Project: **499**

Project title: **GFZ - Erdsystem-Modellierung**

Principal investigator: **Maik Thomas**

Report period: **2021-08-31 to 2022-10-31**

A central focus of the scientific discipline Geodesy is the precise measurement of the Earth's external gravity field and its time-variable rotation. Beside the large-scale dynamics of atmosphere and terrestrial hydrosphere, the spatially and temporally highly variable ocean bottom pressure plays a major part in determining gravity and rotational variability. Therefore, the processing of global geodetic measurements - including the satellite gravimetry missions GRACE (2002 - 2017) and GRACE-FO (launched May 22nd, 2018); Very Long Baseline Interferometry based on a network of globally distributed radio telescopes; and station positions of a permanent network of stations receiving Global Navigational Satellite System (GNSS) signals - requires prior information from numerical ocean models in order to separate signals caused by ocean bottom pressure variability from other geophysically relevant signal sources.

Within four peer-reviewed projects

> **NAODEMO** ("Next-Generation Non-Tidal Atmospheric and Oceanic De-Aliasing Models", DFG-Geschäftszeichen: DO1311/4-1)
>
> **TIDUS** ("Improved Tidal Dynamics and Uncertainty Estimation for Satellite Gravimetry", DFG-Geschäftszeichen: TH864/15-1)
>
> **G3P** ("Global Gravity-based Groundwater Product", Horizon2020 program of the European Union, Grant No. 870353)
>
> **DISCLOSE** ("Disentangling Climatic Signals in Earth Orientation Parameters", DFG-Geschäftszeichen: DO1311/6-1)

we performed new simulations of the time-evolution of large-scale mass variations in the Earth's system. This includes experiments with the primitive equation model MPIOM (Jungclaus et al., 2013) that focus in particular on the wind-driven circulation with the aim to further improve the standard de-aliasing model for the GRACE mission (Dobslaw et al., 2017), and also experiments with the shallow water equations in a global setting (Weis et al., 2008) describing mass variability to a wide range of ocean tide constituents including over- and compound tides. Further simulations focus on the dynamics of the terrestrial water cycle with the Land Surface and Discharge Model LSDM (Dill, 2008). The work performed in 2021 and 2022 was focussed on the following topics:

Global Ocean Tides Modelling with TiME:

Substantial effort has been invested to thoroughly revise and improve the shallow-water equation code TiME (Weis et al., 2009) originally developed by University of Hamburg and DKRZ. The latest version includes flexible rotated grids to avoid singularities in the model domain; the incorporation of explicit feedbacks of self-attraction and crustal surface deformation to ocean dynamics; the consideration of atmospheric forcing like periodic pressure and wind variations; the inclusion of sea-ice drag and ice-drift effects; as well the consideration of energy dissipation due to internal wave drag. Model performance has been shown to improve drastically by 78% with respect to the previous version for the main semidiurnal M2 tide (Sulzbach et al., 2021). Subsequently, this new model configuration has been utilized for a number scientific application studies including the assessment of ocean tides excited by the 3rd spatial degree of the tide-rising potential (Sulzbach et al., 2022), and the quantification of the atmospheric contributions to global ocean tides (Balidakis et al., 2022). Experiments from TiME also contributed to a revised estimation of ocean tide model errors that are highly relevant for satellite gravimetry from GRACE and GRACE-FO (Abrikosov et al., 2021). In addition, initial experiments were carried out to quantify the effect of spatially variable elastic properties of the Earth in both crust and upper mantle on geodetically observable ocean tidal loading deformations (Huang et al., 2022). The work on ocean tides is being continued in the frame of the TIDUS project within the DFG-funded research group NEROGRAV.

Ocean Bottom Pressure Variability from MPIOM:

Recent MPIOM simulations focussed on selecting an optimal model configuration to predict global ocean bottom pressure variability at temporal scales from a few hours to many months including the implementation of the explicit feedback of self-attraction and surface loading deformations also into MPIOM (Shihora et al., 2022b). Preliminary experiments were evaluated with along-track GRACE-FO laser-interferometer data (Ghobadi-Far et al., 2022) in order to make processing decisions for the new release 07 of the atmosphere and ocean non-tidal background model AOD1B for GRACE-FO (Shihora et al., 2022a). The new release is expected to remove various issues identified in the previous release 06 from extensive comparisons against independent observational data including daily gravity field solutions (Schindelegger et al., 2021). This GRACE-related work is being continued in the frame of the NAODEMO project as a German contribution to the joint U.S.-German Science Data System of the GRACE-FO mission.

Terrestrial Water Storage from GRACE and LSDM:

Time-series of the gravity field as obtained from GRACE and GRACE-FO were augmented with uncertainty estimates that allow for the quick and reliable derivation of uncertainties for arbitrary averaging regions without the need to revert to the spectral representation of the data (Boergens et al., 2022). This work is still being continued with the aim to also explicitly incorporate spatial leakage errors into this assessment, by means of, e.g., also simulated terrestrial water storage from the LSDM model. In the long run, those activities particularly contribute to the development of a global groundwater product based on GRACE-FO data that is currently being attempted within the H2020-funded project G3P.

Earth Orientation Parameter Analysis and Prediction:

The rotational speed of the Earth and the position of the rotational pole vary slowly in time caused by angular momentum changes due to mass re-distributions in atmosphere, oceans, and the terrestrial hydrosphere. Short-term forecasts from ECMWF and DWD were used to force both MPIOM and a land surface discharge model (LSDM) to predict the Earth's rotation variations for up to 10 days into the future (Dill et al., 2021). Angular momentum series have been also used to interpret pole position changes observed during dedicated VLBI campaigns (Raut et al., 2022). This work is currently being extended within the DISCLOSE project funded by DFG.

Elastic Surface Deformations:

Elastic surface deformation as calculated based on high-resolution surface mass distributions from MPIOM and LSDM are important for the proper treatment of non-linear motions of geodetic instruments attached to the crust. No new experiments have been performed in 2021, but several studies have been finally published that make use of numerical results achieved at DKRZ in the past. This includes an assessment of the impact of surface loading on the orbit accuracies of altimetry satellites (König et al., 2020) and the characterization of GPS sensitivity to different non-tidal loading sources in a wide range of temporal scales (Klos et al., 2021).

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ISI Publications based on project #499 results from the last two years

Abrykosov, P., **Sulzbach, R.**, Pail, R., **Dobslaw, H., Thomas, M.** (2022): Treatment of ocean tide background model errors in the context of GRACE/GRACE-FO data processing. - Geophysical Journal International, 228, 3, 1850-1865. doi: 10.1093/gji/ggab421

Balidakis, K., Sulzbach, R., Shihora, L., Dahle, C., **Dill, R., Dobslaw, H.** (2022): Atmospheric Contributions to Global Ocean Tides for Satellite Gravimetry, J. Adv. Mod. Earth Sys., https://doi.org/10.1029/2022MS003193.

Boergens, E., Kvas, A., Eicker, A., **Dobslaw, H.**, Schawohl, L., Dahle, C., Murböck, M., Flechtner, F. (2022): Uncertainties of GRACE-Based Terrestrial Water Storage Anomalies for Arbitrary Averaging Regions. Journal of Geophysical Research: Solid Earth, 127, 2, e2021JB022081. doi: 10.1029/2021JB022081

Dill, R., Saynisch-Wagner, J., Irrgang, C., **Thomas, M.** (2021): Improving atmospheric angular momentum forecasts by machine learning. - Earth and Space Science, 8, 12, e2021EA002070. doi: 10.1029/2021EA002070

Ghobadi-Far, K., Han, S., McCullough, C. M., Wiese, D. N., Ray, R. D., Sauber, J., **Shihora, L., Dobslaw, H.** (2022): Along-orbit analysis of GRACE Follow-On inter-satellite laser ranging measurements for sub-monthly surface mass variations. - Journal of Geophysical Research: Solid Earth, 127, 2, e2021JB022983. doi: 10.1029/2021JB022983

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.

Klos, A., **Dobslaw, H., Dill,** R., Bogusz, J. (2021): Identifying the sensitivity of GPS to non-tidal loadings at various time resolutions: examining vertical displacements from continental Eurasia. - GPS Solutions, 25, 89. doi: 10.1007/s10291-021-01135-w

König, R., Reinhold, A., **Dobslaw, H.,** Esselborn, S., Neumayer, K., **Dill, R.,** Michalak, A. (2021): On the effect of non-tidal atmospheric and oceanic loading on the orbits of the altimetry satellites ENVISAT, Jason-1 and Jason-2. - Advances in Space Research. doi: 10.1016/j.asr.2020.05.047.

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