found a significant TWS minimum over Lake Victoria corresponding to drought in this region in 2005. Becker et al. (2010) related this water storage minimum to abnormal sea surface temperature conditions in the western part of the Indian Ocean. The 2005 East African drought was followed by a sustained period of wet conditions, and increased water storage, clearly correlated with successive positive Indian Ocean Dipole events in 2006, 2006 and 2008 (the Dipole event is an aperiodic east–west oscillation of positive and negative sea surface temperature anomalies in the tropical Indian Ocean). Another study by Leblanc et al. (2009) showed that GRACE TWS detected the severe 2003–2006 drought within the Murray–Darling basin in southern Australia. The 2003 Western Europe heat wave was found in GRACE TWS by Andersen et al. (2005). This heat wave produced drier than normal conditions, with TWS depletion corresponding to ~−12±2 cm equivalent water height. These studies clearly demonstrate that GRACE provides valuable monitoring of the climate variability and regional hydrology.

Anthropogenic effects on the terrestrial water cycle may also be detectable by GRACE. Two recent studies estimated groundwater storage change between August 2002 and October 2008 in the Ganges–Brahmaputra river basins (India) by combining GRACE TWS and estimates of shallow soil water from the GLAS hydrological model (Rodell et al., 2009; Tiwari et al., 2009). These studies found significant groundwater depletion in the northwest India region amounting to a loss rate of ~17.7±4.5 Gt/yr. In the absence of significant rainfall deficit during that period, they attributed this

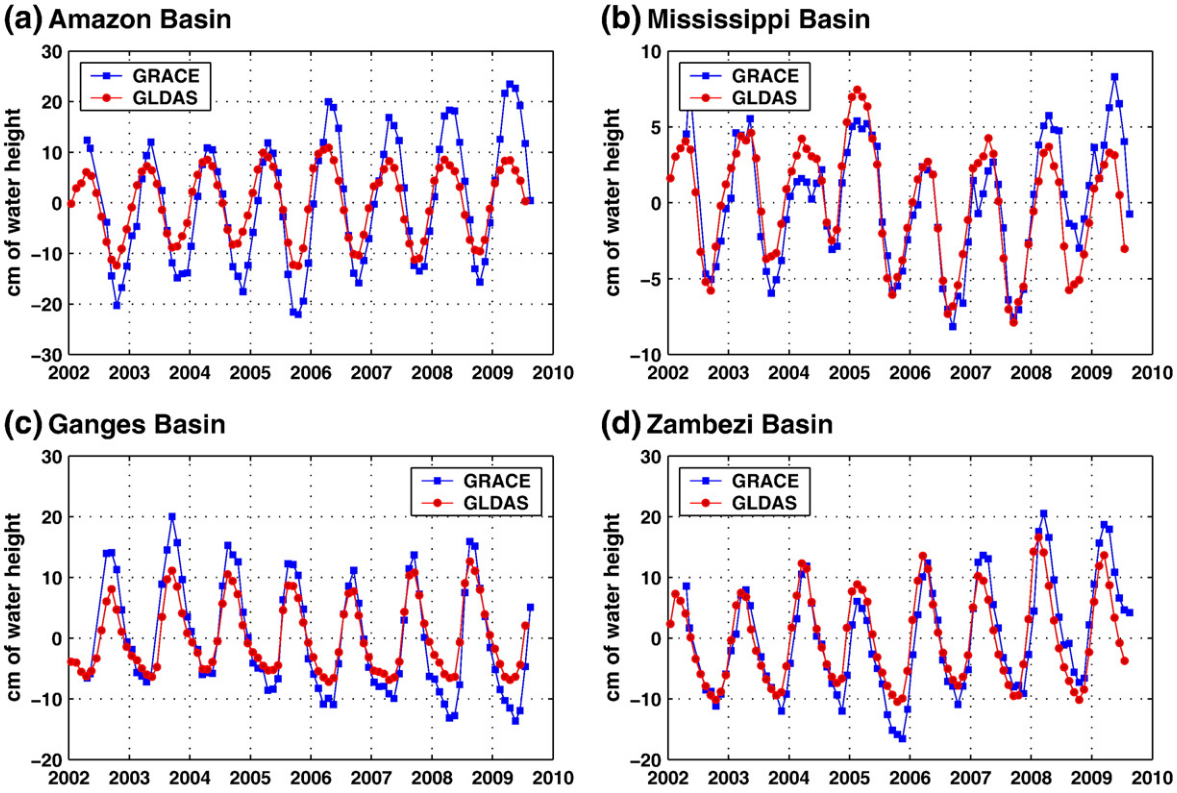


Fig. 5. Averaged total (vertically-integrated) water storage evolution from GRACE over 2002–2009 over the Amazon, Mississippi, Ganges, and Zambezi river basins and estimates from the GLDAS hydrological model. Units are in cm of equivalent water height change. A two-step filter (P4M6 decorrelation + 300 km Gaussian) is applied (see Chen et al., 2008 for details).

groundwater depletion to anthropogenic water withdrawal from aquifers for domestic use and crop irrigation. This is illustrated in Fig. 6a and b, which shows groundwater depletion since 2002 in Northwest India from GRACE TWS minus surface and soil water estimated from the GLDAS model.

Despite the great potential of GRACE for monitoring groundwater resources, as highlighted by these studies (Rodell et al., 2009; Tiwari et al., 2009), these preliminary quantifications of groundwater depletion rate are subject to possibly significant errors from neglecting other contributions to GRACE-observed TWS decrease in the region (northwest India). We assume that surface water and biomass stocks can be neglected in this case. However, ice mass change in the nearby high mountain glaciers could have significant effect on GRACE estimates, due to the limited spatial resolution of GRACE data. A recent study based on GRACE data (Matsuo and Heki, 2010) indicates that the Asian high mountain glaciers (in that broad region) are losing ~47 ± 12 Gt/yr of ice in recent years. Large leakage effect is expected between groundwater depletion and glaciers melting in that region. How to correctly quantify the leakage effect will play a key role for accurately estimating (and separating) groundwater depletion and ice melting rates. Both are important information for understanding the Earth climate and environment changes. With a longer record of GRACE data and improved data processing techniques, such as the high-resolution mascon (Luthcke, et al., 2006) and forward modeling (Chen et al., 2008; Chen et al., 2009a), we expect to have a clearer picture of groundwater depletion in northwest India and ice melting in the nearby mountain glaciers in the near future.

Fig. 7 shows a map of GRACE apparent surface mass rates for the globe (for the period September 2002 through August 2009) from best-fit linear trends to time series at every location (grid point or pixel). Units are in equivalent water height per year. This map shows predominantly water mass gain or loss in major river basins, and ice mass loss in ice-covered regions including ice sheets, (Section 4) and glaciers (Section 5). The large positive mass rate over northern Canada is due to post-glacial rebound (Section 7.2).

Studies have used GRACE TWS in combination with additional information to estimate changes in vertical or horizontal fluxes, e.g., $P_l - E_l$, E_l or Q. For example, using the water balance equation, Rodell et al. (2004a) and Ramillien et al. (2006b) estimated E_l rate over the Mississippi and other major river basins. Such an approach to estimate basin-scale E_l is particularly useful for climate studies, climate models, and weather prediction because in situ evaporation measurements are scarce and limited to point measurements. Similarly, river discharge has been estimated regionally and globally by combining GRACE TWS and other data and models (Syed et al., 2005, 2008). Other studies estimated $P_l - E_l$ (e.g., Swenson and Wahr, 2006b). Individual land storage components (e.g., surface and soil water, groundwater, and snow) have also been estimated from GRACE TWS, either by removing other storage elements using models (e.g., Niu and Yang, 2006; Niu et al., 2007a; for snow; Yeh et al., 2006; Strassberg et al. 2009; Rodell et al., 2009; Tiwari et al., 2009; Becker et al., 2010 for groundwater) or by means of inversion techniques (e.g., Ramillien et al., 2005; Frappart et al., 2006).

An increasing number of studies have used GRACE TWS to improve global and basin-scale hydrological models (e.g., Swenson and Milly, 2006; Ngo-Duc et al., 2007). The review by Guentner (2008) discusses how cross validation between GRACE measurements and hydrological models, allows identification of model deficiencies (e.g., model input, structure, and parameterization). Clearly, progress in this area will consist of assimilating GRACE TWS into hydrological models as currently done in meteorology and oceanography. Preliminary work in this direction has already been attempted (e.g., Zaitchik et al., 2008). Assimilation of GRACE TWS change into future generations of hydrological models provides an opportunity to significantly improve accuracy in modeling the global water cycle, especially in reproducing major climate events such as droughts and floods.

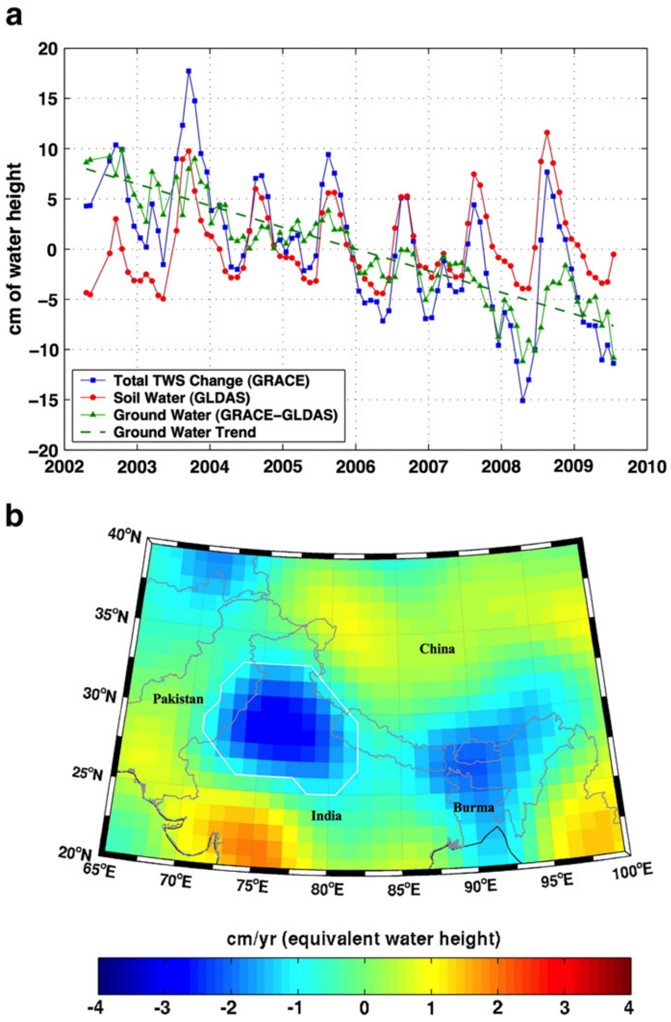


Fig. 6. a) Averaged groundwater depletion in northwest India (see Fig. 6b) during the period April 2002 to August 2009. Groundwater variations are estimated from GRACE-observed total TWS (terrestrial water storage), minus GLDAS (Global Land Data Assimilating System) estimates of soil water. A two-step filter (P4M6 decorrelation + 300 km Gaussian) is applied. b) A significant mass decrease in northwest India (region circled by white lines) is captured by GRACE, and is attributed to groundwater depletion in the region (Rodell et al., 2009; Tiwari et al., 2009). GRACE mass rate (Fig. 6b) is based on CSR RL04 for the period September 2002 to August 2009.

GRACE estimates of global land water storage also have applications in sea level studies. Until recently, the land water contribution to sea level change was poorly known and estimated from models only (e.g., Chen et al., 1998; Cazenave et al., 2000; Milly et al., 2003; Ngo-Duc et al., 2005). Although the GRACE time series is still quite short to accurately quantify this effect at time scales beyond the seasonal cycle, recent investigations have used GRACE to estimate a net global mean land water trend (Ramillien et al., 2008a, b; Lettenmaier and Milly, 2009; Llovel et al., 2010a). Results confirm earlier model-based findings, that at time scales exceeding several years/decades, land water storage change makes a minor contribution to sea level change. It is worth noting however, that land water storage change is a key component of the annual mean sea level oscillation (Chen et al., 1998; Milly et al., 2003), and plays a non-negligible role in year-to-year fluctuations of global mean sea level (corrected for thermal expansion) (Llovel et al., 2010a).

4. Mass balance of polar ice sheets

The mass balance of the polar ice sheets is of considerable interest in the context of global warming and present-day sea level rise. If totally melted, Greenland and Antarctica would raise sea level by approximately 7 and 50 m, respectively. Thus, even a small amount of ice mass loss from these ice sheets would produce substantial sea level rise, with adverse societal and economic impacts on vulnerable low-lying coastal regions. Observations over the past two decades show rapid acceleration of outlet glaciers along the northwest and southeast coasts of Greenland (e.g., Allison et al., 2009). Draining into the Amundsen Sea sector, West Antarctic glaciers have also rapidly retreated (e.g., Wingham et al., 2006; Rignot et al. 2008a). These observations have been attributed to a dynamical response of the ice sheets to recent warming, in particular heating of sea water surrounding the ice sheets in areas where the grounding line is below sea level. Quantification of polar ice sheet mass balance and its contribution to global sea level rise has long been a challenge owing to the lack of in situ observations. Remote sensing data, especially from air- or spaceborne radar altimeters, satellite Interferometric Synthetic Aperture Radar (InSAR), and the satellite laser altimeter onboard the Ice, Cloud, and land Elevation Satellite (ICESat) have been used to study polar ice sheet mass balance. Estimates of mass balance are based either on elevation change from altimetry (e.g., Zwally et al., 2005), or ice flow velocity from InSAR — combined with surface mass balance modeling — (e.g., Rignot and Kanagaratnam, 2006; Rignot et al., 2008a,b). These are limited by spatial and temporal coverage and by uncertainties in snow density and ice thickness (and other related estimates).

GRACE offers the opportunity to study mass balance of polar ice sheets from a new perspective, using GRACE gravity change estimates to directly measure mass variation or redistribution. Using the first few years of GRACE time-variable gravity data, a number of studies (Velicogna, 2009, 2006a, 2006b; Chen et al., 2006a,b; Ramillien et al., 2006b; Luthcke, et al., 2006; Baur et al., 2009; Slobbe et al., 2009) provided the first GRACE estimates of 'secular' mass rates over the Greenland and Antarctic ice sheets. These early GRACE results quantified the significant ice losses in East Greenland and West Antarctica, and confirmed estimates from other remote sensing data (e.g., Krabill et al., 2004; Rignot et al., 2005; Rignot and Kanagaratnam, 2006; see Fig. 5 of Cazenave and Llovel, 2010, for a compilation of remote sensing-based results). As more GRACE data became available, a series of more recent studies has created a clearer picture of present-day ice loss from the two largest ice caps on Earth and demonstrated the unique potential of satellite gravimetry for monitoring large-scale ice mass change. Using extended GRACE time series (6–7 years), recent studies (e.g., Wouters et al., 2008; Cazenave et al., 2009; Peltier, 2009; Velicogna, 2009; Chen et al., 2009a,b) showed clear acceleration of ice loss from both ice sheets in the past 3–4 years. These new estimates indicate that Antarctica is losing ice at 220–246 Gt/yr during the period 2006–2009, an alarming acceleration of the already large loss rates of 104 to 144 Gt/yr estimated for 2002–2005 (Velicogna, 2009; Chen et al., 2009a). Over Greenland, GRACE shows an ice loss rate 267–286 Gt/yr during 2006–2009, compared with a loss rate of 137–159 Gt/yr during the period 2002–2005. Fig. 8 (from Velicogna, 2009) illustrates loss of Greenland ice mass between 2002 and 2009 from GRACE observations.

The majority of Antarctic ice loss is from West Antarctica, dominated by two prominent losses in the Amundsen Sea Embayment (ASE) and Antarctic Peninsula (see Fig. 9a). Recent GRACE data also suggest that East Antarctica may have begun losing a significant amount of ice in recent years, mostly from coastal regions (Chen et al., 2009a). Recent results (Wouters et al., 2008; Chen et al., submitted for publication) also show continued ice loss along Greenland's periphery, with low rates of accumulation in the interior (Fig. 9b). Loss rates in Eastern Greenland are about twice those in the west. The majority of West Greenland's loss is at higher latitudes (north of 68°N), and extends farther north, relative to early GRACE results (e.g., Chen et al., 2006a). The most recent GRACE estimates agree well with recent InSAR flux estimates (which include a surface mass balance model) (Rignot et al., 2008a,b).

Despite these encouraging results, GRACE estimates vary significantly among published studies, indicating a fair level of uncertainty.

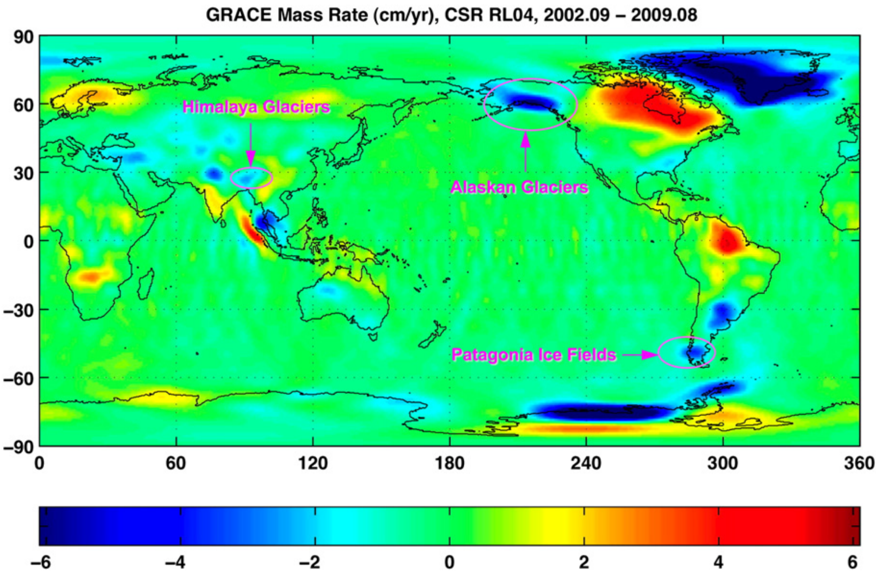


Fig. 7. Global mass rate (units: cm/yr of equivalent water height rate) estimated from GRACE time-variable gravity data (CSR RL04) for the period September 2002–August 2009, with a two-step filter (P4M6 decorrelation + 300 km Gaussian) applied (see Chen et al., 2008 for details). As atmospheric and oceanic mass changes have been removed during GRACE dealiasing data processing (Bettadpur, 2007), signals over the oceans represent residual error, unmodeled atmospheric and oceanic signal and leakage from land.

The main source, especially in Antarctica, is inadequate understanding of post-glacial rebound, which contaminates GRACE estimates of ice mass change (see Section 7.2). PGR effects can be removed using numerical models, e.g., the ICE5G model (Peltier, 2004, 2009; Paulson et al., 2007) and southern hemispheric IJ05 model (Ivins and James, 2005) but variability among these models is a source of the uncertainty. Over Greenland, direct PGR effect is believed to be small, with an integrated contribution of ~5 Gt/yr to the GRACE estimate (Velicogna and Wahr, 2006a; Peltier, 2009). However, over Antarctica, the PGR signal is of the same order as the ice loss signal (Velicogna and Wahr, 2006a; Peltier, 2009). A recent study by Riva et al. (2009) that combines GRACE and ICESat observations, suggests that the PGR impact on GRACE estimates of Antarctica mass balance amounts to 100 ± 67 Gt/yr. This PGR error translates directly into GRACE mass balance estimates.

5. Mountain glacier mass balance from GRACE

Although mountain glaciers contain less than a few percent of the ice on Earth, their rapid disintegration constitutes a significant and accelerating cause of global sea level rise, suggesting particular sensitivity of mountain glaciers to climate change (Lemke et al., 2007). From 1993 to 2003, losses from mountain glaciers was estimated at ~−288 Gt/yr, equivalent to ~0.8 mm/yr sea level rise (Lemke et al., 2007). In addition, acceleration in glacier melting has been reported in recent years (e.g., Kaser et al., 2006; Meier et al., 2007; Cogley, 2009). Most recent estimates of total glacier mass loss since about 2003 indicate a loss rate of ~−390 Gt/yr (Meier et al., 2007; Cogley, 2009). Thus, glaciers contribute to sea level rise at the present time an amount comparable to Antarctica and Greenland combined and accurate quantification of mountain glacier mass balance is critical in understanding sea level rise and climate change. Despite the potentially large sea level contribution, quantification of mountain glacier mass balance has been a challenge, limited by temporarily and spatially sparse measurements. Consistent records are only available for a small number of benchmark glaciers. Considering the great variations in melting rates from region to region, and among glaciers in the same region, understanding of global losses has been very limited using conventional data types (e.g., Lemke et al., 2007).

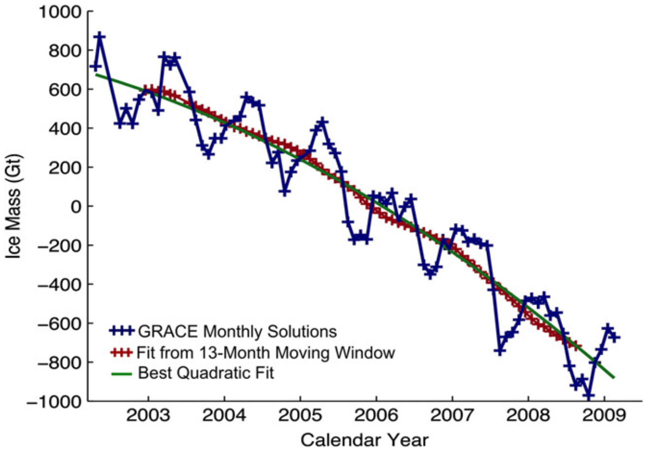


Fig. 8. Temporal evolution of Greenland ice mass from GRACE between 2002 and 2009 (from Velicogna, 2009).

GRACE provides unique estimates of mass rates of mountain glaciers providing the signal is large enough (e.g., Tamisiea et al., 2005; Chen et al., 2006c, 2007; Luthcke et al., 2008a,b; Matsuo and Heki, 2010). We presented above the global mass rate estimated from GRACE (CSR RL04) for the period April 2002–August 2009 (Fig. 7). The map clearly shows features related to mountain glaciers, including the Alaskan glaciers (the largest mountain glacier complex), the Patagonia Ice Fields in South America, and Himalayan glaciers (marked in Fig. 7). Although loss of mass in these regions is evident, it is difficult to quantify the rates, given the limitation of spatial resolution in GRACE data. The situation is similar to that for polar ice sheets, but more difficult because mountain glaciers have scales even smaller than the polar ice sheets, and are surrounded by regions with conventional terrestrial hydrologic cycles.

Studies using GRACE data show that the Alaskan glacier complex lost a significant amount of ice, 101 ± 22 Gt/yr during the period April 2002–November 2005 (Chen et al., 2006c). Another study (Luthcke et al., 2008a) based on GRACE mascon solutions shows a loss of 71 ± 6 Gt/yr for July 2003–July 2008. These results are generally consistent with loss rate of ~96 ± 35 Gt/yr from airborne laser altimetry data for the period mid-1990s to 2001 (Arendt et al., 2002), and confirm the largely anticipated ice loss associated with the Arctic warming.

GRACE data indicate that the Patagonia Ice Fields, about one-quarter the size of the Alaskan complex lost a substantial amount of

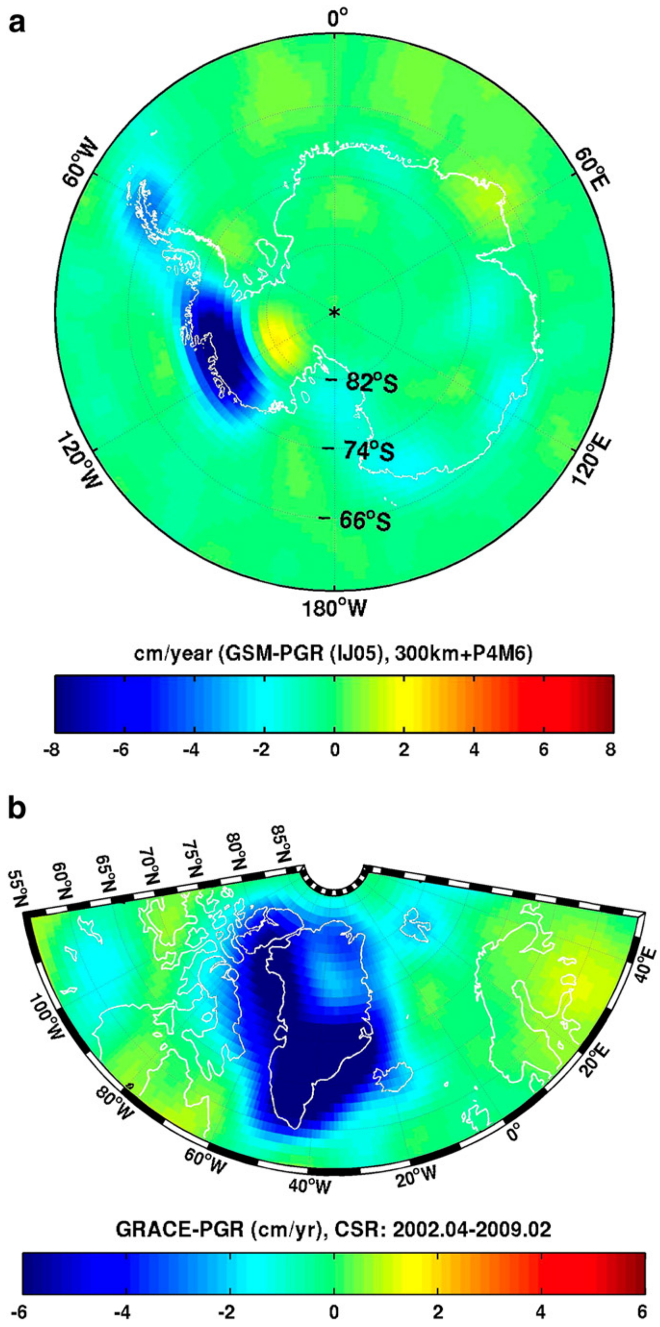


Fig. 9. a) GRACE-observed mass change rate (in cm/yr of equivalent water height change) over Antarctica during the period Apr. 2002 and Jan. 2009. PGR (post-glacial rebound) effect based on the IJ05 model (Ivins and James, 2005) has been removed [see Chen et al., 2009a) for details]. b) GRACE-observed mass change rate (in cm/yr of equivalent water height change) over Greenland during the period Apr. 2002 and Feb. 2009. PGR effect based on the ICE5G model (Paulson et al., 2007) has been removed.

ice, 27.9 ± 11 Gt/yr from April 2002 through December 2006 (Chen et al., 2007). Ice loss from the Patagonia glaciers is equivalent to an average loss of ~1.6 m/year ice thickness change if evenly distributed over the entire ice field (Chen et al., 2007). This is an independent confirmation of relatively large melting rate estimates from earlier studies employing topographic and cartographic data. As mentioned earlier, GRACE data also shows that the Asian high mountain glaciers are losing a significant amount of ice (~47 ± 12 Gt/yr) in recent years (Matsuo and Heki, 2010).

6. Ocean mass and sea level change

Net water flux into and out of the ocean causes its mass to change Eq. (3). Such changes cause gravitational variations detectable by GRACE (Chambers et al., 2004). This has allowed, for the first time, direct estimates of the global ocean mass contribution to sea level change (Chambers et al., 2004; Chen et al., 2005b; Lombard et al., 2007; Willis et al., 2008; Cazenave et al., 2009; Peltier, 2009; Leuliette and Miller, 2009). Published trends of global ocean mass for the recent years (2002–2008) range from a low value of 0.8 mm/year (Willis et al., 2008) to a high value close to 2 mm/year (Lombard et al., 2007; Cazenave et al., 2009; Peltier, 2009). Most differences among estimates of ocean mass rates are due to differences among adopted post glacial rebound -PGR- models. The PGR correction introduces a secular trend in the gravity field and is of the same order of magnitude as the expected ocean mass trend. However, PGR models vary significantly with respect to this effect. The PGR correction averaged over the oceans is in the range −1 mm/yr to −2 mm/yr (e.g., Paulson et al. 2007; Peltier 2009) (note: the −1 to −2 mm/yr is for equivalent water thickness change and the ocean bottom subsidence should be on average of ~0.7 mm/yr due to the higher density of the Earth crust and mantle). Differences are large and associated with different treatments of Earth's rotational feedback and disagreement persists within the PGR community as to the correct rotational feedback model. However a recent study by Chambers et al. (submitted for publication) seems able to reconcile the different PGR ocean mass corrections, tightening the range within −1.2 mm/yr to −1.6 mm/yr. The uppermost GRACE ocean mass rate estimate is compatible with recent ice melt estimates (e.g., Allison et al, 2009; Rignot et al., 2008a,b; see also the discussion above on ice sheet and glaciers mass balance from GRACE). In this way, GRACE ocean mass rates combined with observed ice melt rates places an independent constraint on the PGR correction. However, given uncertainty in the ice melt contribution from land, it is important to improve the PGR estimate (see Section 7.2). Uncertainty on the current ocean mass rate from GRACE is also large. For example, Quinn and Ponte (2010) examined different GRACE solutions from different groups and the effect of post-processing corrections applied to GRACE data. They reported differences in GRACE-based ocean mass rates up to 0.5 mm/yr, with the largest discrepancies arsing from GRACE data processing by the different centres.

Satellite altimetry allows precise measurement of present-day global mean sea level change (e.g., Cazenave and Llovel, 2010). When combined with the GRACE ocean mass rate, the steric component of sea level change (effects of vertically-integrated sea water temperature and salinity changes) can be deduced (e.g., Chambers et al., 2004; Chambers, 2006; Lombard et al., 2007; Llovel et al., 2010b). In principle, this is possible because satellite altimetry measures the sum of thermal expansion and ocean mass change, while GRACE measures the ocean mass change only. As in situ ocean temperature and salinity measurements (e.g., from the Argo profiling floats) are limited to the upper oceans (above 1000–2000 m), the altimetry-GRACE estimate combined with in situ data should provide information on the deep ocean contribution to sea level, and related changes in heat storage. However current uncertainties in Argo-based steric sea level (e.g., Lyman et al., 2010) and GRACE-based ocean mass change (Quinn and Ponte, 2010) still prevent from constraining the deep ocean contribution.

7. Solid Earth applications

Besides the refinement of Earth's static gravity field (Fig. 1), GRACE has contributed to understanding solid Earth processes. Examples are briefly discussed below.

7.1. Coseismic and postseismic deformation

The Sumatra–Andaman earthquake (Mw = 9.3) of December 26, 2004 is the largest recorded in about 40 years. The ruptures caused by it and the companion Nias earthquake (Mw = 8.7) on 28 March 2005 extend over approximately 1800 km in the Andaman and Sunda subduction zones. Expectations were that both events would be followed by vigorous afterslip and viscoelastic relaxation involving both the upper and lower mantle (Chlieh et al., 2007; Hashimoto et al., 2006; Pollitz et al., 2006). Even though the rupture is one of the largest in recent history, the sub-sea location, about 250 km off the west coast of northern Sumatra, prevents accurate mapping of near-field deformation and afterslip. GRACE offers a unique way to detect the sea floor deformation, afterslip, and viscoelastic relaxation associated with this gigantic earthquake. However GRACE gravity solutions are subject to spatial noise and other errors, making detection of earthquake-related deformation a challenge. To avoid noise problem with early releases of the GRACE spherical harmonic solutions, Han et al. (2006) used Level-1 GRACE satellite range and range-rate measurements to estimate gravity change due to the earthquake. They detected the gravity change associated with coseismic subduction and uplift, in agreement with model predictions (see Fig. 10).

With the improved quality of GRACE RL04 gravity solutions and refined data processing techniques, Chen et al. (2007) successfully captured mass change from the sea floor rupture (due to the Sumatra–Andaman earthquake) by comparing GRACE gravity changes between two 2-year periods, before and after the earthquake, and found results consistent with other geodetic measurements and the previous study using Level-1 range-rate results (Chen et al., 2007). This and other studies (Ogawa and Heki, 2007; Panet et al., 2007; de Viron et al., 2008) also demonstrate the unique value of GRACE in studying both coseismic and postseismic deformation from major earthquakes.

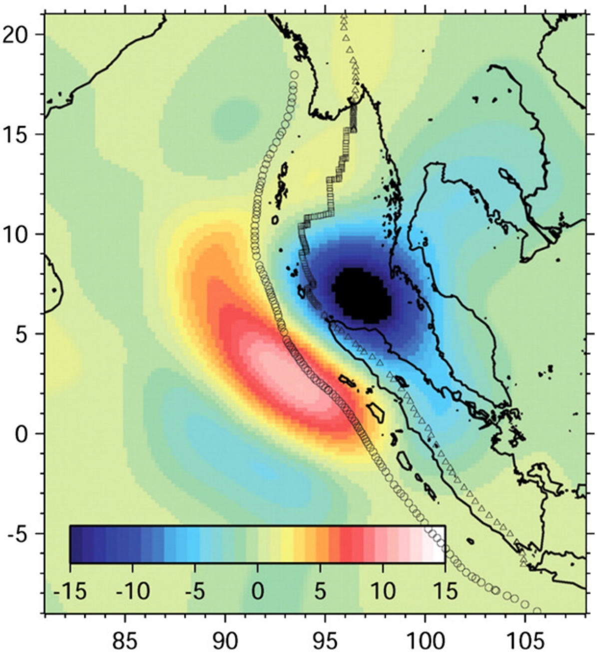
7.2. Post-glacial rebound

Large-scale readjustment of Earth's crust and mantle (post-glacial rebound or PGR) follows melting of ice loads. PGR induces secular gravity field changes observable by GRACE. The large positive mass rate centered over Hudson Bay (Canada) in Fig. 7 is one of the most prominent signatures of this process. Comparisons between GRACE and other measures of PGR (surface gravity change, vertical motion rates, estimates of ice load extent and melting history) have confirmed that GRACE is detecting Earth's recovery following melting of the Laurentide ice sheet at the end of the last ice age. This is illustrated by Fig. 11 (from Peltier, 2009), which shows GRACE and PGR (using the ICE-5G-VM2 model) mass change over the North American continent and their difference. Other PGR signals are also visible in Fig. 7 over Scandinavia and parts of Antarctica.

The use of GRACE to improve PGR models is a promising research direction as current models suffer from uncertainty in ice load history and use relatively simple parameterizations of Earth's elastic properties, density and viscosity. Paulson et al. (2007) used GRACE and other geological observations to refine PGR modeling and constrain upper and lower mantle viscosity. Following an approach initially proposed by Wahr et al. (2000), GRACE has been combined with ICESat laser altimetry to separate PGR from present-day, climate-driven ice mass loss (Riva et al., 2009).

As GRACE and other geodetic time series (e.g., GPS, ICESat, and ocean radar altimetry) are extended, there is promise of greatly improving PGR models. Since PGR corrections are significant for GRACE but less so for altimetry, long time series of altimetry, GRACE, and steric sea level (from Argo float data) will be available to test various PGR models. For example, in terms of global mean sea level, rates from radar altimetry minus steric sea level can be compared with GRACE ocean mass minus PGR (Section 6). Similarly, GRACE ocean mass changes (after PGR correction) can be compared with ice loss over land from remote sensing techniques (InSAR, laser and radar altimetry). Finally, Antarctic mass balance from GRACE and other techniques will provide constraints on PGR in this region. Comparisons among varied data types will thus help quantify PGR model uncertainty.

(a) GRACE Gravity Change (μGal)



(b) Model Prediction (μGal)

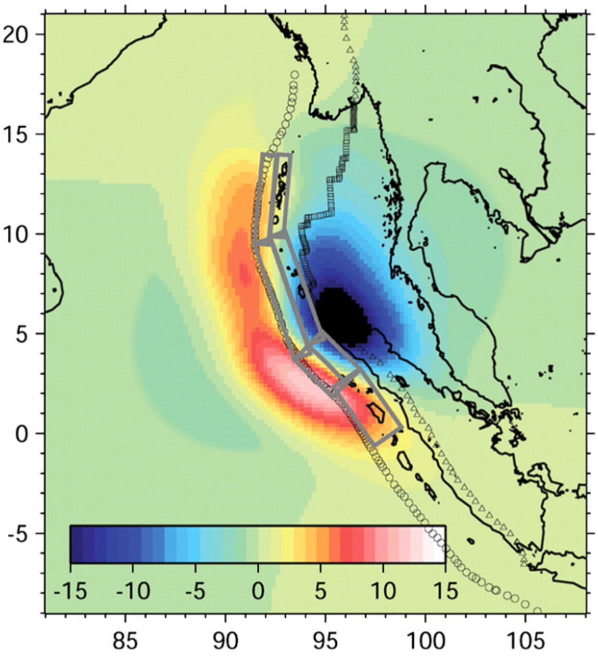


Fig. 10. (a) Coseismic gravity changes (in μGal) due to the Sumatra–Andaman earthquake, computed from gravity changes between two different time periods before and after the earthquake; (b) Predicted coseismic gravity changes (in μGal) from seismic model, inferred by combining vertical displacement and dilatation (from Han et al., 2006).

8. Conclusions

Since its launch in 2002, GRACE has provided unique and valuable information on large-scale mass redistribution within the Earth

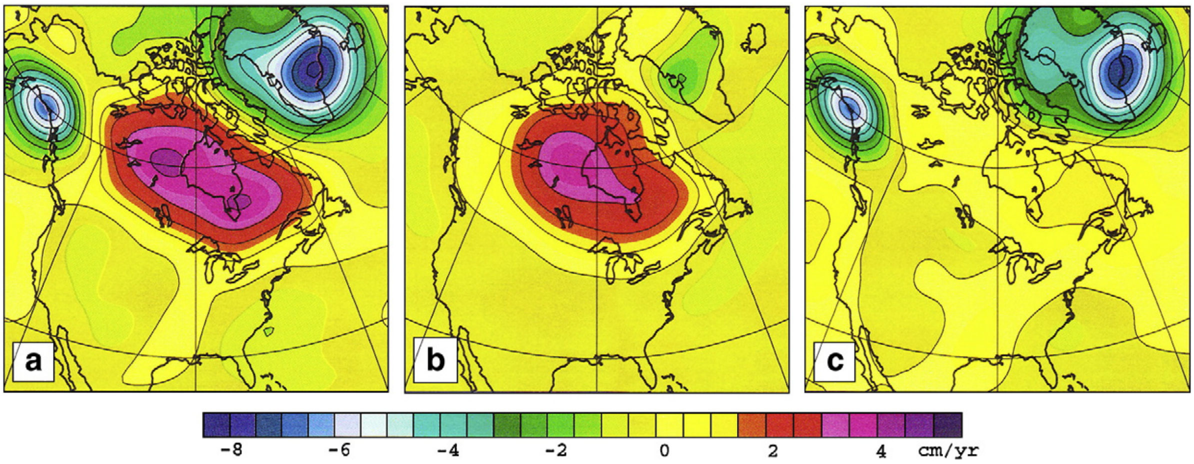


Fig. 11. Comparison between (a) GRACE-observed mass rate field over North America and (b) prediction of the PGR process from the ICE5G (VM2) model. The difference between these fields is shown in (c) (from Peltier, 2009).

system. This has led to improved understanding of mass fluxes within Earth's near-surface fluid envelopes and relationships with global climate change and variability. GRACE is now considered a basic component of the sea level observing system, because of its unique capability to measure mass balance of ice sheets, mountain glaciers and the entire ocean. In many respects, GRACE has revolutionized large-scale land hydrology and provided new perspectives for detecting impacts of climate change and variability on river basins and aquifers. GRACE has contributed to improved global hydrological models used in climate studies and for assessing planetary-scale water resources. Combining GRACE data with other information can be used for detecting anthropogenic effects on water resources such as depletion of aquifers.

GRACE is currently not expected to operate beyond 2012. A GRACE-Follow-On mission (with improved performances) has been recommended by the US NRC (National Research Council) Decadal Survey (NRC, 2008) for launch in the 2017–2020 timeframe. Meanwhile, a GRACE-Gap-Filler mission (jointly developed by NASA and the German Space Agency) should take over the current GRACE mission around 2015. In Europe, a successor to GRACE is supported by the scientific community but no firm plan has yet been made.

A new gravity mission, Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) based on gradiometry technology has been successfully launched recently by the European Space Agency (March 2009). The objective of GOCE is to measure the static gravity field with unprecedented precision (a few cm in geoid height) and resolution (~100 km). Major applications are expected in oceanography and geophysics. The major development expected from GOCE in geoid precision is accurate determination of the dynamic ocean topography (when combined with satellite altimetry), and associated improved measures of the ocean circulation. GOCE will also provide high-resolution gravity data over continental areas, opening new research opportunities related to continental lithosphere structure and mantle convection, among others. Due to its low altitude (~250 km, to insure required spatial resolution), GOCE life time is limited (<2 years). Thus GOCE will not be suitable for time-variable gravity studies. However, combination of GOCE and GRACE data should allow more accurate determination of long-term global gravity field change, provided that GRACE-type observations are able to continue. GRACE has shown that continuous monitoring of the gravity field provides fundamental understanding of how our home planet is changing, either by natural or human-induced processes. Continuing this monitoring beyond the lifetime of the current mission is clearly a high priority!

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Anny Cazenave Senior scientist at the 'Laboratoire d'Etudes en Géophysique et Océanographie Spatiale', 'Centre National d'Etudes Spatiales', Toulouse, France. Research interest: satellite geodesy and space research (gravity field, Earth rotation, precise positioning from space, temporal changes in gravity, sea level variations at regional and global scales -observations and climatic causes-, land hydrology from space). 170 publications in refereed international journals. P.I. of several space missions. Lead author of the IPCC Working Group I (4th and 5th Assessments Reports). Fellow of the American Geophysical Union. Member of the French Academy of sciences. Foreign member of the National Academy of Sciences (USA) and of the Indian Academy of Sciences.

Jianli Chen is a Senior Research Scientist at the Center for Space Research (CSR), University of Texas (UT) at Austin. He received his Ph.D. in Geophysics from UT in 1998. He works on problems that involve climate change, glaciology, land hydrology, space geodesy, and solid earth geophysics, and has been working in the forefront of geophysical applications of GRACE satellite gravity measurements. He has published about 60 peer reviewed journal papers. He received the prestigious US Presidential Early Career Awards for Scientists and Engineers (PECASE) in 2005, and was a recipient of the NASA New Investigator Program award in 2004.