Proposal for a DFG Priority Programme

Mass Transport and Mass Distribution in the Earth System

Causes and effects of spatial and temporal mass variations based on novel satellite observations of gravity field changes and surface deformations

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Summary

This priority research programme aims at a breakthrough in the recovery of mass transport and mass distribution and in the understanding of the underlying dynamic processes on the Earth's surface and in its interior. Following mass signals and processes will be investigated and interrelated:

- absolute transports in the ocean and their temporal variability,
- continental water storage variability on large scales and related water fluxes,
- mass balance of ice sheets,
- global and regional sea level changes,
- steady-state and time dependent dynamics of the Earth's interior, and
- lithospheric structure and surface processes, including hazard monitoring.

In all of these areas, fundamental questions are still open today, which could be answered by the programme. The processes are intimately coupled by mass exchange between ocean, ice, continents and atmosphere and by their forcing mechanisms. Therefore, the programme aims at an integrated and interdisciplinary Earth system modelling. The results will be essential for the understanding and the prediction of the global water cycle. New insights into processes responsible for the stability and variability of our climate are expected.

The mass signals will be analyzed on the basis of spatial and temporal variations of the Earth's gravity field and of changes in the surface geometry which are observed by a new and unique constellation of simultaneously operating gravity and altimetry satellite missions. The temporal variability of mass distribution will be determined from gravity changes, which are now for the first time observed by the satellite gravity missions CHAMP and GRACE, and from height changes of water and ice surfaces, which are simultaneously observed by satellite altimetry missions. For the oceans, for the first time the absolute surface current velocities will be determined from the combination of satellite altimetry with geoid data from the GRACE and GOCE satellite gravity missions. Furthermore, the unprecedented quality of geoid and gravity anomalies from the new satellite gravity field models will be used to improve dynamical models of the Earth's mantle and structure models of the Earth's crust. The homogeneous and extremely precise observations of the novel satellite sensor systems are the only possible way to recover these mass signals directly and globally. Thus, the satellite-based data sets are triggering a new research field in geosciences at present. No terrestrial equivalent does and will ever exist.

Based on only two years of gravity data from the GRACE mission, the feasibility of global mass change detection and its relevance to global sea level and hydrology has been demonstrated just recently. However, an integrated and interdisciplinary approach and an intensive exchange of data, model results and techniques are required for the correct interpretation and the separation of the complex superimposed signals, such as sea level change due to thermal expansion and mass increase through ice melting.

The programme will bring together leading scientists from geodesy, oceanography, hydrology, glaciology, geophysics and other geosciences. A particular objective is to stimulate in Germany a network of young geoscientists participating in the use of the novel and excellent satellite data. The next six years mark a unique time window to achieve the above goals through the availability of data sets of unprecedented quality, allowing us to carry out hitherto impracticable, but now urgently needed investigations. It is expected that the integrated research proposed will contribute to revolutionize our understanding of the dynamical processes on the Earth's surface and in its interior.

1. Scientific programme

1.1 State of research and own preparatory work

The present state in gravity field recovery as well as altimetric water and ice surface geometry determination is outlined, and the status in the research areas of oceanic mass transport, continental hydrology, ice mass balance, sea level changes as well as dynamics and structure of the Earth's crust and mantle is reviewed. A detailed description focussing on satellite gravity and altimetry missions can be found in the extended document submitted together with this proposal (ILK et al., 2005).

1.1.1 Gravity field recovery

In view of the geoscientific requirements, plans for dedicated satellite gravity missions have been worked out since more than 30 years and have been realized in the years 2000 and 2002 with the missions CHAMP (REIGBER et al., 1999) and GRACE (TAPLEY et al., 2004a) to be followed in the year 2006 by ESA's GOCE mission (ESA, 1999). The novel measurement techniques are satellite-to-satellite tracking and satellite gradiometry, respectively. As a result, a breakthrough in accuracy and resolution has been achieved with the gravity field models (REIGBER et al., 2004a) derived from data generated by the single satellite mission CHAMP, and in particular by the dual-satellite mission GRACE. Meanwhile, next to the highly accurate and high resolution models, also monthly snapshots of the gravity field have been computed from GRACE. These allow for the first time the resolution of temporal variations over a wide spatial and temporal spectrum. German scientists are deeply involved in the preparation, development, realization and exploitation of the satellite gravity missions. In particular, Ch. Reigber is PI for CHAMP and Co-PI for GRACE and R. Rummel is PI for the gravity field analysis of ESA's GOCE mission. The new observational techniques stimulate and require advanced processing methods. Important progress has been achieved very recently in dynamic and kinematic precise satellite orbit determination (SVEHLA & ROTHACHER, 2003). Besides the further developed classical method in satellite gravity analysis (REIGBER et al., 2003a), alternative methods are now successfully applied, e.g. based on the energy balance along the satellite's orbit (GERLACH et al., 2003), on integral equation solutions (MAYER-GÜRR et al., 2004), and on direct orbit acceleration exploitation (REUBELT et al., 2003). Of particular interest are also new developments in the validation and verification of the products of the satellite missions (LÖCHER & ILK, 2005).

As far as temporal gravity field variations are concerned, the variation in the Earth's gravitational flattening has been studied since some time and interpreted in terms of geophysical and environmental processes (CAZENAVE & NEREM, 2002; COX & CHAO, 2002). First suggestions for extracting and separating higher resolution time-dependent signal constituents from GRACE data were given by WAHR et al. (1998). MOREAUX & BALMINO (2002), SWENSON et al. (2003) and RAMILIEN et al. (2004) in particular investigated the recovery of hydrological signals. VELICOGNA & WAHR (2002) studied the recovery of post-glacial rebound signals from gravity variations. Oceanic mass signals and their detectability from GRACE were investigated by LEULIETTE et al. (2002) and WAHR et al. (2002). These concepts are presently applied and improved using GRACE mission results. First promising results have been obtained with regard to seasonal continental water storage changes derived from GRACE monthly gravity field solutions (SCHMIDT et al., 2004; TAPLEY et al., 2004b; WAHR et al., 2004). Further analyses are now concentrating on oceanic and glacial mass variations.

1.1.2 Recent results from the CHAMP and GRACE missions

CHAMP and GRACE mission data and products are made available to the international user community through well-established data centres. A large variety of CHAMP and GRACE study results were presented during the two 'CHAMP Science Meetings' in 2002 and 2003 and the 'Joint CHAMP/GRACE Meeting' in summer 2004 at GeoForschungsZentrum Potsdam and published in two Springer books (REIGBER et al., 2003b; REIGBER et al., 2005). The contributions to the third workshop are presently under preparation for publication. With regard to Earth gravity field recovery, the efforts are concentrating on so-called *static gravity field models* averaging over a long time interval and on a time series of *monthly gravity field solutions* to investigate temporal gravity variations.

Static gravity field models form the basis for isostatic, geotectonic and geodynamic interpretation (mass anomalies and fluxes). The static geoid represents the reference surface for geodetic applications and the altimetric determination of sea surface topography and, by this, the absolute ocean circulation pattern. The presently best satellite-only static model is derived from three years of CHAMP and four months of GRACE observations (Reigber et al., 2004a). A corresponding high-resolution model is derived by adding satellite altimetry as well as terrestrial, ship- and air-borne gravimetry data (Reigber et al., 2004b). The satellite-only model resolves features in the gravity field larger than 200 km (pixel size), and the combination solution has a resolution of 50 km (cf. Figure 1). The achieved accuracies at these resolutions are 10 cm to 20 cm (geoid) and 1 mgal to 5 mgal (gravity anomalies). The geoid accuracy threshold of 1 cm, which is important for oceanographic applications, is attained with the satellite-only solution at a resolution of 250 km.

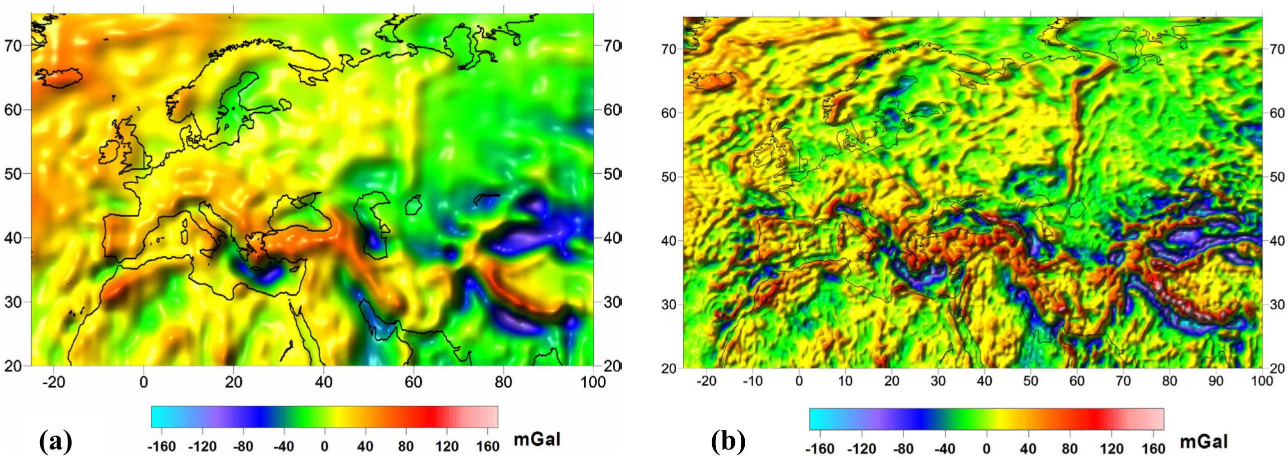

Figure 1. *Gravity anomalies over Europe from (a) CHAMP and GRACE mission data only, and (b) after incorporating altimetry surface and terrestrial gravity data.*

It could be demonstrated, that from the sequence of GRACE monthly gravity field models seasonal continental water storage variations can be traced. Largest variations are observed over the principal tropic and Russian river basins (Schmidt et al., 2004). As a first important result, it has been found that the GRACE observed amplitudes are about 50% larger than those predicted by global hydrological models (cf. Figure 2). This is due to the limited capabilities of the hydrological models to represent *total* water storage variations. This success proves that the GRACE configuration is capable to observe environmentally relevant processes from space, with global coverage.

At the given temporal resolution of one month and a spatial resolution of 1000 km (pixel size), an accuracy of 1 mm (geoid), 1 µgal (gravity anomaly) and 25 mm (equivalent water column), respectively, is achieved with the present monthly GRACE gravity field solutions. It is expected that by advances in data exploitation, by improvements in the background models (atmosphere, tides, cf. Velicogna et al., 2001; Schrama, 2005), and by the enlargement of the data base and the decaying orbit altitudes of CHAMP and GRACE as well as by the rigorous combination of CHAMP and GRACE data, a gain in accuracy of a factor 2 to 4 will be obtained in both the CHAMP and GRACE based static global gravity field models and the series of monthly gravity field solutions.

1.1.3 Water and ice surface geometry from satellite altimetry observation

Satellite altimetry is a remote sensing technique mapping the ocean surface in a fast, precise and nearly global way (Chelton et al., 2001). Combining the data of different altimeter missions with complementary sampling characteristics – currently realized in particular by Jason-1 and Envisat – allows monitoring the mean sea level and its changes with high spatial and temporal resolution. The time series of altimetric sea surface heights available up to now shows regionally rather different evolutions of the mean sea level (Bosch et al., 2001). The amplitudes and phases of seasonal and long-period variations are accurately known (Stammer, 1997). Anomalous developments of the sea level, as associated for example with the El Niño events, can be clearly identified (Bosch, 2001). The accuracy of sea surface heights achieved so far is of the order of a few cm only. However, up to now it is not clear if altimeter systems have sufficient long-term stability to estimate the global sea level rise with an accuracy of 1 mm/year (Mitchum, 1998). Problems that require further research are the realization and stability of the reference systems, the harmonisation of models required to correct altimeter observations (LeTraon et al., 1996) and the absolute and relative calibrations of all missions (Christensen et al., 1994).

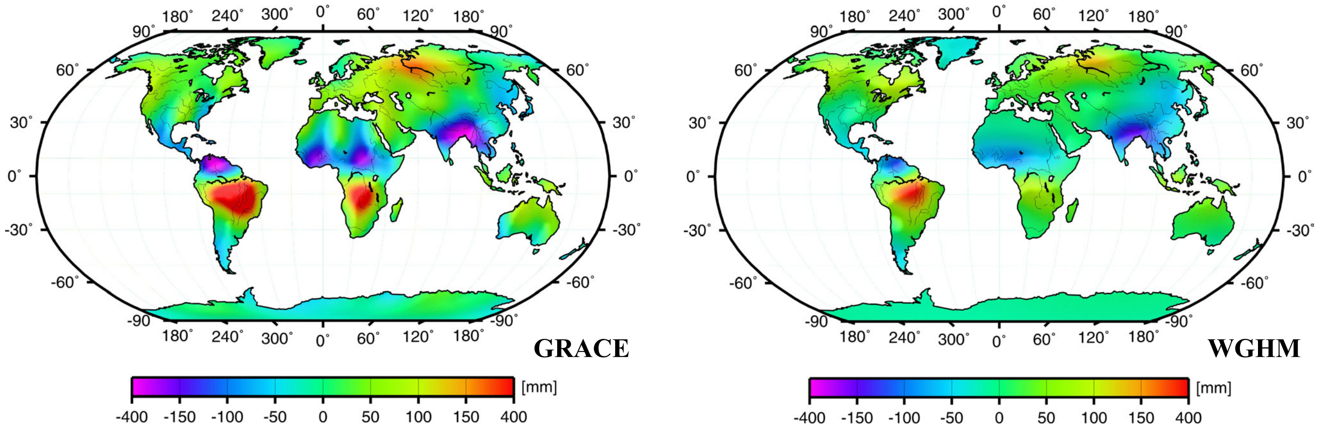

Figure 2. *Differences in continental water storage between summer and spring 2003 derived from GRACE gravity field solutions compared to those predicted by the global hydrologic model WGHM (Döll et al., 2003); in units of equivalent water column.*

While in the past most attention was focussed primarily on time-varying sea surface height measurements (due to the lack of accurate geoid fields), the future research will shift its focus to absolute sea surface height fields and associated currents, including the time mean component. This will require, however, that the same effort will be spent on understanding time mean signals and time-mean error structures as it was done for time-varying components in the past. As an example, Chelton et al. (2001) estimate that the time mean electromagnetic bias error in satellite altimetry could be as large as 15 cm over the region of the Antarctic Circumpolar Current (ACC). If this is true, the oceanographic community can make full use of the new and precise geoid fields only after fully understanding and reducing the errors in the time mean sea surface height fields. An error of 15 cm in sea surface height across would result roughly in a 15 cm/s error in the ocean flow field which is close to 20% of the mean ACC amplitude, an unacceptable situation. Only the joint analysis of the new geoid fields, the absolute sea surface height fields, in situ data and ocean circulation models by taking into account uncertainties in all individual components can lead to the success required in this research programme for the determination of the absolute and time-varying ocean flow field and transports.

The past altimeter missions (in particular ERS-1/2) also allowed the determination of the height and height changes of the polar ice caps (Wingham et al., 1998). However, they were limited to latitudes of +/- 82° and areas with rather smooth topography. With innovative sensor technologies, the new missions ICESat (http://nsidc.org/daac/icesat/) and, starting 2005, CryoSat (Francis, 2001) will overcome these limitations and provide a nearly complete coverage of the polar ice caps with improved resolution and accuracy. For the first time, CryoSat will also completely observe the distribution and thickness of sea ice. In addition, satellite altimetry is used to determine the water levels for lakes, rivers and wetlands (Birkett, 1998; Alsdorf et al., 2000). The new altimeter missions with their increased accuracy (Bjerklie et al., 2003) together with global water level analysis (Berry & Pinnock, 2003) can significantly contribute to the determination of large scale water storage variations.

1.1.4 Oceanic transport

The analysis of satellite data during the last 10 years has revolutionized our understanding of the dynamical processes in the ocean. In particular, the TOPEX/Poseidon mission has lead to entirely new insights into the variability of ocean circulation, into mixing processes and into changes in the density and mass distributions (Fu & Cazenave, 2001). Due to the previously large errors in the existing geoid models on spatial scales relevant to energetic ocean currents, the focus of previous studies was primarily on the transient signals (LeTraon & Morrow, 2001). As a result, the use of geoid models in ocean studies remained the exception (e.g., Stammer et al., 2002, Seufer et al., 2003). With the newly or soon available geoid models from the GRACE and GOCE missions, a leap in our understanding of the absolute ocean circulation on those scales can be expected (WUNSCH & STAMMER, 2003).

Among the open questions are those related to regional and global sea level change. Previously, the important question of the separation of heat- and mass-induced sea level changes remained largely unresolved. In particular, the changes in circulation that are related to mass changes in the ocean cannot be detect using traditional data; they are at present the source of large uncertainties when estimating the transports and the mass balance changes in the ocean (SCHRÖTER et al., 2002).

1.1.5 Continental hydrology

Mass transports on the continents are mainly determined by water transport processes (precipitation, runoff in rivers and in the groundwater, water transfer to the atmosphere by evapotranspiration). Imbalances in the related flows lead to changes in the water storage (surface, soil, groundwater). Continental water storage however currently cannot be determined satisfactorily for large areas. As a consequence global and continental water balances are not sufficiently known either. The considerable uncertainties in water balance are a result of difficulties in measuring hydrological variables for large areas, i.e., measurements of precipitation, evapotranspiration, river discharge and water storage as groundwater, surface water, snow or ice. Ground-based measurements of the water storage provide point data and, thus, are of limited value for large areas. Remote sensing approaches so far were restricted to the surface storage (surface water bodies, snow, ice, near-surface soil moisture) and are, due to methodological constraints regarding their accuracy and spatial coverage, still of limited practical use. Estimates of continental water storage changes exhibit a strong spatial variation between less dynamic areas in the temperate zone or in drylands and regions with strong seasonal water storage variations such as in the tropics (RODELL & FAMIGLIETTI, 1999; GÜNTNER et al., 2004). Due to the lack of adequate measurements of water storage changes, the evapotranspiration rate is only approximately known for large areas until now. Furthermore, the contribution of different storage components to total water storage changes is insufficiently known for large scales. Hydrological models are used at different spatial scales to quantify the water transport between the various storage components and to describe the relevant hydrological processes (BÁRDOSSY & HUNDECHA, 2004; RIEGGER et al., 2001; GÜNTNER & BRONSTERT, 2004; DÖLL et al., 2003). In most cases, however, model validation is performed by a comparison with the observed river discharge only. Thus, any conclusions regarding the accuracy of these models for simulating storage changes are of limited value. Therefore, the measurement of large-scale water storage variations is essential in hydrology for the evaluation of models as prognostic tools in water resources assessment as well as for the validation and improvement of climate models. First results of the GRACE mission show a seasonal hydrological signal at the continental scale and for large river basins (TAPLEY et al., 2004a,b; WAHR et al., 2004; SCHMIDT et al., 2004). The results emphasize the importance of these new satellite-based data for an improved quantification of the continental water cycle and its related mass transport processes.

1.1.6 Ice mass balance and sea level

The traditional method to determine the balance of the polar ice sheets is to model the individual mass balance terms and to make up the budget. The mass balance terms are accumulation by precipitation, ablation by melting, evaporation, sublimation and mass discharge to the ocean. With present-day models, based on relatively few measurements, the budget method cannot constrain the total balance of both polar ice sheets to better than ± 20% of their mass input (CHURCH et al., 2001), with the major error source being the determination of the mass loss terms (since the output velocity and the ice thickness must be known). Taken together, current mass budget results suggest that the mass balance of the Antarctica and Greenland ice sheets lies between – 35% and + 5% of their mass input, i.e., the combined imbalance is equivalent to a sea-level contribution of between + 2.4 and – 0.2 mm/year. Thus, due to the lack of data (surface heights, surface velocities, mass changes over large areas), it is still unknown, whether the polar ice sheets are loosing or gaining ice mass in total and how they contribute to the global sea level rise. From glaciological in-situ data, the ice flow and mass balance can be determined in detail for selected areas. The coverage of large areas, however, is only possible by the use of satellite data. A critical topic is the unknown vertical motion of the bedrock (postglacial rebound), which may overlay signals of ice surface changes (JAMES & IVINS, 1997). Concepts for the separation of the superimposed signals in the satellite data have been developed by VELICOGNA & WAHR (2002).

Dynamical ice flow models, which are driven by climatological models coupled with the ocean and the atmosphere, describe the development of the ice sheets over long periods (CHARBIT et al., 2002; HUYBRECHTS, 2002). To improve the boundary conditions of such ice models, an improved monitoring of ice changes along the ice margins and, in particular, the monitoring of changes of the grounding line is required. In order to understand the present-day sea level rise as observed by tide gauges (between 1.0 and 2.0 mm/year for the last century, cf. CHURCH et al., 2001; NEREM et al., 2003; MUNK, 2002), the contribution of the polar ice sheets needs to be estimated with much better accuracy than currently known.

1.1.7 Dynamics and structure of crust and mantle

While the moving lithospheric plates represent the directly visible part of mantle convection, the style of convection and the deep flow field continue to be inadequately known. As the 660 km discontinuity inhibits vertical flow (e.g., TETZLAFF & SCHMELING, 2000), some combination of whole mantle and layered convection modes have been suggested, possibly augmented by small scale convection beneath the lithosphere (e.g., MARQUART et al., 1999). New seismic tomography models will provide estimates of the spatial distributions of temperature and density in the mantle. From these, mantle flow models can be derived, which allow the determination of the mantle viscosity by fitting the modelled to the observed geoid. Thus, the static gravity potential can be used to constrain mass transport in the mantle. A new generation of mantle flow models on different spatial scales, constrained by gravity data available from CHAMP, GRACE and GOCE and new crustal models, will help us to resolve the open questions about the style of mantle convection and lateral viscosity variation. The temporal geoid variations of traditional mantle flow models exhibit only moderate time dependence, close to the detection threshold of GRACE (MARQUART et at., 2004). However, non-linear mantle rheology and lateral viscosity variations may be related to fast mass transport processes, such as ultrafast plumes (LARSEN et al., 1999), detaching lithospheric roots (SCHOTT & SCHMELING, 1998) and fast roll back of subduction zones (e.g., ENNS et al., 2004), thus representing promising targets for GRACE.

Temporal gravity variations are also caused by glacial isostatic adjustment related to ongoing ice melting in Antarctica and Greenland (e.g., FLEMING at al., 2005) and postglacial uplift in Canada and Fennoscandia (e.g., MARTINEC & WOLF, 2004). To constrain these causative processes, only changes in the longest wavelength terms of the geopotential have been used so far, which renders discrimination between the processes very difficult. From the time dependent GRACE gravity data, an improved determination of the postglacial adjustment process is expected, which in turn allows improved estimates of the controlling mantle viscosity.

Asperities are areas of greater seismic slip and moment release with respect to the surrounding regions, which seem to be associated with stronger aseismic slip. They have been recognized for many subduction zones. Their origin and their role in earthquake recurrence are much debated (e.g., WELLS et al, 2003). Global bathymetric and gravity data show that asperities are commonly correlated with fore-arc basins, gravity lows and mechanically strong upper-plate blocks. SONG & SIMONS (2003) found that trench-parallel gravity and topography anomalies are positively correlated. This correlation is expected because gravity anomalies are intrinsically tied to topographic variations by a given compensation mechanism. Results from numerical modelling suggest that spatial variations in the magnitude of shear traction on the plate interface can modulate surface topography and hence gravity in the fore-arc. These models indicate that increasing shear tractions on the plate interface induce stresses, which depress fore-arc topography and gravity.

1.2 Scientific objectives

1.2.1 An emerging research field – Overview

The goal of this priority programme is a deeper understanding and improved modelling of dynamic processes at the Earth's surface and in the Earth's interior. Details are given in the extended document that has been submitted together with this proposal (ILK et al., 2005). Mass transport processes and mass distribution will be recovered based on satellite gravity data and altimetric data of water and ice surface geometry, in particular (cf. Figure 3):

- absolute oceanic transports and their temporal variations (Section 1.2.3),
- large scale water transport and water cycle on the continents (Section 1.2.4),
- ice mass balance and sea level changes (Section 1.2.5) and
- transport, dynamics and structure in the Earth's mantle and crust (Section 1.2.6).

Within the programme, three types of mass signals will be investigated which can only now be observed by the novel gravity and altimetry satellite missions: The ***first type*** is the temporal variation of mass distribution in the oceans, in continental water storages, in ice sheets, in the atmosphere and in the Earth's interior, with seasonal, annual and inter-annual periods as well as secular trends. These mass changes and redistributions will be determined from small amplitude, but large scale changes of gravity and the geoid, which are now for the first time observed by the satellite gravity missions CHAMP and GRACE. The analysis of the first GRACE gravity field observations already proved the feasibility of this concept for mass variations in continental hydrology, cf. Section 1.1.2. The gravity changes will be combined with height changes of water and ice surfaces which are simultaneously observed by satellite altimetry missions with centimetre accuracy. This approach will for the first time allow a reliable quantification of climate relevant processes such as Antarctic ice mass balance, deep ocean current variability and the various contributions to sea level change.

For the oceans, the combination of precise altimetry and gravity (geoid) information leads to the determination of the ***second type*** of mass signal, the absolute surface current including its time mean and time varying part. Combined with in-situ data the absolute ocean flow field and the corresponding transports of water masses and heat will be determined - a long-standing problem of physical oceanog-

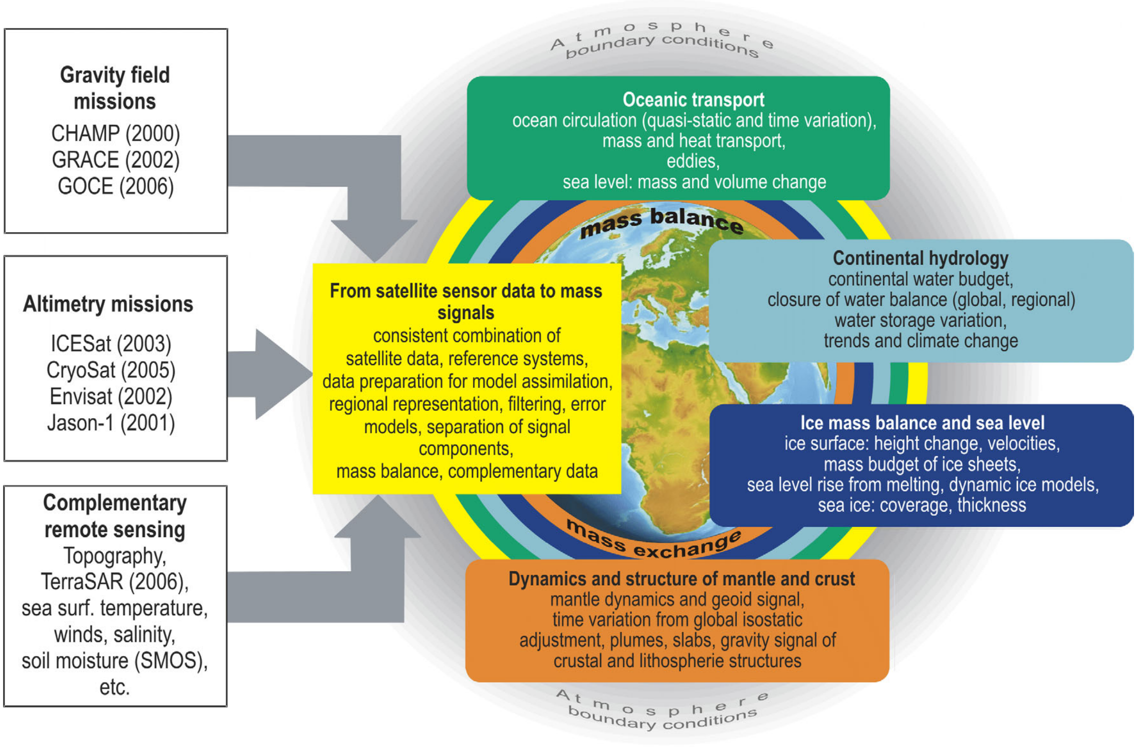

Figure 3. *Exploitation of satellite gravity and altimeter mission products to determine mass transport and mass distribution in the Earth system.*

raphy that finally seems in reach through the modern satellite technology, and a major mechanism for the stabilization of the Earth's climate. Only the combination of satellite altimetry, in-situ data and geoid information from the GRACE and GOCE satellite missions can provide the new information required to model and understand the ocean flow field, its changes and the role of the ocean in the climate system.

The ***third type*** of mass signals is the stationary mass and density structure of the Earth's mantle and crust. Observations of the stationary geoid and gravity anomalies will be used to constrain dynamical models of processes in the Earth's interior such as convection flow, sinking plate slabs and rising mantle plumes, as well as to infer the structure of the crust, for instance, in plate collision zones. Major progress is expected in these areas as the gravity field models obtained from GRACE and GOCE will – in particular for large and medium spatial scales – be globally homogeneous and more accurate by orders of magnitude than the information available before.

The programme will pursue an interdisciplinary approach (cf. Sections 1.2.2, 1.2.8) aiming at

- a consistent combination of satellite gravity, altimetric surface geometry and complementary data,
- the separation of mass signals superimposed in the gravitational and altimetric observations,
- the contribution to an integrated global geodetic-geodynamic observing system, and
- an integrative modelling of mass exchange and mass balances.

The target signals are very small and must be derived from the various sensor systems of the satellite gravity and altimeter missions and from complementary data sources and models, all of which must be tied together consistently in space and time in a common high-precision reference frame. For the reliable recovery and the separation of the different sources of temporal variations, it is of particular importance that simultaneous multi-annual observations of the gravity field and the surface geometry are evaluated in a combined approach, together with complementary geophysical models. For the reference frame and the products of the satellite missions, new computational standards and user-oriented processing methods must be developed. Special attention will be given to atmospheric mass variations and Earth and ocean tides (cf. Section 1.2.7). These external influences must be taken into account applying precise models or global data sets. The complementary fields of Earth rotation and the Earth's magnetic field will not be studied in the programme, although their relevance for mass transport will be kept in mind (cf. Section 1.2.9).

A particular interdisciplinary objective of the programme is the joint monitoring and understanding of mass exchange between oceans, ice, land and atmosphere, and of mass balances for sub-systems such as ice sheets, ocean basins, or river catchments. The interdisciplinary aspects represent a new research field on mass transport and mass distribution. The close cooperation of scientists with expertise in geophysics, glaciology, oceanography, hydrology and geodesy will enable a consistent, integrative and complete investigation of this field, including the coupling between the Earth system components.

1.2.2 Satellite geodesy: from sensor data to mass signals

Within the framework of the proposed research project, the fundamental observations concerning mass transport and mass distribution within the Earth system are referred, first, to the gravity field of the Earth, and second, to the geometry of ocean and ice surfaces. All spatial and temporal variations of the Earth's gravity field are due to mass distribution and redistribution within and among the solid Earth, the ice sheets, the oceans and the atmosphere. The gravitational forces of sun, moon, and the planets cause additional periodic variations. The global and precise mapping of the spatial and temporal variations of the gravity field is performed by means of gravimetric sensor systems of the satellite missions CHAMP, GRACE, and GOCE. Over water and ice, satellite altimetry is applied in order to survey the surface geometry and the temporal variations of ocean, ice, lake and river surfaces. Currently, Jason-1 and Envisat are important complementary altimeter missions, while the missions ICESat and CryoSat are dedicated to marine and continental ice surfaces. The consistent combination of gravity and geoid models with altimetry and other complementary data provides the basis for deriving the mass signals and constitutes the frame for modelling surface processes and geodynamics (cf. Figure 3). The target quantities are obtained by the following steps:

- Computation of precise Earth gravity field models with high spatial and temporal resolution and elaboration of the small temporal variations as an integrated signal, and analysis and reprocessing of altimeter data with uniform and improved standards and precise sensor calibration, thereby implying consistent elimination of external high frequency mass contributions by means of models (ocean tides, atmosphere) to avoid aliasing.

- Transformation of gravity field models, altimeter products and complementary observations and models to a uniform computational standard and a common reference system.
- Development of spatially localizing analysis methods and dedicated spatial and temporal filters to extract the signal from globally distributed observations and global gravity field parameters.
- Development of strategies in close cooperation with the research of Sections 1.2.3 to 1.2.6 for a separation of the individual components in the total signal of observed temporal gravity field variations: initial stepwise reduction of the mass signal into the components of atmosphere, ocean, cryosphere, continental hydrology, and crust and mantle using geophysical forward modelling; analysis of residuals to identify temporal and spatial coherence; finally assimilation and inversion of the signals to improve the geophysical models applied in 1.2.3 to 1.2.6; iteration to achieve an optimal agreement of observed and predicted mass variation patterns in space and time.
- Development of procedures for error estimates, error propagation and statistical rigorous combination of data.

1.2.3 Oceanic transport

For the first time in oceanography, the new and extremely precise observations of the gravity field and the shape of the sea surface enable us to estimate on a global scale the dynamically induced changes in sea level. The slope in sea level relative to the geoid is a direct measure of near-surface geostrophic ocean currents. From altimetric observations combined with traditional hydrographic measurements, it is possible to infer the ocean circulation over the entire water column. We expect that the precision of the circulation estimates available through the existing altimetric data and the new geoid models will lead to new insights into the global and regional transports of heat and mass. In particular, the dynamics associated with changes in the oceanic mass distribution are difficult to detect by any other data source in the ocean. Using the new GRACE data, such mass changes can be observed and will enable us to determine geostrophic barotropic transports and their role in regional and global sea level changes. As a consequence, the following oceanographic studies will be carried out within this programme:

- Determination of the absolute, but temporally changing ocean circulation. The technique of data assimilation provides the framework to combine geoid, altimetry and in situ data with ocean dynamics to obtain an optimal and dynamically consistent description of the ocean flow field on all relevant space and time scales. The results will enable us to understand the dynamical coupling of the temporally averaged and transient components of the circulation.
- Joint evaluation of global sea level, freshwater changes in the ocean, melting of ice, changes in the Earth's angular momentum and changes in the oblateness of the Earth. Determination of steric and eustatic changes in sea level and separation of barotropic and baroclinic currents.
- Determination of the aliasing effects of the barotropic circulation in geoid models, separation of oceanic and hydrological signatures in time-dependent geoid models.
- Examination of the consistency between estimates of the ocean dynamic topography and geoid models and of their respective error co-variances.
- Joint estimation of time varying altimetry and the marine geoid in order to avoid leakage of signals from the land and to separate continental hydrology from oceanic mass movement by filtering.

1.2.4 Continental hydrology

Measurements of the time-variable gravity field with GRACE allow for the first time to quantify mass variations on the continents that are caused by changes in the continental water storage. In addition, satellite altimetry provides estimates of storage changes for ungauged surface waters (lakes, rivers, wetlands) on the continents. The new satellite data thus allow to close the large-scale water balance at different temporal scales and to quantify the related (water) mass transport processes. The main objectives of research are:

- Evaluation of continental water storage variations derived from mass changes by comparing with ground-based hydrological measurements, complementary remote sensing data and model results for well-observed areas.

- Global quantification of temporal and spatial variations in the continental water storage and its storage components, and characterization of storage changes for regions with specific climatic and physiographic conditions.
- Determination of water balances and of related water fluxes at large scales, including an improved quantification of actual evapotranspiration.
- Validation and improvements of hydrological models and of land surface schemes in climate models by data on water storage variations.
- Analysis of trends and anomalies in the observed mass variations and their relation to changes in continental water storage due to climate variability and human impact (e.g., irrigation, reservoirs).

1.2.5 Ice mass balance and sea level

The polar ice masses play a key role in the Earth system. The impact of any ice mass imbalance with resulting sea level changes is global. With the GRACE gravity field mission in combination with the dedicated ice altimetry missions, the mass balance of the ice sheets will for the first time be directly determined, instead of using differences of large and uncertain balance terms. Satellite altimetry provides dense observations of ice surface heights, and with the new missions also the steeper edges of the ice sheets can be monitored, which are especially sensitive to climate change. Interferometric SAR (Envisat, TerraSAR) allows the determination of ice surface velocities, which can be compared with “balance velocities” provided by models. A precise monitoring of sea ice thickness and coverage (CryoSat) will give new insights into recent climate change. The main topics of research are:

- Determination of changes of mass and surface heights for the complete polar ice sheets, analysis of seasonal, interannual and long-term signals.
- Calculation of mass balance of complete polar ice sheets and their contribution to global sea level change.
- Observation of ice-induced recent crustal deformations (glacial isostasy), development of strategies in order to separate ice mass signals from isostatic signals (GPS observations on bedrock in polar regions), validation of models for ice load history.
- Improvement of firn and ice compaction models based on CryoSat and ICESat data, determination of space-time variability of compaction and snow accumulation fluctuations.
- Validation and improvement of glaciological models as an important component in coupled climate models, based on satellite data and complementary data sets (radar echo sounding for ice thickness, GPS, aerogravimetry).

1.2.6 Dynamics and structure of crust and mantle

The new generation of satellite missions opens new dimensions for the study of geodynamic mass anomalies and transport in the earth's interior: GOCE will increase the spatial resolution for the intermediate and short wavelength static gravity potential and its gradients by more than one order of magnitude, which will substantially improve data acquisition in remote areas, such as Antarctica, high mountains and the tropics. GRACE will resolve the temporal variations of the gravity potential down to the hitherto unreached length scale of 400 km. This unprecedented situation allows us to pursue the following scientific objectives:

- Forward and inverse modelling of the *instantaneous* gravity and topography signals caused by geodynamic mass anomalies and movements (quasi-steady state mantle convection, small scale convection, vertical deflections of the seismic discontinuities at 410 and 660 km depth, etc.). These models will be constrained by new seismic tomography and global crustal models.
- Forward and inverse modelling of the *temporal* gravity and topography signals caused by geodynamic mass transport (glacial isostatic adjustment, strongly time dependent mantle convection, subduction, orogenic processes, etc.).
- Inference of the 3-D distribution of the mantle viscosity.
- Study of the decoupling process at active subduction zones and the interrelation between seismic asperities and the gravity signal. In combination with other interdisciplinary monitoring this contributes to the seismic and volcanic hazard assessment.

- Improvement of global and regional crustal and lithospheric models including active and passive continental margins using high resolution static and temporal gravity data and their gradients (directly measured by GOCE) for better understanding of deep structure and time dependent processes acting at continental margins and orogenic regions (e.g. tectonic uplift, denudation etc.). Such processes are also important controls for regional climatic processes.
- Use of new long wavelength geopotential models for determination of geophysical residual gravity fields, to improve the modelling of crustal structures and the exploration of gravity data.

1.2.7 Atmosphere, tides and Earth core

Atmospheric circulation and solid Earth and ocean tides are an integral part of mass variations and transports in the Earth system. For the purpose of the proposed programme, these components are regarded as known from observations and models and are reduced during gravity field analysis. The reductions will be based on the best available information, to avoid blurring and aliasing effects from high frequency components. However, the contribution of their uncertainty to the total error budget of mass variation recovery has to be assessed. Furthermore, the atmospheric conditions are required as input for models of ocean circulation, the continental hydrosphere and the cryosphere to drive mass transport and mass exchange processes. The impact of Earth core convective flow and oscillations on the gravity field and on surface deformations is below the accuracy level of current satellite missions and shall therefore not be regarded. The proposed programme shall address the following issues:

- Validation of atmospheric data sets and impact of uncertainties to the gravity field solutions.
- Test of inverse barometer assumption over the oceans and impact of deviations to gravity field solutions.
- Validation of tide models and impact of uncertainties to the gravity field solutions.

1.2.8 Interconnection of themes within the research programme

The research themes outlined in Sections 1.2.2 to 1.2.6 are strongly interconnected; see also the extended document (ILK et al, 2005). Figure 4 shows the coupling between mass changes within different components of the Earth system. In order to understand the complete system, knowledge about processes within the sub-systems, and their interactions are required. This can only be performed with a consistent, interdisciplinary determination of mass exchanges between the components and with the estimation of complete mass budgets. Many budget terms for the mass exchange between the sub-systems in Figure 4 are very poorly known today. The research programme will merge balance estimates obtained from modelling the sub-systems, and will improve global and regional mass balance estimates. Also mass exchange involving the atmosphere has to be taken into consideration.

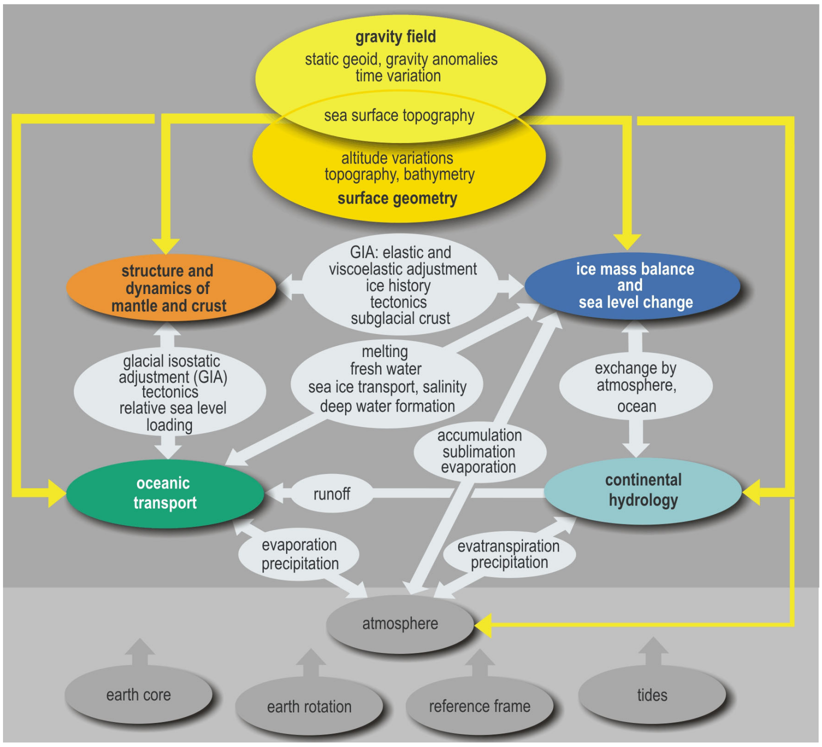

Figure 4. *Interconnections between processes and research themes related to mass transport and mass distribution. Arrows in the centre of the figure indicate mass exchange and dynamic feedback mechanisms. Other arrows connect the gravimetric and geometric observations (on top of the figure) to the physical processes or indicate external influences and complementary fields (at the bottom of the figure).*

In Figure 4, the connections between observables and mass related processes are shown as well. The observations can only yield integral signals and cannot distinguish between different processes or components. In particular, the temporal variations of the gravity field and surface geometry result from superimposition of several processes. In the priority programme, strategies for signal separation will be developed and validated, based on the available methods. The identification of the contributions from single processes in the observed integral signal will be very challenging. The elements shown at the bottom of Figure 4 are not in the main focus of the priority programme. They are considered as external influences which have to be taken into account by models. This is particularly important for the interrelations with mass variations in the atmosphere.

1.2.9 Complementary research fields

The research programme will not include all sub-systems and mechanisms involved in mass exchange in the Earth system. In particular, atmosphere and tides will only be considered in a limited sense, cf. Section 1.2.7. Furthermore, the ionosphere, the magnetic field, and the structure of the Earth's core will not be studied. There are methods other than observations of gravity field or surface geometry changes to address models of these sub-systems and mechanisms.

The relation to Earth rotation research requires a special remark. Any mass change within the Earth system and exchanges within the sub-systems cause changes of Earth rotation, i.e. in the Earth's precession, nutation, and in changes of rotational velocity and polar motion. As the gravity field, also Earth rotation reflects the integral effect of all variations of angular momentum. By analysis of typical time periods and with the support of external models these signals can be separated. The investigation of variations of Earth rotation perfectly complements the research to be carried out in this priority programme. Therefore, a close cooperation and exchange with the DFG research unit on "Earth rotation and global dynamic processes" (cf. Section 2 and SCHUH et al., 2004) is planned.

1.3 Work programme

In Sections 1.2.2 to 1.2.7, work programme items have been outlined for the involved research areas geodetic signal analysis, oceanic transport, continental hydrology, ice mass balance and sea level, dynamics and structure of the mantle and crust, and atmospheric and tidal reductions. In this section, the emphasis is on the interdisciplinary and integrative approach of the programme.

1.3.1 Work programme frame

Mass transport and mass distribution are determined from the new gravimetric and geometric satellite sensor data. This results in the following characteristics, which set up the frame of the work programme: From all processes in the Earth system, only mass phenomena and their interaction with the surface geometry of the Earth are considered. In the sense of a system definition all exogenous influences are taken into account through models. These are the tidal influence of moon, sun and planets and the atmospheric influence on the solid Earth, ice and oceans. The extremely small gravity and geometry signals are derived from the combination of very precise and novel sensor systems distributed over several satellite platforms. This requires the development of processing algorithms that take into account consistently all disturbing influences on the measurements (atmosphere, non-gravitational forces, orbit characteristics).

For the work programme, it is necessary to distinguish between the analysis of temporal variations of the gravity on the one hand and the analysis of (quasi-)static spatial variations on the other hand:

a) ***Temporal variations*** are always caused by the transport of mass in the Earth system. For the various system components (water, ice, solid Earth), the characteristic time scales of processes vary from seasonal over interannual and decadal to secular and, at the same time, the geographical patterns change. The global distribution of these time variations can now be measured for the first time with the missions CHAMP and GRACE. This implies that the assimilation of the data generated requires a fundamental extension of existing models for the system composed of solid Earth, ice, ocean and continental water.

b) For the (quasi-)static ***spatial variations***, it is necessary to distinguish gravity anomalies and geoid undulations from the dynamic sea surface topography.

    b1) ***Gravity anomalies and geoid undulations*** represent the deviation of the parameters describing the real Earth from those of some idealized Earth model. Geoid undulations express particularly the imperfections of our modelling at greater depths (upper and lower mantle), whereas gravity anomalies indicate deficits in our modelling at shallower depths (crust and the lithosphere).

b2) The dynamic ***sea surface topography*** describes the deviation of the real ocean surface, as observed by altimetry, from a hypothetical ocean surface defined by an ocean at rest, as represented by the geoid. Thus, in the case of gravity anomalies and geoid undulations, the real signal is compared to an idealized Earth model, whereas, in the case of sea surface topography, the real ocean is compared to a hypothetical surface. The dynamic sea surface topography directly yields the barotropic part of the ocean circulation and, thus, provides a novel global boundary condition for all ocean circulation problems.

The topics a) and b2) are important for ocean modelling. The topics a) and b1) are important for geodynamic modelling of the Earth's crust and mantle, and for modelling of ice sheets. Topic a) is important for modelling in continental hydrology.

1.3.2 Integrative data analysis

In the first period of the programme, a special focus will be on geodetic signal analysis (cf. Section 1.2.2) covering data preparation for model assimilation, consistent combination of data from different missions, improvement of error models, global and regional modelling. These activities take place in close interaction with the scientific goals outlined in Sections 1.2.3 to 1.2.6. At a later stage, the geodetic analysis will continue to be a connecting element for model integration of the various processes. The availability of a spatially and temporally consistent reference system, including a homogeneous height system, is a central issue. Based on spatial, temporal or spectral characteristics, joint strategies for signal separation will be developed by the individual disciplines. For an unbiased signal analysis, a thorough de-aliasing is required to avoid disturbances from high frequency signal components with periods shorter than 1 to 2 months. For this, the best available models for the computation of correction terms must be applied, in particular for tidal and atmospheric mass variations. In addition, the importance of high frequency components in the hydrological signal must be investigated.

1.3.3 Work flow

The programme will follow a sequential approach. First, the stronger signal components are analyzed. With the increasing data time span and quality, and according to the implementation of model improvements, the analysis will be extended to the weaker signals. After several iterations, the exchange of increasingly accurate correction terms leads to a more realistic modelling of the coupled processes. Experience shows that this approach is practicable. The medium term objective is the construction of a comprehensive model based on coupled sub-models and the simultaneous computation of all model parameters.

For ***time variable processes***, the work flow sequence will be as follows (cf. Figure 5):

(A) Connection of data in a well-defined homogeneous reference system, derivation of integral mass signals from gravity, altimetry (geometry) and complementary data.
(B) Forward computation of mass signals from process models and supplementary data for oceanic processes, continental hydrology, ice mass balance, glacial isostatic adjustment, mantle plumes, tectonics, and atmosphere.
(C) Signal separation and comparison of results from (A) and (B) (coherence patterns, filtering, and localization).
(D) Introduction/assimilation/inversion of results from (C) as boundary conditions or observables to improve the process models:
    (D1) Modelling of the time variable ocean circulation, in particular the deep circulation, separation of steric expansion and mass change.
    (D2) Modelling of large scale variations in continental water storage, in continental evapotranspiration and in the water balance.
    (D3) Modelling of the mass balance of ice sheets, improvement of dynamic ice flow models, separation of ice mass balance, postglacial uplift and compaction.
    (D4) Modelling of glacial isostatic adjustment in crust and mantle, modelling of mantle plumes and sinking slabs.

(E) Exchange of mass balance terms between process models of the coupled subsystem, analysis of aliasing, overlaps, and leakage effects.
(F) Check of consistency between observed mass signals and superimposed process models.
(G) ***Iteration***: (A) to (F).

The analysis of ***stationary (averaged over time) spatial variations*** will consist of the following steps:

(A) Connection of data in a well-defined homogeneous reference system, derivation of stationary gravity and geoid models and mean altimetric sea level.
(B) Error estimation and propagation, filtering, localization.
(C) Combination of data and assimilation into models, forward modelling with parameter variation, inversion:
    (C1) Modelling of quasi-stationary barotropic ocean circulation, in particular of near surface circulation, analysis of resulting mass and heat transport.
    (C2) Introduction of the gravity field model as boundary condition for lithosphere and mantle modelling, combination with seismic data.
(D) Validation of results.
(E) ***Iteration***: (A) to (D).

Both work flow sequences will end with a mutual exchange between improved static models and time variable process models for the coupled subsystems. In this and in earlier steps, the results will be exchanged in terms of geoid and gravity contributions as well as water column equivalent and surface deformation.

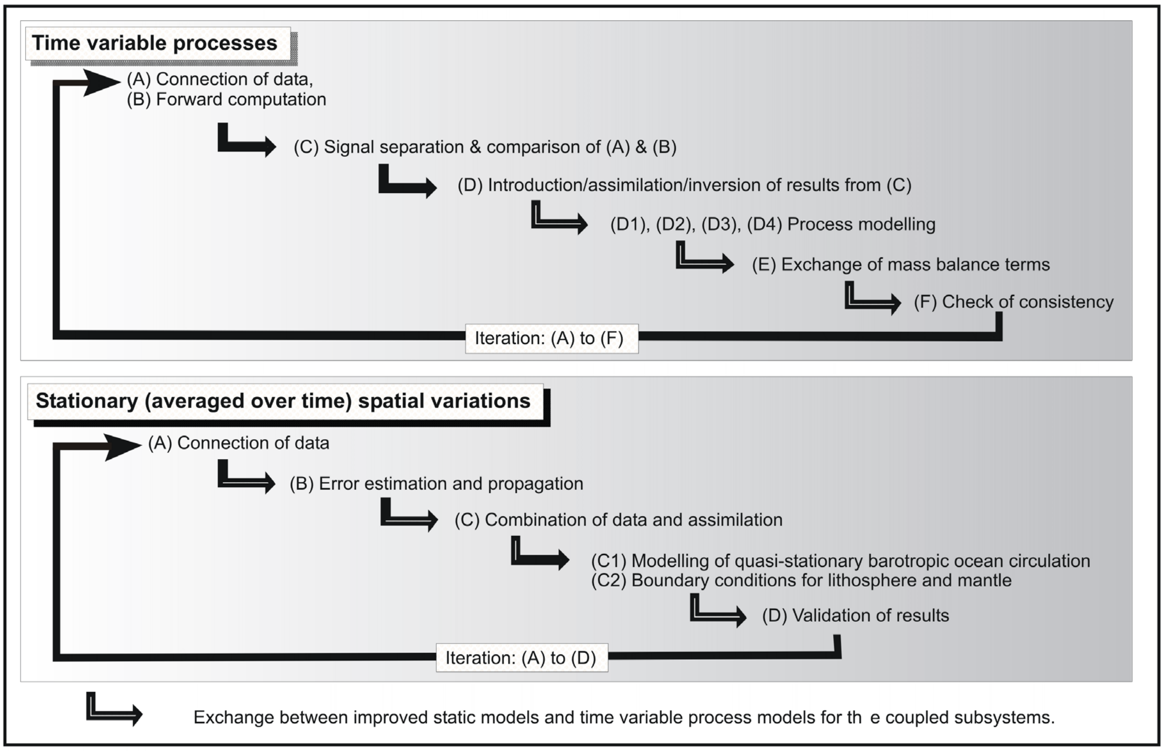

Figure 5. *Flow chart of programme work flow*

1.3.4 Programme management and networking

The recovery of mass transport and mass distribution in the Earth system requires an intensive interdisciplinary cooperation, as discussed in Section 1.2.8. The cooperation between geodesy, oceanography, geophysics and glaciology is partly well established. It has to be extended to other parts, in particular to hydrology. The research projects related to the work programme items will be organized in working groups. A total of 5 to 10 working groups with 3 to 6 research projects each are planned. Every working group will assign a group coordinator; together with the general coordinator these will be responsible for the overall programme management. The working groups will organize workshops. In addition, general programme science meetings will be held to guarantee the scientific exchange and the work flow sequence as shown in Section 1.3.3, and to achieve the interdisciplinary scientific objectives. The results will be published in meeting proceedings or in special issues of international peer reviewed journals. Cooperation with international scientific meetings related to the gravity and altimetry satellite missions (such as the ESA GOCE workshops) is planned.

For internal and external exchange of data sets, model results, documentation and publications, an internet platform will be established and maintained by the programme coordination bureau. It will be based on a content management system which allows the autonomous user access and input according to rules for metadata structure. Standards will be established with respect to spatial and temporal resolution of data sets and with respect to the type of mathematical representation. The internet platform will also serve as an interface to international scientific organisations such as the Global Geophysical Fluids Center (GGFC) of the International Earth Rotation and Reference Systems Service (IERS) and the Earth Rotation Information System of the DFG Earth rotation research unit. The aim is to reach a complete collection of data sets with global data coverage and sufficient temporal and spatial resolution for all major effects.

1.3.5 Promotion of young scientists

A particular objective is to stimulate in Germany a network of young geoscientists participating in the use of the novel and excellent satellite data. It is envisaged to employ brilliant students from the various disciplines and to educate them in a new environment of interdisciplinary cooperation. Postdoc researchers will be enabled to perform independent research. Every junior scientist shall be appointed two senior scientists from two different disciplines. This shall support the understanding of the different ways of thinking in the other involved disciplines. The training of the young scientists will be supported by summer schools, doctoral and post-doctoral seminars and specific workshops performed by the junior scientists.

2. Relations to other German projects and programmes

The priority programme is concerned with current geo-scientific questions. It is based on a broad expertise at universities and research institutes from geodesy, oceanography, hydrology, glaciology and geophysics. It will be – on national and international level – the first coordinated programme that brings together this complete constellation of geosciences, including hydrology. The objectives of the programme complement those of several other ongoing or planned programmes.

In the years 2002 - 2004, research projects covering the gravity field satellite missions CHAMP, GRACE and GOCE have been funded within the framework of the "Geotechnologien" research and development programme of the Federal Ministry of Education and Research (BMBF) and the DFG under the title "Observation of the Earth System from Space" (DFG, 1999). These projects provided a first generation of gravity field models and developed methods for the computation of gravity field models from satellite-to-satellite tracking and satellite gravity gradiometry data, including methods for sensor calibration and for validation and verification of the satellite data products. A continuation of this programme is currently envisaged. The present proposal for a DFG priority programme constitutes an effort to complement the "Geotechnologien" programme – with its limited range of research themes – with a programme focussing on fundamental research.

Recently, a proposal for a DFG research unit on the topic "Earth rotation and global dynamic processes" has been accepted. The topics of both programmes have been coordinated and both groups of initiators are in close contact to each other, cf. Section 1.2.9. The study of motions of the Earth's core, which are not considered in this programme (cf. Section 1.2.7), is at present part of a DFG priority programme on geomagnetic variations. The German project bureaus for the coordination of the scientific use of the ESA satellite missions GOCE and CryoSat are represented in the programme committee. They will enable a close contact to the mission operation teams of the involved satellite missions and to the respective principal investigators.

3. International involvement and visibility

The priority programme is closely linked to international activities. Many scientists in the programme committee and among those interested in participation have been and still are involved in leading roles in the scientific preparation, realization and data analysis of the satellite missions. They are represented at the corresponding scientific advisory groups and are principal investigators in the international data analysis consortia. This holds for the German CHAMP mission, for the American-German GRACE mission, for the ESA missions CryoSat, GOCE and Envisat, for the altimetry missions TOPEX/Poseidon and Jason-1, as well as for the complementary remote sensing missions Aquarius and SMOS. Aquarius is a NASA mission for the determination of the near surface ocean salinity; SMOS is an ESA mission aiming at the observation of soil moisture and ocean salinity. The initiators also actively participate in a range of international projects in oceanography, hydrology and glaciology, such as CLIVAR (Climate Variability and Predictability Experiment), GEWEX (Global Energy and Water Cycle Experiment) and SCAR (Scientific Committee on Antarctic Research).

The increasing availability of satellite data will intensify the international scientific competition on the research areas covered by the priority programme. This takes place also within international groups, such as the GRACE Science Team or the European GOCE Gravity Consortium EGG-C. An intensive competition with American and French scientists exists. The participants in the priority programme will represent one of the most important user groups of the gravimetric and altimetric satellite missions. Coordinated proposals in reaction to the international announcements of opportunity for data use will be prepared. To enhance the international visibility of the priority programme, special sessions at the international meetings of EGU, AGU, IUGG and IAG will be organized. At the end of the two funding periods of the programme, international symposia will be organized within the frame of IAG, IUGG and EGU to present the success of the programme. With reliable funding available for the coming years, German scientists will be in an excellent position to play a leading role in the modelling of the gravity field with emphasis on its time variability and the detection of mass transport and mass distribution.

4. Programme coordinator and programme committee

The strongly interdisciplinary structure and objectives of the programme as well as the number of involved institutions require an intensive coordination of the planned work. The general coordinator has a leading role in gravity field research and in the preparation of the gravity field satellite missions since many years. He is experienced in leading coordinated research programmes on this field, and he has a leading role in various scientific committees. For the programme management, the general coordinator will be supported by a programme coordination bureau and by the working group coordinators.

General coordinator:

Prof. Dr. K.H.Ilk, Institut für Theoretische Geodäsie, Universität Bonn

Programme committee:

Dr. W. Bosch, Deutsches Geodätisches Forschungsinstitut München
Prof. Dr. R. Dietrich, Institut für Planetare Geodäsie, Technische Universität Dresden
Dr. J. Flury, Institut für Astronomische und Physikalische Geodäsie, Technische Universität München
Prof. Dr. H.-J. Götze, Institut für Geowissenschaften, Universität Kiel
Dr. A. Güntner, GeoForschungsZentrum Potsdam
Dr. C. Haas, Alfred-Wegener-Institut Bremerhaven
Prof. Dr. H. Miller, Alfred-Wegener-Institut Bremerhaven
Dr. J. Riegger, Institut für Wasserbau, Universität Stuttgart
Prof. Dr. R. Rummel, Inst. für Astronomische und Physikalische Geodäsie, Technische Universität München
Prof. Dr. H. Schmeling, Institut für Meteorologie und Geophysik, Universität Frankfurt/Main
Dr. J. Schröter, Alfred-Wegener-Institut Bremerhaven
Prof. Dr. D. Stammer, Institut für Meereskunde, Universität Hamburg
Prof. Dr. D. Wolf, GeoForschungsZentrum Potsdam

5. Programme participants

The following scientists manifested their interest to participate in this priority programme by their participation in 2 DFG round tables and by submitting proposals for research projects:

Competence: oceanography

Prof. Dr. C. Böning, Leibnizinst. f. Meeresforschung, Kiel
Prof. Dr. R. Käse, Leibnizinst. f. Meeresforschung, Kiel
Dr. S. Kern, Institut für Meereskunde, Univ. Hamburg
Dr. A. Köhl, Institut für Meereskunde, Univ. Hamburg
Dr. J. Schröter, Alfred-Wegener-Institut Bremerhaven
Prof. Dr. U. Send, Leibnizinst. f. Meeresforschung, Kiel
Prof. Dr. D. Stammer, Institut für Meereskunde, Universität Hamburg
Dr. M. Thomas, Institut für Planetare Geodäsie, Technische Universität Dresden
Prof. Dr. W. Zahel, Inst. f. Meereskunde, Univ.Hamburg

Competence: glaciology

Dr. L. Braun, Komm. für Glaziologie, Bayerische Akademie der Wissenschaften München
Prof. Dr. R. Dietrich, Institut für Planetare Geodäsie, Technische Universität Dresden
Prof. Dr. H. Goßmann, Institut für Physische Geographie, Universität Freiburg
Dr. C. Haas, Alfred-Wegener-Institut Bremerhaven
Dr. P. Huybrechts, Alfred-Wegener-Institut Bremerhaven
Prof. Dr. M. Lange, Inst. für Geophysik, Univ. Münster
Prof. Dr. H. Miller, Alfred-Wegener-Inst. Bremerhaven
Dipl.-Geogr. F. Rau, Institut für Physische Geographie, Universität Freiburg
Dr. M. Scheinert, Institut für Planetare Geodäsie, Technische Universität Dresden

Competence: solid Earth geophysics

Prof. Dr. P. Bunge, Institut für Angewandte Geophysik, Universität München
Prof. Dr. H.-J. Götze, Inst. für Geowissensch., Univ. Kiel
Dr. R. Hackney, Inst. für Geowissenschaften, Univ. Kiel
Prof. G. Jentzsch, Inst. f. Geowissenschaften, Univ. Jena
Dr. M. Kaban, GeoForschungsZentrum Potsdam
Dr. G. Kaufmann, Inst. für Geophysik, Univ. Göttingen
Prof. Dr. R. Kind, GeoForschungsZentrum Potsdam
Dr. V. Klemann, GeoForschungsZentrum Potsdam
Dr. G. Marquart, SRON Utrecht / Inst. für Meteorologie und Geophysik, Univ. Frankfurt/M.
Prof. Dr. Z. Martinec, GeoForschungsZentrum Potsdam
Prof. Dr. H. Schmeling, Inst. für Meteorologie und Geophysik, Univ. Frankfurt/Main
Prof. Dr. D. Wolf, GeoForschungsZentrum Potsdam

Competence: continental hydrology

Prof. Dr. A. Bardossy, Inst. für Wasserbau, Univ.Stuttgart
Prof. Dr. P. Döll, Institut für Physische Geographie, Universität Frankfurt/Main
Dr. A. Güntner, GeoForschungsZentrum Potsdam
Dr. B. Merz, GeoForschungsZentrum Potsdam
Dr. J. Riegger, Institut für Wasserbau, Univ. Stuttgart

Competence: geodesy

Dr. W. Bosch, Deutsches Geodätisches Forschungsinstitut München
Dr. F. Flechtner, GeoForschungsZentrum Potsdam
Dr. J. Flury, Institut für Astronomische und Physikalische Geodäsie, Technische Universität München
Prof. Dr. W. Freeden, Institut für Geomathematik, Technische Universität Kaiserslautern
Dr. T. Gruber, Institut für Astronomische und Physikalische Geodäsie, Techn. Univers. München
Prof. Dr. B. Heck, Inst. für Geodäsie, Univ. Karlsruhe
Prof. Dr. K.H. Ilk, Inst. f. Theoret. Geodäsie, Univ. Bonn
Prof. Dr. W. Keller, Geodätisches Institut, Univ. Stuttgart
Dr. U. Meyer, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover
Prof. Dr.-Ing. J. Müller, Institut für Erdmessung, Universität Hannover
Prof. Dr.-Ing. R. Rummel, Institut für Astronomische und Physikalische Geodäsie, Techn. Universität München
Dr. T. Schöne, GeoForschungsZentrum Potsdam
Prof. Dr. W.D. Schuh, Institut für Theoretische Geodäsie, Universität Bonn
Dipl.-Ing. R. Schmidt, GeoForschungsZentrum Potsdam

6. Funding periods and required amount of funding

Funding will be subdivided in two periods of three years each. The regular funding period for single projects will be three years. A continuation shall be possible in specific cases after approval by experts. After three years a review of the programme will be performed, and changes in the scientific tasks and working group organization will be possible.

It is expected that about 30 single research projects will be selected within the frame of the priority programme. Most of them will be provided with Ph.D. candidate positions (BAT IIa (75 k€) or BAT IIa/2 (37.5 k€). For travel expenses, assistants and publication costs 10 k€ per project and year will be needed. In some cases, computational capacities will be required that are not available from the basic equipment of the involved institutions. For this, in the first year an amount of 100 k€ is expected, and 50 k€ for each of the following years. For the coordination of the priority programme, one scientific position (BAT IIa) with travel expenses and augmented running costs (100 k€, including workshops and tutorials) is required. Thus, the overall funding requirement is about 2.3 M€ per year.

7. Reasons for the establishment of a DFG priority programme

The intimately coupled problems addressed by this project – the modelling and understanding of mass exchange processes and dynamic feedback mechanisms between the ocean, the cryosphere, the terrestrial hydrosphere and the Earth's interior – together form a new research field, which can only be attacked by an ***interdisciplinary and overarching approach*** that reaches across many disciplines of Earth sciences. The challenging goals can only be achieved under the umbrella of a special focus programme which can provide the required organizational and scientific infrastructure, including coordination of research and organization of numerous dedicated meetings. The expertise required for this programme is distributed ***all across Germany,*** indicating that local efforts would never be able to bring the required insight and understanding together to tackle this complex problem. The present proposal for a DFG priority programme constitutes an effort to complement the "Geotechnologien" programme with a programme focussing on fundamental research.

Through the unique constellation of satellite missions, the next 6 years provide an unprecedented opportunity during which the data base will be available that is required for achieving substantial scientific progress. This stage required more than 20 years of preparation and we finally can reach to the fruits of this long process. Given this unique situation, action is ***urgently required***. It will most likely lead to a large step forward in our understanding of the Earth system. Finally, we have never had such an obvious opportunity to build and teach the next generation of researchers in such an overarching interdisciplinary context.

The work programme requires a close collaboration between ***universities and research institutions***. The programme structure was designed to optimize this cooperation. As an example, research built on ground truth observations from the polar regions clearly depends on related work performed by the Alfred-Wegener-Institut Bremerhaven. For the analysis of gravity field and altimetry data, the support by the GeoForschungsZentrum Potsdam as well as by the Deutsches Geodätisches Forschungsinstitut München is very important. On the other hand, the programme is based on a very broad range of university institutions, which has been documented through round-table discussions during the preparation phase. This broad basis at universities is essential for achieving the intellectual excellence of the proposed work.

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