Surv Geophys (2015) 36:743–772
DOI 10.1007/s10712-015-9348-9

Science and User Needs for Observing Global Mass Transport to Understand Global Change and to Benefit Society

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Received: 10 June 2015 / Accepted: 16 October 2015 / Published online: 27 October 2015

Abstract Satellite gravimetry is a unique measurement technique for observing mass transport processes in the Earth system on a global scale, providing essential indicators of both subtle and dramatic global change. Although past and current satellite gravity missions have achieved spectacular science results, due to their limited spatial and temporal resolution as well as limited length of the available time series numerous important questions are still unresolved. Therefore, it is important to move from current demonstration capabilities to sustained observation of the Earth's gravity field. In an international initiative performed under the umbrella of the International Union of Geodesy and

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The names of members of the IUGG Expert Panel are given in Appendix 2

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Geophysics, consensus on the science and user needs for a future satellite gravity observing system has been derived by an international panel of scientists representing the main fields of application, i.e., continental hydrology, cryosphere, ocean, atmosphere and solid Earth. In this paper the main results and findings of this initiative are summarized. The required target performance in terms of equivalent water height has been identified as 5 cm for monthly fields and 0.5 cm/year for long-term trends at a spatial resolution of 150 km. The benefits to meet the main scientific and societal objectives are investigated, and the added value is demonstrated for selected case studies covering the main fields of application. The resulting consolidated view on the required performance of a future sustained satellite gravity observing system represents a solid basis for the definition of technological and mission requirements, and is a prerequisite for mission design studies of future mission concepts and constellations.

Keywords Mass transport · Earth system science · Satellite gravimetry · Sustained observation · Climate change

1 Introduction

Global satellite gravity measurements provide unique information on mass distribution and mass transport processes in the Earth system, linked to changes and dynamic processes in continental hydrology, cryosphere, oceans, atmosphere, and solid Earth. Dedicated gravity missions such as CHAMP (Challenging Minisatellite Payload; Reigber et al. 2002), GRACE (Gravity Recovery And Climate Experiment; Tapley et al. 2004) and GOCE (Gravity field and Steady-State Ocean Circulation Explorer; Drinkwater et al. 2003) initiated a revolution in our understanding of near-surface mass transport processes. Spectacular science results and new insights into the Earth's subsystems, and their interaction, could be achieved.

The quantification of dynamic processes in the components of the Earth system and their coupling with each other provide an improved understanding of the global-state behavior of the Earth as well as direct and essential indicators of both subtle and dramatic global change. To separate human-induced from natural climate changes, a sustained observation of mass transport at fine scales for long periods is mandatory. A future satellite gravity observing system operating at even finer scales than the first generation gravity satellites is expected to realize a similarly dramatic advancement in application capabilities and scientific discoveries. Therefore, it is important to address mission concepts beyond those of the GRACE Follow-On (GRACE-FO) mission (Watkins et al. 2015) which is scheduled for launch in 2017, and to move from demonstration capabilities to sustained observations with improved accuracy and resolution while continuing the medium-scale heritage from GRACE and GRACE-FO.

Science needs and mission goals have been already addressed in several previous studies, such as two studies on the "Assessment of a Next Generation Mission for Monitoring the Variations of Earth's Gravity" funded by the European Space Agency (ESA), which were performed in parallel by two independent study teams (ESA 2010 [NGGM]; ESA 2011 [NG2]), and the mission proposal "e.motion—Earth System Mass Transport Mission" (Panet et al. 2013) submitted to the ESA Earth Explorer 8 call. A German national preparatory study for a future gravity field mission constellation funded by the

German Aerospace Center (DLR) was performed in preparation of the upcoming ESA call for an Earth Explorer 9 mission as a joint effort of science and industry (Gruber et al. 2014 [NGGM-D]).

These and other studies have resulted in quite different science requirements for future gravity mission concepts. Figure 1 shows a summary of the science requirements defined in these studies for the thematic fields hydrology, ocean, sea level (SL), ice mass balance (IMB) and glacial isostatic adjustment (GIA). It illustrates the signal amplitude in terms of equivalent water height (EWH) to be captured, in dependence of the spatial resolution. The EWH expresses the height of a mass-equivalent column of water per unit area. At this point it should be mentioned that it is difficult to directly compare the numbers of these different studies, because of different underlying assumptions and different interpretation of the phenomena especially regarding temporal scales, which makes the picture even more blurred.

In order to obtain a more consolidated view on these requirements, in a joint initiative of the International Union of Geodesy and Geophysics (IUGG), the Global Geodetic Observing System (GGOS) Working Group on Satellite Missions, and the International Association of Geodesy (IAG) (Sub-Commissions 2.3 and 2.6), all relevant scientific and user communities' needs have been collected, and consensus on the expected and desired performance of a future satellite gravity field observation system has been achieved by a representative panel of about 70 international experts covering the main fields of application of satellite gravimetry. They are representatives of five member associations of IUGG: International Association of Hydrological Sciences (IAHS), International Association for the Physical Sciences of the Oceans (IAPSO), International Association of Cryospheric Sciences (IACS), International Association of Seismology and Physics of the Earth's Interior (IASPEI), and International Association of Geodesy (IAG), with additional

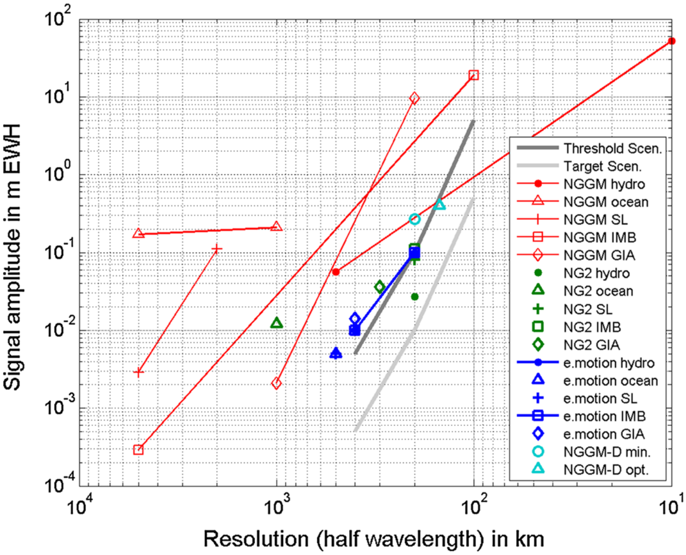

Fig. 1 Science requirements derived in previous studies for individual fields of applications: NGGM (ESA 2010; *red*), NG2 (ESA 2011; *green*), e.motion (Panet et al. 2013; *blue*), NGGM-D (Gruber et al. 2014; *cyan*). *The light* and *dark gray curves* show two scenarios for the consolidated requirements derived in this study; *SL* sea level, *IMB* ice mass balance, *GIA* glacial isostatic adjustment

contributions by the International Association of Meteorology and Atmospheric Sciences (IAMAS).

The aim of this paper is to summarize the findings of this expert assessment initiative. In Sect. 2, the achievements and limitations of current gravity field missions are briefly reviewed. Based on the current situation, in Sect. 3 the still pending scientific and societal questions and challenges and their relation to gravity field observation from space are discussed. In Sect. 4, the main target signals and their spatial and temporal scales are addressed. Section 5 presents the definition of consolidated science and user needs for a sustained gravity field observation infrastructure, and how the corresponding scenarios would contribute to meet the main scientific and societal objectives. In Sect. 6, the benefit of mission scenarios derived in Sect. 5 is discussed specifically for the main fields of application, and the added value is demonstrated for selected case studies. Finally, in Sect. 7 conclusions are drawn and an outlook to future aspects is given.

On purpose, in this study we limited ourselves to the definition and consolidation of science and user needs, unbiased from potential trade-offs regarding mission requirements, technological readiness of the key satellite payload, or restrictions related to programmatic issues or cost efficiency. However, technical feasibility within the next decade was kept in mind when formulating the users' wish lists.

2 Achievements and Limitations of Current Gravity Field Missions

Spectacular science results have been achieved by the analysis of temporal variations of Earth's gravity field sensed by the GRACE mission. It has for the first time unequivocally shown that the large ice sheets of Greenland and Antarctica are losing mass and are contributing significantly to ongoing sea level rise. The mass loss of the ice sheets in the years from 2003 to 2010 is estimated to be of the order of 230 Gt/year in Greenland and 80 Gt/year in Antarctica (Shepherd et al. 2012). An acceleration of mass losses has been observed (e.g., Velicogna et al. 2014), although longer time series may be required to pinpoint the mechanisms causing this increase in mass loss (Wouters et al. 2013). GRACE has also significantly contributed to the assessment of mass changes of glaciers and ice caps, such as in Alaska, the Canadian Arctic, Patagonia and Himalaya (e.g., Gardner et al. 2013). It has also provided for the first time global observations of seasonal, inter-annual and long-term water storage variations for large- and medium-size hydrological catchments (e.g., Lettenmaier and Famiglietti 2006). This allows to impose innovative constraints on the estimation of water fluxes such as precipitation, evapotranspiration and river discharge, and supports the closure of the terrestrial water budget (Lorenz et al. 2014). GRACE also enables to investigate and monitor extreme hydrological events such as the spatio-temporal evolution of droughts and floods (Reager et al. 2014). Due to its sensitivity to otherwise hidden subsurface storage variations, a big achievement of GRACE is the detection of anthropogenic groundwater depletion, e.g., in Northern India (Tiwari et al. 2009) due to an excessive use of non-renewable freshwater resources. The mission has also lead to an improved understanding of global mean sea level rise (currently $\sim$3 mm/year; Willis et al. 2010), which is the sum of the thermic expansion due to temperature rise, and the mass component related to influx from melting ice sheets, glaciers, and continental hydrology. Since gravimetry is only sensitive to the latter one, these effects could be separated and the mass component could be quantified to be in the order of 2 mm per year (Ivins et al. 2013). Additionally, mass displacement in connection with large earthquakes such as the Sumatra (2004), Chile (2010), and Japan (2011) events could be measured (Han et al. 2013), which provides constraints for the physical modeling of earthquake mechanisms.

The even higher-resolution static gravity field determination from the GOCE mission (Pail et al. 2011; Brockmann et al. 2014) provided the equipotential surface of the geoid, which can be combined with sea surface height (SSH) from satellite altimetry to determine the mean dynamic ocean topography (MDT). The horizontal derivatives of the MDT are directly proportional to surface geostrophic currents, which can now be resolved over widths of <80–100 km (Bingham et al. 2011; Rio et al. 2014). Providing a global physical reference surface and thus a globally uniform level of zero height, the GOCE geoid can also significantly contribute to the global unification of height systems (Rummel 2013).

In spite of the great contributions by the first generation of satellite gravity missions, our current knowledge of mass transport and mass variations within the Earth system still has severe gaps. Due to a currently achievable resolution of only 200–500 km (depending on signal strength, time scale and geographical location) on a monthly basis, worldwide only about 10 % of the hydrological basins can be resolved (Longuevergne et al. 2010), and not even the largest individual outlet glacier drainage basins of ice sheets can be resolved (Luthcke et al. 2013). This limited spatial resolution also hampers the separation of different superimposed processes, thus leading to leakage problems and the misinterpretation of signals. As an example, current uncertainties in the knowledge of glacial isostatic adjustment (GIA), resulting from past deglaciation, overprint ice mass variations in Antarctica (Ivins et al. 2013) and are the largest error contribution when determining the Antarctic ice mass balance. For ocean applications, a higher spatial resolution and measurement accuracy is required to monitor the variability of the main processes driving ocean circulation, such as the Atlantic Meridional Overturning Circulation (AMOC; Bingham and Hughes 2009). Due to limited measurement accuracy, presently only the very strongest earthquakes with a magnitude >8.5 can be detected (Han et al. 2013). Many applications also suffer from the limited length of the currently available time series. More reliable separation of anthropogenic and naturally induced changes of the water cycle, ice mass melting and sea level rise on global to regional scales requires a sustained observation infrastructure. Natural processes like decadal fluctuation of Earth's global mean surface temperature obscure secular anthropogenic change in climate, and therefore make it difficult to predict. The currently too short time series prevents us from disentangling the effect of climate modes on global and regional sea level, which would need at least three decades of observations (Wouters et al. 2013). Limited temporal and spatial resolution together with rather long product latencies hamper the use of satellite gravity products for near real-time applications and services.

3 Scientific and Societal Questions and Challenges and Their Relation to Gravity Field Signals

Based on the inventory of achievements and limitations of the current gravity field observation infrastructure in Sect. 2, the still pending scientific and societal questions and challenges and their relation to gravity field observation from space shall be addressed and discussed here. The central focus for space gravimetry missions is to gain an improved understanding of the global-state behavior of the Earth and the coupling between dynamic processes of the main components of the Earth system. Since these processes, many of them already addressed in Sect. 2, indicate a change in forcing or of feedback loops, they can be considered as a proxy and indicator for natural or anthropogenic climate change. In this respect, satellite gravimetry is a unique measurement technique that is directly sensitive to distributed mass and mass change in the Earth system and is complementary to geometrical techniques such as precise positioning with global navigation satellite systems (GNSS), remote sensing or satellite altimetry.

Currently, changes in the Earth system are usually investigated and modeled on the level of individual subsystems, without fully taking into account the global, large-scale coupling with other subsystems, feedback loops and the input/output balance, thus neglecting mass conservation in the total system. Therefore, *consistency of the global mass balance* is a key scientific challenge to obtain a consistent picture of the Earth system and its changes.

Most of the mass redistribution processes are related to the global water cycle, by which the ocean, atmosphere, land, and cryosphere storages of water interact through temporal and spatial water mass variations, at time scales ranging from daily to decadal periods. The understanding of the dynamics and the variations of the global water cycle requires the *closing of the water balance*, i.e., the variation of water mass input, output and storage in time and space, and a solid understanding of all *processes governing the water exchange between all subsystems*. Today, many of these processes are still poorly understood, which is also due to the fact that they are hardly accessible through direct measurements. For example, almost no direct observational techniques for evapotranspiration (Long et al. 2014) and for storage changes in groundwater and deep aquifers exist for large areas (Feng et al. 2013; Joodaki et al. 2014). Also, other water flux terms of the continental water budget (precipitation, run-off) have been provided with large uncertainties only (Sheffield et al. 2009). It has been difficult if not impossible to validate global hydrological models until space gravimetry data became available (Güntner 2008; Grippa et al. 2011). Time-lapse gravity observations are an integral measure of water storage changes. These observations have the potential to close the terrestrial water budget, and they serve as an important constraint to evaluate and complement observed and modeled fluxes, provided that they are available with sufficiently high temporal and spatial resolution. As already addressed in Sect. 2, currently the size of many river basins is smaller than the spatial resolution of satellite gravimetry. However, the societal relevance of closing the terrestrial water balance and of observing changes in the water storage lies in providing sound information on changing freshwater supply for human consumption, for agriculture and industry, facing the challenge of steadily growing demands that are anticipated for the future (Famiglietti and Rodell 2013). Thus, gravity data may provide, in combination with existing observations systems (Alley and Konikow 2015), a basis for developing sustainable *water resource management strategies*, including near real-time observations for the monitoring and prediction of extreme hydrological events such as floods and droughts.

Knowledge on the state of continental ice masses and the processes of past and present *evolution of ice sheets and glaciers* is also key for the understanding of the Earth and climate system, because they represent very sensitive indicators of climate change. In contrast to geometrical observation methods, satellite gravimetry is relatively little affected by problems of incomplete sampling and avoids the inherent difficulty of making the conversion from ice volume to mass, as is required when working with elevation changes from, e.g., satellite altimetry. As already discussed in Sect. 2, the shortness of available time series still makes it difficult to separate anthropogenic effects from natural long-term variability, and due to their limited spatial resolution, current GRACE observation capabilities are restricted to larger aggregations of catchments. Consequently, the current understanding of cryospheric mass balance and coupling processes, such as the dynamic response of ice flow to changing oceanic and atmospheric boundary conditions and interactions with subglacial hydrology, remains limited.

Interaction of continental hydrology and cryosphere with the ocean results in changes in the *mean sea level*, as the sum of mass in (out) flux and a thermosteric component. With the help of gravity observations, a separation between these two components can be achieved on global to regional level, and the individual contributions can be quantified (Chambers et al. 2010; Willis et al. 2010; Leuliette and Willis 2011; Boening et al. 2012). The monitoring and prediction of sea level change has an important societal impact to address coastal vulnerability and for the mitigation and adaptation of global coastal industrial infrastructure (Nicholls and Cazenave 2010). Additionally, in combination with complementary data sources, surface and deep ocean circulation, the latter being an essential but hidden part of the climate system, can be quantified, and thus we have the possibility to greatly improve models of the energy transport in the oceans, atmosphere and land hydrosphere (Hughes and Legrand 2005). *Closing the sea level budget* still poses a great challenge due to the fact that complementary observations of dissimilar temporal and spatial character and of entirely differing sampling, error budgets and bias corrections must be dealt with.

The *solid Earth* experiences *mass variability associated with its deformation*. The associated time scales vary: viscous deformations are rather slow processes, while much faster deformations occur, when the solid Earth responds to external fluid forcing or in the case of a great earthquake. GIA is due to long-term viscoelastic rebound of the solid Earth and results in variations of the relative sea level. Thus it is an important example for the coupling of solid Earth with cryosphere and oceans. Together with this viscoelastic deformation, the elastic response of the Earth due to loading effects related to changing surface water, ice and atmospheric masses as well as the co- and post-seismic solid Earth deformation hold important information about the Earth's rheology. In the gravimetry observations, solid Earth mass variations are superimposed on those that are fluid in nature. Consequently, this mixing of signals, part of which have a solid Earth origin, requires careful treatment. This is especially true when trying to interpret climate trend signals, which must be separated from the trend signals related to GIA and tectonic uplift. Accurate model representation of the solid Earth signal can be crucial for deriving precise estimates of continental water and cryospheric mass balance and sea level changes. In the future, it also might be possible to detect mass change signals due to plate tectonics, rising mantle plumes, dynamical processes in the mantle and core motions, which are currently too small to be observed. Finally, in addition to the mitigation of natural hazards and an improved understanding of geophysical processes, also the *exploration* and evolution *of natural resources*, such as minerals, hydrocarbons or geothermal energy, pose a great challenge with a high societal relevance.

Due to its coupling with many other Earth subsystems, the atmosphere will move into the focus of gravity field research much more strongly than is currently the case. Atmosphere models are currently used in gravity field processing as external information, mainly for reducing short-period mass variations with periods which cannot be temporally resolved by current satellite gravity mission. Correspondingly, errors in these atmospheric models cause temporal aliasing effects such as the typical GRACE striping errors in the gravity field. However, as gravity missions measure the sum of all masses/mass variations, they also sense atmospheric signals. With a higher temporal resolution and accuracy of a future gravity field mission, atmospheric parameters derived from gravity field satellites could be fed into atmospheric models, thus helping to improve the model quality in an iterative feedback loop. Additionally, in contrast to standard GRACE processing approaches currently it is attempted to avoid de-aliasing by reducing atmospheric (and ocean) signals as a pre-processing step, but rather to estimate the full time-variable signal with high temporal resolution, which also contains atmospheric mass variations. By this, a future gravity field mission constellation could set the grounds for a new and strongly improved processing logic. The potential and added value for atmospheric modeling and the impact on medium-term weather forecast and climate modeling still needs to be assessed.

Combined observations and their uncertainties have to be assimilated and consistently integrated into physical process models, because the physical understanding of processes forms the basis to facilitate reliable predictions. The assimilation of bottom pressure data into ocean models, for example, can improve the determination of the oceanic circulation (Saynisch et al. 2015), and assimilation of water storage changes into hydrological and land surface models helps to better represent water flow processes and the exchange among storage compartments as well as to disaggregate the integral gravity observations (Li et al. 2012). For satellite gravimetry data this will remain a challenging task, as the gap in spatial resolution between model increments and observations is huge (Eicker et al. 2014) and the short length of the GRACE time series prevents a reasonable constraint of long-term changes. To enable the analysis of complex coupling and feedback processes between subsystems, it will be beneficial to assimilate future satellite gravity data with enhanced spatial resolution and long time series into fully coupled land surface/ocean/atmosphere

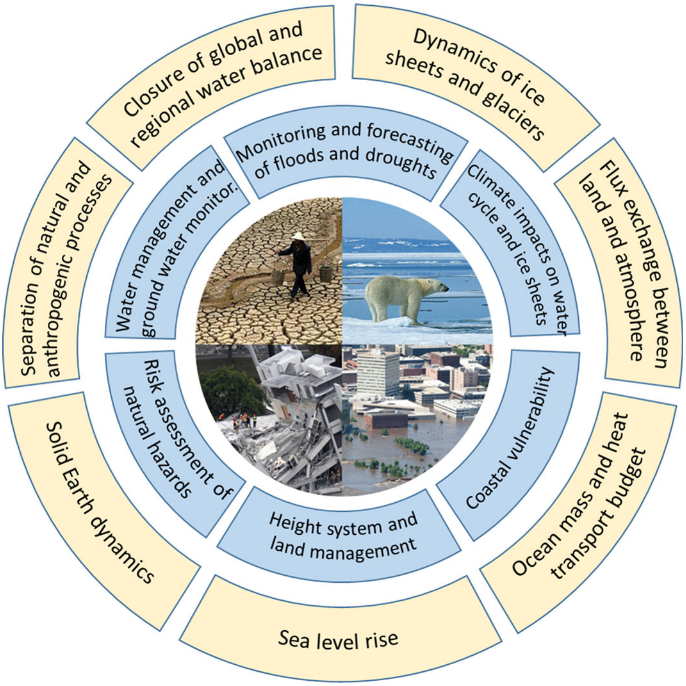

Fig. 2 Main scientific (*yellow*) and societal (*blue*) challenges addressed by a future satellite gravity constellation

Table 1 Spatial and temporal scales associated with gravity changes relevant to investigations in continental hydrology, cryosphere and ocean applications

Signal	Time scales	Expected signals: temporal variation in equivalent water height (EWH)	Spatial scale
Continental hydrology			
Groundwater storage	Years to secular	Up to ~2–4 cm/year on large scales, a few cm more on smaller scales	A few 10 km to ~1000 km
	Monthly to (inter-)annual	Up to 10–20 cm on larger scales, up to 30–40 cm on smaller scales of a few 10 km	Same as above
Surface water storage	Decades to secular	Up to 0.5 m/year on large scales (a few 100 km), up to 1 m/year on smaller scales (a few km)	A few meters up to a few hundred km
	Monthly to (inter-)annual	Up to ~10 m, on different scales	Same as above
	Daily to monthly	Up to a few meters	Same as above
Soil moisture	Monthly to (inter-)annual	Up to ~40 cm	A few km up to a few 100 km
	Hourly to daily	Linked to precipitation and evapotranspiration (see below)	A few km up to a few 100 km
Snow water equivalent	Years to secular	Up to 1 cm/year	A few 10 km to a few 100 km
	Daily to annual	Up to several m on small scales, up to ~50 cm on scales of a few 100 km	A few meters up to several 100 of km
Precipitation	Hourly to daily	Up 1 m on small scales, up to a few 10 cm on larger scales	A few km to >100 km
Evapotranspiration	Hourly to daily	Up to a few cm	A few 100 m to a few 100 km
Cryosphere			
Changing ice flow dynamics of ice sheets	Long-term	10 m/year 10 cm/year	10 km 500 km
	Monthly to interannual	10 m 10 cm	10 km 500 km
	Daily to weekly	10 m	10 km
Changing SMB of ice sheets	Long-term	2 m/year 20 cm/year	50 km 1000 km
	Seasonal and interannual	2 m 20 cm	50 km 1000 km
	Daily to weekly	1 m 20 cm	10 km 1000 km
Supraglacial, englacial, and subglacial hydrology of ice sheets	Seasonal and interannual	5 m 50 cm	10 km 200 km
	Daily to weekly	10 m	10 km

Table 1 continued

Signal	Time scales	Expected signals: temporal variation in equivalent water height (EWH)	Spatial scale
Glacier mass changes	Long-term	10 m/year 1 m/year	10 km 200 km
	Monthly to interannual	10 m 1 m	10 km 200 km
	Daily to weekly	1 m 10 cm	10 km 50 km
GIA (as a disturbing signal for ice mass balance estimates)	Long-term	5 cm/year 1 cm/year	100 km 1000 km
Oceans			
Mass input (global)	Secular	1 mm/year	Global
	Interannual	1 mm (with peak-to peak variations of ∼5 mm)	
	Seasonal	10 mm	
Basin-scale ocean dynamics/heat content changes	Secular	1 mm/year	O(1000–10,000) km
	Interannual	few mm	
	Seasonal	5 mm	
Regional-scale ocean dynamics/heat content changes	Secular	∼3 mm/year	O(100–1000) km
	Interannual	5 mm, locally up to 15 mm	
	Seasonal	10–50 mm with local peaks up to 20 cm	
Boundary processes (incl. meridional overturning circulation)	Decadal	1–20 mm	20–200 km
Ocean tides	Hours to years	0–5000 mm	O(100–1000) km

models with the long-term aim to feed an Earth system model directly with mass change observations rather than to extract each contributing source as is done today.

There are also geodetic applications such as the global unification of height systems, with major impact on land management applications especially in developing countries. Currently, globally more than 100 national and regional height systems exist, which refer to a local datum realized by a single tide gauge measuring the local mean sea level. This situation constitutes a significant problem for many across-border engineering projects. Currently, one of the main problems is the spectral limitation of satellite gravity field missions, resulting in omission errors, i.e., non-resolved gravity signals, which can amount to high-frequency geoid height signals of several decimeters in mountainous regions. A future satellite gravity constellations will be able to reduce the omission error to only a few centimeters, even in regions where no or only low-quality terrestrial gravity data are available, and on top could provide also temporal changes in the geoid and correspondingly of heights. This is particularly important in regions with strong gravity trends, e.g., due to GIA signals, and contributes to a correct description of regional relative sea level changes.

Table 2 Spatial and temporal scales associated with gravity changes relevant to solid Earth investigations

Signals	Time scales	Expected signals: temporal variation in geoid, or gravity	Spatial scale
Solid Earth			
Earthquakes (Mw 7–9) Coseismic	Instantaneous	0.1–1 mm geoid or 5 μGal Geoid amplitude decrease by >10 times when Mw reduced by 1	Mw 9:>300 km Mw 8: 200–300 km Mw 7: 60–130 km
Earthquakes (Mw 7–9) post-seismic	Up to decades	0.01 to 0.1 mm geoid change/year or 1 μGal/year	Same as above
Slow and silent earthquakes	Up to years Possibly periodic	Can be equivalent to a Mw 6–7 earthquake	~100–200 km
Glacial isostatic adjustment	Decades up to secular	1 mm/year geoid	From global to tens of km
Mantle convection and global scale plate tectonics	Secular	Sinking slabs: 0.005 mm/year	1000 km
Mid-ocean ridges	Secular	0.5 mGal/year	Few 10 km
Regional plate tectonics, mountain building, crustal thickening at a rate 0.1–2 cm/year	Decades to secular	2 μGal/year	10 km to few 100 km
Subsidence or emergence of volcanic islands; fast movements in volcanic regions	Decades to secular, also higher rates possible	0.1–1 μGal/year	Local: few km to few 10 km
Core motions, magnetic pressure at the CMB	Years	100 nGal (large uncertainty exists)	Large-scale
Slichter mode, FCN, FICN	Hours	1 nGal	Large-scale
Seismic normal modes	<1 h	1 nGal	Large-scale

FCN free core nutation, *FICN* free inner core nutation, *CMB* core-mantle boundary

Beyond scientific questions, a stronger commitment to turn satellite gravimetry into an observation system would enable us to include gravimetric data sets into operational modeling and forecasting systems. Ensuring short latencies of data availability, significant contributions to applications of water management, short-term prediction and operational forecasting of floods and droughts, risk management and disaster mitigation related to natural hazards, and monitoring changes of a globally unified height reference surface for land management applications will serve important societal needs. Understanding the dynamics of coastal sea level variability will support medium-term forecasting of coastal vulnerability, and understanding the climate forcing on continental hydrology, cryosphere, ocean and atmosphere will enable significant contributions to near-future climate predictions.

Figure 2 summarizes the main scientific (yellow) and societal (blue) challenges that should be tackled by such a future sustained gravity observing system.

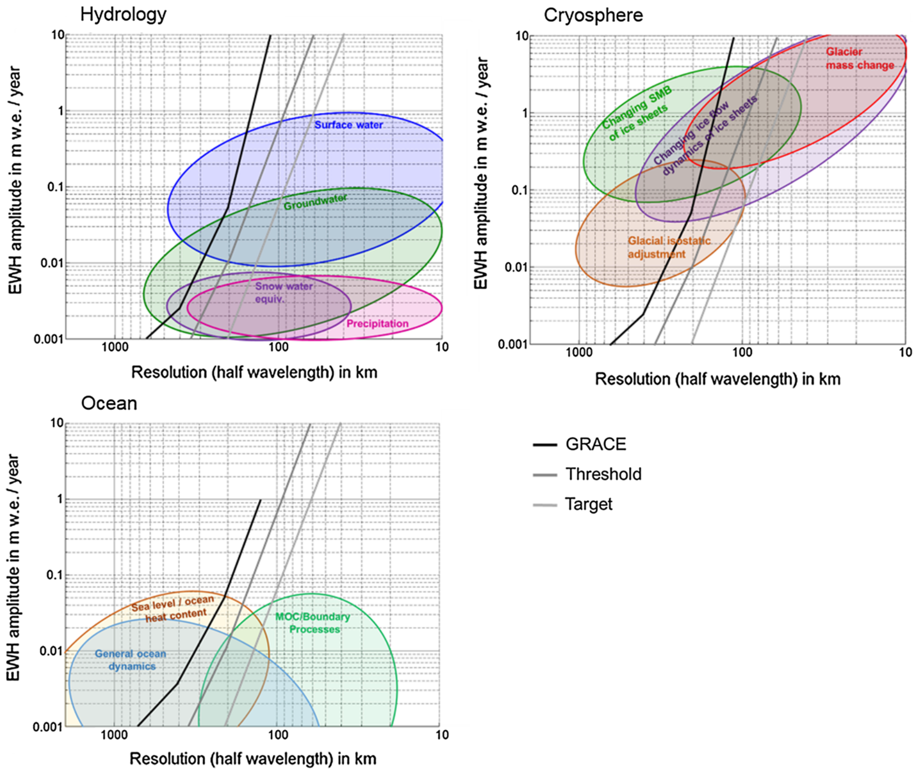

Fig. 3 Target long-term signals of continental hydrology (*upper left*), cryosphere (*upper right*) and ocean (*lower left*)

4 Target Signals and Their Spatial and Temporal Resolution

In four fields of applications of mass transport observations, the main target signals and the related spatial and temporal scales have been discussed within and among the expert panels, and the corresponding values have been identified and agreed upon. Table 1 provides the results for the themes continental hydrology, cryosphere and ocean. The expected signals are given in EWH. Table 2 shows the results for solid Earth applications. The amplitude measure in this case are either geoid heights, which are the deviations of the physical equipotential surface of the geoid from a reference ellipsoid, or gravity anomalies in mGal (=1 × 10^{-5} m/s^2), μGal (=1 × 10^{-8} m/s^2) or nGal (=1 × 10^{-11} m/s^2).

Figures 3, 4, 5 and 6 visualize the amplitudes of these target signals in dependence of the spatial wavelength by bubble plot graphics. Figures 3 and 4 show signals of continental hydrology, cryosphere and ocean in terms of EWH for various temporal scales: trend and long-term signals are provided in Fig. 3, and monthly to interannual signals in Fig. 4. For the themes hydrology and cryosphere, also bubble plots for short-term signals (daily to weekly) are provided in Fig. 5. Corresponding bubble plots for solid Earth applications (in terms of μGal instead of EWH) are shown for quasi-static and long-term variation signals

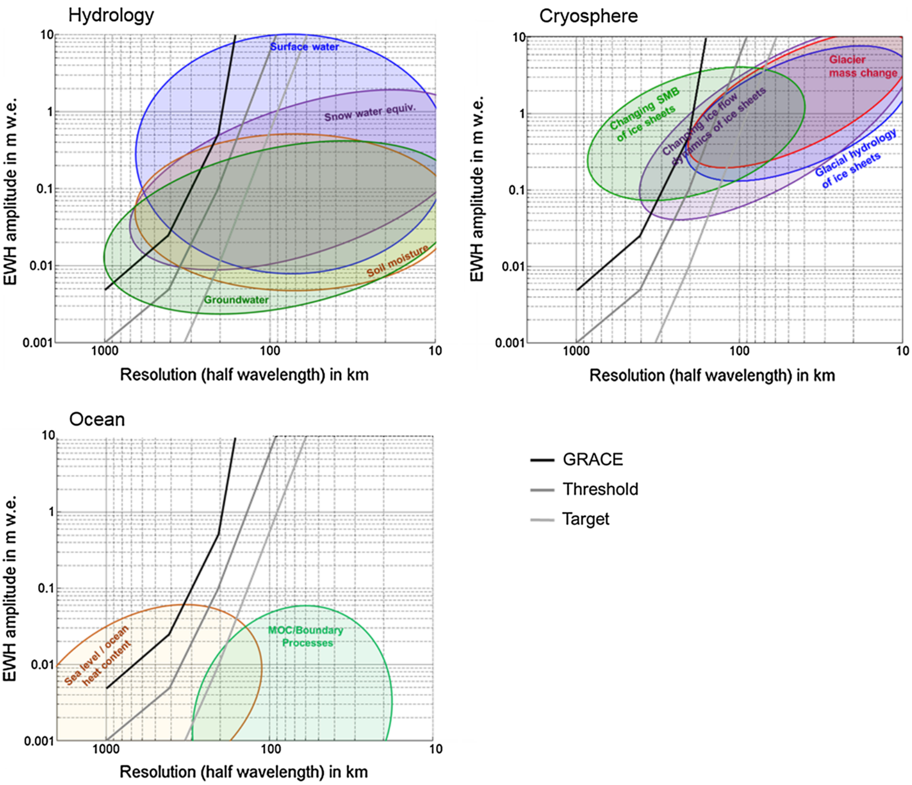

Fig. 4 Target monthly to interannual signals of continental hydrology (*upper left*), cryosphere (*upper right*) and ocean (*lower left*)

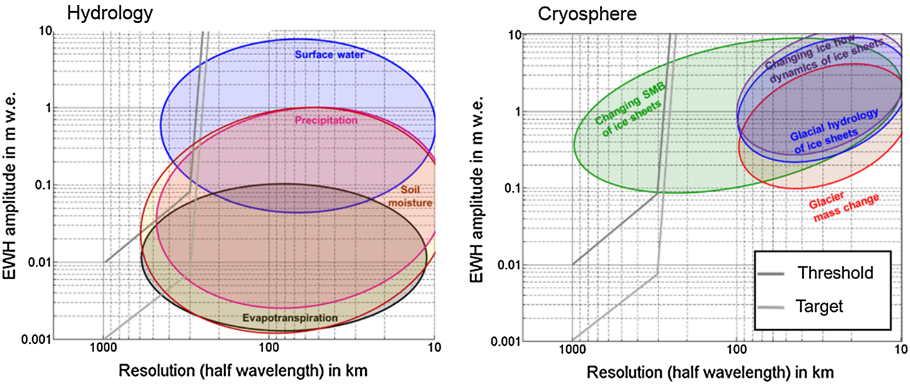

Fig. 5 Target short-term (daily to weekly) signals of continental hydrology (*left*), cryosphere (*right*)

in Fig. 6. Although not quasi-static, co-seismic signals have been added in the respective figure as well. These amplitudes are compared with the currently achievable performance of GRACE (black), as well as future mission threshold (dark gray) and target (light gray) scenarios as defined in Sect. 5.

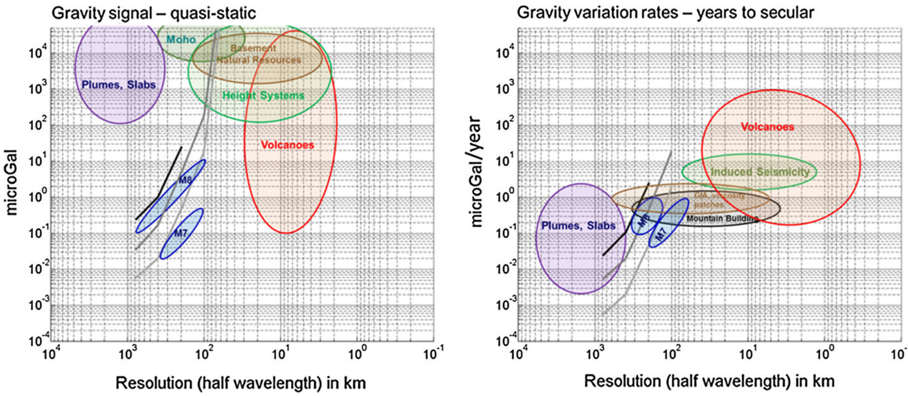

Fig. 6 Target solid Earth signals: quasi-static (*left*) including co-seismic signals, and long-term, years to secular (*right*) signals

5 Consolidated Science and User Needs

Based on the science and user requirements derived by the individual thematic fields, joint requirements for a future satellite gravity observation system have been derived. Naturally, the individual requirements differ in the various fields and even among different applications within one field. Therefore, the following joint requirements shall be interpreted as a compromise for a mission configuration which is able to cover a wide range of applications, but which could be optimized further for a specific discipline.

In general, from a purely scientific point of view the conclusion in all four fields (hydrology, cryosphere, oceans, solid Earth) is that, apart from the extension of the currently available time series of global gravity measurements, an increase in spatial resolution is given priority over an increase in temporal resolution. Therefore, the joint product needs first are given as performance numbers of monthly fields. The performance of submonthly down to daily resolution is derived from the monthly scenarios, because they can be simultaneously realized through mission design by appropriate choice of subcycles, or additional satellite pairs.

A future mission is on the one hand driven by science needs and novel science opportunities, but must on the other hand also serve a significant number of applications with societal benefit. Therefore, gravity field products on short time scales of 1 to a few days and their availability with short latencies are also needed.

In the following, the consolidated science and user needs are given as threshold and target requirements using the following definition:

- A mission that meets the *threshold requirements* enable us to achieve a significant improvement with respect to the current situation and to perform a significant number of new applications, which clearly justifies the realization of such a mission.
- A mission that meets the *target requirements* means a significant leap forward and enable us to address completely new scientific and societal questions.

Table 3 Performance numbers of the Threshold Scenario of a future satellite gravity observing system

Spatial resolution (km)	Equivalent water height		Geoid	
	Monthly field	Long-term trend	Monthly field	Long-term trend
400	5 mm	0.5 mm/year	50 µm	5 µm/year
200	10 cm	1 cm/year	0.5 mm	0.05 mm/year
150	50 cm	5 cm/year	1 mm	0.1 mm/year
100	5 m	0.5 m/year	10 mm	1 mm/year

5.1 Threshold Requirements

Table 3 provides the threshold values for a future satellite gravity mission constellation. For the sake of lucidity, the numbers are given only as equivalent water heights and geoid heights. The respective numbers for other gravity field functionals can be derived from Appendix 1.

Roughly speaking, this scenario is an improvement with respect to the current GRACE performance by approximately a factor of 5, cf. also Figs. 3, 4 and 6. The resolution of daily to weekly signals, as shown in Fig. 5, is hardly feasible with GRACE without additional prior information; therefore, GRACE has been omitted in Fig. 5.

In combination with GRACE and GRACE-FO, such a scenario would provide an extension of the available time series to about three decades, which would result in a more reliable estimate of trends as well as an improved potential to separate anthropogenic from natural effects. The improved spatial resolution would improve the ability of disentangling different sources, and the improved temporal resolution would support the reduction of temporal aliasing effects.

Referring to the scientific and societal challenges identified in Fig. 2, Table 4 summarizes the benefits of a mission with such a specification (not exhaustive).

5.2 Target Requirements

The target values for a future satellite gravity mission constellation are provided in Table 5.

With such a mission scenario, the scientific and societal benefits summarized in Table 6 can be achieved (not exhaustive).

The Target Scenario represents an improvement by a factor of 10 compared to the Threshold Scenario. As is demonstrated by Table 6, it represents a leap forward regarding a significantly increased spatial and temporal resolution, as well as measurement accuracy, and thus opens many new applications with scientific and societal benefit. The increased temporal resolution will help to significantly reduce temporal aliasing, because short-periodic signals which currently are aliasing into the gravity field solutions can be directly measured and parameterized, thus avoiding large parts of the aliasing effect. The increased spatial resolution will significantly improve the resolvability of small-scale hydrological and drainage basins, and the separation of superimposed gravity signals.

In Fig. 1 the requirements related to the Threshold Scenario (dark gray) and Target Scenario (light gray) are compared with the requirements derived from previous studies. The main added value of the new definition is the fact that the performance numbers of the present study have been consolidated in an internationally coordinated process by a broad multi- and interdisciplinary expert panel. Figure 1 shows that the Threshold Scenario fits

Table 4 Scientific and societal challenges addressed by the Threshold Scenario

Scientific challenges	
Closure of global and regional water balances	Water storage in medium-scale river basins
	Derivation of long-term storage trends
	Understanding climate change impacts on the water cycle
	Assessing the human impact on the water cycle
Dynamics of ice sheets and glaciers	Mass balance of major ice sheet drainage basins in Greenland and Antarctica and of large glacier clusters
	Cryosphere contribution to global and regional sea level
Flux exchange between land and atmosphere	Determination of atmospheric mass variations
	In-situ observation of atmospheric density as input to atmospheric models
Ocean mass and heat transport budget	Improved determination of Mean Dynamic Topography
	Improved determination of ocean bottom pressure and deep ocean flow, in particular AMOC
Sea level rise	Global to regional sea level estimates
	Improved separation of mass and steric contributions to sea level
Solid Earth dynamics	Monitoring the mass shifts due to earthquake events with magnitude $M \geq 7.8$ (about 1 event per year)
	Monitoring of large tectonic movements in restricted areas
	Monitoring of underground anthropogenically driven mass variations
Separation of natural and anthropogenic processes	Separation of anthropogenic and natural effects on large spatial scales
Societal challenges	
Water management and ground water monitoring	Significant contribution to applications of water management and ground water monitoring on medium to large scale
Monitoring and forecasting of floods and droughts	Early warning for extreme events, such as floods and droughts
Climate impact of water cycle and ice sheets	Contribution to separation of anthropogenic and natural effects on large spatial scales
	Contributions to near-future climate predictions
Coastal vulnerability	Global to regional sea level estimates
	Improved separation of mass and steric contributions to sea level
Height systems and land management	Monitoring of large- to medium-scale changes in global height reference surface
Risk assessment of natural hazards	Risk management related to natural hazards

quite well to the science requirements of the e.motion proposal and to some extent also the NG2 study (ESA 2010), while the Target Scenario is more ambitious.

6 Theme-Specific Requirements and Selected Examples of Added Value

In this section, the consensus scenarios as defined in Sect. 5 are evaluated for the four main application fields, and the benefit is demonstrated based on selected showcases.

Table 5 Performance numbers of the Target Scenario of a future satellite gravity observing system

Spatial resolution (km)	Equivalent water height		Geoid	
	Monthly field	Long-term trend	Monthly field	Long-term trend
400	0.5 mm	0.05 mm/year	5 μm	0.5 μm/year
200	1 cm	0.1 cm/year	0.05 mm	5 μm/year
150	5 cm	0.5 cm/year	0.1 mm	0.01 mm/year
100	0.5 m	0.05 m/year	1 mm	0.1 mm/year

6.1 Continental Hydrology

Apart from a pure extension of the time series, which will have already significant benefit by itself for capturing global change impact on the hydrological cycle, for large parts of the hydrological user community, the most important requirement for a future satellite gravity mission is an increase in spatial resolution. While the resolution and accuracy of the Threshold Scenario is seen as an additional benefit, the specifications provided by the Target Scenario will certainly mean a breakthrough for hydrological applications. Regarding the monitoring of water storage changes in smaller river basins and aquifers, Fig. 7 shows a histogram of worldwide hydrological (sub-)basin sizes exceeding a size of 25,000 km^2. If an accuracy of 1.5 cm EWH is taken as reference, this can be reached for approximately 550 km resolution with GRACE (see Fig. 4), corresponding to only about 10 % of the basins. The same accuracy can be achieved with the Threshold Scenario for a resolution of approximately 330 km, which covers almost 40 % of the (sub-)basins. By an increase in accuracy as specified by the Target Scenario, a large step toward the closure of the terrestrial water balance will be achieved, as according to Fig. 7, the Target Scenario allows the investigation of about 85 % of all worldwide river (sub-)basins.

Such an accuracy would be greatly beneficial for water budget analysis in small- to medium-size basins and aquifers, for signal separation and for data assimilation. For water management applications, an improved spatial resolution is a clear necessity to work at the scale of river basins and aquifer management. Including gravity data of such a high quality will significantly enhance the predictive capability of hydrological models, both on seasonal time scales and for inter-annual variations.

For the study of long-term effects and the separation of climatic from anthropogenic drivers, a time series length of at least 30 years is required for achieving accurate, reliable and unambiguous results. These long time series provided with a trend accuracy of 1 mm/year on scales of 200 km (as envisaged by the Target Scenario) will be sufficient to provide reliable estimates of groundwater depletion and the effects of permafrost thawing and glacier melt on the regional scale and, as a novel application, to distinguish the effect of land use change on water storage from other anthropogenically induced climate change impacts and from natural climate variability.

Even though improved spatial resolution is prioritized over temporal resolution by large parts of the user community, there is nevertheless considerable interest in high temporal resolution and near real-time applicability of gravity data with a temporal resolution and/or a latency of a few days, which is a prerequisite for early warning and risk management of extreme events, operational forecasting systems and short-term forecasting.

Table 6 Scientific and societal challenges addressed by the Target Scenario

Scientific challenges	
Closure of global and regional water balances	Closure of global water balance on scales down to 150–200 km
	Water storage in small river basins
	Separation of medium-scale drainage basins
	Derivation of long-term storage trends with high accuracy and reliability
	Assimilation of gravity into hydrological models
Dynamics of ice sheets and glaciers	Cryosphere mass balance at monthly to decadal time scales to understand climate forcing on ice sheets and glaciers
	Cryosphere contributions to global and regional sea level
	Determination of mass changes of individual ice sheet drainage basins, mountain glacier systems and ice caps, supporting their modeling and prediction
Flux exchange between land and atmosphere	Support atmospheric modeling by observing processes related to surface mass balance changes
Ocean mass and heat transport budget	Recovery of the AMOC, which plays a crucial role in the Earth's heat transport, and retrieval of interannual AMOC variations
	Monitoring regional variations of the Antarctic Circumpolar Current (ACC) strength and identification of individual fronts
	Potential to estimate barotropic component of ocean circulation
	Mass and heat exchange between upper and lower layers of ocean
Sea level rise	Regional sea level estimates
	Regional separation of mass and steric contributions to sea level to improve understanding of ocean–atmosphere heat fluxes
Solid Earth dynamics	Monitoring the mass shifts due to earthquake events with magnitude $M \geq 7.0$ (about 12 events per year)
	Signal separation of tectonic, GIA, hydrological and cryospheric effects due to reduction of leakage effects
Separation of natural and anthropogenic processes	Separation of anthropogenic and natural effects on regional scale
	Monitoring of underground anthropogenically driven mass variations
Societal challenges	
Water management and ground water monitoring	Significant contribution to applications of water management on regional scale
Monitoring and forecasting of floods and droughts	From long-term to short-term and operational forecasting of flood events
	Regional-scale forecasting and monitoring of droughts
	Observation of glacier and ice caps processes for hydrological and disaster mitigation applications (flooding, water storage, hydro power)
Climate impact of water cycle and ice sheets	Cryosphere mass balance at monthly to decadal time scales to understand climate forcing on ice sheets, glaciers and ice caps
	Contribution to separation of anthropogenic and natural effects on medium spatial scales
	Sustained contributions to near-future climate predictions
Coastal vulnerability	Understanding dynamics of coastal sea level variability and boundary processes, and medium-term forecasting
Height systems and land management	Improved estimation of global height reference surface
	Monitoring of changes in global height reference surface

Table 6 continued

Risk assessment of natural hazards	Monitoring of earthquakes with magnitude M > 7.0: understanding stress distribution and trends to assess risks
To natural hazards	Significant contributions to risk management related

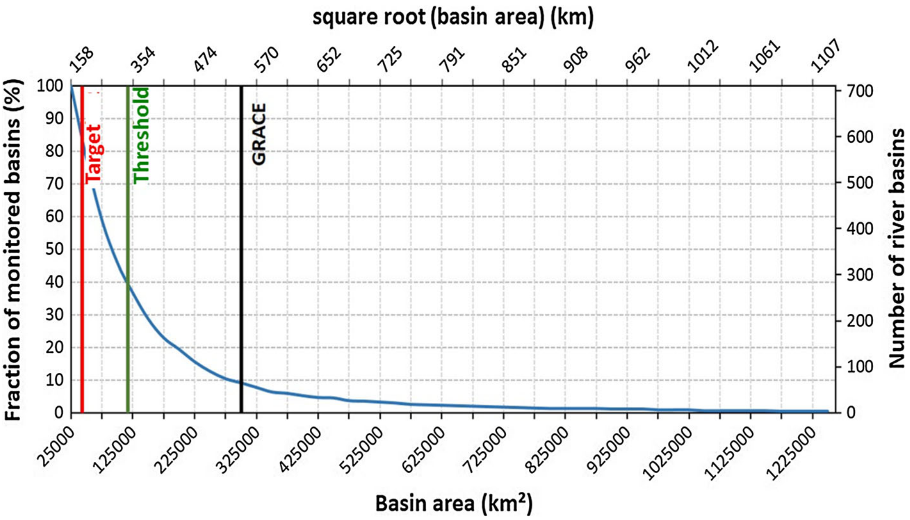

Fig. 7 Histogram of river basin sizes, based on a global watershed delineation (HydroBASINS; Lehner and Grill 2013; data are available at www.hydrosheds.org). For the histogram, all river basins and sub-basins worldwide exceeding a size of 25,000 km^2 according to the Pfaffstetter classification (Level 4) were selected. The black, green and red lines show the number of river basins that can be investigated by the mission scenarios when an accuracy of 1.5 cm EWH is required

6.2 Cryosphere

The most basic need of the cryospheric user community consists in the continuation of satellite gravity missions to reach the climatic time scales that are a demand for applications like the derivation of cryosphere mass balance time series at monthly to multi-decadal time scales to understand climate forcing on ice sheets, glaciers and ice caps, and the cryosphere contribution to global and regional sea level. As the second priority, they should have improved spatial resolution, or equivalently, less noise at small spatial scales. The third priority is an increased temporal resolution.

The increase in spatial resolution offered already by the Threshold Scenario would mean an essential step forward for cryospheric sciences. The leap in accuracy offered by the Target Scenario, as compared to the Threshold Scenario, would be a breakthrough for applications like the quantification of cryosphere contributions to global and regional sea level, the separation of GIA effects which is a prerequisite to understand feedbacks between ice mass change and regional sea level, the determination of mass changes of glaciers, technique combinations (using the complementarity of information from gravity and geometrical techniques such as satellite altimetry, remote sensing and GNSS) for the separation of individual processes, and supporting ice sheet modeling and prediction by the determination of mass changes of individual ice sheet drainage basins. It is worth mentioning that a satellite

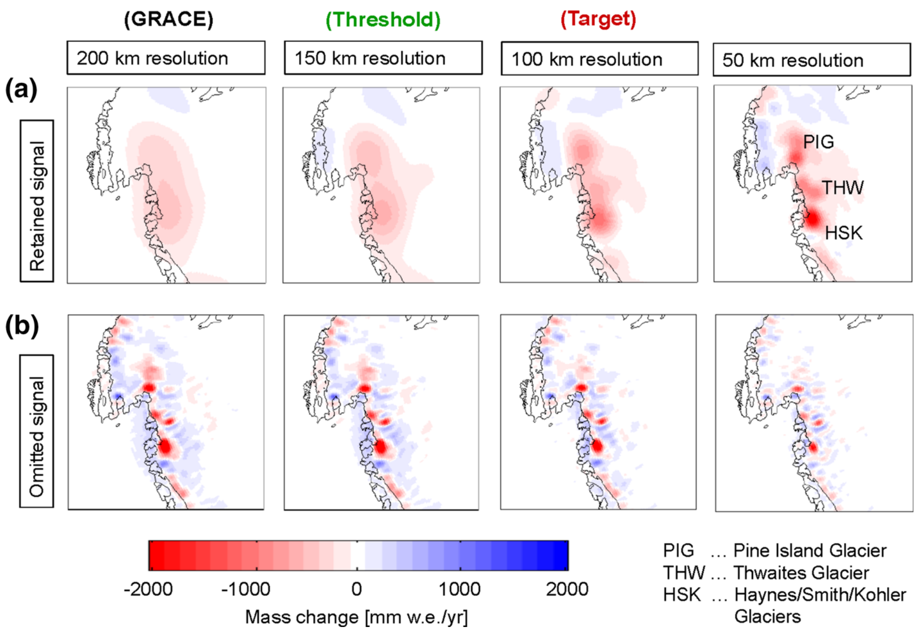

Fig. 8 Illustration of ice sheet mass change signal content and signal omission for different spatial resolutions. For this simulation, elevation trends from ICESat laser altimetry (Groh et al. 2014) are used as a proxy for the spatial patterns and spectral properties of the actual mass change signal. **a** Signal retained by different spatial resolutions for the example of the Amundsen Sea Sector of West Antarctica. **b** Signal omitted due to the respective resolution limits. The sum of (**a**) and (**b**) in each column gives the full signal. The first three columns illustrate the resolution at which the three scenarios “GRACE”, “Threshold” and “Target” may resolve long-term trends with a 5 cm EWH/yr accuracy. This accuracy level is taken as an example here

gravity mission concept involving near-polar orbiting satellites provides a better accuracy in polar regions than on a global average (e.g., better by a factor of two for GRACE).

Concerning the separability of ice sheet drainage basins, the glaciers in the Amundsen Sea Sector (Pine Island Glacier; Thwaites Glacier; and Haynes, Smith and Kohler Glacier system; see Fig. 8) are an important test case. The distance between the glacier trunks is about 150 km. Given the large amplitude of mass changes (of the order of 0.5 m EWH over 1 year on the 150 km scale), these basins may be separated by the Threshold Scenario at a 5 cm EWH/yr accuracy, while they cannot be separated by GRACE without the use of external information. An accuracy of the Target Scenario is required to allow a separation of the different drainage basin signals on a 5 cm EWH/year accuracy level on the 100 km scale.

6.3 Oceans

The main challenge in using satellite gravimetry for oceanographic purposes is the small amplitude of target signals. Therefore, an increase in accuracy and spatial resolution are regarded as top priority in the oceanographic user community. Regardless of the specific configuration of a future satellite gravity observation system, also oceanography will benefit from the extension of the gravimetric time series. This will allow a better understanding of the internal climate modes occurring in the ocean, such as the El Niño-

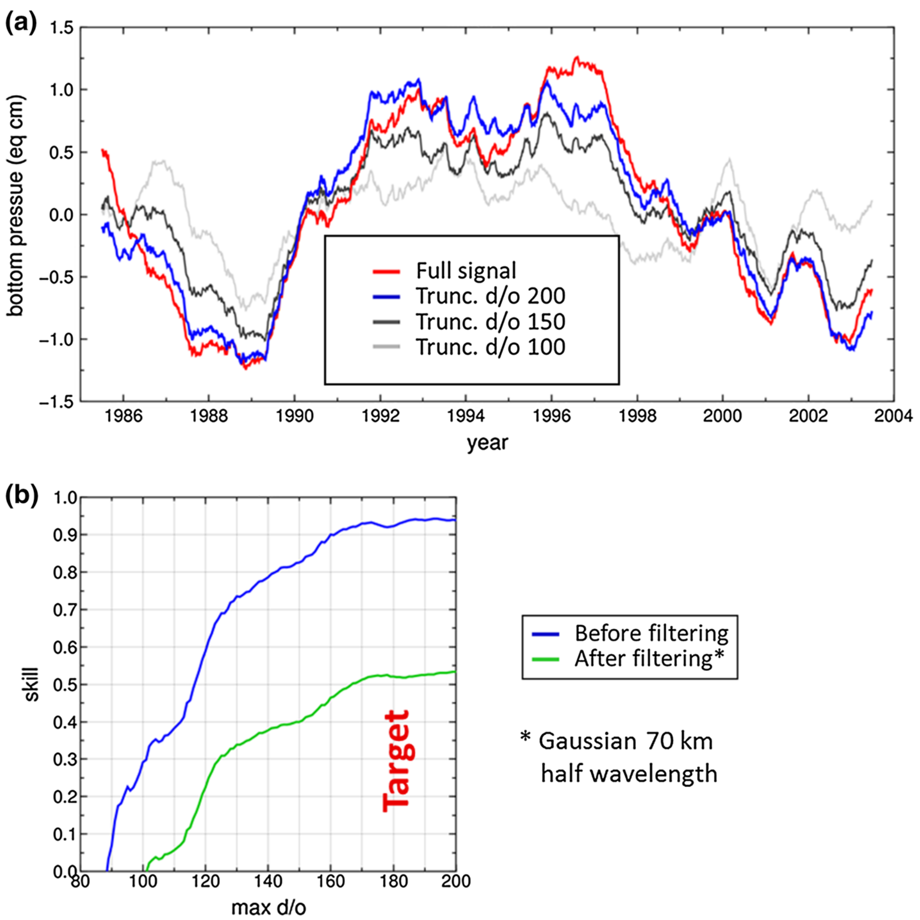

Fig. 9 **a** Interannual bottom pressure variations averaged over the lower (1300–3000 m) part of the western continental slope (in cm EWH; *red*). Reconstructions of the bottom pressure signal based on spherical harmonic expansions with maximum degree and order truncations of 200 (*blue*), 150 (*dark gray*) and 100 (*light gray*). **b** The skill of truncations as a function of maximum d/o without filtering (*blue*) and with a Gaussian filter with half-weight radius of 70 km (*green*)

Southern Oscillation, Pacific Decadal Oscillation and the North Atlantic Oscillation, and their role in re-distributing mass within the Earth system. In turn, this will lead to a better separation of anthropogenic and natural signals in global and regional sea level change.

The Threshold Scenario provides an overall improvement of the current oceanographic applications. The increased spatial resolution will narrow (but not close) the gap with altimetry observations (currently available at about 1/3 degree resolution), hence allowing a better separation of mass and steric contributions to sea level variability. By combining satellite gravity (mass), altimetry (total sea level) and Argo floats (upper ocean temperature and salinity), deep ocean heat content changes can be inferred. Since the coarse distribution of the Argo floats is the limiting factor with respect to the spatial resolution of these deep ocean heat estimates, the main benefit will come from the higher accuracy, which is especially important here since three different observations are differenced. Ocean circulation models, and likewise coupled climate models, will benefit from the increased spatial resolution and lower noise in the gravity data used in the assimilation process. Similarly, near-future climate projections are expected to gain skill from the improved quality of the data used in the initialization of the models.

The Target Scenario has the potential to recover variations in the AMOC, which would transform our ability to study and monitor the ocean using satellite gravity missions. A model simulation was performed to examine more closely which specifications physical oceanographers would require from a satellite gravity observation infrastructure to monitor the AMOC. This simulation was performed using bottom pressure determined from an Ocean Circulation and Climate Advanced Modeling (OCCAM) project model run (Saunders et al. 1999). The model output was supplied as 5 day means from which bottom pressure and the AMOC were calculated. Here we focus on the western boundary pressure signal on the lower (1300–3000 m) part of the continental slope. This is associated with deep return flow of the AMOC and may correspond to fluctuations in the deep western boundary current.

Figure 9a (red) shows the western boundary pressure signal averaged over the lower 1300–3000 m part of the continental slope which has a lateral extent of approximately 80 km. This represents the signal to be recovered. In order to evaluate which spatial resolution is required to resolve the signal, it is truncated at different degrees of resolution. Figure 9a (blue) shows the bottom pressure time series recovered for a spherical harmonic degree and order (d/o) of 200, corresponding to spatial scales of 100 km or greater. The true signal is well reproduced, accounting for 95 % of the total variance. Figure 9b (blue) demonstrates that, as expected, the skill (percent of variance accounted for) declines as the d/o at which the spherical harmonic expansion is truncated, is reduced. Figure 9a provides examples of the estimated time series with truncation at d/o = 150 (133 km; dark gray), where the skill is reduced to 80 %, and at d/o = 100 (200 km; light gray), where the skill is reduced to only 30 %. Figure 9b shows that the skill of the estimated signal falls below 50 % and can therefore be considered effectively useless, for truncations less than d/o = 120. The Target Scenario to recover AMOC variability is derived from this “perfect-world” analysis.

However, since the observations will contain a certain amount of noise, some form of filtering will be necessary, in the process attenuating the signal, and thereby reducing the ability to accurately estimate AMOC variability. Figure 9b (green) shows the impact of a Gaussian filter with a half-width radius of 70 km. A skill score of 50 % is only just achieved. With a half-weight radius any greater than 70 km the skill falls below 50 %, effectively destroying the ability to recover AMOC variability. This result is not surprising given the ambitious goal of extracting bottom pressure variations with a lateral extent of only approximately 80 km. However, with the development of more sophisticated filtering techniques, combined with noise reduction through temporal averaging, it may be possible to recover inter-annual AMOC variations within the performance of the Target Scenario.

The high resolution and accuracy of the observations of the Target Scenario would also allow several other high-impact oceanographic objectives to be achieved. Coastal sea level variability and boundary processes would be observed at an unprecedented resolution, giving a better insight in the dynamics governing these processes. Similarly, while current altimetry and gravity observations allow the surface fronts and geostrophic velocities of the Antarctic Circumpolar Current (ACC) to be measured, the Target Scenario offers the opportunity to study, in combination with other data sources, the full depth structure of the ACC and its interaction with the topography that exerts a powerful control on the dynamics and energy balance of the ACC. Globally, the barotropic component of ocean circulation may be observed by the Target Scenario, which would provide a unique set of assimilation data and constraints for ocean modeling. Given the strong coupling between ocean and atmosphere, this would lead to a better understanding and prediction of decadal fluctuations in surface temperature and precipitation, thus providing essential contributions to improved near-future climate forecasts and the separation of human-made and natural processes (e.g., Volpi et al. 2013).

6.4 Solid Earth

Also from the solid Earth perspective, the top priority is the increase in spatial resolution together with improved accuracy. A spatial resolution of 200 km with an accuracy of 0.5 μGal (as provided by the Target Scenario) will allow to detect tectonic activity equivalent to magnitude 7 events, including seismic and aseismic movement. This would considerably increase the number of events that could be monitored, as shown in Fig. 10. For this, an analysis of earthquake magnitudes was performed based on the National Earthquake Information Center (NEIC) catalogue for the time interval 1900–2014. The Threshold Scenario allows to monitor events with $M > 7.8$ (corresponds to 1 event per year on an average), the Target Scenario even $M > 7$ earthquakes, amounting to 12 events/year. This is compared with the current situation with GRACE, which detects $M > 8.5$ earthquakes and thus 0.14 events/year. For crustal evolution monitoring, this increased accuracy together with the continuity of time series with GRACE and

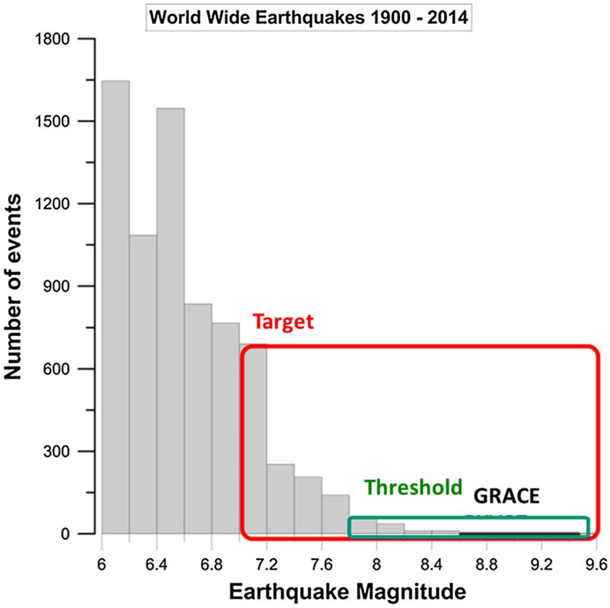

Fig. 10 Histogram of number of earthquakes with magnitude greater 6, worldwide for the time interval 1900–2014 based on the NEIC global earthquake catalogue. The *rectangles* depict the observability of these events by the different mission scenarios

GRACE-FO would allow us to distinguish tectonic movement from the superimposed GIA signal, and to approach scales of single orogens.

An extension of the time series to at least 30 years is also beneficial for the identification of long-term effects and the separation from annual to interannual climatic factors which contribute to the surface deformation. These long time series provided with a trend accuracy of 0.05 μGal/year on scales of 200 km, corresponding to the Target Scenario, will be sufficient for the first time to provide estimates of solid Earth mass movements at topography, at ocean bottom, and at the lower crust on regional scale. As a novel application it is planned to distinguish creeping versus locked parts of subduction zones, which is crucial for hazard estimation and understanding the recurrence interval of large earthquakes.

There are also applications for increased temporal resolution. Weekly resolution allows distinguishing the co-seismic effect on mass redistribution from the following post-seismic processes. With a daily resolution and longer wavelength sensitivity of 400–800 km, the threshold earthquake magnitude would still be smaller than $M = 8.0$. With daily resolution, post-seismic transient gravity change would be observed, which may be useful to discriminate various processes, including others than seismic signals.

7 Conclusions and Outlook

In a joint initiative for IUGG, an international panel of experts in the main fields of application—continental hydrology, cryosphere, ocean and solid Earth—has achieved consensus on consolidated science and user needs for a future satellite gravity observation infrastructure. Purposefully, they have been derived independently of any technological constraints. The science and user needs defined in this document can be considered as important input and basis of future mission design, on the one hand, and programmatic considerations, on the other hand.

Of course, the performance numbers of the scenarios identified in Sect. 5 have to be interpreted as a compromise of all application fields and could be further optimized for a specific discipline. As an example, due to the low signal amplitudes of their target signals (cf. Figs. 3, 4), the oceanographic community requests even more challenging performance numbers than defined for the Target Scenario. This has been justified by a study on the AMOC variability in Sect. 6.3, where it could be shown that the Target Scenario will be at the edge to resolve monthly AMOC variability (cf. Fig. 4), but will be sensitive to interannual variability and longer periods (Fig. 3).

Still, the performance of the Target Scenario, which would roughly mean an improvement of the current GRACE mission performance by a factor of 50, might at the first glance appear to be unrealistic to achieve with current technology. However, with innovative measurement technologies in combination with optimized satellite constellations, ideally being composed of several satellites or satellite pairs, and improved processing techniques, such an ambitious goal is not too far off. Already in GRACE-FO, a laser interferometer is used as a demonstrator in parallel to the established K-band microwave ranging system, with the potential to improve the inter-satellite ranging accuracy by at least one order of magnitude. Today, such an improvement in measuring accuracy cannot be fully exploited, due to other factors limiting the performance such as temporal aliasing of high-frequency tidal and non-tidal gravity changes (Murböck et al. 2014). However, instead of single-pair missions such as

GRACE and GRACE-FO, with double-pair or even multi-pair missions both, the spatial and temporal resolution can be increased significantly. It can be shown that already a double-pair mission with one polar and one 60°–70° inclined pair, the so-called Bender configuration, can reduce the temporal aliasing effect of the typical GRACE striping by at least one order of magnitude (Visser et al. 2010). Murböck et al. (2014) show that by a proper choice of the orbit altitude aliasing effects can be significantly reduced, or at least migrated toward higher spherical harmonic degrees. Additionally, improved processing strategies, such as innovative methods for a better spatio-temporal parameterization, can help to further improve the gravity field results. As an example, Wiese et al. (2011) and Kurtenbach et al. (2012) investigated daily parameterization of long-wavelength signals, thus largely avoiding that these signals are aliasing as systematic errors into the gravity field models.

Finally, a key challenge will be the improvement of geophysical tidal and non-tidal background models, which are currently used in standard gravity field processing for a priori reduction of certain high-frequency signal content. Among other strategies, this can be achieved by an iterative feedback loop of gravity field products into these geophysical models helping to improve both the geophysical background models and the gravity field products simultaneously.

A combination of innovative measuring concepts makes it quite realistic to achieve the required performance of the apparently very ambitious Target Scenario even with current and near-future measuring, processing and modeling technologies.

Such a long-term satellite gravity observation system with high accuracy would respond to the aforementioned need for sustained observation of mass transport processes in the Earth system.

Acknowledgments The contributions by more than 70 international scientists to this project initiative is highly acknowledged. We also acknowledge the valuable comments of two anonymous reviewers.

Appendix 1

Table 7 presents the relations between geoid height differences, gravity anomalies, vertical gravity gradients (in milliEötvös, mE) and equivalent water heights (EWH) for different spatial resolutions and spherical harmonic (SH) degrees.

Table 7 Conversion between cumulative geoid heights in mm, gravity anomalies in μGal, gravity gradients in mE and total water storage in cm EWH depending on the spatial resolution in km (from Murböck 2015)

Spatial resolution in km	SH degree	1 mm geoid height			1 μGal gravity anomaly			1 mE gravity gradient			1 cm EWH total water storage		
		Gravity anomaly in μGal	Gravity gradient in mE	Total water storage in cm EWH	Geoid height in mm	Gravity gradient in mE	Total water storage in cm EWH	Geoid height in mm	Gravity anomaly in μGal	Total water storage in cm EWH	Geoid height in mm	Gravity anomaly in μGal	Gravity gradient in mE
10	2004	217,555	559,555	520,277	0005	2572	2391	0002	0389	0930	0002	0418	1075
20	1002	108,723	140,196	260,653	0009	1289	2397	0007	0776	1859	0004	0417	0538
30	668	72,446	62,446	174,068	0014	0862	2403	0016	1160	2788	0006	0416	0359
40	501	54,308	35,203	130,749	0018	0648	2408	0028	1543	3714	0008	0415	0269
50	401	43,425	22,579	104,745	0023	0520	2412	0044	1923	4639	0010	0415	0216
60	334	36,169	15,714	87,404	0028	0434	2417	0064	2302	5562	0011	0414	0180
70	286	30,987	11,571	75,016	0032	0373	2421	0086	2678	6483	0013	0413	0154
80	250	27,100	8878	65,724	0037	0328	2425	0113	3053	7403	0015	0412	0135
90	223	24,077	7030	58,499	0042	0292	2430	0142	3425	8321	0017	0412	0120
100	200	21,659	5707	52,719	0046	0263	2434	0175	3795	9238	0019	0411	0108
200	100	10,777	1458	26,727	0093	0135	2480	0686	7392	18,331	0037	0403	0055
300	67	7150	0662	18,058	0140	0093	2525	1510	10,799	27,273	0055	0396	0037
400	50	5337	0380	13,709	0187	0071	2569	2629	14,028	36,032	0073	0389	0028
500	40	4250	0249	11,089	0235	0059	2609	4021	17,087	44,585	0090	0383	0022
600	33	3526	0176	9336	0284	0050	2648	5670	19,985	52,919	0107	0378	0019
700	29	3009	0132	8078	0332	0044	2685	7559	22,730	61,034	0124	0372	0016
800	25	2620	0103	7130	0382	0039	2721	9669	25,332	68,936	0140	0367	0015
900	22	2319	0084	6394	0431	0036	2757	11,991	27,793	76,626	0156	0363	0013
1000	20	2078	0069	5802	0481	0033	2792	14,502	30,126	84,122	0172	0358	0012
2000	10	0997	0021	3148	1003	0021	3158	47,648	47,485	149,965	0318	0317	0007
3000	7	0643	0011	2301	1564	0018	3584	89,151	56,911	204,100	0436	0279	0005
4000	5	0464	0008	1895	2158	0016	4087	133,011	61,636	251,925	0528	0245	0004

Table 7 continued

Spatial resolution in km	SH degree	1 mm geoid height			1 µGal gravity anomaly			1 mE gravity gradient			1 cm EWH total water storage		
		Gravity anomaly in µGal	Gravity gradient in mE	Total water storage in cm EWH	Geoid height in mm	Gravity gradient in mE	Total water storage in cm EWH	Geoid height in mm	Gravity anomaly in µGal	Total water storage in cm EWH	Geoid height in mm	Gravity anomaly in µGal	Gravity gradient in mE
5000	4	0359	0006	1678	2788	0016	4677	176,096	63,161	295,420	0596	0214	0003
6000	0297	0005	1564	3465	0016	5366	215,604	62,333	334,104	0642	0189	0003	
7000	3	0245	0004	1471	4174	0016	6102	252,363	60,929	369,697	0681	0166	0003
8000		0215	0004	1422	4947	0017	6933	283,376	58,353	398,841	0706	0150	0003
9000		0184	0003	1373	5721	0018	7764	314,390	55,776	427,986	0731	0133	0002
10,000	2	0154	0003	1324	6495	0019	8595	345,403	53,199	457,130	0755	0116	0002

Appendix 2

IUGG Expert Panel comprises: Gianpaolo Balsamo, Melanie Becker, Decharme Bertrand, John D. Bolten, Jean-Paul Boy, Michiel van den Broeke, Anny Cazenave, Don Chambers, Tonie van Dam, Michel Diament, Albert van Dijk, Petra Döll, Jörg Ebbing, James Famiglietti, Wei Feng, Rene Forsberg, Nick van de Giesen, Marianne Greff, Jun-Yi Guo, Shin-Chan Han, Edward Hanna, Kosuke Heki, György Hetényi, Steven Jayne, Weiping Jiang, Shuanggen Jin, Georg Kaser, Matt King, Armin Köhl, Harald Kunstmann, Jürgen Kusche, Thorne Lay, Anno Löcher, Scott Luthcke, Marta Marcos, Mark van der Meijde, Valentin Mikhailov, Christian Ohlwein, Fred Pollitz, Yadu Pokhrel, Rui Ponte, Matt Rodell, Cecilie Rolstad-Denby, Himanshu Save, Bridget Scanlon, Sonia Seneviratne, Frederique Seyler, Andrew Shepherd, Tony Song, Wim Spakman, C.K. Shum, Holger Steffen, Wenke Sun, Qiuhong Tang, Virendra Tiwari, Isabella Velicogna, John Wahr, Wouter van der Wal, Lei Wang, Hua Xie, Hsien-Chi Yeh, Pat Yeh, Ben Zaitchik, Victor Zlotnicki.

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