Towards a sustained observing system for mass transport to understand global change and to benefit society

NASA/ESA Interagency Gravity Science Working Group (IGSWG)

12 May 2016

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Members IGSWG:

Pieter Visser	Delft University of Technology, The Netherlands
Srinivas Bettadpur	University of Texas at Austin, USA
Don Chambers	University of South Florida, USA
Michel Diament	INSU-CNRS, France
Thomas Gruber	Technical University of Munich, Germany
Edward Hanna	University of Sheffield, United Kingdom
Matthew Rodell	NASA Goddard Space Flight Center, USA
David Wiese	Jet Propulsion Laboratory, California, USA

Coordinaters ESA and NASA:

John Labreque, Thomas Johnson, Ben Phillips (NASA)
Roger Haagmans, Luca Massotti, Christian Siemes (ESA)

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1 Executive summary

Observing mass transport with the highest possible accuracy and spatial resolution and with temporal resolutions from daily to monthly is crucial for understanding the functioning and evolution of the system Earth (climate, geo-hazards, water cycle). GRACE and GOCE have shown the great potential and uniqueness of observing mass distribution and transport from space and the need for not only sustained, but also improved observation of global mass transport in terms of temporal and spatial resolution. Such improvements would benefit a diversity of Earth science domains (e.g. hydrology, oceanography, cryospheric sciences, solid Earth sciences, atmospheric sciences) for both scientific and application focused users, and are necessary to fully characterize diverse global change processes. Specifically, improved spatial and temporal resolution of global mass transport would allow for: (1) an enhancement of our ability to monitor, model and predict changes in the global water cycle, including extreme events, (2) the ability to separate mass balance processes on the ice sheets (glacial dynamics and surface mass balance), ultimately allowing for improved predictions of sea level rise through ice sheet model validation, (3) monitoring and understanding climate-relevant variations of two important ocean currents: the Antarctic Circumpolar Current and the Atlantic Meridional Overturning Circulation and (4) monitoring mass changes linked to large earthquakes and other solid-Earth processes. Mass transport observations provide information on several essential climate variables defined by GGOS. Due to the importance and uniqueness of mass transport observations, we recommend to include mass transport explicitly as an essential climate variable.

The most mature technology that can realistically achieve the desired advances in observing global mass transport is the measurement of inter-satellite distance variations together with non-gravitational accelerations, i.e. the GRACE measurement concept. Technological developments in inter-satellite distance metrology, accelerometers, star trackers and GNSS receivers offer improved precision, but will not meet the user needs of the future, primarily because of space/time sampling limitations associated with a single pair of satellites. For improved sampling, multiple missions are required and the largest benefit will be gained if those missions are closely coordinated with respect to each other, both in terms of timing and orbit selection. In case of future gravity missions, multiple coordinated missions will provide much larger benefits than the individual missions together. Improved sensor technology and flying multiple missions in parallel leads to new challenges concerning data analysis and processing methods/strategies, optimal constellation design, calibration and validation of instruments and data products, and most importantly how to coordinate and cooperate between satellite providers (space agencies).

Further studies are required to assess the impact of technological developments and to design optimal constellations and data processing strategies. At the same time, cooperation and coordination needs to be defined and formalized between the contributing space agencies, user communities and – very important – policy and decision makers: the proper liaisons need to be established. Moreover, it is important to move forward from science demonstration missions to real sustained observation of mass transport in the Earth system supporting relevant application areas and benefit society.

Both NASA and ESA acknowledge the need for continued global observation of mass transport, which is reflected by the selection of GRACE Follow-On after GRACE and GOCE, and the establishment of the Interagency Gravity Science Working Group (IGSWG). This document addresses the compatibility between user requirements, constellation concepts, and expected performance. In addition, a roadmap for implementation in the post-2020 time frame is included. This roadmap defines the path towards sustained observation of mass transport with the required accuracy and spatio-temporal resolution, while addressing the need for cooperation between different space agencies and/or providers, and assessing required activities such as studies and technological developments for both the near and longer terms. While this document focuses primarily on the need for improved observations of global mass transport, we stress the critical importance of extending the length of the current data record, minimally at current achievable spatio-temporal resolutions. This objective should have the highest priority, as observations of mass transport on climatic time scales (> 30 years) allows for the separation of natural and anthropogenic changes in the global water cycle.

2 Introduction

A Joint Programme Planning Group was established between NASA and ESA for cooperation in the field of Earth Observation. Under this umbrella different working groups between ESA-NASA exist and their activities are coordinated through bilateral meetings. In the Mission and Technology working group led by Steve Volz (NASA), later succeeded by Steve Neeck (NASA), and Pierluigi Silvestrin (ESA), a joint activity aims at defining possible and appropriate mission and constellation concepts for improved and sustained observation of mass transport through measurements of time-variable gravity in the Earth system, like a virtual constellation of GRACE-II (NASA) and NGGM (ESA). For this purpose the Interagency Gravity Science Working Group (IGSWG) was set up in June 2013 composed of experts from the user community. The IGSWG members are:

Name	Affiliation	Expertise Domain	
Srinivas Bettadpur	University of Texas, US	Gravity missions	NASA
Don Chambers	Univ. of South Florida, US	Oceanography	NASA
Michel Diament	INCU-CNRS, France	Geophysics	ESA
Thomas Gruber	Technical Univ. of Munich, DE	Gravity missions	ESA
Edward Hanna	Univ. of Sheffield, UK	Climate, Ice	ESA
Matt Rodell	GSFC, US	Hydrology	NASA
Pieter Visser	Delft Univ. of Technology, NL	Gravity missions	ESA
David Wiese	JPL, US	Gravity Missions	NASA

The points of contact in NASA and ESA and coordinators of the IGSWG are John LaBrecque, later succeeded by Thomas Johnson and Ben Phillips (all NASA) and Roger Haagmans, Luca Massotti and Christian Siemes (all ESA). This report is an outcome of the activities of the group, and is provided through the Mission and Technology working group to the ESA-NASA Joint Programme Planning Group.

Experience acquired in the last decade with the GRACE and GOCE missions has shown that knowing the gravity field and how it changes over time with the highest possible accuracy and spatial resolution is crucial for understanding the functioning and evolution of the system

Earth (climate, geo-hazards, water cycle). The GRACE mission has clearly demonstrated the value and diversity of applications of global mass transport measurements across multiple Earth science domains. At the same time, the success of mean Earth gravity field measurements has been amply demonstrated with GOCE mission results. The nearly 15-year experience with spaceborne gravimetry has also shown that significantly enhancing the spatio-temporal resolution of measurements of mass transport in the Earth system will be of immediate and great value. Mass transport observations provide information on several essential climate variables (ECV) defined by GGOS (Table 2-1). Due to the importance and uniqueness of mass transport observations, we recommend to include mass transport explicitly as an essential climate variable. The sustained observation of mass transport is necessary to fully characterize diverse global change processes, and to meet the needs of a growing user community, including both scientific and applications focused users.

The remainder of this document is comprised as follows: Section 3 describes in detail how GRACE and GOCE have contributed to the fields of hydrology, oceanography, cryospheric sciences, solid Earth sciences, and atmospheric sciences, both scientifically and with regards to application-based services. User requirements regarding spatio-temporal resolution, accuracy, and latency of mass transport measurements related to future gravity missions are then detailed for each discipline, along with expected scientific advances. Section 4 describes the mission concept that can achieve the user requirements discussed in Section 3, including the satellite design, necessary scientific instruments, and data processing strategies. Finally, Section 5 provides a roadmap for the necessary coordination and cooperation between satellite providers (space agencies), along with required technological studies for both the near and longer terms.

Table 2-1 In the GCOS implementation plan 2010, gravity observations are necessary for essential climate variables (ECVs) related to ocean, groundwater and ice sheets (see https://www.wmo.int/pages/prog/gcos/index.php?name=ClimateObservationNeeds). A copy of the GCOS table with ECVs is shown below. It is indicated where present and future gravity field observations can or are expected to support other climate variables. The significance of the expected contribution is indicated in color: red large, blue medium, green smaller.

Domain	**GCOS Essential Climate Variables**
Atmospheric (over land, sea and ice)	**Surface:** Air temperature, wind speed and direction, water vapour, pressure, precipitation, surface radiation budget. **Upper-air:** Temperature, wind speed and direction, water vapour, cloud properties, Earth radiation budget (including solar irradiance). **Composition:** Carbon dioxide, methane, and other long-lived greenhouse gases, Ozone and aerosol, supported by their precursors.
Oceanic	**Surface:** Sea-surface temperature, sea-surface salinity, sea level, sea state, sea ice, surface current, ocean colour, Carbon dioxide partial pressure, ocean acidity, phytoplankton. **Sub-surface:** Temperature, salinity, current, nutrients, Carbon dioxide partial pressure, ocean acidity, Oxygen, tracers.
Terrestrial	River discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation (FAPAR), leaf area index (LAI), above-ground biomass, soil carbon, fire disturbance, soil moisture.

3 Challenges & User requirements and needs

3.1 Heritage

GRACE has demonstrated that spaceborne gravimetry is indispensible for global observation of mass transport variability in the Earth system; in fact, it is unique in the sense that it is the only measurement that can observe these processes. This unique measurement is used in a variety of Earth science disciplines, and has made significant advances in the fields of hydrology, oceanography, cryospheric sciences, solid Earth sciences, and atmospheric sciences.

In the field of hydrology, spaceborne gravimetry has enabled first measurements of changes in total water storage, including changes in deep soil moisture and groundwater, which would not be possible using any other spaceborne remote sensing technique. Hydrological analyses and applications supported by GRACE have included groundwater variability and depletion, drought monitoring, flood potential and prediction, basin scale water budget closure and estimation of evapotranspiration, estimation of lake water storage changes and river discharge, evaluation of precipitation data, global hydro-climate monitoring, and numerical model calibration and data assimilation.

In the cryospheric sciences, spaceborne gravimetry has proven crucial for monitoring the mass balance of the Arctic and Antarctic ice sheets and their contribution to global sea level change. GRACE has shown the acceleration of ice mass loss for the Greenland and West-Antarctic land areas. GRACE has also quantified mass changes in the mountain glaciers of Patagonia, Alaska, Himalaya and Tibet, Iceland, and the Canadian arctic. GRACE data are now one essential element of understanding ocean-ice interactions, and the future evolution of the ice-sheets and their potential contribution to sea level rise.

In oceanographic sciences, the results from gravity missions GRACE and GOCE have shown the potential to extract mean dynamic topography to resolutions down to 100 km and below. Related accomplishments include support for establishment of global, unified height systems, and demonstrating the potential to infer large scale ocean heat and mass transport. Large scale time-variable ocean processes have been observed using GRACE data in every major ocean basin, and several enclosed or inland seas, adding to our understanding of ocean dynamics, at timescales ranging from the synoptic, i.e. extreme events related to atmospheric forcing, to seasonal to inter-annual. Mass transport observations have also been a key element enabling the understanding of large scale exchange of mass between land and ocean, including studies of sea-level rise processes.

In solid Earth sciences, GRACE and GOCE have contributed significantly to our knowledge of the Earth's crust, especially in areas previously poorly surveyed by surface or airborne means, e.g. high mountains, parts of Africa and South America. Processes deep inside the Earth linked to convection or mantle plumes could be described and understood for the first time by discriminating large-scale but tiny density variations. Mass transport associated with some solid Earth dynamic processes has also been measured for the first time by GRACE, e.g.

the co-seismic and post-seismic mass transport in areas of very large earthquakes (magnitude > 8.5), while others have been significantly refined with GRACE, e.g. mass transport due to glacial isostatic adjustment.

Finally, the GRACE and GOCE missions provide observations for studying the thermosphere at the finest spatial scales and with unprecedented precisions in terms of neutral density and winds. The GOCE accelerometers were capable of sensing for the first time in history an acoustic wave caused by the 2011 Tohuku earthquake in space. Moreover, it has been shown that precise spaceborne accelerometer observations from GRACE and GOCE were valuable for monitoring the cooling trend of the upper atmosphere, which is probably partly caused by the increase of greenhouse gases in the lower layers of the atmosphere.

A common thread running through the complete range of studies of mass transport observations is that significantly greater insights lie just over the horizon, just beyond the reach of present-day GRACE and GOCE missions. While it may be in general a truism that something is to be gained from every gain in precision of any observation, spaceborne gravimetric observations stand apart in that in most of its applications, there is truly no substitute observation. The societal significance of water cycle applications, the impossibility of global *in situ* high-resolution water balance measurements, the cost of instrumenting the global oceans, and the interconnectedness of global mass transport – all imply that the optimal approach to make gains in the spatio-temporal resolution of global mass transport observations, is through advanced concepts using spaceborne measurements of time-variable gravity.

A comprehensive range of possible future observational goals are discussed in other community documents, e.g. (Pail et al. 2015a; 2015b). This led to Resolution 2 *Future Satellite Gravity and Magnetic Mission Constellations* of the International Union of Geodesy and Geophysics (IUGG) adopted at the XXVI General Assembly in Prague, 2015. This resolution urges international and national institutions, agencies and governmental bodies in charge of supporting Earth science research to make all efforts to implement long-term satellite gravity observation constellations with high accuracy that respond to the need for sustained observation. We draw from those documents, and from our experience with GRACE and GOCE data processing and applications, and identify some key observational goals based on spaceborne gravimetric measurements that represent meaningful achievements for the future. The next section discusses some of these observational requirements that (i) meet existing user needs that are not met by GRACE or GOCE; (ii) are accessible with some modifications to our current spaceborne gravimetric observation concepts; and (iii) offer significant new insights into the Earth system sciences.

3.2 Future needs

3.2.1 Hydrology

The terrestrial water cycle exhibits significant natural seasonal and inter-annual variability, but it also is affected by direct human impacts (e.g. surface water management, groundwater pumping, irrigation) and climate change. These pressures, combined with the increased demand for freshwater associated with population growth and economic development, create considerable challenges for water resources managers and policymakers. Further, water cycle extremes, including severe storms, flooding, and drought, are growing more and more costly.

Enhancing our ability to monitor, model and predict changes in the water cycle has never been more important.

Ground based observational networks will never be sufficiently dense and comprehensive to monitor the terrestrial water cycle globally due to the high spatial variability of hydrological processes, the associated expense of installing and maintaining in situ observing systems with adequate coverage, and the reality of political boundaries which restrict sensor emplacement. Spaceborne gravimetry is the only means possible for global assessment of variations in groundwater and deep soil moisture, and it also contributes to global monitoring of snowpack and surface water storage.

GRACE has already demonstrated the value of spaceborne gravimetry for hydrology. The next generation's infrastructure could enable significant new breakthroughs by (in order of priority):

1. *Improving the spatial resolution to be compatible with other hydrology remote sensing techniques*. This is the highest priority. Most hydrological processes occur on scales ranging from meters to hundreds of kilometers (Figure 3-1); other satellite remote sensing instruments relevant to hydrology have resolutions ranging from 15 meters to 35 km (Figure 3-2); global atmospheric and land surface models typically have length scales ranging from 14 km (0.25° grid) to 140 km (2.5° grid) (Figure 3-3); and watersheds and climate divisions are typically delineated on length scales of 30 km to 1000 km (Figure 3-3). The maximum spatial resolution that can be resolved by GRACE with sufficient accuracy (±3 cm/month equivalent height of water) to infer terrestrial water storage variations is on the order of 220 km at mid-latitudes.

2. *Improving the temporal resolution to weeks or days*. Most near surface hydrological processes are variable on timescales of hours to weeks, while deep soil moisture, groundwater, deep snowpack, and lake and reservoir storage vary on timescales of days to months (Figure 3-1). The observational frequency of other remote sensors is on the order of minutes to several days, and most are delivered as instantaneous observations or daily fields. The nominal temporal resolution of GRACE products is monthly, and those are monthly means as opposed to instantaneous measurements.

3. *Improving the data latency to 10 days or better*. This has the same priority as improvements in the temporal resolution. For most operational applications, observations must be no older than about 10-14 days in order to be useful, with the possible exception of snowpack monitoring, for which maximum winter snowpack is the critical variable for estimating spring stream flows.

4. *Facilitating vertical disaggregation of the terrestrial water storage changes*. Estimates of the individual components of terrestrial water storage (groundwater, layered soil moisture, snow, and surface water storage) are required for most scientific and practical applications other than large-scale water budget studies.

5. *Ensuring gap-free data delivery*. Adoption of any new data type by operational agencies is much more rapid if the data are (1) known to be valuable to the application and (2) guaranteed to be available for many years into the future. Further, multi-decadal time series would be necessary to distinguish real, on-going secular trends from natural variability. Authorization of the GRACE Follow On mission and efforts

to extend the life of GRACE have helped to alleviate the uncertainty about future data availability and minimize a data gap, and future missions would increase the value of spaceborne gravimetric observations for trend detection and attribution.

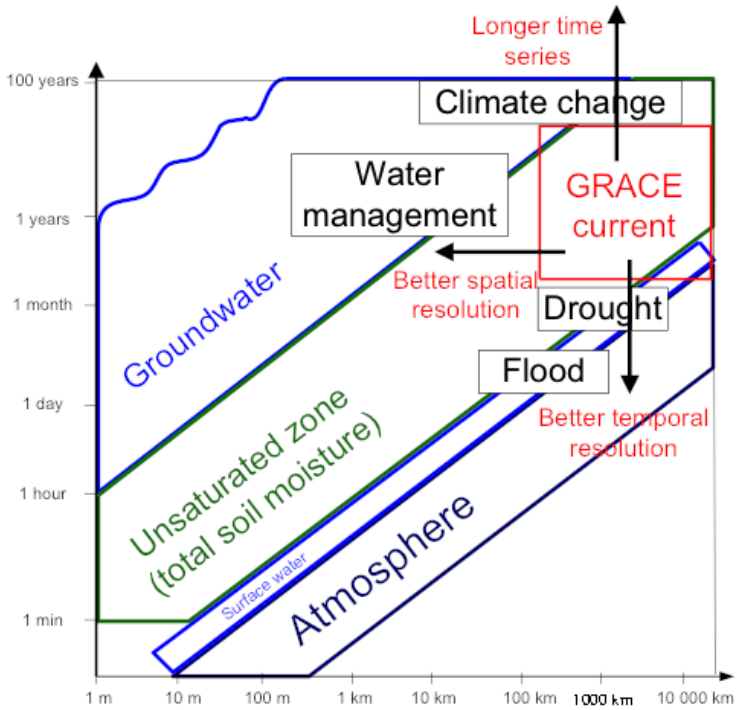

Figure 3-1 Spatial and temporal scales of hydrological processes in various storage compartments, current GRACE sensitivity, and several applications.

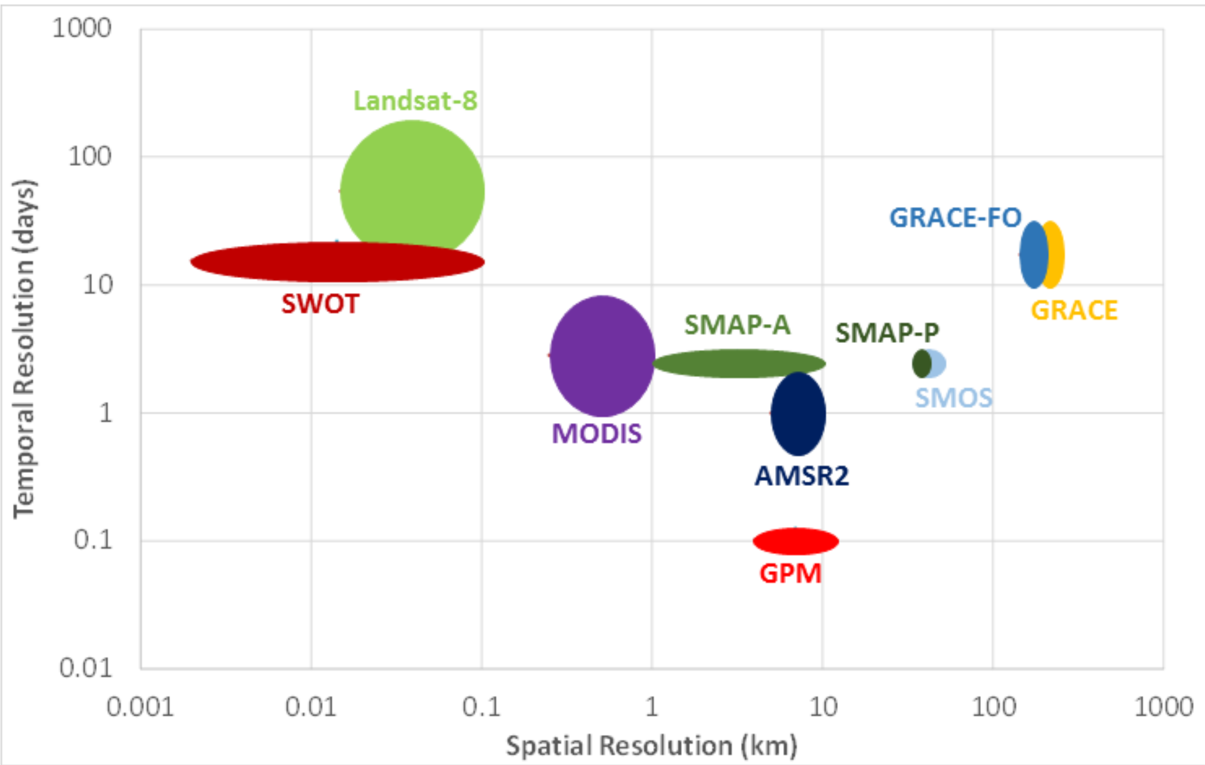

Figure 3-2 Horizontal and temporal resolutions of various remote sensing instruments relevant to hydrology.

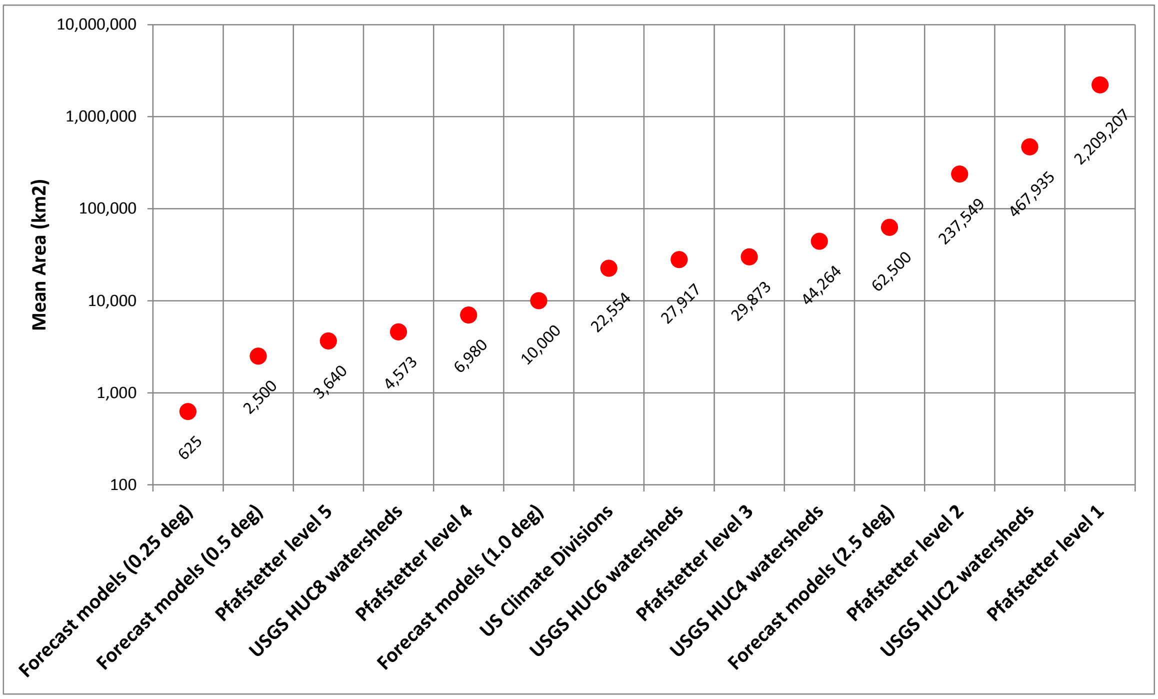

Figure 3-3 Mean area size of watershed delineations and U.S. Climate Divisions, and resolutions of global atmospheric and land surface models.

A future mission with improved spatio-temporal sampling would enable progress on at least four of these five objectives, though clearly the amount of progress depends on the specific characteristics of such a mission. Referring to Figure 3-3, to reach an inflection point in direct uptake of data, it is suggested that a future mission must be able to quantify changes in terrestrial water storage with a reasonable signal to noise ratio at a spatial resolution of about 100 km at mid-latitudes. For comparison, the smallest scale that can be resolved by GRACE with a large enough signal to noise ratio to be useful for water cycle studies is about 220 km at mid-latitudes. A more conservative assessment of the GRACE error budget indicates that GRACE achieves an accuracy of 1.5 cm equivalent height of water at a spatial scale of 550 km. That allows GRACE to observe about 10% of the global river basins exceeding 25,000 km^2 in area. Using GRACE and the 1.5 cm monthly accuracy as a baseline, some example scenarios can be compared:

1. 370 km resolution: almost 30% of the global river basins exceeding 25,000 km^2 area (using the square root of that area as the length scale) could be resolved.

2. 270 km resolution: almost 60% of the global river basins exceeding 25,000 km^2 area could be resolved.

3. 180 km resolution: about 95% of these global river basins could be resolved. At this resolution, the ability to separate adjacent signals (from neighbouring river basins or bodies of water) would be greatly enhanced, which would further reduce uncertainty and enable coastal hydrology studies. Moreover, the gravimetry data could be used directly in coarse resolution global models, which have grid resolutions in the range of 2-2.5°.

4. 100 km resolution: all large river basins would be resolved. Impacts of groundwater withdrawals on smaller aquifer systems could be isolated. Direct application of the data to drought and flood mapping and snowpack monitoring would be enabled. Data can be directly ingested by most global models.

In addition to spatial resolution, considerations of temporal resolution and data latency should also be emphasized, as hydrological processes occur on a variety of timescales (Figure 3-4). Weekly products in combination with a latency of 10 days or less, with all else being similar to or better than GRACE, would be necessary to produce a significant improvement in direct applicability to operational needs such as drought mapping and snowmelt monitoring for runoff prediction. Daily data with at most a few days latency would be required for flood response efforts and forecast model initialization.

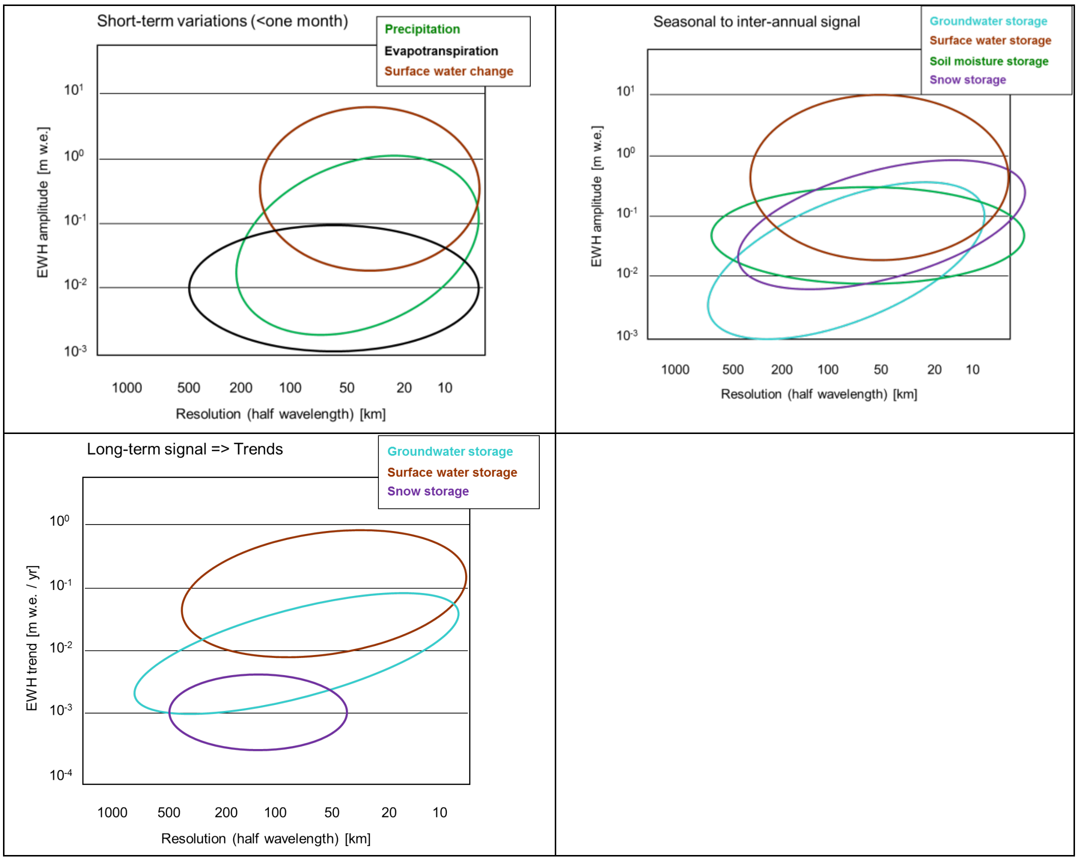

Figure 3-4 Amplitudes of water fluxes and storage changes (meters equivalent height of water) versus length scale, for short term, seasonal to inter-annual, and secular timescales.

3.2.2 Cryosphere/Ice sheets

Gravimetry is instrumental in combinatorial use with other glacier-/ice-sheet observations and models, because it provides a direct and globally consistent measure of mass transport. However, currently the large horizontal resolution gap between spaceborne gravimetry and other spaceborne remote sensising techniques (e.g. laser and radar altimetry, microwave radiometry and radar) and regional climate modelling poses serious limitations on combining and comparing/cross-validating the different techniques. There is an expectation from the glaciological community that these complementary observational and modelling techniques will be continued for the next 30 years.

Current understanding of mass balance processes is insufficient to predict the near future (next 10–100 years) evolution of the ice sheets, and consequently a significant part of sea level change. The largest uncertainty in predictions of sea level change until 2100 comes from dynamical changes in land ice, which is currently insufficiently monitored. Therefore, observations are crucial to validate ice sheet model development. Spaceborne gravimetry avoids issues of incomplete sampling and provides a direct measure for ice mass change estimates. Next to observing mass transport with better resolution in space and time, Global Isostatic Adjustment (GIA) models need to be improved as well. GIA is the rebound of the Earth's surface after the melting of the several kilometer thick ice sheets that covered much of North America and Europe around 20,000 years ago. This GIA results in a gradual large scale redistribution of mass in the Earth interior. The mass transport estimates together with the mean gravity field from GOCE are major contributors for improving the GIA models. Better observations also support better modeling.

Mass transport related to changes of the ice sheets can have relatively small space/time scales (1–100 km/1–10 days), especially given established strong feedbacks involving topography and albedo. The effects of such small-/short-scale surface mass balance changes on the total mass balance are unresolved by GRACE. Moreover, the current generation of gravimetry data does not resolve even the largest individual outlet glacier drainage basins. The complex spectrum of timescale of glacier and ice-sheet mass variations poses critical limitations on extrapolating observations beyond the observation interval and on resolving accurate long-term trends from the current observational time series, which still spans little more than a decade.

Narrowing the glacier mass changes down to individual glaciers or subsets of glaciers situated in climatologically well-defined regions would be ideal, given the large amplitude of mass changes (~0.2–0.5 m equivalent water height over 1 year), but is a tricky and necessary challenge, which should be tackled through future gravity missions. The distance between the glacier trunks is ~100 km. At the opposite end of the spatial scale spectrum, uncertainties in the large-scale components of mass transport estimates propagate to significant errors for signals of very large spatial dimension but small amplitude, like in the interior East of Antarctica. Antarctic glacio-isostatic adjustment patterns extend ~200 km into the ocean, with magnitudes of ~10 mm equivalent water height per year. To separate these patterns unequivocally, i.e. make sure that observed mass change is correctly attributed to land or ocean areas, we should aim to obtain the secular trend with 2 mm equivalent water height per year accuracy at 150 km resolution.

Both the longer record of spaceborne gravimetric observations and the greater accuracy of future gravity missions will allow us to infer ice sheet response to climate change more accurately and at higher spatial resolution than today. This will enable the separation of ice mass, ocean mass, and glacio-isostatic adjustment signals based on their specific fingerprints in the mass transport trends and on enhanced possibilities of combinations with complementary approaches. Moreover an enhanced spatial resolution (to ≤50–100 km) will also enable distinction between patterns of mass change due to ice dynamics or other mass change processes, which is not yet possible to reliably achieve for the ice sheets but is critical for understanding future ice-sheet evolution and global sea level rise. Crucially, the vastly improved resolution and the extension of the record of spaceborne gravimetric observations by future gravity missions will do much to help link continental ice mass changes with climate change, including the climate forcing of mass balance and the resulting feedbacks. For establishing those links conclusively, we need to comprehensively observe cryospheric mass transport over climatic timescales of at least 30 years. This emphasizes the need for sustained observation of mass transport.

The monitoring of smaller glaciers and ice caps (≤100 km scale) can also benefit from gravimetric observations.

3.2.3 Oceanography

Ocean mass exhibits significant and measureable short-term, annual, and inter-annual variability, albeit with magnitudes considerably smaller than those from hydrology. Spatial-scales range from 100 km or less for time-averaged geostrophic circulation, to approximately 500 km or larger for monthly to inter-annual variability, particularly at high latitudes where the signals are stronger. Changes in global mean ocean mass, the largest component of global mean sea level change, can be measured at monthly periods with an accuracy of 1 mm.

GRACE and GOCE have already demonstrated the value of spaceborne gravimetry for ocean applications such as improving the mean dynamic topography and large-scale mean ocean circulation, measuring the mean ocean mass component of sea level change, and understanding slow mass exchanges within the ocean at large-scales. Future gravity missions should enable significant breakthroughs for measuring and understanding climate-relevant variations of ocean currents, which are explained in detail for the following two important ocean currents:

1. *The Antarctic Circumpolar Current (ACC)*. The ACC is the largest current system in the world, and connects the three major oceans. This allows an interbasin exchange of heat, salt, carbon, and other chemical and biological properties. The ACC isolates Antarctica from much of the poleward heat transport in the ocean, so knowledge of how this transport is changing in time is vital to understanding future climate change. Although the Antarctic Circumpolar Current is often thought of as a single current, it is comprised of multiple fronts (Figure 3-5) and narrow, bifurcating jets which makes calculating integrated ocean mass transport across the width of the ACC difficult. Much of our knowledge of the mean and variable transport of the ACC comes from studies in the Drake Passage, where the fronts and jets are tightly constrained by topography. These studies have generally relied on either repeated hydrographic sections or short-term deployments of moored instruments. Such deployments rarely last longer than 2-3 years, which limits the ability to measure long-term changes and variability of the ACC transport. Moreover, bottom pressure recorders have significant drifts, which limits their ability to quantify long-term changes.

2. *The Atlantic Meridional Overturning Circulation (AMOC)*. The AMOC consists of an upper branch flowing northward between the surface and approximately 1200 m depth from the Southern Ocean, and a lower branch of denser, colder, fresher waters returning southward from the North Atlantic between 1200 m and 5000 m. The AMOC is responsible for much of the meridional transport of heat in the mid-latitude Northern Hemisphere. Coupled climate models find that a slowdown of the Atlantic Meridional Overturning Circulation in the next decades is very likely, though with uncertain magnitude. A consequence of this would be significant climatic changes

over Europe and North America, as less heat is transferred to the atmosphere during the winter months, leading to colder winters. There have been few regular observations of the AMOC until after 2000 (Figure 3-6). Although measurements at different latitudes show similar sizes of variability, the coherence is poor – when transport goes up at one location, it may go down at another. Theoretically, it should balance. If transport increases to the north, the return circulation should also increase. The imbalance on inter-annual periods is likely due to missing important contributors to the AMOC, such as the western boundary currents.

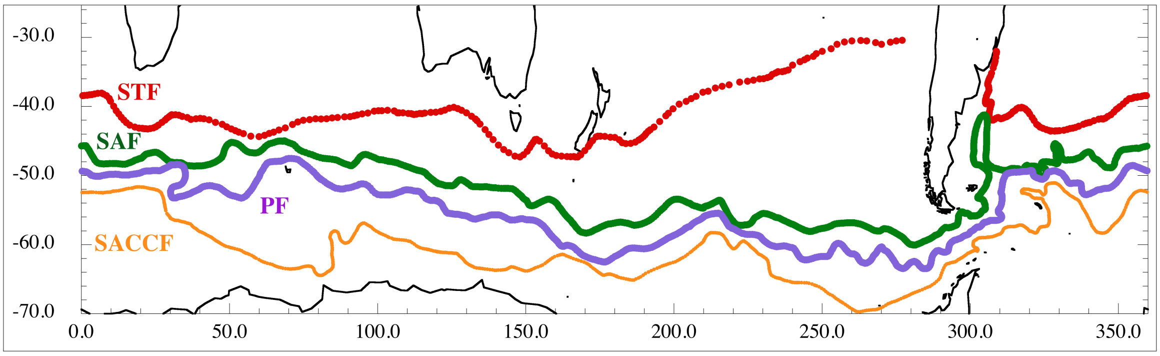

Figure 3-5 Fronts of the Antarctic Circumpolar Current. From north to south: the Subtropical Front, the Sub-Antarctic Front, the Polar Front, and the Southern Antarctic Circumpolar Current Front.

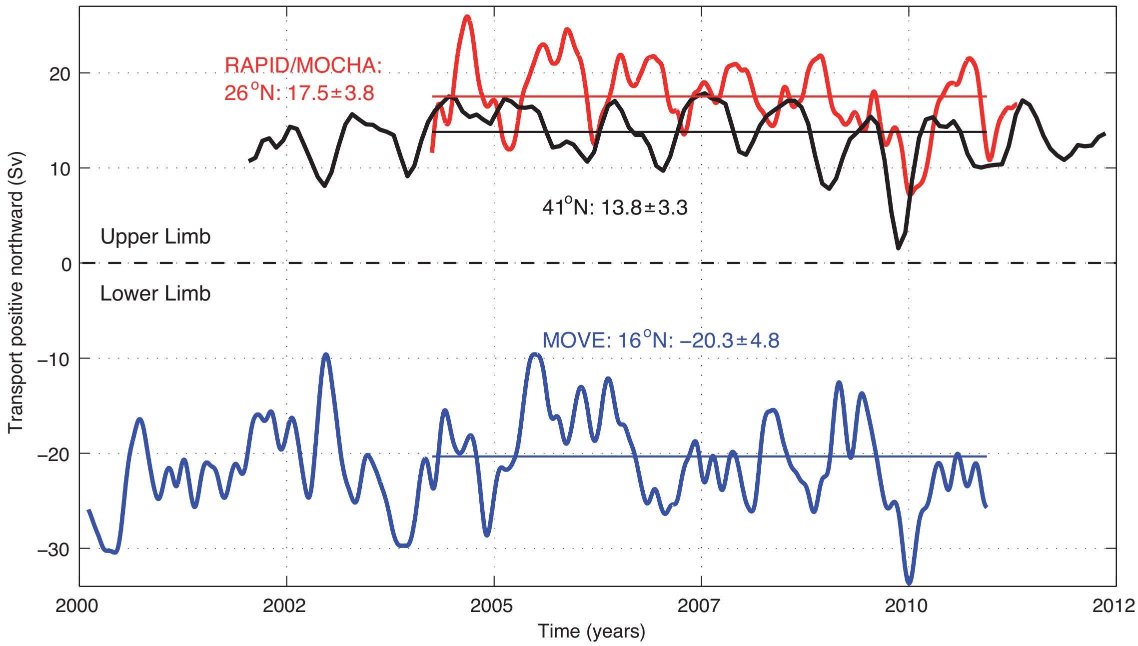

Figure 3-6 Estimated volume transport in Sverdrups (1 Sv = 10^6 m^3 s^{-1}) of the Atlantic Meridional Overturning Circulation upper and lower limbs from: 26.5°N RAPID/MOCHA (Rapid Climate Change programme/Meridional Ocean Circulation and Heat flux Array), 41°N based on Argo float measurements in the upper 2000 m only, and 16°N from the Meridional Overturning Variability Experiment (MOVE) measuring transport of North Atlantic Deep Water in the lower limb of the Atlantic Meridional Overturning Circulation between 1100 m and 4800 m depth between the Caribbean and the mid-Atlantic Ridge [IPCC report].

A GRACE-like system is capable of quantifying low-frequency transport (period > 1-year) of the ACC with an accuracy of ~ 1 Sverdrup (1 Sv = 10^6 m^3 s^{-1}) after averaging over an area that has a size of 60° in longitude. However, this can only be done by integrating between all the fronts of the Antarctic Circumpolar Current, including the Sub-Tropical Front over most of the Southern Ocean (Figure 3-5). The Sub-Tropical Front is highly variable in location and strength, does not pass through the Drake Passage, and only contributes to 7% of the Antarctic Circumpolar Current transport in the Atlantic and Indian Ocean. The Sub-Antarctic Front and Polar Front combined are responsible for over 80% of the transport through the Drake Passage. Thus, one would ideally want to be able to measure the transport variability of the fronts separately, or at a minimum to be able to separate the Sub-Antarctic Front and the Polar Front from the Sub-Tropical Front and the Southern ACC Front. This puts a constraint on the spatial resolution one requires for a future gravity mission.

The Sub-Antarctic Front and Polar Front are separated by a minimum of ~200 km and a maximum of about ~500 km. The Sub-Tropical Front and the Southern ACC Front are typically more than 500 km away from the Polar Front and Sub-Antarctic Front except in a few locations. If a future gravity mission could resolve ocean bottom pressure to an accuracy comparable to the current GRACE mission (~1.5 cm equivalent water height standard deviation after post-processing), but on spatial-scales of 200 km or better, the transport fluctuations of the Sub-Antarctic Front and Polar Front could be separated from those of the Sub-Tropical Front and the Southern Antarctic Circumpolar Current Front. The accuracy and resolution requirements do not need to be met at monthly time-scales to be useful. Since one is interested in long-term changes, seasonal or even annual averages would be sufficient.

Current satellite gravity missions cannot observe the AMOC for all latitudes, although its variability does cause an ocean bottom pressure signal that is theoretically observable. GRACE has been used to observe the AMOC at a single latitude with a favourable bathymetric profile. However, it is not possible to estimate the AMOC for all latitudes using GRACE. Observing the AMOC across all latitudes is desirable such that transport coherence can be studied, and is a goal for future gravimetry missions.

The deep western boundary current, flowing southwards under the Gulf Stream is the primary contributor to the return limb of the AMOC in the North Atlantic. This causes ocean bottom pressure signals on the continental shelf of the US east coast associated with a magnitude around 2 cm (equivalent water height) for each Sverdrup drop in AMOC transport strength (Figure 3-7). The challenge is that the signal is small (order 1 cm of equivalent water height) and has a short length scale (order 100 km). Moreover, the signal is correlated north-south, so one needs to compute the east-west gradient of bottom pressure. Current single polar-orbiting missions are insensitive to these gradients.

Using output from an ocean model, we can test the resolution needed to resolve AMOC variability. Figure 3-8 (top) shows the western boundary pressure signal averaged over the lower 1300-3000 m part of the continental slope. This represents the signal we wish to recover. To test the ability of a gravity mission to recover this AMOC bottom pressure signal, the global ocean bottom pressure fields from the model were reconstructed on the global grid to differing spatial scales ranging from 100 to 200 km. The true signal can be well reproduced, to about 80% of the total variance, for a spatial scale smaller than 133 km (Figure 3-8), assuming uncertainty at this scale of less than 0.5 cm RMS (equivalent water height). The accuracy and resolution requirements do not need to be met at monthly time-scales to be useful. Since one is interested in long-term changes, seasonal or even annual averages would be sufficient, provided there are records approaching ten years in length in order to resolve inter-annual changes.

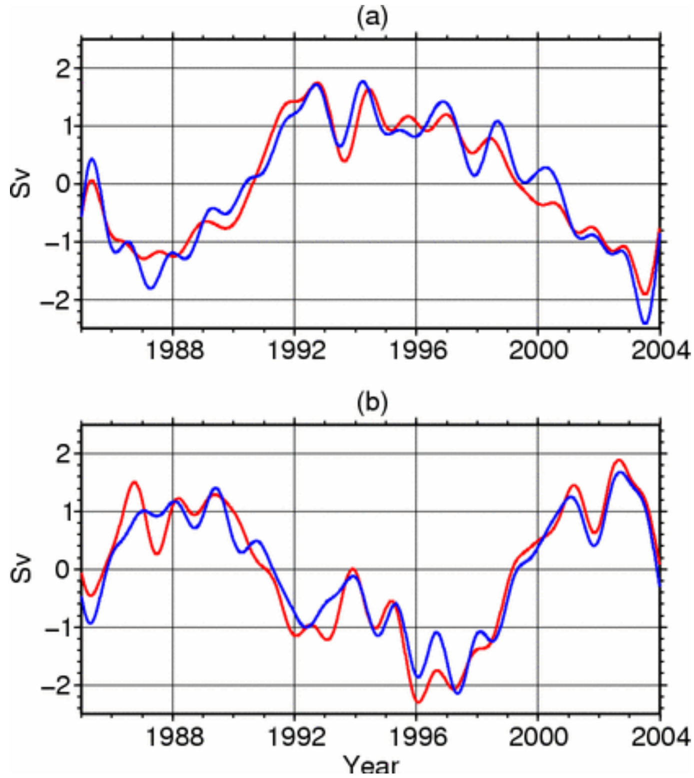

Figure 3-7 (a) Inter-annual fluctuations in the total upper layer (100-1300 m) zonally integrated meridional transport at 42°N in the Atlantic in an ocean model (red) and as estimated from the ocean bottom pressure variations on the western continental slope (blue). (b) As in (a) but for the lower layer (1300-3000 m). [Figure courtesy R. Bingham]

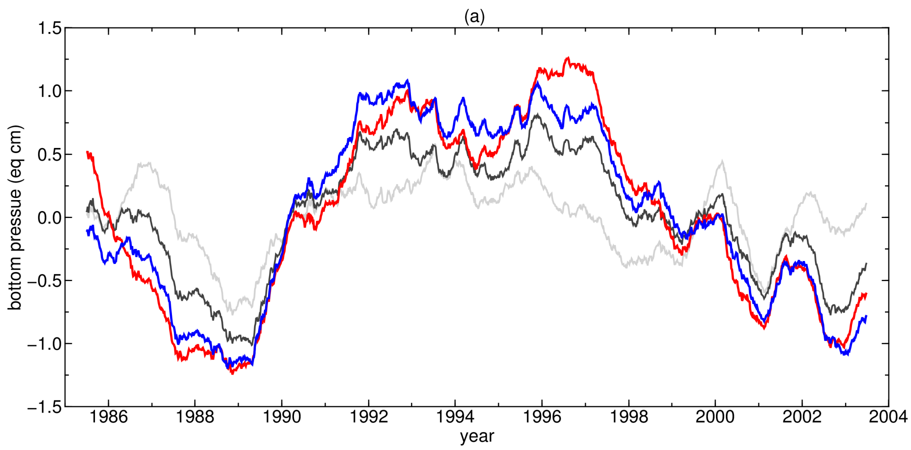

Figure 3-8 Inter-annual bottom pressure variations averaged over the lower (1300-3000 m) part of the western continental slope (in cm of equivalent water height; red). Reconstructions of the bottom pressure signal based on spherical harmonic expansions with a resolution of 100 km (blue), 133 km (dark grey) and 200 km (light grey).

3.2.4 Atmosphere

It is currently possible to combine spaceborne gravimetric data with weather-station observations and output from meteorological models to improve the determination of mass transport in the atmosphere and atmospheric pressure at the ~100–500 km spatial scale. The typical range of surface air pressure variation is ±1–2% (maximum ~±5%) of the total atmospheric pressure acting at the surface and typically oscillates non-regularly on the above-mentioned spatial scales over a 1–10 day or longer period.

Conversely, if the air pressure signal can in the future be directly derived from spaceborne gravimetric data (by first subtracting other mass transport signals from hydrology, cryosphere and solid-earth), there is the intriguing possibility of using the long-term (inter-annual) variations in this signal to provide novel information on climate variability and change, including in regions where not many conventional weather station observations are available. Similarly, although more challenging, it might be possible to use highly sensitive future gravity missions to help monitor variations in the mass of atmospheric water vapour, even though these represent only 1% or less of the total atmospheric mass. Such a study might reveal changes in poleward water mass transport as well as the water cycle, storm tracks and jet stream dynamics. Although more focused exploratory efforts are clearly needed here, it is anticipated that greater accuracy and resolution of data from future gravity missions will help achieve these aims. The above observational-based effort has to be accompanied by a dedicated comprehensive modelling effort where all mass transport signals are included.

In addition to gravimetric observations, the instrumentation and orbital characteristics of the past gravity missions CHAMP, GRACE and GOCE have proven to be especially well suited for the derivation of data sets of upper atmospheric air density and crosswind speed at the altitude of these satellites (Figure 3-9). The latter have been derived from an aerodynamic analysis of the satellite accelerations observed by high-precision accelerometers. The thermosphere data sets from these missions continue to have a large impact on research of the dynamics of the neutral upper atmosphere and its relation with solar activity as well as with upwards propagating waves from the lower atmosphere, and coupling with ionospheric and magnetospheric processes.

Simultaneous observations from a multi-satellite mission in multiple orbital planes separated in right ascension of the nodes (and therefore in local time) will allow for better observations of transient phenomena in the upper atmosphere, such as travelling atmospheric disturbances, as well as better separation of local time and seasonal variations. If one of the orbital planes has a relatively low inclination, the crosswind measurements will be able to provide unique information on meridional winds at lower latitudes. The addition of instrumentation such as a neutral mass spectrometer for determining the composition, temperature and/or wind speed, would provide great synergy with acceleration-derived data, and be of enormous benefit for upper atmospheric research. The additional data would provide the means to accurately determine the absolute scale of thermospheric density.

Continuing and improving the measurement and data processing of accelerometer-derived thermospheric density and crosswind speeds with future gravity missions would be of great benefit to these science disciplines and significantly increase the science return from these missions.

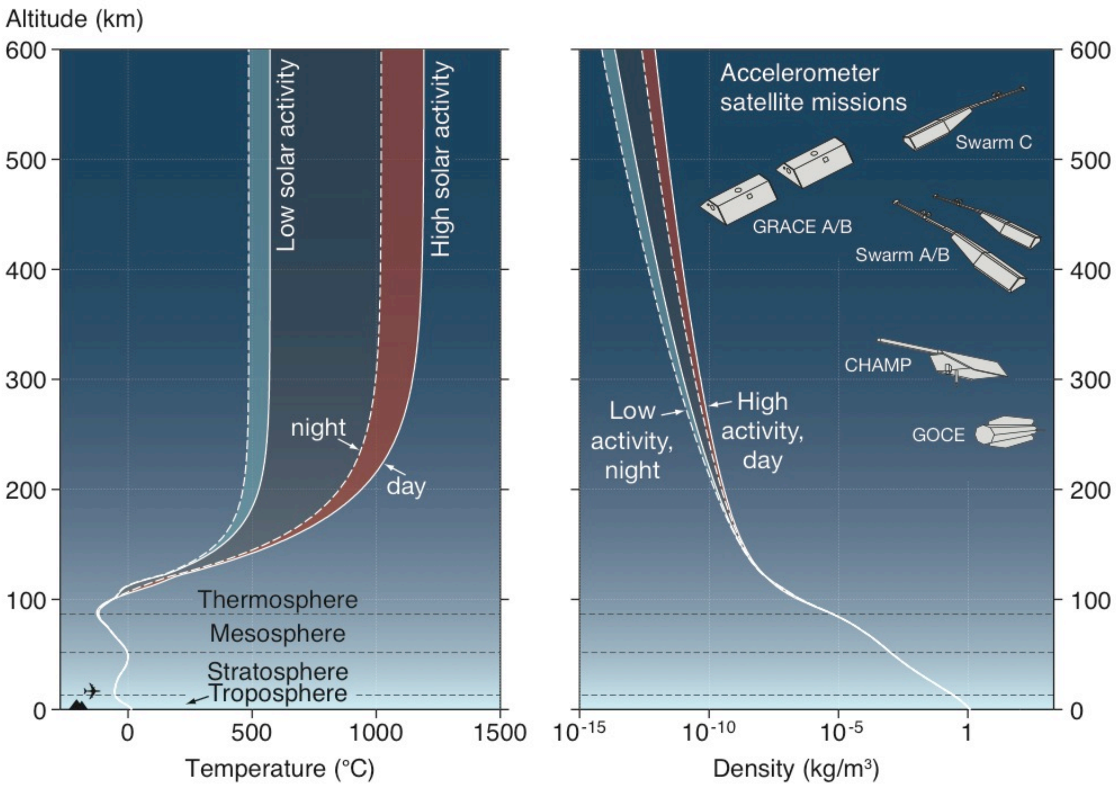

Figure 3-9 Spaceborne accelerometry for the observation of neutral thermospheric density and winds.

A simple extension of the current data sets over even longer time periods will already provide important additional scientific benefits. For example, additional data is required for a better separation of seasonal, local solar time, longitudinal and solar activity variations in the structure and dynamics of the thermosphere. In addition, the future availability of density data, spanning multiple decades, will allow for a very detailed investigation of long-term cooling of the upper atmosphere, which is thought to be partly caused by the increase of greenhouse gases in the lower layers of the atmosphere. The interaction between neutral atmospheric particles and charged particles means that long-term changes in the Earth's magnetic field might play a role in long-term change processes as well. The separation of such changes from changes introduced by variability of the solar energy input requires the availability of accurate observations of thermospheric density over multiple solar cycles (1 solar cycle = 11 years), starting in 2000 with CHAMP and extending at least beyond 2022.

3.2.5 Solid Earth

Solid Earth is the largest compartment of the Earth System, characterised by processes acting on very different time scales, from fractions of seconds (e.g. Earthquakes) to billions of years (e.g. continental drift), and very different spatial scales (from molecules to the globe). These processes shape and control the structure and dynamics of our planet. The present state of the Earth is a record of its dynamic history from its very origin, including the origin of life.

Natural hazards like earthquakes are a major threat for mankind, and the natural resources needed to sustain modern life are rooted in the Solid Earth.

The solid Earth is part of a fully coupled Earth system and strongly interacts with the surface, the fluid envelopes and the biosphere both on human and much longer time scales. Precise and comprehensive knowledge of the solid Earth is therefore mandatory both for exploring and understanding the inner globe itself but also as a component of the Earth system in which many past and on-going processes affect the other compartments, and contribute to the climate and environmental evolutions.

To address societal concerns and urgencies in order to understand and predict the evolution of the geosphere and its habitability at the human time scale, we need to have a better understanding of the underlying deep dynamic processes of the solid Earth, of how they interact with each other and of how they interact with the ones acting in the outer envelopes. This has to be known over a wide range of spatial and temporal scales. This requires a multi-scale, three-dimensional and time-varying imaging, as well as dynamic modelling of the Earth's interior.

Knowledge about Earth's gravity field complements other geophysical information provided by e.g. seismology, geochemistry, geology and magnetic field observations or models. All these information sources have to be jointly interpreted or inverted to provide comprehensive models of the inner structure and processes. GOCE provided for the first time observations in three directions of the fine structures (spatial scale as small as 80 km) of the Earth's gravity field. This allowed a much better delineation of the shape of the heavy and light zones leading to gravity anomalies.

The increase of accuracy and resolution both in space and time of future gravity missions should allow to much better identify the various sources of the gravity signal that are today not separable thereby hampering a proper understanding of inner processes.

Several scientific questions that would strongly benefit from future improved spaceborne gravimetry have great relevance for society since they deal with improving our understanding and thus mitigation of natural hazards, with resources and their sustainable exploitation.

1. The understanding of the various tectonic processes that shape the surface of the Earth where we live. This encompasses the monitoring and understanding of the entire seismic cycle, from pre-seismic to post-seismic phases. Previous gravity missions have demonstrated the efficiency and uniqueness of spaceborne gravimetry for very large, and fortunately rather seldom earthquakes. Preferably, earthquakes with magnitude as small as 7.0 and also the so-called silent or slow earthquakes might become observable by future missions. It must be recalled that the most devastating earthquakes (causing e.g. tsunamis) are located under the sea, in areas that cannot - or only with extreme difficulties - be monitored by ground geodesy (Figure 3-10).

2. The glacio-isostatic adjustment (GIA) is the response of the viscous Earth to the (un)loading of former (de)glaciation periods. This yields a signal, still badly modelled because of difficulties in its determination due to our still limited knowledge of the Earth's viscosity. This signal largely contributes to the uncertainties in the determination of the ice mass balance, and consequently, regional and global sea level variations resulting from the present day global climate change.

3. The combination of density contrasts derived from gravimetric data with other information such as seismologic data facilitates the assessment of 4-dimensional (3 spatial directions and time) variations of density and viscosity in the inner globe at various time and spatial scales. This makes gravity a fundamental and mandatory input for the 4-dimensional global Earth model that geoscientists are eager to get. This will allow to decipher the geodynamic and sedimentary processes involved in the creation, evolution and destruction of the Earth's crust, in the mountain building and the deep-seated processes from which originate the volcanic chains, super volcanoes and large igneous provinces lying on the Earth surface.

4. The unprecedented space and time resolutions of future gravity missions should also allow a significant step forward in the exploration and monitoring of Earth's natural resources (geothermal energy, minerals, water).

5. Finally, such missions should help improving the understanding of processes acting in Earth's core, by comparing and combining secular gravity changes with other geophysical information. This should not only allow exploring the most hidden part of the world, but also help better understanding the Earth magnetic field dynamics and its reversals.

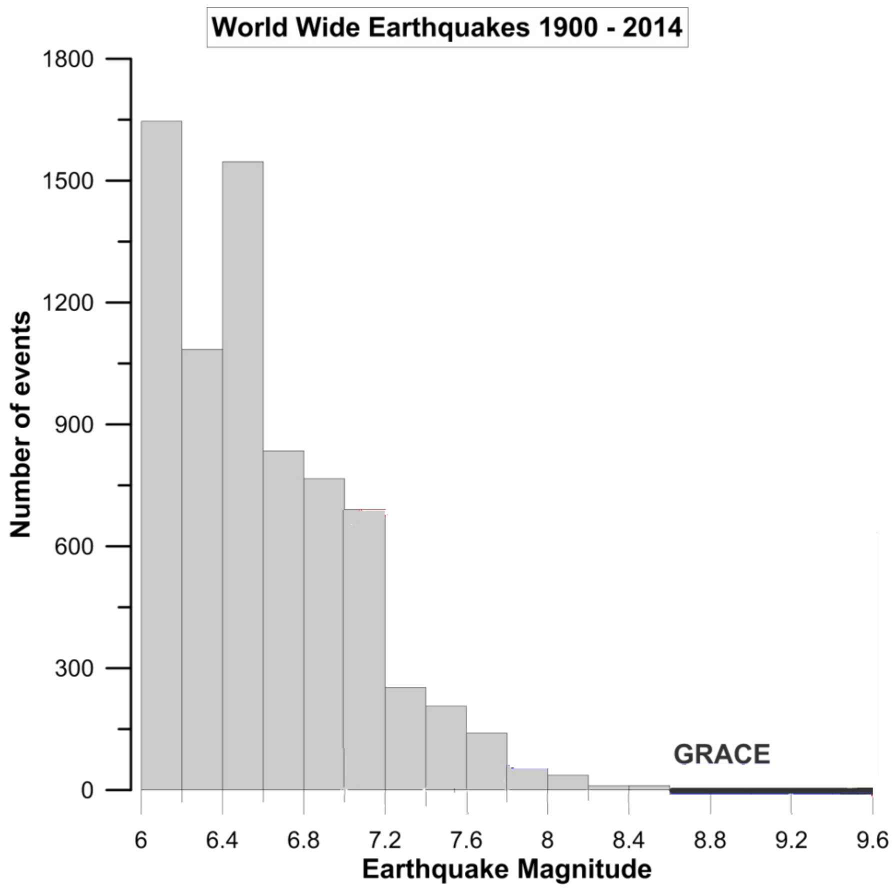

Figure 3-10 Global number of earthquakes with magnitude greater 6 for 1900-2014 (NEIC Database, From Pail et al. "Science and User Requirement Document, For a Future Satellite Gravity Constellation, An initiative by an international science team supported by IUGG, 2015"). The sensitivity of GRACE has been indicated for reference.

3.3 Applications and services

GRACE data have resulted in a number of scientific insights as evidenced by the nearly 2000 scientific publications related to the mission. Meanwhile, GRACE observations of climate-related issues contribute to the reports of the Intergovernmental Panel on Climate Change (IPCC). However, the potential for turning that scientific windfall into a benefit for society has been alluded to, but has not been fully realized. The main reasons are a low latency data provision and the limited resolution in space and time of present mass transport observations.

Currently, it takes approximately two months from the time that the actual observation is taken to the time when scientists can access and examine the data. Temporal sampling is at best 7-10 days but most reliably one month. Both of these time constraints limit the potential of using the results in time-critical monitoring applications. This applies in particular for early-warning and forecasting systems of extreme hydrological events. Flood forecast models need near-real time information to estimate the probable development of the event in terms of flood stage or river discharge with typical lead times of a few days for larger river basins. Also, the usefulness of high-resolution follow-up observations such as optical and radar observations for emergency management is strongly influenced by the time-span from alert reception, satellite programming, satellite acquisition and data reception. An overview of GRACE applications can be found on the GRACE Tellus webpage (http://grace.jpl.nasa.gov/applications/overview/).

At present the spatial resolution of mass transport observations is often lower than the area of interest for hydrological management and early-warning purposes. This applies in particular for Europe where the relevant size of river basins or sub-catchments is in the order of 10,000 km^2 or smaller, while the current available resolution of GRACE products is at best between 70,000 and 100,000 km^2.

Under the umbrella of the EC Horizon 2020 programme, the ongoing feasibility study EGSIEM aims at establishing prototype services for emergency management especially focussed on hydrology. One of the objectives is to provide a fast response/early warning by making use of mass transport observations in combination with e.g. altimetry, GNSS, SLR and other Copernicus satellite data and models. In case of a successful development this service should become part of the Copernicus emergency management services.

The main objectives related to applications and services are therefore to reduce the latency of data provision and increase the spatial and temporal resolution of mass transport products. An increased temporal resolution from one month to one day (for very large spatial scales) and the provision of mass transport products with smaller latency (close to near real-time) will translate into tremendous added value for warning and forecasting the onset of natural hazards.

Gravity-based indicators for extreme hydrological events need to be developed and their value for flood and drought forecasting and monitoring services demonstrated in support of operational satellite-based flood information services. A careful assessment of the performance of mass transport products as early warning indicators is mandatory and can be enhanced by a combination of modelling and comparison with complementary ground-based and satellite data, e.g. Synthetic Aperture Radar (SAR), altimetry, Global Navigation Satellite System (GNSS) data, gauge data (water level and river discharge).

In a similar manner as the potential to contribute to the ECVs as shown in Table 2-1, there is also a potential for enhancing and elaborating applications to support for example the Copernicus emergency management, marine environment, atmospheric monitoring and climate services.

3.3.1 Hydrology

The value of GRACE observations, and of observations from future gravity missions, is maximized when complementary observations are available. For example, integration of GRACE with other information (i.e., surface meteorological data and vegetation, soil, and topographical properties) within a numerical hydrology model enables spatial and temporal downscaling and vertical disaggregation of the GRACE data, and hence application for drought and water availability monitoring and high-resolution studies. More generally, complementary observations of variables including precipitation (GPM), runoff (SWOT), soil moisture (SMOS and SMAP), and snow cover (MODIS and VIIRS), facilitate the interpretation of gravimetric observations and enable a holistic understanding of the water cycle. Improvements in observation of other hydrology-relevant processes concurrently with improvement in spaceborne gravimetry could enable breakthrough science. For example, given a gravity mission with 100 km resolution as described above, high-resolution observations of precipitation and river stage (used to derive flow rates) could be used to estimate evapotranspiration as a water budget residual worldwide at a 25,000 – 50,000 km^2 river basin scale. Using those together with thermal remote sensing data-derived evapotranspiration maps, which provide high spatial and temporal resolution but require calibration, would go a long way towards the goals of accurate, high resolution global water budget closure and freshwater availability monitoring. Another potential breakthrough would be in the area of high-resolution groundwater monitoring and modelling, but that would require much better global maps of aquifer properties.

3.3.2 Atmosphere

The availability of spaceborne accelerometric observations provides a welcome and necessary information source for improving and, possibly near real-time, calibrating models of thermospheric neutral density. Knowledge of the variations in thermospheric density is required for improving the modelling and prediction of the motion of satellites. Air drag causes satellites to steadily decrease their orbital altitude. Many will eventually end up in the dense lower layers of the atmosphere, where friction gets large enough for them to burn up in the heat, either partially or completely. Density models are therefore required to determine a mission's life span and propellant budget. In addition, for large spacecraft that do not completely burn up on re-entry, models are used in order to predict the impact location of their debris. Another, more frequently applied application of such models is the prediction and prevention of possible collisions between spacecraft and space debris objects. With the increasing growth of space debris, this application is growing in importance.

4 Concepts

The primary objectives for science applications related to the observation of mass distribution and transport are to achieve higher spatial and temporal resolution with increased accuracy as well establishing a long-term continuous and consistent time series in terms of quality and resolution. Table 4-1 provides a summary of the observational requirements while Figure 4-1 shows a condensed impression of the spatio-temporal observational requirements and the challenges to be addressed. Both are derived to a large extent from the contents of Chapter 3 of this document. Meeting these objectives will improve existing and enable new scientific applications and services while also providing a multi-decadal, sustained observation system for mass transport as a primary source for global change monitoring and research. In order to reach these objectives, new observation concepts are required.

Based on a number of technological and scientific studies, as well as on the ongoing developments for GRACE Follow-On (GRACE-FO), it has been identified that a mission concept based on measuring the distance variations between two independent pairs of satellites is required for fulfilling the objectives in Table 4-1. We concisely refer to this mission concept as dual pair mission concept, in contrast to a mission concept with only one pair of satellites (single pair mission concept). Considering technological readiness, a dual pair mission with enhanced measurement precision can be realized within a decade from now guaranteeing continuity after end of life of the GRACE-FO mission. Other promising mission and sensor developments, such as cold atom interferometry, are currently underway. However, these technologies are not yet at sufficient Technological Readiness Level (TRL) to be considered for continuous observation after GRACE-FO. Nevertheless, due to their projected performance, it is recommended to fly them on demonstrator missions for proof of concept and to advance the maturity level of the technology. The remainder of this section describes in detail the envisaged dual pair mission concept, including the required spacecraft orbits, instrumentation, and data processing, along with expected outcomes. Future work necessary to realize such a system is additionally identified.

Table 4-1 Summary of observational requirements per application (refer to Chapter 3)

Requirement	Hydrology	Cryosphere & Ice Sheets	Oceanography	Atmosphere	Solid Earth
Spatial Resolution	30-1000 km	50-100 km	100-200 km	100-500 km	>100 km
Temporal Resolution	daily to weekly	1-10 days and longer	monthly and longer	1-10 days and longer	daily to monthly
Continuity	Decades (>30 years) with guaranteed continuity	decades (>30 years)	decadal (>10 years)	long-term, multiple of solar cycle (22 years)	long term
Latency	10 days or better			short for water vapour, long for re-analysis	
Products	disaggregated components	disaggregated components	disaggregated components	disaggregated components	

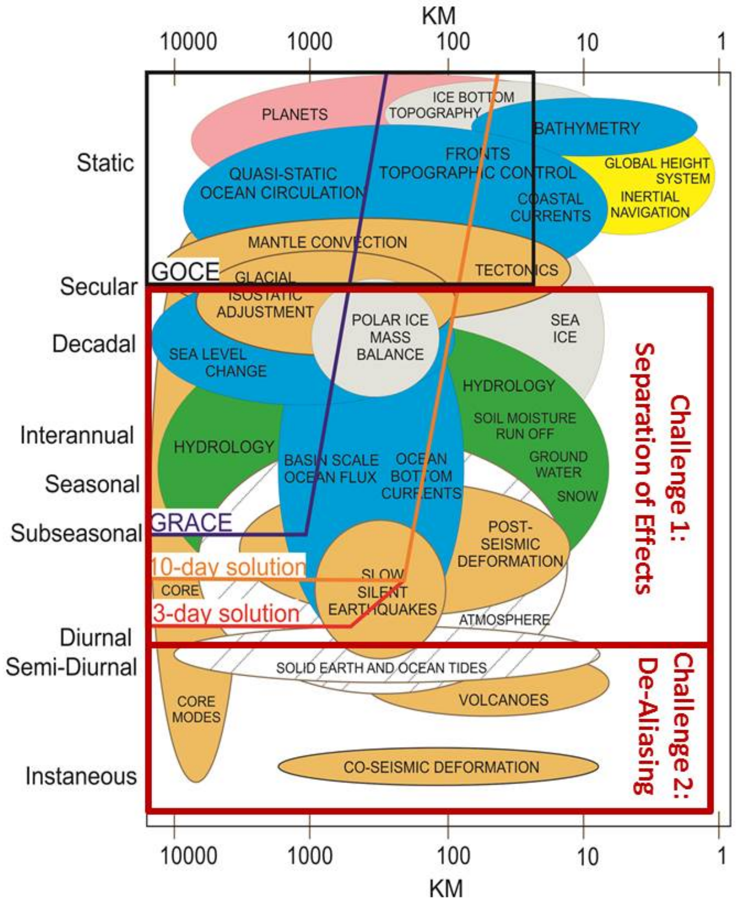

Figure 4-1 Spatio-temporal observation requirements, challenges and achievable results for future gravity missions.

The recommended dual pair mission concept consists of two independent satellite pairs flying in in-line formations utilizing satellite-to-satellite tracking between the satellites of each pair. In the preferred orbit constellation, one satellite pair flies in a near-polar orbit and the other in a moderately inclined orbit (Figure 4-2). It has been recognized that a concept with one pair of in-line satellites utilizing satellite-to-satellite tracking will be unable to fulfil the science requirements necessary for increased accuracy at the increased spatial and temporal resolutions desired, even if such a concept makes use of improved instrumentation (see e.g. Figure 4-3 and Figure 4-4 for the contrast in performance between a single pair and dual pair mission concept, assuming GRACE-II/NGGM performance). However, a concept consisting of two pairs of in-line satellites can provide significant increases in accuracy, and spatial and temporal resolution over what one pair of satellites can provide. For example, Figure 4-4 shows that a dual pair mission concept flying at a low satellite altitude will achieve 1.5 cm accuracy at a spatial resolution of approximately 270 km; this corresponds to being able to resolve 60% of the world's river basins (Section 3.2.1) rather than 30% of the world's river basins that a single pair concept at the same altitude could monitor. To achieve this performance, the second pair of satellites must be in a lower inclined orbit (between 65º and 75º is recommended), as this concept delivers an almost homogeneous quality while reducing errors across all spatial scales, and only necessitating post-processing at spatial resolutions smaller than approximately 400 km, unlike the single pair concept which necessitates post-processing at all spatial scales.

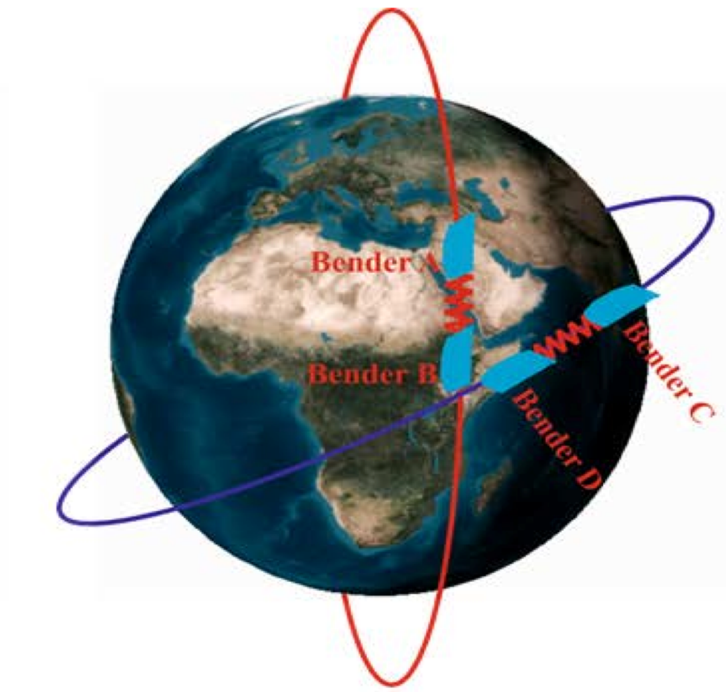

Figure 4-2 Example of a dual pair mission concept (often termed a “Bender concept”) consisting of two independent satellites pairs: one in a polar orbit and the other in a moderately inclined orbit.

The second pair of satellites is also essential for fulfilling the science requirement of increasing the temporal resolution, providing the capability of estimating mass transport over a range of temporal scales (daily to seasonal) at various spatial resolutions (1000 km to 100 km). A single pair mission concept does not provide the required temporal resolution for recovering mass transport at short temporal scales. As a consequence, rapid atmospheric and oceanic mass transport cannot be recovered and needs to be accounted for in the data processing using geophysical models. The ability of a dual pair mission concept to estimate mass transport at daily resolution at large spatial scales offers the possibility to reduce the reliance upon those geophysical models and consequently to reduce geophysical model errors that detrimentally affect the estimated mass transport. Significant progress has been made in optimizing the orbits of dual pair concepts for recovering mass transport. However, refinements of the associated search space of possible orbits with regards to scientific requirements are necessary to further optimize the relevant parameters (orbit height, inclination, repeat period, sub-cycles). Furthermore, it is important to realize that there is a trade-off between targeted temporal and spatial resolution of the estimated mass transport that should be addressed within the orbit design process.

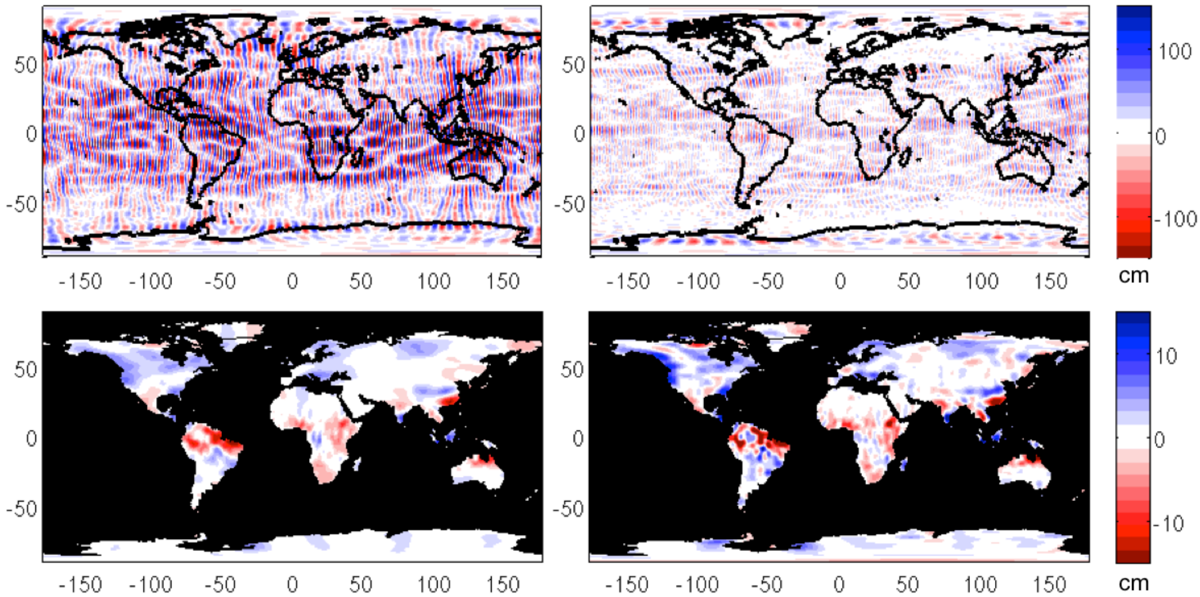

Figure 4-3 Recovered monthly gravity fields before post-processing from a single pair of satellites (top-left), and a dual pair mission concept (top-right) for recovering mass transport at 200 km spatial scales. Recovered monthly gravity fields after post-processing for a single pair of satellites (bottom-left) and a dual pair mission concept (bottom-right). The better apparent spatial resolution after post-processing of the dual pair concept relative to the single pair concept is evident (bottom row) as well as the reduction in the magnitude of the correlated error in the gravity field solution (top row).

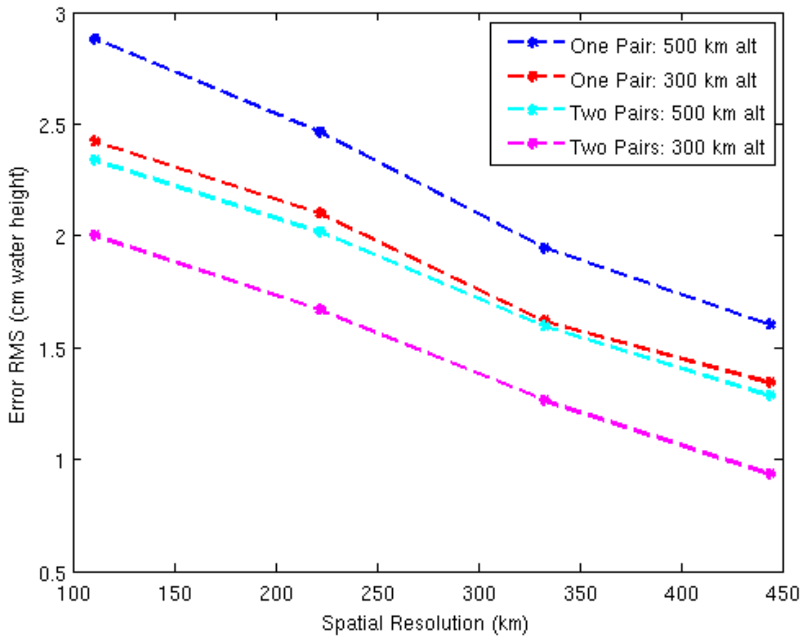

Figure 4-4 Error in the derived monthly gravity fields as a function of spatial resolution for single pair and dual pair mission concepts at altitudes of 300 km and 500 km (assuming GRACE-II/NGGM performance).

To enhance accuracy and spatial resolution of the mass transport models, an improved sensor system as compared to the GRACE instrument concept needs to be implemented. This consists of a laser interferometer for measuring distance changes between the satellites at a level of a few tens of nanometers (replacing the microwave system on GRACE and GRACE-FO). The level of sensitivity of the electrostatic accelerometers (which measure the non-gravitational forces like drag) needs to be at a minimum as accurate as the ones being flown on GRACE-FO, and optimally an order of magnitude more accurate. For both sensors there exists heritage from the developments made for the GOCE (accelerometers) and GRACE-FO missions (laser interferometer and accelerometers), which can be regarded as demonstrators for the proposed sensors. Largest gains in performance will be achieved if the satellites are flown at lower altitudes (see Figure 4-4); this would require either full or partial drag compensation, at a minimum in the flight direction and optimally in all 3 directions, to allow for extended mission lifetimes. Additionally, a drag compensation system allows to maintain the preferred orbits and constellation, which is crucial for achieving long-term consistency in spatio-temporal resolution of the mass transport models. This already illustrates that there is a trade-off among drag compensation, orbit altitude, orbit repeatability, targeted spatial and temporal resolution of gravity field models, and mission lifetime.

Processing of satellite-to-satellite tracking data to estimate mass transport has matured substantially throughout the GRACE mission lifetime, and will continue maturing during the mission lifetime of GRACE-FO. The dual pair concept will take advantage of these processing improvements and also implement entirely new processing methodologies. The dual pair concept that we recommend has the unique capability of resolving rapid mass transport at time scales as short as one day. Optimal processing strategies still need to be investigated, but available techniques show that the spatial resolution can be improved simply by, for instance, concurrently estimating daily mass transport together with that averaged over a longer time interval (e.g. one month). The choice of the processing strategy is directly linked to the orbit parameters. For instance, we envision a scenario in which the satellites are placed in a long-term seasonally repeating ground track (~90 days), with sub-cycles on the order of a week and a month. This coverage would allow to estimate daily, weekly, monthly, and seasonal mass transport at varying spatial resolutions and accuracies, meeting a broad range of science requirements (Table 4-1). This processing strategy has the advantage of reducing reliance on geophysical models to represent rapid mass transport during the data processing. However, it is unlikely that mass transport can be estimated on timescales less than one day, and as such it will still be imperative to forward model high frequency mass variations (both tidal and non-tidal) at sub-daily timescales. Simulations show that errors in these geophysical models will still likely be the limiting source of error for the dual pair concept, and as such, we recommend that the geophysical models (tidal and non-tidal) be improved for the timescales that are not directly resolvable. Since the largest ocean tide constituents have a predictable frequency that is higher than the dual pair mission concept can resolve, ocean tide model errors alias into the mass transport estimates at known periods. The orbit design procedure shall take into consideration favourable aliasing periods for ocean tides such that the tide model can be iteratively improved by co-estimating tide model corrections over long averaging times (years). First steps towards this end have already been taken with the GRACE data, but we expect the dual pair mission concept to provide significantly improved outcomes. Alternative basis functions such as mascons shall also be utilized to extract the maximum signal from the data for specific scientific application areas. Since gravimetric observations always represent the total signal from all sources of mass transport, it is required that methods for signal separation are further developed and refined to extract the signal of interest for specific scientific applications. These methods can be based on the spatial and temporal characteristics of mass transport and/or make use of ancillary/complementary data and models. For new applications, designated products may need to be defined.

Initial simulation studies show that a dual pair mission concept as described above enables the observation requirements to be met to a large extent (refer to Figure 4-1 and Figure 4-4). Results depend on the assumptions made for orbit configuration, measurement performance, uncertainties of geophysical models that are needed to model rapid mass transport during the data processing as well as signal separation. As the agencies move forward in mission concept and technical development, conclusive performance analyses need to be assessed using end-to-end simulations from satellite sensors to mass transport models in order to further optimize the mission scenarios and processing strategies. It is recommended to perform competitive simulation campaigns applying consistent simulation parameters and involving both space agencies in order to consolidate optimal mission and processing scenarios.

5 Roadmap

This roadmap is relevant for implementation in the post-2020 time-frame. Sustained and improved observation of mass transport in the Earth system is a prerequisite for better understanding global change and related societal issues (Chapter 3). This Chapter provides a time line for such sustained observation (Section 5.1), addresses the need for cooperation between different space agencies and/or providers (Section 5.2), and assesses required activities, such as studies and technological developments for the longer term (Section 5.3).

5.1 Timeline

GRACE has been providing observation of global mass transport and is expected to do so until 2017–2018, after which GRACE-FO will take over (Figure 5-1). Ideally there will be an overlap between these two missions that will enable a cross-calibration and verification. During the 2009-2013 time frame, GOCE provided crucial information for determining the mean gravity field with higher accuracy and spatial resolution. The continuous provision of GRACE mass transport models has led to a strong user community and initiatives for operational use. In the short term, the infrastructure for full exploitation of these mass transport models will continue to be built up (supported by the Horizon 2020 program), which will lead to an excellent starting position for GRACE-FO. GRACE-FO includes improved sensor systems (amongst others laser inter-satellite ranging as a demonstrator), thus it is anticipated that mass transport will be slightly better observed. However, GRACE-FO will not be able to solve problems that are inherent to mission concepts consisting of a single pair of in-line satellites in a polar orbit, such as inhomogeneous quality (e.g. leading to striations, Figure 4-3) and insufficient temporal resolution. GRACE-FO has a nominal lifetime until 2022 (5 years), after which GRACE-II is planned to continue observations of mass transport (NASA 2007 decadal survey). With the scenario of GRACE, GRACE-FO and GRACE-II, sustained observation of mass transport for the short to medium term can be guaranteed, be it with the limitations of having only a single pair mission (Figure 5-1).

A second pair of satellites, e.g. ESA's Next Generation Gravity Mission (NGGM) mission concept to be launched around 2025, flying (partly) simultaneously with GRACE-II in a suitable constellation would allow for meeting the user requirements for observing mass transport, and would be the start of sustained observations at high spatial and temporal resolution. This supports the further construction of a fully coupled Earth system model (mass conserving), which does not exist today.

For the post GRACE-II/NGGM period, i.e. in a 2035 time frame, alternative technologies such as cold atom interferometry may become feasible for spaceborne instrumentation, which could lead to significant further enhancements of observing mass transport, especially in terms of spatial resolution.

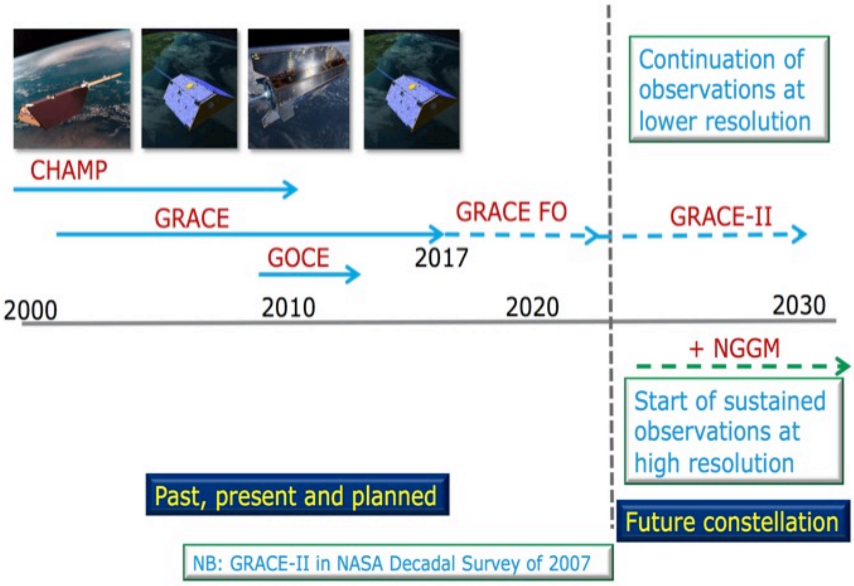

Figure 5-1 Timeline of spaceborne gravimetry

5.2 A Model for Cooperation

The GRACE-FO mission is scheduled for launch in August 2017 and has a planned lifetime of 5 years. NASA and ESA should develop timely plans for a constellation around the so-called GRACE-II concept for the post-2020 era, to enable discovery and understanding of small amplitude, rapid and high spatial resolution mass transport signals, in addition to the continuation of larger seasonal and decadal time-scale measurements begun by GRACE and planned to be continued by GRACE-FO.

It is understood that implementation of constellations for sustained and improved global observation of mass transport with technological improvements are demanding endeavours. Space agencies, including NASA and ESA have established models for cooperation to make implementation feasible. Possibilities for sharing knowledge and technology (e.g. in-kind contributions to each others missions) need to be explored and established in order to expedite the implementation of new missions and reduce cost. It is also strongly advised that the contributing space agencies and possible other partners aim at harmonizing ground segments as to guarantee timely and quality checked mass transport products and make optimal use of shared experience and processing methods and procedures.

Besides NASA and ESA, other parties are heavily interested in building spaceborne gravity missions. China has expressed a clear interest in implementing/building such missions. This has already led to a Round table Satellite Gravity Exploration China-Europe meeting in Beijing in 2013. It is advised to further exchange information with other parties and propose studies for optimizing constellations of more than two satellite pairs. NASA and ESA should therefore continue to explore bilateral cooperation with third parties to acquire additional resources. NASA and ESA should also continue to explore the use of international forums, such as CEOS, to coordinate the implementation of future gravity missions, and to enrol additional space agencies and sponsors to enable implementation.

In the past, gravity workshops in The Netherlands (2007) and Austria (2009) have further established and strengthened an active global user community of spaceborne gravimetry. The need for sustained observation of global mass transport at higher spatio-temporal resolutions was expressed already at those workshops. This also led to a resolution by the International Union of Geodesy and Geophysics (IUGG) that was communicated to NASA and ESA. Several working groups for future gravity missions have been established under the umbrella of IUGG, such as the GGOS Satellite Mission Working Group and the IAG special commissions 2.3 Dedicated Satellite Gravity Missions and 2.6 Gravity and Mass Displacements. Furthermore, NASA and ESA established the Interagency Gravity Science Working Group (IGSWG) in 2013.

5.3 Long Term Roadmap (post 2020)

As outlined in Section 5.1, the GRACE-FO mission guarantees continuity of observing mass transport for the short term, but only a minor part of the needed improvements in accuracy and spatio-temporal resolution can be met. For the post-2020 period, the possibility arises that for the first time mass transport can be observed with sufficient accuracy and spatio-temporal resolution if the NASA GRACE-II and ESA NGGM would be implemented.

5.3.1 Flight Systems

The NASA and ESA space agencies are urged to make plans for the post-2020 GRACE-II and NGGM missions, based on an assessment of the current technology (e.g. laser inter-satellite ranging, drag-free system, accelerometers) and initiate the programmatic steps needed to ensure a timely implementation. Both agencies must continue development of key technologies needed for a near-2030 GRACE-III implementation.

For the short term (2016-2018 time frame), studies for consolidating the mission concept for GRACE-II and NGGM need to be initiated/continued. The purpose of these studies is to solve recognized challenges for the implementation of future gravity missions, to reduce the cost of the implementation, to maximize available opportunities for launch, and thus to maximize the potential for realization of constellations without compromising data quality. It is important to identify and initiate the development of potential long-lead technology items, including:

- Improved metrology for measuring non-gravitational acceleration, in particular to ensure higher accuracy at low frequencies;
- Improvement of drag-free systems in the appropriate bandwidth.

For the long term (post GRACE-II/NGGM), it is important to advance possible alternative observing technologies and increase their technological readiness (e.g. cold-atom interferometry).

5.3.2 Ground Segment

Full exploitation of the data from future gravity missions requires the coordination of ground segments and information exchange between the associated space agencies and user communities. It is expected that NASA and ESA will continue their vigorous support of Engineering and Earth System Science research. In the following, some specific needs to maximize the utilization of the spaceborne gravimetric data are highlighted.

Geophysical models continue to improve due to ongoing efforts of the scientific community. It is required to assure the availability of geophysical models for mass transport that are accurate over long and short periods, consistent (e.g. mass conserving) and are continuously available.

Previous discussions have clearly identified the challenges that accompany the exploitation of the spatially integrated nature of the gravimetric observations of mass transport. It is recommended that NASA and ESA support studies focusing on the disaggregation, data assimilation, reduction of latency, and increase of temporal and spatial resolution. With the increased accuracy of next generation missions, these problems are compounded, and there is an incentive to solve this as part of the design of future gravity missions and the orbit constellations. The sponsorship should acknowledge that this research spans the range from data analyses, modelling and field data campaigns. The benefits of such support will be an increased data product user base, a larger and more diverse user community, and more direct application of mission outcomes to the solution of societal problems.

6 Conclusions

The observation of mass transport makes unique contributions to several essential climate variables and its continued observation is crucial for understanding global change and its impact on society. We recommend to make mass transport itself an essential climate variable. Although there is already an enormous potential for studying the system Earth with the ongoing GRACE mission (and soon GRACE-FO), the full set of user requirements in terms of accuracy and spatial and temporal resolution can only be met by constellations of spaceborne future gravity missions. This will allow the construction of a fully coupled, mass conserving Earth system model, which does not exist today. This is important for better understanding global change, geohazards (e.g. floods, earthquakes, sea level change) and related societal issues (e.g. freshwater supplies, safe access to space).

Future gravity missions need to come along with service providers that deliver the best mass transport products for applications in Earth and environmental science research, reduce the latency and increase the temporal resolution of the mass transport products, and develop indicators based on mass transport for extreme hydrological events and demonstrate their value for flood and drought forecasting and monitoring services.

Necessary scientific and technological activities are driven by and building upon both GRACE, GRACE-FO and GOCE mission heritage, as well as past high quality proposals for gravity field missions (e.g. Licody, e.motion). A constellation would be feasible around the 2025 time frame if NASA, ESA and the user community team up and closely coordinate the realization of the GRACE-II and NGGM missions. The framework for this has recently been established, both concerning the scientific user community (IUGG, IAG, GGOS, IGSWG) and the interaction with and between space agencies (NASA and ESA).

7 Abbreviations

ACC	Antarctic Circumpolar Current
AMOC	Atlantic Meridional Overturning Current
CEOS	Committee on Earth Observation Satellites
CHAMP	CHAllenging Minisatellite Payload
ECV	Essential Climate Variable
ESA	European Space Agency
IUGG	International Union of Geodesy and Geophysics
GIA	Glacial Isostatic Adjustment
GCOS	Global Climate Observing System
GGOS	Global Geodetic Observing System
GNSS	Global Navigation System
GPM	Global Precipatation Measurement
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GRACE	Gravity Recovery and Climate Experiment
GRACE-FO	Gravity Recovery and Climate Experiment Follow-On
IAG	International Association of Geodesy
IGSWG	Inter-agency Gravity Science Working Group
IPCC	Intergovernmental Panel on Climate Change
MODIS	Moderate Resolution Imaging Spectroradiometer
MOVE	Meridional Overturning Variability Experiment
NASA	National Aeronautics and Space Administration
NEIC	National Earthquake Information Center
NGGM	Next-generation Gravity Mission
RAPID/MOCHA	Rapid Climate Change-Meridional Overturning Circulation and Heatflux Array
RMS	Root-Mean-Square
SAR	Synthetic Aperture Radar
SMAP	Soli Moisture Active Passive
SMOS	Soil Moisture and Ocean Salinity mission
SWOT	Surface Water and Ocean Topography
TRL	Technological Readiness Level
VIIRS	Visible Infrared Imaging Radiometer Suite

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