Kusche, J., Klemann, V., Bosch, W. (2012): Mass distribution and mass transport in the Earth system. - Journal of Geodynamics, 59-60, 1-8

DOI: 10.1016/j.jog.2012.03.003

Mass distribution and mass transport in the Earth system

Jürgen Kusche(1), Volker Klemann(2) and Wolfgang Bosch(3)

(1) Institute of Geodesy and Geoinformation,
University of Bonn, Bonn, Germany

(2) Section 1.3, Earth System Modelling,
GFZ German Research Centre for Geosciences, Potsdam, Germany

(3) Deutsches Geodätisches Forschungsinstitut, Munich, Germany

Abstract

Melting of continental ice sheets and glaciers, changes in ocean circulation pattern and in sea level, variations of surface and ground water levels and river discharge, glacial-isostatic adjustment, mantle convection and tectonics, all this causes transport and (re-) distribution of mass inside the Earth and at its surface. Equipped with precise sensor systems, gravity field and altimeter satellites observe these mass-transport processes. During 2006-2012, the German Research Association DFG had established the SPP 1257, `Mass distribution and Mass Transport in the Earth System' as a coordinated research program to facilitate integrated analysis of these data, to improve our knowledge about several transport processes within the Earth system and to investigate their interactions. This special issue reports about the findings of the first four years within the program.

Keywords. Satellite gravity, altimetry, hydrology, oceanography, sea level

1. Introduction

The current generation of satellite altimetry and gravity missions has changed the way we look at dynamic processes at the Earth's surface. With the Jason-1 and -2 altimeters, new and more accurate maps of the time-variable ocean surface have been drawn (e.g. Beckley et al., 2007). Similary, the ICESat and CryoSat missions track changes in ice-sheet elevations (e.g. Abshire et al., 2005, Wingham et al., 2006). The Gravity Recovery and Climate Experiment (GRACE, Tapley et al., 2004) allowed, for the first time, to determine small changes in the Earth's gravitational field due to mass transport in the cryosphere, hydrosphere, and in the world's oceans, while the Gravity field and steady-state Ocean Circulation Explorer (GOCE) mission now provides the most detailed model of the mean geoid for spatial scales of less than 100 km (Pail et al., 2011). While the altimeter observations track mass changes through elevation variations, the gravity field enables one to view changes in mass distribution directly and, so, to trace mass transport by hypothesizing transport models.

These geodetic products are being explored in many ways: For example, the monthly GRACE-gravity models quantify more accurately than ever how much of the melting at the polar ice sheets and in the glacier regions of the Earth contribute to sea-level rise. Moreover, GRACE constrains water-storage change over continental regions and thus allows validation of our understanding of climate- and anthropogenic-driven changes in the hydrological cycle. It is also used to investigate solid-Earth mechanisms like glacio-isostatic adjustment (GIA), alongside with GPS and other measurements. Altimetry data have been processed in tailored re-tracking schemes to provide height changes in coastal areas and for inland water bodies such as lakes and rivers. Synergies between these new geoid and sea surface measurements have been explored to obtain the dynamic topography of the ocean at higher resolution than was available before, and to resolve ocean warming and deep ocean currents. It is similarly true for ice caps and glaciers, where new and tailored altimeter missions provide volume change with homogeneous coverage over large regions. Expectations are therefore high for the future, with a number of altimetry and gravity missions being under development.

Clearly, a large part of this success has been facilitated through coordinated research efforts. In this special issue we report about the coordinated research program, SPP1257, conducted during the previous five years in Germany and funded by the German Research Foundation DFG. However, before discussing recent findings to measure the enormous progress made during recent years, it is helpful to trace back our state of knowledge just a few years ago.

Back in 2005, the GRACE level-2 data type – monthly models of the gravity field in terms of spherical harmonic representation with certain background fields removed was still quite new and efforts focused on validating these release-1 data sets from geophysical modelling. Compared to the pre-GRACE era, with laser-ranging satellites and the GPS-tracked Challenging Minisatellite Payload (CHAMP), these models allowed resolution of the temporal gravity field at spatial scales at a factor of 10-20 smaller than before. Research had just begun to consider the CHAMP and GRACE geoids as a viable means of constructing the dynamic ocean topography (e.g. Rio and Hernandez, 2004), while GOCE was a then “future” geodetic mission exploited only within simulation scenarios. Overall, these new satellite-derived gravity models were considered as somewhat uncommon data by many scientists – certain signals were already removed during the processing, as with the Atmosphere and Ocean De-aliasing (AOD) models, or as the secular behaviour in certain spherical harmonic coefficients, which needed to be restored depending on the application. GRACE data miss degree-0 and degree-1 harmonics, and need to be strongly smoothed or “de-striped” to provide useful maps. As some users of GRACE data put it, one needed a “friendly geodesist” to work with. Gravity data are linked to vertically aggregated mass change which, on one hand, was considered to be one of the less well-known parameters in geophysical models, and on the other hand, necessitates the separation of different contributions from modelling or direct measurement which is difficult.

It is worth noting that, in the realm of altimetric observation of the sea surface, measurement accuracy was progressing more gradually but equally spectacularly. While with Topex/Poseidon a single measurement of the SSH may have been accurate to 5-10 cm, this has improved to 1-2 cm with Jason-1 and -2 (Cazenave and Llovel, 2010). This allows determination of sea-level rise with uncertainties of some 0.1 mm/a, which is only few percent of its total value.

Concerning knowledge of processes, we will only mention one example. With the IPCC Third Assessment Report published in 2001, the most uncertain contribution to sea-level rise was considered to be the total (world-wide) contribution from land/water-storage changes, since an integrated measurement of this quantity did not exist and the aggregation of run-off from gauges and other data was considered as extremely difficult. Compared to this, the contributions of glaciers and the Greenland and Antarctic ice sheets were even thought as well-constrained. In contrast, today we assume that land/water storage is much better known, while we believe that earlier estimates of ice-mass contributions could have been flawed for several reasons and that the uncertainty of thermal expansion of the oceans might be much larger than previously assumed.

In this situation, DFG decided in 2006 to establish the priority research program SPP1257 „Mass transport and mass distribution in the Earth system”, in order to enable scientific analysis and interpretation of data from the new generation of gravity and altimetry satellite missions. Priority research programs are meant to stimulate interdisciplinary research in enabling fields, and they support universities and research centres with about 2 Million Euro per year for six years. In the SPP1257, hydrologists, glaciologists, oceanographers, geophysicists, geodesists and mathematicians work together towards the understanding of Earth system processes. Today we can conclude that the program has enabled German research groups to play their part in the world's top groups in various areas of Earth system research.

In the beginning, the research areas of the SPP1257 were discipline oriented, with the aim of embracing a new type of data within the hydrology, oceanography, solid-Earth physics and glaciology communities, while at the same time geodesists would try to understand the detailed behaviour of new sensor systems like the micrometer-precise ranging instrument aboard GRACE, and to optimize the processing of new data. Figure 1 illustrates the interdependence of processes and their relation to the observables. In addition, a major goal was to educate a new generation of multidisciplinary Earth scientists, growing up with a common language.

Whereas the SPP1257 is now near its end, disciplinary research has evolved into three interdisciplinary themes along which we have also organized the remaining part of this introductory article: (1) developing a complete and thorough understanding of the signals that are present in the new types of data, and characterizing uncertainty, resolution and consistency of theses data; (2) at weekly to decadal timescales, assessing, harmonizing and integrating all relevant contributions to water-mass transports and water-storage variations in the global hydrological cycle by exploiting the new data sets; and (3) at longer timescales, gain insight into processes such as GIA, mantle convection, ice-mass balance, sea-level rise and steady-state ocean circulation by constraining models with consolidated GRACE, GOCE and altimetry data sets of improved accuracy and consistency. Scientists from about 20 institutions, including European and overseas groups, have participated in the program with about 25 collaborative research projects. Numerous Ph.D. theses have been completed or are nearing completion.

2. Contributions

Overall, this volume contains 21 contributions (including this editorial) which we have arranged according to the above mentioned research themes (see Table): understanding the satellite signals (Section 2.1), short-term processes (Section 2.2), and steady state and long-term processes (Section 2.3). The main synergies are between the first and the two later ones (9 contributions), due to the fact that the understanding of the satellite signals benefits substantially from investigating the underlying geophysical processes. This holds not only for the short-term processes (5 contributions), which represent the main objectives of the GRACE mission, but holds also for the long-term processes (4 contributions). In particular, the GRACE mission was designed from the beginning for a 5-year lifetime, but this year will reach its 10th year in orbit and, so, provides a much longer time baseline than expected at first. This allows a better understanding of inter-annual variability and long-term trends which are especially important to aspects of global change. The 11 further contributions confront data interpretation and their scientific applications. In most cases, other geodetic or geophysical data like GPS, altimetry or surface gravity are assessed in combination with GRACE gravity fields. This shows the complementary information of GRACE contributing to understanding mass-transport processes.

2.1. Understanding the satellite signals

As of today, the information content of the new satellite-gravity data sets is yet to be fully explored in terms of uncertainty, resolution and consistency. Before such data sets can be used operationally, e.g. by combination with other data or assimilation into physical models, it is mandatory that their characteristics in time and space are fully understood. The quality of these sets depends critically, amongst others, on the quality of background models, on consistent data processing and on the use of application-tailored filters. The ultimate goal of decomposing the integrated mass signal into its geoscientific constituents is complicated by the simultaneous use of the same background models for de-aliasing purposes and for mass-signal separation. Within the SPP1257 theme "Understanding the Satellite Signals" a number of projects dealt with these issues, and some of them report their findings below.

Zenner et al. (this volume) investigate improvements for the fundamental GRACE-de-aliasing problem caused by notorious under-sampling of short-term mass variations. Standard GRACE processing applies error-free geophysical models to reduce short-term mass variation in the GRACE observations and to add back their mean values (the so-called AOD de-aliasing products) to monthly gravity-field solutions. The authors compare this error-free scenario with those accounting for atmospheric and oceanic uncertainties. The most significant impact is recognized by taking the differences of ECMWF and NCEP as a proxy for atmospheric uncertainties. Such uncertainties propagate into the AOD products but remain within a magnitude of a mm. Comparing standard and modified AOD products, the difference in the K-band range-rate residuals of GRACE becomes regionally visible, but no effect can be observed in the gravity-field solutions. Zenner at al. conclude that the impact of uncertainties in the background models still stays below the actual GRACE-error level.

Riegger et al. (this volume) address different types of uncertainty in GRACE level-2 data and their contribution to the error budget of monthly sets of spherical-harmonic coefficients. Their approach is to compare GRACE mass derivatives, dM/dt, with mass-change rates from evaluating the hydrological and hydro-meteorological water balances for river catchments with available runoff measurements. On this basis, Riegger et al. (this volume) are able to identify “outliers” in the GRACE data sets (those monthly sets of coefficients which would imply physically impossible consequences such as negative evaporation). Their removal significantly improves the correlation of GRACE solutions with modelled hydrological output, long-range correlations, which are still under investigation, and random errors.

Mayer-Gürr et al. (this volume) rate the impact of GRACE solutions on the improvement of the altimetry based empirical ocean tide model EOT08a as small. They identify the limited baseline of the GRACE time series as the main reason why they were not able to improve specific harmonic constituents of the model. Nevertheless GRACE helped to improve some tidal constituents in the Arctic oceans above 60°N where altimetry is sparse or not available due to the respective orbit design.

Kurtenbach et al. (this volume) deal with the important topic of increasing the temporal resolution of GRACE gravity-field solutions. Compared to monthly, 10-day, or weekly solutions, the investigation aims to resolve daily variations of the Earth gravity field. The significant decrease of observational redundancy is compensated by a Kalman-smoother approach introducing stochastic a-priori information for the daily gravity variations that are derived from the spatio-temporal correlation pattern of geophysical models for atmosphere, ocean and continental hydrology. The approach is first tested by a closed-loop simulation and then applied to GRACE level-1b data. The analysis results in a time series of daily gravity-field solutions, developed for degree and order 2–40, which form a part of the gravity-field model series ITG-Grace2010s (Mayer-Gürr et al., 2010). The validation with ocean-bottom pressure data and the time series of continuously operating GPS sites demonstrates a reduction of RMS values when the effect of the daily GRACE solution has been subtracted.

Sasgen et al. (this volume) inferred from level-2 products of the different centres (CSR, GFZ, ITG and JPL) the linear trend in gravity change by only considering those spectral coefficients that appear as statistically significant for this contribution. By this form of a statistical filter, they could reduce the striping of the unfiltered GRACE solutions markedly and propose in this way an alternative to the commonly used Gauss filter.

Rietbroek et al. (this volume a, b) discuss two time ranges of interest in joint inversion, seasonal and secular signals. Due to the different physical processes apparent in the respective signals, different analysis techniques have to be applied. In their paper on periodic signals (this volume a), these authors concentrate on the geocenter (GC) motion, which describes the average motion of the Earth’s surface against its centre of mass and is mainly influenced by net mass redistribution in the Earth system. In addition to the assessment of the motion itself, they discuss the need to consider the GC motion when interpreting ocean-bottom-pressure (OBP) data. With respect to secular signals, Rietbroek et al. (this volume b) discuss the influence of different mass transport processes like present ice sheets, land glaciers, GIA and terrestrial hydrology by applying a joint inversion using the so called fingerprint method. They conclude that the GIA contribution dominates the secular GC motion.

Weise et al. (this volume) employ the data of the – relatively sparse – network of superconducting gravimeters (SG) of the 'Global Geodynamics Project' (GGP) in order to validate GRACE data. However, they show that local hydrological effects in the SG observations, station stability of the SG sites with respect to vertical deformations, and filtering of the GRACE spherical harmonic models are all of serious concern for this kind of comparison. A maximum correspondence between the SG and GRACE time series is achieved when GRACE data are smoothed with Gaussian filters of about 1000 km; this is in line with previous publications involving SG data but much coarser to what is believed to be the resolution where GRACE data contains true geophysical signals.

In Janjic et al. (this volume), spectral consistency between geoid and sea-surface data is studied through two different approaches: a global, spherical harmonics based technique, and a regional, profile-based method. The global approach requires that the altimetric sea surface is mathematically extended to the land areas in order to cover the whole Earth’s surface; this usually necessitates an iterative remove–extrapolate–restore procedure. On the contrary, the rationale for the profile approach is to avoid any initial gridding of the sea-surface heights because it implies an undesirable smoothing which is difficult to control. Profile-wise filtering in the spatial domain also requires specific attention. After the spectrally filtered geoid heights are sampled to the altimeter profiles, the along-track sea-surface heights have to be filtered consistently. To this end, the authors introduce a filter correction. Both geodetic approaches for estimating the dynamic topography are applied to multi-mission altimetry data (TOPEX/Poseidon, ENVISAT, Jason-1, and GFO) and the GRACE geoid.

Consistency of error estimates is extremely important when one seeks to improve ocean circulation modelling from combining observations of sea surface height and the geoid, since different spatial representations are involved. Becker et al. (this volume) suggest a procedure to estimate the MDT on an arbitrary model grid as the difference between altimetric SSH and geoid height, while taking into account omission errors explicitly. They show how different assumptions about the omission error lead to different MDT estimates.

For ice altimetry, Ewert et al. (this volume) examine the mass changes of the Greenland ice sheet derived from ICESat repeat-track analysis, and compare them to estimates inferred from GRACE. ICESat was the first Earth-orbiting laser altimeter satellite and since its launch in January 2003, the GLAS laser-altimeter system has provided data with an unprecedented level of accuracy and resolution with a footprint only varying between 60 and 70m. There are several methods to retrieve elevation changes from these data, and, in order to make use of the full potential of ICESat high-resolution altimetry, Ewert et al. develop a repeat-track approach that avoids the use of external digital elevation models.

2.2 Short-term processes

At weekly to decadal timescales, water mass redistributions within and exchanges among near-surface Earth subsystems, such as oceans, cryosphere and continental hydrosphere, dominate the GRACE signal. It is mandatory that assessments of all relevant contributions to water-mass transports and water-storage variations in the global hydrological cycle be harmonized and integrated consistently. This includes a harmonization of the different physical models as well as the validation of integrated water-mass and -flow modelling using GRACE, satellite altimetry and complementary data. Research in SPP1257 aims at improvements of physical modelling approaches and GRACE processing required for achieving a successful integration. A number of contributions to this special issue deal with mass transport in a more general sense, i.e. they aim at a consistent description of the total mass-transport field associated with all changes in atmosphere, ocean and continental hydrosphere at the weekly to decadal time span.

Rietbroek et al. (this volume a) derive weekly surface-loading variations from a joint LSQ inversion using GRACE gravimetry, load-induced GPS site displacements, and simulated OBP from FESOM. This emphasises the need of a joint inversion of different processes that contribute to global signatures in the observational data. Especially the GC motion as an integral observable is contributing significantly with 24.5 mm amplitude to the signal of the main hydrological regions such as Amazon, Australia, SE Asia and Europe, and, also has a significant effect on the OBP. Furthermore, the authors suggest applying background loading models in the analysis of GPS networks due to a consistent decrease in RMS of at least 10% in the seasonal amplitude.

Schmeer et al. (this volume) develop a statistical method to separate the total mass transport field as derived from the GRACE data into individual contributions from the atmosphere, the ocean and the continental hydrosphere. While this separation is conventionally performed by reducing “background models” from the GRACE data, it is known that these models have problems and their errors map into the “residual” contributions which are of interest. Schmeer et al. adjust the leading principle components of model output from GRACE data, and show that their technique improves all contributions simultaneously. In particular, they consider limitations of their separation approach by studying correlations between modes, potentially across the physical compartments.

Fritsche et al. (this volume) look at the load-induced deformation of the crust due to temporal mass variations in the continental hydrosphere and in the atmosphere. In their study, water mass variations as computed by the WGHM model (see also Döll et al., this volume) and surface pressure as provided by the re-analysis product of NCEP are used to describe the loading, respectively. In order to assess the model admittances, reprocessed GPS observations from more than 200 globally distributed stations were used to estimate scaling factors for the load-deformation time series. Site-specific factors are identified for hydrological and for air-pressure loading. Averaged over all GPS sites, WGHM is found to slightly overestimate temporal variations of water storage, while it agrees well with GRACE. Regarding atmospheric-pressure loading, a relatively large discrepancy for the dominant vertical component indicates an underestimation of the model predictions.

One of the prominent processes that accompany climate change and significantly contribute to sea-level change both on annual and interannual time scales is the loss of ice mass over the ice caps and the glaciated regions of the planet. Ewert et al. (this volume) use ICESat and GRACE to provide estimates of 205 km^3/yr volume change and 191 Gt/yr mass change for the Greenland ice sheet within 2003-2008, corresponding to 0.53 mm/yr eustatic sea-level rise, which is more than twice the value from the IPCC 2007 report.

Zenner et al. (this volume) investigate the impact of errors for atmospheric and oceanic background models applied to account for the inevitable under-sampling of short-term mass variations by GRACE. They conclude, however, that even the significant differences between ECMWF and NCEP data, taken as a proxy for atmospheric uncertainties slightly affect the range-rate residuals. But, the differences remain below the actual GRACE error level when further propagated to the gravity-field solutions.

In addition to physical models of natural hydrological transport processes, global ground-water transport models like WaterGAP must also contain water-use models for irrigation, livestock, households etc. Döll et al. (this volume) perform the first global-scale analysis of water withdrawals on water-storage variations. They estimate 35% of the water withdrawn worldwide to be ground water. Due to the fact, that most data are based on point measurements, GRACE data might contribute assessments of seasonal net-mass flux between the compartments. In case of the less intensively irrigated Mississippi basin, they could not confirm this assumption. Furthermore, they identified the merit of deriving area-averaged groundwater storage from point measurements.

Aus der Beek et al. (this volume) discuss a new version of WaterGAP, WaterGAP3, which is regionally adjusted for investigating the Mediterranean and Black-Sea river basins. Comparison with GRACE-determined mass change demands a correction for leakage. They found a higher agreement for the Mediterranean than for the Black Sea. Furthermore, they determined the annual signal to be slightly underestimated in WaterGAP3 when compared to WaterGAP2.

Riegger et al. (this volume) assess continental water-storage changes at monthly time-scales by using GRACE and several combinations of hydrological and hydro-meteorological fields. Since these represent three independent data sources, comparison among them enables the quantification of uncertainties. They find that GPCC V4 precipitation data and ERA-INTERIM atmospheric moisture flux perform best in statistical analyses along with GRACE data. However, these authors identify a problem with the EOF mode 1 of the GRACE mass derivative; i.e. spatially correlated errors that deteriorate the correlation with hydrological and hydro-meteorological fields. The origin of this signal component is not clear and needs further investigation.

While these and other studies have impressively demonstrated the potential of GRACE to improve hydrological models, few alternatives exist to validate the GRACE data with independent observations. Weise et al. (this volume) employ superconducting gravimeter (SG) data for this purpose. Their study focuses on the dense SG network in Central Europe with its long-term gravity observations. Weise et al. can show that after the separation and reduction of local hydrological effects in the SG observations, especially for subsurface stations, the time-variable gravity signals from GRACE agree well with the terrestrial observations from this SG-station network.

Fenoglio-Marc et al. (this volume) investigate for a period of six years water mass variations of the Mediterranean and Black Sea. The basins' mean mass signals observed by GRACE and expressed in equivalent water heights are compared with time series of altimetry-derived sea-surface heights that are corrected for the steric effect. A variety of additional data and models are consulted in order to identify the most convenient steric correction, to account for the leakage of continental hydrology and to estimate the freshwater budget. For the Mediterranean Sea, an excellent agreement at seasonal and inter-annual time scale is achieved while, in the Black Sea, the consistency between GRACE and altimetry data is lower, in particular for the non-seasonal time series. Based on mass-conservation principle the mass transport at the Bosporus and the Gibraltar Strait are also derived.

The most important short-term process of the ocean is its periodic response to gravitational forces. Mayer-Gürr et al. (this volume) present the empirical ocean-tide model EOT08a, which is based on the analysis of multi-mission altimetry data. In this context, they discuss the ability of using GRACE data to improve this type of models, and conclude that the contribution of GRACE data remains small due to the present baseline accuracy, but may change by applying a different analysis technique.

2.3. Steady-state and long-term processes

Steady-state processes associated with the solid Earth, such as crustal structure and mantle convection, map themselves onto the static gravity field, whereas mass redistribution associated with the steady-state ocean circulation is better revealed by how it affects the mean sea surface. New and consolidated satellite data sets therefore provide an opportunity to improve our knowledge of these processes. For example, marine gravity data have been improved by reprocessed and extended altimetry, and, with the March-2009 launch of GOCE, gravity data of improved accuracy and resolution have become available. Research includes the aim of achieving a successful integration of satellite data into models. Likewise, long-term processes such as GIA, ice-mass balance and sea-level rise can be further constrained with the improving accuracy and duration of the consolidated GRACE and satellite-altimetry time series. In addition, by considering complementary data, new insights into these processes can be developed.

Density heterogeneity of the mantle, which has also an effect on dynamic deformations of the Earth’s surface, controls to a large extent the long-wavelength part of the gravity field. Therefore, in addition to seismic velocities the observed geoid is used for a joint inversion to constrain mantle properties and convection flow. Kaban et al. (this volume) extend such an inversion by taking into account the mantle transition zone with discontinuities at 410 and 660 km. Velocity-to-density scaling factors and density jumps at these discontinuities are solved for. While the results for the 410 km discontinuity is close to predictions of mineral physics the density contrast at 660 km is underestimated by a factor of four. These authors suggest that a decreased gravity effect may be explained by the presence of multiple phase transformations within a depth range of 640-720 km. Due to the negative sign of the Clapeyron slope, which characterizes these discontinuities, the total gravity effect is reduced. The estimated mantle flow across the transition zone is ± 20 mm/yr, which corresponds to a whole-mantle convection. The geoid fit improves if the inversion is performed by accounting for the mantle transition zone.

Another process that maps into the steady-state gravity field is the upwelling of plumes – bodies of hot buoyant rock material – in the Earth’s mantle. Sharaki and Schmeling (this volume) study the impact of rheological variations, i.e. temperature and depth-dependent viscosity, on the shape of the geoid and of the dynamic topography above a plume through a series of numerical convection simulations. They determine different categories of the geoid, which are related to the considered type of rheology.

Köther et al. (this volume) focus on Central America and derive the stress state of the lithosphere from gravity data, where they combine surface and satellite data. They conclude that especially in regions with a rough terrain, the downward continuation of existing satellite gravity data like GRACE is not sufficient for the inference of structural features in the lithosphere but demands higher resolutions like that of the GOCE mission.

For this mission, they estimate the minimum extension of lithospheric structures to be about 45 km if a 10% change in density is assumed. Analysis of the existing surface data in the forearc region results in consistency between the gravity-derived stress field and that determined from Earthquake distributions.

The long-term time variable gravity signal can be related to secular processes in the Earth’s system. Here, Sasgen et al. (this volume) invert GRACE-based time series of monthly gravity-field solutions from four different processing centres in order to estimate actual ice-mass changes for Alaska and Greenland as well as mantle viscosities for North America by a two-step procedure. First, a statistical filter is applied reducing the noise in the GRACE gravity fields and removing their artificial North-South striping pattern. Second, present-day ice-mass changes and forward-modelled GIA models are taken and rescaled by simultaneously adjusting their gravity effect on the trends of the filtered GRACE fields. The authors derive the recent sea-level contribution of Alaska and Greenland in the order of +0.2 and +0.6 mm/a, respectively, and conclude that, for optimal mantle viscosities beneath North America, the glaciation load history requires a rescaling of less than 10% to reconcile the GRACE data.

Brunnabend et al. (this volume) emphasize the importance of regional sea-level variations due to fresh-water influx from Greenland ice melting. Applying the finite-element sea-ice/ocean model FESOM, these authors find regionally strong deviations from global mean sea-level change due to temperature and salinity variations in the upper ocean that mainly follow the surface currents. These deviations are much larger than the global corrections due the gravitational effects on the sea level induced by the Greenland ice-mass loss and must, be considered in regional studies.

Rietbroek et al. (this volume b), in contrast, discuss the gravitational influence of mass redistribution on the sea level. This signal is detectable in GRACE as in altimetry data and is therefore suitable for a joint inversion. In contrast to an altimetry-only solution, together with GRACE-gravity data it is possible to explain a large part of the variability in Pacific, Atlantic and Indian oceans.

Janjic et al. (this volume) revisit the subject of incorporating dynamic ocean topography (DOT), observed from geodetic satellites, into a general ocean circulation model, by means of a state-of-the-art data-assimilation system. This topic is highly relevant, particularly since GOCE mean gravity fields are rapidly improving in accuracy and spatial resolution and in view that the first satellite-only combined models from GRACE and GOCE have been released only recently (Pail et al. 2010). The authors show that assimilation of GRACE and multi-mission altimetry reduces the RMS difference between model and data from 16 cm to 5 cm. Assimilation of geodetic DOT data improves transport estimates, and the assimilated DOT estimates are available in the polar or coastal regions where the geodetic DOT alone is not adequate.

Becker et al. (this volume) combine consistent MDT solutions from altimetry - here in form of the CNES CLS 2010 sea surface - and gravimetry - the ITG-GRACE2010s geoid - with the Inverse Finite Element Ocean Model (IFEOM). Their combined solutions show some remarkable new features that are a consequence of both the new gravity field data and the new combination method. For example, large differences in temperature compared to earlier solutions can be found in the Gulf Stream area, whereas water is found less saline at the southern boundary of the Gulf Stream. Deep water masses along the coast of Greenland and in the Labrador Sea are found to be somewhat cooler and more saline in the combined solution than in earlier solutions, and these differences are within the range of the assumed prior errors in this model region. The authors interpret this finding as an increase in deep water formation rates when more cold and saline surface water sinks to greater depths. However, depending on their combination strategy, meridional overturning stream functions and estimates of poleward oceanic heat transport differ, for example, among the various solutions.

3. Summary and Outlook

In summary, we can state that the coordinated interdisciplinary research of SPP1257 has helped to improve the quality of satellite-data products and to generate new, tailored products, e.g. through improved background products, new level-1/2 processing and post-processing techniques. For example, new ocean-tide models have been developed which serve to improve altimetry and GRACE processing. We now better understand the limitations of GRACE, when the resolution is pushed for investigation of small ocean or catchment basins. We also begin to use GRACE for calibrating sensitive parameters of hydrological models and understanding rheological properties of the Earth's interior. New methods for separating the vertically aggregated GRACE and altimetry data into contributions from atmosphere, cryosphere, ocean and hydrosphere, or even into layers within ocean or hydrosphere have been developed. Furthermore, the separation of present and past ice-mass changes improves with the time span of the GRACE mission. In general, the procedures to exploit GRACE (and also GOCE) gravity data have been significantly consolidated, and the number of groups working with these data is still increasing (Figure 2).

And finally, a growing number of both disciplinary and interdisciplinary Ph.D. theses have been completed. A more complete overview of the scientific "output" of the SPP1257 can be found at the program's website www.massentransporte.de.

4. Acknowledgements

We would like to thank all contributors to this special issue, and all reviewers who have helped to improve the presentation of the results shown here. Special thanks go to editor-in-chief Randell Stephenson for guiding us smoothly through the compilation of this issue. Finally, we would like to acknowledge DFG's program supervisor Johannes Karte and former SPP1257 spokesman Heinz Ilk. The results presented here would not have been possible without their efforts in shaping the program. We would also like to thank the German Space Operations Center (GSOC) of the German Aerospace Center (DLR) for providing continuously and nearly 100% of the raw telemetry data of the twin GRACE satellites.

References

Abshire, J. B., Sun, X., Riris, H., Sirota, J. M., McGarry, J. F., Palm, S., Yi, D., and Liiva, P.: Geoscience Laser Altimeter System (GLAS) on the ICESat mission: on-orbit measurement performance, Geophys. Res. Lett., 32, L21S02, doi:10.1029/2005GL024028

Aus der Beek T., L.Menzel, R. Rietbroek, L. Fenoglio-Marc, S. Grayek, M. Becker, J. Kusche, E. Stanev (this volume), Modelling the water resources of the Black and Mediterranean Sea river basins and their impact on regional mass changes

Becker S., W.-D. Schuh, M. Losch, G. Freiwald (this volume), Rigorous Fusion of Gravity Field, Altimetry and Stationary Ocean Models

Beckley B. D., F. G. Lemoine, S. B. Luthcke, R. D. Ray, and N. P. Zelensky (2007), A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits, GRL 34(14): L14608, doi:10.1029/2007GL030002

Brunnabend S.-E., J. Schröter, R. Timmermann, R. Rietbroek, J. Kusche (this volume), Modeled steric and mass-driven sea level change caused by Greenland Ice Sheet melting

Cazenave A. and W. Llovel (2010), Contemporary Sea Level Rise, Annu. Rev. Mar. Sci. 2:145–73

Döll P., H. Hoffmann-Dobrev, F.T. Portmann, S. Siebert, A. Eicker, M. Rodell, G. Strassberg (this volume), Impact of water withdrawals from groundwater and surface water on continental water storage variations

Ewert H, A. Groh, R. Dietrich (this volume), Volume and mass changes of the Greenland ice sheet inferred from ICESat and GRACE

Fenoglio-Marc L., R. Rietbroek, S. Grayek, M. Becker, J. Kusche, E. Stanev (this volume), Water mass variation in the Mediterranean and Black Sea

Fritsche M., P. Döll, R. Dietrich (this volume), Global-scale validation of model-based load deformation from continental water mass and atmospheric pressure variations using GPS

Janjic, T., J.Schröter, A. Albertella, W. Bosch, R. Rummel, R. Savcenko, J. Schwabe, M. Scheinert (this volume), Assimilation of geodetic dynamic ocean topography using ensemble based Kalman filter

Kaban M., V. Trubitsyn (this volume), Density structure of the mantle transition zone and the dynamic geoid

Köther N., H. J. Götze, B. D. Gutknecht, T. Jahr, G. Jentzsch, O. H. Lücke. R. Mahatsente, R. Sharma, S. Zeumann (this volume), The seismically active Andean and Central American margins: Can satellite gravity map lithospheric structures?

Kurtenbach E., A. Eicker, T. Mayer-Gürr, M. Holschneider, M. Hayn, M. Fuhrmann, J. Kusche (this volume), Improved daily GRACE gravity field solutions using a Kalman smoother

Mayer-Gürr, T., R. Savcenko, W. Bosch, I. Daras, F, Flechtner, C. Dahle (this volume), Ocean tides from satellite altimetry and GRACE

Pail, R., Goiginger, H., Schuh, W.-D., Höck, E., Brockmann, J. M., Fecher, T., Gruber, T., Mayer-Gürr, T., Kusche, J., Jäggi, A., and Rieser, D., 2010. Combined satellite gravity field model GOCO01S derived from GOCE and GRACE. GRL, 37:20314–+, doi:10.1029/2010GL044906.

Pail, R., S. Bruinsma, F. Migliaccio, Ch. Förste, H. Goiginger, W.-D. Schuh, E. Höck, M. Reguzzoni, J. Brockmann, O. Abrikosov, M. Veicherts, T. Fecher, R. Mayrhofer, I. Krasbutter, F. Sansò and C. Tscherning, (2011), First GOCE gravity field models derived by three different approaches, J. Geodesy 85(11): 819-843, doi: 10.1007/s00190-011-0467-x

Riegger J., M. J. Tourian, B. Devaraju, N. Sneeuw (this volume), Analysis of GRACE uncertainties by hydrological and hydro-meteorological observations

Rietbroek R., M. Fritsche, S.-E. Brunnabend, I. Daras, J. Kusche, J. Schröter, F. Flechtner, R. Dietrich (this volume a), Global surface mass from a new combination of GRACE, modelled OBP and reprocessed GPS data

Rietbroek R., S.-E. Brunnabend, J. Kusche, J. Schröter (this volume b), Resolving sea level contributions by identifying fingerprints in time-variable gravity and altimetry

Rio M.-H. and F. Hernandez (2004), A mean dynamic topography computed over the world ocean from altimetry, in situ measurements, and a geoid model, JGR Oceans, 109:C12032, doi: 10.1029/2003JC002226.

Sasgen, I., V. Klemann, Z. Martinec (this volume), Towards the inversion of GRACE gravity fields for present-day ice-mass changes and glacialisostatic adjustment in North America and Greenland

Sharaki M. and H. Schmeling (this volume), Plume-induced geoid anomalies from 2D axi-symmetric temperature- and pressure dependent mantle convection models

Schmeer M., W. Bosch, F. Seitz, M. Schmidt (this volume), Separation of mass signals within GRACE monthly gravity field models by means of Empirical Orthogonal Functions

Tapley B. D., S. Bettadpur, J.C. Ries, P.F. Thompson and M. M. Watkins (2004), GRACE measurements of mass variability in the Earth system, Science 305(5683): 503-505, doi: 10.1126/science.1099192

Weise A., C. Kroner, M. Abe, B. Creutzfeldt, C. Förste, A. Güntner, J. Ihde, T. Jahr, G. Jentzsch, H. Wilmes, H. Wziontek, S. Petrovic (this volume), Tackling mass redistribution phenomena by time-dependent GRACE- and terrestrial gravity observations

Wingham D. J., C.R. Francis, S. Baker, C. Bouzinac, D. Brockley, R. Cullen, P. de Chateau-Thierry, S.W. Laxon, U. Mallow, C. Mavrocordatos, L. Phalippou, G. Ratier, L. Rey, F. Rostan, P. Viau, D.W. Wallis (2006), CryoSat: A mission to determine the fluctuations in Earth’s land and marine ice fields, Advances in Space Research, 37:841-871

Zenner L., E. Fagiolini, I. Daras, F. Flechtner, T. Gruber, T. Schmidt, G. Schwarz (this volume), Non tidal atmospheric and oceanic mass variations and their impact on GRACE data analysis

Contribution	Further theme	GRACE+GPS	GRACE+OBP	GRACE+terr. grav.	GRACE+alt.	GRACE+ICESat	Atmosphere	Ocean	Hydrosphere	Cryosphere	Solid Earth	Main feature
1. Understanding of signals												
Zenner et al	2.						x	x				De-aliasing
Riegger et al	2.						x		x			Uncertainty
Mayer-Gürr et al.	2.				x			x				Ocean tides
Kurtenbach et al.												Daily solutions
Sasgen et al.	3.							x		x		GIA
Rietbroek et al. a	2.	x	x					x	x			Joint inversion
Rietbroek et al. b	3.				x			x	x	x		Sea-level
Weise et al.	2.			x			x		x			SG GRACE
Janjic et al.	3.				x			x				Data assimilation
Becker et al.	3.				x			x				Consistency
Ewert et al.	3.					x		x		x		Ice-mass balance
2. Short-term processes												
Schmeer et al.							x	x	x			Signal separation
Fritsche et al.		x					x		x			Surface loading
Döll et al.									x			Water storage
aus der Beek et al.					x			x	x			WaterGAP3
Fenoglio-Marc et al.					x			x	x			Small basins
3. Steady-state and long-term processes												
Kaban & Trubitsyn											x	Convection
Sharaki & Schmeling											x	Mantle plume
Köther et al.				x							x	Tectonics

Brunnabend et al.		x	x	Freshwater influx

Table 1: Relation of contributions to themes, application of data in addition to GRACE, investigation of processes and their main feature.

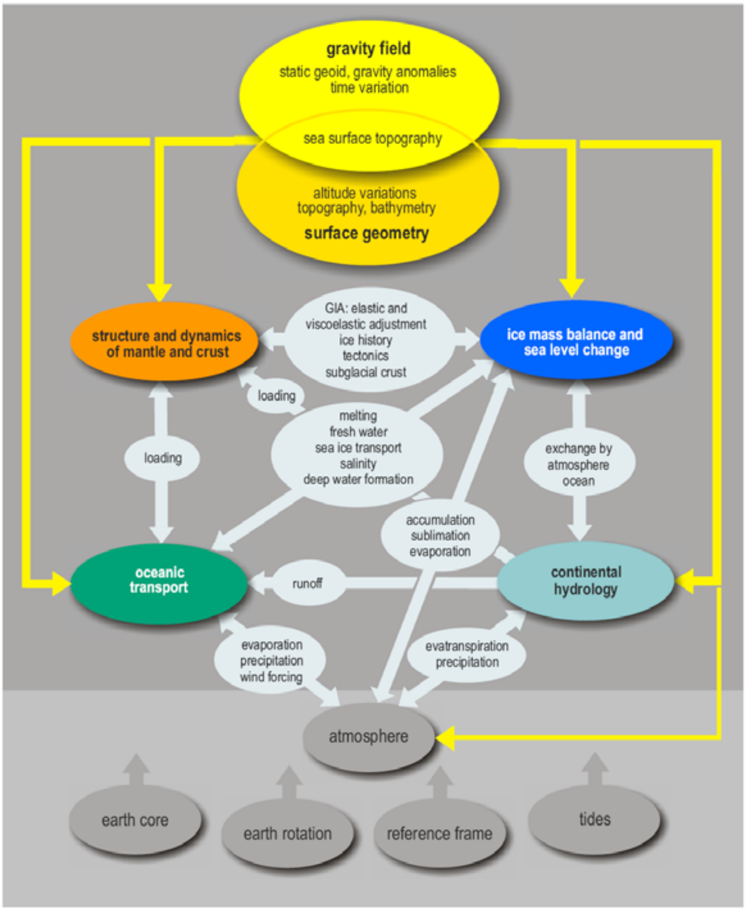

Figure 1: Interdependence of the main processes under consideration in the SPP 1257 and their relation to the geodetic observables

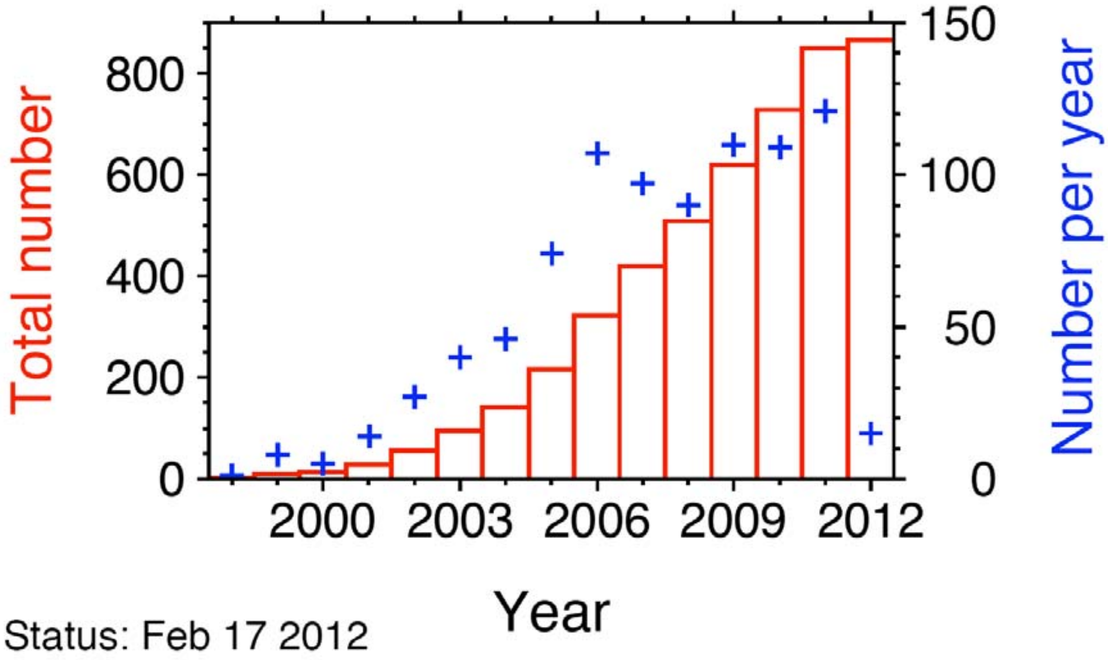

Figure 2: Histogram of peer-reviewed publications related to GRACE (www.gfz-potsdam.de/portal/gfz/Struktur/Departments/Department+1/sec12/projects/grace/grace_publications). Figure shows distribution and cumulative distribution of publications (in total 864) until mid of February 2012.