2. ICCC Workshop

„Geodesy for Climate Research“

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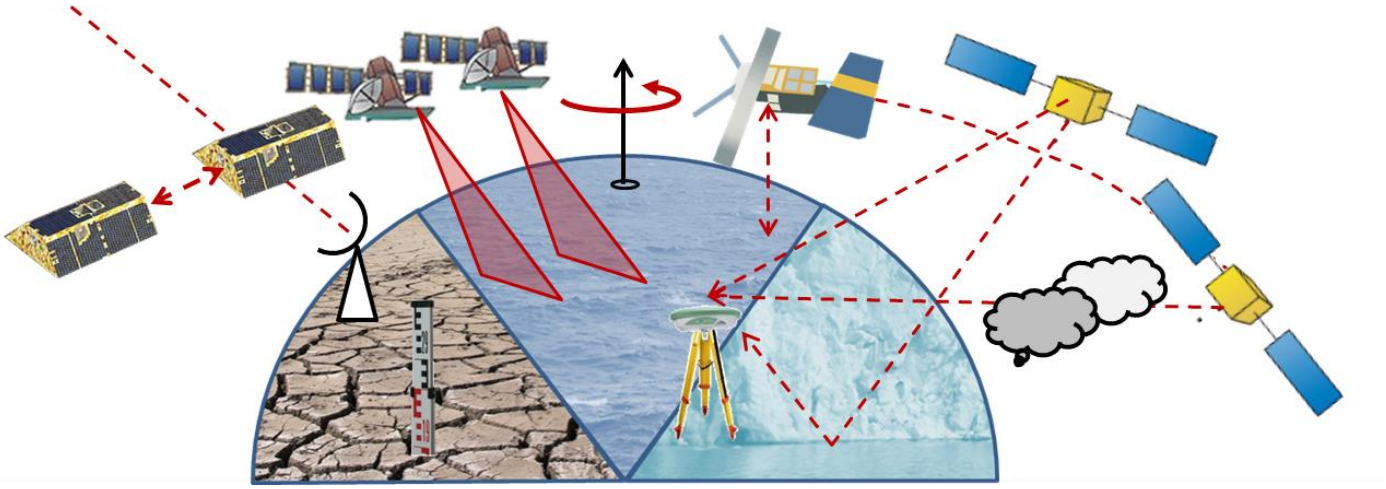
Abstract book



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

International Association of Geodesy

Session 1
Tuesday morning: 8 a.m. CEST (UTC+2)

S01C01 Global coastal attenuation of wind-waves observed with radar altimetry

M. Passaro (DGFI), M.A. Hemer, G.D. Quartly, C. Schwatke, D. Dettmering, F. Seitz

Coastal studies of wave climate and evaluations of wave energy resources are mainly regional and based on the use of computationally very expensive models or a network of in-situ data. Considering the significant wave height, satellite radar altimetry provides an established global and relatively long-term source, whose coastal data are nevertheless typically flagged as unreliable within 30 km of the coast. This study, recently published in Nature Communications (Passaro et al., 2021), exploits the reprocessing of the radar altimetry signals with a dedicated fitting algorithm to retrieve several years of significant wave height records in the coastal zone. We show significant variations in annual cycle amplitudes and mean state in the last 30 km from the coastline compared to offshore, in areas that were up to now not observable with standard radar altimetry. Consequently, a decrease in the average wave energy flux is observed. Globally, we found that the mean significant wave height at 3 km off the coast is on average 22% smaller than offshore, the amplitude of the annual cycle is reduced on average by 14% and the mean energy flux loses 38% of its offshore value. The results shown in this study also highlight the wide range of possibilities to study the coastal wave climate provided by the latest Sea State Climate Change Initiative dataset of the European Space Agency, since this product benefits from an even more advanced version of the algorithm at the heart of this work, as well as from data of several cross-calibrated missions..

S01C02 Monitoring mountain lake variation from satellite altimetry: improvements during the last decades (1992 - 2021)

L. Jiang (SUSTech), K. Nielsen, O. B. Andersen

Satellite altimetry has been widely used for inland water monitoring and modeling in the present decade. In this paper, the availability, data quality, and quantity of a number of spaceborne radar altimetry missions (including Topex/Poseidon, ERS-2ERS-2, Envisat, Jason-1/-2/-3, CryoSat-2, Saral, and Sentinel-3) are investigated. This is the first paper to investigate the influences of onboard trackers, satellite flying directions, and land contamination on Level-1 waveforms and Level-2 measurements over mountainous lakes. The analyses were conducted over eight Tibetan lakes, which were sampled by multiple altimeters. From the results presented in this paper, it is demonstrated that the previous generation of altimeters, such as TP, Jason-1, ERS-2, and Envisat, shows a higher percentage of data unavailability and invalidity. Investigations of Level-1 waveforms show failures of locking on the lake surface, resulting in data loss or invalid measurements. In addition, the onboard tracking systems are sometime unstable, resulting in large along-track standard deviations (SD) (SD > 15 cm). In contrast, the recent generation of altimeters, i.e., Jason-3 and Sentinel-3 with open-loop tracking mode, significantly increases the data availability (> 90% passes and > 60% individual observations) and delivers high precision measurements (SD around 10 cm). Moreover, the waveform leading edge is very consistent, indicating more stable onboard tracking. High quality Jason-3 and Sentinel-3 data allow monitoring of sub- and quasi-monthly lake variations, which are not revealed by e.g., TP and ERS data due to poorer signal-to-noise ratio. Exceptionally, Saral Ka-band altimeter, operated in closed-loop tracking mode, is less affected by flying directions and land contamination (topography and landscapes), delivering high quality of measurements (SD around 7 cm for 40 Hz). This study provides a comprehensive comparison of multiple altimeters in monitoring lakes in mountainous areas, and demonstrates the substantial improvements achieved in the past decades. However, care has to be taken when merging with data from old generation altimetry missions over mountainous lakes.

S01C03 Estuarine water level change from high resolution altimetry

L. Fenoglio (Univ. Bonn), H. Uyanik, J. Chen, J. Staneva, Hereon B. Jacob, J. Pein, J. Kusche

Tidal rivers and coastal-to-land sites are mostly affected by climate changes and are at multi-risks due to coastline retreat, flooding storms and river floods. New altimeter processing and new missions open new possibilities to observe fine-scale spatial changes in these regions. In the present study, we first consider the improvement in sea level change detection obtained from unfocused SAR (USAR) and fully focused techniques (FF-SAR) along the

Sentinel-3 and Sentinel-6 tracks in the Elbe estuary and tidal river. We show that results depend also on the retracking method. The SAMOSA+ retracker gives the best results for both FFSAR and USAR. The ability of the ocean modelling to reproduce this high variability at fine spatial-scale is then investigated using two regional ocean models for the Elbe estuary and tidal river, the HzG and the BSH models. Ocean modelled sea level is compared to nadir-altimetry along the satellite ground tracks. While the coverage of nadir-altimeter is limited by the number of ground-tracks, the future SWOT mission provides a uniform coverage. In the second part of this study we investigate using simulations the signal expected from the SWOT mission. For this, SWOT data of the 1-day repeat are simulated using the two ocean models as input to the SWOT simulators for ocean and hydrology. De-tided and not de-tided ocean model input cases are considered. The first case is preferable to derive reach-averaged outputs, while the second case can be used for lower level output which may account for the tidal component, that is challenging for the wide-swath mission. Different methodologies to study level change and river discharge in the tidal river ad estuary from future SWOT data are considered and compared. Due to the differences between along-track altimetry and swath-altimetry, new methods to derive accuracy and precision of the measurements are considered.

S01C04 Differences between sea level measured by conventional and SAR altimeters in the Southeastern North Sea

S. Esselborn (GFZ Potsdam), T. Schöne

Since the beginning of the 1990's global and regional sea level has been continuously monitored by satellite altimetry. Based on this data plenty studies have shown the close relationship between climate and sea level change. During the past 30 years the measurement and data processing techniques have been improved constantly which might introduce inconsistencies in the sea level record. Recent missions carry Synthetic Aperture Radar (SAR) altimeters which enable better accuracy and spatial resolution than conventional altimeters. In the end of 2020 the Sentinel-6 Michael Freilich mission has been launched and is now the new reference mission for all currently active altimeter missions. To ensure the continuity of the 30 years altimetric sea level record Sentinel-6MF can perform conventional and SAR measurements in parallel. Here, we use five GNSS-contolled tide gauges located in the German Bight (southeastern North Sea) to assess the regional accuracy and precision of instantaneous sea level derived from conventional and SAR altimeter measurements in coastal waters. The results are compared to analyses obtained for the predecessor Jason-1/2/3 missions. Differences and drifts between the two types of altimeter measurements are investigated and possible implications for the long time series are discussed.

S01C05 Signatures of Greenland melting in the North Atlantic: Model simulations vs. Argo, GRACE, radar altimetry and ocean reanalysis

J. Kusche (Univ. Bonn), S. Stolzenberger, C. Wekerle, R. Rietbroek, B. Uebbing

Greenland ice mass loss contributes to global mean and regional sea level rise and changes in ocean circulation. In Stolzenberger et al. (2022), we explore whether signatures found in ocean model simulations are identified in radar altimetry, satellite gravimetry and Argo float observations. We have included Greenland freshwater flux (GF) in the global Finite-Element-Sea ice-Ocean Model (FESOM) for the years 1993–2016. Experiments are performed on a low (~24 km) and high resolution (~6 km) eddy-permitting grids and simulations are compared to different variables from Argo floats, satellite observations, and reanalyses. We find that surface GF maps into signatures in temperature and salinity down to about 100 m in the surroundings of Greenland. Melting signatures are particularly visible in steric heights in Baffin Bay and Davis Strait where we find model-data fits improved by up to 30% in MSE when including GF. For the Nordic part of the Nordic Seas, however, we find no improvement when including GF. We compare steric height change with reanalyses and a new setup of the Uebbing et al. (2019) inversion utilizing GRACE and altimeter data. We cannot confirm that GF temperature and salinity signatures are visible in the Argo observations on the time scales and sampling areas considered We also show that model resolution has generally a larger influence on the results than the impact of the meltwater forcing.

S01C06 Investigating the sea level budget in the East China Sea

C. Strohmenger (Univ. Bonn), Z. Liu, B. Uebbing, J. Kusche, L. Reißner, Y. Shen, W. Feng, Q. Chen

Sea level change is not uniform around the globe. We focus on regional sea level change in the East China Sea (ECS), a Western Pacific marginal sea of 770.000 km2, with a densely populated and economically important coastal area. Several challenges arise when investigating past and current sea level change and budgets in this region.

Ocean mass change is observed by GRACE(-FO). However, one needs to account for hydrological signals leaking from land into the ocean, as well as for sediment discharge from rivers. Steric contributions are usually measured by Argo floats, but from the shallow inner shelf of the ECS only few data are available. Thus, ocean reanalyses should be handled with caution. Total sea level change from altimetry can be compared to tide gauge data, but gauges are sparsely distributed in the ECS area and only few stations are co-located with GNSS to account for vertical land motion.

In this contribution, we analyze and compare different data products to better understand regional sea level change and its contributors. Time series of ECS- averaged levels (total from altimetry, mass from GRACE and GRACE-FO and steric from ORAS5 reanalysis) are computed and compared in terms of trend, seasonal amplitudes and correlations. Additionally, spatial patterns are investigated, revealing that the shallow coastal regions, vast continental shelf areas and deep sea areas show distinct characteristic behaviors of sea level change. Altimetry and tide gauge data show a correlation of higher than 70% for 11 of 13 available records. Finally, we compare the individual data sets to results of a joint sea level inversion framework (Uebbing, 2022).

S01C07 Intrinsic Ocean Bottom Pressure Variability from MPIOM Ocean Circulation Ensemble Simulations

J. Liu (GFZ Postdam), L. Shihora, K. Balidakis, H. Dobslaw

Observations of the Earth's time-variable gravitational field provides valuable information on the Earth's climate system and the impact of climate change. Over the oceans, the Gravity Recovery and Climate Experiment (GRACE) satellite data primarily provides information about ocean bottom pressure changes caused by both barystatic sea-level rise and changes in the ocean general circulation. Improvement in GRACE data precision helps deepen the applications of satellite gravimetry in climate research. To this end, new ensemble simulations with the Max-Planck-Institute for Meteorology Ocean Model (MPIOM) are systematically altered for (i) initial conditions, (ii) atmospheric forcing, and (iii) and ocean physics. we attempt to identify the relative importance of deterministic bottom pressure and intrinsic variability. A consolidation of simulation driven by the Modern-Era Retrospective Analysis for Research and Applications version 2 (MERRA-2) was selected to compare with existing simulations forced by the ECMWF Reanalysis version 5 (ERA5). The difference is chosen to represent the new error time-series AOerr v7.0. A particular emphasis will be placed to identify regions with dominant intrinsic variability at time-scales longer than 60 days, since such signals cannot be predicted well from a priori background models and thus are potential targets for existing (and future) satellite gravity missions.

S01C08 A geodetic approach to volume transport estimation in the Southern Ocean from satellite data

J.A. Vargas-Alemañy (Univ. of Alicante), M. I. Vigo, D. García-García, F. Zid

The Southern Ocean is a major component in the climate system, being its main current, the Antarctic Circumpolar Current (ACC), the most powerful ocean current in the world. It circumnavigates eastward around Antarctica and connects the Pacific, Atlantic and Indian oceans. As the ACC is the only current that connects the major ocean basins, an accurate knowledge about the ACC transport is key to understanding the global circulation of the oceans as well as the heat and water transports. In this work a geodetic estimation of the Surface Geostrophic Currents (SGC) is obtained from satellite data by combining the Sea Surface Height (SSH) provided by altimetry missions and the geoid provided by gravity missions. These SGC are propagated downward through temperature and salinity profiles proving a 3D geostrophy near full-depth in 41 layers, with a 1º spatial resolution and monthly temporal resolution, covering the 12 years period from 2004 to 2015. We analyze the obtained 3D geostrophy over the Southern Ocean region, where the ACC and its several fronts are clearly depicted, as well as other major currents as the Agulhas current, the Malvines current or the East Australian Current. From the 3D geostrophic currents, we estimate the associated water Volume Transport (VT) as well and

present the results for the ACC and the Drake Passage in the context of existing literature. The spatial resolution of our space data-based approach allows us to provide VT estimates for the different paths followed in the different in-situ campaigns at the Drake Passage, the results not only validate our study but also reconciles the different estimates, showing a general good agreement for the different campaigns and how the existing estimates differences depend on the exact location where the in-situ measurements were taken.

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S01C09 Space-based Geodetic Technology for Integrated Coastal Vulnerability Mapping along the West Africa

S. Akande (FUTA, Nigeria)

Coastal areas throughout the world are being challenged more and more by climate change and its link to sea level rise (SLR). Through the development of an SLR vulnerability assessment, this study aims to fill the gap in existing studies and evaluations of the West African coasts. Given that they provide environmental services that are essential for people's well-being, it is imperative to protect coastal ecosystems from the effects of increasing sea levels. Daily and monthly downscaled archived climatic datasets were retrieved online for rainfall, runoff, sea surface temperature, significant wave height and swells, u-v wind components, as well as sea level heights. The results from the climate change scenarios predict an increase in rainfall across all future periods and under both emission scenarios, with the highest projected increase during the last three decades of the century. The daily and monthly downscaled archived climatic datasets were retrieved online for rainfall, runoff, sea surface temperature, significant wave height and swells, u-v wind components, as well as sea level heights. The results from the climate change scenarios predict an increase in rainfall across all future periods and under both emission scenarios, with the highest projected increase during the last three decades of the century. The 12-month Standard Precipitation Index (SPI) under the RCP 8.5 emission scenarios predicted an exceedance in the extreme wet threshold (i.e., SPI > 2) during all future periods (2021-2060) and across major parts within the region. In addition, the social survey conducted in twelve cities across the four countries (Ghana. Togo, Benin Republic and Nigeria) resulted into a total number of 594 out of the 600 copies distributed during the survey. The results from the outputs then suggested that households were vulnerable to climate change induced extreme events, currently with low coping capacity. On the socio-economic importance of the inhabitants along the coastal communities, the respondents affirmed that the various communities had in one time experienced the impacts of the storm surges, flooding and marine heat waves, despite their various level of educational awareness. Residents along the river banks, lagoons, creeks and those near the estuaries near often experience increased frequencies of coastal flooding, with great impacts and severe damages to lives and properties. Hence, the integrated coastal vulnerability index (ICVI) map over the region had showed how a consistent coastal vulnerability analysis and methodology may serve to collect, analyze and visualize coastal features and support risk management strategies. Furthermore, discrepancies existed between global and regional climate models on the projected change considered and their characteristics over the region. The study findings suggest an increasing risk of coastal hazards within the projected periods. The findings could be useful to policymakers for the formulation and planning of coastal hazard mitigation and adaptation measures.

S01C10 Investigating Recent Irish Flood Events with Satellite Radar Imagery

O. Memarian Sorkhabi (Univ. College Dublin), O. Boydell

Floods cost Ireland several million Euro every year, and according to climate change models, flood frequency in Ireland will increase. On the other hand, by investigating flood events in the recent past, it is possible to assist government, crisis management, land-use planning and disaster response. In this research, flooding in Ireland from 2015 to 2021 has been analysed using Sentinel-1 radar images across a number of different locations. Satellite radar imagery before and after flooding has been processed and flood maps have been produced. It has been shown that the studied areas have been flooded in different years, which requires land use change and adaptation of these areas. Among the advantages of flood mapping with radar imagery are: spatial coverage of large areas, robust to different weather conditions (e.g. cloud cover), low uncertainty of numerical and

hydrological models and low cost of data collection. Flood mapping with satellite radar imagery can be useful for crisis management, evacuation of flooded areas, response planning and reducing human and financial losses. Although floods have caused significant human and financial damage, by understanding past flood events, flood mapping and learning from them, preparedness and resilience can be increased.

S01C11 Detecting the Great Wall dynamic response under thunder loading with GNSS and MEMS accelerometers

J.Wang (Beijing University), X. Liu

Thunderstorm is one of the most dangerous factors affecting the safety of the Great Wall, an ar-chitectural marvel of the ancient world. To evaluate how thunderstorm excitation can affect the stability of the Great Wall, an integrated vibration monitoring system that includes a Global Nav-igation Satellite System (GNSS) receiver and 3-axis MEMS accelerometers was developed to obtain the dynamic responses of the Great Wall with the thunder loading. Firstly, a new denoising algo-rithm for thunderstorm-induced vibration data was proposed based on Variational Mode De-composition (VMD) and the characteristics of white noise, and the low-frequency disturbance was separated from the GNSS displacement time series. Then, Power Spectral Density (PSD) analysis using both GNSS and accelerometer data was carried out to extract the low/high natural frequen-cies of the bricks of the Great Wall. Finally, field monitoring data collected at Huanghuacheng, Hefangkou, and Qilianguan in Beijing's Huairou District were used to validate the effectiveness of the proposed integrated processing scheme. According to the results, thunderstorms can cause the Great Wall to vibrate with a maximum displacement of 14.3 cm. Moreover, the Power Spectral Density (PSD) analysis based on both GNSS and accelerometer data can completely extract the natural frequencies of the Great Wall. The high natural frequencies detected from the accelerometer data of the four Great Wall monitoring stations excited by the thunderstorms are 42.12 Hz, 12.94 Hz, 12.58 Hz, and 5.95 Hz, while the low natural frequencies detected from the GNSS are 0.02 Hz, 0.019 Hz, 0.016 Hz, and 0.014 Hz.

Session 2
Tuesday afternoon 5 p.m. CEST (UTC+2) **ORALS**

S02C01 GNSS interferometric reflectometry (GNSS-IR): current status of open source software for environmental sensing

K. Larson (Univ. Bonn), S.D.P. Williams, F.elipe Geremia-Nievinski, K. Enloe, T. Dittmann, M. Karegan, D. Purnell

Initially ground-based GNSS reflectometry experiments used either specially-designed GNSS equipment or off-the-shelf GNSS equipment that had been modified in some way to enhance the reflected signal. Using standard geodetic-quality GNSS instruments with a zenith-pointing antenna for GNSS reflection applications was for the most part ignored. In the past fifteen years many groups have demonstrated that despite their multipath suppressing antenna and receiver designs, reflected signals can still be observed in the SNR observations collected by these geodetic instruments. Data from hundreds of continuously operating GNSS reference stations that were installed by geodesists and surveyors have been used for a variety of environmental sensing applications, including surface soil moisture, snow accumulation, vegetation water content changes, permafrost melt, tides, storm surge/tsunami detection, and river/lake level monitoring. We use the term GNSS interferometric reflectometry (GNSS-IR) to describe this method. Unfortunately, most GNSS-IR experiments described in the refereed literature use software that has not been made publicly available; this leaves most people having to build their own software from scratch. Furthermore, many of the environmental scientists that might like to use GNSS-IR not only do not have access to processing software but are also unfamiliar with GNSS concepts, data formats and data archives. In order to make GNSS-IR more generally available to non-geodesists, we have built an open source software package in Python called “gnssrefl”. It is currently hosted at github and pypi.org, with Jupyter Notebooks accessible from Earthscope. It can read RINEX (versions 2.11 and 3) and NMEA

data formats and SNR data from the GPS, Galileo, Glonass, and Beidou constellations. Downloads from a dozen GNSS data archives are also supported. In this presentation we will summarize the main parts of the gnssrefl software and share representative environmental results using it, including soil moisture, snow depth, lake/river monitoring, and tides.

S02C02 GNSS-based observational analysis of an extreme Atmospheric River event: Signatures in GNSS-RO and ground-based troposphere products

M. Aichinger-Rosenberger (UCAR), J. Braun, T. Vanhove, Y.-H. Kuo

Atmospheric water vapor denotes a crucial meteorological parameter, influencing weather and climate processes on various scales, as well as the most important greenhouse gas. Nonetheless, observations are still sparse and common techniques like satellite imaging or radiosonde profiling have significant disadvantages such as operation restriction to cloud-free conditions or poor resolution.

Observations from Global Navigation Satellite System (GNSS), which can be collected under all weather conditions, are refracted and thus delayed due to the presence of water vapor along the signal ray path. Using different retrieval methods, such as radio occultation (GNSS-RO) and troposphere estimation from ground-based stations, they offer the possibility to observe water vapor at a high temporal and spatial resolution.

One phenomenon which is strongly connected to huge amounts of water vapor are Atmospheric Rivers (ARs). ARs are defined as long, narrow bands of high water vapor flux, commonly observed in the Pacific and Atlantic Ocean. They account for most of the poleward water vapor transport in midlatitudes and therefore are responsible for a significant proportion of yearly precipitation in coastal regions, such as the westernmost United States.

This study shows how AR signatures are captured in GNSS products, such as GNSS-RO profiles and ground-based tropospheric delays. We analyze a specific extreme AR event, which brought record amounts of precipitation to the Pacific north-west coast between 11-13 January 2021. Characteristics of the AR, from its initial stage to landfall, will be examined using Cosmic-2 and other GNSS-RO mission profiles as well as tropospheric delays from ground stations in affected regions.

S02C03 Continuous observation of canopy water content changes with GNSS sensors

V. Humphrey (ETH Zürich), C. Frankenberg

Satellite microwave remote sensing techniques can be used to monitor vegetation optical depth (VOD), a metric which is directly linked to vegetation biomass and water content. However, these large-scale measurements are still difficult to reference against either rare or not directly comparable field observations. So far, in-situ estimates of biomass or water status often rely on infrequent and time-consuming samplings, which are not necessarily representative of the canopy scale. Here, we present a simple technique based on Global Navigation Satellite Systems (GNSS) with the potential to bridge this persisting scale gap. Because GNSS microwave signals are attenuated and scattered by vegetation and liquid water, placing a GNSS sensor under a vegetated canopy and measuring changes in signal quality over time can provide continuous information on VOD, and thus on vegetation biomass and water content.

We test this technique at forested site in Southern California for a period of 8 months. We show that variations in GNSS signal to noise ratios reflect the overall distribution of biomass density in the canopy and can be monitored continuously. For the first time, we show that this technique can resolve diurnal variations in VOD and canopy water content at hourly to sub-hourly time steps. Using a model of canopy transmissivity to assess these diurnal signals, we find that temperature effects on the vegetation dielectric constant, and thus on VOD, may be non-negligible at the diurnal scale or during extreme events like heatwaves. The rainfall and dew deposition events also suggest that canopy water interception can be monitored with this approach. The technique presented here has the potential to resolve two important knowledge gaps, namely the lack of ground truth observations for satellite-based VOD, as well as the need of a reliable proxy to extrapolate isolated and labour-intensive in-situ measurements of biomass, canopy water content, or leaf water potential. We provide recommendations for deploying such off-the-shelf and easy-to-use radar systems at existing ecohydrological monitoring networks such as FluxNet or SapfluxNet.

S02C04 Continuous observation of canopy water content changes with GNSS sensors

M. Santos (Univ. New Brunswick), J. Rees, K. Balidakis, A. Klos, R. Pacione

We summarize results of an ongoing effort to assess long-term ZTD trends for eventual use in climate models, either for assimilation or validation. We have been analyzing the ZTD time series estimated from the six REPRO3 IGS Analysis Centers (ACs) who made them available, and compared their long-term trends, hear meaning 20 years or longer. A subset of the IGS global network composed of thirty stations were selected. After being homogenized, using ERA-5 derived ZTDs as reference, the estimated ZTD time series were averaged to daily values to minimize potential influences coming from different estimation strategies used by individual ACs. Two combinations, using weighted mean and (a robust) least median of squares are then generated from the six homogenized and averaged time series. The combinations serve as quality control to each ACs. Analysis of the generated trends is performed both in time and frequency domains. Results vary depending on the geographical location. For example, ALBH, in Canada, shows inter-AC scatter is 0.47 mm/decade for the trends, 0.11 mm for the annual amplitudes, and 0.29 degrees for the annual phase. The work to be presented is under the scope of JWG C.2: Quality control methods for climate applications of geodetic tropospheric parameters.

Session 3
Tuesday afternoon 5 p.m. CEST (UTC+2) **POSTERS**

S03C01 Identifying water storage changes in the Parana river basin from GRACE/FO and its connection with ENSO events

Ayelen Pereira (Univ. de Rosario), C. Cornero, A. C. O. C. de Matos, C. Pacino

The Parana river basin is the major contribution to the La Plata basin in South America, and the fifth largest hydrographic system in the world. Moreover, it constitutes the most dynamic area of Argentina in economic terms, being also a region of great hydrological significance and sensitive to extreme events.

In the last 20 years, this basin has had episodes of extraordinary floods with human losses and property damages, as well as severe situations of water storage deficit. Gravimetric satellite missions can monitor water mass distributions in the Earth system, which is closely related to the consequences of climate change.

In this work, data from GRACE and GRACE FO were used to analyze the water mass variation in the Middle-Low Parana river basin. Interpretation of results was carried out by associating the mass anomalies derived from GRACE/FO data with satellite and terrestrial information, like global rainfall models and hydrometric heights; and linked to ENSO events that occurred in the period 2003-2022. The results indicate that most of the water storage variations are related to climate extreme events (e.g. the floods that occurred in the 2015-2017 period, and the 2009 and 2019-2022 drought), and also to El Niño and La Niña episodes.

S03C02 Integrated Water Vapor from SIRGAS troposferic products, meteorological and ERA5 data.

M.F. Camisay (Centro de Ingeniería Mendoza), M.V. Mackern, M. L. Mateo, P.A. Rosell

The american network of GNSS continuous stations, called SIRGAS-CON, currently has more than 450 stations. Since 2014, SIRGAS implemented a strategy to combine the tropospheric parameters estimated by different analysis centers (ACs), in their weekly routine. The ZTDs obtained from the combination are considered final SIRGAS products and are published weekly on the SIRGAS website (https://sirgas.ipgh.org/en/products/tropospheric-delays/). From the Neutral Atmosphere Analysis Center of SIRGAS, Centro de Ingeniería Mendoza Argentina (CIMA), the final tropospheric products are used for compute the integrated water vapor (IWV) in each GNSS station. This contribution presents the IWV time series of the Uruguayan stations (17), for a period of 10 years (2013-2022). The calculated monthly IWV mean values are showed.In addition, we present the results of the IWV computations, using insitu meteorological data from stations of the Instituto Uruguayo de Meteorología INUMET (www.inumet.gub.uy). Both IWV solutions were compared. Agreement was evaluated in terms of mean bias and rms of IWV between CIMA estimations (with

ERA5 data) and new series computeted with meteorological insitu data (mean bias 0.029 kg / m2, mean rms 0.405 kg / m2 and mean standard deviation 0.282 kg / m2). Likewise, the comparison of pressure and temperature extracted from ERA5 with respect to meteorological records is presented.

S03C03 Machine Learning approaches for troposphere delays

B. Gankhuyag (MAS, Mongolia), A. Sharav, N. Baasan

Abstract: Atmospheric water vapor is directly reflected in the tropospheric delay of satellite signals. In this work we use Machine Learning algorithms. The most traditional PWV observation method is the radiosonde and it is often used as a standard to validate those derived from GNSS. Therefore, GNSS zenith total delays of 2 permanent stations in Mongolia and permanent meteorological data of the Meteorological and Environment Research Agency. The distribution of the two sites are at different altitudes and with different climatic conditions. This work is a contribution to the use of ML, the algorithms compensate for the atmospheric error of the GNSS signal and compare its capabilities with empirically derived models.

S03C04 Insights into the feedback of vegetation health and growth to the changes in different water storage compartments

B.N.R. Komali (Indian Inst. of Techn. Kanpur), B. Devaraju

Water is an essential quantity for vegetation. Changes in surface water and soil moisture of water storage influence vegetation growth. Similarly, vegetation affects water storage in different compartments, predominantly soil moisture and groundwater. In this study, we aim to explore the relationship between water storage anomalies in different compartments and vegetation. Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) are used to assess vegetation health, and Leaf Area Index (LAI) for vegetation growth. Likewise, water storage anomalies in different compartments are derived from Gravity Recovery and Climate Experiment (GRACE) and Global Land Data Assimilation System (GLDAS) Land Surface Modeled data. The GRACE data contains noise, which is removed by filtering the data. However, filtering makes the data smoothed and brings leakage from nearby catchments. This problem is addressed using a data-driven correction method to correct the filtered GRACE data. For consistency, a similar procedure is applied to other datasets. Then, water storage anomalies of different compartments and NDVI data were aggregated over sub-basins of the Ganga catchment, and a correlation analysis and causality test were performed. This helped in understanding the response of vegetation growth to changes in different water compartments.

S03C05 The Water Cycle of the Baltic Sea Region From GRACE/GRACE-FO Missions and ERA5 Data

A.K. Boulahia (Univ. of Alicante), D. Garcia-Garcia, I. Vigo, M. Trottini, J.-M. Sayol

The water cycle of the Baltic Sea has been estimated from the Gravity Recovery and Climate Experiment (GRACE) and the GRACE Follow-On satellite time-variable gravity measurements, and precipitation and evaporation from ERA5 atmospheric reanalysis data for the periods 06/2002 to 06/2017 and 06/2018 to 11/2021. On average, the Baltic Sea evaporates 199 ± 3 km3/year, which is overcompensated with 256 ± 6 km3/year of precipitation and 476 ± 17 km3/year of water from land. This surplus of freshwater inflow produces a salty water net outflow from the Baltic Sea of 515 ± 27 km3/year, which increases to 668 ± 32 km3/year when the Kattegat and Skagerrak straits are included. In general, the balance among the fluxes is not reached instantaneously, and all of them present seasonal variability. The Baltic net outflow reaches an annual minimum of 221 ± 79 km3/year in September and a maximum of 814 ± 94 km3/year in May, mainly driven by the freshwater contribution from land. On the interannual scale, the annual mean of the Baltic net outflow can vary up to 470 km3/year from year to year. This variability is not directly related to the North Atlantic Oscillation during wintertime, although the latter is well correlated with net precipitation in both continental drainage basins and the Baltic Sea.

Keywords: Baltic Sea, water cycle, water transport, runoff, Skagerrak–Kattegat, Danish straits

S03C06 Use of an iterative SSA-based algorithm for GNSS data gap-filling with application to monitoring of hydrological loading

O. Abedi Khorasgani (Univ. of Isfahan), S. Iran-Pour, A. Klos, A. Amiri-Simkooei

Global Navigation Satellite System (GNSS) measurements are utilized for many applications in geodetic research fields. In particular, the GNSS measurements can be employed for monitoring of hydrological loading. However, missing values may cause misreading in the data analysis, consequently resulting in misinterpretation of the events in an area. In a region with dominant hydrological behavior, the main parts of GNSS time-series are trend, annual and semi-annual periods. Clearly, the more we know about the time-series signatures, the better we can interpret the underlying geophysical and hydrological processes.

In this work, we take the advantage of Singular Spectrum Analysis (SSA) to fill the data gaps in the GNSS and groundwater level time-series in California and surrounding areas with hydrological loading as the predominant behavior in the land deformation. We design an iterative SSA-based algorithm to extract the time-series signatures where the powers of the extracted modes have key roles in mode selection for reconstruction. In the grouping procedure, as a step inside the SSA algorithm, we use weighted correlation (w-correlation) statistics to show the association within the selected eigenvectors. The data of this work are divided in two parts, namely synthetic and real data where we first try to make use of the synthetic data for performance analysis of our gap-filling algorithm. At the end, to interpret the results, we compare the main signatures extracted from GNSS and groundwater measurements for the sake of hydrological loading analysis.

S03C07 Exploiting grouped CMIP6 models to determine hydrological excitation of polar motion

J. Nastula (Polskiej Akademii Nauk),Tomasz Kur, J. Śliwińska, M. Wińska, A. Partyka

Interpretation of the polar motion (PM) variations and identifying origin of their disturbances is an important task in contemporary geodesy and geophysics. It is known that at seasonal time scales, PM is affected mainly by mass distribution of atmosphere, ocean and continental hydrosphere. A wide variety of models and observations can be used to assess the impact of the continental hydrosphere on PM excitation. However, despite many studies on the subject, hydrological angular momentum (HAM) is still the source of the largest errors in the PM excitation budget.

In recent years, scientific interest in the subject of climate change has increased significantly, and research centres around the world have intensified their work on developing models of future changes in the physical and chemical properties of the atmosphere, oceans and hydrosphere. Such models are collected and made available to users in a standardized format as a part of the Coupled Model Intercomparison Project (CMIP). The data from CMIP can be used in many studies that focus on interpreting changes in global mass distribution.

In this study, we use historical simulations from climate models provided by sixth phase of the CMIP – CMIP6 – to determine hydrological signal in PM excitation described with HAM series. Because of large variety of climate models, we focus on the analysis of HAM calculated from models grouped by providing institute. We also study multi-model mean as well as several combinations of CMIP6-based HAM. The obtained HAM series are analysed in different spectral bands and evaluated taking the hydrological signal in geodetically observed PM excitation (geodetic residuals, GAO) as a reference. As an additional reference, we use Level-3 data from Gravity Recovery and Climate Experiment (GRACE) mission. Because climate models cannot reliable simulate ice mass changes over Greenland and Antarctica, we exclude these areas from our research. We demonstrate that masking Greenland and Antarctica has not a noticeable impact on seasonal variation in HAM estimated from CMIP6 and GRACE, but it has a visible effect on HAM trends.

Our research shows that despite the large differences between the HAM series obtained from single CMIP6 simulations, it is possible to choose the groups or combinations of models that allow for quite reliable determination of HAM, especially in seasonal spectral band. However, it is not possible to find one model that provides the best agreement between HAM and GAO in terms of both amplitude and phase, and in terms of both annual and semiannual oscillation. In terms of phase, the chosen models perform better than GRACE for annual prograde and semiannual retrograde term. In terms of amplitudes, the chosen models perform better than GRACE for annual prograde and annual retrograde term.

S03C08 Attempts to determine ocean tides velocities based on GRACE solutions

M. Birylo (Univ. of Warmia and Mazury), Z. Rzepecka

The presentation presents the idea of using GRACE solutions to determine the velocity of the Atlantic ocean tides at a depth of 2000 m. At this depth, the assumptions of geostrophic motion are met. The form of the Navier-Stokes equation, assuming geostrophic equilibrium, is presented, and the resulting relationship between the water velocity and the Ocean Bottom Pressure (OBP), determined on the basis of solutions of the L2 level from GRACE, is shown. The obtained velocities were compared with the results of selected programs implementing direct measurements of ocean currents, carried out in the Atlantic area. A preliminary analysis of the obtained results and their summary are also shown. The research covers the period from April 2002 to April 2021.

Session 4
Wednesday morning 8 a.m. CEST (UTC+2)

S04C01 Current availability and distribution of Congo Basin's freshwater resources

M. Tourian (Univ. Stuttgart), F. Papa, O. Elmi, N. Sneeuw, B. Kitambo, R. M. Tshimanga, A. Paris, S. Calmant

The Congo Basin is of global significance for biodiversity and the water and carbon cycles. However, its freshwater availability remains highly unknown. Here, we leverage a method to characterize the relationship between Drainable Water Storage Anomaly (DWSA) and river discharge across the entire basin. We obtain DWSA by subtracting spaceborne estimates of the Lake Water Storage Anomaly (LWSA) and the Wetland Water Storage Anomaly (WWSA) from the Total Water Storage Anomaly (TWSA) of GRACE. Our results show that currently the Congo Basin's Total Drainable Water Storage lies within a range of 476 km3 to 502 km³, unevenly distributed throughout the region, with 63% being stored in the southernmost sub-basins, Kasa ̈ı (220–228 km³) and Lualaba (109–169 km³), while the northern sub-basins contribute only 173±8 km³. We further estimate the hydraulic time constant for draining its entire water storage to be 4.3 ± 0.1 months, but, regionally, permanent wetlands and large lakes act as resistors resulting in greater time constants of up to 105 ± 3 months. Our estimate provides a robust basis to address the challenges of water demand for 120 million inhabitants, a population expected to double in a few decades.

S04C02 Inference of river signal in hydrological loading effects in South America from space geodesy

J. Nicolas (Cnam / GeF), J. Verdun, J.-P. Boy F. Durand, A. Koulali, P. Clarke

Continental water storage changes induce an important part of the loading signals recorded by space geodetic techniques. Nevertheless, discrepancies exist between surface deformation time series computed from GNSS (Global Navigation Satellite System), derived from GRACE (Gravity Recovery And Climate Experiment) / GRACE-Follow On missions and predicted loading signal computed from global circulation models. Indeed, some of the hydrological components, and in particular surface waters, may be missing in some hydrological models. This is especially an issue in South America where almost half of the seasonal water storage variations are due to surface water changes, e.g., rivers and floodplains. We derive river storage variations by rerouting runoffs of global hydrology models for the main river basins of South America. Using Multichannel Singular Spectrum Analysis (M-SSA), we extract coherent seasonal GPS displacements in the East, North and vertical directions. We investigate the benefit of introducing surface water circulation in loading models in South America using a set of more than 240 permanent GPS stations. We demonstrate that modeling the river storage induced loading effects significantly improve the agreement between observed vertical and horizontal displacements and loading models. Such an agreement has been markedly achieved in the Amazon basin. Whilst the initial models only explained half of the amplitude of GPS, the new ones compensate for these gaps and remain consistent with GRACE. Better inferring loading signals using these new models will help to extract and better understand signals induced by extreme events and climate change interannual signature.

S04C03 Assessment of level-2 data products from GRACE Follow-On satellite mission using water mass variations in lakes

P. Ditmar (TU Delft)

Since the launch of GRACE satellite mission in 2002, satellite gravimetry became a commonly used tool to study mass redistribution in/between different compartments of the Earth system. More than 10 data processing teams deal with level-1b data delivered by the GRACE mission and its successor, GRACE Follow-On (GFO). They produce, among other, different variants of the level-2 data product: monthly "snapshots" of the Earth's gravity field, each of which is composed of a set of spherical harmonic coefficients. In this study, we assess level-2 data products based on about 4 years of GFO data. To that end, we use information about water level variations is selected lakes, which is delivered by satellite altimetry. In doing so, we focus on interannual variatio<ns, which allows us to mitigate the impact of steric signals (those signals are predominantly caused by thermal expansion of water and demonstrate a pronounced annual periodicity). Then, water level variations can be directly converted into variations in water mass in a given lake. A comparison of GFO-based and altimetry-based water mass time-series includes a co-estimation of a scaling factor per lake that is to be applied to the former time-series in order to ensure its best match to the latter one. This scaling factor is compared to the "theoretical" one which reflects the fact that GFO-based time-series only contain signals up to a certain maximum spherical harmonic degree. In this way, different variants of GFO data products are compared in terms of signal damping. Such a damping may be caused, e.g., by an attempt to co-estimate too many auxiliary parameters in the course of gravity field modelling, which may partly absorb signals in the data. Of course, a comparison of GFO-based and altimetry-based water mass time-series also allows noise levels in the former time-series to be estimated. The obtained results may help the community of GFO data users to make a motivated choice of the data product(s) to be used as input in their studies

S04C04 Sediment transport in Indian rivers high enough to impact satellite gravimetry

A. Klemme (Univ. of Bremen), T. Warneke, H. Bovensmann, M. Weigelt, J. Müller

Satellite gravimetry is a key component in the investigation of groundwater depletion on the Indian subcontinent. Terrestrial mass loss by sediment transport in rivers is assumed to be below the detection limit of current satellites like GRACE-FO. Thus, it is not considered in the calculation of terrestrial water budgets. However, the Indian subcontinent is drained by the Ganges and Brahmaputra rivers, which constitute one of the world’s most sediment rich river systems. We find that the impact of sediment mass loss within the combined Ganges-Brahmaputra-Meghna catchment accounts for (4±2)% of the long-term gravity decrease currently attributed to groundwater depletion. For erosion-prone Himalaya regions, the correction for sediment mass loss reduces the local trend in equivalent water height by 0.22 cm/yr, which is 14% of the observed trend.

S04C05 Towards separating temporally-correlated noise from residual gravity signals in GRACE TWS time series data

R. Hohensinn (ISSI Bern), U. Meyer, M. Lasser, M. Rast

A major scientific product of the GRACE/GRACE-FO missions are observations of terrestrial water storage (TWS). Being provided for over two decades, these data provide unique insights into hydrological dynamics on a global scale, and allow for quantification of climate-change related effects. For a reliable quantification of TWS variations, it is important to provide functional and stochastic models that best explain the data. Although spatial covariance models of GRACE TWS data are well developed, temporal covariances are often left unexplained. However, this results in unrealistic and too optimistic parameter uncertainties, i.e., those of TWS trends.

By assessing the post-fit residuals of the global gravis TWS dataset, we show that the standard TWS time series model should account for the existence of temporal correlations that are present in the data. For a major part of TWS data, power-law noise models best explain temporal covariances. We further show that the magnitude of estimated uncertainties of the trend function strongly depend on the intensity of time correlations. By means of a clustering analysis it is demonstrated, that regions (e.g., river basis) can be characterized and separated by common-mode TWS signals, which supports the explanation of regional hydrological effects. We highlight how these signals can be parameterized in the functional model, and how optimal model combinations can be chosen by means of information criteria. This also includes the choice of temporal covariance models other than power-

law noise (e.g., autoregressive noise). To the end, we apply the same methodology to the JPL mascon RL06 dataset, and explore differences in noise and signals w.r.t. the gravis dataset.

We conclude that – in order to accurately quantify hydrological variations – the TWS uncertainty budged should account for temporal correlations present in the data. For providing unbiased parameters, both the functional and the stochastic model should be jointly estimated. Until not all TWS signal constitutes are explained and validated, an empirical noise calibration method provides a realistic explanation of TWS data uncertainties..

S04C06 The second release of COST-G GRACE-FO combined monthly gravity fields

U.Meyer (Univ. Bern), M. Lasser, C. Dahle, C. Förste, S. Behzadpour, I. Koch, A. Jäggi

The Combination Service for Time-variable Gravity fields (COST-G) provides monthly gravity fields of the GRACE, GRACE-FO and Swarm satellite missions, which are derived by combination of the individual time-series of the analysis centers around the world. The GRACE-FO combination has been operationalized and further developed in the frame of the Horizon 2020 project Global Gravity-based Groundwater Product (G3P). A significant reduction of noise could be achieved by the adaption of the weighting scheme, the inclusion of the new AIUB-GRACE-FO-RL02 time-series, which makes use of empirical noise modelling techniques, and the use of an alternative accelerometer transplant product, which improved the determination of the C30 gravity field coefficient, important for the derivation of ice mass change in polar regions. We present the new time-series of combined GRACE-FO monthly gravity fields and compare it in terms of signal and noise content to the original RL01 combination.

S04C07 Redefining the Deterministic Model for the GRACE Total Water Storage Time Series

O. Gunes (Yildiz TU), A. Klos, A. Lenczuk, C. Aydin, J. Bogusz

Total Water Storage (TWS) has been monitored by the Gravity Recovery and Climate Experiment (GRACE) mission and its successor, the GRACE Follow-On mission. Groundwater, surface water, and water from snow and glaciers are all included in the TWS description of the hydrosphere's natural variability. Harmonic regression functions are used to estimate monthly variations in global TWS values, assuming a linear trend and seasonal signals. However, climate change, floods, or droughts, as well as increased human water withdrawals as a potential cause of the nonlinearity in the actual long-term variations of the TWS time series may be mentioned. For the purpose of quantifying and explaining this nonlinearity, we present a novel approach to a deterministic model of TWS time series derived from the Goddard Space Flight Center (GSFC) global mascon solution. The redefined deterministic model incorporates a polynomial function along with the seasonal components. These polynomial functions have a third, fourth, or fifth degree; the optimal degree is chosen independently for each mascon. We showed that the form of a polynomial function is physically reasonable and spatially consistent. Greenland, Antarctica, Alaska, the Great Lakes of North America, the Mississippi River Basin, the eastern part of South America, the Tigris and Euphrates River Basins, southern Africa, and the Caspian Sea region are mostly affected by long-term changes other than linear ones. The proposed model can determine nonlinearity in the long-term changes caused by dry and wet periods, which are captured by the climate index. This aids in the comprehension of GRACE signal complexity. Overall, the results indicate that polynomial functions improve TWS time series modeling. We note that the RMS values improved by up to 50% in the areas with the largest nonlinearities. This model also allows the mapping of extreme dry and wet periods that result in nonlinearity.

Keywords: GRACE, deterministic model, polynomial function, nonlinearity

S04C08 Long-term Trend Estimation of Climate Related Mass Transport in Satellite Gravity Simulations

M. Schlaak (TU Munich), M. Graf, R. Pail

To reliably distinguish long-term trends from interannual variations an observation time span of 30 years is necessary. With GRACE and GRACE-FO already covering two decades of observation, and the future Mass change And Geosciences International Constellation (MAGIC), as a cooperation of ESA and NASA, planned to be launched in the late 2020’s, the necessary observation period comes into reach.

In this contribution different parameter models are compared that directly estimate the long-term trend from simulated satellite gravity observations. To evaluate the different parameter models a closed-loop simulation environment is set up using mass transport trends in components of the Terrestrial Water Storage (TWS) as input signal, which is extracted from a GFDL-CM4 (SSP5-8.5) timeseries. This study examines parameter models such as the direct estimation of long-term trend and annual signal as well as a trend co-estimation in addition to monthly solutions. In the example of local basins, the global spherical harmonic parameter models can be compared to mascon basis functions. The potential of satellite gravity missions to contribute to the determination of long-term trends will be emphasized. The results show that satellite gravity observation may become an important measure to improve and/or validate climate models in the future.

S04C09 Climate variability as a major forcing of recent Antarctic ice-mass change

M. King (Univ. of Tasmania), K. Lyu, X. Zhang

Multiple geodetic datasets show the Antarctic Ice Sheet has overall lost mass over recent decades, and hence contributed to sea-level change. The forcing of the multi-decadal mass trend is not well understood; its shorter-period variability has been partly associated with El Niño Southern Oscillation (ENSO) both for the grounded ice sheet and its bounding ice shelves, but the connection with the dominant climate mode, the Southern Annular Mode (SAM), is not clear. Here we show that space gravimetric (GRACE) estimates of major ice-mass variability over 2002-2021 may be largely explained by a simple linear relation with both SAM and lagged-ENSO. We decompose the detrended GRACE time series using empirical orthogonal functions and show that the principal components are dominated by decadal variability that correlate closely with detrended, time-integrated SAM and ENSO indices. Multiple linear regression reveals that SAM and/or ENSO explain much of the decadal variability from the whole ice sheet down to individual drainage basins, while approximately 40% of the net whole-of-ice-sheet change (2002-2021) can be ascribed to persistent SAM forcing. Understanding the forcings of SAM variability over the GRACE period, which is largely anthropogenic over multi-decadal timescales, may be a pathway to partially attributing ice-sheet change to human activity.

S04C10 Time series of Mass Trends for the Greenland Ice Sheet and Peripheral Glaciers

M. Graf (TU Munich), M. Schlaak, R. Pail

In our study, we want to combine gravity field time series and geometric information on changing ice volumes in order to estimate high-resolution ice mass balances for the Greenland ice sheet and its periphery.

Ice mass estimations, only based on gravity field time series, suffer from the so-called leakage effect due to the limited resolution of a few 100 km. Consequently, there are physically unreasonable assignments of negative mass changes to nearby oceanic areas. In our approach, we handle this effect by a redistribution algorithm. In addition to reducing the leakage effect, we infer geometric information on the changing ice volumes in order to localize regions, where one can expect immense mass changes. To properly introduce the geometric information, we use a Tikhonov regularization with different parameters depending on the surface type: sea surface, land surface and ice-covered surface.

In an iterative procedure we gain the optimal weighting from simulated GRACE-type gravity field time series based on ESA's earth system model (ESM). After applying the resulting weights, the de-leakaged field is compared to the full-resolution AOHIS by a statistic measure. Assuming that our simulated gravity field time series is sufficiently similar to a real GRACE time series, we apply the regularization parameters within the combination approach of GRACE gravity fields and geometric information.

Applying this method to GRACE data in the period 2002 to 2016, maps of mass rates for five year intervals are determined. Furthermore, we compute mass rates for the total ice sheet and achieve similar results of ca. -100 Gt/a to -260 Gt/a as the Ice sheet Mass Balance Inter-comparison Exercise (IMBIE).

S04C11 Spatially resolved glacial isostatic adjustment and ice sheet mass changes within a global inversion framework: feasibility proven by experiments with simulated satellite data

M. Willen (TU Dresden), M. Horwath, TU Dresden A. Groh, V. Helm, B. Uebbing, J. Kusche

Mass loss estimates for the Antarctic Ice Sheet and Greenland Ice Sheet over 2010–2019 vary from 94 to 202 gigatons per year and from 197 to 290 gigatons per year, respectively, according to the 6th IPCC Assessment Report quoting The IMBIE-Team. For gravimetric mass balance estimates, a large part of the uncertainty propagates from the modelled Glacial Isostatic Adjustment (GIA) mass effect. For both ice sheets, solutions of the GIA mass effect differ by several tens of gigatons per year.

We present work towards resolving the present-day effect of GIA over ice sheets by combining satellite gravimetry, satellite altimetry, and regional climate and firn modelling. To overcome limitations of regional investigations, we set up a global inversion framework. In Greenland, we parametrize GIA with a single fingerprint. In Antarctica, we apply a more spatially resolved GIA parametrization using a number of locally concentrated, globally defined GIA patterns. Furthermore, we parametrize ice mass changes and changes of the firn air content over both ice sheets.

Here, we examine whether a joint estimate of GIA and ice mass change is feasible under the presence of realistic errors in the data sets. Simulation experiments demonstrate that the GIA signal in Antarctica can be spatially resolved when realistic error covariance information is incorporated. From simulation experiments we find that, over an observation period of 10 years, the error of the integrated Antarctic GIA effect is 8 % and 5 % of the integrated GIA signal from two alternative global GIA models. Further we find that the spatial RMS error is 31 % and 51 % of the RMS of the two GIA signals.

S04C12 AGATA – A new SCAR Programme Planning Group

M. Negusini (INAF – IRA), L. Alfonsi, N. Bergeot

The Antarctic Geospace and ATmosphere reseArch (AGATA) Programme Planning Group is a coordinated, worldwide effort to monitor, investigate and better understand the physics of the polar atmosphere and the impact of the Sun-Earth interactions on the polar regions. It is endorsed by SCAR (Scientific Committee on Antarctic Research). If successful, AGATA will establish a new Research Programme representing the geospace and the polar atmosphere sciences within SCAR after more than 10 years of lack of similar topics (https://www.scar.org/science/agata/home/).

AGATA ambition is to contribute to answering the outstanding scientific questions within atmospheric and space physics:

- How are different atmospheric layers coupled in the polar regions?
- How does the upper polar atmosphere respond to increased geomagnetic activity, including energy transfer from space into the ionosphere?
- How can we improve the understanding of the Antarctic atmosphere by radio signals from the GNSS or other satellites, and from ground-based radars?

AGATA was proposed by experts coming from 40 international institutions, taking advantage of existing and planned instrumentation in Antarctica and in the Arctic and satellite-based observations, and it aims to coordinate research efforts and data exchange. This bi-polar perspective allows the study of significant interhemispheric asymmetries in the atmospheric response observed in the polar regions.

AGATA started in January 2023 and this paper will give an overview of the endeavour trying to attract new scientists (especially early career researchers and students) to support the application of the new Research Programme.

Session 5
Wednesday afternoon 5 p.m. CEST (UTC+2)

S05C01 Quantifying impact of drought and groundwater management on the Santa Clara Valley aquifer-system using InSAR deformation timeseries over 2017-2022

K. Ghobadi-Far (Virginia Tech), S. Werth, M. Shirzaei

Groundwater is essential in the Santa Clara Valley (SCV), since about half of the water used in the Santa Clara County is pumped from aquifers. To ensure a sustainable groundwater supply and to prevent permanent aquifer compaction, particularly during drought periods, the SCV Water District employs a comprehensive groundwater management plan. We used ~100 thousands of vertical deformation timeseries with weekly sampling over 2017-2022 from Interferometric processing of Sentinel-1 SAR images to i) examine the mechanical response of the SCV aquifer-system to varying groundwater levels, ii) quantify the groundwater volume loss during the most recent California drought (2019-) applying a poroelastic model, and iii) evaluate the success of managed aquifer recharge by the SCV water district starting in late 2021. We show that SCV experienced land subsidence of up to 30 mm during the drought period from March 2019 to November 2021, three times as much as the peak-to-peak mean annual variability. We show that the surface deformation over 2017-2022 is due to the aquifer-system's elastic (i.e., recoverable) response to pore pressure change. Moreover, we demonstrate that most of the surface deformation in the confined aquifer is driven by groundwater dynamics at depths below 120 m, indicating that majority of the groundwater used is pumped from deep aquifer layers. Our InSAR results also confirms that the fast groundwater depletion due to drought conditions since early 2019 has slowed down starting from late 2021, which we attribute to increased managed aquifer recharge by the SCV Water District.

S05C02 2023 Winter Rain and Snow Replenishes Subsurface Water in California, Beginning to Break the Prior Three Years of Drought

D. Argus (JPL), H. Martens, A. Borsa, D. Wiese, M. Swarr, N. Lau, Q. Cao, M..ing Pan, F. Landerer, P. Gardner

Heavy precipitation from a series of atmospheric rivers between Dec 27, 2022 to Jan 15, 2023 delivered 92 cubic kilometers of water into California's Sacramento-San Joaquin (SSJ) river basin, an amount equal to the median annual precipitation over the past seventeen years. In this study, we (a) integrate GPS elastic displacements and GRACE gravity to extend the time series of Sacramento-San Joaquin-Tulare water storage in Argus et al. [GRL 2022] to the present; (b) infer the accompanying change in subsurface water, and (c) track the daily flux of surface water through the basin. Contrary to predictions of minimal subsurface storage in surface hydrology models, we find that 30% of annual rain and snowmelt is stored as subsurface water. Drought is conventionally assessed in terms of water availability in mountain snowpack, soil moisture, and artificial reservoirs. Our findings of large subsurface water changes suggest that subsurface water should be included in metrics for evaluating drought.

S05C03 The Importance of High Sierra Nevada Snowpack for Recharging the Central Valley Aquifers

S. Werth (Virginia Tech), M. Shirzaei, G. Carlson, R. Bürgmann

We establish that groundwater wells in deep aquifers of the Central Valley, California, USA, exhibit different timing for annually maximum groundwater levels (GWL) compared to maximum groundwater storage (GWS). This difference in annual phase indicates that, besides water storage redistribution, further hydrogeological processes must be driving at least one of these hydrological variables. It is well known that groundwater level changes in confined aquifer units as well as corresponding land deformation are driven by changes in water pressure as much as by storage. Through a wavelet-based time-frequency analysis, we carefully quantify, assess and compare the annual variations in hydrological and geodetic datasets: meteorological fluxes, groundwater levels, water cycle components including GWS variations from GRACE satellites, and vertical land motion from GNSS as well as InSAR. Our findings indicate that the Sierra Nevada Mountains play a more prominent role in the recharge of California’s deep Valley aquifers than previously assumed. We formulate a conceptual model providing an explanation for this connection, which is consistent with the made observations. Process-based model experiments for vertical water pressure propagation further support our findings. We suggest that

hydrological models used for groundwater management plans include the Sierra Nevada Mountains for accurate predictions of groundwater development impacts in the Central Valley.

S05C04 Characterization of changes in groundwater storage in the Lachlan Catchment, Australia, derived from observations of surface deformation and groundwater level data

M. Razeghi (ANU), P. Tregoning, M. Shirzaei, K. Ghobadi-Far, S. McClusky, L. Renzullo

Global Positioning System (GPS) deformation measurements were combined with groundwater level data to examine the spatiotemporal variability of groundwater storage in the Lachlan Catchment located in central New South Wales (Australia). After correcting for effects of glacial isostatic adjustment, non-tidal oceanic and atmospheric loading as well as hydrologic loading using existing models, we show that the seasonal and interannual variability of ground deformation and hydraulic head level data, extracted using wavelet time-frequency analysis, exhibits an in-phase behaviour, indicating that the observed surface deformation is the poroelastic response to groundwater pressure change in aquifer system. Combination of GPS displacement and groundwater level change enables the estimation of elastic skeletal specific storage coefficients, which were then used for estimating groundwater storage changes. The estimated groundwater storage changes clearly reflect the four climate events of the Lachlan catchment since 1996: (1) the Millennium drought over 1996–2009, (2) the 2011–2012 La Nina and two significant floods in 2012 and 2016, (3) the drought conditions from mid–2017 to late–2019, and (4) the return of La Nina conditions since early 2020. We also found annual and long-term groundwater storage variations of respectively ~25±2.7 GL and ~-5±0.57 GL/yr over the period 2012 - 2021. Moreover, we show that groundwater level fluctuations can be predicted from GPS displacement measurements and storage coefficients with sufficient accuracy (80% correlation and 70% RMS reduction when compared in terms of seasonal cycle). This study provides essential information that can contribute to future groundwater planning, management, and control over the Australian continent.

S05C05 Climate Change and Anthropogenic Impacts on Disappearing Water Sources (Lake Urmia)

M. Khorrami (Virginia Tech), M. Shirzaei

Lake Urmia, located in the northwest of Iran, is one of the largest hypersaline lakes in the world. This lake has shrunk dramatically over the last two decades because of a variety of climate and mismanagement reasons. Lake Urmia lost almost 45 percent of its area and 85 percent of its volume causing more than 1.6 million $US of loss to ecotourism and outdoor recreation in 2019. Here, we use Synthetic Aperture Radar (SAR) data acquired by Sentinel-1A/B satellites to investigate the lake water surface change from 2017-2022. For this purpose, we apply a Bayesian approach to generate probabilistic water area maps, which contain each pixel its probability to be water rather than binary information. Using lake water level change over a long period of 1965-2022, we then calculated the water volume change in the lake. We further evaluated the in-situ data such as precipitation, drought index variations, and anthropogenic data such as dam construction in the region to understand the link between climate change and anthropogenic with the shrinkage of this lake. The outputs of this study can be used to improve our understanding of the current situation of this lake and to increase the hope of saving the lake by managing the water resources in the area.

S05C06 Analysis of diurnal IWV cycle and evaluation of artificial mismatches in ERA5 over Europe by using GNSS

P. Yuan (KIT), R. Van Malderen, X. Yin, H. Kutterer

Atmospheric water vapor is generally characterized by a diurnal cycle, although its intraday irregular variations can be very intensive. The diurnal Integrated Water Vapor (IWV) cycle is known to be related to various hydrometeorological processes, such as solar heating, evapotranspiration and condensation due to changes in temperature, underlying surface conditions, and advection of air at different spatial scales. Therefore, characterizing the diurnal IWV cycle is crucial for the understanding of the abovementioned processes. However, the accurate estimation of diurnal IWV cycle remains a challenge due to the limitations in precision and temporal resolution in many water vapor sensing techniques. Recently, ECMWF has released its fifth generation reanalysis (ERA5) with a temporal resolution of 1-hour, which is much improved compared to its predecessor ERA-Interim with a resolution of 6-hour. However, few studies have evaluated the diurnal IWV cycle modelled by ERA5.

Ground-based Global Navigation Satellite System (GNSS) is an effective technique of water vapor sensing, with the advantages of high-accuracy and high temporal resolution. In this work, we used 1-hourly GNSS Integrated Water Vapor (IWV) time series from 1994 to 2018 at 108 GNSS stations in Europe to analyze their diurnal IWV cycles. The diurnal IWV cycles in Europe are considered to be associated with solar heating, land-sea breeze, and orographic circulation. Moreover, we noticed obvious mismatches in the diurnal cycle of ERA5 IWV between 09 and 10 UTC as well as between 21 and 22 UTC. Although the mismatches in some meteorological variables are listed as a known issue in the official document of ERA5, their magnitudes and spatiotemporal characteristics have not been precisely evaluated. Therefore, we evaluate the mismatches in the diurnal cycle of ERA5 IWV by using GNSS.

S05C07 Various climate phenomena reflected in precipitable water vapour derived from GNSS observations

Z. Baldysz (Nat. Res. Inst., Poland), G. Nykiel, B. Latos, D.B. Baranowski

The vital role of water vapour in weather and climate sciences is well known. Thus studying its spatiotemporal variability is crucial in understanding atmospheric processes on a regional and global scale. Among many traditional techniques for monitoring its presence and variability over time, the global navigation satellite systems (GNSS) technique is distinguished by several advantages. Firstly, GNSS can deliver a high temporal resolution of observations, which can be collected regardless of weather conditions. GNSS is a relatively low-cost method for integrated moisture monitoring compared to other techniques since it often relies on an already existing geodetic network. Now, networks like International GNSS Service (IGS) have collected data since 1994, making it possible to use them in climate studies. Finally, GNSS is a stuff-free technique which can be used in field campaigns without restrictions related to manual execution/start of measurements.

In this study, 18-year time series of GNSS-derived precipitable water vapour (PWV) from the global tropics have been used to analyse how accurately GNSS can reflect various climate phenomena, such as global warming or interannual variability. We proved that GNSS PWV time series, homogenously reprocessed using the precise point positioning approach, are capable of reliably reflecting integrated moisture variability on the inter-annual time scale. The singular spectral analysis method applied to the long-term GNSS PWV time series allowed us to distinguish anomalies driven by such various climate modes as El Nino Southern Oscillation or Indian Ocean Dipole. Integrated moisture anomalies over part of the stations also showed clear dependency on the smaller-scale phenomena, e.g. North Pacific Gyro Oscillation. Additionally, an analysis of the influence of the local sea surface temperature on GNSS PWV was also performed, showing clear consistency between these two variables. Finally, we show preliminary analyses of the use of GNSS signals in a diurnal time scale.

S05C08 On the approach to GNSS tomography of the troposphere based on multi-GNSS observations from single station

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The broad nature of environmental monitoring requires the integration of various interdisciplinary skills and fields, including geodesy, which is mainly concerned with the creation and analysis of spatial data. These data alone are not sufficient for environmental monitoring and are often integrated with data from other methods. One of them is remote sensing, which aims to collect data about the environment using a wide range of satellite and airborne platforms. This especially applies to the content of water vapor in the Earth's atmosphere. Determining the distribution of water vapor in the troposphere plays a significant role in weather forecasting and climate research. The appearance and implementation of GNSS led to the wide development of their applications, including for monitoring the atmosphere, and, especially, its lower part - the troposphere. GNSS tomography of the troposphere can be used to generate a three-dimensional distribution of water vapor over the part of the troposphere covered by a GNSS station. In this study, one possible approach to GNSS tomography corresponding to the model distribution of GNSS signals is proposed. We have analyzed three spatio-temporal models of water vapor density dependence in troposphere voxels. In the framework of the research conducted, a software implementation of the Levenberg-Marquardt algorithm from the mathematical package ALGLIB was used to evaluate the solutions of the tomography equations. The approach was tested using one station of EUREF Permanent GNSS Network - GANP00SVK (Ganovce - Poprad, Slovak Republic) and evaluated by comparing data

received from the multi-GNSS observations with radiosonde data from the corresponding aerological station 11952 (Poprad - Ganovce, Slovak Republic).

S05C09 A statistical method for the attribution of change-points in segmentation of IWV difference time series

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Many techniques employed for homogenizing climate time-series from station data rely on comparing the data to a reference series. This approach helps eliminate the common climate signals and improves the accuracy of change-point detection methods. However, it can be challenging to determine if the detected change-point originates from the main series or the reference series. This study presents a statistical method to aid in making this decision. It works by combining the data from the main station with the data from at least one nearby station, where the data from each station is actually composed of two series: a target series and a reference series. In our study, we consider daily GNSS Integrated Water Vapor (IWV) measurements as the target series and the Fifth ECMWF reanalysis (ERA5) as the reference series. From these four base series, six series of differences were created, and a statistical test was performed to identify if there was a significant change in mean before and after the tested change-point in each of the six series. Finally, to determine which of the four base series was impacted by the change-point(s), a predictive rule was used.The statistical analysis employed in this study is a generalized linear regression approach taking into account both heteroscedasticity and autocorrelation. The predictive rule is constructed on a dataset built from the test results obtained on the real data using a resampling strategy. Cross-validation was used to evaluate the performance of four popular machine learning methods such as Linear Discriminant Analysis, decision tree (CART), random forest and the k nearest Neighbor. Out of those, the random forest was found to be the most effective. The results of the proposed method applied to a real dataset were consistent and plausible with respect to GNSS metadata and our knowledge of the data. The study concluded that 41% of the change-points are caused by GNSS data, 15% by ERA5 data, and 25% are the result of coincident detections.

S05C10 DORIS-based Precise Orbit Determination and its geodetic applications

V. Kumar

DORIS (Doppler Orbitography Radio positioning Integrated by Satellite) is a space-based piggyback satellite system that when used as a terrestrial measurement system can provide an accuracy of 10 cm in the absolute position measurement and in the order of sub-cm accuracy in relative measurements. When it rides piggyback on any satellite system can provide an orbital accuracy up to cm level. Precise Orbit Determination (POD) is the process of accurately tracking the position and velocity of a satellite in orbit. DORIS is an excellent satellite tracking system supporting the precise orbit determination of satellites. The accuracy of the POD does not affect only the quality of the estimated orbit ephemerides, but also the quantities derived from a free-network solution, mainly the station coordinates and the Earth rotation parameters (ERP). The precisely determined orbit can be used in many altimetric applications including estimating the mean sea surface, marine geoid, and vertical land motion, to derive vertical deflection and mean dynamic topography. Apart from that, the gravity field variations can also be determined more precisely. GNSS data observations alone have been used so far in India to study the plate tectonics movements and earthquake predictions in the Indian subcontinent. Since DORIS and GNSS both have homogeneous network distributions and are complementary to each other, the DORIS data observations can be combined with GNSS data observations to study plate tectonics movements and earthquake predictions more effectively. Not only that since in DORIS the signal is transmitted from the ground, but processing DORIS measurement residue helps us to better understand and model what occurs in between the layers of the atmosphere which can be used for precise tropospheric modeling.

This space-based geodetic measurement technique has been used for the past three decades the world over, for precise measurement on the ground as well as on all oceanographic and altimetric satellite missions, it has not been introduced in India so far. Since our Space Research Organization has been launching several satellite missions and DORIS is being used for computation of the precise orbits, this technique has come to stay for a long time. The National Centre for Geodesy was set up by the Department of Science and Technology at the IIT Kanpur has also plans to set up a Geodesy village, where the DORIS station is going to be established and our

DORIS data will be used in defining ITRF.

S05C11 Regularized Kalman Filter in application to the Chandler wobble of the pole

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We applied regularization procedure to the recurrent least squares and extended it to Kalman filter. Then we estimated polar motion, trying to filter out its eigen mode – Chandler wobble (CW) of the pole. This component has demonstrated very interesting behavior in recent decade. It almost disappeared in 2016-2020, now appears again. The phase of CW is changing. This happened once before in the history of observations around 1930s. The analysis of input excitation and comparison with oceanic, atmospheric angular momentum shows that their contributions do not quite explain the observed damping. The processes inside the Earth could be very important to explain the observed anomalies in the Earth's rotation.