1. ICCC Workshop

„Geodesy for Climate Research“

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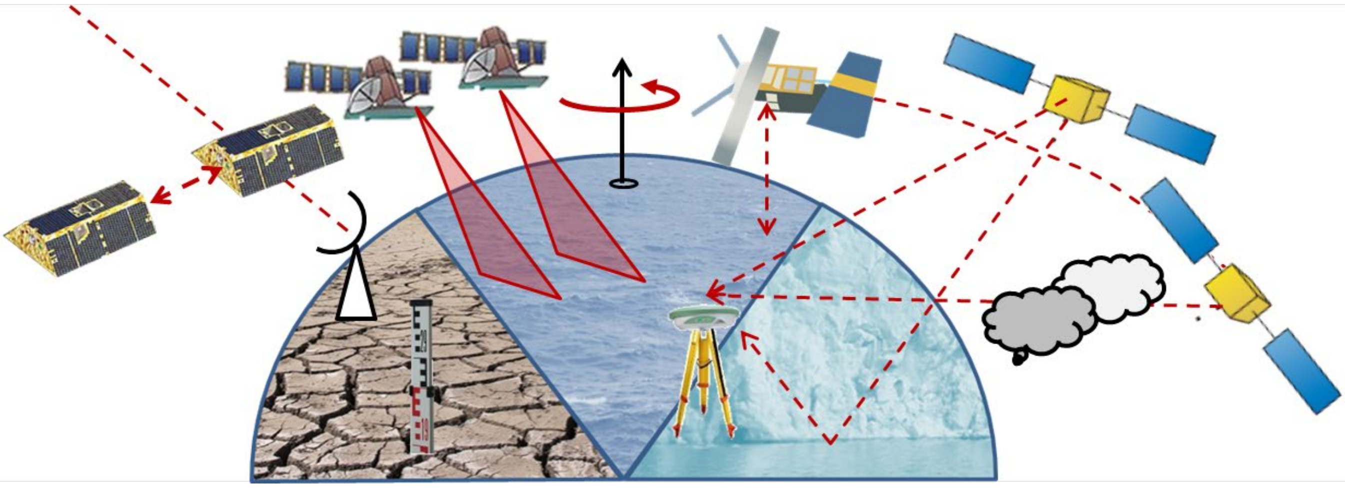
Abstract book



Organized by the Inter-Commission Committee on “Geodesy for Climate Research” of the International Association of Geodesy (IAG)

International Association of Geodesy

Monday morning: 8 a.m. CEST (UTC+2)
Session 01: Hydrology & data processing (Hydrology I)
Convenors: Mehdi Khaki & Balaji Devaraju

Essential Climate Variables (ECVs) and the contribution of geodetic observations: an overview

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The Global Climate Observing System (GCOS) defines Essential Climate Variables (ECVs) as variables that are critical for characterizing the climate system and its changes. ECV datasets provide the empirical evidence needed to understand and predict the evolution of climate, to assess risks, to guide adaptation measures, to underpin climate services, among others. We present an overview on ECVs and the way they are defined and described by panels in GCOS such as TOPC, the Terrestrial Observation Panel for Climate (TOPC), and via public consultation on ECV requirements. An overview will be given of potential contributions of geodetic observations to measuring different ECVs before focusing more closely on two ECVs: In the terrestrial branch, one of the established ECVs is groundwater. Furthermore, the Steering Committee of GCOS recently recommended to establish Terrestrial Water Storage (TWS) as a new ECV. While the European Union's Earth Observation Programme Copernicus does not yet provide data products for these ECVs, this gap is about to be filled by the EU research project G3P (Global Gravity-based Groundwater Product). Data products for both ECVs (groundwater and TWS) may largely benefit from geodetic observations, in particular by satellite gravimetry.

Geodetic monitoring of the hydrological changes in Nepal Himalaya

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Mass of the Earth's system although remains constant, it gets transported between various Earth's system components. These mass transports are found to induce deformations of the Earth's surface known as surface mass loading and are driven by climate patterns. Therefore, temporal mass variations within the Earth's system and hence surface mass loading is the direct impact of climate change. One of the major sources of mass transport in the Indian subcontinent is the monsoon. This subcontinent receives a significant amount of rainfall during the monsoon period. The mass transports caused by the Indian monsoon deform the Earth's surface which can be detected with space geodetic techniques such as Global Navigational Satellite Systems (GNSS) and dedicated gravity satellite missions, in particular, the Gravity Recovery and Climate Experiment (GRACE) and GRACE-Follow on (GRACE-FO) satellite missions.

The overarching objective of this study is to monitor the hydrological changes in Nepal Himalaya using geodetic data. In particular, it is aimed at investigating the contribution of mass transports from various catchments in the Nepal Himalaya and its surrounding areas to the hydrological signal observed by the continuously operating GPS (Global Positioning System) stations. GRACE/GRACE-FO satellite missions' data, hydrological models and spatio-temporal modelling techniques have been used to ascertain the aforementioned contribution. The results obtained were presented, analysed and discussed.

Keywords: GNSS, GPS, GRACE /GRACE-FO, mass transports within the Earth's system, Surface Mass Loading

The Use of National CORS Networks for the Determination of Mass Transport within the Earth's System and for Improving GRACE Solutions

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The Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE–FO) satellite missions provide very valuable data for the determination of mass transport within the Earth's system on a regional/global scale, while Global Navigation Satellite System (GNSS) data can sufficiently be used to detect the effect of mass transport on a local scale. The aim of this contribution is to investigate the usefulness of national GNSS CORS (Continuously Operating Reference Stations) networks for the determination of mass transports within the Earth's system and for improving GRACE solutions. The ASG–EUPOS (Active Geodetic Network of the European Position Determination System) – the national CORS network in Poland - has been chosen as a case study. Monthly vertical deformations of the Earth's surface Δh and monthly variations of equivalent water thickness ΔEWT have been determined at the sites of the ASG–EUPOS CORS network using GRACE–based GGMs and GNSS data. Furthermore, models of ΔEWT were developed by combining ΔEWT obtained using data from GRACE satellite mission with the corresponding ones determined from GNSS data. The results obtained have been analyzed and discussed. They revealed that for the determination of mass transport within the Earth's system, GNSS data from CORS network stations provide valuable information, complementary to the one obtained from GRACE satellite mission data.

Keywords: equivalent water thickness; GNSS CORS network; GRACE; mass transport within the Earth's system; vertical surface deformation

Spatial downscaling of GRACE water storage change using a copula-supported Bayesian framework

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The satellite missions GRACE and GRACE FO provided mass variations as a fundamentally new observation-type for a wide spectrum of Earth science applications. They have fostered a number of novel applications in oceanography, geophysics, hydrology and hydrometeorology. Despite all the revolutionary findings, the utility of GRACE data has mainly been limited to large catchments due to their poor spatial resolution. We propose a method to downscale GRACE data by incorporating the data and the distribution of available high-resolution hydrological data and models. For this purpose, we propose a Bayesian framework that facilitates the estimation of downscaled GRACE data in the face of auxiliary data and their distribution. While it is common for Bayesian problems to consider a predefined model for the Bayesian ingredients (likelihood function and the prior distribution), we rely on the copula method to obtain nonparametric distributions from the data itself. We employed our method over the Amazon Basin and, given the lack of large scale ground truth, assessed the plausibility of our results by comparing them with spaceborne surface soil moisture data. The results show that the proposed methodology can successfully estimate downscaled GRACE terrestrial water storage changes and its uncertainty.

GRACE data processing: direct conversion of spherical harmonic coefficients into mascon-type solutions

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A mascon representation of GRACE-based mass anomalies is usually superior to a spherical harmonic (SH) representation. However, officially computed mascon solutions are a regularized level-3 data product. As such, they offer a very limited flexibility when it concerns an adjustment of data processing parameters. This is likely the reason why various research groups compute their own mascon-type solutions from SH coefficients. Typically, the procedure consists of two steps. First, SH synthesis is applied to compute a low-resolution gravity field functional, such as gravity disturbances at the satellite altitude or low-pass filtered mass anomalies. Second, the synthesized quantities are inverted into mascon-type estimates. Such a procedure is not straightforward, requiring an empirical fine-tuning of various parameters. Furthermore, an error propagation from SH coefficients into mascons is in this case problematic, since the error variance-covariance matrix of the quantities synthesized in the first step may be ill-posed.

We have investigated a direct regularized inversion of SH coefficients into a global set of mascons. The usage of preconditioned conjugate gradients allows us to deal with a large number of unknown parameters, so that a high spatial resolution can be achieved. As soon as the regularization parameter is small, the obtained solution is similar to the one obtained by the straightforward SH synthesis of mass anomalies. This is an expected result in view of an equivalence of a spatial and a spectral representation of a function (provided that the spatial

discretization is sufficiently fine to prevent noticeable discretization errors). . On the other hand, a proper modification of the applied regularization facilitates a computation of more realistic solutions. For instance, a spatially-varying regularization with a large regularization parameter over the ocean allows the signal leakage into the ocean to be reduced to minimum. This behaviour is particularly favourable when estimating mass anomalies associated with ice sheets and ice caps.

At the same time, we demonstrate that the direct inversion of SH coefficients into mass anomalies can only be done globally, so that the inversion process does not suffer from model errors. If some areas are excluded (even if those areas are characterized by only minor mass variations, like the ocean), model errors may result in noticeable distortions of the obtained mass anomalies. p

Consolidated and validated monthly gravity field combinations of the GRACE, Swarm and GRACE-FO satellite missions

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The satellite missions GRACE and GRACE-FO, dedicated to the observation of the time-variable Earth gravity field, provide invaluable insight into continental total water storage, mass changes of the Polar ice sheets and glaciers, and mass variations in the oceans at spatial scales of 200-400 km and monthly time-resolution, covering the time-period 2002 to present. The Combination Service for Time-Variable Gravity Fields (COST-G) of the International Association of Geodesy (IAG) collects the monthly gravity fields of its associated or partner Analysis Centers (ACs) and performs a weighted combination to provide a consolidated time series of monthly gravity fields at Level-2 (spherical harmonic coefficients) and user-friendly Level-3 (post-processed global grids or regional averages) mass change products. Gaps in the GRACE or GRACE-FO time-series may be bridged by monthly gravity fields derived from orbits of the Swarm satellites, dedicated to the observation of the Earth's magnetic field, however, with significantly reduced spatial resolution.

COST-G performs quality control and harmonization of the contributing GRACE, Swarm or GRACE-FO time-series. The combined gravity fields undergo consistency checks and internal validation by the COST-G validation centers at GFZ and GRGS. An independent board of experts in hydrological, oceanic and cryosphere applications irregularly performs external validations. A combined re-processed GRACE time-series COST-G GRACE RL01 is available at the International Center for Global Earth Models ICGEM (Level-2 products) or the Gravity Information Service GravIS (Level-3 products), both operated by GFZ. The operational GRACE-FO time-series is updated regularly with a latency of less than 3 months, Swarm gravity fields are operationally combined in a quarterly processing scheme.

Monday afternoon 5 p.m. CEST (UTC+2)	
Session 02: Climate model evaluation -	
Convenors: Anna Klos & Roland Pail	

Keynote lecture: Climate models for geodesy

V. Humphrey (1)

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Introductory lecture to introduce climate models to geodesists.

Evaluating CMIP6 soil water storage with GRACE satellite observations

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Soil moisture is a key component of the hydrological cycle, and plays an important role in the surface energy budget and in water-carbon cycle interactions. Accurate representation of soil moisture in Earth System Models is necessary for the prediction of future hydrological extremes, freshwater availability, and terrestrial carbon uptake. Total soil moisture is determined by the interplay of sources (precipitation) and sinks (evapotranspiration, runoff). The 6th iteration of the Coupled Model Intercomparison Project (CMIP6) shows divergent future projections of soil moisture between the models.

Here, we use empirical orthogonal functions to compare patterns of monthly soil moisture variability in CMIP6 models to terrestrial water storage changes obtained from the GRACE satellites. Using this methodology, we identify which models best match the EOF patterns derived from GRACE and analyze what structural model characteristics may explain differences between the simulated and observed patterns of water storage variability. We investigate whether observed total water storage can be used as a constraint to reduce the spread of soil water storage projections in CMIP6 models.

Land Water Storage Variabilities in GRACE and Climate Models – How do they compare and which future changes can we expect?

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Climate change will affect terrestrial water storage (TWS) during the next decades by impacting the seasonal cycle, interannual variations, and long-term linear trends. But how exactly will the variability change in the future? Reliable projections are needed not only for sensible water management but also as input for long-term performance studies of possible Next Generation Gravity Missions (NGGMs).

In this contribution, an ensemble of climate model projections provided by the Coupled Model Intercomparison Project Phase 6 (CMIP6) covering the years 2002 – 2100 is utilized to assess possible changes in TWS variability. To demonstrate performance and identify shortcomings of the models we first compare modeled TWS to globally observed TWS from the Gravity Recovery and Climate Experiment (GRACE) and its follow-on mission (GRACE-FO) in the time span 2002 – 2020. We then analyze changes in the variability of TWS from model projections until the end of the century and the consensus on such changes within the model ensemble.

Based on these projections, we find that present-day GRACE accuracies are sufficient to detect amplitude and phase changes in the seasonal cycle in one third of the land surface after 30 years of observation, whereas a five times more accurate NGGM mission could resolve such changes almost everywhere outside the most arid landscapes of our planet. We also select one individual model experiment out of the CMIP6 ensemble that closely matches both GRACE observations and the multi-model median of all CMIP6 realizations. This model run might serve as basis for multi-decadal satellite mission performance studies to demonstrate the suitability of NGGM satellite missions to monitor long-term climate variations in the terrestrial water cycle.

Hydrological angular momentum estimates from CMIP6 simulations

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(1) Space Research Centre, Polish Academy of Sciences
(2) Warsaw University of Technology

Climate models give us information about past climate changes and its future evolution. Such simulations are complex as they deliver physical, chemical and biological properties of the atmosphere, oceans and continental hydrosphere both in the past and in the future. The Coupled Model Intercomparison Project phase 6 (CMIP6) aims to make publicly available the results of climate models developed by multiple modeling groups in a standardized format.

In this study, we use soil moisture and snow water equivalent variables provided by the chosen climate models from CMIP6 to assess the role of land hydrosphere in polar motion excitation. Such temporal variations of polar motion are described with hydrological angular momentum (HAM) series. We analyse HAM variability in a wide variety of oscillations, taking into account trends, seasonal, and non-seasonal oscillations We consider past changes in HAM but also analyse its future evolution. This will allow to determine how future changes in the terrestrial hydrosphere will affect the movement of the Earth's pole. The consistency between HAM obtained from various CMIP6 models is assessed as well.

How to interpret severity of linear trends from GRACE time series

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Decomposing the GRACE time series into a few periodic components and a linear trend to identify temporal characteristics of water mass redistribution in a region is a usual step when using GRACE data for climate research. The magnitude of trend is directly associated with severity of water storage change, without considering the spatiotemporal variability in water storage. Therefore, it is not always known to what extent resultant trends are truly representative of severity of change, or whether the trends in short time series are driven by long wavelength signals that can only become apparent when additional years of data are available. In this study, we demonstrate that multi-decadal natural variability in water cycle influenced previous interpretations of linear trends from relatively short (<20 year) GRACE time series. Since, natural hydrological variability is different for different regions, same value of trend has different interpretation for different river catchments. We propose a new metric (trend to variability ratio or TVR) that incorporates standard deviation of historical natural variability to better interpret the severity of trends inferred from GRACE. Using this metric, we find that several regions that were thought to be losing water at a moderate rate are actually more endangered and vice-versa. We also provide a map that demarcates river catchments that have experienced severe water storage change between 2003 to 2015.

Session 03: Poster breakout I
Monday afternoon

Atmospheric angular momentum variations over many time scales, Earth rotation, and climate signals

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The atmosphere has been shown to transfer its angular momentum to and from the solid Earth below, so that changes in atmospheric angular momentum (AAM) are mirrored in that of the rotation of the Earth. We review many of the time scales in which AAM changes from rapid diurnal scales, to intraseasonal, interannual, and beyond. In particular, changes of the length of day are directly proportional to the axial AAM variability. Analyses of the atmosphere are made by the world's large weather centers from the variety of observations from the global world weather watch network in near-real time for purposes of weather analysis and forecasting. Furthermore, models of the atmosphere are being used to make possible projections into the future, and might be used as proxies for analyzing changes in Earth rotation at the end of the century. Lastly, Earth rotation parameters in theory can be considered a low degree of freedom constraint on the global climate system, though how this information would be used in weather forecasting or climate research is not certain.

Temperature Effect on Reflected GNSS Signals from Mid-Latitude Lake Ice

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Global Navigation Satellite System Interferometric Reflectometry (GNSS-IR) is a promising tool for studying lake ice parameters z lake ice phenology and lake ice thickness. With the capabilities of penetrating through freshwater ice and snow, L-band signals of GNSS reach the bottom of the ice and their reflection from the ice-water interface provides us with an opportunity to estimate ice thickness. To investigate the capability of GNSS-IR for the estimation of lake ice thickness, an experiment was conducted at a mid-latitude lake site during the ice season of 2019-2020. Installation of a five-meter height tower equipped with a standard GNSS antenna on the shore of MacDonald Lake, Haliburton, Ontario, Canada, allowed us to collect reflected GNSS signals off lake ice. We then analyzed time series of GNSS-IR observations to estimate lake ice thickness and on-ice snow depth. We found that the reliability of this technique is highly dependent on the temperature. Mid-winter melt events caused by warm temperatures can result in the appearance of wet layers within ice columns and the overlaying snowpack. These wet layers produce a high dielectric contrast with their host layers (snow and/or ice) and, by implication, lead to strong reflections causing an error in ice thickness estimation. However, this impact can be used as an indicator for temperature variation during ice seasons. Comparing the amplitudes of the Signal-to-Noise Ratio (SNR) of reflected GNSS signals against temperature, we see that as temperature rises the SNR amplitude drops due to an increase in scattering and decrease in reflection towards the GNSS-IR antenna. Moreover, SNR amplitudes can be analyzed as an indicator of ice-water interface roughness as it affects the power of GNSS signal reflection. The impact of roughness on SNR amplitudes can be also modeled through microwave radiative transfer models such as Snow Microwave Radiative Transfer (SMRT).

Polar Land Mass Change and Geodesy for the Solid Earth in the 21st Century

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The influence of climate change on geodetic parameters such as Earth's surface topography, ellipsoidal shape and gravity, polar motion and sea-level change is well known. The geodetic parameters are sensitive to local, regional and global changes in surface mass changes which may be separated into seasonal, inter-decadal and secular components. While these components are now robustly quantified by GRACE and the GRACE-FO mission data, they are complemented by longer data sets that are global in nature, polar motion (1899-present), satellite laser ranging (1976-present) and measurement of sea-level from space altimetry since 1992. Each of these data sets must be decontaminated by a glacial isostatic adjustment (GIA) model. These models require simplifying the Earth's mantle response with a Maxwell constitutive model. The analogue 1-D model setup is a Hookean spring connected in series with a viscous dashpot. It is increasingly understood that models of the mantle deformation following the end of the global Little Ice Age (LIA) may not be sufficient to give model description to geodetic measurements, and therefore, may be problematic in their ability to decontaminate geodetic measurements for interpretation as 'climate mass signals'. Here I discuss the evidence in favor of more complicated 1-D setups for post-LIA mantle response with emphasis on a seismologically based perspective.

Antarctic Peninsula Mass Trends and driving processes from 2003 until present through assimilation of geodetic data using a Bayesian Hierarchical Model approach

S. Chuter (1), A. Zammit-Mangion (1), J. Rougier (2), G.Dawson (1), J. Bamber (1)

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The mass balance of the Antarctic Peninsula has undergone rapid changes over the last two decades, exemplified by the presence of grounding line retreat and increases outlet glacier ice velocity after the collapse of the Larsen A and B ice shelves. These events provide potential analogues for other regions of Antarctica, which are susceptible to marine ice sheet instability. Better understanding of the processes driving these changes, including their subsequent impact on regional sea level change, require long-term continuous monitoring from multiple observation approaches.

Over the last decade, there has been disagreement in mass balance estimates for this sector of the ice sheet, due to the challenges the region's topography and geometry pose to accurate monitoring by Earth observation platforms. Conventional pulse limited satellite altimetry suffers from data loss over regions of mountainous topography, whereas geodetic observations from GRACE operate at a coarse resolution and therefore unable to resolve small scale changes over outlet glaciers, in addition to being susceptible to signal leakage. Conversely, datasets such as stereo-image DEM differencing are limited in their wider spatial coverage and temporal resolution. As a result, it is difficult to integrate these diverse observations to provide a single reconciled mass balance estimate, in addition to assessing the contribution of each driving process to the mass change.

To help resolve this, we have developed an optimised Bayesian hierarchical model to specifically investigate this region. It incorporates a diverse range of observations including CryoSat-2 swath altimetry, stereo-image DEM differencing, GPS and observations of mass change from GRACE. We will present results from the regionally optimised model from 2003 until present, including basin-scale mass trends and changes in spatial latent processes at an annual resolution. The approach also addresses the gap in observational coverage between GRACE and GRACE-FO. Additionally, we will discuss future opportunities, such as the extension of the technique into the next decade.

Retrieving Sea Level Heights around Turkish Coasts using GPS Interferometric Reflectometry

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Monitoring of sea level variation is one of the most important parameter in climate change scenarios. Therefore, realizing and determining sea level variations both on a regional and global scales are of the great importance. Conventionally, the sea level variations are determined using tide gauge. However, the tide gauge records are also impressed by vertical land motions. The Global Navigation Satellite System (GNSS) is one of the major satellite technique and the GNSS signals have some characteristics that can be used for the remote sensing applications. GPS Interferometric Reflectometry (GPS-IR) technique allows to effectively determinate GPS-based sea level variations. In this context, this study aims to investigate the contribution to the GNSS stations located in the coasts of Turkey to determination of sea level heights by using GPS-IR method. For this purpose, first, utilized existing the Signal to noise ratio (SNR) data from TEKR GNSS station of the Turkish National Permanent Real Time Kinematic Network (TUSAGA-Active) and MERS GNSS station from the International GNSS Service (IGS) network. The GPS L1 signals are selected to retrieve sea level heights at these stations. The dominant multipath frequency of SNR signal is computed with Lomb-Scargle periodogram (LSP). Finally, the GPS-based sea level heights for these stations are compared to sea level records from nearby tide gauges. Secondly, the Singular Spectrum Analysis (SSA) method is applied to sea level heights derived from GPS-IR. SSA is a powerful filtration technique and split the noise from the signal. It is aimed to evaluate the effect of SSA method on sea level heights derived from GPS-IR. The results are compared with the original time series of sea level variations. Consequently, it is demonstrated that the GPS-based sea level variations have improved correlation with SSA.

Distinguishing between Models of Glacial Isostatic Adjustment using GPS, GRACE, and Relative Sea Level Observations: Inferring the Viscosity of the Top Third of the Lower Mantle

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Accurately estimating solid Earth's viscous response to unloading of the former ice sheets is essential for inferring changes in water at Earth's surface using GRACE and GPS positioning. An accurate model of glacial isostatic adjustment also contributes to understanding vertical displacements and relative sea level changes observed using space geodesy and geology. Inferring the rise of global sea level from satellite altimetry furthermore involves correcting for the collapse of the seafloor in the peripheral bulge of the former ice sheets. In this study, we distinguish between three models of glacial isostatic adjustment in North America using GPS positioning, GRACE gravity, and relative sea level data. We determine a comprehensive set of GPS rates of vertical motion in North America that is an advance in that:

(1) we estimate site velocities using Jet Propulsion Laboratory's reprocessed satellite orbits and clocks and Nevada Geodetic Laboratory's reprocessed series of positions as a function of time, all in the International GNSS Service 2014 (IGS14) reference frame,

(2) the velocities of 144 campaign GPS sites in the Canadian Base Network tightly constrain uplift near the center of the former Laurentide ice sheet, and

(3) we account for elastic loading produced by the increase in surface water in the Great Lakes by 285 cubic kilometers since 2012.

The GPS data suggest that central Canada is rising at about ≈12 mm/yr, in agreement with the ICE-6G_D (VM5a) model of glacial isostatic adjustment, but significantly slower than both the 24 mm/yr of uplift predicted by the model of Lambeck et al. [2017] and the 16 mm/yr of uplift predicted by the model of Caron et al. [2018]. Correcting GRACE for the ICE-6G_D (VM5a) of glacial isostatic adjustment results in realistic fluctuations of water change at Earth's surface in Canada, whereas correcting for either Lambeck et al. [2017] or Caron et al. [2018] results in implausibly fast estimates of water loss. Relative sea level data also support the slower rate of relative sea level change from 4,000 years ago to Present predicted by ICE-6G_D (VM5a) compared to the other two models. All three data sets suggest that the viscosity of the top third of the lower mantle to be about 1.6 x 1021 Pa s, about three times larger than the viscosity of the upper mantle, which is ≈0.5 x 1021 Pa s.

An integrated, data-driven approach for estimating global glacial isostatic adjustment, VLM, land ice, hydrology and ocean mass trends.

J. Bamber (1)

(1) University of Bristol

Correctly separating the sources of sea level change is crucial for improving future sea level predictions. Traditionally, changes in each component of the integrated signal have been tackled separately, which has often lead to inconsistencies between the sum of these components and the integral as measured by satellite altimetry. To address these issues, the European Research Council funded a six year project aimed at producing the first physically-based and data-driven solution for the complete coupled land-ocean-solid Earth system that is consistent with the full suite of observations, prior knowledge and fundamental geophysical constraints. This project is called "GlobalMass" (www.globalmass.eu) based at the University of Bristol.

Observed mass movement from the GRACE mission and vertical land motions from a global network of permanent GPS stations are used in a data-driven approach to estimate the glacial isostatic adjustment (GIA) without invoking any assumptions about the Earth structure or ice loading history. A Bayesian Hierarchical Model (BHM) is used as the framework to combine the satellite and in-situ observations alongside prior information that incorporates the physics of the coupled system such as conservation of mass and characteristic length scales of different processes in both space and time. The BHM enables dimensional reduction of the observations so that a simultaneous solution can be obtained at a global scale. It also combines observations in a manner that is consistent with their uncertainties and spatial covariance. The BHM is fully flexible and can assimilate point data such as GPS, alongside global grids from, e.g. GRACE, sea surface height from satellite altimetry and ocean density variations from Argo buoys. It is being used to produce a consistent partitioning of the integrated sea level trend into its steric (temperature and salinity) and barystatic (mass) component for the satellite era. The latter component is caused by land hydrology and melting ice sheets and glaciers, all of which are solved for simultaneously. Here, we describe the approach, data sets used and illustrate the concept for North America by deriving GIA and land hydrology and comparing the results with forward numerical models.

Regional patterns of ocean mass sea-level change over the satellite altimetry era (1993-2017)

C. Camargo (1), R. E.M. Riva (2), A.B.A. Slangen (1)

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Ocean mass variation is one of the main drivers of present-day sea-level change (SLC). Also known as barystatic SLC, those fluctuations are due to the melting of continental ice from glaciers and ice sheets, and variations in landwater storage. While a large number of studies have quantified the contribution of barystatic SLC to global mean SLC, fewer works have looked into how much ocean mass has contributed to regional SLC. Besides, most of the regional studies have focused only on the effect of one of the components (e.g., melt from Antarctica), or on the period and results of the GRACE satellite mission (since 2002). This work aims at providing a comprehensive analysis of global and regional barystatic SLC since 1993. We collected a suite of estimates of the individual freshwater sources, namely the Antarctic and Greenland ice sheets, glaciers and terrestrial water storage. We then use them as input on the sea-level equation to obtain regional patters (fingerprints) of barystatic SLC, and validate our results by comparing the individual estimates with the values obtained from GRACE products. We finalize our analysis by looking into trend uncertainty patterns related to each contribution.

Groundwater Mass Removal During the 2012-2016 Drought, Inferred from 3D GPS Displacements Around Great Salt Lake, Utah

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Great Salt Lake (GSL), Utah, lost 1.89 meters of water during the 2012 to 2016 drought. During this timeframe, data from the GRACE mission did not detect an anomalous mass loss, but nearby Global Positioning System (GPS) stations showed significant shifts in position. We find that the observed GSL unloading alone cannot fit the GPS displacements, suggesting contributions from additional water storage loss surrounding GSL. This study applies a damped least squares inversion to the 3D GPS displacements to test a range of distributions of radial mass load rings to fit the observations. When considering the horizontal and vertical displacements simultaneously, the inversion provides the most realistic distributions and most consistently resolves the (un)loading on the lake. Our preferred model identifies comparable lake mass loss to the observed and infers radially decreasing mass loss up to 64 km from the lake. The contribution of exterior groundwater loss is substantial (10.92 km3 vs. 5.46 km3 on the lake itself), and greatly improves the fit to the observations. Nearby groundwater wells exhibit significant water loss during the drought, substantiating the presence of significant water loss within modeled region. We observe that seismicity within the study area is modulated within the inferred load region. Drier periods exhibit higher quantities of events than wetter periods and changes in trend of the earthquake rate are correlated with regional mass trends.

Groundwater storage determination with downscaled remote-sensing-based observations

M. Birylo (1), Z. Rzepecka (1), J. Sliwinska (2), J. Nastula (2)

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Groundwater is extremely important, it is essential for the overall water balance, it is of great economic significance and is one of the most important sources of drinking water worldwide. Such great significance of the groundwater causes the necessity of its continuous monitoring.

The aim of the paper is to present a methodology for elaboration an innovative high-resolution groundwater storage (GWS) variations model based on many sources of data: GRACE/GRACE-FO (Gravity Recovery and Climate Experiment/Gravity Recovery and Climate Experiment Follow On) products, groundwater wells data, DTM (Digital Terrain Model), soil types data, meteorological and hydrological data.

To elaborate high-resolution groundwater model, artificial neural networks (ANN) is used as an adequate level of accuracy is needed for understanding, observing, and analysing all phenomena occurring in the hydrosphere, especially when considering local groundwater changes. Low-resolution GRACE/GRACE-FO data are used together with higher resolution, but related to single locations, hydrological, meteorological, geodetic, and geological data in order to quantify GWS variations at the local scale.

Groundwater Drought Index assessment based on wells and remote sensing techniques over area of Poland

M. Birylo (1), Z. Rzepecka (1)

(1) University of Warmia and Mazury in Olsztyn

Recently, according to climate change, a very important thing is to monitor groundwater storage and changes constantly, as this is the source of drinking water. In the paper we propose to assess groundwater availability with Groundwater Drought Index (GDI), which is based on monthly climatology and let us focus on seasonality in regular groundwater records.

For the purpose of groundwater storage a remote sensing-based data was used – total water storage computed on a basis of Gravity Recovery and Climate Experiment (GRACE) mission, assisted by assimilation model Global Land Data Assimilation System (GLDAS). Final GRACE/GLDAS GDI was compared with GDI based on a well observations from the Polish National Geohydrological Service.

Based on a research we notice a strong seasonality of GDI in area of Vistula and Odra basins. Higher amplitudes of GDI were observed from 2011. In years 2007-2017 similar phase and amplitude is noticed in both GDI determination, only with small shift for both basins; from 2017 in the area of the Odra basin an opposite phase was observed.

Greenland meltwater effects in geodetic and oceanographic data

S. Stolzenberger (1), R. Rietbroek (2), C. Wekerle (3), B. Uebbing (1), J. Kusche (1)

(1) University of Bonn, (2) University of Twente, (3) Alfred Wegener Institute Bremerhaven

This contribution looks at Greenland meltwater signatures in the North Atlantic found in ocean model simulations and its visibility in ocean observations. Therefore we evaluate ocean simulations including and excluding Greenland freshwater. Variations of steric heights and sea level anomalies are estimated and compared to altimetric and gravimetric data. The most prominent benefits can be detected in the Baffin Bay, which is sensitive to Greenland freshwater due to the local currents. We will look at other regions around Greenland and discuss the model experiments with respect to the horizontal resolution.

Multiannual Ocean Mass Variability from GRACE/-FO

B. Gutknecht (1), A. Groh (1), M. Horwath (1)

(1) TU Dresden

The combined 18+ years long time series of observations of the Earth's gravity field from the satellite missions GRACE and GRACE-FO provides us with the opportunity to analyze mass change and re-distribution in the Earth system. As the mission continues, we may also gain more insight into those types of variability in the water mass system that act over time scales of several years and possibly even decades.

For our analysis presented here, we updated the previous Ocean Mass Change (OMC) product by the ESA CCI Sea Level Budget Closure project, including corrections for Glacial Isostatic Adjustment, restorement of background fields from the original processing, and replacement of dedicated low-degree coefficients in the spherical harmonic gravity field solutions. We applied least-squares minimization of the residual of a multi-parameter functional fit to the OMC series, including i.a. linear trend, semi-/annual signals, and an optional quadratic fit. We analyzed the complete residual series based on the four monthly GRACE and GRACE-FO RL06 solutions from CSR/GFZ/JPL and ITSG-Grace2018 after removal of linear trend and seasonal cycles.

The remaining signal shows clear evidence of interannual oscillations and correlates (>0.5) with the Multivariate ENSO index. By spectral analysis and by an independent simulated annealing approach, we locate several primary modes of the residual between 130 and 29 months. The phase of the lowest of these partial frequencies approximates that of solar flux data representing the solar cycle and the shortest major mode resembles the frequency of the Quasi Biennial Oscillation. However, minor phase-shifts and a direct physical link in this regard are not yet fully understood. Furthermore, the extrapolation of the fit including three prominent interannual modes between 29 and 130 months is able to predict recent La Niña related negative ocean mass anomalies and similar pre-GRACE events. Our findings might support and integrate in similar analyses of the global sea level and other ECVs elsewhere. However, we must emphasize that an analysis of near-decadal oscillations from a sub-20 year lasting data set is yet to become more stable with increasing observation length from GRACE-FO.

Tuesday morning: 8 a.m. CEST (UTC+2)	
Session 04: Cryosphere	
Convenors: Ingo Sasgen & Bert Wouters	

Can the Combination of Satellite Gravimetry and Altimetry Aid in the Regional Evaluation of Modeled Firn Change in Antarctica?

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(1) NASA's Jet Propulsion Laboratory, Pasadena, USA

The evolution of Antarctica's firn air content constitutes a key uncertainty in altimetry-based estimates of ice-sheet mass balance. Therefore, accurate model representation of firn change is integral for the quantification of observed ice-sheet mass change. Taking advantage of the Jet Propulsion Laboratory's 1-degree joint inversion product of Antarctic Ice Sheet mass balance, which is spatially informed by satellite altimetry patterns, we derive a remote-sensing-based firn air content (FAC) product and use it to evaluate model estimates of historic trends in firn evolution. Previous analysis revealed a good match between the products around most of East Antarctica, but indicated that the firn models estimated larger negative trends than the remote-sensing-based FAC product in the West Antarctic Ice Sheet. Here, we investigate sources of this disagreement in an effort to improve model estimates of FAC, characterize its uncertainties, and determine sources of discrepancy between gravimetric- and altimetric- based estimates of ice sheet mass balance.

This work is performed at the California Institute of Technology's Jet Propulsion Laboratory under a contract with the National Aeronautics and Space Administration's Cryosphere, Sea Level Change Team, and MAP Programs and the ICESat-2 and GRACE Science Teams.

Time dependent contributions to the mass balance of Antarctic drainage systems from satellite geodesy and model products

M. O. Willen (1), T. Broerse (2), A. Groh (1), B. Wouters (2), P. Kuipers Munneke (2), M. Horwath (1), M. R. van den Broeke (2), L. Schröder (3)

(1) TU Dresden, (2) Utrecht University, (3) Federal Agency for Cartography and Geodesy

We use satellite gravimetry (GRACE) and satellite altimetry observations to study time-dependent contributions from ice-dynamics and climatological forcing to mass changes of the Antarctic drainage basins. Products from regional climate modelling and firn modelling allow the separation of contributing signals to the mass balance. Linear trends over discrete time periods are a common method to investigate the mass balance of drainage systems. To overcome limitations of those deterministic approaches, we apply a coupled state space model to time series of Antarctic drainage systems from April 2002 to August 2016. We evaluate time series from GRACE, multi-mission altimetry, modelled surface mass balance (SMB), and modelled firn thickness change. The state space model enables the separation of long-term and short-term changes. We parametrize long-term variations by a trend with a time-variable rate which we assume is present in GRACE and altimetry observations. Further we allow for cyclic, auto-correlated, or uncorrelated residual short-term variations. Benefits of this approach are: (1) We can avoid restrictions due to predefined time-periods, (2) we do not enforce a single density to relate mass and volume changes, and (3) we allow for unmodeled SMB and firn thickness changes which are absorbed in the state space filtering framework. Our results confirm the accelerating ice-dynamic contribution in West Antarctica and low temporal variability of the long-term signal in East Antarctica.

Towards a temporal error covariance matrix for ice mass change products

A. Groh (1), M. Horwath (1), M. O. Willen (1), E. Buchta (1), T. Döhne (1), B. D. Gutknech (1) t, M. T. Kappelsberger (1)

(1) TU Dresden

Ice mass changes derived from satellite-observed time-variable gravity field solutions are important for studying the temporal evolution of the cryosphere under changing climatic conditions. These products can be used to evaluate alternative mass change products, e.g. from satellite altimetry, the input-output method or geophysical models on cryospheric processes. For these purposes comprehensive uncertainty measures, accounting for temporal error correlations, are crucial. However, available mass change products derived from GRACE/GRACE-

FO monthly solutions are mostly provided with monthly uncertainties accounting for the temporal uncorrelated noise only. In some instances an uncertainty measure for the linear trend, considering e.g. errors of the glacial isostatic adjustment (GIA) correction and leakage errors, is provided.

In this study we set up a full error covariance matrix for a GRACE/GRACE-FO-derived mass change time series for the Antarctic Ice Sheet, which accounts for a wide range of error types. In addition to the monthly uncorrelated noise, we consider uncertainties: (1) of the GIA correction, derived from a model ensemble, (2) of the added degree one time series, based on different realisations of a data combination approach, (3) related to the C20 replacement, using a set of SLR-based time series, (4) of the monthly gravity field solutions assessed by the spread between different solution series, and (5) caused by signal leakage, quantified by means of perennial model time series and independent observations addressing different compartments of the Earth system. Deviations within each data ensemble as well as the leakage time series are used to derive an individual error covariance matrix for each error component. In this step we distinguish between stationary and non-stationary constituents. For the stationary component, error correlations are derived by means of empirical auto-correlation functions. Uncertainties of the monthly solutions and their time derivatives, i.e. linear trends and accelerations, are inferred using the individual error covariance matrices as well as the combined matrix. If future mass change products are released in combination with a full error covariance matrix, users will be able to perform a rigorous error propagation for any period or mass change functional under investigation.

GPS estimates of GIA in East Antarctica considering the effects of recent ice mass balance fluctuations

M. King (1)

(1) University of Tasmania, Australia

GPS estimates of GIA-related deformation in Antarctica include contaminating signals due to recent ice mass changes, associated with surface mass balance and dynamic mass change. We explore the impacts of these signals on GPS bedrock time series and show that elastic displacements associated with surface mass balance variations show a strong power-law relation, with the largest power at the lowest frequency, mirroring the strong power-law relation of the underlying Antarctic surface mass balance. We also show that altimetry-derived loading displacements, which also include the impacts of ice dynamics, also show a strong power-law relation. We explore the impact of these corrections on GPS bedrock time series and velocities from a new network of GPS sites in East Antarctica, located along a 1000km transect of East Antarctica near the Denman and Totten Glaciers. We will show a comparison of the resulting velocities with a range of forward and inverse GIA models, within the context of robust measurement uncertainties, and provide recommendations on the optimal GIA models (if any) for this critical region of East Antarctica.

Assessing the accuracy of GIA models through a combination of GRACE, GPS, and satellite altimetry data

M. Razeghi (1), S.-C. Han (2), M. King, P. Tregoning (1)

(1) Australian National University, (2) University of Newcastle, Australia, (3) University of Tasmania, Australia

Glacial Isostatic Adjustment (GIA) refers to the gradual response of the solid Earth to the deglaciation of historic ice sheets. This ongoing rebound is contributing to the measurements of gravity change and land deformation, respectively, by Gravity Recovery And Climate Experiment (GRACE) and Global Positioning System (GPS). When these space geodetic data are used to quantify the present-day ice mass change, the effect such as GIA must be accounted for. In this study, we developed a method to estimate GIA and elastic deformation by the present-day ice mass change in the GPS time series with the example of Casey station in East Antarctica. We determined a high-resolution, present-day ice mass change model on the outlet of Totten Glacier and calculated the elastic rebound over the area. Our high-resolution model indicated a total mass loss of 15.7 ± 0.5 Gt/yr on the outlet of Totten Glacier from 2002 to 2017 with the accelerated loss in the last half of the period. We estimated the viscoelastic deformation attributed to GIA by removing the predicted elastic deformation from GPS measurements. Four different GPS position solutions for the Casey station, the continuously operating GPS station near the area, were examined. The estimated GIA signal appears to be within 0.3 – 1.3 mm/yr which shows its contribution on the vertical deformation between 30 – 60 % among different GPS solutions. On the other hand, the vertical elastic deformation trend is predicted to be 0.7 mm/yr from the ice mass change model. The GPS measured seasonal variation is explained equally by atmospheric-oceanic loading and degree-1 loading

with a couple mm amplitude in vertical time series. The elastic rebound from the present-day ice mass change also perturbed the horizontal displacement by 0.13 mm/yr in west and 0.21 mm/yr in north directions. This is in the opposite to the plate motion of the East Antarctica around the Casey station and amounts approximately up to 10 % of the measured tectonic motion.

Session 05: Poster breakout II
Tuesday morning

How well can VLBI probe long-wavelength climate-induced variations in Earth rotation?

S. Raut (1), K. Balidakis (1), S. Modiri (2), R. Heinkelmann (1), S. Belda (3), C. Kitpracha (1), H. Schuh(1)

(1) GFZ German Research Centre for Geosciences, Potsdam, (2) BKG Frankfurt, (3) IPL Valencia

Climate change as a potential enhancement of hazards globally, plays a significant role for world’s society.

The Earth’s axis of rotation varies on different time scales i.e., ranging from hours to decades, plus a long-term trend. These variations are mainly excited by many relevant internal geophysical processes such as changes in the fluid core, by atmospheric tides, hydrosphere, and ocean tides, and external processes such as libration effects. The internal and external processes affect Earth's rotational axis relative to its crust and have an impact on its rotational speed. As opposed to most external effects, the influence of the internal processes on the Earth rotation is not accurately known. The internal effects must be separated from the weather-induced variations. Making use of precise Earth Rotation Parameters, previously estimated from space geodetic VLBI observations from 1979 till now, this work focuses on how long-wavelength weather processes in space and time drive Earth rotation. We assess how long time series of polar motion and UT1-TAI, as well as the time derivatives thereof, correlate with climatic phenomena such as El-Nino, Madden-Julian Oscillation, North Atlantic Oscillation changes in the effective angular momentum such as Atmospheric Angular Momentum and Oceanic Angular Momentum. To study the relationship between Earth rotation and climatic phenomena, we applied the statistical tool method of ‘wavelet-based semblance analysis’. This investigation is a contribution to climate research by comparing on Earth rotation variations recovered by VLBI with climate indices obtained from numerical weather models.

PWV Distribution During of Severe Weather Events in Black Sea Region of Turkey Derived From GPS Measurements, ERA-Interim/ERA-5 and Radiosonde

E. Tanır Kayıkçı (1), M. Yalçınkaya (1), V. Tornatore (2), S. Zengin (1), S. C. Tuncer (3), M. Demircan (4)

(1) Karadeniz Techn. Univ., (2) Politecnico di Milano, (3) Hitit University, (4) Turkish State Meteorol. Service

In this study, we present the retrieval of PWV (precipitable water vapour) by GNSS observations to monitor severe weather events. In order to determine PWV distribution by GNSS meteorology, four new GNSS stations (SAME, SOMU, TRAB, MACK), established in cities of Samsun and Trabzon of Black Sea Region of Turkey within the TUBITAK research project 116Y186 have been used. Additionally, some GNSS stations from existing 15 CORS-TR network belonging to Turkish continuously operating network and IGS/EPN network have been added. All calculations to get ZTD (Zenith Total Delay) were carried out with Bernese GNSS Software version 5.2. The four GNSS stations in Samsun and Trabzon are not equipped with meteorological sensors. To overcome this limitation, we interpolated surface pressure and temperature from all available meteorological stations located in the area of the study. Alternatively, The GPT3 empirical and ECMWF numerical weather model were used to provide meteorological parameters at those stations. For the conversion from GNSS ZTD to PWV, we used surface pressure and temperature derived by those three methods. PWV estimations from GNSS meteorology, radiosonde and ERA-Interim heve been evaluated during severe events, in May and June 2019, happened in the region.

Utilizing the Full Potentials of GNSS Interferometric Reflectometry for Quantifying Permafrost Changes in a Warming Climate

L. Liu (1), J. Zhang (1)

(1) Chinese Univ. of Hong Kong

In this study, we present the retrieval of PWV (precipitable water vapour) by GNSS observations to monitor severe weather events. In order to determine PWV distribution by GNSS meteorology, four new GNSS stations (SAME, SOMU, TRAB, MACK), established in cities of Samsun and Trabzon of Black Sea Region of Turkey within the TUBITAK research project 116Y186 have been used. Additionally, some GNSS stations from existing 15 CORS-TR network belonging to Turkish continuously operating network and IGS/EPN network have been added. All calculations to get ZTD (Zenith Total Delay) were carried out with Bernese GNSS Software version 5.2. The four GNSS stations in Samsun and Trabzon are not equipped with meteorological sensors. To overcome this limitation, we interpolated surface pressure and temperature from all available meteorological stations located in the area of the study. Alternatively, The GPT3 empirical and ECMWF numerical weather model were used to provide meteorological parameters at those stations. For the conversion from GNSS ZTD to PWV, we used surface pressure and temperature derived by those three methods. PWV estimations from GNSS meteorology, radiosonde and ERA-Interim have been evaluated during severe events, in May and June 2019, happened in the region.

Inter-comparison of time-variable gravity field releases for the application in ice sheet studies

A. Groh (1), U. Meyer (2), M. Lasser (2), C. Dahle (3), A. Kvas (4), J.-M. Lemoine (4) , A. Jäggi (2), F. Flechtner (3), T. Mayer-Gürr (3)

(1) TU Dresden, (2) University of Bern, (3) GFZ German Research Centre for Geosciences, (3) Graz University of Technology, (4) Centre National d'Etudes Spatiales, France

In this study we inter-compare different GRACE/GRACE-FO time-variable gravity field solutions and assess their suitability for studying mass changes of the ice sheets. We consider the releases AIUB RL02, GFZ RL06, ITSG-Grace2018, CSR RL06, JPL RL06 and an unconstrained variant of GRGS RL05. In addition, we also include the first monthly gravity field solution series released by COST-G, the International Combination Service for Time-variable Gravity Fields. This IAG product center provides a consolidated gravity field series derived from individual releases contributed by the aforementioned analysis centers (AC).

We quantify the noise level of the GRACE/GRACE-FO solutions series provided by COST-G and the contributing ACs. This assessment is based on residual variations of the spherical harmonic (SH) coefficients with respect to a long-term and seasonal model and is performed both in the SH domain and in the space domain, with focus on the polar regions. A regional integration approach using tailored sensitivity kernels is applied to derive mass change time series for individual drainage basins and the entire ice sheets in Greenland (GIS) and Antarctica (AIS). We quantify and compare both the noise level and the signal content, e.g. the mass balance, of the different mass change time series. In so doing, we are able to assess if and to which extent mass change products for GIS and AIS can benefit from the combination of different solution series. We also make use of external data products on ice sheet mass changes and assess their level of agreement with the gravimetric products. This includes mass change time series from satellite altimetry, the input-output method and time series of cumulated surface mass balance anomalies provided by a regional climate model. The comparison to the latter provides insights on the level of agreement between observed and modeled ice sheet changes on seasonal and inter-annual time scales.

A state-space representation of the water storage dynamics at basin scale to do hydrology backward

K. Douch (1), P. Saemian (1), N. Sneeuw (1)

(1) University of Stuttgart

A physically based modelling of surface and subsurface flow at a catchment scale can quickly become intractable as the physical processes involved are spatially heterogeneous and can be extremely complex. However, the sum of all these different processes can lead in some cases to an apparent simpler behaviour at a global scale. In this work we put forward lumped state-space representations as an effective way to model the dynamics of storage and discharge averaged over a whole basin for such cases. To illustrate this method, we use the Amazon basin and sub-basin as a case study. This basin has the particularity to exhibit a relatively simple dynamics which can be well approximated by a first order differential equation coupling discharge and storage. Combined with the equation of mass conservation, we obtain a physically consistent, linear state-space representation of the basin global dynamics, which can be calibrated against TWSC (Terrestrial Water Storage Change) derived from GRACE data and the runoff measured at the outlet of the basin of interest. A first direct consequence of this modelling is the possibility to estimate the total amount of drainable water stored across the basin.

In addition, such a simple representation allows to benefit from the wealth of tools and concepts developed in the field of control theory to characterize linear dynamical system. In particular, we discuss the conditions under which the system is observable, that is, TWSC can be reconstructed from discharge records and vis-versa. More challenging is the possibility to do backward hydrology, that is, estimating simultaneously the TWSC and the unknown input precipitation minus evapotranspiration from discharge records. This can be critical when some observed quantities are no more available or temporally not reliable.

Remote sensing-based determination of the Water Storage Deficit Index under different land cover types

B. Kalisz (1), M. Birylo (1)

(1) University of Warmia and Mazury in Olsztyn, Poland

Due to climate change, research and monitoring of its state become extremely important. Of particular importance is the ability to store water in the ground. The problem of drought was discussed by the Commission on Sustainable Development in several sessions and one of the SDGs is to fight it through sustainable land use. Drought conditions during most of the growing season can have a profound impact on soil heath, just as extreme wet conditions. In the paper we propose to assess climatic changes, which can profoundly affect agricultural land, under different land cover types on the example of the Polish area with index based on geodetic remote sensing-based observation from the Gravity Recovery and Climate Experiment (GRACE) mission. In the paper Water Storage Deficit Index (WSDI) is determined. For the purpose of computing the index, total water storage anomaly is calculated using JPL spherical harmonics product RL06.

Poland, a country in the middle Europe, has the area of 312 679 km2. Approximately 31% of land is under forests, 61% of the land is under agricultural use, including grasslands and plough lands. Within agricultural land, plough lands constitute approx. 73% and grasslands 20%. In the paper we categorized the land depending on a level of dryness and wetness basing on the obtained results and presented a forecast of changes based on modelling. In order to moderate future drought events, it’s essential to know the climatic changes in the past and expected changes in the future.

Keywords: WSDI, land cover, GRACE, total water storage, drought, agriculture

Remote sensing based drought severity assessment for small area case study

M. Birylo (1), Z. Rzepecka (1)

(1) University of Warmia and Mazury in Olsztyn, Poland

Recently, according to climate change, a very important thing is to monitor climate state, especially taking into account hydrological events, like drought. In the paper we propose to assess climatic changes with indices based on geodetic remote sensing-based observations: Gravity Recovery and Climate Experiment (GRACE) mission, assisted by assimilation model Global Land Data Assimilation System (GLDAS).

In the paper three indices are presented: Water Storage Deficit Index (WSDI), Combined Climatologic Deviation Index (CCDI) and Multivariate Standardized Drought Index (MSDI). For the purpose of computing indices we used total water storage anomaly from GRACE, and soil moisture and precipitation from GLDAS. Final results were categorized depending on a level of dryness and wetness.

Based on the research, it was concluded that in polish basins, Vistula and Odra a strong seasonality is noticeable with most months of dry category.

Multi-mission Satellite Remote Sensing Data for Improving Land Hydrological Models via Data Assimilation

M. Khaki (1), H.-J. Hendricks Franssen (2), S.-C. Han (1)

(1) University of Newcastle, Australia, (2) Forschungszentrum Jülich, Germany

Satellite remote sensing offers valuable tools to study Earth and hydrological processes and improve land surface models. This is essential to improve the quality of model predictions, which are affected by various factors such as erroneous input data, the uncertainty of model forcings, and parameter uncertainties. Abundant datasets from multi-mission satellite remote sensing during recent years have provided an opportunity to improve not only the model estimates but also model parameters through a parameter estimation process. This study utilises multiple datasets from satellite remote sensing including soil moisture from Soil Moisture and Ocean Salinity Mission (SMOS) and Advanced Microwave Scanning Radiometer Earth Observing System (AMSR-E), terrestrial water storage (TWS) from the Gravity Recovery And Climate Experiment (GRACE), and leaf area index (LAI) from Advanced Very-High-Resolution Radiometer (AVHRR) to estimate model parameters. This is done using the recently proposed assimilation method, unsupervised weak constrained ensemble Kalman filter (UWCEnKF). UWCEnKF applies a dual scheme to separately update the state and parameters using two interactive EnKF filters followed by a water balance constraint enforcement. The performance of multivariate data assimilation is evaluated against various independent data over different time periods over two different basins including the Murray-Darling and Mississippi basins. Results indicate that simultaneous assimilation of multiple satellite products combined with parameter estimation improves model estimates during the calibration and forecast periods compared with single satellite products and/or state estimation alone.

Extreme Weather Signatures in Indonesia from GRACE and GRACE-FO satellites data

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(1) Institut Teknologi Sepuluh Nopember

This study uses a complete eighteen-year period (August 2002 to August 2020) of the Earth's gravity field monthly solutions from the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow On satellite missions. The GRACE-derived equivalent water height (EWH) values are analyzed over the Indonesian region in terms of the secular trend and RMS-variability to reveal specific study areas for the statistically-based Principal Component Analysis (PCA). The PCA is applied over these selected areas to reveal the most dominant spatial and temporal variations of the GRACE gravity signal. The results show prevailing trends over areas that suffered from floods and droughts. In a second analysis, the annual signal and trend are removed from the original data, and the PCA is re-applied to the reduced data. Results show that the PCA can reveal longer periodic and aperiodic signals that are presumably associated with climate change.

Constraining the contributions of ice sheets to sea-level rise in a global inversion framework

M. O. Willen (1), B. Uebbing (2), M. Horwath (1), J. Kusche (2)

(1) TU Dresden, (2) University of Bonn

About 50 % of global mean sea level rise (GMSLR) is caused by changes in global-mean ocean mass which are hydrological variations and melting of land glaciers as well as melting of the major ice sheets in Greenland and Antarctica. Those mass changes are detected by the Gravity Recovery and Climate Experiment (GRACE) mission and its follow-on mission (GRACE-FO). Over ice sheets melting and accumulation of snow and ice leads to geometric surface changes which are observed by high-inclination altimetry missions. Further the solid-earth deformation due to glacial isostatic adjustment (GIA) is of special interest in polar regions, because the signal superimposes ice mass changes.

By combining GRACE and ocean-altimetry data the global fingerprint inversion (Rietbroek et al., 2016) estimates individual mass and steric contributors to the sea-level budget in a joint approach. Here, we present benefits from additionally integrating ice-altimetry data (from ERS-2, Envisat, ICESat, CryoSat-2 missions) to constrain the ice-sheet contributions to GMSLR.

Generally, the inversion accounts for GIA as an a-priori correction from GIA forward modelling. In particular in Antarctica, forward models predict GIA differently. Moreover, the signals due to GIA and ice mass change are in

a similar order of magnitude. We demonstrate the potential to parametrize and estimate GIA and ice mass change within a global framework by synthetic experiments. Further we investigate the observational covariance information to account for correlated errors.

Integrated water vapour monitoring from ground-based GNSS observations in the south-central Andes

N. Antonoglou (1), K. Balidakis (2), B. Bookhagen (1), G. Dick (2), F. Zus (2), J. Wickert (2), A. de la Torre

(1) University of Potsdam, Germany (2) GFZ Potsdam, Germany (3) Universidad Austral, Argentina

The Central Andes are characterized by a steep climatic and environmental gradient with large spatial and temporal variations of associated hydrological parameters. There are two main atmospheric processes that influence climate conditions in our study area in the northwestern Argentina: the South American Monsoon System that transports moisture via the low-level jet and the orographic barrier of the Eastern Cordillera that forces focused rainfall at the windward facing slopes.

As part of the International Research Training Group-StRATEGy project, our research aims at monitoring integrated water vapour (IWV) in the south-central Andes, in order to track moisture propagation. In accordance with the needs of the research, we processed data from two new Global Navigation Satellite System (GNSS) ground stations that were installed in spring 2019 along with - already calculated - solutions that were derived from an existing network. We used 10 year-long time-series from 31 stations spanning an altitude range from from 198 to 5141m asl and stretching from the mountain front to the interior of the mountain range. This enhanced network helped us to examine spatial correlations, as well as differences in behaviour of the IWV across the climatic gradient. Moreover we retrieved the gradients of the IWV at single positions, in order to study seasonal correlations between wind and gradient direction.

Effect of solar cells degradation on Geostationary satellite power subsystem

S. Oukil (1), W. Belgacem (1)

(1) Algerian Space Agency-Satellite development center

One of the important requirements in each space mission is designing a system for providing uninterruptible energy with desired quality and quantity. The design of the satellite power subsystem should satisfy its required electrical power during the mission.

In order to obtain this electrical power, the required satellite structure area for installation of solar panels was calculated. Also in the design of each solar panel, the number of strings, series cells in each string and the size of cells must be defined. The main objective of this study is to minimize the power of the satellite subsystem, which subject to the space environment and under the impact of various environmental factors on a photovoltaic system's performance taking into account the solstice and equinox periods during temperature.

From the results obtained in this paper, the total power of the system was decreased by 8.20 % of the total power. The degradation and output power characteristics of the solar panels were calculated for different temperature values.

The results have shown that the power prediction of the designed solar array for the mentioned satellite completely satisfies its mission requirements.

Tuesday afternoon: 5 p.m. CEST (UTC+2)
Session 06: Atmosphere
Convenors: Rosa Pacione & Jolanta Nastula

Keynot lecture: Ground-based GNSS for climate research: review and perspectives

R. Pacione (1) M. Santos (2), G. Dick (3), J. Jones (4), E. Pottiaux (5), A. Rinke (6), R. Van Malderen (7), G. Elgered (8)

(1) e-GEOS/ASI-CGS, (2) University of New Brunswick Fredericton, (3) GFZ Potsdam, (4) U.K. Met Office, (5) Royal Observatory of Belgium, (6) Alfred Wegener Institute, (7) Royal Meteorological Institute of Belgium, (8) Chalmers University of Technology

In climate research, the role of water vapour can hardly be overestimated. Water vapour is the most important natural greenhouse gas and is responsible for the largest known feedback mechanism for amplifying climate change. It also strongly influences atmospheric dynamics and the hydrologic cycle through surface evaporation, latent heat transport and diabatic heating, and is, in particular, a source of clouds and precipitation.

Atmospheric water vapour is highly variable, both in space and in time. Therefore, measuring it remains a demanding and challenging task. The Zenith Total Delay (ZTD) estimated from GNSS observations, provided at high a temporal resolution of minutes and under all weather conditions, can be converted to Integrated Water Vapour (IWV), if additional meteorological variables are available. Inconsistencies introduced into long-term time series from improved GNSS processing algorithms, instrumental, and environmental changes at GNSS stations make climate trend analysis analyses challenging. Ongoing re-processing efforts using state-of-the-art models aim at providing consistent time series of tropospheric data, using 24+ years of GNSS observations from global and regional networks. GNSS is reaching the "maturity age" of 30 years when climate normal of ZTD/IWV (and horizontal gradients) can be derived. Being not assimilated in numerical weather prediction model reanalyses, GNSS products can also be used as independent datasets to validate climate model outputs (ZTD/IWV). However, what is the actual use of GNSS ZTDs in climate monitoring? What are the advantages of using GNSS ZTDs for climate monitoring? In addition, what would be the best ZTD time series to serve the climate community? The presentation will provide a review of the progress made in and the status of using GNSS tropospheric datasets for climate research, highlighting the challenges and pitfalls, and outlining the major remaining steps ahead. We will show examples demonstrating the

Long-Range Predictability of the Length of Day and Extratropical Climate

A. Scaife (1), L. Hermanson (1), A. van Niekerk (1), M. Baldwin (2), S. Belcher (1), P. Bett (1), R. Comer (1), N. Dunstone (1), R. Geen (2), S. Hardiman (1), S. Ineson (1), J. Knight (1), Y. Nie (3), H. Ren (3), D. Smith (1)

(1) U.K. Met Office, (2) University of Exeter, UK, (3) Chinese Meteorological Administration (3)

Angular momentum is fundamental to the structure and variability of the atmosphere and hence regional weather and climate. Total atmospheric angular momentum (AAM) is also directly related to the rotation rate of the Earth and hence the length of day. However, the long-range predictability of fluctuations in the length of day, atmospheric angular momentum and the implications for climate prediction are unknown. Here we show that fluctuations in AAM and the length of day are predictable out to more than a year ahead and that this provides an atmospheric source of long-range predictability of surface climate. Using ensemble forecasts from a dynamical climate model we demonstrate predictable signals in the atmospheric angular momentum field that propagate slowly and coherently polewards into the northern and southern hemisphere due to wave-mean flow interaction within the atmosphere. These predictable signals are also shown to precede changes in extratropical surface climate via the North Atlantic Oscillation. These results provide a novel source of long-range predictability of climate from within the atmosphere, greatly extend the lead time for length of day predictions and link geodesy with climate variability.

GNSS-based Precipitable Water Vapor: Certification for the Global Climate Observing System

G. Dick (1), J. Jones (2), J. Wang (3), K. Rannat (4), J. Wickert (1), F. Zus (1), K. Balidakis (1), K. Wilgan (1)

(1) GFZ Potsdam, (2) U.K. Met Office, (3) University at Albany, (4) Tallinn University of Technology

For almost three decades, Global Navigation Satellite Systems (GNSS) signal delays have been exploited to provide accurate estimates of atmospheric Precipitable Water Vapor (PWV), known to be the most abundant greenhouse gas which plays a key role in the Earth climate. Due to the inherent high accuracy and long-term stability, GNSS-derived PWV was identified as a key measurement for the Global Climate Observing System Reference Upper Air Network (GRUAN), an international climate reference observing network. GRUAN is designed to provide data records for the reliable determination of climatological trends, to fill the gaps in existing global observing systems and to provide further insight into atmospheric processes. GRUAN observations are required to be of reference quality, with known biases removed and with an associated uncertainty value, based on thorough characterization of all sources of measurement.

GRUAN currently comprises 30 globally distributed observing sites. The final network is envisaged to consist of around 40 stations. GFZ contributes to GRUAN by running the GNSS Data Central Processing Centre for PWV products according to defined requirements and maintains a number of GNSS sites. Currently half of the GRUAN sites are equipped with GNSS receivers. At the beginning of this year the data processing of GNSS-PWV and its associated documentation has been GRUAN certified.

We overview GRUAN and its GNSS component, including the current status and future developments. GNSS-PWV products including uncertainty estimation and results of selected validation studies are presented.

Tracking inhomogeneities in long reprocessed GNSS data sets for climate monitoring

O. Bock (1), N. Khanh Nguyen, E. Lebarbier

(1) Université de Paris

Long time series of Integrated Water Vapour (IWV) contents estimated from GNSS measurements are useful to document global and regional climate trends and variability. However, the GNSS data are impacted by several sources of inhomogeneities: equipment changes, changes in the environment around the antenna, processing changes, and uncertainties in the ZTD to IWV conversion method. Although the magnitudes of the changes are most of the time small, they are nevertheless comparable in size to the trend and variability estimates that are sought for. The detection and correction of these inhomogeneities is a difficult and tedious task which motivated for the development of new segmentation and homogenization techniques based on statistical concepts. However, the importance of proper and homogeneous GNSS data processing should not be overlooked.

In this paper we compare two long reprocessed GNSS ZTD/IWV data sets: the IGS repro1 processed by JPL using GIPSY OASIS II software and the CODE REPRO2015 processed by AIUB using Bernese GNSS software v5.3. The different processing approaches (PPP for JPL and DD for AUIB), processing options (e.g. tropospheric models), and satellite products (clocks, orbits, EOPs) result in small differences in ZTD and station position estimates although the raw GNSS measurements are the same. We evidence a number of sites and periods where the two GNSS solutions are offset by a significant amount that is detrimental to trend analysis. In some cases, it seems that not exactly the same metadata were used by both analysis centres (e.g. antenna models). Small differences in the noise in the time series is also shown to have a strong impact on the segmentation results.

How accurately we can probe climate change with VLBI, GNSS, and ERA5?

F. Bamahry (1), K. Balidakis (2), R. Heinkelmann (2), H. Schuh (1)

(1) TU Berlin, (2) GFZ Potsdam

Integrated water vapor (hereinafter IWV) monitoring from microwave-based space geodetic techniques has been performed for over four decades. Since IWV is one of the most efficient greenhouse gases and its variations are associated with temperature changes, analyzing long-wavelength IWV variations provides insight into climate change. However, in the absence of a reference, one may ponder over the accuracy and reliability of the trends estimated from the analysis of space geodetic observations. To address that question, we have assessed long-term IWV trends estimated from Very Long Baseline Interferometry (VLBI) by varying the estimator, the data span, and the logging interval. Our investigations indicate that there is no difference (for statistical significance level $(p) < 0.05$) between estimation using weighted least-squares and Median Interannual Difference Adjusted for Skewness (MIDAS), provided seasonal variations have been factored in. Accounting for the correlation between neighbouring data points in the time domain affects the uncertainty estimation significantly, especially at high sampling rates, that is, daily or higher. Without the auto-correlation taken into account, the uncertainty is erroneously deflated several times (10 -12 times), what renders the uncertainty unrealistic and distorts the interpretation of the trends. We also found that long-term trends estimated employing the IWV series averaged in monthly bins are not significantly different from the hourly data, provided the auto-correlation is considered. Moreover, an inter-technique comparison between IWV trends from VLBI, Global Navigation Satellite Systems (GNSS), and numerical weather model (ERA5 reanalysis) has been performed as a function of data span, in an effort to validate the IWV trend accuracy. We demonstrate that the agreement between IWV trends from different techniques varies as a function of the data span, that has to be long enough to draw realistic conclusions.

Tropospheric Products validation in the GNSS SIRGAS Network

M.V. Mackern (1), M. L. Mateo (1), M. F. Camisay (1), P.A. Rosell (1)

(1) Univ. Maza, Argentina

Within the weekly processing of the SIRGAS Continuously Operating Network (SIRGAS-CON), latinamerican Analysis Centres operationally estimate tropospheric Zenith Total Delays (ZTD) with an hourly sampling rate. These ZTD are the input data for the weekly SIRGAS combined tropospheric products, computed by the Analysis Centre for the Neutral Atmosphere (CIMA). They are generated and available in daily SINEX TRO files since January 2014, with a latency of 30 days.

This contribution presents the latest advances made in the validation of the estimated tropospheric parameters in GNSS stations distributed in the different regions of Latin America. Our results show that the ZTDs estimated at the SIRGAS-CON stations are consistent throughout the region and provide reliable time series of troposphere parameters, which can be used as a reference in future research.

The study covers the ZTD and IWV series over a period of 7 years (2014-2020), in GNSS estations distributed from south america, central america and the caribian region.

The results are validated using IGS ZTD products at 62 stations and data from 42 radiosondes. Agreement was evaluated in terms of mean bias and rms of the ZTD differences with respect to IGS products (mean bias of -0.75 mm and mean rms of 6.56 mm) and IWV differences with respect to the radiosonde IWV data (mean bias -1.08 kg / m2, mean rms 4.92 kg / m2 and mean standard deviation 2.22 kg / m2).

Wednesday morning: 8 a.m. CEST (UTC+2)
Session 07: Sea level
Convenors: Roelof Rietbroek & Riccardo Riva

Keynote lecture: A tango between ice and sea level

R. Rietbroek (1), T. Frederickse (2), I. Sasgen (3)

(1) University Twente, (2) JPL Pasadena, (3) AWI Bremerhaven

Introductory lecture on sea level and cryosphere.

Observational constraint on the equilibrium climate sensitivity from space geodesy measurement of the ocean thermal expansion

J. Chenal (1), B. Meyssignac (1), A. Blazque (1)

(1) LEGOS (CNES)

Energy budget estimates of the effective climate sensitivity (EffCS) are derived based on estimates of the historical forcing and of observations of the surface temperature variations and the ocean heat uptake. Recent revisions to surface temperature estimates and to greenhouse gas forcing and aerosol forcing estimates are included and the data is extended to 2018. The ocean heat uptake is derived over 2002-2018 from a combination of satellite radar altimetry data and GRACE-GRACE-FO gravimetry data. The ocean heat uptake, the change in temperature and the change in radiative forcing are estimated with respect to the base period 1869-1882 (following Lewis and Curry 2018). When accounting for the uncertainty in the forcing, the surface temperature and the ocean heat uptake estimates plus the uncertainty due to the internal variability we find a range of EffCS of [0.9;8.3] (at the 95%CL) with a median of 1.8 K. This is more stringent a constraint than if we use an ocean heat uptake derived from ocean in situ temperature data (the in situ approach leads to an EffCS of [1.0;9.7] with a median 2.0 K).

This EffCS that is estimated over the historical period is representative of the climate feedback experienced by the climate during the historical period. To derive a constraint on the equilibrium climate sensitivity we need to account for the pattern effect and the temperature dependence of the feedback. To do so we use climate model simulations of the 21st century to derive new estimates of the EffECS that should now encompass the equilibrium climate sensitivity (assuming that climate model simulate properly the pattern effect and the temperature dependence of feedback). We find that adding the pattern effect and the temperature dependence of the feedbacks shifts upwards the median of the EffECS and increases significantly the uncertainty range. For the space based estimate the median is now 2.1 K and the uncertainty range [1.0;12.0] while for the in situ estimate the median is 2.5 K and the uncertainty is [1.1;17.2].The space based approach performs better than the in situ approach essentially because it covers a longer period.

For the time being the observational constraint from space geodesy is not tight enough to improve the estimates of the climate sensitivity. But in the near future we will extend this method to the whole altimetry period (1993-2018). It may improve drastically the results.

Observing sea level and climate change at the coast and the polar latitudes with reprocessed satellite altimetry: a review

M. Passaro (1)

(1) TU Munich

Being Geodesy the science of the Earth's shape and size, satellite altimetry is the perfect example of a practical application of this discipline, in its effort to study the shape of the oceans in terms of sea level. In order to observe climate-related variability in sea level, it is essential to consider long time series. Satellite altimetry provides almost three decades of continuous global observations of sea level, but the quality of the data was problematic in areas of key importance, such as the polar latitudes and the coastal zone.

This talk is a partial review of the progresses driven by the use of improved signal processing techniques to enhance quality and quantity of sea level retrievals in the coastal zone and at the polar latitudes. The objective is to review the science applications based on the adoption of the ALES-suit of algorithms, which is used in combination with other techniques in the context of several international studies, including the European Space Agency's Sea Level Climate Change Initiative, Sea State Climate Change Initiative and Baltic+ SEAL.

To improve our understanding and prepare to rising sea levels in the wider context of climate change is fundamental to take a regional and local perspective of sea level variability. This will be highlighted through examples of key findings. In the Arctic Ocean, the availability of reprocessed altimetry allowed the observations of the sea level drop along the Greenland coast, linked to the missing gravity pull from the melting glaciers. In the coastal zone, we are now able to observe trends up the last 0 to 5 km from the coastline. In the vast majority of the studied cases, coastal trends do not differ from neighboring offshore observations, with important implications for coastal planners. Increasingly, we are able to evaluate sea level variability at a sub-regional scale in connection with large-scale atmospheric variability, as in the Baltic Sea, where gradients in sea level variability between the extremes of the basins are related to shifts of wind regimes in winter.

In perspective, the importance the observations of coastal wave height will be considered. This is particularly significant in the case of extreme events such as storm surges. The recent and future efforts aim therefore at a full picture of the total water level reaching the coasts, where infrastructures, important ecosystems and the largest amount of the human population is located.

Coastal sea level from SAR altimetry, tide gauges and GPS

L. Fenoglio (1), S. Dinardo (2), S. Bruni (3), F. Raicich (4), S. Zerbini (3), B. Uebbing (1)

(1) University of Bonn, (2) CLS France, (3) University of Bologna, (4) Istituto di Scienze Marine, CNR, Trieste

Sea level change is one of the essential indicators of global warming. Satellite radar altimetry and tide gauges corrected for the vertical land motion measured by GPS give the absolute sea-level referred to the Earth's center of mass. The sea level trend of co-located altimetric and tide gauge@GPS time-series reflect the differences of sea level change at the two locations and the noise in the measurements, assuming the VLM as known.

The hypothesis is that the coastal variability is better observed with SAR altimetry than with classical altimetry. The choice of the processing SAR scheme could also be relevant. We investigate SAR CryoSat-2 products of the ESA G-POD altimetry service over the mission period 2010-2020.

The study focuses along the Mediterranean, North Sea and Baltic Sea coasts, where conventional altimetry shows a sea level rise between 2 and 4 mm/year and differences within ±1 mm/year between the various estimations of VLM trends from GNSS and altimeter minus tide gauge, 48 stations are considered in the Mediterranean Sea and 11 stations in the North Sea and Baltic region.

Constraint of GIA in Northern Europe and the North Sea with Geological RSL and GPS Data

K. Simon (NIOZ), R.E.M. Riva (2), L.L.A. Vermeersen (2)

(1) NIOZ Royal Netherlands Institute for Sea Research, (2) Delft University of Technology

This study focusses on improved constraint of the millennial time-scale glacial isostatic adjustment (GIA) signal at present-day, and its role as a contributor to present-day sea-level budgets. The study area extends from the coastal regions of northern Europe to Scandinavia. Both Holocene relative sea level (RSL) data as well as vertical land motion (VLM) data are incorporated as constraints in a semi-empirical GIA model. Specifically, 71 geological rates of GIA-driven RSL change are inferred from Holocene proxy data. Rates of vertical land motion from GNSS at 108 sites provide an additional measure of regional GIA deformation; within the study area, the geological RSL data complement the spatial gaps of the VLM data and vice versa. Both datasets are inverted in a semi-empirical GIA model to yield updated estimates of regional present-day GIA deformations. A regional validation is presented for the North Sea, where the GIA signal may be complicated by lateral variations in Earth structure and existing predictions of regional and global GIA models show discrepancies. The model validation in the North Sea region suggests that geological data are needed to fit independent estimates of GIA-related RSL change inferred from tide gauge rates, indicating that geological rates from Holocene data can provide an important additional constraint for data-driven approaches to GIA estimation. The geological proxy rates therefore provide a unique dataset with which to complement or validate existing data-driven approaches that use satellite era rates of change.

Instantaneous Sea-Level Prediction with Machine Learning Methods in Aegean Sea

A. Yavuzdoğan (1), T. Kayıkçı Emine (2)

(1) Gümüşhane University, Turkey (2) Karadeniz Technical University, Turkey

Forecasting instantaneous sea-level is of great importance in terms of determination of geodetic vertical datum, conservation of coastal areas, monitoring coastal ecosystems, maintenance, and planning of coastal structures, monitoring of climate change effects. Also, they have a very complex dependency structure, as the contributors to sea levels are very diverse and their effects vary from region to region. These conditions make it very difficult to predict instantaneous sea levels with high accuracy. Recently, machine learning prediction methods have been frequently used in the modeling of complex dependency structures between variables. Within the scope of this study, to predict the instantaneous sea level with high accuracy and to compare linear estimation methods and nonlinear estimation methods, the Multiple Linear Regression linear model, Support Vector Regression non-linear model, and Random Forest Regression non-linear model algorithms were used, and their prediction performances were compared. Instantaneous sea level data were obtained from the two tide gauge stations operated by the Turkey General Directorate of Mapping. As a result of the study, the highest prediction performance for instantaneous sea level was obtained with random forest regression, and the lowest prediction performance was obtained with the multiple linear regression method. Also, it has been shown that instantaneous sea level can be predicted with high precision using random forest regression with the features used in this study, and the linear prediction models are insufficient in modeling the complex dependency structure of instantaneous sea level.

Bulgarian geodetic contribution to the multidisciplinary research on Livingston Island for the period 1998 - 2020

B. Alexandrov (1), L. Pashova (1),

(1) University of Architecture Civil Engineering and Geodesy

(2) Bulgarian Academy of Sciences

The acquisition of accurate geodetic data is vital to supporting almost all aspects of Livingston Island multidisciplinary research. The first Bulgarian Antarctic expedition has taken place in the summer of 1987/88, organized on the occasion of the centenary of Sofia University. The interdisciplinary research started in 1996 in the Bulgarian base "St. Kliment Ohridski" and 28 expeditions have been realized since then. This report presents the main geodetic activities carried out by Bulgarian surveyors over the past three decades. The surveys such as classical geodetic measurements, GNSS observations and mapping of the island's topography and the seabed are considered, and the main achievements are summarized. Special attention is paid to the 28th National Antarctic

Expedition conducted in 2019-2020. Within this expedition, marine geodetic activities were carried out, and the foundations of a new research laboratory were laid. Preliminary analyses of the tide gauge data, the GNSS observations from the installed site, the conductivity, salinity, and ocean water temperature around the coast and in-depth are presented. An overview of the last 29th Bulgarian Antarctic expedition's research activities in 2020/2021 is also outlined. A database which will comprise the data and information collected during the all Bulgarian expeditions is now under construction. The planned research projects that will be implemented in the future under the Bulgarian Antarctic Institute program are briefly introduced.

Wednesday afternoon : 5 p.m. CEST (UTC+2)
Session 08: Hydrology II
Convenors: Mehdi Khaki & Balaji Devaraju

Utilising geodetic estimation of crustal response to changes in hydrological loading as a tool to measure climate change: opportunities and challenges

M. Vijayan (1), A. Vincent (1), K. Rajendran (1)

(1) CSIR Fourth Paradigm Institute (CSIR-4PI), Bangalore, India

The advent of modern satellite geodesy, particularly Global Navigation Satellite Systems (GNSS) and Gravity Recovery And Climate Experiment (GRACE) satellite mission, provided estimates of 4D deformation of the crust induced by the hydrological loading. Recent studies show that elastic response of the crust to hydrological loading (hydrological deformation) modelled using GRACE observations are matching well with hydrological deformation of the crust estimated from GNSS observations at major river basins. Recent studies show that inversion of hydrological deformation estimated using GNSS at snow covered areas of western United States matches reasonably well with in-situ snow observations and can be useful to fill the observational gap between GRACE and GRACE-FO missions. We also found that the GRACE and GNSS data analysis carried out over the central Himalayas also show distinct signatures of snow and water induced crustal deformation, particularly in the vertical component. These results provide promising direction to use GRACE and ground based GNSS together as a tool, in near future, to measure snow accumulation as well as melting, particularly at remote areas like the Himalayas. However, horizontal components of hydrological deformation modelled using GRACE observations and GNSS estimations do not match well. Another bottleneck towards using the geodetic observations to study climate change is removal of non-tidal atmospheric loading components from the total seasonal deformation obtained using GRACE and GNSS. The non-tidal atmospheric loading over the complex terrains, particularly over the Himalayas, are poorly constrained, which, eventually, leaks into hydrological loading and makes the separation of deformation associated with snow and water loading inaccurate. In this work, we discuss the opportunities and challenges in using both GRACE and GNSS to study the climate change in the light of seasonal hydrological deformation obtained from GNSS and GRACE observations and differences in atmospheric loading simulated by various climate models in upper Ganges (Nepal Himalaya) and Brahmaputra (North-East India) river basins. We also compare the geodetic estimates with Meteorological Research Institute (MRI) climate model simulations and discuss possible ways for the combined use of these two satellite geodetic techniques to study the regional scale hydrological mass variations.

Unravelling teleconnections of terrestrial water storage via complex networks

R. K. Guntu (1), A. Agarwal (1), B. D. Vishwakarma (2)

(1) Indian Inst. of Techn., (2) University of Bristol

Terrestrial water storage (TWS) is a dynamic component of the hydrological cycle that exerts an essential control in water-energy-food nexus and plays a pivotal role in studying the changes in the Earth's climate system. Since TWS consists of water stored on and below the Earth's surface, its measurement has always been challenging. However, after the launch of the GRACE satellite gravimetry mission in 2002, we have been able to map TWS changes at monthly time scales. This novel information has helped us better understand the water budget, monitor ice sheet mass loss, measure groundwater depletion, and map severe TWS changes at spatial scales of several 100 km. Since TWS changes are driven by climate change and human intervention, we are yet to understand how climate change affects water availability and more importantly, how the variability of TWS

connected spatially. In this study, complex network concepts like degree, degree distribution are employed to quantify the spatial connections of TWS across major river basins worldwide. Complex networks received broad attention in hydroclimatology and can offer new avenues to assess TWS spatial connections. A complex network of TWS anomalies is created using GRACE (Gravity Recovery and Climate Experiment) satellite data. The dataset is of coarse spatial resolution, and therefore, we are able to study 169 major river basins covering most global land areas except for permafrost regions. In the TWS complex network, each river basin is considered a node, and links between each pair of basins are established based on the significant statistical relationship between them. Pearson correlation coefficient is used to derive the statistical relationship between two TWS anomaly time-series. A cutoff threshold obtained from the edge-density approach is applied to retain only the network's most significant features. Our results reveal that spatial connections of positive correlated TWS anomalies have local connections, and on the other side negatively correlated ones have teleconnections. Basins with significant negative correlation indicate dominant modes of climate variability influence interannual variations of TWS anomalies. Our findings demonstrate that climate feedback networks influence in driving hydrological variability can be seen in TWS observations from GRACE data.

Combination of observed data and remote sensing based Geodesy data for groundwater monitoring and management in India

P. Chinnasamy (1)

(1) Indian Inst. of Techn.

India is the world's largest groundwater user with an approximate annual groundwater draft of 231 Billion Cubic Meter (BCM). Agricultural activities consumes 92% of this draft (213 BCM), while industrial and domestic use consumes 8%. In addition to the on-going human induced stressors, climate change factors (e.g. prolonged droughts/shorter monsoons) can lead to further unsustainable groundwater extraction. Due to lack of observation data, the efficiency of management plans are limited. In such scenarios, big-data, with high spatiotemporal resolutions, from remote sensing tools (e.g. Gravity Recovery and Climate Experiment–GRACE) can be used to augment available observation data. To urge future scientists in creating unison between observation and remote sensing data, this presentation will discuss results from various studies (n=8) that used observed (social/physical) data with GRACE data. Results from Gujarat state showed high correlations (r2=0.89) between observed and GRACE data, while another study showed increase in groundwater depletion (2.34 BCM/year) after the introduction of groundwater markets in West Bengal. Gujarat study showed that an increase in surface water distribution canal network resulted in an increase of groundwater storage by 30% and 80% during monsoon and non-monsoon seasons, respectively. Results from Tamil Nadu state indicated that if the on-going irrigation overuse of groundwater (at 21.4 BCM/year, which is 8% more than the annual recharge) continued, current Green Revolution benefits would collapse and lead to more socio-economic stress. In other studies from the Ganges basin and Rajasthan, the potential of groundwater storage to buffer floods (by 20%) and reduce flood damage was estimated. These results increase confidence in the unison of observed and remote sensing data, and create opportunities to understand and manage Indian groundwater resources, holistically, by developing new conceptual frameworks and hydrological models.

Study on groundwater signatures in GPS position time series

A. Lenczuk (1), A. Klos (1), J. Bogusz (1)

(1) Military University of Technology, Warsaw, Poland

Highly dense GPS network with constantly growing number of stations worldwide is an amazing source of information on global and local effects. GPS time series were used to study various types of geophysical changes, including Earth's crust loading due to environmental changes, including terrestrial hydrosphere loading. Hydrosphere has few components, i.e. surface water, soil moisture, snow water, canopy and groundwater, which sum up to the TWS. TWS changes were proven to contribute to the GPS time series mainly in the seasonal band, but little attention has been given to particular components. In this study, we provide an assessment of sensitivity of GPS technique to record changes in groundwater component, whose variations are recognized as a global phenomenon. We used Nevada Geodetic Laboratory GPS vertical position time series provided for 47 stations localized in 6 regions, i.e. Amazon, Central Brazil, Central and East Africa, Bangladesh and North Australia, which are characterized by extreme values of annual amplitude of groundwater. To determine the groundwater changes from the GPS, we reduced the time series by non-tidal oceanic and atmospheric effects using loading models from GFZ. Compartments of TWS, other than groundwater, were removed from the GPS time series by using two hydrological models: Noah GLDAS and WGHM; for both models, TWS was converted to vertical displacements. To assess the adequacy of GPS-derived groundwater-induced displacements, we determine the vertical displacements associated with groundwater changes using observations from GRACE and GRACE Follow-On missions, available from the CSR mascon solution. For both, same hydrological models were removed to retrieve displacements induced by groundwater changes. We demonstrate that correlation estimated between GPS- and GRACE-derived Earth's crust vertical displacements caused by groundwater are above 0.6 for all considered areas, except Central Africa. High similarity of both time series is also emphasized by similar values of annual amplitude. Annual amplitude and trend values were higher after subtracting the WGHM model than the GLDAS for Bangladesh, North Australia and African regions, which is associated with significant human impact, modelled in WGHM. We conclude that GPS position time series are contaminated by Earth's crust displacement induced by groundwater changes mainly in the seasonal band. Also, strong hydrological events as drought or floods are well-resolved by the GPS.

The Central European Drought of 2018-2020

E. Börgens (1), A. Güntner (1), H. Dobslaw (1), C. Dahle (1)

(1) GFZ Potsdam

In the years 2018 to 2020 Central Europe experienced a severe drought. With the data of the GRACE Follow-On (GRACE-FO) mission we are able to quantify the water deficit of these years. Since May 2018 GRACE-FO continues the observations of GRACE (2002-2017) allowing to compare the most recent drought with earlier droughts in 2003 and 2015.

In July 2019 the water mass deficit in Central Europe amounted to -154 Gt, which has been the largest deficit in the whole GRACE and GRACE-FO time series. In November 2018 the deficit reached -138 Gt and in June 2020 -147 Gt. Comparing these deficits to the mean annual water storage variation of 162 Gt shows the severity of the drought. With such a water mass deficit, a fast recovery within one year cannot be expected. The, so far, most recent data of October and November 2020 do not indicate any recovery yet. In comparison to the recent years, the droughts of 2003 with a deficit of -55 Gt and of 2015 with a deficit of -111 Gt were less severe.

The GRACE and GRACE-FO total water storage data set also allows for analysing spatio-temporal drought patterns. In 2018 the drought was centred in in the South-West of Germany and Eastern France while Poland was hardly affected by the drought. In 2018 the drought reached its largest extent in late autumn. However, the exact onset of drought is not determinable due to missing data between July and October. Both in 2019 and 2020 the centre of the drought is located further East and the months with the largest deficit were July and June, respectively. Also in the later years, the drought was more evenly spread out over the whole of Central Europe.

Additionally, we compared the GRACE and GRACE-FO data to an external soil moisture index. To this end, we derive a drought index from the GRACE and GRACE-FO mass anomalies. For the whole time series, the GRACE drought index shows a high congruency to the soil moisture drought index. Further, a comparison to surface water drought indices for Lake Constance and Lake Müritz is done. Overall, the surface water drought index also fits well together with the GRACE drought index. However, the comparison reveals the influence of regional effects on surface waters not observable with GRACE or GRACE-FO.

The total continental water storage variation during 2018 extreme drought of Rhine basin from daily global GNSS network solution

L. Wang (1), D. Thaller (1), M. Weigelt (2), A. Susnik (3), T. van Dam (4)

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In 2018 summer of 2018, a once-in-a-century extreme drought event hit the north Europe and causing the Rhine River and groundwater level dropped to a historical low, severely impacting on the river shipping, agriculture, water resource management, and even the forest ecosystem. This event reminds us the impact of climate change at the local scales.

In this study, we discuss the continental water storage variations in Rhine basin and compute the induced loading displacement on GNSS observations in the vertical direction. Due the sparse GNSS network, we focus this study on the basin scale effects. Geophysical processes not associated with the drought dynamics, such tidal and non-tidal atmospheric and oceanic loading, are removed at the GNSS observation level in GNSS global network reprocessing. Then we can treat the GNSS observed station displacements as being driven by continental water mass variation. We discuss the GNSS displacements in terms of changes in water storage and compare them with displacements derived from independent continental water storage models.

The seasonal variations of the Rhine basin continental water storage were obtained from the GNSS observations and validated using the GRACE derived mass variations for the region. Due to the gap between the GRACE and GRACE Follow-On mission, the Drought event is only visible in the GNSS observations. We analyze the mass variations during the drought event as well as some other extreme weather events, for instance the storm caused flood in May of the same year using high temporal resolution of the daily GNSS solutions.

Estimating water change at Earth's surface using GRACE gravity and GPS positioning

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We estimate change in total water and its components each month from January 2006 to the Present using geodetic observations from space and complementary hydrologic measurements. Estimates of changes in total water inferred from GPS elastic displacements are used to strengthen the spatial resolution of GRACE observations of mass change, resulting in sharper images of water change. We furthermore distinguish between different components of water change. Change in surface water in man's artificial reservoirs and natural lakes are known from gauging measurements of water levels. The distribution and magnitude of snow accumulation is inferred from sticks and scales on the ground. We remove the effect of surface water and snow to infer change in water in the ground, consisting of soil moisture and groundwater. This determination is bringing powerful insights into understanding the water cycle. We are finding more water to be lost during drought and gained during heavy precipitation than in the hydrology models, suggesting that the hydrology models must be revised to have a greater capacity to store water in the ground. Not all rain and melting snow that falls on the mountains of California, Oregon, and Washington is found to runoff into rivers taking water to the ocean. Rain and melting snow is instead found to infiltrate the ground in the wet fall and winter and and to be parched from the ground in the dry spring and summer.

Retrieving geophysical signals from GPS in the La Plata River region

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Over the last few years, efforts to model short-term deformations of the Earth's crust have multiplied. Sudden water level rise can cause sporadic, but significant, motions in the solid Earth's surface. In this work, we address the problem of retriev- ing reliable estimates of the vertical displacement of a Global Positioning System (GPS) station located very close to the eastern shore of the La Plata River, during a strong storm surge event. Capturing sub-daily GPS displacements demands an elaborate processing strategy because several highly correlated parameters must be estimated simultaneously. We present a successful strategy that reduces the number of unknowns that have to be estimated simultaneously, by using an empirical model that describes the elastic response of the Earth's crust to the hydrological load variations. We incorporate this model into the observation equations so that, instead of estimating the station position, we estimate every epoch a single parameter of the empirical model, i.e., the empirical elastic parameter EEP, that is assumed to be a constant of the Earth's crust in the region of the GPS station. We verify that the estimated parameter agrees well with the value calculated from the CRUST 1.0-A model of the Earth's crust. The GPS receiver was tied to an external cesium clock, which allowed us to process the data according to two different strategies: (a) estimating the receiver clock error (Δt) as an epoch-wise free parameter, which is equivalent to ignoring the presence of the external clock, and (b) conditioning the variability of that estimate with a small a priori variance compatible with the external clock's variability. We find that, without having an external atomic clock, the estimation of all the parameters, i.e., the zenith tropospheric delay, Δt, and the EEP, worsens when the GPS station is affected by sub-daily vertical displacements.