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„Geodesy for Climate Research“

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Abstract book

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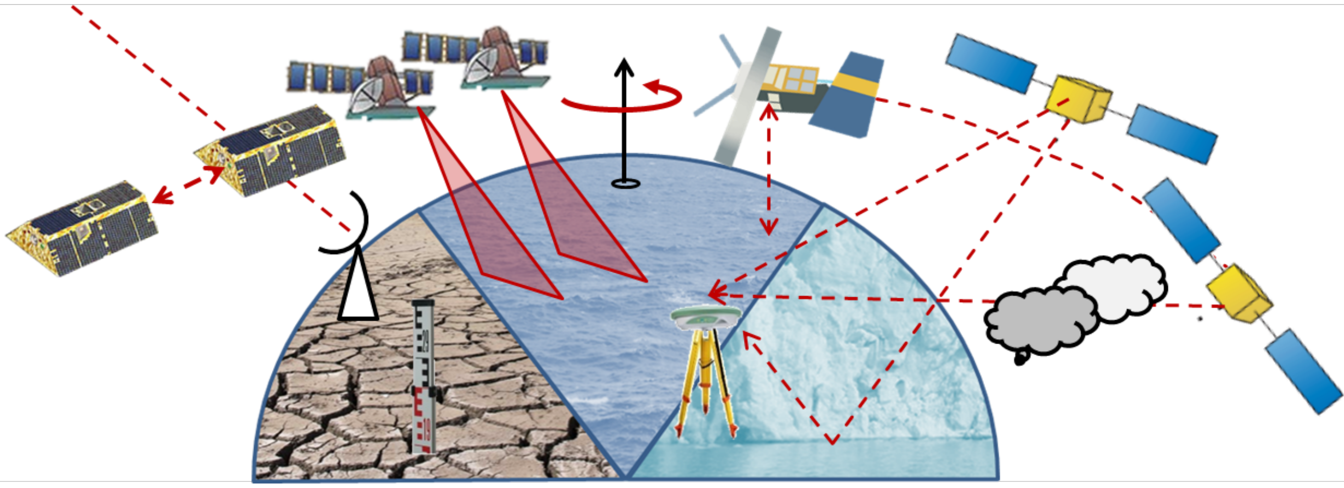

Organized by the Inter-Commission Committee on “Geodesy for Climate Research” of the International Association of Geodesy (IAG)

International Association of Geodesy

Session 1
Monday morning: 10 a.m. CET (UTC+1)

S01C01 PSDI: A Probabilistic Approach to Characterizing Drought Using Satellite Gravimetry

P. Saemian (Uni Stuttgart), M. J. Tourian, O. Elmi, N. Sneeuw, A. Kouchak

In recent years, the Gravity Recovery and Climate Experiment (GRACE) and its successor, GRACE Follow-On (GRACE-FO), by measuring Total Water Storage Anomaly (TWSA), have become essential for drought monitoring. However, many existing approaches fail to incorporate uncertainties inherent in GRACE-derived TWSA, such as those arising from orbital configurations, background models, and measurement errors. To address this limitation, we propose a novel perspective: instead of a deterministic view on the drought index, we move to a probabilistic view by introducing the Probabilistic Storage-Based Drought Index (PSDI). There we employ Monte Carlo simulations to generate a range of plausible TWSA realizations, capturing uncertainty and allowing for a probabilistic classification of drought severity. Then, instead of assigning a fixed drought category to each epoch, PSDI provides a probability value for different severity levels.

We assessed PSDI's performance against the conventional deterministic Storage-Based Drought Index (SDI) across major global river basins. The results reveal that the deterministic method frequently overestimates the severity of storage-based droughts. Furthermore, we analyzed PSDI's reliability during notable hydrological events spanning multiple continents, including North America, Europe, the Middle East, Southern Africa, South America, and Australia. Across all regions, PSDI characterized drought successfully with the added information of the probability. By offering a probabilistic perspective, PSDI enhances the realism of TWSA-based drought assessments, making it better suited for adaptive strategies and practical risk management.

S01C02 Impact of Climate Change on Drought Severity in the Great Artesian Basin: A Geodetic Approach Using GRACE and Climate Models

M. Razeghi (Uni. Of Southern Queensland)

This study investigates the projected impacts of climate change on drought severity in the Great Artesian Basin (GAB), Australia, using Gravity Recovery and Climate Experiment (GRACE) satellite observations and climate model outputs. By applying a multi-model ensemble approach, we evaluate the spatial and temporal variations in drought conditions under various future climate scenarios. We utilize Total Water Storage (TWS) anomalies from GRACE as a basis for calibrating climate model projections of terrestrial water storage (TWS) in the basin. The results indicate that all scenarios project an intensification of drought conditions in the GAB by the late century, with more pronounced effects under higher-emission pathways. This study highlights the value of remote sensing in refining climate model projections and underscores the importance of accurate TWS data for improving water resource management, particularly for agriculture and mining industries. Our findings suggest that integrating GRACE data with climate model predictions can provide enhanced accuracy for drought prediction, offering critical insights for decision-making in the context of climate adaptation and water management strategies.

S01C03 Potential of current and future satellite gravity missions for the evaluation of extreme events in global coupled climate models

K. Middendorf (HCU Hamburg), M. Schlaak, R. Pail, L. Jensen, H. Dobslaw, A. Eicker

Under the assumption that a warming climate leads to an intensification of the global water cycle, it can be hypothesized that also the occurrence frequency and severity of extreme events such as droughts or floods will increase in the upcoming decades to centuries. Global coupled climate models, which project the future evolution of various variables of the Earth's climate system are important tools for the analysis of such expected changes. To assess the reliability of the models and to identify possible systematic discrepancies, it is essential to evaluate the model output against observations.

In this study, present and future occurrences of extreme events are analysed in water storage time series simulated by coupled global climate models participating in the Coupled Model Intercomparison Project Phase 6

(CMIP6) using Extreme Value Theory and compared against spatio-temporal changes in water mass derived from GRACE and GRACE-FO. To assess the benefit of future satellite gravity missions such as the MAGIC double-pair constellation regarding the analysis of extreme events, we evaluate 50 years of long-term end-to-end simulations comparing GRACE-like and MAGIC like performances. The simulation environment is based on the acceleration approach and considers tidal and non-tidal background model errors as well as instrument noise of the acceleration and ranging instruments following the current MAGIC mission design studies. To evaluate the improved temporal resolution expected from the MAGIC constellation, extreme values derived from 5-daily gravity field models are compared to results obtained from monthly fields.

S01C04 Enhanced Water Budget Estimation for Small River Basins Using Machine Learning-Based Downscaling of GRACE Data

S.I. Deliry (Eskisehir Techn. Univ.), U. Avdan

Accurate estimation of terrestrial water storage (TWS) is critical for understanding hydrological dynamics in small river basins. However, the coarse spatial resolution of GRACE and GRACE-FO satellite data limits their applicability in localized water budget assessments. This study presents a machine learning-based spatial downscaling approach to refine GRACE/GRACE-FO TWS anomalies from ~55 km to 10 km resolution, using Random Forest regression with auxiliary datasets from NASA's FLDAS hydrological data and MODIS land cover data. Sub-basins of the Amu Darya River Basin, a highly water-stressed region in Central Asia, served as the validation site due to its diverse hydrological conditions. Our downscaling methodology demonstrates a strong correlation ($R^2 = 0.99$) between the downscaled and original datasets, significantly enhancing spatial detail while maintaining temporal consistency. The results reveal improved water budget estimations, with accurate representation of seasonal and long-term hydrological trends. By addressing resolution limitations, this approach offers new opportunities for improved hydrological modeling and sustainable water resource management in basins smaller than 150,000 km². The enhanced TWS dataset is compatible with high-resolution precipitation, evapotranspiration, and runoff datasets, enabling more precise integration in water availability and climate adaptation planning across diverse geographical settings. This research underscores the potential of advanced machine learning techniques in bridging data resolution gaps, supporting global applications in water-stressed regions, and ensuring robust monitoring of regional water dynamics for improved decision-making.

S01C05 Study of Terrestrial Water Storage variations in Cameroon using Satellite Gravimetry

M.M. Wako (Univ. de Yaoundé 1), F. Ghomsi, A. Vondou

Cameroon, a Central African country, is experiencing quantitative variations in water storage as a result of climate change and human activities. The aim of this study is to analyze the variations in water reserves in Cameroon using satellite gravity data (soil moisture), while linking them to climatic parameters, in particular rainfall. The data used were obtained from the GRACE (Gravity Recovery and Climate Experiment) and GRACE-FO (Gravity Recovery and Climate Experiment- Follow-On) satellite gravity missions for soil moisture, and from CHIRPS (Climate Hazards Group Infrared Precipitation with Station data) for precipitation for the period 2002-2021. The results, spread over annual and interannual time scales, reveal significant variations in terrestrial and groundwater storage. This study contributes to a better understanding of the dynamics of terrestrial water resources in Cameroon and can thus help to improve the management of this resource in the region.

S01C06 High-resolution land water storage simulations with OS LISFLOOD over six decades

L. Jensen (GFZ Potsdam), R. Dill, S. Grimaldi, H. Dobslaw

We employ the open-source OS LISFLOOD hydrological model to globally simulate time series of terrestrial water storage (TWS) and its individual storage compartments soil moisture, groundwater, surface water, and snow. To evaluate the quality of the model results we make use of different geodetic observation techniques, i.e., GRACE/-FO satellite gravimetry, GNSS station displacements, and satellite altimetry. We demonstrate that OS LISFLOOD with its various recent model improvements and developments is highly competitive to other hydrological models commonly used in the geodetic community, while providing global TWS in a so far unprecedented high spatial resolution of 1/20°.

In this contribution we focus on our ongoing work to further improve TWS simulations with OS LISFLOOD. This includes the consideration of anthropogenic water abstraction used for irrigation and industrial, domestic, energy, and livestock demands, as well as endorheic lakes (i.e., lakes without an outlet like the Caspian Sea, Lake Balkhash, or Lake Chad), which have not been so far accounted for. We will also present preliminary results from a first six decades-long (back to 1960) OS LISFLOOD experiment, which states an important data set for climate studies of TWS changes also beyond the GRACE era.

S01C07 COST-G: a note on uncertainty information

U. Meyer (Univ. Bern), M. Lasser, E. Boergens, A. Jäggi

The Combination Service for Time-variable Gravity fields (COST-G) provides consolidated monthly gravity fields (L2-products) and, thereof, derived global mass change models (L3-products) based on satellite gravimetry. The COST-G products contain uncertainty information, which, in the case of the L2-products, is derived empirically from the spread of the individual contributions to the combination and, in the case of the L3-products, has been calibrated over quiet ocean areas, where little geophysical short-term variability is expected.

We discuss the difficulties of formal uncertainty propagation in satellite gravimetry and compare the formal, empirical and calibrated uncertainty information of the individual products of the COST-G Analysis Centers (ACs) and the combined products derived thereof.

S01C08 Interferometric radar satellite and in-situ well time-series reveal groundwater extraction rate changes in urban and rural Afghanistan

N. Kakar (GFZ Potsdam), S. Metzger, T. Schöne, M. Motagh, H. Waizy, N. A. Nasrat, M. Lazecký, F. Amelung, B. Bookhagen

Population growth, climate change, and a lack of infrastructure have increased water demand and groundwater exploitation in urban and rural Afghanistan, resulting in significant ground subsidence in various regions.

Using Sentinel-1 radar-interferometric time-series data based on over 7-years (2015-2022), we assess country-wide Afghan subsidence rates for groundwater levels, precipitation, and changes in irrigation practices. Urban Kabul city and the growing agricultural sector of rural Ghazni provinces are of particular focus. In Kabul city, we compare spatiotemporal subsidence patterns to water table heights and precipitation amounts. In Ghazni, we monitored the transition from ancient to modern irrigation techniques by mapping solar-panel arrays as a proxy for electrical water pumping and evaluating the vegetation index as a proxy for agricultural activity.

Several provinces such as Kabul, Ghazni, Helmand, Farah, Baghlan, and Kunduz exhibit significant subsidence of more than ~5 ± 0.1 cm/yr. In Kabul, ground subsidence is most pronounced in the city center with a 6-yr total of 31.2 ± 0.5 cm, but it's the peripheral wells of the Kabul basin that exhibit the highest water-table drops, where aquifers are also thinner and wells are deeper. In Ghazni, a 7-yr total of 77.8 ± 0.5 cm ground subsidence was recorded. Before 2018 barren lands were transformed into farmland throughout the province, and traditional irrigation such as Kariz networks were replaced by electrical water pumps to tap groundwater, which enabled the conversion of barren land into farmland and marked the acceleration of ground subsidence after 2018. In addition severe droughts in 2020 and 2021 further exacerbated groundwater depletion, leading to m-wide and km-long desiccation cracks that appeared in the area with the highest irrigation volume.

S01C09 Regional Impacts of the El Niño-Southern Oscillation on Terrestrial Water Storage and Hydrological Angular Momentum: A GRACE-Based Cross-Correlation Analysis

L. Stumpe (GFZ Potsdam), R. Dill, H. Dobslaw

The El Niño-Southern Oscillation (ENSO) represents the most prominent inter-annual climate mode on Earth, characterized by quasi-periodic fluctuations in sea surface temperature and atmospheric pressure (Southern Oscillation) across the equatorial Pacific. Its warm (El Niño) and cold (La Niña) phases drive large-scale atmospheric circulation patterns, causing climate anomalies across all seasons. While ENSO primarily originates in the Pacific, its teleconnections extend globally, influencing the terrestrial water cycle worldwide. A growing body of research highlights significant linkages between ENSO and terrestrial water storage (TWS) in various regions, shedding light on its hydrological impacts. Given these connections, ENSO signals are expected to influence hydrological excitation functions of Earth rotation variations derived from terrestrial water mass distributions. On a wide range of time-scales, variations in Earth's rotation are caused by angular momentum exchanges of surface geophysical fluids with the solid Earth.

We investigate the influence of ENSO signals on the hydrological angular momentum using a two-step time domain cross-correlation approach. Lagged cross-correlation and regression analysis were performed between the MEI.v2 climate index and TWS anomalies using three datasets: GRACE/-FO time-variable gravity field solutions, the distributed hydrological rainfall-runoff model OS LISFLOOD, and the operational Land Surface Discharge Model (LSDM). The inter-annual time series were derived through decomposition using least squares fitting, followed by Butterworth low-pass filtering to capture ENSO periodicity. A global analysis of 100 hydrological basins enabled a spatial and temporal differentiation of ENSO impacts on regional TWS variability, forming the basis for computing regional hydrological angular momentum (HAM) functions. We will both discuss contributions from tropical latitudes that directly respond to modified atmospheric moisture flux pattern, but also extra-tropical regions that respond to ENSO conditions in the tropics only later in time. We thus aim to localize regional HAM contribution with a significant ENSO influence.

S01C10 Lunar factor as possible cause of anomalies in ERP and climate indexes

L. Zotov (SAI MSU, MIEM HSE), N. Sidorenkov, C. Bizouard

IIn the 2020s, we are observing anomalies in the Earth Rotation Parameters (ERP): the deepest minimum of LOD since 1930, Chandler wobble (CW) disappearance and phase change, and free core nutation (FCN) amplitude decrease. These changes are classified as decadal variability; their causes are not quite revealed. Their possible connection to climate variability indicates the fact that some climatological cycles have been in anomalous mode recently, in particular Quasi-Biannual Oscillation (QBO) and El Niño Southern Oscillation (ENSO) [1].

Since K. Lambeck described in his book [2] the anticorrelation of LOD and global Earth temperature, it is considered enigmatic. Now we see that the 90-year natural cycle is present in temperature, namely in the Atlantic Multidecadal Oscillation (AMO), which is now in a maximum positive phase, in LOD, and in CW variability. On the role of its common cause, we propose the lunar orbital cycle. Namely, the meetings of the perigee and ascending node, generally occurring every 6 years, happened in 1922, 1940 in the autumn equinox, and in 2006, 2024 in the vernal equinox, strongly modulating the tides [3]. These epochs correspond to anomalies in EOP and climate indexes, which could imply their connection.

[1] N. Sidorenkov, The Interaction Between Earth's Rotation and Geophysical Processes, Wiley-VCH Verlag, Weinheim, 2009

[2] K. Lambeck, The Earth variable rotation, Cambridge University Press, 1980

[3] L. Zotov, N. Sidorenkov, Ch. Bizouard, Earth Rotation Variations and the Moon Apsidal-Nodal Effects, Proceedings of Problems of XV conference and school Geokosmos-2024, Snt-Petersburg, Springer, 2025

Session 2
Monday afternoon 4 p.m. CET (UTC+1) **ORALS**

S02C01 Understanding Rain Gauge Systems: Installation Guidelines and Geodetic Applications (invited presentation)

F. X. Mengouna Ntsengue (Univ. of Yaoundé I), D. A. Vondou

This presentation explores the fundamental aspects of rain gauge systems and their critical role in geodetic applications. The focus is on two main components: the technical requirements for proper rain gauge installation and the integration of rainfall data in geodetic studies.

The discussion extends to practical aspects like data collection methods, quality control measures, and integration within larger geodetic networks. It also explores the role of precipitation monitoring in correcting geodetic measurements and its significance in long-term deformation monitoring studies. Special attention is given to challenges such as calibration procedures and data validation methods, along with solutions for maintaining accurate measurements.

S02C02 Rapid Water-Storage Gains in the Western US Driven by Atmospheric Rivers (invited presentation)

H. R. Martens (Univ. of Montana)

Geodesy is playing an increasingly significant role in observing, evaluating, and advancing our understanding of Earth's water cycle and climate variability. With ongoing improvements in observational precision, the extension of continuous data records, and the expansion of global monitoring networks, new opportunities are emerging to explore interactions between the solid Earth, atmosphere, and hydrosphere over multi-decadal timescales and with enhanced spatiotemporal resolution. Key applications include tracking extreme precipitation events, quantifying water storage changes at the watershed scale, and forecasting hydrological drought. This presentation will showcase examples from the western United States, a region characterized by recurring cycles of severe drought and rapid recovery, largely influenced by the frequency and intensity of seasonal atmospheric rivers (ARs). Observations of terrestrial water storage (TWS) from Global Navigation Satellite Systems (GNSS) indicate that strong AR seasons play a vital role in replenishing TWS reserves after prolonged drought. Moreover, substantial gains in subsurface storage can help to sustain water resources into subsequent dry years. Despite their benefits for drought mitigation, powerful ARs also pose risks to human communities, highlighting the need for careful water resource management. GNSS geodesy provides valuable perspectives not only on water quantity but also on watershed behavior, particularly in terms of infiltration and subsurface water retention, complementing independent tools for advancing the water and climate sciences and offering meaningful insights for decision-makers.

S02C03 Daily Hydrologic Drought Assessment using the United States GPS-Based Drought Index (US-GDI)

Z. Young (Univ. of Montana) H. R. Martens, Z. H. Hoylman, W.A. Franke, W. P. Gardner

Currently, drought management relies heavily on meteorologically derived metrics, such as the Standardized Precipitation Evapotranspiration Index. These methods provide valuable input constraints by characterizing precipitation variability; however, they are unable to provide insight into the quantity of total water storage retained within specific hydrologic pools (i.e., rivers, lakes, and groundwater). To better understand variability within these storages, we present an update on the status of the United States GPS-Based Drought Index (US-GDI). Our methodology advances those presented by Young et al, 2024. We produce an automated framework which provides rapid US-GDI hydrologic drought assessment solutions with a latency of ~48 hours. Final solutions are expected within 10-14 days. Solutions for the full study period are calculated daily, with hydrologic load estimates, GDI evaluations between one day and 48 months, and step offsets in the vertical component updated daily. To assess the sensitivity of the US-GDI to hydrologic resources, we present an analysis of the correlation between US-GDI timescales and to stream discharge, surface-reservoir storage/elevations, and groundwater across specific hydrologic units across the United States. To facilitate the distribution of the results, we introduce a webpage which provides direct access to all solutions provided by the US-GDI (including both hydrologic loading estimates, and US-GDI solutions for various time scales. The US-GDI represents an opportunity to significantly improve hydrologic resource preservation and management during periods of sustained hydrologic drought.

S02C04 Assessing hydrological loading impact on SIRGAS-CON geodetic coordinates through EMPCA correlation analysis

M. Carbonetti (Instituto Geográfico Nacional Argentino), M. Gende

This study analyzes the correlation between geodetic and hydrological time series in the Río de la Plata Basin and surrounding areas to assess the impact of water mass redistribution on vertical deformations observed in the SIRGAS-CON network. The WaterGAP Hydrological Model was used to quantify surface mass variations.

To achieve this, the Modified Principal Component Analysis (MPCA) method was applied, enabling the identification of predominant spatial characteristics and temporal variability. This approach decomposes time series into a reduced set of vectors that capture most of the data variance, providing a percentage estimate of each variability pattern's contribution. The modification introduced with respect to the classical method enabled the analysis of series that present discontinuities, missing data, or varying precision.

The optimal number of Principal Components was determined to ensure a meaningful representation of the dataset's variance. Homogeneous correlation maps were then computed to analyze spatial patterns, followed by an assessment of their temporal evolution. Finally, the correlation between geodetic and hydrological results allowed us to infer distribution patterns in which mass redistribution influences the coordinates of

GNSS stations in the SIRGAS-CON network.

S02C05 Enhanced Hydrological Frequency Analysis Using Advanced Signal Processing Techniques: Empirical Mode Decomposition and Hilbert-Huang Transform on GNSS Time Series

M. Esfandyari-Kaloukan (Univ. of Isfahan), S. Iran-Pour, A. Amiri-Simkooei

The Global Navigation Satellite System (GNSS) provides high-quality data with exceptional temporal resolution, making it ideal for studying hydrological frequencies. However, its ability to capture temporal and spatial variations is challenged by unknown high-frequency signals, often linked to tidal effects, which act as noise and interfere with hydrological analysis. Identifying and removing these components is essential for enhancing the clarity of key signals, such as annual and semi-annual cycles, which are crucial for understanding drought and rainy seasons. To address these challenges, GNSS time series data from California and Nevada were analyzed using signal processing techniques. The Fourier Transform provided an initial overview of dominant frequency components but struggled with the non-stationary nature of the signals. To overcome its limitations with non-stationary signals, advanced methods such as Empirical Mode Decomposition (EMD) and Hilbert-Huang Transform (HHT) were employed. These techniques decomposed complex time series into intrinsic mode functions (IMFs), allowing precise time-frequency analysis. High-frequency components, such as 158.56, 138.03 and 128.79 cpy, likely linked to tidal effects, were detected and removed, significantly improving signal clarity. The combined EMD and HHT approach successfully detected and clarified annual and semi-annual signals related to hydrological patterns. These signals revealed significant drought events in the GNSS time series, particularly during the periods of 2007-2009 and 2012-2016, along wetter periods observed in 2010 and 2017. The filtering of tidal disturbances which enhanced the detection of seasonal variations, providing valuable insights into regional water distribution, climate impacts, and improved clarity for environmental and hydrological monitoring.

S02C06 Assessment of hydrometeorological and hydroclimatic events using a new multivariate drought severity index

A. Lenczuk (Military Univ of Techn. Warsaw) C. Ndehedehe, A. Klos, J. Bogusz

The ongoing prominent regional and global changes in water resources are strongly affected by meteorological and climatic events. These changes are being successfully recorded by geodetic techniques, including the Global Positioning System (GPS) and the Gravity Recovery and Climate Experiment (GRACE). However, due to the several limitations of both techniques (such as low or sparse spatial resolution or systematic errors), not all hydrometeorological and/or hydroclimatic events are captured by single data sets. Therefore, to analyze them more reliably, we determine a novel Multivariate Drought Severity Index (MDSI). MDSI is estimated through the concept of Frank copulas and is based on DSIs determined from GPS-observed and GRACE-derived vertical displacements. GPS- and GRACE-DSIs are estimated for short-term (<9 months) signals of monthly-resampled displacements for locations of 25 permanent stations that are classified as benchmarks for hydrogeodesy over Amazon river basin. To assess the quality of results, we compared them with the traditional climate indices (Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI)), DSI-based on hydrological Global Land Water Storage (GLWS) model, and precipitation anomalies. We show that the proposed MDSI is a step towards improving the reliability of detection of dry and wet periods. We note that the wet and dry periods captured by MDSI are temporally consistent with rainfall extremes above 400 mm/month and below 100 mm/month, respectively. Moreover, we show that MDSI is most robust for more than 90% of selected stations identifying the exact number of events recorded in a particular Amazon climate zone. We also suspect that new MDSI would contribute to a better understanding of the impact of climate change on freshwater.

Session 3
Monday afternoon POSTERS

S03C01 The response of the ionospheric vTEC (Vertical Total Electron Content) to solar events, highlighting its variability (scintillation, ROTI index) occurring at high latitudes using GNSS data

N.K. Aimouche (Univ. of Science and Techn. Houari Boumediene), H. A. Omar

The ionosphere exerts a disruptive influence on GNSS signals, often amplified by plasma instabilities linked to solar events. In this work, we studied the response to solar events of the ionospheric vertical total electron content (vTEC) and scintillation activity (measured by the scintillation index, ROTI) occurring at high latitudes, using GNSS data from the IGS network. Our results highlight the spatiotemporal variation of the ionospheric environment. As we observed a hemispheric asymmetry in vTEC amplitude, significantly correlated with polar cap magnetic indices (PCS/PCN). In addition, the vTEC value shows a decrease at higher latitudes, illustrating the latitudinal dependence of the ionospheric response. Concerning scintillation activity, high-latitude stations show rapid fluctuations in vTEC, in contrast to the almost Gaussian curve observed at a mid-latitude station. As a result, scintillation measured by the ROTI index is much more frequent at high latitudes, we also noted a maximum ROTI value for stations located in or near the auroral zone, while the mid-latitude station shows low scintillation. The ultimate aim is to improve our ability to anticipate and forecast ionospheric disturbances caused by solar events in the high latitude regions where these disturbances are amplified, to improve our understanding of the fundamental mechanisms of the ionosphere and to perfect ionospheric models.

S03C02 A Kalman-based approach to simultaneously estimate regional vertical land motion and mission-specific systematic errors using combined altimeter, tide gauge, and GPS records

M.-H. Rezvani (Univ. of Tasmania), C. S. Watson, M. A. King

Many studies have sought to integrate absolute sea-level from altimeters (ASL, ALTs) and relative sea-level from tide gauges (RSL, TGs) to investigate vertical land motion (VLM) along the coastlines. Previous studies often assume the VLM is linear and regional geographically correlated errors in altimetry records are negligible. We developed a Kalman-based approach to simultaneously quantify the TG-specific VLM and altimeter-specific systematic errors at regional-scales. We assimilated specific datasets from multi-mission altimeters, long-running TGs, and permanent GPS sites since the early 1990s wherever available. We did this while including space-time covariances and time-correlated errors within the altimeter minus TG data, altimeter tandem and dual crossovers, and GPS heights. We evaluated the performance of three variations of the approach in study regions including the Baltic Sea, Australia, and South America extending to the Antarctic Peninsula. These separate case studies quantified the long-term variability of VLM across the TG lifespans in the Baltic Sea and around Australia, typically ~1.1 mm/yr (but up to ~4.5 mm/yr), that otherwise cannot be inferred from spatially interpolated GPS velocities or from predicted GIA rates alone. We examined the capabilities of the method in determining significant non-linear VLM in terms of co- and post-seismic deformation in the Chilean subduction zone, and ongoing ice-mass loss in the Antarctic Peninsula. We detected small but significant trends in regional altimetry systematic errors within a typical range of ~0.5-2.5 mm/yr over mission lifespans. Appropriately capturing these systematic errors narrowed the deviation between the ASL estimates inferred from the TG and nearby ALT records, reducing the RMSE of the differences by ~40%. Here we review our approach, present the key findings, and discuss potential limitations of the technique including unresolved differential oceanographic signals between the ALT and TG measurement locations that can in part be mitigated by incorporating non-reference-mission measurements. The developed approach advances the ALT minus TG technique to estimate VLM at TG locations, and places bounds on regional altimeter-specific systematic errors. Such VLM estimates can further be used to improve geophysical interpretation following their use as new constraints in inverse geophysical modelling applications given the sparsity of early GPS-based VLM records across space and time.

S03C03 Multidecadal computation of homogeneous time series of ZTD, ZWD and IWV in South America: methods, current progress and future applications

G. P. Anasimele (Univ. Nacional de La Plata), L. P. O. Mendoza, M. E. Dillon, S. Y. García

The Zenith Total Delay (ZTD), the Zenith Wet Delay (ZWD), and the Integrated Water Vapour (IWV) can be calculated from Global Navigation Satellite Systems signals (GNSS-GB) and meteorological observations. These parameters provide valuable information on atmospheric moisture content, and are therefore used in weather forecasting. In particular, their incorporation into Numerical Weather Prediction (NWP) models is carried out through data assimilation processes (Bonafoni et al., 2019) to improve the initial conditions of the forecasts.

For several years we have been openly providing the community with near-real-time ZTD and IWV products derived from GNSS-GB observations in South America (https://wilkilen.fcaglp.unlp.edu.ar/tro/latest.html, Aragón Paz et al., 2023, https://doi.org/10.1007/s10291-023-01436-2). Our focus is on achieving real-time assimilation of these products to improve regional weather forecasts. These joint efforts, between the University and the National Weather Service of Argentina are twofold: first, a few selected month of historic GNSS data, along several years, are being processed in order to perform comprehensive tests of GNSS-GB derived data assimilation during selected extreme weather events. Secondly, a homogeneous reprocessing of all available regional GNSS-GB observations from 2003 to the present, covering over 700 tracking sites, will be performed. The goal is to generate a multi-decadal, homogeneous dataset for further assimilation tests and to provide a robust basis for computing long-term trends, contributing to climatological studies through regional GNSS infrastructure.

For the GNSS-GB data analysis, we applied a PPP processing strategy (Zumberge et al., 1997), enabled by the recent availability of highly accurate and consistent GNSS products. In particular, we are using the co3 time series produced by CODE (Germany and Switzerland) within the IGS repro3 campaign (Selmke et al., 2020). These series include orbits, clocks, ERPs, and instrumental biases, enabling the computation of integer ambiguities even at the zero-difference level. The PPP method avoids introducing regional frame realizations by constraining coordinates or Helmert parameters, as required in Differential analysis. This poses a challenge for multi-decadal GNSS studies in South America due to frequent seismic-induced coordinate changes.

We present the first results of the GNSS data analysis, in context with the selected meteorological events.

S03C04 Correlation of GNSS-Derived Tropospheric Parameters with Local Weather Events in Mzuzu, Malawi

R. G. Suya (Malawi Univ. of Business and Applied Sciences)

Accurate and timely prediction of extreme weather events remains a significant challenge, particularly in regions with limited meteorological infrastructure. Although Global Navigation Satellite System (GNSS)-derived tropospheric parameters have shown potential for atmospheric monitoring, their correlation with local weather events, including storms, is not well understood. This gap limits the effectiveness of early warning systems that rely on atmospheric data for disaster preparedness and risk reduction. This study investigated the correlation between GNSS-derived tropospheric parameters and storms in Mzuzu City. By using observations from a single GNSS station processed with GPS and GLONASS constellations, statistical analysis was applied to examine how fluctuations in tropospheric parameters correlate with changes in weather conditions. The findings revealed significant relationships between specific tropospheric parameters and weather events in the same location, highlighting the potential for GNSS-derived data to serve as an early indicator of extreme weather. These results provide valuable insights for strengthening early warning systems and enhancing disaster preparedness in regions that rely on GNSS for atmospheric monitoring.

Keywords: Tropospheric parameters; Weather prediction; Correlation; Warning systems; Atmospheric monitoring

S03C05 Groundwater Depletion and Land Subsidence in the Minab Coastal Plain: Insights from InSAR Time-Series and Aquifer Modeling

M. Mohseni Aref (Univ. of Potsdam), H. Kamali

Land subsidence due to excessive groundwater extraction is a growing concern in arid and semi-arid regions, including the Minab Aquifer in southern Iran. This coastal aquifer serves as a vital resource for drinking water, agriculture, and industry, yet it faces significant challenges from overextraction, salinization, and land deformation. In this study, we integrate Interferometric Synthetic Aperture Radar (InSAR) time-series analysis with groundwater modeling to investigate the spatial and temporal patterns of land subsidence and its relationship to groundwater dynamics. Sentinel-1 ascending and descending datasets from 2014 to 2024 were analyzed to capture both vertical and horizontal deformation components, with atmospheric corrections applied to minimize tropospheric delay effects.

Our approach employs inverse modeling through a Markov Chain Monte Carlo (MCMC) framework to estimate key hydrogeological parameters, including elastic and inelastic skeletal storage coefficients. By correlating InSAR-derived surface deformation with groundwater-level fluctuations, we quantify the contribution of different aquifer layers to observed subsidence and identify the dominant deformation mechanisms. This method allows for the characterization of aquifer system responses to seasonal and long-term groundwater extraction, accounting for the delayed deformation effects associated with changes in hydraulic head. The results reveal cumulative subsidence exceeding 300 mm in areas of intensive groundwater withdrawal, with inelastic compaction being the primary contributor in regions experiencing sustained groundwater level declines.

Additionally, the analysis highlights areas at risk of salinization, driven by seawater intrusion, water-rock interactions, and anthropogenic activities. The integration of InSAR observations with groundwater modeling and MCMC-based parameter estimation provides a robust framework for understanding subsidence dynamics and aquifer behavior, offering critical insights for the sustainable management of groundwater resources in vulnerable coastal environments.

S03C06 Downscaling Ground Water Storage Anomaly (GWSA) derived from GRACE by machine learning; Case study: Urmia Lake basin

F. Sabzehee (Univ. of Isfahan), A.R. Amiri-Simkooei, S. Iran-Pour, B.D. Vishwakarma, R. Kerachian

Understanding groundwater dynamics is critical for long-term water management, especially in data-scarce areas such as Iran's Urmia Lake basin. This research work tackles the difficulty of using coarse-resolution Gravity Recovery and Climate Experiment (GRACE) data to predict high-resolution groundwater storage anomalies (GWSA) in this complicated hydrogeological situation. We used machine learning approaches such as Random Forest (RF), Support Vector Regression (SVR), and Multilayer Perceptron (MLP) to downscale GRACE data with seven hydro-climatic variables. RF outperformed because of its resistance to overfitting, which successfully mitigated the uncertainties inherent in machine learning models. The downscaled GWSA showed high correlations with independent well measurements, which confirms the reliability of the results. GWSA are primarily influenced by both natural climate variations and anthropogenic activities. Research indicates that human actions, including agricultural expansion, dam construction, and excessive groundwater extraction, contribute significantly to groundwater depletion. By analyzing the spatial patterns of GWSA, we can identify regions experiencing severe groundwater depletion. This information is crucial for developing effective strategies to manage groundwater resources sustainably. To make sound decisions regarding water resource management within a specific catchment area, it is essential to understand the dominant factors that drive changes in groundwater storage.

S03C07 Monitoring Vegetation Water Stress and Diurnal Moisture Dynamics in Forests Using GNSS Reflectometry

M. Asgarimehr (GFZ Potsdam), D. Entekhabi, A. Camps, J. Wickert

The Amazon rainforest plays a critical role in global climate regulation, yet it faces increasing threats from climate change-induced water stress. Traditional methods for monitoring vegetation water content (VWC) are limited in spatial and temporal resolution, necessitating novel approaches for large-scale ecological assessment. This study explores the potential of Global Navigation Satellite System Reflectometry (GNSS-R) using NASA's CYGNSS constellation to monitor diurnal VWC dynamics and detect water stress in Amazonian forests. Unlike conventional remote sensing techniques, CYGNSS offers high temporal resolution, capturing multiple observations per day. By analyzing GNSS-R reflectivity data from 2019 to 2021, normalized against the Leaf Area Index (LAI), we observe significant diurnal and seasonal variations in VWC. The findings indicate a strong correlation between diurnal VWC fluctuations and vapor pressure deficit (VPD), highlighting atmospheric moisture demand as a key driver of vegetation stress. Comparisons with in-situ flux tower data further validate the effectiveness of GNSS-R in detecting disrupted diurnal cycles during periods of extreme water stress. This research demonstrates the potential of GNSS-R as a powerful tool for monitoring forest moisture dynamics and advancing global vegetation models. The study also aligns with upcoming Earth observation missions, such as ESA's HydroGNSS, reinforcing the importance of GNSS-R in environmental monitoring and climate change mitigation.

Session 4
Tuesday morning 10 a.m. CET (UTC+1)

S04C01 Extending and exploiting the coastal record of the ESA Sea State Climate Change Initiative

M. Passaro (DGFI Munich), F. Ardhuin, G. Dodet, M. Usoltseva

The monitoring of sea state, particularly significant wave height (SWH), relies heavily on the multi-mission altimetry record accumulated over 30 years of satellite observations. As part of the ESA Sea State Climate Change Initiative, the WHALES retracking scheme was adopted, a method that significantly improves the retrieval of valid data in coastal areas. Through the reprocessing of data from missions such as Jason-1, Jason-2, Jason-3, Envisat, CryoSat-2, and AltiKa, the first phase of the project has yielded two decades of coastal SWH records that are ready to be exploited. In parallel, efforts are underway to apply this approach to additional historical missions, potentially extending the record back by another decade.

This presentation will highlight both recent progress in applying WHALES to other missions and the opportunities for leveraging these coastal records. Specifically, we will discuss the challenges and outcomes of applying WHALES to ERS-1 and ERS-2 data, along with statistical insights gained from reprocessing the ERS-2/Envisat and ERS-1/ERS-2 tandem phase data. Additionally, we will show how WHALES not only enhances coastal data accuracy but also reduces the impact of speckle noise and wave group influence, providing a more accurate representation of SWH and its uncertainty—particularly valuable for extreme conditions. Finally, we will demonstrate how these reprocessed datasets can be used effectively for coastal applications, focusing on the monitoring of SWH changes from offshore to coastal zones and the role of coral reefs as natural barriers protecting coastal environments from high sea states.

S04C02 Monitoring Chukchi Sea circulation and Bering Strait flow reversals from satellite radar altimetry (2013–2023)

M. Pisareva (DGFI Munich), F. L. Müller, F. Seitz, D. Dettmering, M. Passaro, C. Schwatke

The Chukchi Sea is an important transition region for Pacific-origin waters entering the Arctic Ocean through the Bering Strait. The inflowing waters bring heat, freshwater, and nutrients, influencing the entire Arctic Ocean. Monitoring processes in the Chukchi Sea is crucial for understanding Arctic Ocean variability, especially in the changing climate. While in-situ oceanographic measurements in this region are limited due to their remoteness, harsh environment, and geopolitical constraints, satellite altimetry offers a valuable alternative, providing precise sea surface observations across various spatial and temporal scales.

In this context, we present a novel long-term altimetry-based observational dataset of sea level and geostrophic currents, processed with the implementation of the recent advanced algorithms and special techniques for the reliable detection of leads and the determination of sea surface heights in the sea-ice-covered ocean. The dataset allows us to observe interannual, seasonal, and mesoscale sea level variability and geostrophic flow in the Chukchi Sea.

Our study focuses on the reversals of the northward flow through the Bering Strait, linking them to anomalously strong northeasterly storms over the Chukchi Shelf. While this phenomenon was previously documented in oceanographic studies from in-situ data, our dataset makes it possible to assess the development of the reversed flow in the strait, as well as the forcing and the flow variability with a high temporal-spatial resolution (10d/8km) over a full decade of 2013–2023. We find that the response of the along-strait flow to strong northerly winds is particularly pronounced in fall when the region is ice-free and remains well-correlated during winter and spring under partial ice cover.

This work overall demonstrates the potential of satellite altimetry for monitoring Arctic oceanographic processes, contributing to an improved understanding of regional circulation and climate variability.

S04C03 The 2023 Major Baltic Inflow Event Observed by SWOT Altimetry

S. Esselborn (GFZ Potsdam), H. Dobslaw, T. Schöne, R. Sulzbach

The Baltic Sea is an intercontinental marginal sea that is vertically stratified with a strong halocline isolating the saline bottom layer from the brackish surface layer. The surface layer is eutrophic and abiotic zones lacking oxygen are common in the deeper regions. While freshwater is constantly flowing into the North Sea, oxygen-rich bottom waters can only occasionally enter the Baltic following a special sequence of transient weather conditions. These so-called Major Baltic Inflow events can be monitored via the sea level gradients between the Kattegat and the western Baltic Sea. Innovative interferometric al-timetry from the Surface Water and Ocean Topography (SWOT) mission give us the the first opportunity to directly observe the sea level signal associated with the inflow in December 2023. In addition, we use observations from recent high-rate multi-mission nadir altimetry. For scales larger than 50 km, SWOT and nadir altimetry are in very good agreement. The SWOT observations are compared to the simulations with the regional 3-D HBMnoku ocean circulation model operated by the German Federal Maritime and Hydrographic Agency (BSH). Both agree very well for most aspects. The north-south gradients of the two data sets differ by about 10% of the total value. Comparison with tide gauges suggests that there may be model deficiencies on daily to sub-daily time scales. In addition, the SWOT data have many fine scale structures such as eddies and fronts that cannot be modelled adequately.

S04C04 Sea-level changes in South America: Insights from modelling ocean mass variations

A. Richter (Univ. Nacional de La Plata), F. S. Corbetta, E. Marderwald, A. Juarez, L. P. O. Mendoza, T. Döhne, M. Horwath

Changes of the mean sea level relative to the coast are one of the big challenges ongoing climate change confronts society, policy makers and scientists with. The causal-quantitative understanding of relative sea-level changes and their projection into future have to extend necessarily over the global domain. However, local conditions and details are to be taken into account for an accurate modelling of local sea-level evolution. Present global sea-level rise is dominated by the redistribution of water mass injected from the continents into the ocean, compliant with the gravity field. GRACE and GRACE Follow-On satellite gravimetry has recently allowed for geodetic estimates of ice-mass change time series of the polar ice sheets and mountain glaciers of monthly resolution and unprecedented consistency. Furthermore, global hydrological models have become available for reproducing the spatio-temporal variations in continental water storage based on ERA5 climate reanalysis. We apply an implementation of the sea-level equation in quasi-spectral domain for an elastic earth (Clarke et al. 2005) to model the ocean mass variation over the global ocean with monthly resolution throughout the GRACE(FO) era, gravitationally self-consistent and compliant with the water-mass conservation in the earth system, based on published GRACE-derived ice-mass time series and the WGHM hydrological model as input. This ocean-mass model is complemented with a global model of the steric contribution to sea-level change based on ARGO floats and a regionalized version of a global model of glacial-isostatic adjustment to derive relative sea-level changes. The analysis of the model results are focussed on the coasts of South America with the aim to identify and quantify the major processes that drive sea-level changes in a continent where decisions on coastal development often rely on scientific advice that priorizes rather distant coasts. Finally, using the mass-change rate projections published in the IPCC-AR6 as input, we predict future relative sea-level change rates along the South American coasts. Our results show that sea-level rise in South America is dominated by the mass effect of ice-mass loss in Greenland while the steric contribution adds short-wavelength variability. Patagonia, in the southern part of the continent, is practically insensitive to ice-mass changes in Antarctica but is strongly affected by the near-field effects of intense mass loss of the Patagonian Icefields.

S04C05 Exploring steric sea level variability in the Eastern Tropical Atlantic Ocean: a three-decade study (1993–2022)

F. Ghomsi (Univ. of Cape Town), B. Mohamed, R. P. Raj, A. Bonaduce, B. J. Abiodun, H. Nagy, G. D. Quartly, O. M. Johannessen

Sea level rise (SLR) poses a significant threat to coastal regions worldwide, particularly affecting over 60 million people living below 10 m above sea level along the African coast. This study analyzes the spatio-temporal trends of sea level anomaly (SLA) and its components (thermosteric, halosteric and ocean mass) in the Eastern Tropical Atlantic Ocean (ETAO) from 1993 to 2022. The SLA trend for the ETAO, derived from satellite altimetry, is 3.52 ± 0.47 mm/year, similar to the global average of 3.56 ± 0.67 mm/year. Of the three upwelling regions, the Gulf of Guinea (GoG) shows the highest regional trend of 3.42 ± 0.12 mm/year. Using the ARMORD3D dataset, a positive thermosteric sea level trend of 0.88 ± 0.04 mm/year is observed, particularly in the equatorial and southern Atlantic regions. The steric component drives the interannual SLA variability, while the ocean mass component dominates the long-term trends, as confirmed by the GRACE and GRACE-FO missions for 2002–2022. For those two decades, the total SLR from altimetry amounts to 3.80 ± 0.8 mm/year, whilst the steric component is reduced to only 0.19 ± 0.05 mm/year, leaving a residual increase in the ETAO of 3.69 ± 0.5 mm/year. The independent mass change from GRACE amounts to 2.78 ± 0.6 mm/year for this region, which just closes the sea level budget within present uncertainty levels. Spatial analysis of the steric components indicates a warming along the equatorial African coast including the GoG and a freshening near Angola. Strong correlations with regional climate factors, particularly the Tropical South Atlantic Index, highlight the influence of persistent climate modes. These findings underscore the urgent need for mitigation and adaptation strategies to SLR in the ETAO, especially for densely populated coastal communities.

S04C06 Including sea-level rise in ship-based GNSS contribution to tsunami warning: application in the Mediterranean region

B. Thomas (Univ. of Stuttgart), J. Foster

Tracking changes in sea-surface height with ship-based GNSS can be used to detect tsunamis in the open ocean. We propose that a network of ships, based on voluntary participation of cargo and tanker vessels, could contribute to tsunami warning, augmenting existing systems in the Mediterranean region (tsunami capable tide gauges). Case studies based on tsunamis generated at the locations of fatal historical events are examined to assess the distribution of ships that would be expected from such a network. In all cases, ships are likely to be the first sensors reached by these tsunamis, regardless of their source (seismic, volcanic, landslide). Each of these ships would add a significant contribution to the characterization of a tsunami event as they typically provide observations from otherwise under-sampled locations. We examine the warning lead times along the current coastline, that would be provided by a combined network formed by the actual tide gauges and the proposed GNSS-equipped ships. This analysis identifies low-lead times and compares them to the probabilities of maximum inundation heights exceeding 1 m. The same methodology is also applied to model projections including sea-level rise to provide a comprehensive survey of locations and cases where a ship-based GNSS tsunami detection network would add a great contribution to augment data from the existing tide gauges.

Session 5
Tuesday morning POSTERS

S05C01 Evaluating Water Storage Variations in the La Plata Basin and Its Sub-Basins: Insights from GRACE Data, Global Models, and ENSO Connections

A. Pereira (National Univ. of Rosario), C. Cornero, A. C. O. Cancoro de Matos, R. Seoane, M. C. Pacino, D. Blitzkow

River environments are of substantial importance in nature, performing critical functions such as climate regulation, flood mitigation, and groundwater recharge. Consequently, it is essential to study these systems, which have significant ecological and economic value, to improve the management and use of water resources.

The La Plata Basin (LPB) is among the largest in the world, extending across five South American countries. Due to its considerable size, the basin displays a wide range of characteristics and physical and environmental conditions. Also, this watershed is the source of numerous major rivers and sub-basins, including the Paraná, Uruguay, and Paraguay basins.

The GRACE satellite gravity mission provides time-variable gravity field models that reflect variations in the Earth's gravity field caused by mass transport processes, including terrestrial water storage (TWS) changes.

This study focuses on assessing TWS variations derived from monthly GRACE estimates over the La Plata Basin. A comparative analysis was performed across its major sub-basins for the period 2003–2017 to identify patterns of continental water changes and surface runoff at regional scales, with particular attention to connections with significant El Niño/Southern Oscillation (ENSO) episodes. To this end, TRMM precipitation and GLDAS runoff data at the sub-basin level were evaluated and subsequently used to validate the TWS estimates. A correlation analysis was also conducted to explore interrelations, potential change points, and trends.

The findings suggest that TWS variability in this basin is predominantly driven by extreme climatic events, such as the 2015 flood and the 2009 drought, which impacted South America and are closely linked to El Niño and La Niña episodes.

S05C02 Assessment of Near-Surface Reanalysis Wind Speeds over the North-Western Indian Ocean A. Varghese (Kerala Univ. of Fisheries and Ocean Studies), P. Shah, A. A V, P. Arayakandy, M. Shafeeque

The increasing availability of both global and regional reanalysis datasets necessitates their careful evaluation in specific oceanic regions to enhance our understanding of ocean processes. This study focuses on identifying the most suitable reanalysis dataset to serve as a reliable proxy for surface wind speeds over the North-Western Indian Ocean, thereby reducing uncertainties related to reanalysis selection.

To achieve this, we assess 10 m wind speed of five reanalyses: JRA3Q, IMDAA, ERA5, MERRA2, and NCEP CFSv2/CFSR. Our assessment employs a satellite-blended wind product validated by buoy observations as the benchmark. We compare spatially averaged reanalysis data with this satellite-blended wind product across both open ocean and coastal regions over a ten-year period.

A suite of statistical methods is employed to rigorously evaluate performance. The results reveal that ERA5 generally outperforms the other datasets in representing climatological wind speeds across most regions. Seasonal analyses indicate that during the DJFM period all reanalyses tend to underestimate wind speeds—with IMDAA showing the smallest bias—whereas ERA5 maintains a consistency during the JJAS season.

In summary, ERA5 demonstrates robust performance in capturing long-term wind speed patterns and seasonal variability during the JJAS period over the North-Western Indian Ocean. Despite this, the study also highlights persistent challenges across all reanalyses in accurately representing wind speeds during the DJFM season.

S05C03 Harmonic analysis of Antarctic Ice mass variations using Singular Spectrum Analysis (SSA) and Fast Fourie Transform (FFT)

F. Esmaeili (University of Isfahan), S. Iran-Pour

Climate change and global warming are the primary drivers of amplitude changes in the annual and seasonal harmonic behaviors of ice mass in the Antarctic Ice Sheet (AIS). Ice mass products derived from GRACE satellite observation are key data sources for studying AIS mass changes. Researchers utilize nonparametric time series analysis methods, particularly Singular Spectrum Analysis (SSA), to examine these ice mass time series. SSA's capability to capture amplitude and phase changes in the extracted components has made it a popular choice for monitoring ice mass variations. While the extracted components reflect these amplitude and phase changes, the absence of a mathematical model limits their interpretation regarding the significance of each component. Thus, assessing the significance of the extracted components is crucial for reconstructing the harmonic behaviors and transient signals of ice mass time series. The primary objective of this study is to establish a criterion for interpreting the SSA components extracted from the AIS ice mass time series. To achieve this, we first analyze the ice mass time series from the GRACE satellite using SSA. Next, we apply a Fast Fourier Transform (FFT) to the associated eigenvectors to determine the dominant frequency for each component. Components sharing a common dominant frequency can be grouped to reconstruct the harmonic behavior. Finally, by studying both the regional aspect and the entire AIS domain, we can determine the spatial distribution of these behaviors across the ice sheet.

S05C04 Developing a concept of an optimized geodetic sensor network for the Vernagtferner Glacier

K. Lechner (TU Munich), R. Pail

Glaciers are a dynamic part of the Earth's system. They are vulnerable to the impacts of climate change, making them a dynamic and rapidly transforming element of the Earth system. The consequences of these changes extend far beyond the polar and alpine regions, affecting ecosystems and water resources globally. Glaciers are important for water management, acting as natural reservoirs and providing millions of people with fresh water. However, their retreat can disrupt water supplies, increase flood risks, and lead to hazards such as rock moraine instability. These challenges underscore the importance of understanding this part of the ecosystem. Monitoring and measuring glacial environments are essential not only for mitigating risks but also for advancing scientific knowledge. By studying the dynamics of glaciers, scientists can better understand their interactions with the Earth's climate system and predict future changes. Such insights are critical for developing sustainable resource management strategies and enhancing societal resilience.

The Vernagtferner Glacier has been a research area for geodetic sensors for over 150 years, beginning with Sebastian Finsterwalder's photogrammetric observations in the 19th century. Since then, the Bavarian Academy of Sciences and Humanities has expanded this database by installing sensors and level bars on and around the glacier. The current challenge lies in leveraging observational data to develop a glacier model capable of assimilating geodetic observations. This research aims to design an optimized geodetic sensor network that enhances the integration of field observations into glacier modeling. Sensitivity studies evaluate the model's response to various data inputs, identify observation errors, and refine the network design. Starting with the existing sensor infrastructure, the study explores innovative measurement strategies, including low-cost sensors, to increase spatial and temporal data coverage. At the workshop, a preliminary concept for the sensor network is presented, including best practice examples from other monitored glaciers.

S05C05 Continuous Radar Altimetry Quality Control at the Lake Issyk Kul Observatory (Kyrgyzstan)

T. Schöne (GFZ Potsdam), A. Zubovich, J. Illigner, C. Zech, S. Esselborn, N. Stolarczuk, A. Sharshebaev M. Borisov

Lake Issyk Kul in Kyrgyzstan is a large high-altitude inland lake but ice-free the year around. Due to its E-W extension of ~170km all active radar altimetry missions cross this lake. Starting in 2016 CAIAG (Kyrgyzstan) and GFZ (Germany) installed five GNSS-controlled tide gauges and two ROMPS climate monitoring stations around the lake. The lake surface is neither influenced by ocean tides nor by inverse barometric effects. Seiches, which occur from time to time, are identifiable by data of the wind sensor at the east coast and the distinct variations of the lake level. Tide Gauge data (radar and pressure) is sampled every minute and climate data, such as wind or air pressure, every five minutes. The lake is calm except during strong winds detectable from our wind sensors in the East and South. Also surge effects are small.

Starting in 2017 we performed repeated ship-based lake surveys with GNSS/radar and a GNSS buoy for profiling the lake surface along the satellite passages. All tide gauges are regularly levelled to nearby GNSS sites, thus by combining the tide gauge readings with the ship-based profiles we are able to reconstruct the instantaneous lake profile in the geocentric reference system (ITRF) for any altimeter passage. For our study we analyzed the 20Hz GDR Level 2 data of Jason-3 (since 2016) and Sentinel-6MF (since 2021, STC/NTC both LRM/SAR) for all passages. In 2022 we performed control surveys along the 35-day orbits (ERS-1, ERS-2, ENVISAT, Saral) and the GFO-1 track, in 2023 in a joint expedition with LEGOS (France) a dedicated survey for the cal/val of the SWOT mission. Along each pass stretching up to ~60km we testing all retracker available in the GDR. We estimated the individual retracker offsets and the internal accuracy. For, e.g., Sentinel-6MF the SAR-OCOG retracker performs best (revision F08/F09) after applying an offset of more than 33cm in respect to the GNSS reference pass. For Jason-3 (Rev. F) the OCOG also performs best with an offset of ~19cm.

Our analyses show the capability of the Lake Issyk Kul Observatory for the short-latency monitoring of radar altimetry missions as well as for the performance control of all altimeters starting with ERS-1 in 1992.

S05C06 Geodetic mass balance determination of Fedchenko Glacier in the Pamir Mountains based of TanDEM-X data

A. Wendt (Bavarian Academy of Sciences and Humanities), C. Mayer, D. Floricioiu

There are several methods to determine the state of a glacier described as its mass balance. While the glaciological method is based on the pointwise measurement of accumulation and ablation in a stake network distributed over the glacier surface, the geodetic method monitors the geometry changes of a glacier by comparing digital elevation models (DEMs) of different epochs. Here we use DEMs derived from the German TanDEM-X mission of Fedchenko Glacier in Tajikistan, one of the longest glaciers outside the polar regions and the dominating glacier of the western Pamir Mountains. The glacier has a long history of glacier monitoring based on a first geodetic survey using terrestrial photogrammetry in 1928.

The TanDEM-X image stack of the glacier acquired since 2011 provides a comprehensive database to select same geometry same season pairs to infer multi-annual surface elevation changes.

Resorting to the elevation data of the Shuttle Radar Topography Mission in 2000, the time series of InSAR-based elevation change rates and resulting geodetic mass balances covers now more than 20 years. The relatively dense time series with repeated acquisitions in winter as well as during the summer months additionally allows the study of intraseasonal changes in order to understand the influence of snow and ice properties on signal penetration effects. In this context, the period from late summer to early fall is of special interest as the transition from melting to freezing conditions results in a rapid variation of the penetration depth of the radar signal.

Session 6
Tuesday afternoon 4 p.m. CET (UTC+1)

S06C01 Regional ice-mass change from GRACE and GRACE Follow-On: The role of global GIA correction models

A. Romero (Univ. Nacional de La Plata), T. Döhne, A. Richter, M. Horwath

Between 2002 and 2017 the GRACE satellite mission, and since 2018, its successor GRACE Follow-On (GRACE-FO), have provided an efficient tool for quantifying mass redistributions on Earth. These gravity missions provide Level 2 products, consisting of monthly solutions of the gravitational field expressed in spherical harmonic coefficients (SHC). At regional scales, the analysis of Level 2 data allows for precise, reliable, and detailed determinations of water and ice distributions, accounting for specific regional characteristics and the contributions of multiple simultaneous processes to observed gravity changes. Among these other geophysical processes is the glacial isostatic adjustment (GIA), the ongoing uplift of Earth's surface due to the delayed response of the mantle to the melting of ice sheets from the last ice age. To accurately quantify surface mass changes, the secular effects of GIA must be carefully subtracted. Eicker et al. (2024) showed the importance of GIA corrections for monitoring long-term changes in terrestrial water storage from GRACE(FO).

Focusing on the Southern Andes—a region undergoing rapid uplift due to GIA—our work aims to study the Patagonian Ice Fields mass change by isolating its signal from other global sources, such as hydrology, other ice bodies, ocean mass variations, and particularly GIA. In this study, we investigate the influence of global GIA correction models on GRACE(FO)-derived ice-mass balance estimates. From the monthly SHC sets, we generate pseudo-observations on a global grid in the form of three-dimensional gravity change vectors at orbital altitude (Richter et al., 2019). By comparing global residuals after removing the effects of all known gravity effective processes and applying different GIA models, we quantify the variability introduced by model-dependent corrections and evaluate their implications for the reliability of mass change estimates based on GRACE(FO). Our results highlight the critical role of selecting appropriate GIA models to account for regional geodynamic effects. These findings contribute to improving the reliability of cryosphere monitoring and understanding global climate dynamics.

S06C02 Surface elevation changes of the Patagonian Icefields derived from satellite altimetry

F. Suad Corbetta (Univ. Nacional de La Plata), A. Richter, A. Romero, E. Marderwald, A. Juarez, L. Mendoza, M. Braun, M. Willen, M. Horwath

The Patagonian Icefields represent the largest extrapolar ice concentration in the southern hemisphere and have responded very sensitively to climate changes on various time scales. A geodetic quantification of their present-day ice-mass changes is not only crucial to quantify sea-level changes but also for guiding the sustainable development in this region, e.g. the fresh-water availability or the water supply of hydroelectric power plants under construction. Moreover, improved estimates of ice mass changes will aid our understanding of glacial-isostatic adjustment in this region. However, steep ice-surface slopes, the fragmented glacier extent and a considerable small-scale variability limit the estimation of ice-mass rates from satellite altimetry. Previous studies employing different remote sensing techniques since 2000 document a rapid decrease in surface elevation, extent, volume and mass of the glaciers that compose the icefields. Yet the derived mass-loss rates vary significantly among different observation periods and observation techniques. Satellite gravimetry analyses tend to estimate more intense ice-mass loss than digital elevation model (DEM) differencing based on radar imagery. The question whether the Patagonian ice loss is accelerating is still controversial, in part due to such inter-technique biases and their unequal spatial and temporal resolution. Laser satellite altimetry from ICESat and ICESat-2 missions may overcome the limitations of other observation techniques. In this work, we isolate temporal variations through a combined crossover analysis of both missions at the intersections of surface-elevation profiles observed at different epochs. Our results show negative surface-elevation changes all over the icefields. In 349 inter-mission crossovers (time span of 11 to 19 years) we derive a mean surface-elevation change rate of -2.6 m/a. The ice-surface subsidence is most intense in the low-elevation glacier ablation zones, where surface-elevation change rates in excess of -10 m/a (time span of 5 years) are observed. The sparse availability of crossovers limits the spatial and temporal coverage of the icefields' surface, motivating the use of complementary data products such as Cryosat-2 swath altimetry and a SRTM radar-based DEM to improve the spatial and temporal coverage of ice surface-elevation changes.

S06C03 Monitoring surface water storage change in lakes and reservoirs with satellite altimetry

L. Fenoglio (Univ. of Bonn), J. Chen, J. Kusche, F. Frappart, B. Naz

Switzerland is today rich in water, and retreating glaciers give new landscapes with a larger number of lakes. We have analysed surface water storage change and river discharge using historical data and satellite altimetry. Goal is to extend and densify accurate records and detect long- and short-term changes.

We distinguish two groups of lakes: natural lakes and reservoirs. The first group includes both ancient large lakes of small variations related to long-term changes in temperature and small lakes formed in the deglaciated area rapidly changing and related to glacier melting. The second group includes reservoirs with large water variations related to resource management, like hydropower and irrigation.

Nadir and SWOT altimetry contribute to monitor seasonal and intra-annual surface water storage variability between 2016 and 2024. Novelty in this study is a precise estimation of the seasonal water storage change derived by the SWOT satellite altimetry. We investigate water bodies with area larger than 0.5 km**2, water height and water extension are evaluated against in-situ, bathymetrie and Sentinel-1 images and have accuracy of 10 cm and 10%. Annual minima are found in April for hydroelectric, in November for irrigation reservoirs. Natural lakes have their maximum in late Summer with a seasonal amplitude lower than two meters, while the seasonal amplitude of storage change in hydroelectric reservoirs is 70% higher than in irrigation reservoirs and is 80% higher than in natural lakes. The long-term change is derived from historical data of water level and discharge for selected lakes.

This study highlights the contribution of the new satellite altimeter observations to study climate change and human land and water use. The project is part of the Collaborative Research Center (SFB 1502) funded by the German Research Foundation (DFG).

S06C04 Understanding Rain Gauge Systems: Installation Guidelines and Geodetic Applications (invited presentation)

M. H. Erkoç (Yildiz Techn. Univ.)

The current research paper deals with the impact of climate change on Lake Van-the largest lake in Turkey-between 1995 and 2024. In this study, variations in lake water level, temperature, and precipitation trends, SPEI-12 drought indicators, and changes in surface area by using a traditional approach, such as the classical linear model and Mann-Kendall test, together with a machine learning algorithm like LS-SVM, were analyzed. The annual lake level decline was -4.2 cm and -3.9 cm according to in-situ measurements and HydroWeb satellite altimetry data, respectively. Meteorological station data confirmed the increasing temperature and decreasing precipitation trends that have been intensifying drought conditions in the region. SPEI-12 analyses revealed that from the last decade onward, the hydrological drought has been in moderate to severe conditions. Landsat satellite imagery analysis presented a loss of 0.0477 km²/yr in lake surface area. The result clearly presents the ecological imbalance and the mismanagement of water resources caused by the change in climate over Lake Van. The presented work points out the relevance of the application of machine learning techniques combined with classic approaches in identifying climate change indicators and contributes effectively to the literature. The findings emphasize that sustainable management of the lake and the ecosystem requires the identification of relevant strategies.

S06C05 Sensitivity analysis of hyperparameter tuning with various input variables for nowcasting extreme weather in Indian coastal city using deep learning

S. Pandey (MNNIT Allahabad), R. Dwivedi

Accurate short-term forecasting (nowcasting) of extreme weather, such as heavy rainfall, is crucial for aviation, transportation, and public safety. Atmospheric water vapor (PWV) significantly influences severe weather, with GNSS-derived PWV widely used for meteorological applications, including extreme rainfall prediction. Weather station data and GNSS-derived zenith wet delay (ZWD) provide high-resolution moisture information, while radar and lightning data offer real-time insights into severe weather formation.

Given the limitations of numerical simulations, deep learning models like Recurrent Neural Networks (RNNs) have gained traction. This study develops a Long Short-Term Memory (LSTM) model to predict precipitation in Thiruvananthapuram, Kerala, India, leveraging radar from the Thumba Equatorial Rocket Launching (TERL) station, lightning data from the Indian Meteorological Department (IMD), GNSS-derived atmospheric water vapor, and ERA5 reanalysis weather data. Data preprocessing included handling missing values, normalization, and correlation-based feature selection. The dataset (2019–2021) was split into 80% training and 20% testing.

The LSTM model, optimized for capturing long-term dependencies, consisted of multiple LSTM layers and a dense output layer. The best configuration included 70 epochs, batch size 32, 128 dense neurons, and 128 LSTM units, with an optimal 12-time step sequence. The Huber loss function yielded the lowest test loss (3.31E-05). The model achieved high Probability of Detection (POD), a 9.19% False Alarm Rate (FAR), and a 90.81% Critical Success Index (CSI).

Various nowcast correction models were tested, with Extra Trees and XGBoost performing best, achieving RMSEs of 0.5431 and 0.5941, with correlations of 0.9981 and 0.9977, respectively. The most effective configuration integrated weather station, GNSS, radar, and lightning data, yielding a post-correction correlation of 0.9983 and an RMSE of 0.497.

The study highlights the effectiveness of LSTMs in meteorological forecasting, particularly in data-limited regions. Integrating multi-source data significantly improved prediction accuracy, demonstrating its potential for early warning systems. Future work will refine the model and incorporate additional data sources to enhance forecasting precision.

S06C06 Optimal processing and post-processing of GNSS-PW climate data records within the ICCC JWG C.8

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JWG C.8 is a newly established joint working group of the ICCC, bringing together experts from the geodetic community to produce high-quality GNSS Precipitable Water (PW) climate data records for use in climate research. The group focuses on developing rigorous methodologies at both the processing and post-processing stages to minimize biases and inhomogeneities in GNSS tropospheric products, while also providing realistic uncertainty estimates and quality control/assurance information.

We will present results on the following topics:

- The accuracy assessment of GNSS PW compared to reference radiosonde data.
- The intercomparison of zenith tropospheric delays (ZTD) from the IGS repro3 solutions of individual Analysis Centers.
- The evaluation of GNSS station metadata from various sources for thousands of stations.
- The development of a statistical machine learning technique for the homogenization of GNSS PW time series..

S06C07 Relationship between GNSS-derived tropospheric water vapor and precipitation at daily scale in Chile

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Atmospheric water vapor is a fundamental ingredient for precipitation formation. Its long-term abundance and scarcity dictate precipitation variability for example, in humid forest and arid regions. Water vapor variability at daily scale, however, shows a complex relationship with precipitation. In this study we take long-term time series of GNSS-derived tropospheric water vapor (TWV) and examine its relationship with gauged precipitation at a daily scale in different climatic contexts, including the arid climate of northern, mediterranean climate of central, temperate humid climate of southern Chile, as well as the tundra climate of Patagonia. We found that most of the TWV time series exhibit a reasonable relationship with precipitation, although the relationship is degraded for time series of the arid environment. Some potential mechanism that explains this discrepancy are discussed.

S06C08 Tropospheric products at SIRGAS GNSS stations. Analysis of a 22 years' time series

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SIRGAS is the official American Terrestrial Reference Frame. Since its establishment in 1993, it has guaranteed the reference frame's reliability. Its main objective is to promote growth, development, long-term sustainability, and appropriate reference frame use.

Within the weekly processing of the SIRGAS Continuously Network (SIRGAS-CON), Analysis Centers (AC) operationally estimate tropospheric Zenith Total Delays (ZTD) with an hourly sampling rate. These ZTDs are the input data for generating SIRGAS final tropospheric products. The SIRGAS Analysis Center for the Neutral Atmosphere (CIMA) assures high reliability by combining these products weekly. They have been generated and available in daily SINEX TRO files since January 2014, with a latency of 30 days.

This contribution presents the latest advances in combining the ZTDs from the second reprocessing campaign carried out by the DGFI-TUM and GNA, SIRGAS ACs. These completed the ZTD series from 2002 to 2013. These SIRGAS reprocessing campaigns were conducted to obtain homogeneously computed SIRGAS daily and weekly solutions referring to the IGS14/IGb14 reference frame.

The study covers the analysis of the 22-year (2002-2023) time series of the estimated tropospheric parameters in GNSS SIRGAS stations distributed in America. The results were validated using IGS ZTD products at 62 stations and data from 61 radiosondes (86 SIRGAS sites compared). The agreement was evaluated in terms of mean bias (less than 1 mm) and mean rms of the ZTD differences with respect to IGS products (mean bias less than 1 mm and mean rms less than 7 mm) and IWV differences with respect to the radiosonde IWV data (mean bias 0.512 kg / m2 and mean standard deviation 2.22 kg / m2)

Our results show that the ZTDs estimated at the SIRGAS stations are consistent throughout the American region and provide a reliable time series of troposphere parameters for over twenty years that can be used as a reference in future research.

S06C09 Long-Term GNSS-Based Water Vapor Determination for Climate Research Using ASG-EUPOS Network Data

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Global Navigation Satellite System (GNSS) technology has emerged as a reliable tool for continuous and high-resolution monitoring of atmospheric water vapour. Water vapour is a crucial component of the Earth's climate

system, significantly influencing atmospheric processes and energy balance. This study uses data from selected ASG-EUPOS stations in the Carpathian region, to investigate long-term variations in precipitable water vapour (PWV) over an 11-year period. GNSS-derived PWV estimates are obtained from precise tropospheric delay modelling, with validation against radiosonde and reanalysis data to ensure accuracy and consistency.

The analysis focuses on temporal trends, seasonal variability, and spatial distribution of PWV, providing valuable insights into climate change patterns in the region. The research results are consistent with global warming trends and regional climate change. The study also highlights the role of GNSS meteorology in climate research.

The long-term dataset from ASG-EUPOS serves as a valuable resource for improving numerical weather prediction models. The findings contribute to a better understanding of atmospheric dynamics and support the development of enhanced climate adaptation strategies.

S06C010 Intercomparison of tropospheric datasets from radiosonde and GNSS at co-located GRUAN sites

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Precipitable water vapour (PWV) is one of the key climate variables according to the Global Climate Observing System (GCOS). The GCOS Reference Upper Air Network (GRUAN) has been providing such measurements from multiple sensors at an increasing number of sites worldwide since 2006. Today, GRUAN consists of 33 sites, nine of which provide a GNSS station that has been co-located with the Vaisala RS41 radiosonde for several years yet.

This study aims to detail the discrepancies between the radiosonde and GNSS time series at the nine co-located GRUAN sites from 2021 to 2023. The GNSS time series are computed by the GFZ software EPOS8, following a consistent computation configuration over the whole period and for all sites, set up for the zenith tropospheric delay (ZTD) retrieval for climatology purposes. The biases and standard deviations need to be well explained in order to use GNSS ZTD products for climate studies.

The GNSS and radiosonde processing procedures are first described, including the conversion of GNSS ZTD to IWV. The following aspects are then discussed: the height difference between the GNSS antenna and the radiosonde height at the start of the launch, the screening of the IWV time series and the IWV differences, the statistics of the differences between the two time series for each of the nine sites, a different IWV computation strategy from the radiosonde relative humidity (RH) and its impact on the statistics of the differences, and finally the way of comparing the GNSS IWV to the radiosonde time series - the closest GNSS measurement from the radiosonde launch time or the average of the GNSS over one hour from the radiosonde launch time. All these aspects address the issue of data representativeness, i.e. the IWV retrieved by both techniques do not actually come from exactly the same spatio-temporal scale.