Abstracts Ocean/Ice/Hydrology

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1. **Ocean generated magnetic field and their temporal variations**

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Conducting ocean water, as it flows through Earth's magnetic fields, generates secondary electric and magnetic fields. An assessment of ocean-generated magnetic fields and their detectability may be of importance for geomagnetism and oceanography. Motivated by the clear identification of ocean tidal signatures in the CHAMP magnetic field data we estimate the ocean magnetic signals of steady flow using a global EM induction code. The required velocity data are from the ECCO ocean circulation experiment and alternatively from the OCCAM model for higher resolution. We assume an Earth's conductivity model with a surface thin shell of variable conductance with a realistic 1D mantle underneath. Besides the expected signatures of the global circulation patterns, we find significant seasonal variability of ocean magnetic signals in the Indian and Western Pacific oceans. Compared to seasonal variation, interannual variations produce weaker signals. In the context of its detect-ability, we discuss the comparison of our predictions with CHAMP magnetic observations at presently achievable resolution.

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2. **Ocean Bottom Pressure Ground-truth Site for GRACE Validati**on

T. Kanzow (1), F. Flechtner (2), R. Schmidt (2), H. Miller (3), Ch. Reigber (2)

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Ocean bottom pressure (OBP) is of particular interest for oceanographers, as the deep flows in the oceans are balanced by pressure gradients. For the first time the temporal evolution of OBP can be observed globally from space using the GRACE monthly gravity field solutions. During gravity field determination a number of corrections have to be applied to de-alias the satellite measurements: All short-term non-tidal atmospheric and oceanic mass variations are taken into account using ECMWF atmospheric fields and a barotropic ocean model. Additionally, an ocean tidal correction based on the FES model is applied.
To validate these products a dedicated experiment is presently carried out jointly by IfM-Geomar, GFZ, AWI, and WHOI based on an array of OBP sites in the tropical West-Atlantic. We will present results of this experiment using the 2000-2003 data, involving comparisons of the in situ observations with the barotropic and tide model in terms of signal amplitudes, spectral properties and horizontal correlation scales. Model limitations will be discussed. Finally, first analyses of the still preliminary GRACE derived bottom pressure will be presented.

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3. **Representation of Ocean-Bottom Pressure and Sea-Surface Height in a Global Topography-Following Non-Boussinesq Ocean Model**

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Satellite observations of ocean-bottom pressure (OBP) and sea-surface height (SSH) are fundamentally important information of ocean dynamics. The GRACE inferred OBP represents ocean mass changes, while the TOPEX observed SSH gives changes in water volume. Their proper representation in ocean general circulation models is essential for studying ocean circulations and performing data assimilations by using those satellite data. This talk will focus on innovative numerical methods for better representation of bottom topography and non-Boussinesq physics in the new model. Long-term simulations of global OBP and SSH will be presented.

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4. **On the impact of baroclinic ocean dynamics on the Earth's gravity field**

Maik Thomas

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By analysing real time model runs performed with the Ocean Model for Circulation and Tides (OMCT) over several decades with various forcing conditions, the impact of non-barotropic ocean dynamics and the sensitivity of oceanic mass redistributions with respect to numerical approximations on the time variable Earth's gravity field are estimated. The applied global ocean model is capable of simulating the three-dimensional thermohaline, wind- and pressure-driven circulation as well as lunisolar tidal dynamics and takes into account several so-called secondary effects, e.g., loading and self-attraction of a baroclinic water column and mass variations associated with sea-ice dynamics. These secondary effects as well as deviations from a pure barometric response to atmospheric pressure are commonly neglected in global numerical ocean models, but turn out to contribute significantly to variations of the Earth's gravity field. In addition to a separation of relevant causative physical processes, corresponding oceanic bottom pressure fields reflecting the ocean's influence on the gravity field are analysed in order to get insight in typical spatiotemporal patterns of oceanic mass redistributions and consequently to identify oceanic regions of high impact on gravity changes.

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5. **Bottom Pressure Signals in the Antarctic Circumpolar Current**

V. Zlotnicki (1), L.-L. Fu (1), D.-N. Yuan (1) and J. Wahr (2)

(1) Jet Propulsion Laboratory, California Institute of Technology
(2) University of Colorado

The preliminary CSR GRACE fields released so far show an accuracy equivalent to ~ 1.4 cm of H_2O when smoothed over 1000km. This accuracy is excellent for land hydrologic signals but comparable to the much weaker ocean bottom pressure (OBP) signals. An exception is the Antarctic Circumpolar Current (ACC) region, where the increased track density probably yields slightly better accuracy and monthly to interannual changes in OBP are the strongest

in the world ocean.
The Indian ocean sector of the ACC has the most distinct signal, a seasonal cycle in bottom pressure that correlates well to the ECCO ocean model, to sea surface height from the TOPEX/POSEIDON and Jason altimeters, and to wind (Ekman pumping) signals. We discuss the properties of this signal using both the original CSR set of gravity model solutions, and a set recently generated at JPL using a different tide model, the largest source of ocean aliasing into the solution.

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6. **The ocean general circulation determined from the GRACE fine resolution geoid**

Manfred Wenzel[1], Verena Seufer[2], Bernadette Fritzsch[1] and Jens Schröter [1]

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2) Geoforschungszentrum Potsdam, Potsdam, Germany

The general circulation is calculated with a global ocean model. The ocean model is designed to study the evolution of sea level and mass distribution in the ocean. It has a free surface and conserves mass instead of volume. Satellite altimetry referenced to the GRACE geoid and hydrographic measurements are assimilated using the 4DVAR technique for the period 1993 to 2001.
We report on the success of the numerical experiment in reproducing the measurements of sea level anomalies, mean sea level (refefenced to the GRACE geoid) and hydrographic data. Key ocean circulation features which cannot be measured directly like heat transports and meridional overturning circulation are determined from the model and compared to independent estimates.

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7. **Mass movements in the ocean: Observed and predicted signals**

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Bottom pressure measurements from the Argentine basin will be presented, confirming the existence of 20-25 day barotropic waves with a half-wavelength of around 1000 km and intermittent amplitude up to 20 cm. At shorter periods, the pressure signal is coherent over longer length scales, but with much smaller amplitude. This coherence extends to periods of about 2 hours, and some coherent structure remains at 1 hour periods. Between 2 and 12 day periods the signal is very well modelled by a global barotropic model, but the 20-day waves are not well modelled at all. This suggests that they are generated by instability of strong baroclinic jets in the region, and may be very difficult to predict. At longer periods, seasonal and decadal signals are investigated in the coupled HADCM3 model, and a dominant decadal mode is identified in which mass shifts between the Atlantic and Pacific. Indirect evidence for this mode is found in the real ocean, and the amplitude of the mode is shown to be large enough for detection by GRACE.

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8. **Preliminary Observations of Global Ocean Mass Variations with GRACE**

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Monthly estimates of the Earth's gravitational field from the GRACE mission are used to construct a time-series of global mean ocean mass variations between August 2002 and December 2003. This time-series is compared to a mean climatology determined from satellite altimeter measurements of global mean sea level corrected for the steric signal. The GRACE observations show a seasonal exchange of water mass with the continents of the same magnitude (~9 mm) and phase (maximum in mid-October) as the steric-corrected altimetry. This is one of the first direct validations over the ocean of the primary GRACE science mission to measure time-variable transports of water mass in the Earth system.

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9. Assessing Observed GRACE Oceanic Mass Variations with a Focus on Southern Ocean

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The traditional methodology to estimate steric sea level utilizes in situ temperature and salinity data. While the current uncertainty of the computed (global) steric sea level seems to be within the requirement, the temperature and salinity measurements are not homogeneously distributed and limited in accuracy, and consequently, the steric sea level is not well known, e.g. in the Southern ocean. This paper presents a study to assess the role of GRACE observed mass variations in potentially improving the steric sea level estimates over the ocean, especially the Southern ocean, where in situ data are scarce. Using satellite altimetry, GRACE gravimetry and steric sea level from in situ measurements and an altimetry-assimilated general ocean circulation model, we examine the low (spatial) frequency variations of steric effect and mass redistribution over the global and Southern ocean. The altimeters covering the high-latitude region, such as Geosat, ERS, GFO and ENVISAT, are used. Time-variable GRACE gravity field data can be used with the spatial resolution of 1300 km and temporal resolution of one month for the mass variation signal. The in situ temperature and salinity measurements from NOAA's WOD01 and potentially from PALACE and ARGO floats are incorporated. Finally, the ocean models used include the one by AWI and ECCO model.

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10. Recent J_2 Changes: Results and Implications

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Olivier de Viron[2], and Ichiro Fukumori[1]

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Earth's dynamic oblateness *(J_2)* has been decreasing due to post-glacial rebound (PGR); however, an increase began in 1997 (*Cox and Chao, Science, 2002*) indicating a pronounced change in the global-scale mass redistribution process. *Dickey et al. (Science, 2002)* have determined that the observed increases in J_2 are caused primarily by a recent surge in sub-polar glacial melting, and mass shifts in the Southern, Pacific and Indian Oceans.
Recently, the geodetic J_2 series has been decreasing rather than increasing, which motivates the further study. Data series have been extended, in particular ocean loading derived from ECCO bottom pressures and hydrology (*Milly, pers. comm.*). Both glacial and oceanic sources had enhanced upward trends around 1998. The sums of the glacial, oceanic and hydrology contributions to J_2 are compared with geodetic observations *(Cox and Chao, 2002; Cox, pers. Comm., 2003*). The modeled excitation captures the rise of J_2 in the late 1990's as well as its subsequent decrease, even though J_2 contributions due to glacial melting maintain a positive slope. Thus it is not necessary for the glaciers to "re-freeze", i.e. switch to a net positive mass-balance, in order to match the decrease in the observed J_2.

11.

Operational oceanic de-aliasing products simulated with a baroclinic global ocean model

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Ocean induced gravity variations simulated with numerical models strongly depend on internal model physics as well as on atmospheric forcing fields. To quantify the sensitivity of resulting oceanic gravity anomalies with respect to forcing fields the baroclinic global ocean model OMCT has been driven with output of various typical model atmospheres, i.e., the unconstrained ECHAM model, recently released data from ECMWF's reanalysis project ERA40, and operational forecast products provided routinely by ECMWF. Since neither an inverse nor a non-inverse barometric approximation is applied, the model ocean's response to atmospheric pressure anomalies is allowed to be dynamic as well as static. When oceanic bottom pressure and atmospheric surface pressure fields are superimposed, the static, i.e., inverse barometric contributions vanish as a consequence of compensation, but dynamical contributions arising from deviations from an exact inverse barometric ocean remain. The simulations indicate that these pressure induced dynamical components significantly influence oceanic mass distributions and, consequently, gravity anomalies. Since the operational ECMWF data is updated every three days, the combined influences of a baroclinic ocean and the applied model atmosphere on the Earth's gravity field can be analysed consistently and will be provided as alternative de-aliasing products in nearly realtime.

P 1

A method to study the sensitivity of simulated ocean circulation to the geoid

Femke C. Vossepoel[1,2], Peter Jan van Leeuwen[1], Radboud Koop[2]

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The availability of gravity data from recent satellite missions (CHAMP, GRACE) and the future GOCE mission will improve our current knowledge of the Earth's geoid. An accurate description of the geoid is essential for a proper interpretation of altimetric sea level data,

which can help us to better understand the ocean circulation. This study describes a method to study the sensitivity of an estimated ocean circulation to the geoid, using a global ocean circulation model (OGCM) and an advanced data assimilation technique.
The analysis system consists of the OPA OGCM, in which observations are being assimilated. The assimilation technique is an ensemble-based method that determines the optimal model trajectory by statistical evaluation of an ensemble of model simulations. Different ensemble members are obtained by perturbing both initial conditions and surface forcing. The performance of this approach is tested with a synthetic experiment.
The generated ensemble has the desired spread. However, only few ensemble members correspond to the synthetic data. The representation of both model and geoid errors in the assimilation method requires further refinement. The use of so-called forcing singular vectors for this purpose is investigated.

P 2 **Verification of an ocean general circulation model with time varying GRACE geoid data**

Manfred Wenzel[1], Frank Flechtner[2], Roland Schmidt[2], Christoph Reigber[2], Verena Seufer[2], Bernadette Fritzsch[1] and Jens Schröter [1]

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2) GeoForschungsZentrum Potsdam, Potsdam, Germany

The annual cycle of GRACE time varying geoid data is used to verify results from a global ocean general circulation model. The ocean model is designed to study the evolution of sea level and mass distribution in the ocean. It has a free surface and onserves mass instead of volume. Fresh water (i.e. mass) is exchanged with the atmosphere via precipitation and evaporation and inflow by rivers is taken into account. Mass is redistributed by the ocean circulation. Additionally, volume changes by steric expansion with changing temperature and salinity. The model is constrained by assimilating satellite altimetry and hydrographic measurements using the 4DVAR technique.
The ocean model reproduces the measured free sea surface determined as the difference between an altimetric mean sea surface and the mean GRACE geoid with success. Regional interannual variability is much smaller than the seasonal cycle. The mass variations are much smaller than the corresponding sea surface variability as most of the sea surface change is compensated locally in the deep ocean by thermal expansion.
The changing bottom pressure is analyzed and it seasonal cycle is compared to that of the secular changes in the geoid provided from the GRACE mission.

P 3 **An inverse ocean model for the North Atlantic circulation using the GRACE geoid**

Dmitri Sidorenko, Genady Kivman, Sergey Danilov and Jens Schröter

Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, Germany

An inverse ocean model for the general circulation of the North Atlantic is presented. The steady state velocity field is determined which explaines the hydrographic observations and is also in agreement with the conservation of momentum. The inverse model is based on the finite element ocean model FEOM.
In addition to hydrogaphy we use the mean sea level referenced to the GRACE geoid to improve the estimations of the ocean circulation. A novel technique is used that keeps the deep ocean circulation in balance and removes earlier difficulties such as a reversal of the

deep western boundary current after assimilation. Now hydrographic changes are concentrated more on the upper layers where they efficiently balance pressure gradients introduced by the improved dynamic sea surface. We will present new current fields and meridional circulation patterns.

P 4

Improving S2 ocean tides using GRACE gravimetry

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Ocean tide errors will not cancel in the GRACE monthly averaged temporal gravity fields. The S2 and the K2 terms have alias frequencies much longer than 30 days, so they remain almost unreduced in the monthly averages. A simple experiment demonstrate that the potential of using GRACE data for improving the ocean tide models may reduce the total errors of the models from 2.2 cm to 0.55 cm.
The first 15 monthly Level-2 gravity field solutions from CSR with calibrated error fields have been used in an optimum estimation of residual S2 signal in the gravity fields based on an alias period of 163 days. The investigation have been carried out to spherical harmonic degree and order 10 and shows consistent pattern of residual ocean tide signal to the west of Britain, on the Patagonian shelf, and on the west coast of the US relative to the CSR4.0 ocean tide model used in the processing of the Level-2 data. In terms of ocean-equivalent water signal the amplitude ranges up to a few centimeters.

P 5

Evaluating mean dynamic topography models within the GOCINA project

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A major goal of the EU project GOCINA (Geoid and Ocean Circulation In the North Atlantic) is to determine an accurate mean dynamic topography model in the region between Greenland and the UK. The mean dynamic topography provides the absolute reference surface for the ocean circulation. The improved determination of the mean circulation will advance the understanding of the role of the ocean mass and heat transport in climate change. To calculate the best possible synthetic mean dynamic topographies a new mean sea surface (KMS03) has been derived from nine years of altimetric data (1993-2001). The regional geoid has furthermore being updated using GRACE and gravimetric data from a recent airborne survey. New synthetic mean dynamic topography models have been computed from the best available geoid models (EGM96, GRACE, GOCINA) and the mean sea surface model KMS03. These models will be compared with state of the art hydrodynamic mean dynamic topography models in the North Atlantic GOCINA area. An extended comparison in the Artic Ocean will also be presented to demonstrate the impact of improved geoid and mean sea surface modeling. Particularly using the GRACE derived geoid models, and the KMS03 mean sea surface.

P 6

Altimetry and Reflectometry with CHAMP using coherent GPS signal reflections: A feasibility study

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Recently, altimetry and scatterometry using reflected GPS signals are increasingly being considered as ocean remote sensing tools. GPS signals reflected from ocean surfaces can be detected and recorded by ground-based or space-based receiver instruments. By correlating coherently reflected signals with a model signal that is phase-locked to the corresponding direct signal (GPS bipath interferometry) weak reflection signatures can be detected. In GPS bipath interferometry the in-phase and quadrature-phase correlation sums, obtained from correlating reflected and model signals, exhibit characteristic interference patterns that are directly related to the optical path length difference between direct and reflected ray. The validity of the method has been successfully demonstrated in a ground-based measurement campaign. Based on these results we expect that with the existing antenna / receiver hardware aboard CHAMP and straightforward changes to the signal tracking software coherent reflection events could be detected up to elevation angles of about 10 degrees.

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12. **Ice loss in Antarctica and lower mantle viscosity from the inversion of SLR time dependent, zonal geopotential components**

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A self-consistent inversion procedure, based on the Levenberg-Marquardt method, has been used to invert simultaneously for the lower and upper mantle viscosity and for present-day ice mass loss in Antarctica and Greenland, within the framework of forward viscoelastic, stratified Earth's models based on an analytical, normal mode theory and on Satellite Laser Ranging data. The observational data are the even and odd zonal time variations of the Earth's gravity field, which we attribute to both Pleistocene deglaciation and present-day ice mass instabilities in Antarctica and Greenland.
If Antarctica is considered as the only source of present-day melting, upper and lower mantle viscosities are 5.5 10^{20} Pa s and 6.0 10^{21} Pa s respectively, with ice loss in Antarctica of -228 Gt/yr. If Greenland is also considered as a contributor to present-day melting, ice loss is partitioned between Antarctica and Greenland, with ice loss of –190 Gt/yr and -90 Gt/yr, respectively. The chi-square analysis show that Pleistocene deglaciation cannot be the only contributor to the time variations of the long-wavelength gravity field up to the harmonic degree 8 and mass redistribution between the polar and equatorial regions of the Earth is ongoing.

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13. **Ice mass imbalance and time variable accumulation from GRACE data**

Isabella Velicogna, John Wahr

University of Colorado

We used the fifteen monthly GRACE gravity field solutions that are now available for analyses. We found that those fields can be used to recover mass imbalance for the Greenland ice sheet and that the GRACE estimate agrees within the measurement error with

available ice mass imbalance estimates from altimeter heights. The GRACE fields can also be used to estimate temporal variations in the distribution of surface mass. In regions such as Antarctica and Greenland, time-varying accumulation of precipitated snow will dominate the non-secular component of GRACE-derived surface mass changes at large spatial scales. We calculate the non-secular component of the time variable signal over the major ice sheets and we evaluate the GRACE estimates of mass change by comparing with ERA40-derived accumulation and runoff fields.

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14. Expected GRACE secular change signal from Greenland ice sheet warming

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Glaciological/climatological models of annual ice sheet melt and refreeze rates may be used to infer the geoid change signals GRACE should measure as a function of warming of the Greenland ice sheet. In the paper a newly constructed model for height change and mass change of the Greenland ice sheet as a function of increased surface temperature is used to compute the secular geoid change. The model predicts height changes in wider areas across southern Greenland, whereas mass changes are limited to the marginal areas of the ice sheet due to thaw-refreeze phenomena. The model predictions are compared to released monthly GRACE gravitational fields from August 2002 onwards.

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15. Regional Glacial Isostatic Adjustment Studies with GRACE and GPS

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The glacial isostatic rebound (GIA) signal is expected to have a significant contribution to both the secular changes in gravity (the viscoelastic adjustment from the Late Pleistocene deglaciation) and its seasonal changes (e.g., present-day glacier melting). These signals are present at a wide range of spatial wavelengths, reflecting both the global nature of the loading/unloading response and the regional variations in glacier mass. We are investigating how GPS and other data may be used to validate rapidly the presence of these signals in the GRACE gravity determinations. Our preliminary results indicate that current global GPS reference-frame issues may limit the utility of the lowest degree variations of the radial deformation field. More regional GPS deformation fields may be more useful, but these coefficients from GRACE are expected to be less accurate. Whether a middle ground exists, where the accuracy of both techniques can be most productively utilized, will be explored.

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16. Initial time-variable gravity results from GRACE

John Wahr (1), Sean Swenson (1), Isabella Velicogna (1) and Victor Zlotnicki (2)

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Fifteen monthly GRACE gravity field solutions are now available for analyses. We Find those fields can be used to recover monthly changes in water storage, both on land and in the ocean, to accuracies of 1.5 cm of water thickness when smoothed over 1000 km. The amplitude of the annually varying signal can be determined to 0.9 cm. Results are 30% better for a 1500 km smoothing radius and 40% worse for a 750 km radius. We estimate the annually varying component of water storage for three large drainage basins (the Mississippi, the Amazon, and a region draining into the Bay of Bengal), to accuracies of 1.0-1.5 cm.

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17. **Temporal Variability in the Earth's Gravity Field: Inferences and Comparisons from SLR tracking to Five Geodetic Satellites, CHAMP, GRACE and Geophysical Data**

P Moore, Q Zhang and A Alothman

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Annual and semi-annual variability in the Earth's gravitational field for degrees two through six has been recovered from SLR tracking to five geodetic satellites, Lageos I, LageosII, Stella, Starlette and Ajisai. In addition temporal variability has been sought from CHAMP by analysing the RSO satellite positioning, accelerometer data, quaternions, thrusters events etc. Details of the CHAMP gravity field recovery including the state vector will be outlined. Results will be presented of the variability from SLR, from the CHAMP analysis and from the combination of SLR and CHAMP at the normal equation stage. These satellite based results will be compared against corresponding variability inferred from geophysical models of mass redistribution within the atmospheric, oceans and continental hydrosphere. Correlations and rms of fit will provide insight into the accuracy of the several alternative models. Finally, the satellite and geophysical data will be compared against the preliminary results from GRACE both in terms of the actual harmonics and in terms of spatially averaged geoographical variations.

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18. **Time-Variable Gravity from GRACE and Hydrology**

R. Schmidt, F. Flechtner, A. Güntner, R. König, Ul. Meyer,
K.-H. Neumayer, S. Petrovic, Ch. Reigber, P. Schwintzer, S.-Y. Zhu

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The primary mission goal of the Gravity Recovery And Climate Experiment (GRACE) mission is to map fluctuations in the Earth's gravity field to unprecedented accuracy over a spatial range from 400 km to 40,000 km with monthly resolution during its nominal 5-year lifetime. GRACE will thus be able to constrain mass transports related to geophysical and climatological processes causing the observed gravity changes. This contribution focusses on mass redistribution induced by changes in global continental water storage as one major source for gravity variations, causing geoid variations at the 1-cm level at seasonal time scales. Based on current monthly GRACE gravity fields generated at GFZ Potsdam, the obtained results indicate a sensitivity to hydrological-related mass redistribution in large river basins down to structures of 800 km half-wavelength. For verification of the GRACE temporal gravity recovery results data from different global hydrology models are used for

comparisons in the spectral and the space domain.

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19. **Time changes of the European gravity field from GRACE: a comparison with ground measurements from superconducting gravimeters and with hydrology model predictions**

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We investigate the time-variable gravity changes in Europe retrieved from the initial GRACE monthly solutions spanning a 20-month duration from April 2002 to December 2003. Gravity anomaly maps are retrieved in Central Europe from the monthly satellite solutions from which we compare the fields according to various truncation levels (typically between degree 10 and 20) of the initial fields (expressed in spherical harmonics to degree 120). For these different degrees, an empirical orthogonal function (EOF) decomposition of the time-variable gravity field leads us to its main spatial and temporal characteristics. We show that the dominant signal is found to be annual with an amplitude and a phase both of which are in agreement with predictions in Europe modeled using snow and soil-moisture variations from recent hydrology models. We compare these GRACE gravity field changes to surface gravity observations from 6 superconducting gravimeters of the GGP (Global Geodynamics Project) European sub-network, with a special attention to loading corrections. Initial results suggest that all 3 data sets (GRACE, hydrology and GGP) are responding to annual changes in near-surface water in Europe of a few microGal (at length scales of ~1000 km) that show a high value in winter and a summer minimum. We also point out that the GRACE gravity field evolution seems to indicate that there is a trend in gravity between summer 2002 and summer 2003 which can be related to the 2003 heatwave in Europe and its hydrological consequences (drought). Despite the limited time span of our analysis and the uncertainties in retrieving a regional solution from the network of gravimeters, the calibration and validation aspects of the GRACE data processing based on the annual hydrology cycle in Europe are in progress.

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20. **Water storage variations in large river basins – comparing results from GRACE and hydrological models**

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In this contribution, temporal variations of the continental water storage derived from monthly GRACE gravity solutions are compared to results of global hydrological models. In terms of storage variations from hydrological models, the focus is on simulation results of the Watergap Global Hydrological Model (WGHM). The contribution of different storage components (snow, soil water, groundwater, surface water) to total water storage variations is assessed based on the simulation results. Results of other hydrological models and water balance estimates are also taken into consideration. The comparison of GRACE and model data is done for the major river basins worldwide, covering a wide range of climatic and

physiographic conditions. The correspondence of the different data sets is discussed, accounting, for instance, for the influence of different filtering techniques to extract regional mass anomalies and for limitations and uncertainties of the hydrological models.

21. **Terrestrial Water Storage Variations From GRACE**

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Early estimates of continental water storage variations from GRACE show tremendous promise for applications in hydrology and Earth system science. Here we review our recent progress, including several ongoing activities. We will present our global mass change fields, with comparison to assimilating land surface models including GLDAS. The impact of different smoothing length scales for resolving the features of the terrestrial mass change fields will be discussed. Mass change fields will be compared to terrestrial hydroclimatology with implications for the information content of the GRACE data. We will discuss ongoing efforts for basin-scale water storage change extractions, including indentifying optimal basin functions that may vary temporally and geographically. We will present GRACE-derived evapotranspiration estimates for the Mississippi River basin and discuss the utility of the proposed method for water balance monitoring. The potential for the GLDAS for modeling the hydrology signal in the data processing stream, and for temporal aliasing studies, will be described. Research plans for the next 6-12 months will be outlined.

22. **Degree-2 Harmonics of the Earth's Mass Load Estimated from GRACE, GPS and Earth Rotation Data**

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A fluid, mobile atmosphere and oceans surrounds the solid Earth and upon its land surface lays a continually changing distribution of ice, snow, and ground water. The changing distribution of mass associated with the motion of these surficial fluids changes the Earth's gravitational field, changes the Earth's rotation by changing its inertia tensor, and changes the Earth's shape by changing the load on the solid Earth. GRACE is currently measuring changes in the Earth's gravitational field at monthly intervals. It has also been recently demonstrated that large-scale changes of the Earth's shape, and hence of the mass load causing the Earth's shape to change, can be measured using the global network of GPS receivers. Here, the degree-2 mass load coefficients determined from GRACE and GPS data are compared with those obtained from Earth rotation observations from which the effects of tides, winds, and currents have been removed. Good agreement is found between these estimates of the degree-2 mass load, particularly at seasonal frequencies.

23. **Time variable gravity and polar motion: assessing the degree 2, order 1 geopotential coefficients from GRACE**

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Changes in the Earth's mass or gravity field can excite variability in polar motion at seasonal timescales. Monthly GRACE solutions provide values of $C_{2,1}$ and $S_{2,1}$ geopotential coefficients from which one can estimate the polar motion excitation associated with the redistribution of mass, including the largely unknown variability in land hydrology. Comparison of these estimates with those derived from highly accurate and independent polar motion data provides a good test of GRACE. To focus on the relation between mass fields and polar motion, the excitation by atmospheric winds and ocean currents is estimated from available model output and removed from the polar motion data. Agreement between the observed excitation derived from GRACE and from polar motion data is poor, particularly for the component along the Greenwich meridian dependent on $C_{2,1}$ (GRACE estimates too large and with different phase). Using the GRACE results does not improve the agreement with polar motion data over what is obtained with model estimates of the variability in the atmospheric and oceanic mass fields only. Errors in the modeled effects of winds and currents (removed from the data) seem unlikely to explain most of the noted discrepancies in the polar motion excitation budget. The uncertainties in the GRACE results remain to be understood.

P 7 **Time variations in the GRACE gravity field: Constraints on global hydrologic mass flux**

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Monthly Gravity Recovery and Climate Experiment (GRACE) geopotential solutions for 12 distinct months covering a time span of 1.5 yrs in 2002-2003 have now been computed by the GRACE project. By analyzing these monthly solutions (from CSR and JPL), we have extracted the seasonal and secular (inter-annual) components of the Earth's temporally varying gravity field. Spherical harmonic components
up to degree and order 36 have been retained and then smoothed by averaging over caps of 8 degrees in radius using a Pellinen operator which suppresses half-wavelengths shorter than 1500 km. Global signals associated with seasonal water mass flux between the continents and oceans are clearly evident. On the continents these GRACE seasonal results indicate water storage variations as large as 15 cm (thickness-equivalent) over the breadth of the Amazon basin and of similar magnitudes over other large drainage basin systems such as the Ob/Lena, the Southeast Asia/Bay of Bengal and the central African systems. Seasonal signals over northwestern North America and southern Greenland are very likely due to snow/glacial fluctuations. Phase results are also shown. Similarities between these GRACE results and hydrological models (drainage runoff, water storage) are shown. In the oceans, the GRACE results reveal seasonal fluctuations with amplitudes as large as 6 cm in water thickness equivalent - NOT geoid - over places such as the western Chukchi Sea, the

Southern Ocean/southernmost Indian Ocean and the south Atlantic. We are investigating the correspondence of these GRACE seasonal oceanic signals with annual tides and other possible contributors to the non-steric (eustatic), regional mass change in the ocean. It appears premature to interpret secular (inter-annual) GRACE gravity variations deduced from the short, 1.5 year-long data set. For example, secular J2dot is poorly constrained by the 1.5 year GRACE time series and suggests that a surprisingly large 'fattening' or oblateness increase of the Earth is occurring. Clearly we must wait for longer GRACE monthly time series

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Gravity field variation from GRACE on annual scales

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GRACE is currently mapping the Earth's gravity field in space and time with un-precedented resolution and accuracy. The first 15 monthly global gravity fields solutions, recently being released to the GRACE science working team, have been used to study the long wavelength component of the annual gravity variation. The GRACE gravity field to harmonic degree 10 data shows an annual component in the gravity field peaking at 7.1 microGal over the Amazon Basin. Over the central southern Africa amplitudes peaks at 4.2 microGal and over Bangladesh at 3.4 microGal. The peaks follow the solar Equinoxes being in opposite phase on the two hemispheres.
11 Monthly gravity fields were initially released to the science team. The gravity fields are continuously being released and recently an additional four monthly gravity fields have been released giving a total of 15 monthly gravity field. The impact of these additional fields on the estimation of annual signal is evaluated.
By using inverse techniques the published calibrated error fields can be used to study the impact of availability of more monthly fields. This also affects the truncation levels which can be used for the investigation. An investigation of the annual signal content at different spherical harmonic degree is presented.
The annual component in the gravity field is compared with gravity changes due to continental water storage from a hydrological model based on NCEP reanalysis data. This model peaks at 6.6 microGal over the Amazon Basin. Comparisons with other models and in-situ data have also been performed to validate the findings. The spatial correlation between the amplitude of the annual gravity signal in GRACE and hydrology computed over 10 degree zonal latitude bands is higher than 80 per cent everywhere.

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Time-Variable Gravity Signal from China's Three-Gorges Reservoir

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By 2009, behind one of world's highest artificial dams standing 175 m tall, China's Three-Gorges Reservoir will be holding 40 cubic km of water, flooding a stretch of middle Yangtze River about 600 km in length. The impounded water represents a net transport of mass from

the oceans onto a concentrated area on land, and represents a geophysical "controlled experiment" offering a unique opportunity for conducting detailed studies of a classical forward/inverse modeling problem of surface loading. The water impoundment of the Three-Gorges Reservoir has begun in phases, with a quarter of the full capacity already impounded during June of 2003. At this point, the resultant time-variable gravity signal (as a step-function) is not quite above the noise level of the GRACE data currently released, and apparently buried in a much larger seasonal hydrological variation in the region. Nevertheless, signal retrieval algorithm in terms of averaging kernels can be implemented, and attempts to retrieve the Three-Gorges time-variable gravity signal is underway. A similar scheme will also be developed for retrieving the GRACE observation for the Mediterranean Sea, to be compared to other geophysical and oceanographic data.

P 10 **Measurements and Modeling of Surface Water Fluxes in the Amazon Basin**

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Seasonal variations in the flow of water through the Amazon Basin constitute some of the largest mass changes measured by GRACE. The spatial resolution of GRACE is currently on the order of 500,000 km^2 which requires modeling to scale between local measurements of hydraulics and GRACE measures of hydrologic mass change. A large unknown in the summed masses that make up the GRACE observations are changes in floodplain water storage. For example, flow exchange between the Amazon floodplain and main river channel is estimated at 25% of the average annual discharge from the Basin. We have found that interferometric processing of synthetic aperture radar (SAR) data can yield estimates of changes in floodplain storage. We have also developed a hydrologic mass balance model that includes a routing scheme which will allow us to understand the storage changes in each mass component summed by GRACE. Geophysical forward modeling of each mass component will then be used to relate the spatial scales of the hydraulic processes to the GRACE measurements.

P 11 **Detectability of geoid displacements arising from changes in global ice volumes by the GRACE gravity space mission**

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Global geoid changes resulting from the spatial and temporal fluctuations of several regions of major present-day glaciation are investigated. The regions of interest are: Antarctica, Greenland, Patagonia, Alaska and Iceland. After taking into account the contribution due to the ongoing isostatic adjustment of the Earth to ice-load changes following the Last Glacial Maximum, predictions for the present-day contributions are made using recently published compilations of these glacial changes. Most of the regions examined show a comparable response when the geoid-change spectra are examined, regardless of the relative size of the ice masses involved. The extent to which the signals may be resolved is, however, dependent upon the final accuracy achieved, which is continuously being updated.
