



Towards reliable high-resolution GNSS-inferred estimates of TWS changes for Europe

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with support and contributions from: Anne Springer, Jürgen Kusche

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Introduction:

1. **Global Navigation Satellite System (GNSS)** becomes an **essential** technique to determine spatio-temporal changes of Terrestrial Water Storage (TWS) at **high resolution**.
2. High **temporal resolution**: daily changes of TWS, compared to monthly TWS changes from the Gravity Recovery and Climate Experiment (GRACE).
3. High **spatial resolution**: far exceeding that of GRACE (approx. 3°), and becoming competitive with the resolution of hydrological models (0.1° / 0.25° / 0.5°).
4. **Conventional approach**: use only well-correlated GNSS-observed displacements wrt. GRACE- or model-predicted displacements.
 - Drawback: not all GNSS stations show a reliable hydrological signal; some are dominated by non-hydrological effects (e.g., tectonics, monument instability, thermal expansion), which limits the credibility of conventional approach.

Introduction:

- For turning GNSS network into an **observing system for TWS changes**, the displacements must be carefully **prepared in advance**.
- Preliminary step:** outlying GNSS displacements must be identified and eliminated before further analysis. BUT this removes the entire station record.
- A step further:** eliminate only non-responsive temporal scale, which leaves more information for hydrogeodesy.
- We use a novel approach of **GNSS benchmarking** (Klos et al., 2023, JGR, DOI: 10.1029/2023JB026988).

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2023JB026988

Key Points:

- Displacements measured by Global Positioning System (GPS) correlate well with surface water levels derived from radar altimetry missions
- Trusted sets of GPS stations are classified at the three pre-defined temporal-scales: short-term, seasonal and long-term
- Benchmarking allows to include more GPS stations in hydrogeodetic analyses

Supporting Information:

Supporting Information may be found in the online version of this article.

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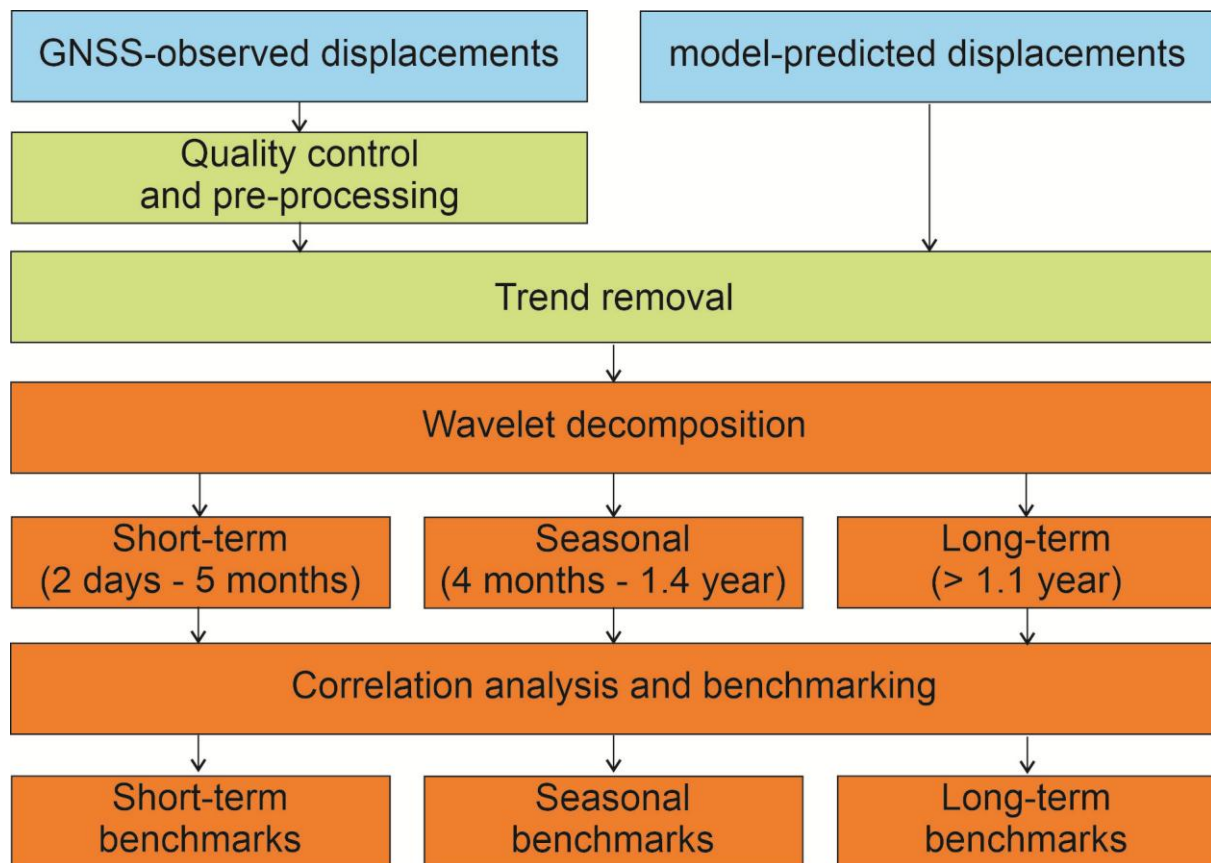
Introducing the Idea of Classifying Sets of Permanent GNSS Stations as Benchmarks for Hydrogeodesy

A. Klos^{1,2}, J. Kusche², G. Leszczuk¹, H. Gerdener², K. Schulze², A. Lenczuk¹, and J. Bogusz¹

¹Faculty of Civil Engineering and Geodesy, Military University of Technology, Warsaw, Poland, ²Institute of Geodesy and Geoinformation, University of Bonn, Bonn, Germany

Abstract We propose a novel approach to classify sets of Global Navigation Satellite System (GNSS) permanent stations as benchmarks for hydrogeodesy. Benchmarks are trusted sets of GNSS stations whose displacements are classified as significantly and positively correlated with hydrospheric changes and identified in a three temporal-scales: short-term, seasonal and long-term. We use 63 vertical displacement time series processed at the Nevada Geodetic Laboratory for the period 1998–2021 from stations located within Amazon basin and show that estimates of trends and annual signals, including the annual phase maximum, are very coherent with water surface levels provided by altimetry missions. We compute vertical displacements from Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On gravity missions and predict those also from Global Land Water Storage (GLWS) v2.0 data set which values are produced by assimilation of GRACE into WaterGAP Global Hydrological Model (WGHM). We divide vertical displacements from the three data sets into the pre-defined temporal-scales of short-term, seasonal and long-term, using non-parametric wavelet analysis. For each temporal-scale, correlation coefficients are computed between GNSS-measured

GNSS benchmarking:



Dataset of daily vertical displacements observed by GPS between 1994 and 2023 for hydrogeodetic studies over Europe

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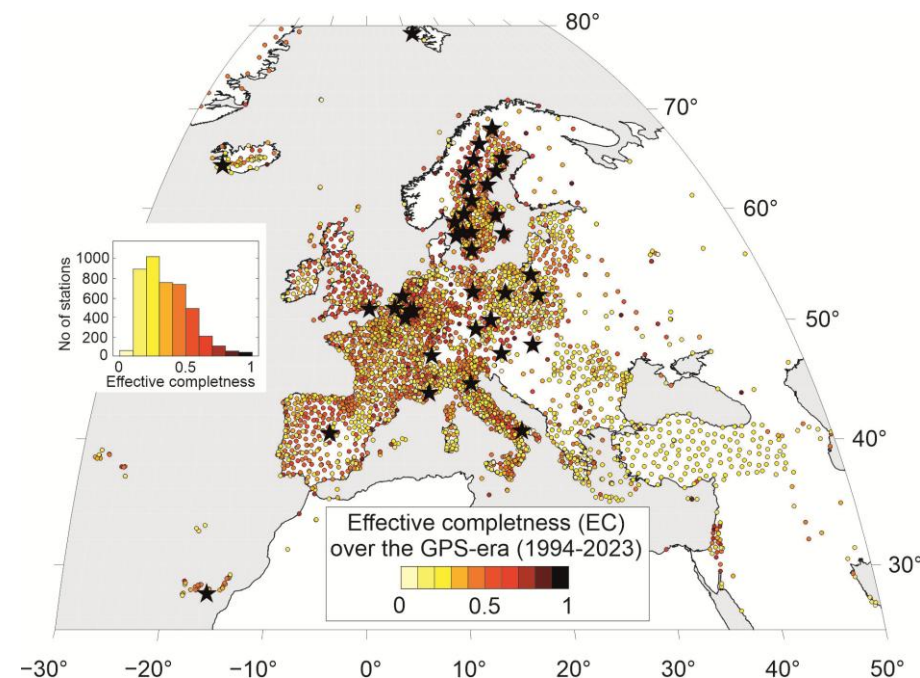
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GNSS benchmarking for Europe:

1. **GNSS-observed displacements:** daily **GPS vertical displacement** time series* for the period 1994-2023 and located in **Europe**: 6,259 GPS stations.
2. **Model-predicted displacements:** the nested high-resolution regional Community Land Model 5.0 (CLM5); more reliable than global models with spatial resolution of 12 km, provided with daily sampling for the 2003-2020 timeframe.
3. **Quality control and pre-processing:** detailed manual check: 4,443 GNSS stations, conventional pre-processing (incl. offsets), NTAL & NTOL corrections**, GIA removal***.



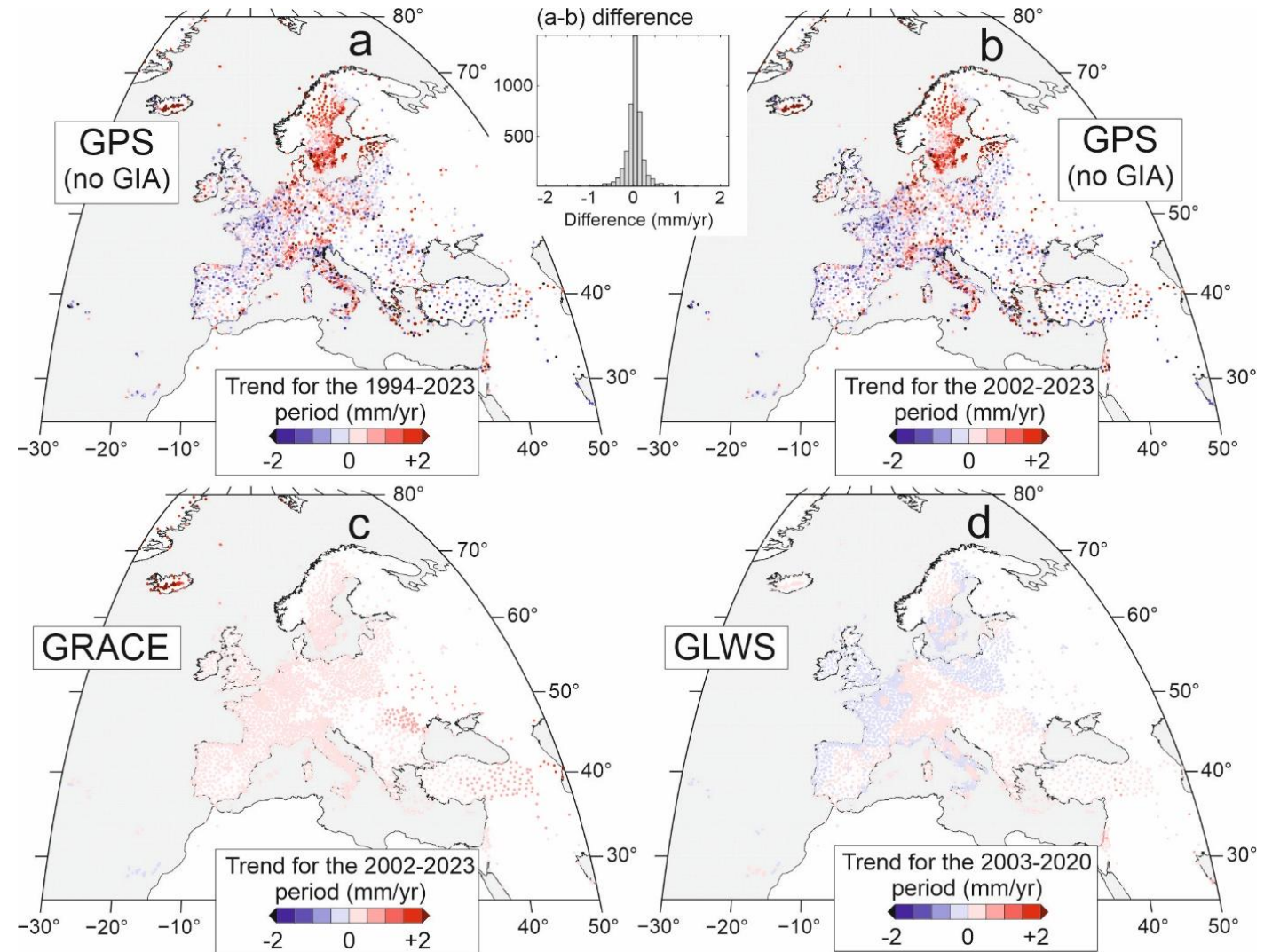
* GPS time series are provided by the Nevada Geodetic Laboratory (NGL).

** NTAL and NTOL loading models are provided by the GFZ Helmholtz Centre for Geosciences. We interpolate the gridded product bilinearly to the exact location of GPS station.

*** The Glacial Isostatic Adjustment model ICE6G_D (Stuhne and Peltier, 2015) is employed.

GNSS benchmarking for Europe:

4. **Trend removal:** trends are inconsistent if we use the entire period.

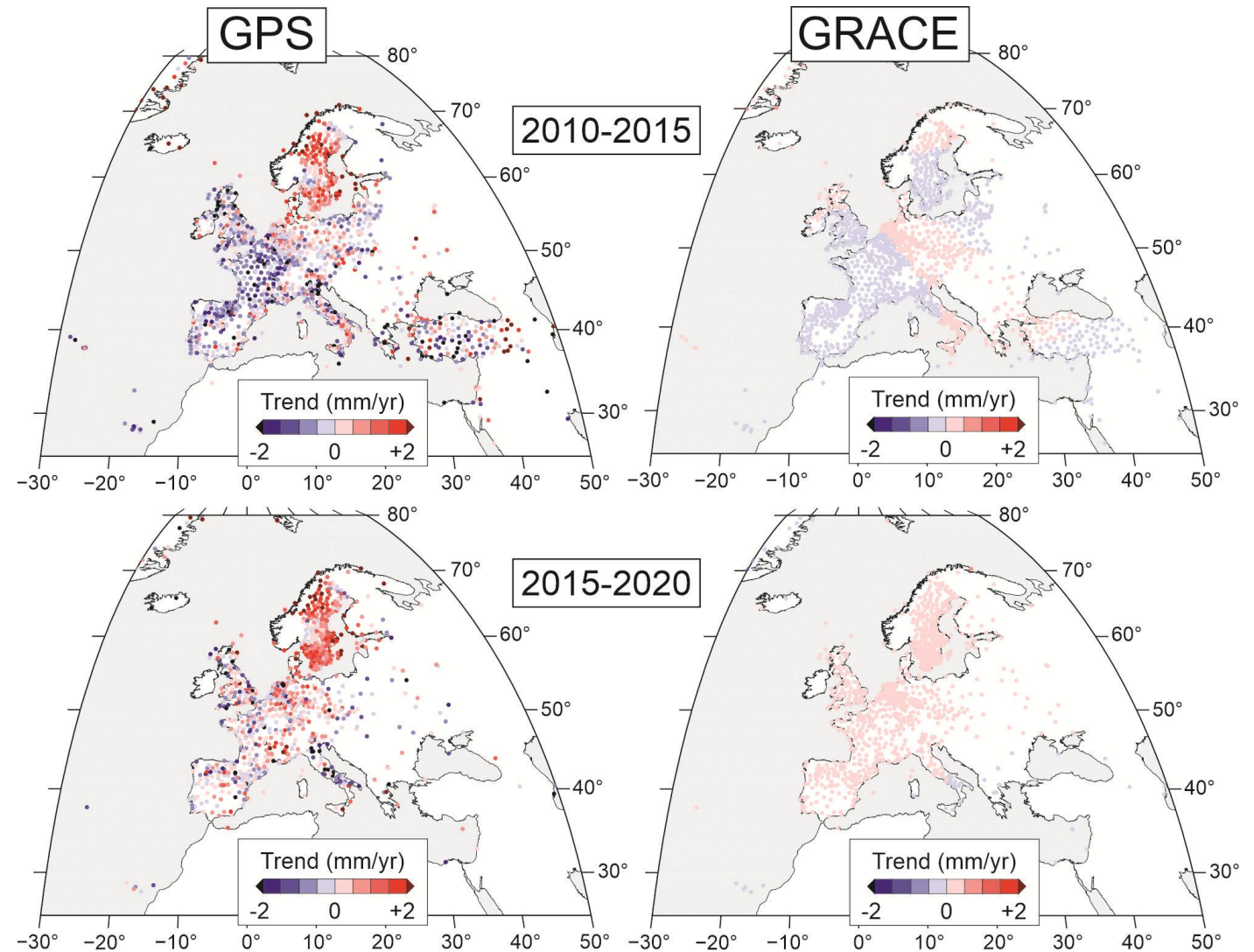


*Global grids of GRACE- (mascon-based product) and GLWS-like gridded TWS changes are transformed into spherical harmonic coefficients to the degree and order equal to 120 and 360, respectively. Then, we apply load Love numbers and methodology given by Farrell (1972) to estimate the vertical displacements for GPS locations. GLWS is a global hydrological model.

GNSS benchmarking for Europe:

4. **Trend removal:** trends are inconsistent if we use the entire period.

However, dividing this period into shorter periods could be helpful for interpretation.

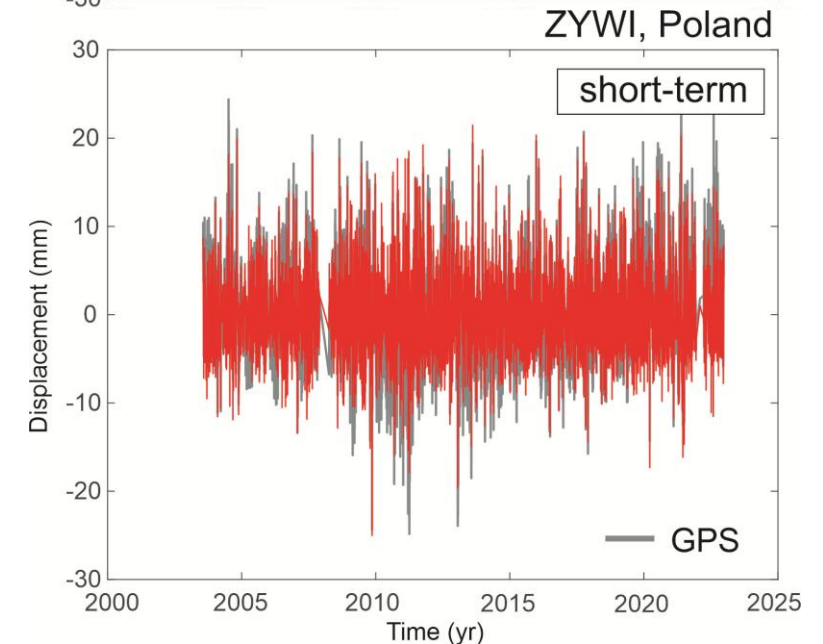
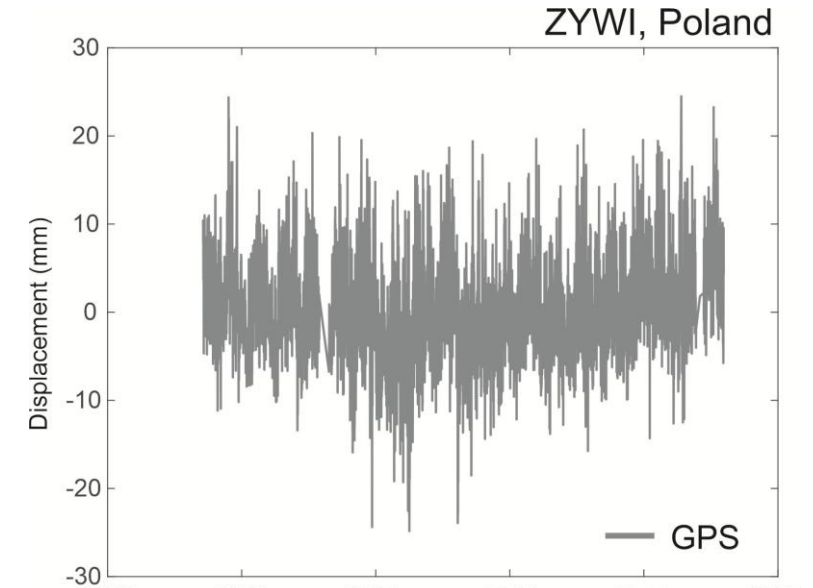
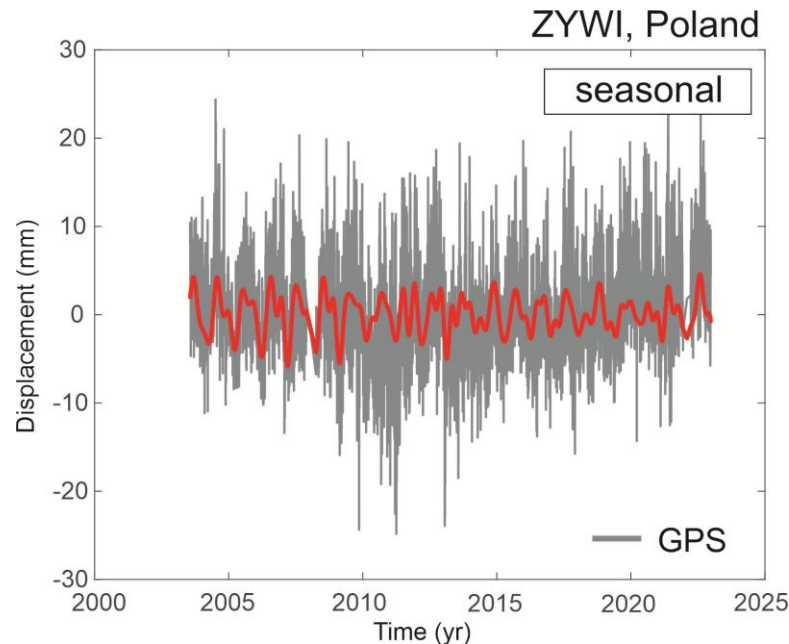
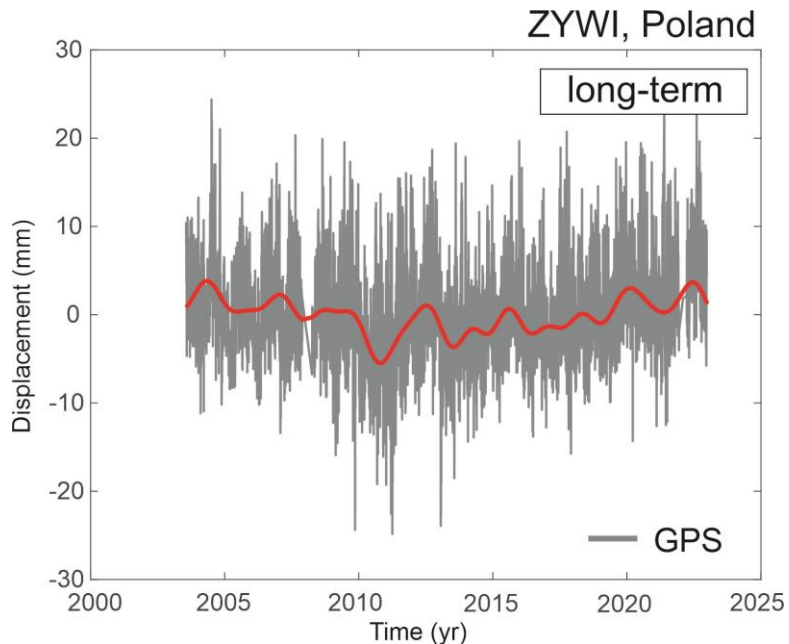


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GNSS benchmarking for Europe:

5. Wavelet decomposition:

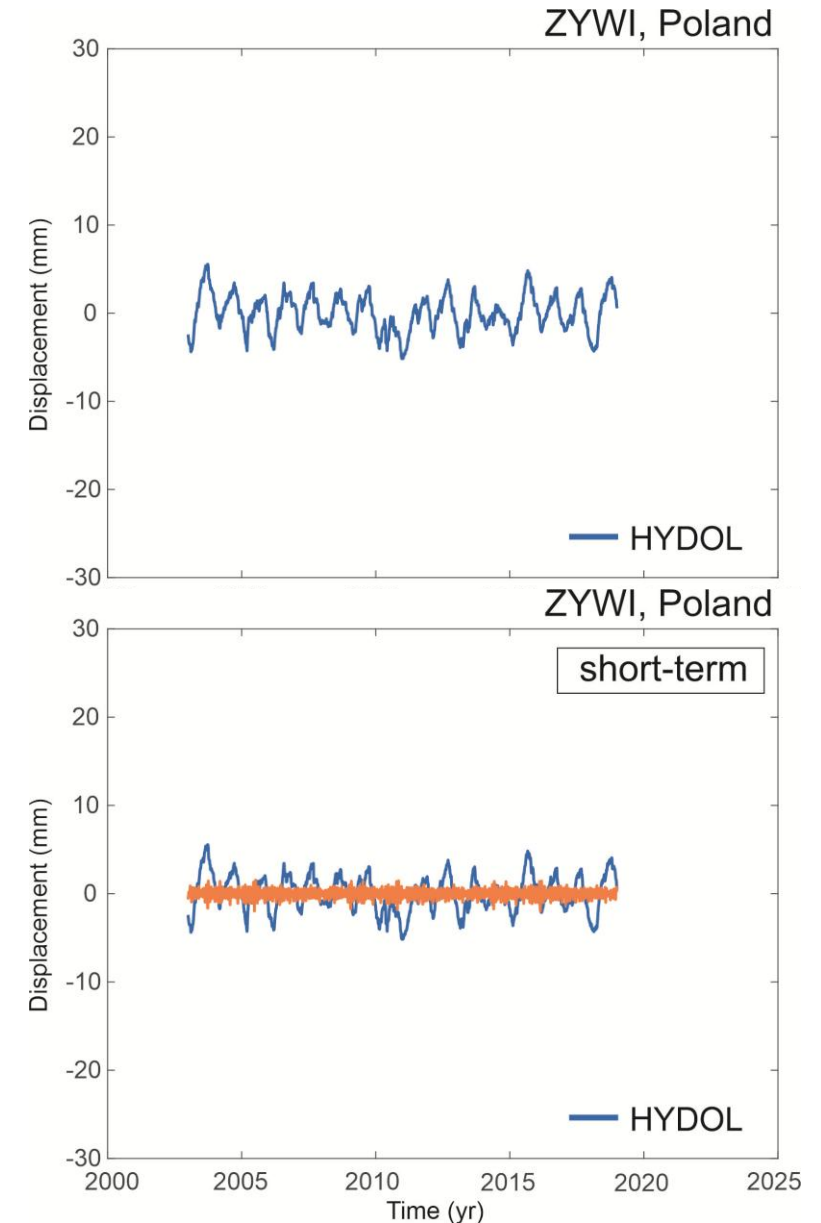
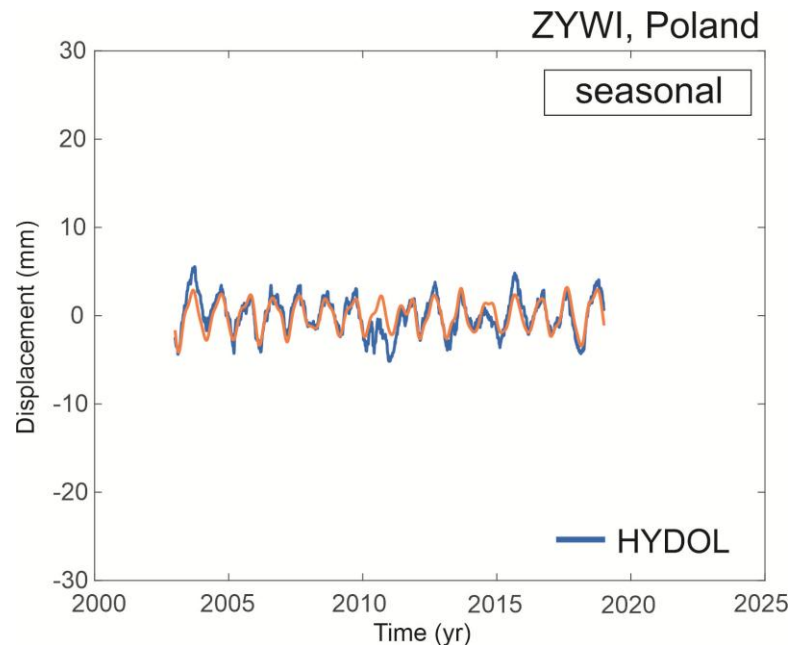
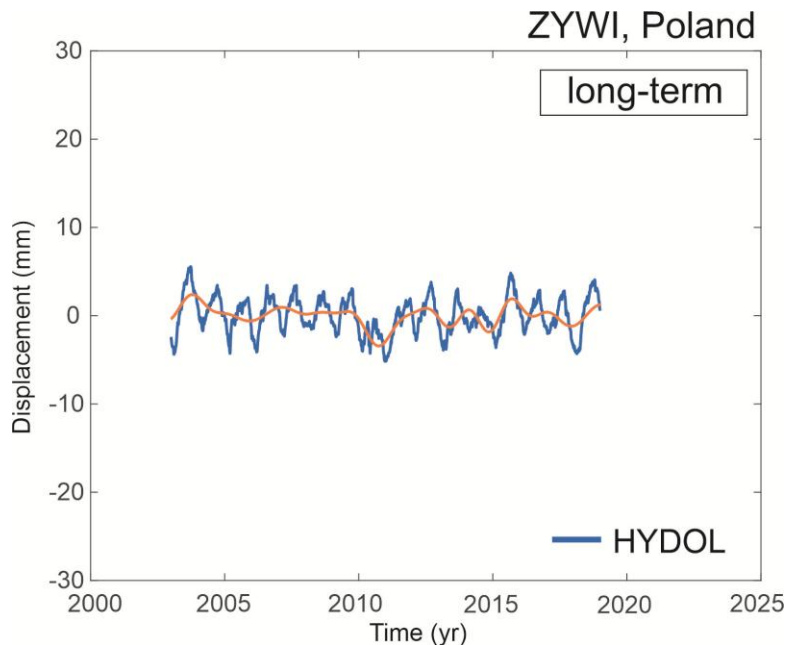
Decomposition level	Period band	Description of band
D1-D6	from 2 days to 5 months	Short-term
D7&D8	from 4 months to 1.4 years	Seasonal band (annual and semi-annual signatures)
D9&A9	from 1.1 years onwards	Long-term



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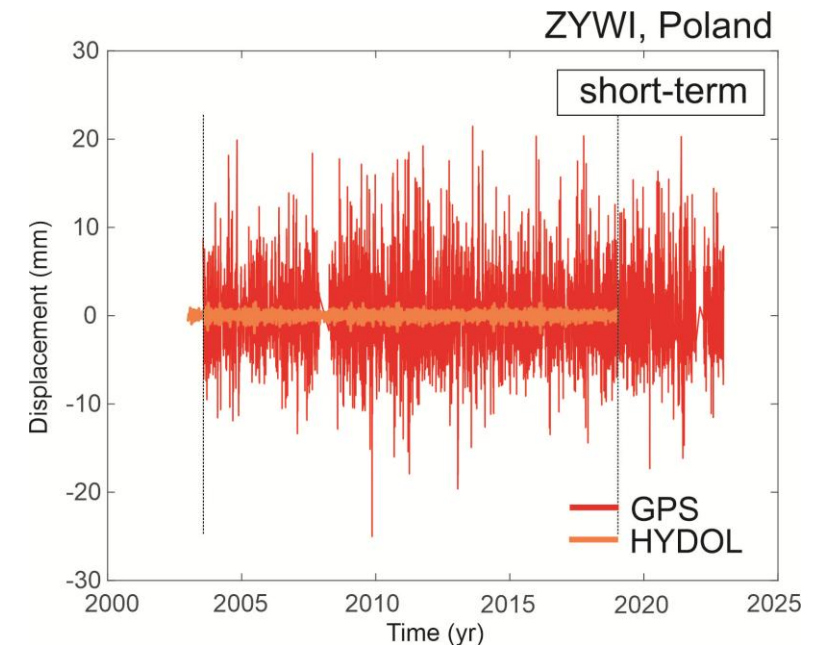
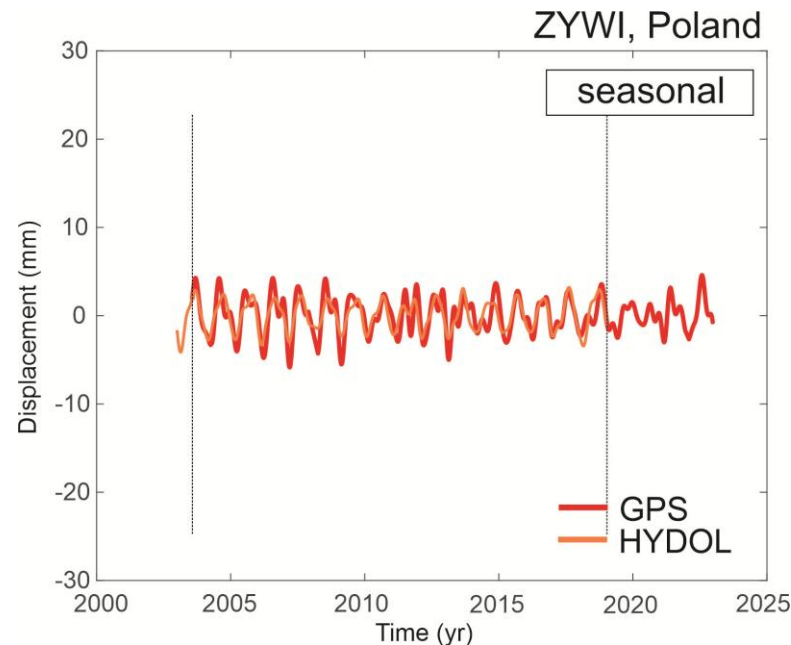
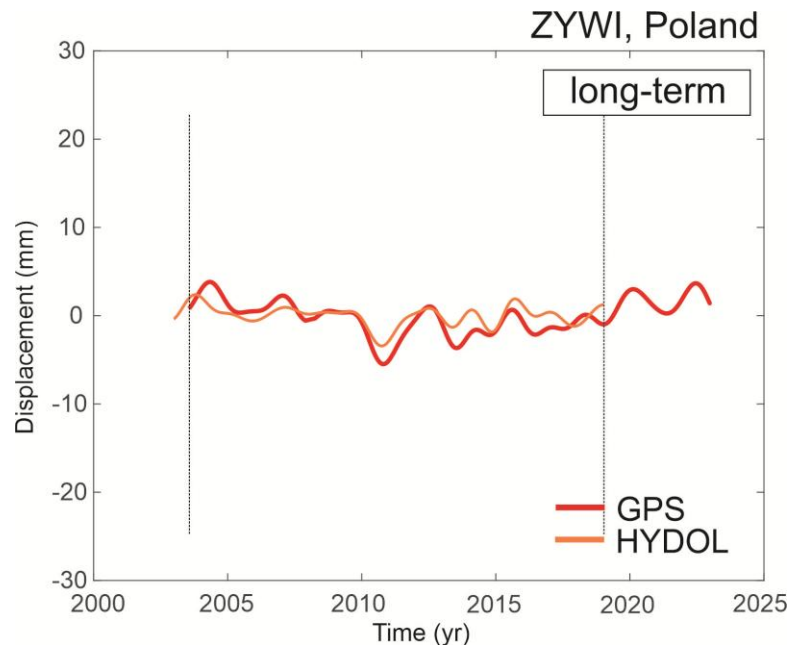
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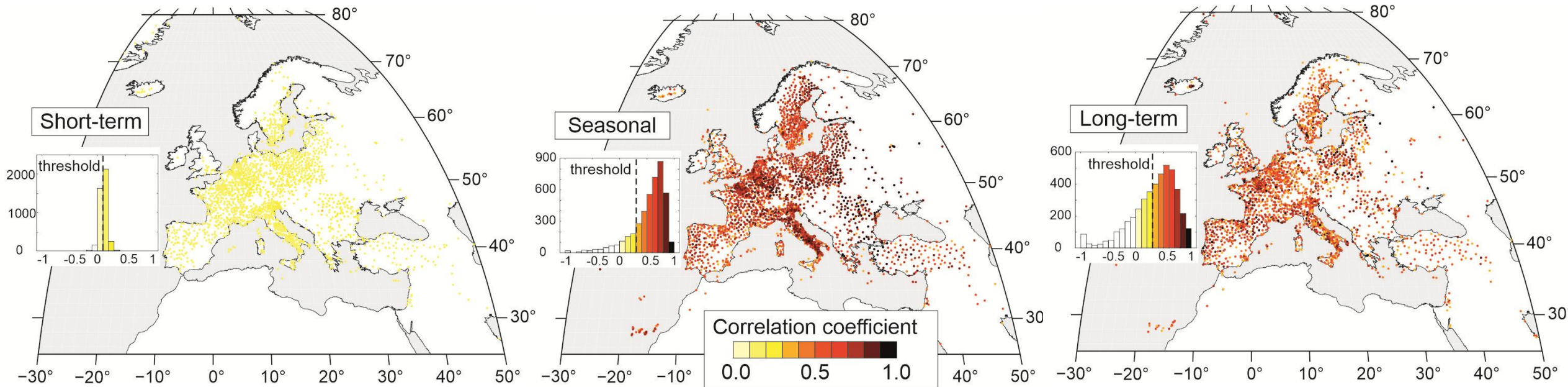
GNSS benchmarking for Europe:

6. **Correlation analysis and benchmarking:**

Different threshold values.

Short-term temporal resolution is showing a weak, but positive correlation (>0.1).

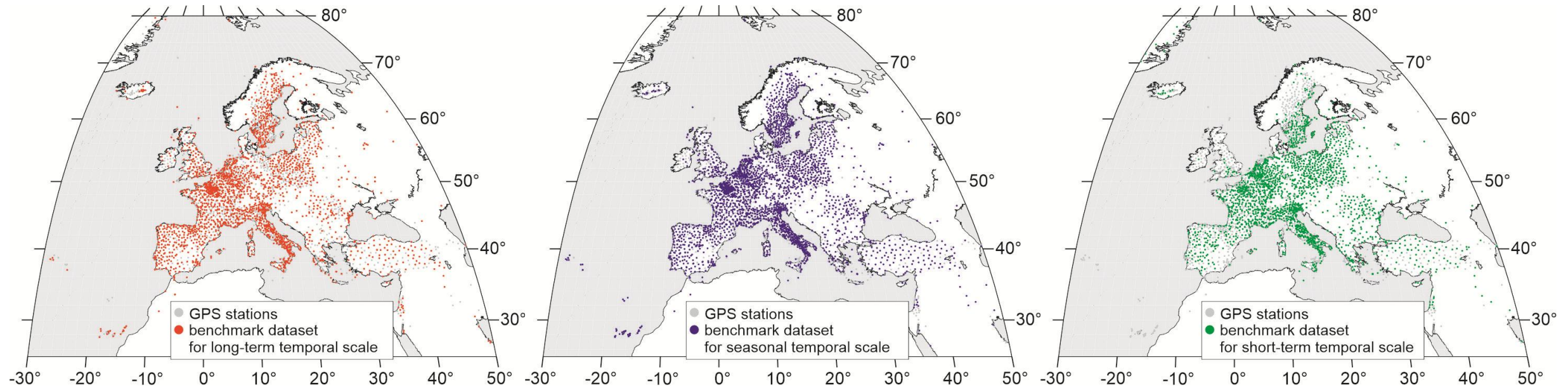
Seasonal and long-term temporal resolutions demonstrate correlation from moderate to strong (>0.3).



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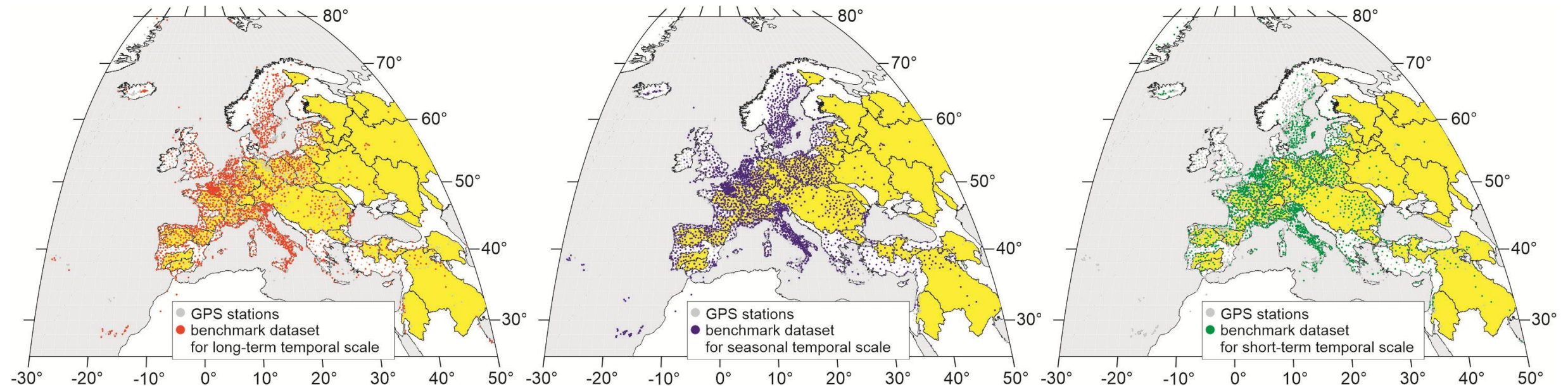
6. Correlation analysis and benchmarking:

- long-term temporal scale, from 1.1 year upwards, **2,521 stations**,
- seasonal temporal scale, from 4 months to 1.4 years, **3,401 stations**,
- short-term temporal scale, from 2 days to 5 months, **2,329 stations**.



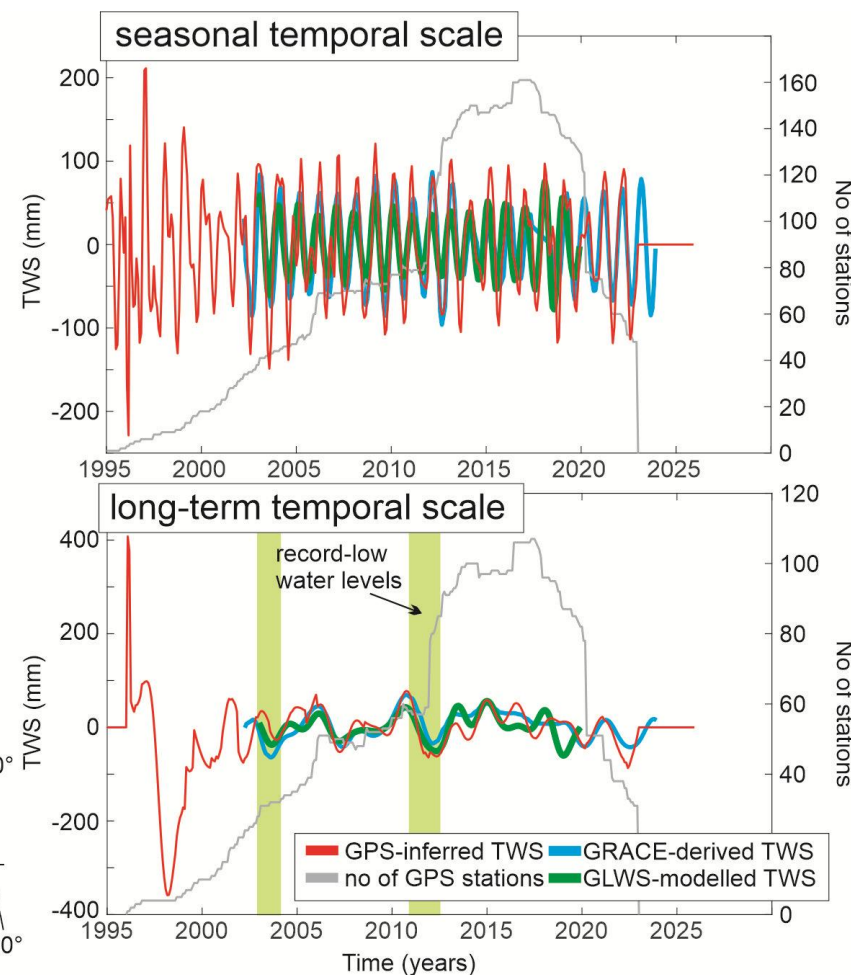
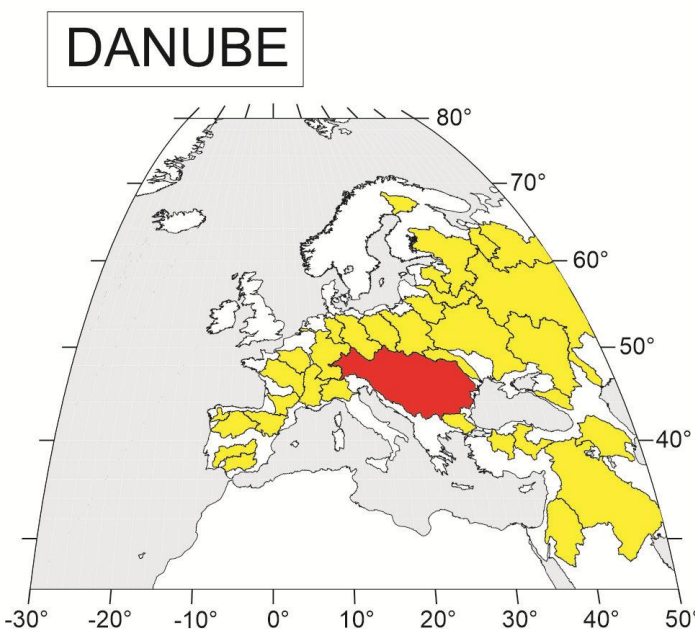
TWS recovery over Europe:

1. Regional inversion (Argus et al., 2014) of benchmark dataset of GNSS displacements for 35 river basins.
2. We provide basin-wise **GPS-inferred TWS time series** at all three pre-defined temporal resolutions for the period 1994-2023, also for the pre-GRACE period (1994-2002).



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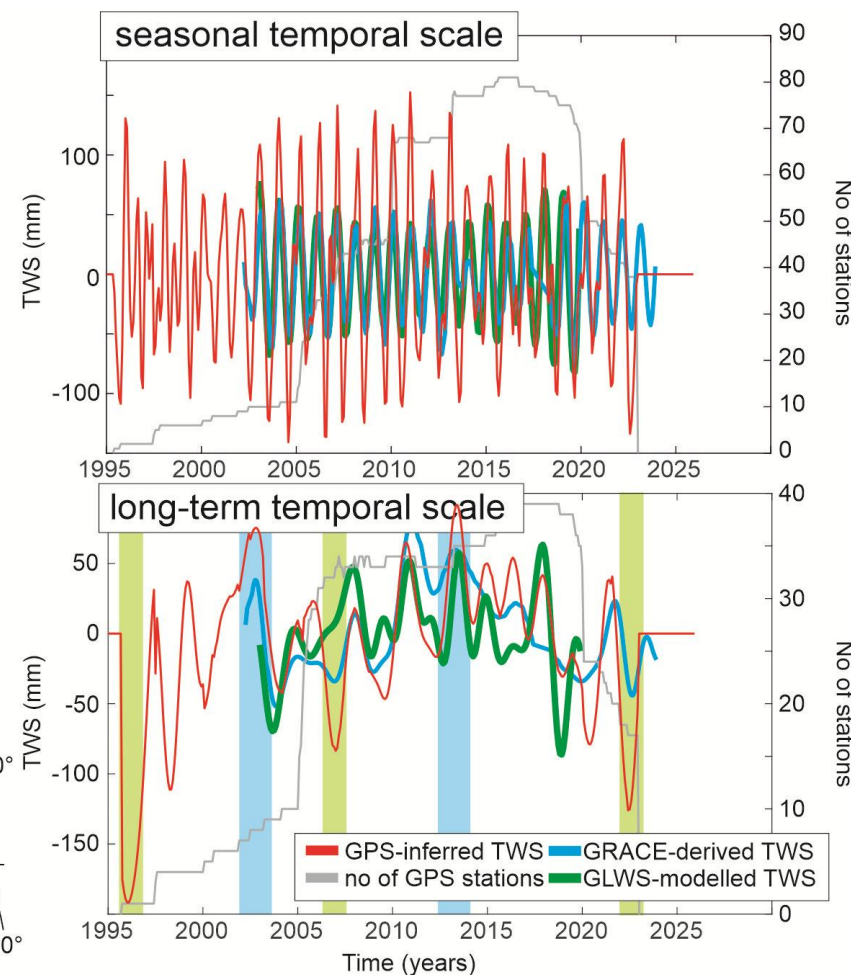
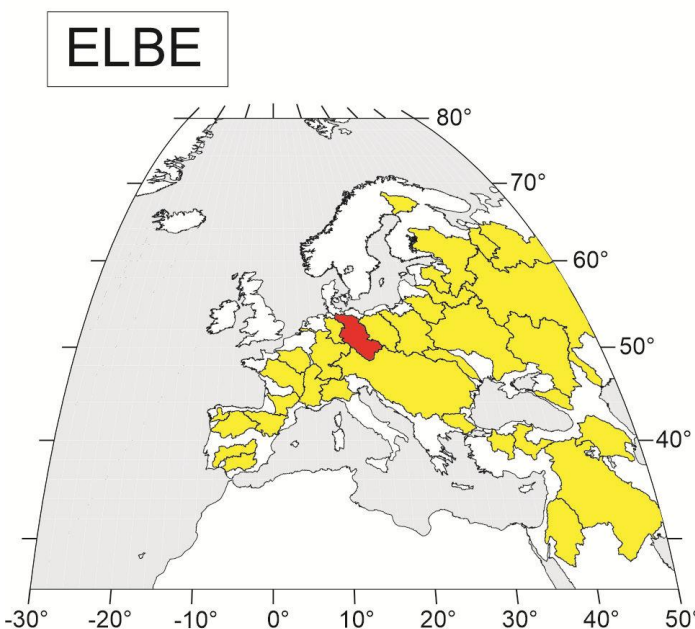
1. Perfect matching of annual phases between the three datasets for seasonal temporal scale.
2. Amplitudes of GPS-inferred TWS slightly larger than in the other two cases; may need further investigation.
3. Excellent matching of TWS changes between GPS-inferred, GRACE-derived and GLWS-modelled values*, for long-term temporal scale.



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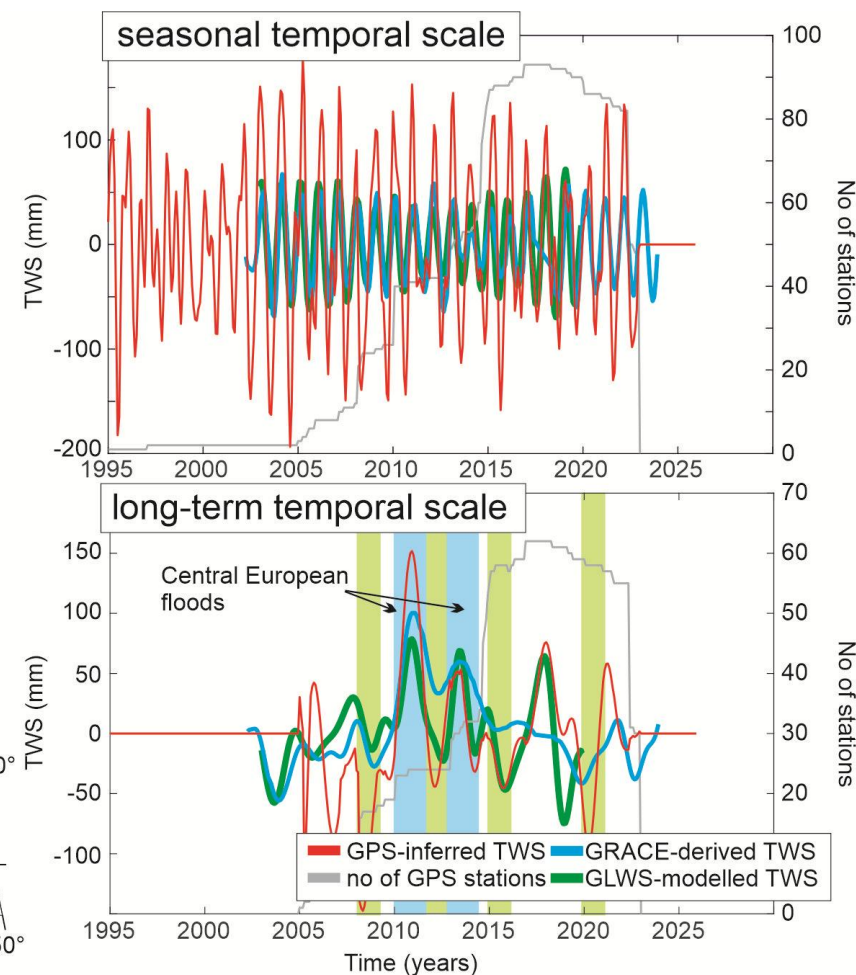
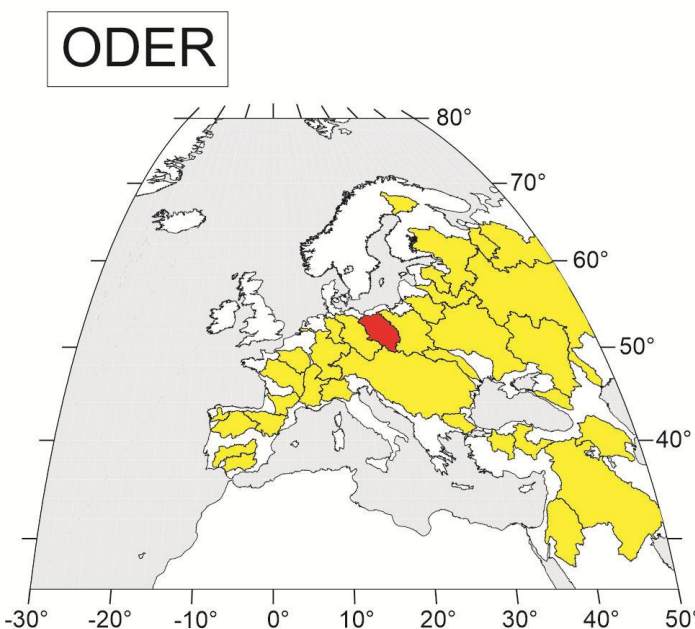
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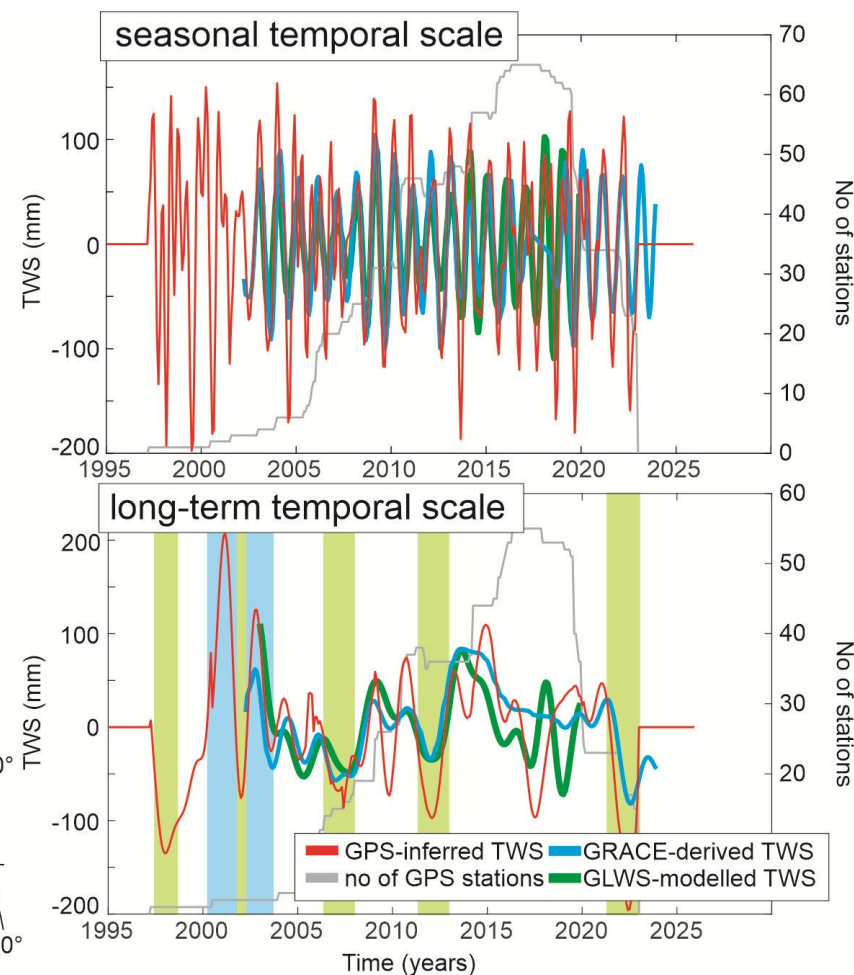
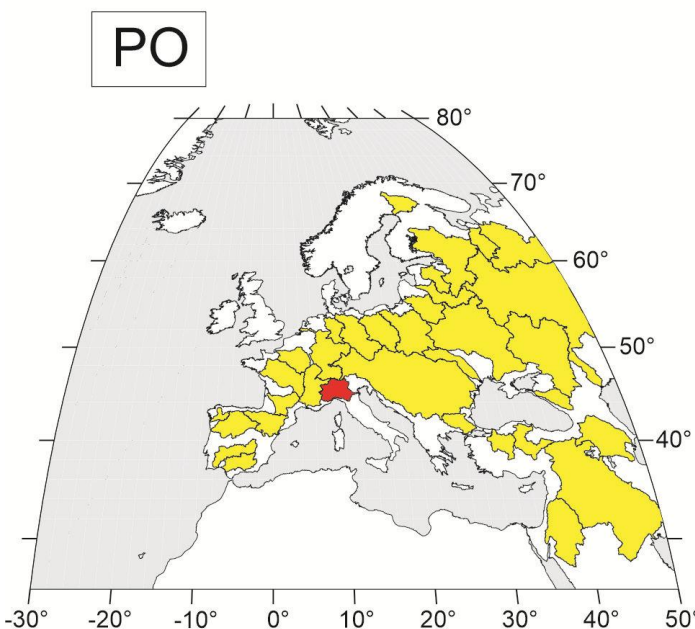
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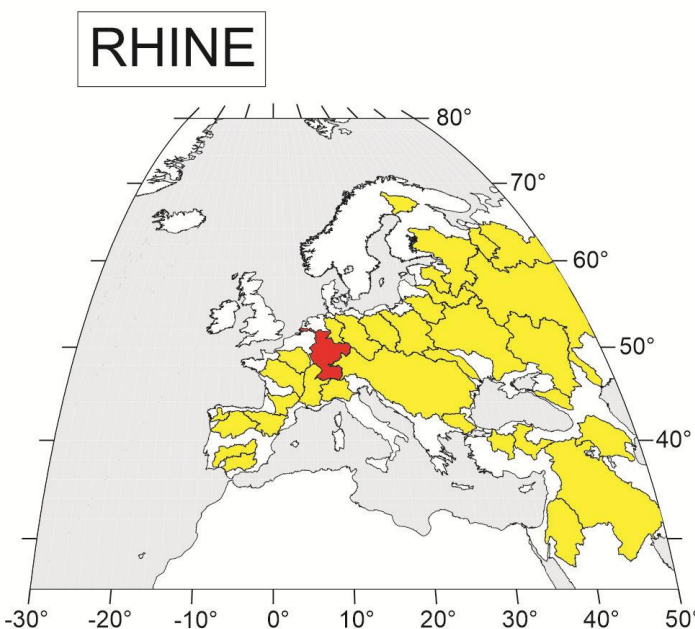
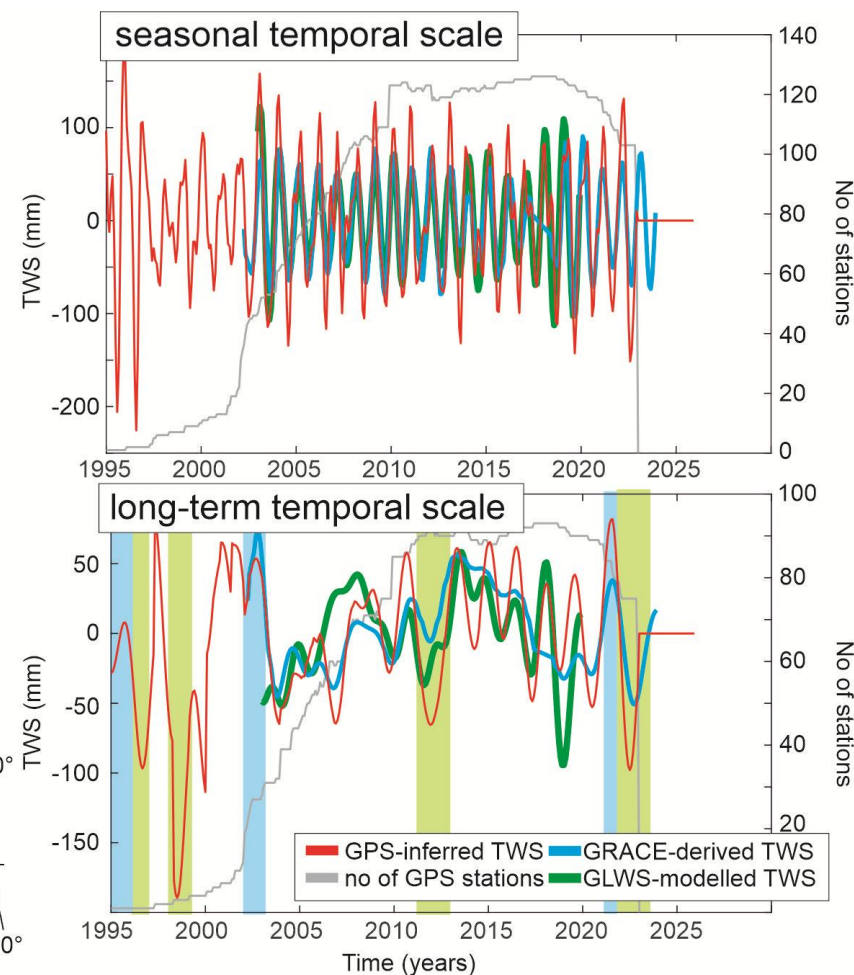
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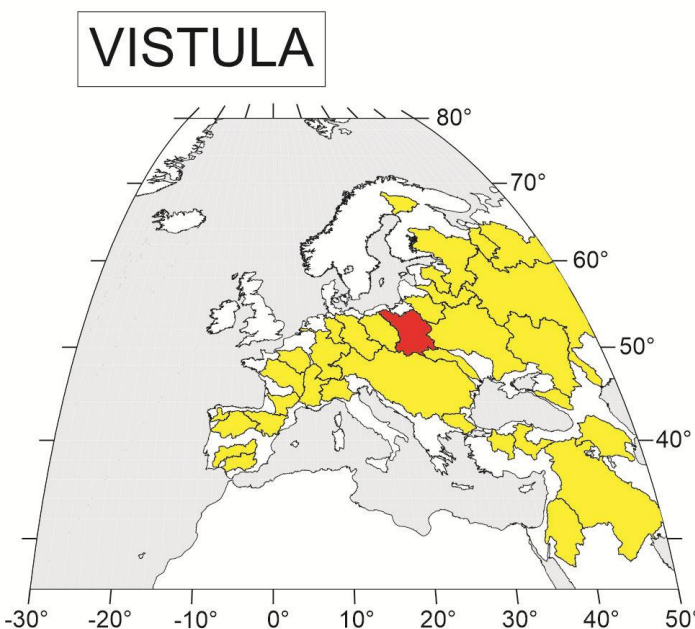
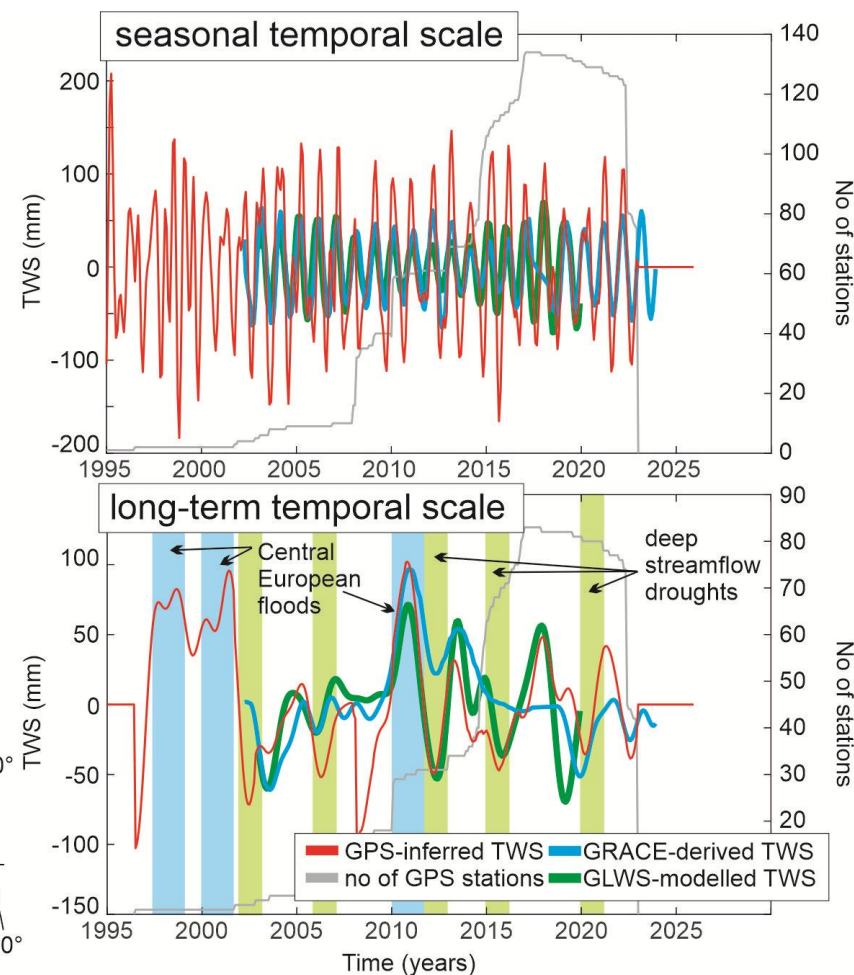
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Conclusions:

1. Dataset of long, daily **TWS time series** over Europe can be inferred from GPS-observed and benchmarked **time series of vertical displacements** at three temporal scales.
2. The (almost) excellent agreement with external datasets is very interesting and inspiring.
3. GNSS provides complementary, higher-spatial-resolution information on hydrological mass changes that are difficult to resolve with GRACE at the scale of many European river basins.
4. GPS-inferred TWS can be also applied for validation of TWS changes recorded by future gravity missions.
5. Dataset of **GPS-inferred TWS time series** will be available soon, contact: anna.klos@wat.edu.pl.

THANK YOU!