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Earth System Mass Transport Mission (e.motion): A Concept for Future Earth Gravity Field Measurements from Space

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Abstract In the last decade, satellite gravimetry has been revealed as a pioneering technique for mapping mass redistributions within the Earth system. This fact has allowed us to have an improved understanding of the dynamic processes that take place within and

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between the Earth's various constituents. Results from the Gravity Recovery And Climate Experiment (GRACE) mission have revolutionized Earth system research and have established the necessity for future satellite gravity missions. In 2010, a comprehensive team of European and Canadian scientists and industrial partners proposed the e.motion (Earth system mass transport mission) concept to the European Space Agency. The proposal is based on two tandem satellites in a pendulum orbit configuration at an altitude of about 370 km, carrying a laser interferometer inter-satellite ranging instrument and improved accelerometers. In this paper, we review and discuss a wide range of mass signals related to the global water cycle and to solid Earth deformations that were outlined in the e.motion proposal. The technological and mission challenges that need to be addressed in order to detect these signals are emphasized within the context of the scientific return. This analysis presents a broad perspective on the value and need for future satellite gravimetry missions.

Keywords Satellite gravity · Earth system · Mass transport · Global water cycle · Earth deformations

1 Introduction

The large-scale mass distribution in the Earth system is continuously changing. Most of the mass transport is associated with well-monitored atmospheric variability, and with the global water cycle. Through this cycle, the ocean, atmosphere, land, and cryosphere storages of water interact through temporally and spatially variable water mass exchanges (Fig. 1). The distribution of water mass in these reservoirs changes at timescales ranging from sub-daily to inter-annual, and decadal, and is strongly related to long-term global change, including sea-level rise, loss of land ice, and extensive droughts and floods. These mass variations may indicate a change in the forcing or the feedback mechanisms that moderate the climate. Water mass variations may therefore be considered a proxy for ongoing climate variations driven by natural and/or anthropogenic causes (e.g., Hegerl et al. 2007), which has the potential for impacting society very strongly.

In recent years, for instance, the mass loss of the Greenland ice sheet has been observed to be between 150 gigatons per year (Gt/year) for years with moderate loss and up to 280 Gt/year for years with extensive loss (see, e.g., Wouters et al. 2008). This mass loss is attributed to increased glacier discharge and meltwater runoff along the margins of the ice sheet. However, the dynamics of this process and the underlying mechanisms are not fully understood. On the contrary, although the Greenland ice mass undergoes substantial inter-annual variability, the snow accumulation within the ice sheet's interior has remained rather stable. Nonetheless, ice mass loss from Greenland contributes to global sea-level

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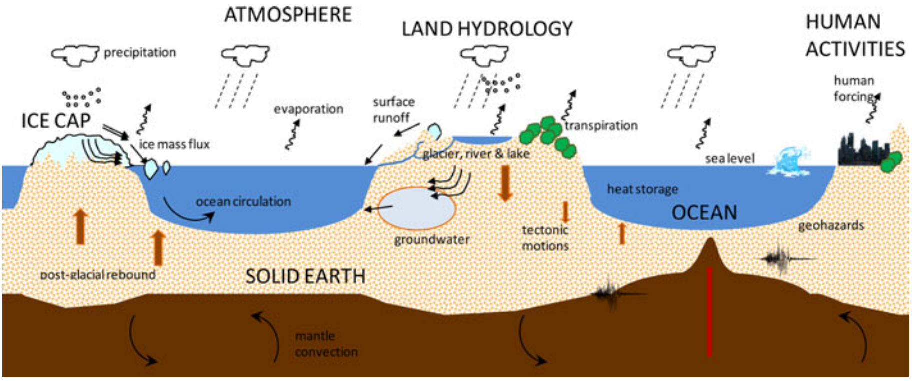

Fig. 1 Processes in the Earth system involving mass transport, mass variations, and mass exchange within and between individual system components

rise. In addition, the increase in freshwater to the oceans has an impact on the ocean salinity that, in turn, affects the meridional overturning circulation. Of particular concern is that the present observations indicate an acceleration of ice mass loss, not only from Greenland and Antarctica but also from smaller, yet significant, mountain glaciers (Meier et al. 2007; Cazenave and Llovel 2010).

To understand the dynamics and variations of the global water cycle, closing the water mass balance is a fundamental goal. Achieving this goal would allow us to determine how water mass in the Earth's water reservoirs varies in time and space and how much water moves between the various reservoirs (Lettenmaier and Famiglietti 2006). Time-variable ocean mass balance and sea-level change is a result of the water balance of all sub-systems. Understanding the global water balance is the key to quantifying the contributions of present-day ice melting to sea-level rise (Cazenave et al. 2009). On regional scales, the time-variable water balance reflects changing water availability for drinking water, agriculture, and industry. In addition, the depletion of freshwater resources is a growing concern for many regions of the world where supplies are under severe threat and where anthropogenic demands and stresses are expected to further increase in the decades to come (Famiglietti et al. 2011; Rodell et al. 2009).

In addition to the mass changes in the Earth's surface fluid layers, the Earth's crust and interior are also undergoing mass variations that are associated with various kinds of deformations. These include glacial isostatic adjustment (GIA), the viscoelastic response of the solid Earth due to Pleistocene continental ice mass melting and the related sea-level variations associated with the glacial cycles, on timescales of millennia to 10s of millennia, elastic surface displacements related to present-day ice mass variations of mountain glaciers and the polar ice sheets, the solid Earth deformation due to earthquakes (i.e., the pre-, co-, and post-seismic deformation and the silent earthquakes), and mantle convection and plate tectonics (Vermeersen 2005). These solid Earth mass variations are superimposed on the fluid-driven changes. Consequently, the observation and estimation of solid Earth mass variations is necessary not only to study the structure and dynamics of the Earth's interior, but also to derive precise estimates of water mass and sea-level change (Tamisiea 2011). In the future, this type of analysis may include mass change signals due to rising mantle plumes and core motions.

To date, our knowledge of mass transport and mass variations within the Earth system has severe gaps. Many processes related to climate change are poorly understood because direct observations of mass variations and mass transport are often difficult to obtain. For example, no direct observations of evapotranspiration (the transport of water from the land surface to the atmosphere) are available. Storage changes in deep soil layers, permafrost, and groundwater are also mostly inaccessible to conventional observation (Rodell and Famiglietti 1999; Güntner 2008). The same holds true for the deep ocean circulation, which is an essential part of the climate system, that plays an important role in heat transport and carbon dioxide sequestration (Garzoli et al. 2010). In addition, the scarcity and often poor precision of high-latitude data, the lack of precise measurements of freshwater runoff, and the limitation of conventional observation techniques along coasts and ice sheet margins (Rignot and Thomas 2002; Send et al. 2010) result in incomplete and biased results with regard to closing of the water mass balance.

Satellite gravimetry, that is, measuring spatial and temporal change in the gravity field caused by mass variations from space, provides a unique opportunity to advance mass transport studies and improve our understanding of the Earth system. From the Gravity Recovery And Climate Experiment (GRACE) mission (Tapley et al. 2004), new fundamental insights into the changing mass distribution have been achieved in the last decade (for a recent review the reader is referred to Cazenave and Chen (2010), which provides an extensive review of results concerning mass distribution that has been compiled from a large number of research papers. Recent results are also presented in Kusche et al. (2012)). The GRACE mission has been extremely valuable in providing insight into continental hydrology (see the recent reviews by Frappart and Ramillien 2012; Güntner 2008; Ramillien et al. 2008; Schmidt et al. 2008), with a focus on large-scale seasonal signals, and the effects of hydrometeorological extremes such as droughts and floods. The decade of GRACE data has demonstrated beyond a doubt that glaciers in Alaska and Patagonia as well as the great ice sheets of Greenland and Antarctica are losing mass (Tamisiea et al. 2005; Chen et al. 2007; van den Broeke et al. 2009; Velicogna 2009). This finding has ended the debate as to whether the ice sheets and glaciers are contributing to ongoing sea-level rise. The GRACE measurements have been essential to closing the sea-level budget at the global scale (Milne et al. 2009; Cazenave and Llovel 2010). Gravity field variations related to the GIA have supported the hypothesis that the Pleistocene ice sheets over Canada consisted of two major domes (Tamisiea et al. 2007), even though part of the interpreted GIA pattern may have been hydrological mass variations (van der Wal et al. 2008; Sasgen et al. 2012). In addition to GRACE, then Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite provides unprecedented maps of the static geoid and gravity field (Rummel 2011; Pail et al. 2011) since 2009. GOCE is providing synergetic information on the ocean circulation and other Earth system processes as well as on lithospheric structure.

Mass variations within the Earth system occur over a wide range of spatial scales as illustrated in Fig. 2. For instance, GRACE in combination with other satellite data can now resolve changes on the order of a few millimeters equivalent water height (EWH) and long-term trends exceeding 0.5 mm/year at scales of 1,000 km. At a spatial resolution of approximately 400 km, on the other hand, detection is limited to only mass changes with an amplitude of 10 cm EWH—or trends exceeding 1 cm/year. While these amplitudes represent an enormous improvement on the situation before the launch of GRACE, many mass signals from very different processes that are relevant to Earth system research remain beyond the current limit of resolution. This includes continental hydrology and ice mass change at smaller scales, many small amplitude signals in the ocean, and all but the very largest signals from solid Earth mass variations. To access the band beyond the current limit of resolution and to address many remaining open questions, higher spatial resolution, higher accuracy, and extended data records are essential. This can be achieved by improved measurement precision and by an optimized orbit configuration, enhancing the satellite sensitivity to the Earth's gravity field. Apart from some supporting instruments, measurement

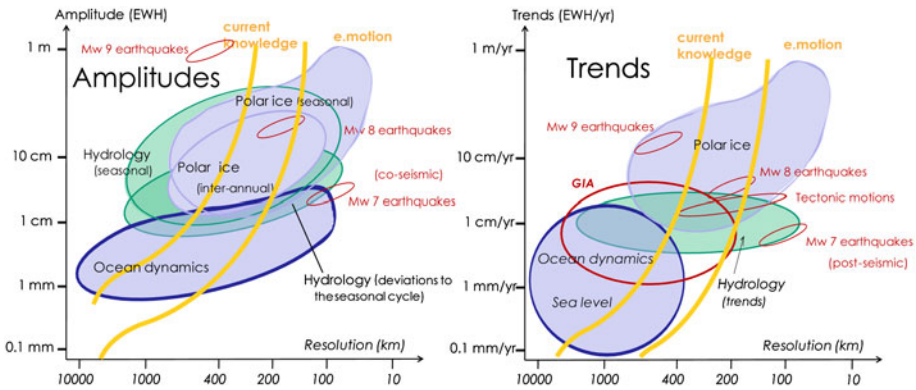

Fig. 2 Signal amplitudes of mass variations in equivalent water height (EWH) as a function of spatial resolution, together with present-day accuracy and resolution and with expected e.motion performance. Solid Earth mass variations are converted to EWH. Contributions from seasonal to inter-annual variations are given in the *left panel*, and contributions from long-term trends are *plotted* in the *right panel*. *Axes* are given in logarithmic *scales* but expanded in the 100–1,000-km interval and in the 1-m (/year)–10-cm (/year) interval in order to emphasize signals at *scales* of 100s of kilometer and amplitudes of 10s of centimeter detectable with satellite gravity missions

precision, in particular, can be increased by replacing the conventional microwave inter-satellite ranging system with a laser interferometer, while sensitivity can be increased by lowering the orbit as compared to the current GRACE mission. The next dedicated gravity field mission will be the US–German GRACE Follow-On mission, planned for launch in the 2016/2017 time frame. This mission is planned to carry an experimental laser interferometric inter-satellite ranging instrument in addition to the microwave ranging system. The Earth System Mass Transport Mission, called “Earth system mass transport mission (e.motion)” that was proposed to ESA by a comprehensive team of European and Canadian scientists, engineers, and industrial partners, builds on this innovation and associated studies. The evaluation of the e.motion proposal by ESA acknowledged the strong need, high scientific merit, and innovation of the mission concept. Nevertheless, it was not among those that were selected in the most recent ESA call for missions.

In this paper the science justification and requirements of the e.motion mission concept are presented and discussed. The concept builds on previous studies, in particular from Beutler et al. (2003), Flury and Rummel (2005), Koop and Rummel (2008), and the Graz workshop “Towards a roadmap for future satellite gravity missions” (2009). As such, it represents a broader perspective on satellite gravimetry. Section 2 addresses the Earth system gravity signals of mass changes at the finer spatial scales not resolved by GRACE specifically targeting: (1) recovery of temporal gravity and mass variations in the Earth system with a spatial resolution of 200 km or better, with global coverage; (2) recovery of small amplitude mass variations with 10 times increased sensitivity compared to current capabilities; and (3) resolution of mass variations at seasonal to decadal timescales, by extending the existing record of satellite data by 7 years or more with enhanced quality and with a temporal resolution of 1 month or better. Section 3 reviews the corresponding challenges regarding technology and mission system requirements. The conclusion then follows in Sect. 4.

2 Earth's System Signals Beyond the Current Limits of GRACE

2.1 Estimating Continental Water Storage and Freshwater Fluxes

Continental water storage is a key component of the global water cycle and plays a major role in the Earth's climate system. Through the processes of precipitation, evaporation, and runoff at the surface and at depth, it governs the exchanges of water between continents, oceans, atmosphere, and ice caps, controlling energy and biogeochemical fluxes. It comes in many forms, such as snow, ice, surface water, soil moisture, and groundwater. Knowledge of its spatial and temporal variations is required to infer changes in the processes affecting the water cycle. By closing the water balance equation, components such as groundwater can be estimated. However, this is made possible only by the availability of integrated mass change that can be derived from gravity observations (Schmidt et al. 2006; Ramillien et al. 2008). Separating the contributions of water mass sub-reservoirs (i.e., surface waters, soil moisture, groundwater) is thus a challenge for the next GRACE-type mission, especially for estimating deep water changes that globally remain unknown.

In many regions, however, zones of different hydrological behavior are spatially too close to each other to be resolvable by GRACE. This spatial resolution refers to different climate zones or important water storage reservoirs such as aquifers, glaciers, or flood plains, which all have strong impacts on the local environment and climate such as ecosystems, agriculture, and the supply of freshwater. Capturing their different temporal dynamics is essential to understand the impact of environmental variability and change on the continental water cycle and future water availability.

Furthermore, improving the spatial resolution to 200 km or better would provide hydrological data at scales that are the most relevant for operational applications in water resource management. With a 400-km resolution, water storage changes can be resolved for

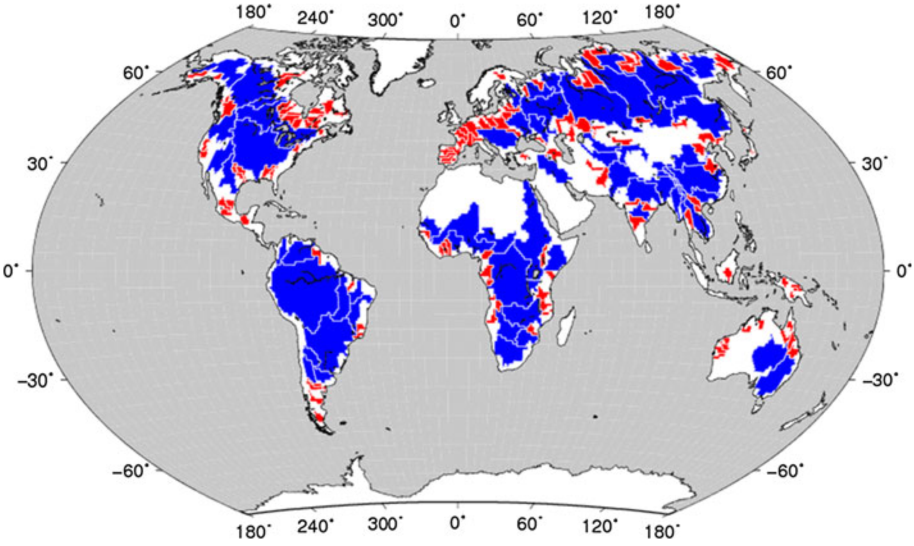

Fig. 3 River drainage basins with a size between 40,000 and 200,000 km^2 (in *red*, from Oki and Sud 1998) that could be resolved by e.motion, as well as basins larger than 200,000 km^2 (in *blue*; this corresponds to the present-day spatial resolution). e.motion will also recover sub-basin variability, which plays an important role in climatic processes

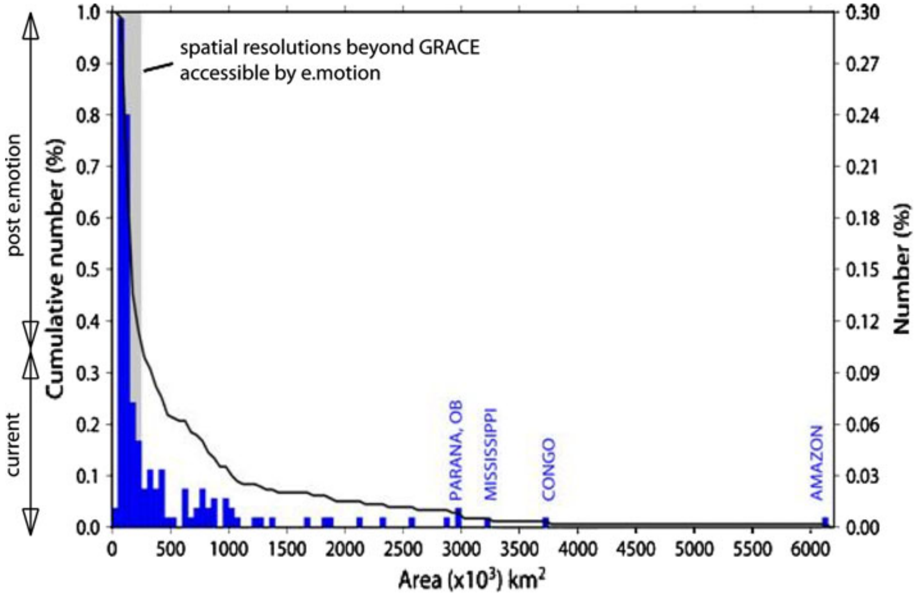

Fig. 4 Distribution of areas of continental hydrology drainage basins (Oki and Sud 1998). The *gray area* to the *left* indicates the spatial resolution improvement of e.motion with regard to current capabilities. The *black curve* indicates the cumulative number of basins. About 33 % of the basins can be studied with GRACE, and almost 100 % with e.motion

18 % of the 182 major drainage basins of the world only. With 150–200-km resolution achievable by laser inter-satellite ranging, basins of 40,000–22,000 km^2 will be resolved, representing about 75 % of the major basins (Oki and Sud 1998), as shown in Figs. 3 and 4.

When lateral transports are sufficiently well observed in individual basins by complementary measurements from, for example, river gauges or groundwater wells, water storage variations can be related to changes in atmospheric freshwater fluxes by evaluating the water budget equation. While precipitation is remotely observed by combining satellite scatterometer measurements with infrared radiances and ground precipitation radars, evapotranspiration is particularly difficult to measure even from in situ observations due to its high spatial variability. Satellite gravity data at higher spatial resolution than GRACE would thus allow us to derive regional estimates of these fluxes, which might be assimilated in order to improve the large-scale freshwater balance of numerical weather prediction models.

Observations of water storage changes via satellite gravimetry indeed provide access to one of the very few large-scale observational data sets available for evaluating and constraining hydrological models or land surface schemes in climate models and weather forecast models. These observations also allow us to develop and constrain global and regional hydrological models and improve their prognostic capabilities. Moreover, water storage time series at the same spatial scale as river discharge measurements, that is, subbasins, allow for a consistent improvement of hydrological models. Indeed, both variables provide an integrated measure of the river basin response and can thus be used simultaneously as model constraints.

Finally, long-term satellite gravity measurements are needed for adjusting model equations and parameters that are relevant for long-term hydrological processes. Even if a model reasonably represents the seasonal hydrological cycle, this does not guarantee realistic model performance for inter-annual variations. The availability of long time series will also allow us to address another challenge, which is to separate the natural variability in continental water storage from human-induced changes, such as by the exploitation of water resources, land use change, or climate change, that produce gradual changes in the water cycle.

2.2 Understanding Ice Sheet Mass Balance

Ice sheets, smaller ice caps, and valley glaciers store most of the Earth's freshwater. Ice mass is accumulated by precipitation and ablated by glacier discharge to the ocean, by meltwater runoff, sublimation, and evaporation. The net balance between the inflow and outflow of ice mass is a sensitive response to climate change. At present, ice mass loss prevails, contributing more than 50 % of the amplitude of the ongoing rate of global sea-level rise in recent years (Cazenave and Llovel 2010).

Many fundamental research questions remain unresolved in this field. We do not know in detail the physical processes that are most relevant for glacier acceleration in Greenland and West Antarctica (Rignot and Thomas 2002, Zwally et al. 2002; Lemke et al. 2007; Pritchard et al. 2012). Due to the complexity of the ice dynamic behavior, it is highly uncertain how the mass loss will evolve in the future, and whether the West Antarctic ice sheet may disintegrate at some point (Bamber et al. 2009). At present, we cannot separate mass movement caused by Glacial Isostatic Adjustment (GIA) with sufficient accuracy from contemporary ice sheet mass changes (Barletta et al. 2008). We do not know whether the current trends reflect a long-term behavior of the ice sheets, or whether they are part of the decadal variability of the ice sheet climate system. Smaller glaciated regions (Svalbard, Arctic Canada, Alaska, Patagonia, etc.) are important contributors to present-day sea-level change (Meier et al. 2007), yet currently poorly resolved.

These processes involve significant variability at scales beyond the limits of resolution of GRACE. To answer the open questions, it will be necessary to resolve ice mass changes at the glacier basin scale. Improving the spatial scale from 400 to 200 km or better, which can be achieved by a mission in an e.motion configuration, will be a major step forward for the recovery of ice mass variations. The number of resolvable glacier basins within ice sheets (Rignot and Kanagaratnam 2006; Rignot et al. 2008) will be more than doubled, for example, for Greenland it would increase from 16 basins presently resolved to 43 basins of size of 40,000 km^2 (Fig. 5). In addition, the higher resolution will increase the comparability with satellite laser and radar altimetry data and will improve the possibility of combining these different observational types.

The increased resolution will strongly enhance the value of observed mass variations for data assimilation into regional climate and ice dynamical models, as the net mass balance and its components of accumulation, melting, and glacier discharge are regionally highly heterogeneous. It will strengthen the role of satellite gravimetry as a unique constraint on ice sheet mass variations, in combination with the mass budget method, satellite altimetry, and in situ measurements. This will shed light onto the processes driving ice dynamics at high resolution and support the development of ice dynamical models. The dynamics in the ablation zone around the Greenland ice sheet will be captured, including inter-annual mass variations that may have varying characteristics in the different regions of the margins of Greenland (Wouters et al. 2008; Van den Broeke et al. 2009). By synthesizing the high-resolution observations with models, it will be possible to quantify whether individual glacier systems lose mass by glacier acceleration or by surface melt. For the Antarctic

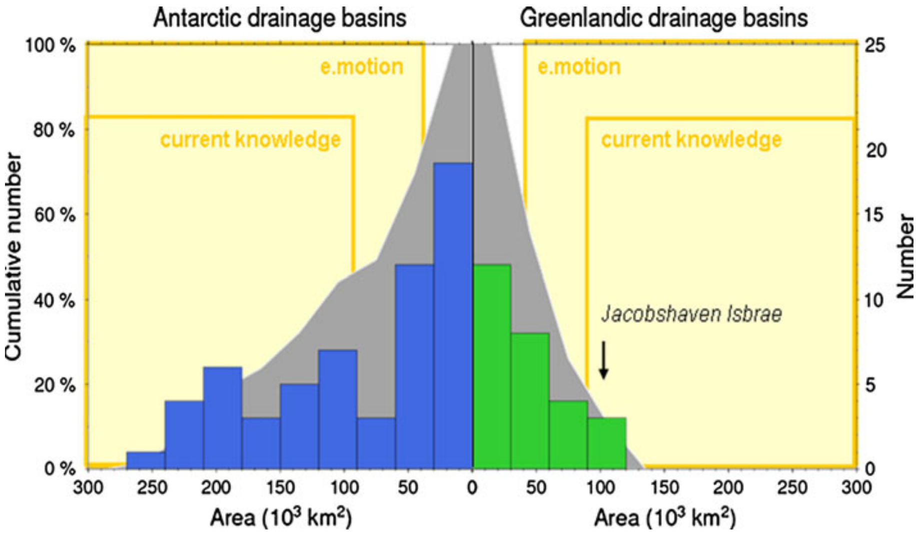

Fig. 5 Distribution of areas of Antarctic (Rignot and Kanagaratnam 2006) and Greenlandic (Rignot et al. 2008) drainage basins and recovery improvement with e.motion with regard to current capabilities. *Gray curve* indicates the cumulative number of basins

Peninsula, it will be possible to determine how glacier discharge rates are affected by ice shelf disintegration. It will also be possible to monitor the behavior of the glacier systems in the Amundsen Sea Embayment, which is considered to be a key region of the West Antarctic ice sheet due to its ongoing glacier thinning and retreat, and to monitor variations along the margins of East Antarctica that appear to be losing mass according to recent gravity data (Chen et al. 2009). Finally, continuous time series of measurements with improved accuracy will help to quantify the teleconnections [(e.g., El Nino Southern Oscillation (ENSO), Southern Annular Mode (SAM) and North Atlantic Oscillation (NAO)] in the global climate system (Sasgen et al. 2010). This will contribute to deciphering the long-term trends in the inter-annual variations of polar ice sheet mass balance associated with changes in the climate system.

2.3 Understanding Changes in Sea Level and Monitoring the Large-scale Ocean Circulation

The oceans are an essential component of the climate system. They play a major role in storing, transporting, and redistributing heat within the Earth system, because of their immense heat capacity. Moreover, precise quantitative and multidisciplinary understanding of the processes that influence sea-level change is one of the major concerns of our time. Continued satellite gravity time series with enhanced accuracy will provide clearer insight into the timescales of variation of the mass components of the sea-level budget and will allow us to better separate between density and mass contributions to sea-level change. This will be necessary in making projections of future sea-level rise.

An important regulator of climate is the deep ocean circulation. At depths >2,000 m, the limit of most Argo floats, there are very few ocean monitoring systems. Yet, flow at these depths plays an important role in global heat transport and the meridional overturning circulation. Via ocean bottom pressure sensing, satellite gravimetry measures the integrated mass change from the near-surface waters down to the bottom boundary layer. This partly overcomes the limited availability of direct observations at depths below 2,000 m. It is advantageous that whereas sea level is dominated by mesoscale (about 10–300 km) variability, bottom pressure tends to vary on much larger length scales and hence filters out much of the mesoscale variability (Bingham and Hughes 2008a). This, coupled with the strong dynamical constraints on bottom pressure variability (Hughes and de Cuevas 2001), makes bottom pressure a particularly suitable quantity for monitoring large-scale changes in the deep ocean circulation (Bingham and Hughes 2008b). Spatial gradients of ocean mass anomalies allow for the derivation of barotropic ocean currents and, hence, transports (Zlotnicki et al. 2007). However, bottom pressure is a challenge to measure, as the signals are small, and averaging over large areas is required to obtain reasonable estimates. A typical amplitude for bottom pressure variability is 3–5 times smaller than for sea level, and this signal is dominated by high-frequency depth-independent changes that are also visible in sea level, and of little relevance to heat transport; the signal of climatic importance is smaller again (Bingham and Hughes 2008a).

Probably, the most valuable measurement related to bottom pressure is that of the Atlantic meridional overturning circulation, responsible for a large fraction of the total ocean heat transport. This is associated with a highly distinctive pattern of bottom pressure variability concentrated on the continental slope of the American continent. With typical spatial scales of approximately 70 km across the slope, and thousands of kilometers along the slope (Roussenov et al. 2008; Bingham and Hughes 2009), and associated signal amplitudes of a few centimeters of EWH, this signal is far too small for detection by GRACE. However, with dedicated processing that is focused on the distinctive pattern of the signal, a higher-accuracy mission such as that outlined in the e.motion proposal may make it possible to detect this mode of variability. The poor observational constraints on deep ocean dynamics mean that measurements such as this will be highly valuable for both validation and initialization of the ocean component of numerical Earth system models.

Regarding sea level, GRACE results have demonstrated both the value and the major sources of uncertainty in estimating changes in global ocean mass from satellite gravimetry. There remain three particular sources of error, each of which may be reduced if higher spatial resolution is attained. (1) The gravitational effect of GIA, which produces a signal of about 1 mm/year EWH when integrated over the ocean and presently has uncertainties of about half that size (Tamisiea 2011); this error source will be reduced by improved GIA models which would result from satellite gravity data with higher accuracy and resolution. (2) Low spatial resolution results in a blurring of the ocean–land boundary that introduces uncertainty in the associated estimates of ocean mass changes, producing potential errors of more than 30 % in the contributions from Greenland and glacier melt (Chambers et al. 2007), and variations of up to 0.4 mm/year in corresponding GIA corrections (Tamisiea 2011); higher resolution would clearly reduce this error source. (3) Lack of information about geocentre motion in the gravity field data leads to a further reduction in estimated Greenland and glacier contributions, increasing the error to more than 60 % unless correctly accounted for (Chambers et al. 2007) (a finer spatial resolution would make no direct improvement on this error, but would enable an improved combination with the local, Earth-based measurements, which must be combined with satellite gravimetry to provide an estimate of the geocentre motion).

Increased spatial resolution and accuracy of gravity data will also be highly beneficial for regional oceanographic applications such as assessing sea-level change for shelf areas along densely populated coasts. Having access to mass changes at a spatial resolution of about 200 km would also, in combination with GOCE, potentially allow for improved knowledge of the static geoid. Hence, the mean dynamic topography could be provided with a possible accuracy of 1–3 cm down to approximately 100–70 km. In turn, the mean surface geostrophic currents along intense current regimes would expectedly benefit from the present strength achieved with GOCE.

2.4 Measuring and Modeling the Glacial Isostatic Adjustment, Large Earthquakes, and Slow Tectonic Motions

Accurate modeling of the deformation of the solid Earth, for example, due to earthquakes and slow deformations such as GIA, requires a reasonable knowledge of the Earth's internal structure. When it comes to understanding the density distribution inside our planet, significant advances are expected from the GOCE static gravity field observations. Another important, yet poorly understood, property of the Earth's interior is the mantle viscosity. It controls the pattern of convective flow, the viscous deformations of the Earth in response to various internal and external forces, and the stress distribution in subduction zones, which are affected by the largest and most violent earthquakes. Laboratory experiments are insufficient for inferring the Earth's viscosity, as realistic mantle temperatures and pressures are difficult to simulate in a laboratory. These limitations make geophysical observations of geoid changes, GIA, and observations of post-seismic deformation extremely important (Hager 1991; Wu and Peltier 1983; Mitrovica and Forte 1997; Pollitz et al. 2001).

GIA alters the Earth's gravity field as a consequence of mass redistribution within the Earth's mantle, as well as by deforming the Earth's surface. Despite observations such as geological and glaciological indicators of paleo-sea level, GPS, and tide-gauge measurements, determinations of GIA and inferences about mantle viscosity remain ambiguous. Moreover, measuring GIA is difficult because many regions where we would expect to observe the viscoelastic response to the melting of the Pleistocene glaciers, that is, the edges of large ice sheets, are also affected by elastic surface displacements due to present-day changes in ice mass, for example, in Alaska, Greenland, and Patagonia (Barletta et al. 2008). For Antarctica, limited accessibility and sparse paleo-constraints on GIA have led to a particularly large uncertainty in GIA model predictions, which are, however, crucial for determining accurate present-day ice mass balance estimates from satellite gravimetry. Current uncertainties in the GIA corrections overprint ice mass variations in Antarctica. Here, a new gravity mission will contribute to the regional separation of present-day ice mass changes from GIA and provide valuable data to be included in viscoelastic modeling. This will also better resolve the GIA contribution to estimates of sea-level change (see the section above on sea-level change).

Due to its spatial coverage, satellite gravimetry is a unique new constraint on the spatial pattern of GIA and, subsequently, on the mantle viscosity and lithospheric thickness (Paulson et al. 2007), and on the ancient ice geometry (Tamisiea et al. 2007). To better distinguish between plausible Earth viscosity profiles, GIA signals must be recovered with a considerably higher accuracy than provided by GRACE (Wahr and Davis 2002). Analysis of longer time spans of satellite gravity data should also allow us to separate more clearly inter-annual hydrological and cryospheric mass variations from the GIA signal. Better mass variation records will also lead to improvements in numerical modeling. This will enhance capabilities to simulate long-term cryospheric mass fluxes and separate them from changes induced by GIA. Finally, combining the estimated GIA trends with the static free-air gravity data from the region, which will be considerably improved thanks to

GOCE, makes it possible to derive important boundary conditions on the buoyancy of the continental tectosphere (Tamisiea et al. 2007).

At smaller spatial and temporal scales, the study of solid Earth deformations associated with earthquakes would greatly benefit from high-resolution satellite gravity data. The most devastating earthquakes of the modern epoch have all occurred at subduction zones, causing extensive damage in densely populated areas. In these highly seismically active regions, satellite gravity data are extremely valuable for constraining the rupture mechanism and quantifying post-seismic deformation, because they "view" undersea epicentral areas that can hardly be surveyed by ground geodetic and geophysical techniques (Mikhailov et al. 2004; Han et al. 2006). By monitoring the seismic cycle and slow aseismic motions, satellite gravity can contribute to a better understanding of the mechanisms of stress accumulation and stress release. Observations of post-seismic response can be used to determine the relative importance of afterslip and viscoelastic relaxation and constrain the shallow rheology and viscosity of the Earth (Panet et al. 2010). This information can then be extrapolated to other earthquake-prone regions. A higher spatial resolution and accuracy is, however, needed in order to detect the gravitational changes associated with earthquakes of Mw 7–8 (de Viron et al. 2008).

2.5 Providing the Gravity Reference in the Global Geodetic Observing System

Better knowledge of time-variable gravity and mass distribution will also—directly or indirectly—improve the accuracy of Earth observation systems and techniques. Mass changes, such as changing water loads, deform geodetic networks such as global navigation satellite systems (GNSS) ground station networks. Changing mass distribution also has an influence on orbits and orbit determination for low Earth observation satellites and manifests itself with complex signatures in Earth rotation and observed Earth orientation parameters. More accurate Earth gravity field models will help to improve the accuracy of orbit modeling and reduce the effect of orbit errors on satellite observations. Consistent combination of more accurate satellite gravity data with geometric techniques such as Global Navigation Satellite System (GNSS) studies, Very Long Baseline Interferometry (VLBI), and satellite laser ranging will further improve knowledge on mass change, and it will help to resolve technique-inherent error sources. This will also improve the International Terrestrial Reference Frame underlying the observation techniques. Mission concepts such as e.motion are needed to advance the implementation of the global geodetic observing system (Plag and Pealrman 2009).

An accurate geoid is needed as a reference for precise height determination. At this time, the GOCE satellite mission is carrying out observations to provide an excellent, high-resolution quasi-static geoid. In many regions, however, heights are affected by significant temporal geoid changes, for example, due to GIA. Temporal geoid changes observed by future satellite gravimetry, combined with the GOCE quasi-static geoid, will reduce inconsistencies between national height systems and advance the establishment of a World Height System for science, engineering, mapping, and geographical information systems (GIS).

2.6 Summary of e.motion Science Requirements

Mass variations associated with the above-described processes occur on a wide range of spatial and temporal scales, as illustrated in Fig. 2. More specific information on their timescales and amplitudes, and on the required precision and resolution to recover these

Table 1 Overview of science requirements to be addressed by e.motion

Research objectives	Timescales	Expected signals: temporal variation in EWH, geoid, gravity	Precision, resolution
Continental water storage variations	Weeks to decades	Several dm EWH mm to cm EWH/year	1 cm EWH @ 400 km, 10 cm EWH @ 200 km 1 mm EWH/year @ 400 km
Ice sheets mass balance	Months to decades	dm to m EWH dm EWH/year	1 cm EWH @ 400 km, 10 cm EWH @ 200 km 1 mm EWH/year @ 400 km
Oceanic mass variations/sea level	Hours to decades	cm to dm EWH mm to cm EWH/year	5 mm EWH @ 500 km 1 mm EWH/year @ global scale
Glacial isostatic adjustment	Secular	2 mm geoid/year	0.01 mm geoid/year @ 400 km
Earthquakes (Mw 7–8) coseismic	Instantaneous	0.1–1 mm geoid or 5 µGal	0.1 µGal @ 200 km or 0.1 mm geoid @ 400 km
Earthquakes (Mw 7–8) post-seismic	To decades	0.01–0.1 mm geoid/year or 0.5 µGal/year	0.01 µGal/year @ 200 km or 0.01 mm/year geoid @ 400 km
Mantle convection and plate tectonics	Decades to secular	0.05 mm geoid/year	0.01 mm geoid/year @ 400 km
Height reference, orbits, combination of observation techniques	Hours to decades	Few cm geoid Few mGal	1 mm geoid @ 200 km 1 µGal @ 200 km

signals from a gravity mission, is given in Table 1. The precision is estimated at 10 % of the signal amplitude. For most research objectives, specifications are given in terms of EWH, but they are provided in terms of geoid or gravity variations where appropriate. The conversion between EWH and geoid variations depends on the spatial scale, and it is described in Appendix 1. Previous comparable tables were given by Sneeuw et al. (2005) and Rummel (2005).

In the following, we give some examples on how to read Table 1. For instance, seasonal variations of hundreds of millimeter of equivalent water height have been detected by GRACE in large tropical basins (around ±500 mm in the Amazon basin, Ramillien et al. 2008). Measuring water height variations with a 10-cm precision at 150–200-km resolution would allow us, for instance, to recover mass variations in basins such as the Rhine and Danube catchments, which cannot be studied with available data. At scales shorter than 200 km, the capabilities of a satellite gravity mission based on the e.motion concept to resolve mass variations would be reduced. However, large mass variations such as those associated with heavy snow accumulation and floods could be recovered and quantified at scales of around 100 km. This length scale also corresponds to the typical size of glaciers terminating in the coastal areas of the polar ice caps, areas of crucial interest, since they contribute a large part of ice mass loss and are not fully covered by altimetry.

Concerning sea level, the current rate of global sea-level rise is 3.3 ± 0.4 mm/year (Cazenave and Llovel 2010). An acceleration of 1 mm/year over a decade would be a large signal, so the accuracy in the monitoring of the mass component of the sea-level signal should be sufficient to detect an acceleration of 0.1 mm/year over a decade, requiring an accuracy of 0.5–1 mm of EWH. For regional ocean dynamics, a typical requirement for sea level from altimetry is 1 cm accuracy, but bottom pressure signals are weaker by typically a factor of 3–10, leading to a requirement of a few millimeter of water accuracy at regional scales.

Concerning solid Earth signals, a study of geoid variations at GRACE resolution associated with earthquakes of varying magnitude can be found in de Viron et al. (2008), while Mikhailov et al. (2004) showed that a mission 10 times more precise than GRACE would allow for the detection of the accumulation of mass along active tectonic zones, discrimination of fault plane models, and the monitoring of asperities on locked seismic zones. Finally, the geoid change due to GIA in the Hudson Bay area is in the order of 1–2 mm/year on the geoid (Barletta and Bordoni 2009); however, distinguishing GIA signals associated with different viscosity profiles within the Earth requires a significantly higher accuracy (Wahr and Davis 2002; Vermeersen 2005).

3 Technological and Mission Configuration Challenges

To observe the mass variation signals discussed in the previous section, an enhanced precision of the inter-satellite ranging measurement system is needed, as well as global coverage with sub-monthly temporal sampling. In this section, these requirements are discussed in the context of the corresponding satellite system challenges.

3.1 Technological Challenges

In order to reach the scientific mission goals as described in the previous section, the measurement precision as compared to what is achievable with the GRACE mission needs to be enhanced significantly. As the primary instrument the microwave ranging system as implemented on GRACE needs to be replaced by a laser interferometric ranging system offering a significantly higher precision of the inter-satellite range measurements. The sensor configuration design for such a system has been recently studied by Sheard et al. (2012). The laser interferometer system is based on the transponder principle: Laser beams (1,064 nm wavelength) are transmitted from each satellite toward the twin satellite. Laser frequencies are locked onboard one satellite. On the other satellite, interferometric phase readout is carried out, and the phase variations are converted to equivalent changes in the inter-satellite distance, with a noise level of 50 nm/sqrt (Hz) or better. This represents a sensitivity gain of a factor of 50 as compared to GRACE, although this term remains far from the technological limit of laser interferometric ranging.

Accelerations originating from non-gravitational forces have to be observed within a dedicated measurement range with a high-sensitive 3D accelerometer. For the e.motion mission design, one needs an accelerometer with a noise level of 10^{-11}–10^{-12} m/s^2/sqrt (Hz), which corresponds to a factor of 10–100 improvement in performance as compared to the GRACE accelerometer. Six of such accelerometers forming a gravity gradiometer are presently operating in the GOCE mission. From the results obtained with GOCE, it can be shown that this accuracy level is achievable when partial drag compensation is implemented (specifically having in mind the lower altitude of 370 km considered for e.motion). Drag compensation is needed in order to improve the resolution of the accelerometers by reducing their measurement range. As it is planned to fly the mission in a so-called pendulum configuration, the flight direction usually is not in-line with the line of sight between both satellites. For this reason, an accelerometer with three highly sensitive

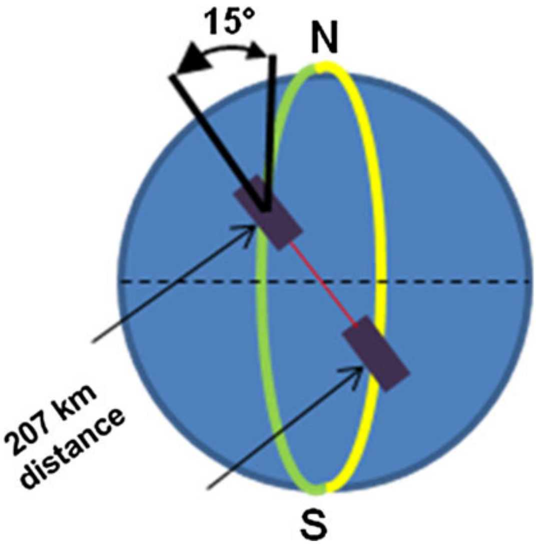

Fig. 6 e.motion pendulum configuration. The two satellites are moving with constant inter-satellite distance, but on two orbital planes slightly rotated relative to each other

axes is needed in order to map the non-gravitational accelerations observed by the three axes to the flight direction, where the main disturbing accelerations happen. This is a major difference to the GRACE configuration, where line of sight and flight direction mostly are in line or deviate only by very small angles.

Finally, as a result of the pendulum orbit configuration (see Fig. 6) together with the pointing requirements for the laser interferometer, which are much higher as compared to the GRACE microwave system, an innovative attitude determination and control system needs to be implemented. This includes a new class of thrusters, which are capable of orienting both satellites permanently with respect to each other with high precision. For this purpose, electric propulsion systems have been identified in the e.motion proposal as the primary choice, despite the fact that their technological readiness has not yet been established.

The position of the satellites has to be observed by GNSS space receivers capable of observing signals from any available global navigation system (for e.motion specifically a GPS and Galileo receiver is foreseen). Having available signals from more navigation satellites would further improve the determination of highly accurate orbits, which are the starting point for gravity field analysis.

3.2 Orbit Configuration

The orbit configuration has to ensure that global measurements, including the poles, are feasible and that the satellites revisit every location with a repeat cycle shorter than 1 month. The latter is needed in order to make sure that time-variable mass signals can be observed at a constant rate with comparable spatial resolution. This leads to the choice of a near “true” polar orbit with an inclination close to 90 degrees. The altitude should provide both excellent sensitivity to the gravity field and offer a sufficiently quiet environment. In the e.motion configuration, satellites are maintained at approximately 370-km altitude. At this orbit height, a repeat period of 28.92 days with an equatorial inter-track distance of about 44 km can be reached. The inter-satellite distance should be commensurate with the

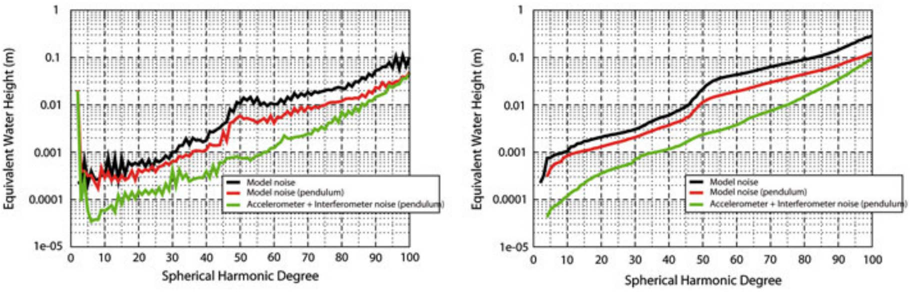

Fig. 7 *Left panel* spectra of gravity field errors for each spherical harmonic degree l in terms of water height. The spatial resolution d in kilometers, equal to the half-wavelength, is related to the spherical harmonic degree l following $d = 20{,}000/l$. *Right panel* spectra of gravity field errors in terms of water height, accumulated up to degree l. *Green curves* indicate errors due to the accelerometer and interferometer noise in the e.motion configuration, *red curves* indicate errors due to imperfect de-aliasing in the e.motion configuration, and *black curves* indicate errors due to imperfect de-aliasing in a coplanar configuration

target gravity field resolution, about 200 km. To achieve homogeneous quality for mass variation results and to overcome limitations of unidirectional ranging observations, we chose a pendulum orbit configuration. By rotating the orbital planes relatively to each other (by change of the right ascension of the ascending node), observations are obtained not only in the North–South direction, but also in other directions, with a maximum tilt of 15° at the equator (see Fig. 6). As simulations have shown, this strategy would improve the isotropy of the estimated gravity field signals, significantly implying that the well known North–South stripes seen in the GRACE monthly fields can be strongly reduced. With such a configuration, it is no longer expected that there will be a need for dedicated post-processing filters, which to some extent also reduce the signal. With a minimum mission duration of 7 years in such an orbit configuration, we expect that long-term mass variation signals can be determined with the required accuracy and spatial resolution.

3.3 Quality of Gravity Field Retrieval

To assess the quality of gravity and mass variation retrievals in the e.motion configuration, many simulations have been carried out (Johannessen et al. 2010) (compare also Visser et al. (2010), Loomis et al. (2011) and Wiese et al. (2012)). Figure 7 shows two resulting error spectra in terms of spherical harmonic degree, in units of EWH per degree (standard deviation), for a time span of 1 month of data. Simulations include interferometer errors and accelerometer errors. In addition, model noise arising from so-called geophysical background models for mass variations has also been introduced. These background models for tides and non-tidal oceanic and atmospheric mass variations are needed to mitigate the effect of aliasing caused by the rapid mass variations that are undersampled by the satellite pair—note that the 10-day repeat sub-cycle of the e.motion orbit allows a direct observation of part of these sub-monthly variations. Here, model noise has been estimated by computing and scaling differences between several background models. This model noise represents the best available estimate of residual aliasing errors, but it is affected by significant uncertainties. As a consequence, the overall error estimates are expected to be realistic but should be considered as rough estimates. To make the simulation results comparable with the signal scales and amplitudes outlined in Fig. 2 and Table 1, the spherical harmonic coefficient standard deviations have been converted to regional error estimates according to Appendix 2. These errors are represented by the two yellow curves depicted in Fig. 2.

4 Conclusion

By monitoring large-scale water fluxes and solid Earth deformation, GRACE has proved to be a pioneering technique for assessing Earth system mass changes and has revolutionized research in many fields of application. The outstanding results obtained, together with the need to understand long-term variations driven by climate change, provide a strong motivation for ensuring continuity of future time-varying satellite gravity missions.

By reviewing Earth system mass signals, we clearly find that, beyond the current limitations of satellite gravimetry, there remains a large ensemble of important processes, which may be accessible with upcoming technological improvements. This implies advances in terms of spatial resolution, retrieval accuracy, and length of records, confirming results of earlier assessments in this field. We underline the associated challenges, in terms of both the measurement system and the configuration of a laser interferometric ranging mission. With the e.motion configuration, the mass signals discussed here can be retrieved, meeting the requirements given in Table 1.

As gravity measurements provide an integrated view of the mass variations, their interpretation in terms of mass transport is inherently multidisciplinary. Satellite gravimetry is thus a vital component of a multisensor Earth observing system, which complements and relates observations of different Earth system constituents in a common and consistent global framework.

The mapping of mass variations and fluxes at the spatial resolution of most basin systems, jointly analyzed with the complementary data sets and models for the different system compartments, will become a central element in the derivation of a more accurate global view of the ongoing interacting processes and the impact of climate variations on the Earth’s equilibrium. Being closely related to changes in sea level, glaciers and ice caps, groundwater, river discharge, snow cover, and other variables in the set of essential climate variables (ECVs) established by the Global Climate Observing System (GCOS) initiative (GCOS 2003, 2006), mass change observations by means of satellites have the potential to significantly improve knowledge of these ECVs and might even be considered an ECV on its own if satellite gravity missions are continued in the future.

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Appendix 1: Amplitude of Geoid Variations Associated with Local Water Loads

The amplitude of geoid variations associated with a water mass load depends on the spatial scale of this load, as shown in Wahr et al. (1998). Here, we computed the geoid effect of a water load spatially distributed as a Gaussian bell, with amplitude of 1 cm of equivalent

Table 2 Geoid effect of water loads with a spatial distribution as a Gaussian bell of varying radii

Gaussian bell radius (km)	Geoid variation (mm)
2,000	0.44
800	0.27
400	0.13
200	0.08
100	0.04

water thickness at the center of the Gaussian. We considered the direct Newtonian attraction of the load and the Earth's elastic deformation as given by the Love numbers. Results are provided in Table 2 for a Gaussian bell of varying radii r. The radius corresponds to the distance to the centre for which the water thickness has decreased by a factor of two. These results allow for easier conversions between EWH signals and geoid variations.

Appendix 2: Local Error Estimates

Earth system mass signals associated with various physical processes are most often local. This means that the estimates of the precision required to recover those signals should be local. Here we recall, following Dickey et al. (1997) and Wahr et al. (1998), how they are related to global spherical harmonics error spectra.

Let $h(\theta, \varphi,)$ denote the water height at the point of colatitude θ and longitude φ, and the average error over an area of interest. A localizing filter $W(\theta, \varphi)$ is associated with this area, describing its shape. However, because of the limited resolution of satellite gravity data, it is not possible to perfectly localize the target area, since an infinite number of spherical harmonics would be needed to build a perfect localizing filter, with a value of 1 inside the study area and 0 outside. Consequently, water height estimates from a truncated spherical harmonic spectrum will never be perfectly localized. Contrarily, a filter with a perfect spectral localization, such as that realized by a cumulative spherical harmonic spectrum, is associated with a highly oscillating spatial window. The construction of local basin filters is extensively discussed in the literature (e.g., Swenson and Wahr 2002; Seo and Wilson 2005).

Let us denote W^c_{lm}, W^s_{lm} and h^c_{lm}, h^s_{lm} the coefficients of the spherical harmonic expansion of the filter and the water height, respectively. The average water height within the approximate shape of the basin, resulting from the truncation at degree L of the spherical harmonic expansion of W, is given by:

$$\bar{h} = \frac{1}{\Omega} \int h^L(\theta, \phi) \cdot W^L(\theta, \phi) \cdot \sin\theta \mathrm{d}\theta \mathrm{d}\phi \tag{1}$$

where Ω is the solid angle subtended by the basin, equal to $4\pi \frac{S_{\mathrm{Area}}}{S_{\mathrm{Earth}}}$, where S_{Area} is the surface of the area and S_{Earth} the surface of the Earth. From the orthogonality of the spherical harmonics, one obtains the following equation:

$$\bar{h} = \frac{1}{\Omega} \sum_{\ell=0}^{L} \sum_{m=0}^{\ell} \left(W^c_{\ell m} \cdot h^c_{\ell m} + W^s_{\ell m} \cdot h^s_{\ell m} \right) \tag{2}$$

Now, let us denote δh^c_{lm} and δh^s_{lm} the errors on the spherical harmonics coefficients of the water height measured by a satellite gravity mission, and $\sigma_\ell^2 = \sum_{m=0}^{\ell}\left(\left(\delta h^c_{\ell m}\right)^2+\left(\delta h^s_{\ell m}\right)^2\right)$ the degree variance. To simplify the expressions, we suppose that δh^c_{lm} and $\delta h^s_{l'm'}$ are uncorrelated for any degrees and orders, and δh^c_{lm} and $\delta h^c_{l'm'}$ (δh^s_{lm} and $\delta h^s_{l'm}$, respectively) are uncorrelated if $\ell \neq \ell'$ or $m \neq m'$. We make the approximation that $\left(\delta h^c_{\ell m}\right)^2 = \left(\delta h^s_{\ell m}\right)^2 = \frac{\sigma_\ell^2}{2\ell+1}$. The variance on the average water height resulting from the errors δh^c_{lm} and δh^s_{lm} can then be written as follows:

$$\operatorname{var}(\bar{h}) = \frac{1}{\Omega^2}\sum_{\ell=0}^{L}\frac{\sigma_\ell^2}{2\ell+1}\sum_{m=0}^{\ell}\left(\left(W^c_{\ell m}\right)^2+\left(W^s_{\ell m}\right)^2\right) \tag{3}$$

Introducing the degree spectrum of the localizing filter $W_\ell = \sqrt{\sum_{m=0}^{\ell}\left(\left(W^c_{\ell m}\right)^2+\left(W^s_{\ell m}\right)^2\right)}$, we end up with:

$$\operatorname{var}(\bar{h}) = \frac{1}{\Omega^2}\sum_{\ell=0}^{L}\frac{\sigma_\ell^2}{2\ell+1}W_\ell^2 \tag{4}$$

If we use a localizing window shaped as an axisymmetric Gaussian bell, then the spectrum W_l is given in Wahr et al. (1998), based on Jekeli (1981). However, this Gaussian is normalized so that its global integral is equal to unity. Thus, to be used in Eq. (4), the W_l coefficients given in equation (34) of Wahr et al. (1998) should be divided by the normalization factor $\frac{b}{2\pi}\frac{1}{1-e^{-2b}}$, with $b = \frac{\ln(2)}{1-\cos(r/a)}$, a the semi-major axis of the Earth's ellipsoid (a = 6,378,136.46 m), and r the distance at the Earth's surface for which the value of the Gaussian window is equal to half its maximum.

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