2021 GRACE-FO Science Team Meeting
- Abstracts -

Oct 12/13 & Oct 19/20, 2021
Virtual Meeting, organized by
Jet Propulsion Laboratory / California Institute of Technology
Pasadena, CA, U.S.A.
gfostm_2021@jpl.nasa.gov

1

GRACE Follow-On Accelerometer Data Recovery

Behzadpour, Saniya; Institute of Geodesy, Graz University of Technology)(Krauss, Sandro; Institute of Geodesy, Graz University of Technology)(Kvas, Andreas; Institute of Geodesy, Graz University of Technology)(Mayer-Gürr, Torsten; Institute of Geodesy, Graz University of Technology
behzadpour@tugraz.at

At the beginning of the GRACE-FO (Gravity Recovery and Climate Experiment Follow-on) mission, the noise on GRACE-D accelerometer (ACC) measurements elevated and resulted in systematical degradation of the data. In order to compute a gravity field model with satisfactory accuracy, the GRACE-D data was replaced by synthetic data, the so-called transplant data, officially generated by the GRACE-FO Science Data System (SDS). The SDS transplant data are derived from the GRACE-C accelerometer measurements, by applying time and attitude corrections as well as adding modeled thruster responses. Preliminary analysis of GRACE-FO Level-2 data proves that the derived low degree zonal harmonics, in particular C20 and C30, are affected by the transplant approach, and as recommended by SDS, are needed to be replaced by SLR-derived values.

The main purpose of this study is to present an improved method to recover the GRACE-D accelerometer data by incorporating non-gravitational force models and analyze its impact on the recovered gravity field solutions. The alternative ACC product contributes to an improved estimation of higher degrees of the recovered monthly gravity field solutions, as well as low zonal degrees 2 and 3. The estimates of the C30 coefficients represent a significant improvement with respect to SLR-derived values, with which the GRACE-FO values are recommended to be substituted.

2

LRI Data Processing and Analysis at AEI

Malte Misfeldt, Vitali Müller, Henry Wegener, Laura Müller, Gerhard Heinzel
malte.misfeldt@aei.mpg.de

The Laser Ranging Interferometer (LRI) onboard the GRACE Follow-On mission is now operational for more than three years. It provides high-quality ranging data with a noise below 1nm/√Hz at Fourier frequencies around 1 Hz as well as attitude information with respect to the line-of-sight between the two spacecraft
In this talk, we present LRI data processing activities at the Albert Einstein Institute in Hannover. These cover the derivation of an alternative LRI1B data product, the calculation of tilt-to-length coupling factors (~CoM position) and the monitoring of so-called momentum-transfer-events, which we believe are micro-meteorite impacts. Furthermore, we address the scale factor of the LRI, where we pursue an alternative method to calculate the scale factor from laser telemetry. For this, we attempt to disentangle thermal effects from the scale factor estimates that are obtained by KBR-LRI cross-calibration.

3

GROOPS: An open-source software package for GNSS processing and gravity field recovery

"Mayer-Guerr, Torsten; TU Graz;
Behzadpour, Saniya; TU Graz;
Dumitraschkewitz, Patrick; TU Graz;
Kvas, Andreas; TU Graz;
Krauss, Sandro; TU Graz;
Strasser, Sebastian; TU Graz;
Suesser-Rechberger, Barbara; TU Graz;
Eicker, Annette; HCU Hamburg; TU Graz;
mayer-guerr@tugraz.at

The Gravity Recovery Object Oriented Programming System (GROOPS) is a software package written in C++ that enables the user to perform core geodetic tasks. The software features gravity field recovery from satellite and terrestrial data, the determination of low-earth-orbiting satellite orbits from global navigation satellite system (GNSS) measurements, and the computation of GNSS constellations and ground station networks. For an easy and intuitive setup of complex workflows, GROOPS contains a graphical user interface to create and edit configuration files. The source code of GROOPS is released under the GPL v3 license and is available on GitHub (https://github.com/groops-devs/groops) together with documentation, a cookbook with guided examples, and installation instructions for different platforms. In this contribution we give a software overview and present results of different applications and data sets computed with GROOPS.

4

GRACE/GRACE-FO data migrating to NASA Earthdata Cloud

Wen-Hao Li, Christopher Finch, Edward M Armstrong, David Moroni
wen-hao.li@jpl.nasa.gov

NASA’s Physical Oceanography Distributed Active Archive Center (PO.DAAC), the main GRACE/GRACE-FO data distribution center in US, has made revolutionary changes to its data publication, access, distribution systems through NASA’s Earthdata Cloud, powered by Amazon Web Service (AWS). Recent updates to the PO.DAAC web-portal provide direct synchronization of dataset content via the Earthdata Search API, seamless integration and distribution of data distributed both in the cloud and on-premise. A growing number of PO.DAAC datasets, including GRACE/GRACE-FO, are already available in the cloud. This is a big step forward for PO.DAAC to enhance and promote the GRACE/GRACE-FO data discoverability, usability and services. Such efforts enable the GRACE/GRACE-FO datasets to be available to a much broader and interdisciplinary user community, and further promote open science and data fusion research. The traditional data access and service tools are being transitioned into the Earthdata Cloud system, but availability will vary due to the configuration steps required for cloud-based integration. An enterprise-level web service API, known as NASA Harmony, for data discovery, download, subsetting and reformatting will be described, including some Jupyter notebook recipes developed by the PO.DAAC. In parallel to the cloud-migration effort, PO.DAAC has also reformed the metadata management and archiving infrastructure by switching the local management service to NASA's Common Metadata Repository (CMR), which is an enterprise-level data and metadata management system. CMR integrates metadata from all 12 NASA DAACS, providing the capability to make data search and extraction through the cloud more efficient than ever before.

5

Atmospheric Contributions to Global Ocean Tides

Balidakis, Kyriakos; GFZ German Research Centre for Geosciences, Earth System Modelling, Telegrafenberg, 14473 Potsdam, Germany
Shihora, Linus; GFZ German Research Centre for Geosciences, Earth System Modelling, Telegrafenberg, 14473 Potsdam, Germany
Sulzbach, Roman; GFZ German Research Centre for Geosciences, Earth System Modelling, Telegrafenberg, 14473 Potsdam, Germany
Dahle, Christoph; GFZ German Research Centre for Geosciences, Global Geomonitoring and Gravity Field, Telegrafenberg, 14473 Potsdam, Germany
Dill, Robert; GFZ German Research Centre for Geosciences, Earth System Modelling, Telegrafenberg, 14473 Potsdam, Germany
Thomas, Maik; GFZ German Research Centre for Geosciences, Earth System Modelling, Telegrafenberg, 14473 Potsdam, Germany
Dobslaw, Henryk; GFZ German Research Centre for Geosciences, Earth System Modelling, Telegrafenberg, 14473 Potsdam, Germany
kyriakos.balidakis@gfz-potsdam.de

To mitigate temporal aliasing effects in satellite gravimetry applications, GFZ is developing tidal and non-tidal background models in order to reduce one of the major error contributions to monthly GRACE and GRACE-FO gravity field estimates. For modelling tides in the atmosphere, we have exploited the higher spatial (31 km) and temporal (hourly) resolution provided by the latest atmospheric ECMWF reanalysis, ERA5. To evaluate the oceanic response to atmospheric forcing, we have run the general ocean circulation model MPIOM in the TP10 configuration accounting for the effects of self-attraction and loading and considering an improved bathymetry around Antarctica. Tides forced by ERA5-derived pressure and instantaneous turbulent surface stress harmonic amplitudes as well as gravitational forces exerted by the Sun and the Moon were also estimated employing an enhanced version of TiME, a global hydrodynamic model based on the shallow water equations. In this contribution we discuss the characteristics of 16 waves with periods between 4 and 24 hours that have been removed from the next release of the non-tidal de-aliasing model AOD1B. To further assess the quality of our ERA5-based tidal products, we have performed comparisons to harmonic estimates from hourly MERRA2 (~50 km), as well as ERA5-derived estimates from other periods.

6

Updates from GSFC: New mascon products from GRACE/GRACE-FO and SLR-only

Loomis, Bryant; NASA GSFC. Sabaka, Terry; NASA GSFC. Rachlin, Kenny; KBR at GSFC. Felikson, Denis; USRA at GSFC. Medley, Brooke; NASA GSFC.
bryant.d.loomis@nasa.gov

We present a summary of our recent work on time-variable gravity estimates derived from GRACE/GRACE-FO and satellite laser ranging (SLR). We show new global high-resolution mascon trend estimates along with global comparisons to other GRACE products. We also compare this new trend solution over the ice sheets to recent mass rates derived from ICESat/ICESat-2 and discuss likely causes of the remaining discrepancies between the altimetry and gravimetry estimates. We briefly summarize the status of our monthly mascon product, which includes a new half-degree equal-angle version that is preferred by researchers for various applications. Lastly, we summarize the latest results of our efforts to estimate continental-scale mascons from SLR data only, which are useful for extending mass change time series back to 1994, bridging GRACE/GRACE-FO data gaps, and independent validation of GRACE/GRACE-FO gravity estimates.

7

GRACE/GRACE-FO Monthly Gravity Field Solutions

"Duwe, Mathias; Leibniz University Hannover Institute of Geodesy
Koch, Igor; Leibniz University Hannover Institute of Geodesy
Prof. Dr.-Ing. Flury, Jakob; Leibniz University Hannover Institute of Geodesy
Dr.-Ing. Shabanloui, Akbar; Leibniz University Hannover Institute of Geodesy"
duwe@ife.uni-hannover.de

At IfE we compute monthly gravity potential solutions from GRACE/GRACEFO level 1B data by using the variational equations approach. The gravity field is recovered with our own MATLAB software "GRACE-SIGMA" that was recently updated in order to stay up to date in terms of the background models. With this changes we present our new reprocessed GRACE time series. In addition we present some laser ranging interferometer gravity field solutions and experimenting with combined KBR and LRI solutions. The obtained solutions are investigated in terms of error degree standard deviation and interesting results of post-fit residuals of the inter-satellite measurements.

8

Quantification of GRACE-FO capabilities to measure range acceleration signals in space and time

Peidou, Athina; Landerer, Felix; Wiese, David; Ellmer, Matthias; Fahnestock, Eugene; McCullough, Christopher; Yuan, Dah-Ning; Jet Propulsion Laboratory
athina.peidou@jpl.nasa.gov

The Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) satellite pair is equipped with two independent range system units, namely the Laser Ranging Interferometer (LRI) and the Microwave Instrument (MWI). We compare gravity fields derived from the two instruments. The LRI captures time-variable gravity field signals up to 21 mHz (~170 km) globally, while MWI reaches frequencies up to 15 mHz (~220 km). Time-variable mass variations free from annual cycles and trends are sensed up to 15 mHz (LRI) and 11 mHz (MWI). Both instruments are shown to be excellent tools for detection and monitoring of sub-monthly geophysical signals. The performance of both instruments as part of the GRACE-FO measurement system depends on constraints posed by the observed system (e.g., low amplitude of localized mass change signals) and the increased measurement system noise at higher frequencies.

9

Preparation for AIUB-RL03 GRACE time-variable gravity field solutions: processing strategies and instrument parametrization

Darbeheshti, Neda
Lasser, Martin
Meyer, Ulrich
Arnold, Daniel
Jaeggi , Adrian
Astronomical Institute, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland"
neda.darbeheshti@gmail.com

AIUB-RL03 is an update of GRACE monthly gravity field solutions that is currently being prepared at the Astronomical Institute of the University of Bern (AIUB). Compared to the previous AIUB-RL02, we updated the input observations and background models, and will adopt improved processing strategies in terms of instrument data screening and instrument parametrization. We use the latest RL03 KBR product and star camera data (L1B RL03), as well as the latest RL06 Atmospheric and Ocean dealising (AOD1B RL06) product. We show that outliers in star camera data may corrupt the KBR antenna offset correction (AOC), and by projecting them onto the line-of-sight direction they may degrade the monthly gravity solutions. Therefore, as the main instrument data screening strategy for AIUB-RL03, we plan to screen the KBR AOC for the whole GRACE years and to eliminate the epochs where the KBR AOC is above a pre-defined threshold. The KBR AOC screening turns out to be very powerful. For 90% of all months of the GRACE period, the derived gravity solutions are close to the other official gravity solutions without adopting any other additional data screening. Concerning the

accelerometer parametrization, we will use arc-wise full scale factor matrices and a third-order polynomial to model the accelerometer biases. The adopted accelerometer parametrization is well suited, especially for years in the later phase of the GRACE mission when the thermal control was switched off.

10

COST-G: Status and evaluation of the new deterministic signal model product

Meyer, Ulrich; Astronomical Institute of the University of Bern, Switzerland
Peter, Heike; PosiTim UG, Germany
Lasser, Martin; Astronomical Institute of the University of Bern, Switzerland
Jäggi, Adrian; Astronomical Institute of the University of Bern, Switzerland
and the COST-G Team
ulrich.meyer@aiub.unibe.ch

Since November 2020 IAG’s Combination Service for Time-Variable Gravity Fields (COST-G) is operationally providing monthly GRACE-FO combinations. In the first part of our presentation we give an overview of the contributing time-series and the combination results based on the COST-G quality control of the first 36 months of GRACE-FO data.

The second part is dedicated to the COST-G deterministic signal model (DSM), a new product issued for the first time in September 2021, which is dedicated to the precise orbit determination (POD) of Low Earth Orbiting (LEO) satellites. The DSM is fitted to the time-series of the monthly COST-G combined gravity fields and will be updated quarterly. We compare the signal content of the DSM to long-term models based mainly on GRACE data, to a GRACE-FO-only static model with co-estimated time-variations determined at AIUB, and to the COST-G monthly combined gravity fields. We also study its application for LEO POD in case of the Sentinel-2B and -3B satellites and conclude that the COST-G DSM is a valuable alternative to long-term models (which are not updated regularly) and is well suited to predict secular and seasonal gravity field variations for operational POD, where the monthly GRACE-FO gravity fields are not yet available.

11

Data-driven self-dealiasing approach for monthly GRACE and GRACE-FO gravity retrieval

Murböck, Michael; TU Berlin, Germany
Abrykosov, Petro; TU Munich, Germany
Dahle, Christoph; GFZ, Germany
Flechtner, Frank; GFZ, Germany
Pail, Roland; TU Munich, Germany"
murboeck@gfz-potsdam.de

The NASA-GFZ GRACE-FO mission is successfully continuing the GRACE time series of mass transport measurements. In addition to continuity, the international Earth system science community is seeking for improved accuracy as well as improved spatial and temporal resolutions of mass transport data. Therefore the research unit NEROGRAV (New Refined Observations of Climate Change from Spaceborne Gravity Missions), funded by the Deutsche Forschungsgemeinschaft, is currently investigating the capability of improving mass transport data from GRACE, GRACE-FO and the Next Generation Gravity Mission.

In this talk, we present the main outcomes of the real data analyses on improving the spatio-temporal parameterization, which is one of the main objectives of NEROGRAV. Based on promising simulation results, a data-driven self-dealiasing approach for monthly GRACE and GRACE-FO gravity retrieval is investigated. We assess the use of daily GRACE/GRACE-FO gravity fields as additional de-aliasing products. This additional de-aliasing product is then used in the standard GFZ GRACE/GRACE-FO Level-2 processing scheme to reduce temporal aliasing errors.

We show results based on different daily solutions with different weighting and filtering schemes in terms of the signal content of the daily solutions themselves and of the effects on the monthly solution. Furthermore, we give insight in the latest results regarding the use of different priori fields. The results are discussed in the spectral and spatial domain for time series of monthly GRACE and GRACE-FO solutions in comparison with the standard GFZ RL06 solutions. Using this new approach, the noise in high spherical harmonic degrees and orders is significantly reduced.

12

Mass conserving filter based on diffusion for GRACE spherical harmonics solutions

(Goux, Olivier; Magellium) (Pfeffer, Julia; Magellium) (Blazquez, Alejandro; LEGOS) (Weaver, Anthony; CERFACS) (Ablain, Michael; Magellium)
olivier.goux@student.isae-supaero.fr

Over the past two decades, the GRACE (Gravity Recovery and Climate Experiment) and GRACE Follow-On mission (GRACE-FO) have provided monthly measurements of the gravity field as sets of Stokes coefficients, referred to as spherical harmonics solutions. The variations of the gravity field can be used to infer mass variations on the surface of the Earth, mostly driven by the redistribution of water. However, unconstrained GRACE and GRACE-FO solutions are affected by strong correlated errors, easily identified as stripes along the North-South direction in the monthly gridded solutions. Here, we develop a filter based on the principle of diffusion to remove correlated errors and access the underlying geophysical signal. In contrast to many filters developed for this task, diffusion filters allow a spatially variable level of filtering, that can be adapted to match spatially variable signal-to-noise ratios. The formalism of diffusion allows the implementation of boundary conditions, which can be used to prevent any flux through the coastlines during the filtering step. As mass conservation is enforced in the filter, global indicators such as trends in the global mean ocean mass are preserved. Compared with classical decorrelation filters, diffusion filters improve the consistency of spherical harmonics solutions with mascon solutions and with independent estimates based on altimetry and in-situ data.

13

A sensitivity kernel perspective on GRACE mass change estimates

(Döhne, Thorben, TU Dresden), (Horwath, Martin, TU Dresden), (Groh, Andreas, TU Dresden), (Buchta, Eric, TU Dresden)
thorben.doehne@tu-dresden.de

Estimates of mass changes from GRACE spherical harmonic solutions have used a variety of methods. Different methods may arrive at different results even if the input spherical harmonic solutions and applied corrections are the same. An assessment and comparison of methods (not only of their results) is important but has not been widely undertaken. A popular distinction between methods is into the two categories of the direct and the inverse approach. In the direct approach surface mass density variations are integrated by using a predefined weight function (also called sensitivity kernel). In the inverse approach mass changes are parametrized based on pre-defined patterns of mass changes. Scaling factors are then estimated for these patterns in a least-squares minimisation approach to fit to (some representation of) observed gravity field variations. We recall that sensitivity kernels are inherent not only to methods of the direct approach. They are also inherent, and may be made explicit, for methods of the inverse approach. If covariance information is used rigorously in either the direct or the inverse approach, then the inherent sensitivity kernels are equal, that is, the approaches are equivalent. We illustrate the value of sensitivity kernels for the example of four previously used methods to estimate Greenland Ice Sheet mass changes. Once sensitivity kernels are made explicit, it is straight-forward to assess leakage errors and GRACE error propagation.
We propose that sensitivity kernels should be communicated and used as a tool to assess and compare methods.

14

Fast mascons from spherical harmonics

"Croteau, Michael; NASA Goddard Space Flight Center
Sabaka, Terence; NASA Goddard Space Flight Center
Loomis, Bryant; NASA Goddard Space Flight Center"
michael.j.croteau@nasa.gov

GRACE mascon solutions have simplified surface mass change studies using GRACE and GRACE-FO compared to Level-2 spherical harmonic products, but restrict users to center-defined regularization and design decisions that bias these studies. We have developed a new method for computing regularized mascons from spherical harmonics and their normal equations (or covariances) by reformulating the traditional rigorous mascon technique employed at GSFC and CSR. Provided that full covariances are available, these “fast mascons” will be mathematically equivalent to similar mascons estimated from Level-1B observations. As a result, this method is more robust and allows greater control of signal leakage than all other spherical harmonic and mascon-from-sphericals techniques. Additionally, this method decouples mascon estimation from GRACE Level-1B processing, opening the door to mascon development to scientists outside those centers which have Level-1B processing capabilities.

Here, we discuss this new method and present a proof of concept and two trade studies recently published in JGR: Solid Earth.

15

Data-Based Geocenter Motion Determination for GRACE-FO Mission

Wu, Xiaoping; Jet Propulsion Laboratory, California Institute of Technology
Kuang, Da; Jet Propulsion Laboratory, California Institute of Technology
Haines, Bruce; Jet Propulsion Laboratory, California Institute of Technology
Heflin, Michael; Jet Propulsion Laboratory, California Institute of Technology
Xiaoping.Wu@jpl.nasa.gov

The degree-1 spherical harmonic coefficients of surface mass variations and their equivalent geocenter motion components between center-of -mass of the Earth system (CM) and the center of figure of the solid Earth surface (CF) are critical parts of the spherical harmonic spectrum. They are also very difficult to measure in unbiased and accurate ways with low-latency due to limitations of current geodetic systems. Direct translational measurement from SLR offers stronger signals than degree-1 deformation, but the motion of geocenter with respect to the center of a very sparse network is considerably different from geocenter motion with respect to CF. The SLR ground data can be supplemented by other geodetic data and local tie measurements through a time series approach to the Terrestrial Reference Frame (TRF). However, TRF realizations currently have very long latency periods.

Recently, a new translational determination of the motion between CM and the center of JPL's Flinn GNSS network (CN) has been demonstrated using GNSS tracking to GRACE satellites and their on-board accelerometer data (Kuang et al., 2019). We use this method to first determine daily offsets between CM and Flinn CN during GRACE and GRACE-FO periods. These are then deducted from JPL's point-positioned site coordinates in the Flinn CN frame to result in geocentric displacements of a wider and optimally distributed network. Unified inversions of the geocentric displacements and GRACE or GRACE-FO gravity data are then carried out to estimate geocenter motion between CM and CF. The unified approach combines both translational and deformational signatures of degree-1 mass variations. The combination of GRACE or GRACE-FO gravity data further improves access to CF. Comparison between geocenter motion results from this approach and from the inversion of TRF displacements + GRACE gravity during a GRACE period shows excellent agreement and demonstrates competitiveness of GNSS GRACE tracking in sensing CM. We will also report inversion results using GNSS displacements with GRACE-FO tracking and GRACE-FO gravity data.

16

Long-term (1979-present) Total Water Storage Anomalies Over the Global Land Derived by Reconstructing GRACE data

Li, Fupeng; Institute of Geodesy and Geoinformation, University of Bonn, Bonn 53115, Germany
Kusche, Jürgen; Institute of Geodesy and Geoinformation, University of Bonn, Bonn 53115, Germany

Chao, Nengfang; College of Marine Science and Technology, China University of Geosciences, Wuhan, 430074, China
Wang, Zhengtao; School of Geodesy and Geomatics, Wuhan University, Wuhan 430079, China
Löcher, Anno; Institute of Geodesy and Geoinformation, University of Bonn, Bonn 53115, Germany
fpli@uni-bonn.de

The Gravity Recovery and Climate Experiment (GRACE) mission has monitored global total water storage anomalies (TWSA) with an unprecedented accuracy since 2002. Yet, there is ~1 year of data gap between the two GRACE missions and many applications require a longer record, i.e. extending prior to the GRACE period. Here, we present a new global reconstruction of long-term (1979-2020) TWSA fields based on machine learning using multiple hydrometeorological variables, including precipitation, land temperature, sea surface temperature, soil moisture, evaporation, surface runoff, ground runoff, and several climate indices, as inputs. For this case, we develop a viable strategy for extending the application of the combined TWSA reconstruction approach - i.e., combine machine learning with statistical decomposition and time series decomposition techniques - as developed in our previous study (https://doi.org/10.1029/2019WR026551) from the basin scale to the global scale. The validation indicates that the new data processing strategy used in this study improves the performance of the combined approach in 26 river basins. We also find that the long-term TWSA reconstructed from GRACE fits well with the GRACE-FO observation over most grids (0.5° resolution) of the global land and we successfully reproduce the strong El Niño signal. Comparisons to Satellite Laser Ranging (SLR) solutions and to observed global mean sea level change suggest our reconstruction (doi: https://doi.org/10.5061/dryad.z612jm6bt) is more reliable than previously published products. This study was published earlier this year (https://doi.org/10.1029/2021GL093492) and it provides a viable approach for both reconstructing past TWSA and filling the GRACE data gap at the global scale.

17
Probabilistic Modeling of GRACE Mass Change Time Series with Missing Data

(Rateb, Ashraf; Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA)
(Sun, Alexander; Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA)
(Scanlon, Bridget R; Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA)
(Save, Himanshu; Center for Space Research, University of Texas at Austin, Austin, Texas, USA)
(Hasan, Emad; Center for Space Research, University of Texas at Austin, Austin, Texas, USA)"
ashraf.rateb@beg.utexas.edu

Gravity Recovery and Climate Experiment (GRACE) and the successor Follow-On (FO) missions have advanced our knowledge of the global mass changes in land, ocean, and cryosphere since 2002. Yet, the missing data within and between the missions disrupt the

continuity of the observations. In addition, the missions' data latency (2-3 months) affects the near-real-time analysis and impacts applications (e.g., data assimilations). This research, therefore, implements a data-driven approach based on the Bayes' theorem to impute the missing observations and infer present observations "nowcasting" that are not yet delivered by the science data centers. We decompose the geophysical signal observed by the two missions between 2002 and 2020 into its temporal structures (e.g., secular trend, interannual, annual, semiannual cycles, and residuals). We use informative priors on intercepts, slopes, range of amplitudes, variability, and frequency of the cycles combined with mathematical approximation (e.g., Markov Chain Monte Carlo (MCMC)) to cover most of the space undertaken by these parameters and the data. By generating posteriors distributions for these components over the missing and exited observations and adding them back using the median of posteriors, we restore the range of the missing observations and derive their credibility. In addition, the predictive posterior distributions of the generated model can be used to infer the present estimates that have not yet been delivered (either monitored or not). Such flexible methodology allows incorporating the new observations when they are available, which is helpful for real-time applications. We incorporated the mascon monthly solutions released by the University of Texas at Austin, Center of Space Research, (UTCSR) at a resolution of 0.25° x 0.25° for this analysis. Results show our modeled data explain most of the original observations with (median: 88%) at the basin scale and (median: 78%) at the grid scale. Our approach does not require external information and relies only on GRACE observations.

18

Radio occultations from GRACE-FO: Data processing and validation with ECMWF

Schmidt, T.; GFZ
Schreiner, P.; GFZ
Wickert, J.; GFZ
Iijima, B. A.; JPL
Ao, C. O.; JPL
Tien, J. Y.; JPL
Meehan, T. K.; JPL
tschmidt@gfz-potsdam.de

An objective of the GRACE-FO mission is the continuation of GRACE radio occultation measurements successfully performed between 2006 and 2017.

GRACE and GRACE-FO measurements contribute to the overall radio occultation dataset used in weather and climate applications.

Since mid-2019 rising occultations from GF1 are available and processed in near-real time for weather service centres. Setting occultations from GF2 are continuously enabled since September 2021 and will be operational after the test phase. Both satellites deliver about 250 global distributed atmospheric profiles daily.

GF1 and GF2 radio occultation data are processed based on different measured variables: For different GPS satellites a combination of L1CA/L2P, L1CA/L2C, or L1CA/L5 is available.

In this study we present first results of GF2 processing complemented by GF1. Refractivity profiles up to an altitude of 60 km will be compared with ECMWF operational analyses. We also evaluate the quality of the refractivity data based on the different second frequency variables (L2P, L2C, and L5).

19

A global analysis of water storage variations from remotely sensed soil moisture and daily satellite gravimetry

Blank, Daniel; HafenCity University Hamburg
Eicker, Annette; HafenCity University Hamburg
Jensen, Laura; HafenCity University Hamburg
Güntner, Andreas; GFZ German Research Centre for Geosciences
daniel.blank@hcu-hamburg.de

Information on water storage changes in the soil can be obtained on a global scale from different types of satellite observations. While active or passive microwave remote sensing is limited to investigating the upper few centimeters of the soil, satellite gravimetry can detect changes in the full column of terrestrial water storage (TWS) but cannot distinguish between storage variations occurring in different soil depths. Jointly analyzing both data types promises interesting insights into the underlying hydrological dynamics and may enable a better process understanding of water storage change in the subsurface.

In this study, we aim to investigate the global relationship of (1) several satellite soil moisture (SM) products and (2) non-standard daily TWS data from the GRACE and GRACE-FO satellite gravimetry missions on different time scales. The six SM products analyzed in this study can be categorized based on their degree of post-processing and the observed soil depth. Original level-3 surface SM data sets of SMAP and SMOS are compared to post-processed level-4 data products (surface and root zone SM) and a multi-satellite product provided by the ESA CCI.

We decompose the signal into different temporal frequencies from seasonal to sub-monthly signals and carry out the comparison with respect to spatial patterns and temporal variability. We will analyze their relationship using Pearson’s pairwise correlation coefficient. Furthermore, a time-shift analysis is carried out by means of cross-correlation to identify time lags between TWS and SM data sets that indicate differences in the temporal dynamics of SM storage change in varying depth layers.

20

The 0,5° global land water storage (GLWS) data set based on GRACE and GRACE-FO data assimilation

Gerdener, Helena; University of Bonn, Institute of Geodesy and Geoinformation, Bonn, Germany
Schulze, Kerstin; University of Bonn, Institute of Geodesy and Geoinformation, Bonn, Germany
Kusche, Jürgen; University of Bonn, Institute of Geodesy and Geoinformation, Bonn, Germany
gerdener@geod.uni-bonn.de

Extreme hydrological events like droughts can lead to disastrous consequences, for example, restricted access to freshwater and crop failure, which in turn can result in famines and death. For analyzing these extremes and for risk assessments, surface observations of precipitation, soil moisture or streamflow are widely used. A major challenge is quantifying subsurface water availability, because the access to in-situ data is irregularly distributed in space and time and it can be restricted, e.g., due to political reasons. Model simulations can provide this information, but they do not perfectly represent reality because they are based on assumptions and error-prone forcing data.

Since 2002, the GRACE (Gravity Recovery And Climate Experiment) satellite mission and its successor GRACE FO (Follow-On) enable to observe total water storage anomalies (TWSA), the sum of surface and subsurface water changes. GRACE/-FO represent a great advantage to derive real observations globally from space, nonetheless, it is restricted to a coarse spatial resolution of about 300 km and cannot distinguish between the storages, while global hydrological models are already available at 50 km resolution. By assimilating the GRACE/-FO derived TWSA into a global hydrological model, we enable spatial downscaling and vertical disaggregation of the GRACE data, while at the same time improving the model realism.

We here present our new global land water storage (GLWS, Release 001) data set which is, for the first time, based on globally assimilating GRACE TWSA into the WaterGAP 2.2d/e global hydrological model (WGHM). GLWS covers 95 % of the global land surface in WGHM (without Greenland). At this time, the data set is provided at 50 km resolution from 2003 to 2018 in two different levels: 1) Global monthly fields of TWSA and 2) global monthly fields partitioned into surface water, soil moisture and groundwater components. Finally we show how, with the help of the GLWS data set, the identification and quantification of hydrological droughts can be improved.

21

Decadal prediction skill and reliability of climate models evaluated by a GRACE-based land water storage data set

Jensen, Laura; HafenCity University, Geodesy and Geoinformatics, Hamburg, Germany
Eicker, Annette; HafenCity University, Geodesy and Geoinformatics, Hamburg, Germany
Stacke, Tobias; Helmholtz-Zentrum Geesthacht, Centre for Materials and Coastal Research, Geesthacht, Germany

Dobslaw, Henryk; Helmholtz Centre Potsdam, German Research Centre for Geosciences (GFZ), Potsdam, Germany
laura.jensen@hcu-hamburg.de

Reliable predictions of terrestrial water storage (TWS) changes for the next couple of years would be extremely valuable for, e.g., agriculture and water management. Recently, decadal predictions have been carried out with climate models taking part in the Coupled Model Intercomparison Project (CMIP). To assess their quality and reliability regarding land water storage-related variables, we evaluate decadal predictions from an ensemble of five CMIP models against a TWS data set based on GRACE satellite observations.
Since data from the models and GRACE is jointly available in only 9 years, we access a GRACE-like reconstruction of TWS derived from precipitation and temperature data sets (Humphrey and Gudmundsson, 2019), which expands the analysis time-frame to 41 years. The model skill is estimated globally and regionally by means of anomaly correlations and root-mean-square deviation (RMSD). Furthermore, we assess the reliability of the predictions by comparing RMSD and ensemble spread, finding that the models are rather underconfident about TWS predictions.
However, we also find that at least for the first two prediction years the decadal model experiments clearly outperform the classical climate projections, regionally even for the third year. We can thereby demonstrate that the observation type “terrestrial water storage” as available from the GRACE and GRACE-FO missions is suitable as additional data set in the validation and/or calibration of climate model experiments.

22

Nearly two decades of groundwater dynamics in California’s Central Valley from GRACE and GRACE-FO

Liu, Pang-Wei, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
Famiglietti, Jay, Global Institute for Water Security, University of Saskatchewan, Canada.
Purdy, Adam, Geospatial Analysis Laboratory, Department of Environmental Science, University of San Francisco, San Francisco, California, USA.
Kim, Kyra, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.
Bindlish, Rajat, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.
Reager, John, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.
McEvoy, Avery, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.
pang-wei.liu@nasa.gov

The goal of this study is to use GRACE and GRACE-FO observations to estimate and monitor groundwater storage dynamics, including its depletion and recharge in California’s Central Valley, one of the most important agricultural regions in U.S. By incorporating soil moisture, snow water equivalent, and surface water storage, groundwater dynamics were derived from GRACE and GRACE-FO TWS products. Results show that groundwater depletion continues unabated, with rates at least as great as in previous drought periods. The groundwater

information was also correlated with surface water allocations managed by the the state and federal governments to highlight the linkages between groundwater storage variations and the availability of surface water resources. As such, the study provides insights into the capability of GRACE/FO in support for California's SGMA.

23

Hydrological Extremes and Trends in the GRACE and GRACE-FO Data Record

(Rodell, Matthew; NASA/GSFC), (O'Neill, Mary Michael; University of Maryland), (Li, Bailing; University of Maryland), (Loomis, Bryant; NASA/GSFC)
Matthew.Rodell@nasa.gov

This presentation will provide an update on our research on terrestrial water storage (TWS) extremes and trends based on the combined GRACE and GRACE-FO data record. First, we compare the TWS trends observed by GRACE and the extrapolated TWS anomalies with those observed by GRACE-FO and the combined GRACE and GRACE-FO TWS trends. We also compare the latter with high resolution trend maps based on a new level 1B data stacking approach. Next, we identify extreme events in the TWS data record and investigate how the frequency and intensity of these events may be linked with various climate signals.

24

Loss of water in the ground in the southwest U.S. during drought in 2020 and 2021

Donald Argus (JPL), Hillary Martens (Montana), David Wiese (JPL), Adrian Borsa (Scripps), El Knappe (Scripps), Stacy Larochelle (Cal Tech), Jean-Philippe Avouac (Cal Tech), Mackenzie Anderson (UCLA), Athina Peidou (JPL), Ashlesha Khatiwada (Montana), Felix Landerer (JPL)
Donald.F.Argus@jpl.nasa.gov

In this study we estimate change in water in the ground in the southwest United States using (1) elastic displacements of Earth's surface observed using the Global Positioning System and (2) changes in mass at Earth's surface estimated from the Gravity Recovery and Climate Experiment. Changes in water in the ground are inferred from total water storage by subtracting estimates of snow water equivalent and known changes in surface water in artificial reservoirs. Harsh drought struck the southwest U.S from October 2019 through July 2021. Precipitation in the two years was less than half the historic average. Snow accumulation in six of the past eight years was furthermore smaller than the mean. Using GPS, we estimate four California mountain provinces (the Sierra Nevada and Klamath mountains and the Coast southern Cascade Ranges) to have lost 24 cubic kilometers of water in Water Year 2020 and 22 cubic kilometers of water in the first eight months of Water Year 2021. GRACE observations support the inference from GPS that total water storage in California is at a historical low. We conclude that water in the ground has declined significantly in the past decade (given that 7 of the 10 years were dry years); such decline reflects soil moisture being parched from the ground and groundwater not being replenished.

25

Comparison of long-term water storage trend estimates based on GRACE/GRACE-FO data in small scale catchments and aquifers

Kvas, Andreas; Graz University of Technology
Boergens, Eva; German Research Centre for Geosciences (GFZ)
Dobslaw, Henryk; German Research Centre for Geosciences (GFZ)
Guentner, Andreas; German Research Centre for Geosciences (GFZ)
kvas@tugraz.at

The satellite missions GRACE and GRACE Follow-On (GRACE-FO) have substantially improved our understanding of the Earth system by providing monthly snapshots of surface mass change. With a growing data record reaching almost 20 years, this data set is well suited to investigate long-term changes in, for example, water storage, ice- and ocean mass.
In this contribution we present trends co-estimated with a long-term mean gravity field based on GRACE and GRACE-FO data. These trends are compared to water storage trend estimates from different monthly level-3 (L3) mass change products (CSR, GSFC and JPL mascon solutions, GFZ GravIS water storage fields). The longer data accumulation period of co-estimated trends reduces the high-frequency spatial noise inherent in GRACE/GRACE-FO solutions. Subsequently, weaker constraints can be applied to reach the same signal-to-noise ratio (SNR) as L3 monthly solutions. Therefore, directly tailoring constraints to the SNR of long-term mass changes, rather than monthly variations, results in better spatial localization and lower signal attenuation. This is showcased by intercomparison of the trend estimates for selected small aquifers and catchments and comparison with independent data. We conclude that co-estimated long-term trends based on GRACE/GRACE-FO are a useful complementary data product to identify and quantify regionally confided drying and wetting trends.

26

Statistical Gap-Filling, Reconstruction and Modal Analysis of GRACE/GRACE-FO Terrestrial Water Storage Record

Benjamin Hamlington, NASA Jet Propulsion Laboratory
Hrishi Chandanpurkar, NASA Jet Propulsion Laboratory
J.T. Reager, NASA Jet Propulsion Laboratory
benjamin.d.hamlington@jpl.nasa.gov

With the addition of GRACE-FO, the satellite-measured record of terrestrial water storage (TWS) is now approaching two decades in length. This record provides the opportunity to investigate a range of timescales of variability in (TWS) including at the interannual period where processes like El Niño-Southern Oscillation play a large role. While still challenging to separate out lower-frequency variability from trends with the available record lengths, it is now possible to investigate decadal shifts in variability. A common approach to identifying these shifts and finding dominant timescales of variability in spatiotemporal climate data records is statistical modal decomposition that includes Empirical Orthogonal Function (EOF)-based techniques. These techniques typically require evenly spaced data with no gaps in the data of interest. To overcome the gaps in the GRACE/GRACE-FO record, we propose a new gap-filling

technique based on cyclostationary empirical orthogonal functions (CSEOFs). We then use this same tool to extend the gap-filled record back in time to 1980 and to identify dominant modes of variability in TWS over the past four decades.

27

Quantifying ET Over the Congo Basin Using Satellite-Based and Ground Measurements

Worden, Sarah; UCLA, Fu, Rong; UCLA, Worden, John; JPL, Bloom, Anthony; JPL, Levine, Paul;JPL
sarahrw27@g.ucla.edu

The Congo Basin hosts the driest rainforest in the world, with large uncertainties in rainfall. Determining the contributions of free-tropospheric moisture to is therefore key for developing a better understanding of the relative influences on precipitation from external SSTA, internal land vegetation, and land-use changes. Bailey et al., (2017) found a linear relationship between net of evapotranspiration minus precipitation (ET-P) and the deuterium content of water at a specific humidity of 4 mmol/mol (dd04), on a tropical scale. Based on their finding, we apply a terrestrial water balance approach to derive ET over the Congo Basin between 2005-2016 using a suite of independent observations, i.e., AIRS deuterium measurements, the Tropical Rainfall Measurement Mission (TRMM) precipitation data, SO-HYBAM river discharge and changes in terrestrial water storage derived by the Gravity Recovery and Climate Experiment (GRACE). We show that ET derived from this approach is greater than atmospheric moisture convergence in all seasons and highest in the rainy seasons. Furthermore, the interannual variation of ET is relatively decoupled with that of rainfall. This result implies a potential resilience of ET, presumably rainforests, to interannual rainfall anomalies.

28

A wavelet-based fusion approach for unifying GRACE- and model-based total water storage changes: preliminary results

Ghobadi-Far, Khosro; Werth, Susanna, Shirzaei, Manoochehr; Virginia Tech
khosro@vt.edu

GRACE observations of total water storage (TWS) change provide us with a unique perspective into Earth's hydrological water cycle and help us to examine the natural and/or anthropogenic causes of variations in water resources. The coarse spatial resolution of GRACE TWS observations (~300 km) limits their applications to large-scale hydrological processes at the (river) basin scale. Assuming TWS provided by global hydrological or land surface models contains some reliable information at higher spatial scales of 25 or 50 km, we apply a 2D multiresolution analysis based on wavelet transform to fuse large-scale TWS spatial components from GRACE with small-scale components from the GLDAS/NOAH model to obtain TWS maps with improved spatial resolution. The spectral characteristic of wavelets makes them an optimal approach for combining such datasets with different spatial resolutions and spectral contents. We demonstrate that the fused TWS data quantify the water budget in the U.S. river

basins equally well as GRACE, while they also contain variability due to, e.g., soil moisture changes at high spatial scales. Rigorous validation of the fused TWS data and their potential use for hydrological applications is the subject of ongoing work. Our approach supports the estimation of accurate multiresolution maps of TWS based on GRACE and complementary datasets.

29

Satellite-based investigations of the Artificial Reservoirs in the Nile Basin

Sultan, Mohamed; Western Michigan University
Abdelmohsen, Karem; Western Michigan University
Save, Himanshu; Center of Space Research, Texas
mohamed.sultan@wmich.edu

We site two examples where GRACE, modelling, and Sentinel-1 data were used to monitor mass variations in artificial reservoirs (Lakes Nasser and Grand Ethiopian Renaissance Dam [GERD]), identify optimum utilization scenarios for impounded waters, and provide accurate and unbiased data on variations in Lake stages and volume. Lake Nasser peaked (>182 m.a.m.s.l) twice (1998 to 2002) and (2019 to present) and its waters were channeled into depressions west of the lake. Using calibrated groundwater and surface-water models, the volume of diverted (1998 to 2002) water was estimated at 27.4 km3, almost all of which was lost to evaporation. We investigated the nature of high lake level events using precipitation (1979 to 2021), GRACE (2003 to 2017) and GRACE-FO (2018 to 2021) CSR mascon solutions over the Nile subbasins. Findings indicate: (1) high lake Nasser level events are associated with increased precipitation over one or more of the Nile subbasins, and a progressive increase in GRACETWS and Lake Nasser levels over a period of 4-7 years preceding the event, and (2) excess Lake Nasser waters should not be left to evaporate, but used for replenishing the fossil Nubian aquifer. The progress on the construction of the GERD has been a contentious issue between the host and downstream countries. Our findings reveal the following: (1) the first stage of filling reached it maximum in August 2020, and resulted in the impoundment of 3.7 km3 in an artificial reservoir (area: 196 km2), elevated surface water levels (566 m.a.m.s.l), (2) 0.2 km3 of the reservoir waters were lost to evaporation and/or infiltration by April 2021 (3) the second stage of filling reached its maximum filling in August 2021 (9.3 km3), elevated its water level to 580 m.a.m.s.l and increased its area to 379 km2, and (4) the estimated volumes of impounded waters are less than the targeted amounts (first filling: 4.9 km3; second filling: 13.5 km3). One interpretation to the discrepancies between targeted and achieved filling is losses to evaporation and infiltration. The latter scenario (losses to infiltration) will be investigated using temporal GRACE solutions.

30

Highly Engineered River Systems, a Potential Adaptation to Climate Variability

Abdelmohsen, Karem;
Sultan, Mohamed;
Save, Himanshu;
karem.abdelmohsen@wmich.edu

Understanding the impacts of climate change on large river basins, and whether engineering structures within these systems can buffer the climate change-related impacts, is of prime importance to the livelihood of large sectors of the world population. The highly engineered (30 dams) Tigris Euphrates watershed was selected as our test site. We first used temporal (1920-2020) precipitation data (GPCC) to identify extreme drought and wet periods, and then evaluated their impact on monthly signals of GRACE and GRACE-FO Terrestrial Water Storage (GRACETWS), Surface Water Storage, and Groundwater Storage. Findings revealed an early prolonged (2007–2018) and intense drought, where the Average Annual Precipitation had no parallels in the past 100 years followed by 1-in-100-year extensive precipitation event in 2019, and an impressive recovery; the recovery amounted to half the losses endured during drought years with some 40% of the recovery captured in artificial reservoirs. Our findings suggest that highly engineered watersheds worldwide are better prepared to deal with the projected increase in the frequency and intensity of extreme rainfall and drought events in the 21st century.

31

Advancing the use of gravity for groundwater: building around GRACE/GRACE-FO in the Central Valley of California

Reager, J.T. (JPL); Kyra Kim (JPL); Zhen Liu (JPL); K.S. Yun (JPL); Anshuman Pradhan (Caltech); Donald Vasco (LBNL)
john.reager@jpl.nasa.gov

Groundwater monitoring represents one of the societally urgent science applications for spaceborne gravity, because these observations present the first globally available information source on the evolution of sub-surface water storage in large-aquifer systems. However, an obstacle in the wide adoption, exploitation, and understanding of gravity observations by hydrologists and water management organizations has been in the intrinsic characteristics of the data products, specifically for groundwater studies, in terms of spatial resolution. This presentation will show ongoing work from a suite of research activities that leverage the GRACE/GRACE-FO data in combination with ancillary data sources to create more actionable and relevant information for groundwater resources applications. Specifically, we discuss ongoing work on 3 topics: (1) to quantify how land-surface model uncertainties propagate into gravity-derived groundwater trend estimates (2) to combine gravity observations with InSAR observations, both from a qualitative contextual perspective and also from a formal joint inversion, and (3) on the construction of a consistent, widely applicable data analysis framework that includes groundwater wells and GPS observations, and expected future research directions.

32

Assessment of Land Surface and Atmospheric Model Mass Flux Using Water Balance Techniques and GRACE/GRACE-FO Data

Krichman, Benjamin; The University of Texas at Austin Center for Space Research
Bettadpur, Srinivas; The University of Texas at Austin Center for Space Research
Pekker, Tatyana; The University of Texas at Austin Center for Space Research
bkrichman@utexas.edu

GRACE mission data is used to derive variations in terrestrial water storage in order to evaluate approaches to the water balance. The data in the span of the GRACE and GRACE Follow-On missions is analyzed, and long-term behavior of a variety of basins is characterized. Terrestrial water storage variations are calculated via a combination of flux quantities from land surface models and atmospheric reanalyses using two common water balance approaches as well as a third approach using a novel algorithm for basin boundary discretization. Results are used to evaluate the new approach and form an understanding of its limitations, in relation to both the model data ingested as well as the characteristics of the regions in question. From the results, we observe significant variations in model performance over diverse geography and climatic conditions, such as diminished accuracy in atmospheric reanalyses under the effect of long term drought. These observations suggest utility as a diagnostic to assess and inform improvement in the studied models.

33

GRACE/GRACE-FO Observations Constrain Plant-accessible Water Storage Influencing Global Grassland Response to Drought

A G. 1), Velicogna I 1)-2), Zhao M.3)
1 University of California, Irvine, Department of Earth System Science,Irvine, CA
2 Jet Propulsion Laboratory, California Institute of Technology,Pasadena, CA
3 Stanford University, Stanford, CA
geruoa@uci.edu

The amount of plant-accessible water storage influences how plant production responds to climate extremes including drought, especially for the grassland ecosystem where water is the primary factor limiting plant production. However, plant-accessible water is rarely quantified due to the lack of regional to global scale observations of water storage at different soil depths, and the influence of deeper water supply on plant-water relation remains unknown. In this study, we show that total terrestrial water storage (TWS) estimates from GRACE/GRACE-FO provide unique information about plant-accessible water storage. In addition to TWS, we use surface soil moisture (SM) estimates form ESA CCI to represent shallow water storage, and MODIS EVI as a proxy for grassland productivity. We delineate water-limitation regime based on the inter-annual correspondence of EVI against both TWS and SM over 83 GRACE mascons covering the majority of the global grassland areas. We find that the seasonal change of TWS during water limited period constrains plant-accessible water storage and show strong correspondence with plant rooting depth derived from in-situ measurements, especially for regions featuring deep roots. Our results further show that land water storage buffers drought impact on plant growth. These results are instrumental in improving Earth system modeling.

34

14 Years of Monthly TWS Fluctuations in California Using a Joint Inversion of GNSS and GRACE

Carlson, Grace; Virginia Tech
Werth, Susanna; Virginia Tech
Shirzaei, Manoochehr; Virginia Tech
gcarlson@vt.edu

Monitoring terrestrial water storage change (ΔTWS) is essential for sustainable management of water resources, particularly in water-stressed regions. One such region is centered in California, USA, a heavily farmed state that experiences repeated, intense, multi-year droughts. This presentation shows high spatiotemporal resolution ΔTWS estimated over California and western Nevada for the period of January 2003-December 2016 achieved through a joint inversion of GRACE coarse resolution ΔTWS and Global Navigation Satellite System (GNSS) local vertical displacements. To this end, we develop and apply a unified time-dependent stochastic model to integrate both observations, including data gaps and variable uncertainties. We decompose the input signals into long- and short-term components, which are separately inverted for relevant mass variations using continuous wavelet transforms. This allows us to preserve annual, interannual, and multi-year changes in the resulting TWS dataset that were previously challenging to capture using satellite-based measurement systems or hydrological models alone. We highlight the advantage of our time-dependent joint inversion results for this tectonically active region by comparing them against inversion results that use only GNSS vertical deformation, maps of ΔTWS from GRACE solutions, and ΔTWS from two global hydrological models: the WaterGap Global Hydrological Model (WGHM), and the Global Land Data Assimilation System, Catchment Land Surface Model (GLDAS-2.1, CLSM). We show that results from our GNSS and GRACE joint inversion agree with the different GRACE solutions. Our results, however, also indicate improved isolation of larger magnitude signals over regions where we expect large ΔTWS signals (mountain ranges and the Central Valley) and smaller magnitude signals over regions where we expect smaller ΔTWS (the Basin and Range). We also show that, in general, our long-term ΔTWS estimates are larger than those from the WGHM and GLDAS hydrological models, indicating that these models may not accurately predict long-term ΔTWS in California.

35

Application of GRACE Satellites To Water Resources Management in Major African Aquifers

(Scanlon, Bridget R; Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA)
(Rateb, Ashraf; Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA)
(Anyamba, Assaf; NASA/Goddard Space Flight Center, Greenbelt, Maryland, USA)

(Kebede, Seifu; Centre for Water Resources Research, University of KwaZulu-Natal (UKZN), South Africa)
(MacDonald, Alan M; British Geological Survey, Lyell Centre, Edinburgh, United Kingdom)
(Shamsudduha, Mohammed; Department of Geography, University College London, London, UK)
(Small, Jennifer; NASA/Goddard Space Flight Center, Greenbelt, Maryland, USA)
(Sun, Alexander; Bureau of Economic Geology, Jackson School of Geosciences, University of Texas at Austin, Austin, Texas, USA)
(Taylor, Richard G; Department of Geography, University College London, London, UK)
(Xie, Hua; Environment and Production Technology Division, International Food Policy Research Institute, Washington, DC, USA)"
bridget.scanlon@beg.utexas.edu

Climate extremes and water scarcity result in too much water during floods and too little water during droughts, presenting major challenges water resource managers in many regions of Africa. The objective of this analysis was to quantify spatiotemporal variability in water storage using GRACE/GRACE-FO satellite data and assess dominant controls, including climate forcing and human water use in major African aquifers. Results show that GRACE derived Total Water Storage (TWS) variability in eastern and southern African aquifers are driven primarily in interannual climate variability linked to droughts and floods. These climate extremes result mostly from climate teleconnections, such as El Nino Southern Oscillation and Indian Ocean Dipole. Linear declining TWS trends were restricted to northern Africa and related to natural discharge and groundwater abstraction. In contrast, rising trends in western Africa are attributed to land use change. Quantifying relationships between climate extremes and water storage will be extremely valuable for developing more sustainable water management approaches in the future.

36

Regional Antarctic Ice Sheet Acceleration from Satellite Gravimetry

Diener, Theresa; Institute of Geography, Department of Geography and Geosciences, Friedrich-Alexander Universität Erlangen-Nürnberg, Germany
Sasgen, Ingo; Division of Glaciology, Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Am Handelshafen 12, 27570 Bremerhaven, Germany
theresa.diener@fau.de

The Antarctic Ice Sheet is subject to increasing atmospheric and ocean temperatures due to changes in large-scale circulation patterns in the Southern Hemisphere. These climatological changes vary regionally and have the potential to trigger a range of processes leading to ice sheet disintegration and global sea level rise. Currently, significant ice mass loss and acceleration of ice flow are observed in the Amundsen Sea Embayment in West Antarctica. In East Antarctica, such processes have so far been spatially restricted to smaller regions, such as to glaciers feeding the Amery Ice Shelf.

The present behavior of the ice is critical to understand its associated contribution to future global sea level rise. In this context, we aim to quantify the ice-dynamic acceleration in Antarctica based on differencing GRACE/GRACE-FO and ERA5-SMB for the period 2002 to

2020. This indirect method presents an alternative to estimates that quantify ice stream acceleration based on satellite observations of the surface-ice velocity, and is justified by the excellent agreement of GRACE/GRACE-FO and SMB at interannual time scales. Our estimate identifies the Amundsen Sea Embayment and Bellingshausen Sea region in West Antarctica as the dominant source of dynamic losses and potential instability, in-line with direct observations. We find that uncertainties of the SMB estimate limit the accuracy of our discharge estimate most, compared to other uncertainty sources. The uncertainties in our estimate can be reduced by further improving regional climate models. In conclusion, we provide an alternative to previous dynamic acceleration methods that can be considered for future assessments on the state of the Antarctic Ice Sheet. Including acceleration of the ice sheet mass loss in the projection of sea level rise results in a contribution more than twice that of linear extrapolation to 2100.

37

Update on mass changes of Greenland, Antarctica and the world’s glaciers and ice caps from GRACE and GRACE-FO Missions

Velicogna I 1)-2), Liang C.1),, Sutterley T 3), A G. 1), Ciraci E. 2), Landerer F. 2)
1 University of California, Irvine, Department of Earth System Science,Irvine, CA
2 Jet Propulsion Laboratory, California Institute of Technology,Pasadena, CA
3 University of Washington, Seattle, WA, USA;
isabella@uci.edu

We discuss the state of mass balance of the Greenland and Antarctic ice sheets and the World’s glaciers and ice caps from 2002 to present using GRACE and GRACE-FO missions, including the gap between missions. We show how the mass balance of the land ice has been evolving in recent years and highlight regions that have displayed the most significant changes. For the ice sheets, we use independent estimates of ice sheet mass balance from altimetry (ICESat-1, Cryosat-2, Operation IceBridge), and the mass budget method (MBM) with several regional climate models (RCM) and global climate models (GCM) to evaluate the GRACE/GRACE-FO results. In particular, we evaluate the impact of the accelerometer transplant on the glacier mass signal during the time span of the GRACE-FO mission. We compare the GRACE-FO mass balance estimates with climate model output in terms of trend and seasonality, and we do so for Greenland, Antarctica and the World’s glaciers since the impact of the accelerometer will vary among these regions and will contribute differently to the total signal.

38

Identification of climate mode fingerprints in GRACE and GRACE-FO measurements

Pfeffer, Julia; Magellium
Cazenave, Anny; LEGOS
Barnoud, Anne, Magellium
julia.pfeffer@magellium.fr

Climate variability exerts profound influences on the water cycle, and therefore society. In order to adapt to new risks and resources in a changing climate, it is necessary to develop tools able to characterize the natural climate variability and pinpoint the mechanisms triggering changes observed in the climate system. In this study, we designed a new model able to identify the fingerprints of eight climate modes in the global water cycle observed with the GRACE and GRACE-FO missions. To assess the robustness of the relationship between climate modes and the water mass changes observed from space, we used a LASSO (Least Absolute Selection and Shrinkage Operator) regularization, performing an efficient selection of the relevant predictors of the climate variability among the candidates considered. We found that over the oceans, ENSO (El Nino Southern Oscillation), SAM (Southern Annular mode) and AO (Arctic Oscillation) contribute significantly to the interannual ocean mass variations in extratropical-basins (up to 25 mm) and in shallow seas (up to 70 mm). Over the continents, a large part of the interannual variability of the terrestrial water storage (up to 100 mm) can be attributed to four climate modes, namely ENSO, AMO (Atlantic Multidecadal Oscillation), PDO (pacific Decadal Oscillation) and NPGO (North Pacific Gyre Oscillation). One important result of this study lies in our ability to track interannual water mass displacements across different reservoirs. For example, we can link the transport of water from intertropical regions to the Southern Ocean, where it contributes to the interannual variability of ice mass changes in West Antarctica in connection with ENSO, SAM and PDO. However, significant residuals in the satellite gravity measurements remain unexplained at interannual time scales and more complex models solving the water mass balance should be employed to better predict the variability of water mass distributions. The climate modes predictions based on LASSO inversions could still be used to reduce the interannual variability in satellite gravity measurements and detect processes unrelated with climate modes but with similar spatio-temporal signatures.

39

The use of GRACE to validate hydrological angular momentum determined from climate data

Nastula, Jolanta; Winska, Malgorzata; Kur, Tomasz; Sliwinska, Justyna; Partyka, Aleksander
nastula@cbk.waw.pl

Polar motion (PM), along with other Earth orientation parameters, is an essential element for transformation between celestial and terrestrial reference frames. However, it is affected by wide range of disturbances. One of such effects are mass variations of terrestrial water storage (TWS), the influence of which is still not fully understood.

Previous studies used TWS variations obtained from hydrological models or from global gravimetric data provided by GRACE to determine time series of hydrological angular momentum (HAM). HAM describes time variations of PM induced by continental hydrosphere. Climate models are a slightly different type of data than hydrological models, however they can also be used for HAM computation. Climate models, in addition to past changes in the mass distribution of TWS components (e.g. soil moisture, snow water), also provide projections of their future variation, which are simulated under various scenarios of carbon dioxide

concentration in the atmosphere. Thanks to this, it is possible to study the impact of future climate change on hydrological polar motion excitation as described by HAM.

Many studies on HAM determination have shown that the use of GRACE data allows for a high agreement between HAM and hydrological signal in geodetically observed PM. Therefore, in this study, we use GRACE to evaluate HAM determined from climate models delivered in the frame of Coupled Model Intercomparison Project phase 6 (CMIP6). To compute CMIP6-based HAM series, we use soil moisture and snow water variables delivered by various CMIP6 historical simulations. Then we compare the obtained series with HAM determined from TWS provided by GRACE. We analyse GRACE-based and CMIP6-based HAM variability in a wide variety of oscillations, taking into account trends, seasonal, and non-seasonal changes. Our results shows that, despite noticeable differences between individual CMIP6 models, it is possible to find models that provide high correlation and amplitude agreement between CMIP6-based and GRACE-based HAM.

40

Earth’s Energy Imbalance and sea-level budget over 2005-2019

Hakuba, Maria; NASA JPL
Frederikse, Thomas; NASA JPL
Landerer, Felix; NASA JPL
thomas.frederikse@jpl.nasa.gov

Earth's energy imbalance (EEI) represents the rate of global energy accumulation in response to radiative forcings and feedbacks. Ocean heat uptake (OHU) poses a vital constraint on EEI and its uncertainty. Here we use the sea-level budget to estimate the EEI. We combine GRACE and altimetry observations, geophysical corrections, and new estimates of the ocean's expansion efficiency of heat to estimate global sea-level rise and the contributions from ocean-mass change and thermosteric expansion, from which we derive the global OHU. With this method, we estimate an OHU of 0.86 [0.62, 1.10, 5%–95%] Wm-2 for the period 2005–2019. Adding components of non-oceanic heat uptake, we obtain an EEI of 0.94 [0.70, 1.19] Wm-2, which is at the upper end of previous assessments, but agrees within uncertainty. Interannual geodetic OHU variability exhibits a higher correlation with top-of-the-atmosphere net radiative flux than hydrographic-only data, but has a three times larger standard deviation. The radiation fluxes and the geodetic approach suggest an increase in heat uptake since 2005, most markedly in recent years.

41

Low-Frequency Ocean Bottom Pressure Response to Barometric Pressure Loading

Piecuch, Christopher (WHOI); Fukumori, Ichiro (NASA JPL); Ponte, Rui (AER); Wang, Ou (NASA JPL); Zhao, Mengnan (AER)
cpiecuch@whoi.edu

Ocean bottom pressure (OBP) retrievals from the Gravity Recovery and Climate Experiment (GRACE) provide an unprecedented view onto ocean dynamics related to mass redistribution. Past studies emphasize wind forcing as the main driver of spatial and temporal variations in OBP observed by GRACE, but surface loading by barometric pressure (PA) can also force a dynamic ocean response, manifested in OBP, depending on frequency, wavenumber, and location. We use twin ocean model experiments, performed in the context of the Estimating the Circulation and Climate of the Ocean (ECCO) project, to quantify magnitudes and spatiotemporal structures of PA-driven OBP variability during 1992—2017 on large scales and long periods relevant to interpretation of GRACE data. To focus on dynamics, PA averaged over the global ocean is removed from model OBP solutions. Forcing by PA excites basin-scale OBP signals with magnitudes as large as ~1 cm equivalent water thickness on monthly time scales. Largest signals are found in marginal seas, on continental shelves, and over deep midlatitude abyssal plains. The geography of PA-driven OBP variability over the open ocean is governed by conservation of planetary potential vorticity, with large-scale regions of coherent OBP anomaly constrained by H/f contours, where H is ocean depth and f is the Coriolis parameter. These OBP signals related to ocean dynamics are equivalent to 1-10% deviations from an expected isostatic “inverted barometer” sea-level response to PA loading. Modeled OBP changes forced by PA are typically 5-10% as large as monthly OBP fluctuations from GRACE, but can reach ~20% in the Arctic Ocean and Hudson Bay. Over vast tracts of the ocean—including the equatorial Pacific, tropical Atlantic, Pacific sector of the Southern Ocean, marginal seas off East Asia, and midlatitude North Atlantic slope and shelf regions—OBP changes forced by PA are significantly correlated with monthly GRACE OBP observations. These results demonstrate that, while it plays a secondary role to wind forcing in generating OBP variability on the space and time scales observed by GRACE, PA forcing is nevertheless significant and important to consider for comprehensive, quantitative understanding of time-variable GRACE mass data over the ocean.

42

Measuring the Earth energy imbalance from space to constrain the global energy budget and estimate the climate sensitivity

Chenal, Jonathan; LEGOS (CNES, CNRS, UPS, IRD), ENPC
Meyssignac, Benoit; LEGOS (CNES, CNRS, UPS, IRD)
Blazquez, Alejandro; LEGOS (CNES, CNRS, UPS, IRD)
Guillaume-Castel, Robin; LEGOS (CNES, CNRS, UPS, IRD)
jonathan.chenal@legos.obs-mip.fr

The energy radiated by the Earth toward space does not compensate the incoming radiation from the Sun leading to a small positive energy imbalance at the top of the atmosphere (0.4–1 Wm–2). This imbalance is coined Earth’s Energy Imbalance (EEI). It is mostly caused by anthropogenic greenhouse gas emissions and is driving the current warming of the planet. Combined with surface temperature measurements the EEI measurement informs on the sensitivity of the climate system to GHG emissions (the so-called climate sensitivity). Thus monitoring precisely the EEI is critical to assess the current status of climate change, estimate the climate sensitivity and by this mean evaluate the future evolution of climate. But the monitoring of EEI is challenging as it is two orders of magnitude smaller than the radiation fluxes

in and out of the Earth system. Over 90% of the excess energy that is gained by the Earth in response to the positive EEI accumulates into the ocean in the form of heat such that the monitoring of Ocean Heat Content (OHC) and its long-term change provides a precise estimate of EEI.

Today, global OHC changes can be tracked from space with a combination of the altimetric measurement of sea level change and the gravimetric measurement of ocean mass change. In this talk we review this current space method to estimate global OHC changes and evaluate its relevance to derive EEI estimates on different time scales. We compare its performance with an independent estimate from direct observations of in situ temperature. Then, we use both the space based and in situ based estimate of EEI along with the surface temperature record to derive estimates of the 20th century effective climate sensitivity. Accounting for the internal variability (with an explicit representation of the so called “pattern effect”) we derive from our observed 20th century effective climate sensitivity an observational constraint on the climate sensitivity. With the EEI estimate from in situ data we find that the climate sensitivity is in the range [1.3;16.3]° (95% confidence level). With the EEI estimate based on space data the range is reduced to [1.3;15.3]°.

For the time being, the EEI records from in situ data or space data are too short to provide an observational constraint on the climate sensitivity that is more stringent than the one that is derived from process based analysis in the literature. However the results are promising. We find that using the longer record of the space based estimate of the EEI improves significantly the accuracy of the observational constraint. These results call for more research to extend the EEI estimate over longer periods in order to tighten up the observational constraint on the climate sensitivity. A possible option is to combine the global coverage of current space based EEI estimate with historical sparse ocean temperature in situ observations to get an EEI record back to 1971. First tests suggest this approach is relevant.

43

Imprints of Ocean Chaotic Intrinsic Variability on Bottom Pressure and Implications for GRACE Data Interpretation and Dealiasing

Zhao, Mengnan (AER); Ponte, Rui (AER); Penduff, Thierry (CNRS); Close, Sally (LOPS); Llovel, William (LOPS); Molines, Jean-Marc (CNRS)
mzhao@aer.com

GRACE and GRACE-FO missions have provided valuable information on the variations in ocean bottom pressure (OBP). Effective de-aliasing procedures and reliable interpretations of GRACE and GRACE-FO data are important for understanding ocean circulation and climate. While most studies have focused on atmospherically driven OBP variability, chaotic intrinsic OBP variability generated by nonlinear oceanic processes has received much less attention. This paper uses eddy-permitting large ocean ensemble simulation output from the OceaniC Chaos — ImPacts, strUcture, predicTability (OCCIPUT) project to isolate intrinsic variations in OBP for the mean seasonal cycle and for subseasonal and intra-annual bands. We find intrinsic variations larger than atmospherically driven ones over eddy-active regions across all timescales, particularly in the intra-annual range, where intrinsic variations dominate in almost 25% of the global ocean area. At scales much larger than mesoscale, intrinsic variability is still considerable, supporting the theory of kinetic energy inverse cascade towards lower frequency and larger scales. Results highlight the importance of intrinsic variability over a range of spatiotemporal scales and reveal the necessity of addressing it in GRACE and GRACE-FO dealiasing procedures and interpretations.

44

Proper masking habits: Important for more than just Covid!

Bonin, Jennifer; USF
Chambers, Don; USF
Save, Himanshu; CSR
Tamisea, Mark; CSR
Meyers, Jordan; USF
Pie, Nadege; CSR
jbonin@usf.edu

Historically, estimates of mean global sea level from spherical harmonic GRACE data necessitated the use of a ~300km coastal buffer to reduce land/ice leakage effects. With modern regularized mascon series from CSR, GSFC, and JPL, estimating ocean signal all the way to the coasts is now potentially possible. However, when including the coastal areas, a clear definition of “ocean” becomes necessary. The mascon series are all computed using regularization schemes which operate on specific land/ocean masks, and these masks differ significantly along the coastlines. Applying a 300km buffer to the mascon data still results in comparable mean ocean heights for all series, whereas averaging to the coasts results in trends which differ, both from each other and from the 300km-buffered estimate. We examine three potential explanations for this. First, there is real coastal signal which impacts the trends. Second, that one or all of the mascon series contain a significant amount of residual land/ice leakage in the coastal ocean areas. And finally, that averaging one series over a different series’ ocean mask can result in the inclusion of land bins and/or the exclusion of ocean bins – another form of leakage.

45

Global Ocean Response to the 5-Day Rossby-Haurwitz Atmospheric Mode Revealed by GRACE

Ponte, Rui, Atmospheric and Environmental Research (AER); Schindelegger, Michael, Institute of Geodesy and Geoinformation, University of Bonn
rponte@aer.com

A dynamic response of the ocean to surface pressure loading by the well-known ~5-day Rossby-Haurwitz mode in the atmosphere has been inferred from limited in situ tide gauge and bottom pressure data, but a global characterization of such response, including details at mid and high latitudes, has been lacking. Here we explore two daily GRACE-based products to obtain a first quasi-global look at the associated ocean bottom pressure (OBP) signals at ~5-day period. The previously reported in-phase behavior over the Atlantic basin, seesaw between the Atlantic and Pacific, and westward propagation in the Pacific are all seen in the GRACE solutions. Other previously unknown features include relatively strong responses in the Southern Ocean and also some shallow coastal regions (e.g., North Sea, East Siberian shelf, Patagonian shelf). Correlation analysis clearly points to the Rossby-Haurwitz surface pressure wave as the main forcing for the large-scale OBP anomalies in satellite data, while wind-driven signals are more spatially confined. The GRACE observations are found to be consistent with in situ bottom pressure data and also with model simulations of the 5-day ocean variability where no in situ data is available. Results illustrate the potential of space gravity measurements for determining large-scale oceanic variability at sub-weekly periods.

46

Closing the global sea level budget by combining GRACE(-FO) and altimetry data in a joint fingerprint inversion

Uebbing, Bernd; Institute for Geodesy and Geoinformation, University of Bonn
Rietbroek, Roelof; Faculty of Geo-Information Science and Earth Observation (ITC), Department of Water Resources (WRS), University of Twente
Kusche, Jürgen; Institute for Geodesy and Geoinformation, University of Bonn
uebbing@geod.uni-bonn.de

Sea level change affects hundreds of millions of people living in coastal regions. In addition to measuring the total sea level change via satellite altimetry, it is important to understand individual mass and steric contributors on global and regional scales. Consequently, deriving accurate sea level budgets is of key interest for understanding the underlying processes and aid in assessing future impacts of sea level rise. Furthermore, steric sea level change is related to the Earth's Energy Imbalance and thus a key indicator of global warming.
The global fingerprint inversion method based on Rietbroek et al. (2016) allows to combine GRACE(-FO) gravity measurements and along-track satellite altimetry observations in order to jointly estimate the individual mass and steric changes in a consistent manner. We use an extended fingerprint approach which allows further separation of the ocean mass variations into contributions from the melting of land glaciers and the Greenland and Antarctic ice-sheets as well as terrestrial hydrology effects and changes of the internal mass transport within the ocean. Furthermore, the updated inversion presented here, aims at splitting the steric sea level change into contributions of the upper 700m and the deeper ocean.

Here, we present the inversion results of a closed sea level budget (within 0.01 mm/yr) during the GRACE era (2002-04 till 2015-12) attributing 1.68 mm/yr and 1.40 mm/yr to ocean mass and steric changes, respectively. Compared to state-of-the art studies the steric contribution is found to be in line while the mass estimates are slightly lower. We provide budgets for major ocean basins and compare our results to individually processed GRACE, altimetry and ocean re-analysis datasets as well as published estimates. Furthermore, we will show preliminary results when extending the inversion to incorporate additional GRACE-FO data.

47

Signatures of degree-3 tidal loading effects in superconducting gravimeter records predicted by data-unconstrained ocean tide modeling

Sulzbach, Roman Lucas; (1) GFZ German Research Centre for Geosciences, Department of Geodesy, Potsdam, Germany, (2) Institute of Meteorology, Freie Universität Berlin, Germany
Wziontek, Hartmut; Federal Agency for Cartography and Geodesy (BKG), Leipzig, Germany
Hart-Davis, Michael; Deutsches Geodätisches Forschungsinstitut der Technischen Universität München, München
Dobslaw, Henryk; GFZ German Research Centre for Geosciences, Department of Geodesy, Potsdam, Germany
Thomas, Maik; (1) GFZ German Research Centre for Geosciences, Department of Geodesy, Potsdam, Germany, (2) Institute of Meteorology, Freie Universität Berlin, Germany
sulzbach@gfz-potsdam.de

Since the advent of satellite altimetry, the accuracy of data-constrained tidal atlases has increased considerably fueled by the continued accumulation of data. On the other hand, the altimetric record length has been insufficient to provide precise empirical estimates of many low amplitude partial tides for a long time. While including these tides is important for gravimetric dealiasing, especially with the enhanced precision of the GRACE-FO laser interferometer instrument, minor tides were routinely estimated by admittance assumptions.

As there are partial tides where this technique is not applicable (e.g. degree-3 tides), their gravimetric signatures are not routinely considered for dealiasing. While the empirical estimation of degree-3 tides was most recently demonstrated by R. Ray, we present an alternative approach to providing minor tide solutions by direct simulation with the barotropic, data-unconstrained tidal model TiME. Recently updated with (i) modern bathymetric maps; (ii) the consideration of the full effect of Self-Attraction and Loading (SAL); and (iii) energy dissipation by topographic wavedrag, TiME was demonstrated to provide accurate solutions for selected minor tides (e.g. OO1, 2Q1). The upgraded model was employed to provide a catalog of the most prominent degree-3 tides including at least one tide for each tidal species (from monthly to terdiurnal frequencies). After optimization of the model parameters, the root-mean-square deviation (rms) of the tidal solutions with a subset of TICON tide gauge data was between 0.9 and 1.3 mm, covering 33-65% of the tidal signal.

A second excellent way to validate the tidal model was employed by identifying signatures of the induced ocean tidal loading in superconducting gravimeter records for a globally distributed ensemble of 16 SGs by tidal analysis. SGs are well-suited for detecting tiny gravity fluctuations of only a few nGal, as their long-term records exhibit a very low noise level. Therefore, a hypothesis-free estimation of tidal parameters with the recently updated program system ETERNA-x was performed. Comparing the results to the modeled tidal gravity signatures, showed an even better agreement of 63-80 % and proves both, the feasibility of the tidal analysis, and the successful modeling of the degree-3 tides without employing data constraints.

48

Monitoring the Ocean Heat Content and the Earth Energy imbalance from altimetry and GRACE(-FO) gravimetry

Marti, Florence; Magellium
florence.marti@magellium.fr

The Earth energy imbalance (EEI) at the top of the atmosphere is responsible for the accumulation of energy in the climate system. While necessary to better understand the Earth's warming climate, measuring the EEI is challenging as it is a globally integrated variable whose variations are small (0.5-1 W.m−2) compared to the amount of energy entering and leaving the climate system (~ 340 W.m-2). Accuracies better than 0.1 W.m−2 are needed to evaluate the temporal variations of the EEI at decadal and longer time-scales, characteristic of the response to anthropogenic and natural forcing.

Since the ocean absorbs about 90% of the excess energy stored by the Earth system, estimating the ocean heat content (OHC) provides an accurate proxy of the EEI. Here, the OHC is estimated at global scale based on the combination of altimetry and GRACE gravimetry measurements. An ensemble of spherical harmonic solutions (update of Blazquez et al., 2018) is used and allows a robust estimation of the uncertainties associated with state-of-the-art ocean mass change estimates based on GRACE(-FO) measurements. Changes in the EEI are derived with realistic estimates of its uncertainty. The mean EEI value is estimated at +0.74±0.22 W m-2 (90% confidence level) between August 2002 and August 2016 and this value is increasing at a rate of 0.02 ± 0.05 W.m-2 (90% confidence level). Comparisons against independent estimates based on Argo data and on CERES measurements show good agreement within the error bars of the global mean and the time variations in EEI. On the other hand, discrepancies are also detected at inter-annual scales indicating that the current accuracy of EEI needs further improvement at these time scales. Estimates of the regional OHC change are also provided preliminarily and will be improved in the following months with a focus on the Atlantic Ocean. In the near future, the extension of the OHC-EEI time series using GRACE-FO data will help to better understand EEI's variations. The space geodetic OHC-EEI product is freely available at https://doi.org/10.24400/527896/a01-2020.003.

Blazquez et al., 2018: https://doi.org/10.1093/gji/ggy293

49

Non-closure of the global mean sea level budget since 2016: contributions of altimetry and Argo

Barnoud, Anne; Magellium, Toulouse, France
Pfeffer, Julia; Magellium, Toulouse, France
Guérou, Adrien; CLS, Toulouse, France
Frery, Marie-Laure; CLS, Toulouse, France
Siméon, Mathilde; CLS, Toulouse, France
Cazenave, Anny; LEGOS and Magellium, Toulouse, France
Chen, Jianli; Center for Space Research, University of Texas, Austin, USA
Llovel, William; LOPS, Brest, France

Thierry, Virginie; LOPS, Brest, France
Legeais, Jean-François; CLS, Toulouse, France
Ablain, Michaël; Magellium, Toulouse, France
anne.barnoud@magellium.fr

The global mean sea level (GMSL) change results from the sum of the steric component and of the ocean mass component. Over 1993-2016, many independent studies have shown that the GMSL budget is closed within the data uncertainties. However, non-closure of the sea level budget after 2016 was reported when using Jason-3 altimetry, Argo and GRACE/GRACE Follow-On data (Chen et al., 2020). This non-closure may result from errors in one or several components of the sea level budget (altimetry-based GMSL, Argo-based steric sea level or GRACE-based ocean mass). We have investigated possible sources of errors affecting Jason-3 and Argo data. Concerning altimetry data, comparisons of Jason-3 GMSL time series with other altimetry missions show agreement within 0.4 mm/yr of standard uncertainty over 2016-2020. However, a potential drift of Jason-3 radiometer could be responsible for about 30 % of the non-closure of the budget. Concerning Argo data, good agreement is found between all available thermosteric products. However, a global non-physical decrease of the halosteric sea level is observed since 2016 with strong discrepancies between the different data providers, attributed to uncorrected salinity measurement drifts. Given that the halosteric component is expected to be negligible in global average, we re-assess the sea level budget using only the thermosteric and ocean mass components and found significant improvement of about 40 % in the budget closure over 2016-2019. The remaining budget residual trends amounts to 1.20 ± 0.72 mm/yr. Potential errors in the other components (i.e. thermosteric component based on Argo data, global mean ocean mass component based on GRACE and GRACE Follow-On data, missing physical contribution) should be further investigated.

50

Improving GRACE-Based Estimates of Ocean Bottom Pressure for Tracking Deep Ocean Mass Transport

Delman, Andrew; JIFRESSE, University of California-Los Angeles
Landerer, Felix; Jet Propulsion Laboratory, California Institute of Technology
andrew.s.delman@jpl.nasa.gov

The multi-decadal time series of gravimetry measurements from the GRACE and GRACE-Follow On satellites provide a unique opportunity to observe variability in the deep ocean from space. Specifically, GRACE ocean bottom pressure (OBP) at basin boundaries can be used to infer the mass transport variability that occurs at a given level in the ocean basin, allowing for remotely-sensed tracking of the deep limbs of the overturning circulation. However, GRACE mascon solutions are limited in resolution and a single mascon can conflate signals from many depth levels along steep continental slopes. To improve estimates of OBP variability along these steep boundaries, ocean bottom pressure observations are downscaled to points along basin boundaries using OBP covariance information from an ocean model (ECCO2) with nominal horizontal resolution of ~18 km. In addition, a depth correction was applied to boost the weighting of mascon data at similar depth levels to the downscaling point. In validations with in-situ bottom pressure recorder time series, the combined downscaling procedure (model covariance + depth correction) improved correlations with in-situ OBP in ~80% of cases, compared to GRACE mascon OBP without any downscaling. Correlations with in-situ OBP are generally improved at locations where OBP variations (on timescales >1 day) have a higher amplitude. Conversely, locations where surface eddy kinetic energy is high (e.g., Gulf Stream extension and North Atlantic Current) are more likely to have lower correlations with in-situ OBP and not be improved by the downscaling procedure. Hence the downscaling procedure has promising applications for monitoring intraseasonal and interannual variability of deep ocean mass transports, provided the OBP variability in a given location is sufficiently large and levels of unstable mesoscale activity near the boundary are not large. Further challenges in downscaling OBP along with possible process studies to address them are also discussed.

51

Barystatic-GRD Fingerprints for Use with Mascons in Oceanographic Applications

Tamisiea, Mark E; Center for Space Research, University of Texas at Austin
Save, Himanshu; Center for Space Research, University of Texas at Austin
Pie, Nadège; Center for Space Research, University of Texas at Austin
Chambers, Don P.; University of South Florida
Bonin, Jennifer A.; University of South Florida
tamisiea@csr.utexas.edu

The exchange of water between the continents, the atmosphere and the ocean will introduce a barystatic (global ocean mean mass) change to the oceans as well as a non-uniform redistribution of this mass associate with gravitational, rotational, and deformational (GRD) changes due to changes in the global redistribution of mass. In order to interpret the GRACE/GRACE-FO mascon mass changes in oceanographic studies, these barystatic-GRD fingerprints must be removed (e.g., Ponte et al., 2018). Calculation of the barystatic-GRD fingerprints from the spherical harmonics of GRACE have been produced (e.g., Adhikari et al., 2019) and are important component of the spherical harmonic degree 1 mass estimation procedure from GRACE data (e.g., Sun et al., 2016, 2017). Typically, though, these estimates of GRD fingerprints have been calculated only considering the continental mass changes, which is the largest component. However, mass changes in the atmosphere and oceans should also affect this redistribution of water (e.g., Tamisiea et al., 2010). We present some initial results of the barystatic-GRD fingerprints calculated from the CSR mascons (Save et al., 2016), both using only continental mass changes only and accounting for the atmospheric and oceanographic mass changes. We compare these results to ocean bottom pressure records and to the mascon estimate over the ocean.

52

Deep Ocean Currents Surrounding Antarctica Observed via GRACE Bottom Pressure and the Southern Ocean State Estimate

Meyer, Jordan; University of South Florida
Chambers, Don; University of South Florida

jordansatrem@usf.edu

Water is transported through the Southern Ocean primarily through the Antarctic Circumpolar Current. Unlike currents in other ocean basins, the zonal flow of this current has no complete eastern or western boundaries, which would normally oppose external momentum put into the ocean. Instead, momentum transferred into the Southern Ocean by surface winds is balanced by pressure forces at large bathymetric features along the path of the Antarctic Circumpolar Current. This is a phenomenon called topographic form stress and is at its maximum at three locations within the Southern Ocean: the Kerguelen Plateau, Macquarie Island Ridge, and Drake Passage.

Topographic form stress, however, is not the only source of bottom pressure fluctuations at these bathymetric features. On the western side of the Drake Passage, Antarctic Bottom Water flows out of the Weddell Sea, where it is formed, as a deep geostrophic current. Bottom pressure fluctuates along the path of the Antarctic Bottom Water flow and combines with the bottom pressure variability associated with topographic form stress to modify the bottom pressure gradients observed at this location.

Here we use the Southern Ocean State Estimate (SOSE) iteration 105 to show the relationship between local wind stress, topographic form stress, and the transport of deep Antarctic Bottom Water. Within the state estimate, we show that Antarctic Bottom Water transport along the South Scotia Ridge can be derived from observations of circumpolar wind stress in the Southern Ocean and bottom pressure sampled at the Kerguelen Plateau, Macquarie Island Ridge, and Drake Passage. Furthermore, we utilize this technique to estimate variability in bottom water transport using observations of bottom pressure from GRACE and GRACE-FO.

53

Impact of solid Earth's anelasticity on surface displacement and tidal dynamics

(Huang, Pingping; German Research Center for Geosciences, Dep. 1 Geodesy, Potsdam, Germany), (Sulzbach, Roman Lucas; German Research Center for Geosciences, Dep. 1 Geodesy, Potsdam, Germany and Freie Universität Berlin, Institute of Meteorology, Berlin, Germany), (Tanaka, Yoshiyuki; The University of Tokyo, Earth and Planetary Sciences, Tokyo, Japan), (Klemann, Volker; German Research Center for Geosciences, Dep. 1 Geodesy, Potsdam, Germany), (Dobslaw, Henryk; German Research Center for Geosciences, Dep. 1 Geodesy, Potsdam, Germany), (Martinec, Zdeněk; Dublin Institute for Advanced Studies DIAS, Dublin, Ireland), (Thomas, Maik; German Research Center for Geosciences, Dep. 1 Geodesy, Potsdam, Germany and Freie Universität Berlin, Institute of Meteorology, Berlin, Germany)
pingping@gfz-potsdam.de

Surface displacements and self-attraction and loading (SAL) elevation induced by ocean tides are known to be affected by material properties of the solid Earth. Recent studies have shown that, in addition to elasticity, anelasticity considerably impacts surface displacements due to ocean tide loading (OTL). We employ consistent 3D seismic elastic and attenuation tomography models to construct 3D elastic and anelastic earth models, and derive corresponding averaged

1D elastic/anelastic models (Huang et al., 2021). We apply these models to systematically study the impact of anelasticity and lateral heterogeneity on M2 OTL displacements and SAL elevation. We find that neglecting lateral heterogeneities highly underestimates displacements and SAL elevation in mid-ocean-ridge regions and in some coastal areas of North and Central America. In comparison to PREM, 3D anelastic models can increase the predicted amplitudes of the vertical displacement and SAL elevation by up to 1.5 mm. The increased amplitudes reduce the discrepancy between GPS-observed OTL displacements and their predictions based on PREM in places like Cornwall (England), Brittany (France) and the Ryukyu Islands (Japan). Applying our results to ocean tides as simulated with the high resolution model TiME (Sulzbach et al., 2021) based on the shallow water equations, we discover that the impact on ocean tide dynamics exceeds the predicted SAL elevation correction with an RMS of about 1 mm, reaching an RMS of more than 5 mm in areas like North Atlantic or East Pacific. Due to the fact that such a value reaches the accuracy of modern data-constrained tidal models, we regard the impact of solid Earth’s anelastic material behavior as significant in tidal modelling.

References

Sulzbach, R., Thomas, M., Dobslaw, H. (2021): High-Resolution Numerical Modelling of Barotropic Global Ocean Tides for Satellite Gravimetry. - Journal of Geophysical Research: Oceans, 126, 5, e2020JC017097. https://doi.org/10.1029/2020JC017097

Huang, P., Sulzbach, R., Tanaka, Y., Klemann, V., Dobslaw, H., Martinec, Z., Thomas, M. (2021): Anelasticity and Lateral Heterogeneities in Earth's Upper Mantle: Impact on Surface Displacements, Self‐Attraction and Loading, and Ocean Tide Dynamics. - Journal of Geophysical Research: Solid Earth, 126, 9, e2021JB022332. https://doi.org/10.1029/2021JB022332"

54

Combining space gravimetry observations with data from satellite altimetry and high resolution visible imagery to resolve mass changes of endorheic basins and exorheic basins

Blazquez, Alejandro; LEGOS, Université de Toulouse (CNES,CNRS,IRD,UPS)
Meyssignac, Benoit; LEGOS, Université de Toulouse (CNES,CNRS,IRD,UPS)
Berthier, Etienne; LEGOS, Université de Toulouse (CNES,CNRS,IRD,UPS)
Longuevergne Laurent; GR, Géosciences Rennes
Creteaux, Jean François; LEGOS, Université de Toulouse (CNES,CNRS,IRD,UPS)
alejandro.blazquez@legos.obs-mip.fr

Continuous monitoring of the Global Terrestrial Water Storage changes (TWS) is challenging because of the large surface of continents and the variety of storage compartments (WCRP, 2018). The only observing system which provides global TWS mass change estimates so far is space gravimetry. Unfortunately, most storage compartments (lakes, groundwater, glaciers…) are too small to be resolved given the current spatial resolution of gravimetry missions. This intrinsic property makes gravimetry-based TWS changes estimates difficult to attribute and to interpret at individual basin scale. In this context, combining gravimetry-based TWS estimates with other sources of information with higher spatial resolution is a promising strategy.

In this study, we combine gravimetry data with independent observations from satellite altimetry and high resolution visible imagery to derive refined estimates of the TWS changes in hydrological basins containing lakes and glaciers. The combination consists in including independent observations of glacier (Hugonnet et al., 2021) and lake (Cretaux et al., 2016) mass changes in the conversion process from gravity L2 data to water mass changes data. The combination is done for all regions of the world on a monthly basis. This approach allows to split properly glacier and TWS changes at interannual to decadal time scales, and derive glacier-free estimates of TWS in the endorheic basins and the exorheic basins. We find that for the period from 2002 to 2020, the total TWS trend of 0.23±0.25 mm SLE/yr is mainly due to a mass loss in endorheic basins TWS of 0.20±0.12 mm SLE/yr. Over the same period, exorheic basins present a non-significative trend of 0.03±0.14 mm SLE/yr. On the contrary, the interannual variability in the TWS change of 4 mm SLE is mainly due to the exorheic basins TWS change.

55

Short Wavelength Along-Track Analysis of Data in the West-Central United States

Bender, Peter: Univ. of Colorado
pbender@jila.colorado.edu

It appears that short-wavelength along-track analysis of the data from the GRACE Follow-On mission will be particular interest in regions where the rapid atmospheric mass variations are very well known. In such regions it will be possible to separate out the short wavelength mass variations due to hydrology more accurately. A leading candidate for such studies is the west-central US. In the region between 35 deg and 45 deg N lat and between 95 and 115 deg W long, there are enough ECMWF and MERRA atmospheric monitoring sites to give at least 1 site per 4 sq deg area. Also, the annual rainfall over most of the area is between 300 and 500 inches, which is fairly low.

To the extent that the atmospheric monitoring can provide accurate information on the resulting short-wavelength geopotential variations, different models for the short-wavelength time variations due to hydrology can be tested with high accuracy. This will be of particular importance if the Next Generation Gravity Missions have strongly increased measurement accuracy, based on replacing the accelerometers on GRACE Follow-On by simplified Gravitational Reference Sensors. With this change, the non-gravitational acceleration noise can be reduced to less than 1x10^-12 m/(s^2)/(Hz^0.5) between 1 and 100 mHz. In this case, the resulting measurement uncertainties in the geopotential height variations along a single arc can be reduced to between 4 and 1 times 10^-9 m/[sq. root (cycles/rev)] from 20 to 120 cycles per revolution.^ This would sharply improve the accuracy with which improved models for the hydrologically caused short period geopotential variations can be tested."

56

The role of ocean mass in the observed increasing Bering Strait ocean inflow to the Arctic

Peralta-Ferriz, Cecilia; University of Washington
Woodgate, Rebecca; University of Washington
ferriz@uw.edu

The oceanic inflow to the Arctic Ocean through the narrow (~80km) and shallow (~50m deep) Bering Strait – the only oceanic pathway between the Pacific and the Arctic – plays an important role in the Arctic's heat and freshwater budgets, the stratification of the Arctic's water column, and is a major source of nutrients critical for Arctic ecosystems. In situ velocity data from long-term year-round moorings in the strait show the Bering Strait inflow to the Arctic has significantly increased (0.01 ± 0.006 Sv/yr, 1Sv = 10e6 km3/s) since 1990. Prior work defines (a) local and (b) far-field forcings of the flow. The local forcing, the meridional winds in the strait, dominates the variability of the winter flow, with northward winds increasing northward flow, and southward winds slowing and sometimes even reversing the flow into the Arctic. The far-field forcing – a presumed sea level (or ocean bottom pressure) differential between the Arctic and Pacific oceans – has been identified and described in detail for the first time using GRACE ocean bottom pressure (OBP) data (Peralta-Ferriz and Woodgate, 2017). This pattern consists primarily of anomalously low OBP in the Arctic's East Siberian Sea (ESS), and to a lesser extent, anomalously high OBP in the eastern Bering Sea. The ESS ocean mass dominates the flow variability more strongly during the summer months. The local wind forcing shows no significant trend over time, thus it is assumed the far-field forcings must drive the observed trends in Bering Strait through-flow. Here we look at the 2003-2021 OBP data from GRACE and GRACE-FO Rel06 mascon solutions, mooring velocity data in the strait, NCEP atmospheric reanalysis data, and a joint dynamic ocean topography product from Envisat, CryoSat-2 and SARAL altimetry to investigate how Arctic ocean mass contributes to the observed increasing trend in Bering Strait through-flow.

Reference

Peralta-Ferriz, C., and Woodgate, R. A. (2017). The dominant role of the East Siberian Sea in driving the oceanic flow through the Bering Strait – Conclusions from GRACE ocean mass satellite data and in situ mooring observations between 2002 and 2016. Geophysical Research Letters, 44. https://doi.org/10.1002/2017GL075179.

57

Error structure of vertical land displacements derived using GNSS measurements

Peidou, Athina; Wiese David; Argus Donald; Landerer Felix; Ellmer Matthias; Jet Propulsion Laboratory
athina.peidou@jpl.nasa.gov

Quantification of uncertainty in surface mass change signals derived from GNSS measurements poses challenges, especially when dealing with large datasets with continental or global

coverage. Our aim is to study the structure and quantify the uncertainty present in estimates of vertical land displacement (VLD) derived from 2740 GNSS stations distributed across the US. Monthly records are available for nearly 15 years. Initially, we remove outliers by performing a 3σ test, and data screening via a number of correlation metrics between the input GNSS VLD estimates and external validation datasets (i.e., VLD predicted from GRACE/GRACE-FO and hydrology models). Afterwards, we employ various processing schemes to characterize the uncertainty of VLD through stochastic modeling and quantification of the spatially correlated errors. In particular, we test for stationary, colored and spatially correlated noise. Stationary noise is described by white noise, and colored noise by a combination of flicker and random walk. To quantify spatially correlated noise, we build on the common mode imaging approach that uses residual information of the neighbor stations and robust statistics, and add a geophysical constraint to derive a more realistic error estimate. When only white noise is considered nearly 30% of the stations exhibit error < 2 mm, 65% error between 2-4 mm and 5% error > 4 mm. In case of colored noise, error smaller than 2 mm, between 2-4 mm and >4mm, is mapped in 20%, 60% and 20% of the stations, respectively. Spatially correlated noise is in family but slightly smaller in magnitude with colored noise.

58

Reexamining Anelastic and Viscoelastic Loading at 20 year and Longer Periods and Potential Issues for the Long-term Space Gravimetry Record

(Ivins, Erik; CALTECH/JPL) (Caron, Lambert; CALTECH/JPL)
lambert.caron@jpl.nasa.gov

We have developed simple solutions to the momentum equation governing glacial isostatic adjustment (GIA) that are tailored to accounting for newly emerging, laboratory-based, anelastic and viscoelastic constitutive relations. The latter have been instrumental in interpreting seismic wave tomography in the shallow oceanic upper mantle. Shear-wave tomography, for example, that account for the laboratory-based laws reveal that the seismic quality factor (the inverse of the measure of attenuation), QS, is lower bound by QS<25 near mid-ocean spreading centers at 100-150 km depth1. Using extrapolations from the anelastic and viscoelastic relations, and the average viscosity for Pacific basin asthenosphere mantle (ha) at this depth range2 (3 – 30 x 10^19 Pa s), asthenospheric mantle proximal to the ridge axis with ages in the range (0-10 Ma) will have viscosity in the range (2 – 20 x 10^17 Pa s) according to the scaling parameters used by Eilon & Abers1 in analyzing the broadband ocean bottom seismometer data from NSF’s Amphibious Array deployment of the Cascadia Initiative. The corresponding Maxwell relaxation times are of the order 1 month to 1 year, and this localized region acts as a fluid with respect to time scales of gravity retrieval using GRACE and GRACE-FO. While the values for the Maxwell times moving further away from the ridge axis are less clear, anelastic processes suggest that effective relaxation times will also be low, certainly below a 20-year time scale. In the presentation we discuss some preliminary calculations of load response of broadscale ocean basins and isolate the significant differences between predictions among elasticisity, the classical Maxwell material assumption and those using the anelastic-viscoelastic relations that have been employed in the analysis of broadband ocean bottom seismometer data.

Government sponsorship acknowledged. This work was performed at the California Institute of Technology's Jet Propulsion Laboratory under a contract with the National Aeronautics and Space Administration's Cryosphere Science Program.

References:
1Z.C. Eilon & G.A. Abers, Sci. Adv. 2017, 3, e1602829
2F. Richards et al., PEPI. 2020, 309, 106559.
3U.H. Faul & I. Jackson, EPSL. 2005, 234, 119–134.

59

GRACE-I: A mission for gapless observation of mass transport and biodiversity

Flechtner, Frank, GFZ Potsdam / TU Berlin
Dahle, Christoph, GFZ Potsdam
Hauk, Markus, AEI Hannover
Wilms, Josefine, GFZ Potsdam
Murböck, Michael, TU Berlin
frank.flechtner@gfz-potsdam.de

NASA´s Earth Science Decadal Survey Report highlights mass transport monitoring as one of top priorities in Earth Observation for the next decade. To realize such a Mass Change Mission, NASA is seeking international partnership. In November 2020 it was decided at ESA's ministerial conference to investigate a Next Generation Gravity Mission (NGGM) as first mission of opportunity as defined in the FutureEO program. This Mass-change And Geoscience International Constellation (MAGIC) is investigated jointly with NASA.

In March 2021 a 10-months Phase-0 study was kicked-off by the German Space Agency (DLR) to investigate a "GRACE-I" mission based on a GRACE-like concept combined with an optional ICARUS (International Cooperation for Animal Research Using Space) payload. The study is closely discussed with JPL/NASA as a future continuation of the very successful GRACE/GRACE-FO technological and scientific partnership is in the involved partners' interest. GRACE-I will be a single pair based on a fully redundant Laser Ranging Interferometer on a polar orbit at 490 or 420 km (with drag compensation) altitude. Launch shall be not later than 2027 to guarantee Mass Change Continuity (MC-C). GRACE-I could then be a component of a hybrid double pair constellation if combined ca. 2031 with a first (inclined) NGGM/MAGIC pair to enable Mass Change Sustainment (MC-S) with increased temporal and spatial resolution.

We will present the proposed mission architecture and simulation results and will discuss next steps towards realization of GRACE-I. Simulations are based on realistic assumptions of background model errors as well as instrument noise characteristics. These are conform with MAGIC's mission requirements in order to be comparable with results obtained e.g. in ESA´s science support study.

60

Scientific simulation studies for a Mass change And Geosciences International Constellation (MAGIC)

Pail, Roland, TU Munich
Flechtner, Frank, GFZ
Bruinsma, Sean, CNES
Visser, Pieter, TU Delft
Güntner, Andreas, GFZ
Abrykosov, Petro, TU Munich
Heller, Betty, TU Munich
The MAGIC Science team
roland.pail@tum.de

In November 2020 it was decided at ESA's Ministerial Conference to investigate a European next-generation gravity mission (NGGM) in Phase A as first Mission of Opportunity in the FutureEO Programme. The Mass-change And Geoscience International Constellation (acronym: MAGIC) is a joint investigation with NASA's MCDO study resulting in a jointly accorded Mission Requirements Document (MRD) responding to global user community needs. On NASA side, a pre-Phase A study to address these needs is expected to start in summer 2021. On ESA side, the MAGIC concept will be investigated in two parallel industry Phase A studies, complemented by a science support study.

In the frame of this science study, several potential mission constellations are investigated and numerically simulated in great depth. This includes Bender-type double pair mission concepts and single/multiple pendulum configurations, with realistic error assumptions regarding the key payload products, in close interaction with the parallel industry studies. Methodological improvements of processing strategies, for example the co-estimation of short-term gravity field models with various resolution, and the optimum treatment of long-term signals and tailored post-processing techniques, will be investigated. Further aspects such as the benefit of including DORIS for improving satellite orbits to support accelerometer calibration and contributing to gravity retrieval, and advanced methods for accelerometer calibration, shall be studied. The results of these studies will be evaluated by an associated science expert panel, leading to potential modifications of the MRD.

In this contribution, we will outline the motivation and set-up of this study, present first results, and evaluate them against the results of a multitude of previous studies such as the ESA ADDCON project.

61

Sensitivity analysis on inter-satellite distance

Abrykosov Petro, Pail Roland, Heller Betty; Technical University of Munich
petro.abrykosov@tum.de

In November 2020 it was decided at ESA's Ministerial Conference to investigate a European next-generation gravity mission (NGGM) in Phase A as first Mission of Opportunity in the FutureEO Programme. The Mass-change And Geoscience International Constellation (acronym:

MAGIC) is a joint investigation with NASA's MCDO study resulting in a jointly accorded Mission Requirements Document (MRD) responding to global user community needs. On ESA side, the MAGIC concept is investigated in two parallel industry Phase A studies, complemented by a science support study.
Alongside the in-depth performance investigations concerning several potential ll-sst-based mission constellations the science study also gives attention to the impact of inter-satellite distances on the performance of gravity field retrieval. In this contribution we present numerical closed-loop simulation results for selected mission scenarios obtained under assumption of various error contributors (various instrument noise specifications, de-aliasing errors) and their interaction with various inter-satellite distances. A discussion as well as recommendations are given towards the choice of optimal inter-satellite distances.

62

Closed-Loop Gravity Simulations in the Framework of the Mass change And Geosciences International Constellation (MAGIC) Mission Concept

(Heller, Betty; Technical University of Munich), (Abrykosov, Petro; Technical University of Munich), (Pail, Roland; Technical University of Munich)
betty.heller@tum.de

The Mass-change And Geoscience International Constellation (MAGIC) satellite gravity mission concept is a joint investigation by ESA and NASA, which arose from NASA's Mass Change Designated Observable (MCDO) and ESA's Next Generation Gravity Mission (NGGM) studies. In the framework of ESA's MAGIC science support study presented in an overview talk by Pail et al., potential mission constellations are investigated and compared using numerical closed-loop simulations. These comprise single- and double-pair low-low satellite-to-satellite tracking configurations. In particular, the effect of pendulum versus in-line formations, the accelerometer instrument specifications and the orbital height are investigated. For all simulated scenarios, the effect of temporal aliasing signals on the retrieved gravity field solutions is analysed by comparing simulation results with and without temporal gravity signals included. The results are assessed with respect to the International Union of Geodesy and Geophysics (IUGG) threshold and target user requirements, and recommendations with respect to the investigated simulation parameters are deduced.

63

LRI Instrument for Mass Change Mission

Ware, Brent; Jet Propulsion Laboratory (JPL)
Francis, Samuel; JPL
Spero, Bob; JPL
Woodruff, Chris; JPL
Romero-Wolf, Andrew; JPL
McKenzie, Kirk; Australian National University (ANU)
Sutton, Andrew; ANU

samuel.p.francis@jpl.nasa.gov

The Laser Ranging Interferometer (LRI) on GRACE-FO surpasses performance requirements, autonomously maintains its inter-satellite laser link, and continues to perform nominally. In this talk we will discuss a LRI-only Mass Change mission, highlighting why the LRI is the clear choice for future missions and describing the work required to take the LRI from technology demo to prime instrument.

64

Results from the NASA Mass Change Designated Observable Study

(Wiese, David; JPL) (Bienstock, Bernard; JPL) (Bearden, David; JPL) (Boening, Carmen; JPL) (Case, Kelley; JPL) (Chrone, Jonathan; NASA Langley) (Horner, Scott; NASA Ames) (Loomis, Bryant; NASA GSFC) (Luthcke, Scott; NASA GSFC) (Rodell, Matt; NASA GSFC) (Sauber, Jeanne; NASA GSFC) (Tsaoussi, Lucia; NASA HQ) (Webb, Frank; JPL) (Zlotnicki, Victor; JPL)
david.n.wiese@jpl.nasa.gov

The 2017-2027 US National Academy of Sciences Decadal Survey (DS) for Earth Science and Applications from Space classified mass change as one of five Designated Observables having the highest priority in terms of Earth observations required to better understand the Earth system over the next decade. In response to this designation, NASA initiated multi-center studies with an overarching goal of defining observing system architectures for each Designated Observable. Here, we discuss the results from the Mass Change Designated Observable study, which recently concluded in September 2021. The study team developed a Science and Applications Traceability Matrix (SATM) using the DS as a starting point, and investigated the viability of different architecture classes to be responsive to the SATM through a quantitative numerical simulation framework. A Value Framework process was used to assess the value of potential architectures in terms of science return, cost, risk, technical maturity, schedule (including potential for overlap with GRACE-FO), and interest from potential international partners. Results highlight the recommendation of satellite-satellite-tracking for the MC observing system, and identify high value variants which have the potential to both maintain continuity with GRACE-FO while also potentially improving upon the quality of current data record. These high value variants are currently under more in-depth study as Mass Change has transitioned into Pre-Phase A formulation.

65

A Report of the Mass Change Decadal Observable Applications Team: Activities Summary & Future Plans

(Srinivasan, Margaret: JPL), (Reager, John; JPL), (Rodell, Matt; GSFC), (Baize, Rosemary; Langley Research Center), (Doorn, Bradley; NASA), (Boening, Carmen; JPL)
margaret.srinivasan@jpl.nasa.gov

In support of NASA and international partners' development of the next Mass Change (MC) satellite mission, the NASA Mass MC Decadal Observables Study Team formed the MC

Applications Team (MCAT) to assess user communities and their needs. Applications requirements were derived from the National Academy of Sciences' 2017-2027 Decadal Survey for Earth Science and Applications from Space (tinyurl.com/ESAS2018) and from community engagement for incorporation into mission planning activities. Engagement mechanisms included a Community Workshop, a review of existing reports and publications (including the GRACE Missions Applications Plan), information derived from the Mass Change Applications Survey (tinyurl.com/MassChangeSurvey), and direct engagement with, in particular, non-research Earth observation (EO) data users.

Assessments were conducted on both communities of practice (existing users of EO gravity mission data), and communities of potential (those who may benefit from future MC mission data or information products). Mass change observations have the potential to support numerous practical applications across a wide range of Earth systems variables. The focus of MCAT user engagement in this analysis was principally on water resources applications, due to the great potential for assessment and management using these observations (for example, groundwater for hydrological extremes).

We will identify common themes and desires among current and potential MC mission data users, and report on key findings of a major user study conducted by NASA Applied Sciences Program-directed consultants in collaboration with the MCAT. The final output of the MCAT will be a Community Assessment Report (CAR), which will identify and characterize select existing/potential user communities, use cases for these communities, pathways for sustained engagement, and recommendations for next steps.

66

Current Status of NASA's Mass Change Pre-Phase A Activities

Dunn, Charley; JPL
david.n.wiese@jpl.nasa.gov

NASA initiated Pre-Phase A activities for Mass Change in Summer 2021 upon the completion of the Mass Change Designated Observable (MCDO) Study. Mass Change is a core component of NASA's Earth System Observatory to be launched within the next decade. Mass Change Pre-Phase A activities are focused on further in depth study of high value architecture variants identified by the MCDO Study team while continuing engagement with potential international partners. This talk will provide a status update and overview of MC Pre-Phase A activities.

67

Hybrid satellite-to-satellite tracking and gravity gradiometry for mass change measurement

(Bettadpur, Srinivas, Center for Space Research) (Rosen, Mitch, Center for Space Research) (Wang, Furun, Center for Space Research) (Jacob, Geethu, Center for Space Research) (Chiow, Sheng-wey, Caltech Jet Propulsion Laboratory) (Yu, Nan, Caltech Jet Propulsion Laboratory) srinivas@csr.utexas.edu

Satellite-to-Satellite (SST) tracking data from GRACE and GRACE Follow-On mission is by now an established method for spaceborne measurement of mass change, with applications in all Earth science disciplines, and with an impact on every Earth domain. The current results are limited by our inability to fully model the effect of rapid (shorter than data span of gravity field representation) variations in the Earth's gravity field. Mitigation of these "aliasing" errors requires post-processing error control with some form of regularization methods. Natural reduction of the aliasing errors, either by measurement architecture improvement or by improved modeling of rapid variations, offers the opportunity to improve the quality and resolution of the derived mass change, thereby expanding the science applications from gravity field missions.
Advancements in the atom interferometric technologies offer an exciting opportunity for injecting a new architectural element into the gravity field measurement toolkit. We focus on its deployment in the form of a quantum gravity gradiometer (QGG). Our hybrid architectural configuration deploys a single-axis QGG oriented in a cross-track direction, conjoined with the customary SST mission in a polar orbit. We present arguments for how such a hybrid configuration can be realized with present-day spacecraft configuration and control capabilities. We use numerical simulations to show and explain the role of the QGG in the mitigation of aliasing errors and assess the achievable accuracy of the gravity field estimates. We close with a discussion of the impact of such a hybrid configuration on science applications of mass change measurements.
JPL investigators were funded under contract with the National Aeronautics and Space Administration (80NM0018D0004); and UT investigators were funded under the JPL Strategic University Research Program and internal CSR funds.

68

Designing an n-pair satellite constellation for recovering daily Earth system mass change using a multi-objective genetic algorithm.

Deccia, Carlos M.A.; University of Colorado Boulder, Nerem, R.Steven; University of Colorado Boulder, Wiese, David N.; Jet Propulsion Laboratory
carlos.deccia@colorado.edu

Recent advances in performance and cost over the past years have led to increased use of small satellites in scientific missions. When applied to a GRACE-like mission this could allow for an improved spatial and temporal resolution. Small satellite constellations have an inherent system redundancy due to their large distribution of risk and lack of single point failure. Additionally, an increased number of satellites reduces the unit cost for production and therefore the cost of replacement and maintenance of such a constellation.

A major challenge when designing an n-pair constellation is the vast search space of variables available. Due to the nature of the discontinuous search space, derivative-based optimization techniques cannot be used to scan the search space efficiently. To address this difficulty a multi-objective genetic algorithm is used.

In this work we investigate the viability and limitations of a genetic algorithm-based optimization and its objective function in order to generate satellite constellations aimed at recovering daily Earth system mass changes. The resulting constellations have an inherent improved spatio-temporal performance which will reduce temporal aliasing errors and allow the characterization of daily mass-change effects. The performance of the designed constellations has then been validated using high-fidelity numerical simulations.

69

Laser frequency readout derived from ULE cavity for next generation geodesy missions

(Rees, Emily Rose; The Australian National University, Wade, Andrew; The Australian National University, Sutton, Andrew; The Australian National University, Spero, Robert, Jet Propulsion Laboratory-Caltech, Shaddock, Daniel; The Australian National University, McKenzie, Kirk; The Australian National University)
Kirk.mckenzie@anu.edu.au

The next generation of Gravity Recovery and Climate Experiment (GRACE)-like dual-satellite geodesy missions proposals will rely on inter-spacecraft laser interferometry as the primary instrument to recover geodesy signals. Laser frequency stability is one of the main limits of this measurement and is important at two distinct timescales: short timescales over 10-1000 seconds to measure the local gravity below the satellites, and at the month to year timescales, where the subsequent gravity measurements are compared to indicate loss or gain of mass (or water and ice) over that period. This paper demonstrates a simple phase modulation scheme to directly measure laser frequency change over long timescales by comparing an on-board Ultra-Stable Oscillator (USO) clocked frequency reference to the Free Spectral Range (FSR) of the on-board optical cavity. By recording the fractional frequency variations the scale correction factor may be computed for a laser locked to a known longitudinal mode of the optical cavity. The experimental results demonstrate a fractional absolute laser frequency stability at the 10 parts-per-billion level at time scales greater than 10 000 seconds, likely sufficient for next generation mission requirements.

70

Optimal combination of satellite formations in future satellite gravity missions

Inácio, Pedro; Ditmar, Pavel; and Klees, Roland; Delft university of Technology
p.g.ditmar@tudelft.nl

GRACE and GRACE Follow-On satellite gravity missions have allowed numerous unique results to be obtained regarding the quantification of large-scale mass changes in the Earth's system. In view of that, ESA, NASA, and the China National Space Administration consider launching in the next years new satellite missions to continue mass change monitoring from space. The new missions may not only increase the number of satellite gravity data, but also deliver data of new

types, which will not suffer from deficiencies of the data acquired now (such as a relatively poor sensitivity to spatial mass anomaly variations in the West-East direction). Therefore, defining the optimal strategy for setting-up and combining future satellite gravity missions remains a highly relevant issue.

In our numerical study, we considered missions consisting of up to three satellite formations in different polar orbital planes. Two aspects were addressed: (i) the optimal combination of orbital planes and (ii) the optimal formation types: GRACE-type (an along-track offset between the satellites), pendulum (a cross-track offset between the satellites), or ""Gamma"" (a 3-satellite combination of a GRACE-type and a pendulum formation). We found that the mission shows the best performance when the orbital planes equipartition the 3D space (e.g., when the orbital planes are nearly orthogonal in the case of a 2-formation mission). As far as formation types are concerned, the best performance was expectedly demonstrated by Gamma formations. More interestingly, we found that nearly the same performance can be achieved by a proper combination of simpler formations: GRACE-type and pendulum (provided that the total number of formations and orbital planes is unchanged). More specifically, we recommend to combine one GRACE-type formation with one or more pendulum formations. We interpret this finding as an evidence that the major problem of pendulum formations is not the anisotropic sensitivity (in contrast to GRACE-type formations), but a poor sensitivity over the polar areas. As soon as this problem of pendulum formations is solved by incorporating just one GRACE-type formation, the overall mission performance increases to the level close to that demonstrated by Gamma-formations.

71

Simplified Gravitational Reference Sensors for Future Earth Geodesy Missions

Conklin, John; University of Florida, Dávila Álvarez, Anthony; University of Florida, Bennett, Stephen; Ball Aerospace, Bevilacqua, Riccardo; Embry-Riddle Aeronautical University, Doughty, Neil; Ball Aerospace, Hollis, Harold; University of Florida, Mueller, Guido; University of Florida, Knudtson, Aaron; University of Florida, Leitch, James; Ball Aerospace, Lee, Jennifer; Ball Aerospace, McDaniel, Glenn; Ball Aerospace, Patel, Unmil; University of Florida, Sanjuan, Jose; University of Florida, Spero, Robert; Caltech/JPL, Ware, Brent; Caltech/JPL, Wass, Peter; University of Florida, Wiese, David; Caltech/JPL, Ziemer, John; Caltech/JPL
jwconklin@ufl.edu

The University of Florida, in collaboration with Caltech/JPL, Ball Aerospace, and Embry-Riddle Aeronautical University, with funding from the NASA Earth Science Technology Office, are developing a Simplified Gravitational Reference Sensor (S-GRS), an ultra-precise inertial sensor optimized for future Earth geodesy missions. Inertial sensors like the S-GRS are used to measure or compensate for all non-gravitational accelerations of the host spacecraft so that they can be removed in the data analysis to recover spacecraft motion due to Earth's gravity field, the main science observable. Low-low satellite-to-satellite tracking missions like GRACE-FO that utilize laser ranging interferometers are technologically limited by the acceleration noise performance of their electrostatic accelerometers, as well as temporal aliasing associated with Earth's dynamic gravity field. The S-GRS is estimated to be at least 40 times more sensitive than the GRACE accelerometers and more than 500 times more sensitive if operated on a drag-compensated platform. The S-GRS concept is a simplified version of the flight-proven LISA Pathfinder GRS. Our performance estimates are based on models vetted during the LISA Pathfinder flight and the expected Earth orbiting spacecraft environment based on flight data from GRACE-FO. The improved performance is enabled by removing the small grounding wire used in the GRACE accelerometers and replacing it with a UV photoemission-based charge management system, enabling more massive test masses and larger gaps between the test mass and its housing. We have shown that the increased S-GRS performance allows future missions to take full advantage of the improved sensitivity of the GRACE-FO Laser Ranging Interferometer (LRI) over microwave ranging systems in the gravity recovery analysis. The low volume, mass, and power consumption enables use of the S-GRS on ESPA-class microsatellites, reducing launch costs or enabling larger numbers of satellite pairs to be utilized to mitigate aliasing by improving the temporal resolution of Earth gravity field maps.

72

The MARVEL concept for future gravity missions

Lemoine Jean-Michel; CNES
Meyssignac, Benoit; CNES
Blazquez Alejandro; CNES
Mandea, Mioara; CNES
Lopes, Louise; CNES
Costes, Vincent; CNES
Bourgogne, Stéphane; Stellar Space Studies
Samain, Etienne; SigmaWorks
Balmino, Georges; CNES Emeritus
jean-michel.lemoine@cnes.fr

The projects for future space gravity missions aim on the one hand to ensure the continuity of the measurements of mass transfers, initiated by the two remarkably successful missions GRACE and GRACE-FO, on the other hand, and if possible, at an improvement in performance compared to current missions in terms of precision, and of spatial and/or temporal resolution. The main way for the enhancement of the gravity observations consists more in improving the geometry of the measurement than in increasing the precision of the inter-satellite link since the LRI experience on GRACE-FO has shown that the remarkable improvement in the precision of measurement compared to GRACE provided only marginal improvement in monthly gravity field solutions (so far). To improve the geometry of the measurement, two concepts are particularly studied: on the one hand the concept of double pair, with one pair in polar orbit and the other one in inclined orbit (this concept is particularly highlighted in the NGGM / MAGIC project); on the other hand the concept of a pendular measurement where the two satellites are in polar orbits, slightly shifted in ascending node and in mean anomaly, such that the inter-satellite measurement sweeps alternately to the right and to the left of the North-South groundtrack. This second concept is particularly supported by the MARVEL project.
The poster will present the current state of the MARVEL study, started at CNES in January 2020 and currently at the end of pre phase-A. The objective is to perform a distance measurement between the two satellites (separated by approximately 200 km) with a precision better than 1

micrometer over an integration time of 5 s, while allowing a side scan of the inter-satellite link ranging from up to +/- 45 ° from the axis of the satellites. This measurement will be carried out by a laser chronometry instrument of different design from the instruments used until now, KBR and LRI. We will present the results of the numerical performance simulations which validate the mission concept as well as the instrumental developpements initiated at CNES in order to design the instrument prototype.