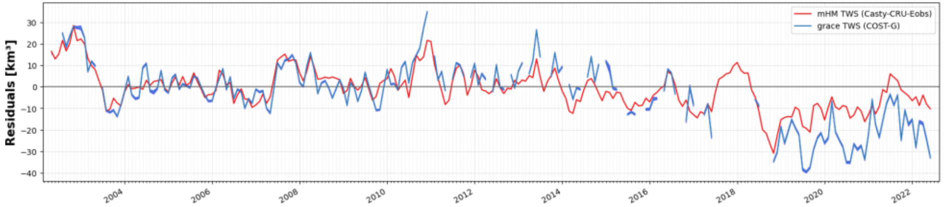
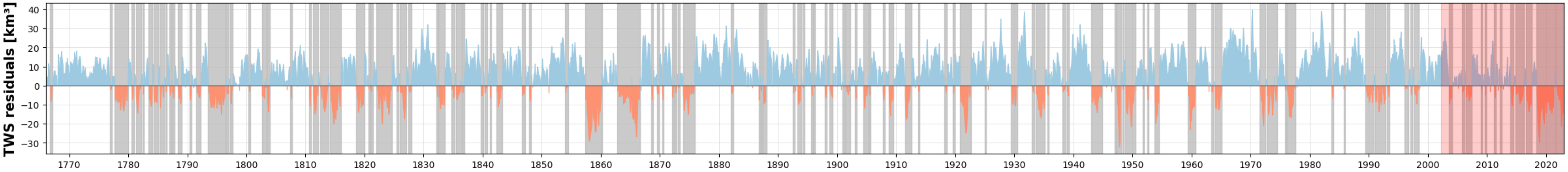
Long-term dynamics of total water storage deficit recovery in Germany

Friedrich Boeing[1,2], Thorsten Wagener[2], Andreas Marx[1], Sabine Attinger[1,2] Contributors: Oldrich Rakovec[1], Rohini Kumar[1]
[1]**Helmholtz Centre for Environmental Research**, [2]**University of Potsdam**





- The most extreme storage deficit periods have highly variable recovery times (3 - 32 months)
- Extremity of storage recovery time for 2018 – 2021 event with respect to historic storage deficit periods
- Increasing influence of above average ET during recent decades

Introduction
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- Motivation
- Research questions

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- GRACE TWS
- MHM simulations

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- Storage deficit concept

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- Storage recovery times

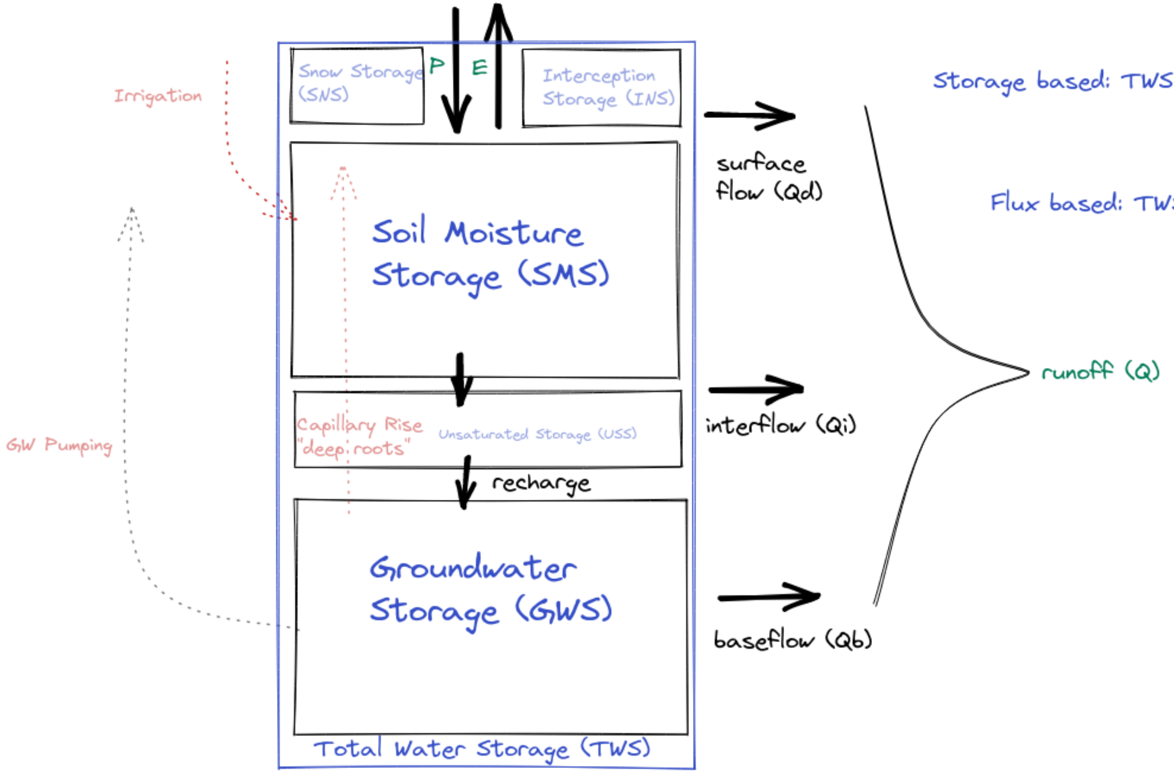
Introduction

- recent years water storage deficit years in Germany 2018 – 2020, 2022 lead to negative impacts and concerns in various water sectors as agriculture, industry, forestry, drinking water supply
- total water storage (TWS) anomalies estimated by the GRACE satellite mission show a strong decline for Germany since measurements began in 2002, but these time series began with a relatively wet period, ended in an exceptional drought situation, and are still relatively short
- resulting trends are not representative for long-term TWS dynamics and should not be used to extrapolate the development into the future (Güntner et al, 2023)
- hydrologic simulations allow for longterm analysis
- research focuses less on the recovery period compared to onset period

Research Questions:
- What are recovery times of water storage deficits in Germany?
- Are the recovery times of storage deficits changing?
  If yes, what are the drivers of this change?

„Der Wasserrückgang in Deutschland beträgt etwa 2,5 Gigatonnen oder Kubikkilometer im Jahr. Damit gehört es zu den Regionen mit dem höchsten Wasserverlust weltweit." Jay Famiglietti (National Geographic 2022/03/22 (https://www.nationalgeographic.de/umwelt/2022/03/hydrologen-warnen-deutschland-trocknet-aus

Introduction
Total water storage concept

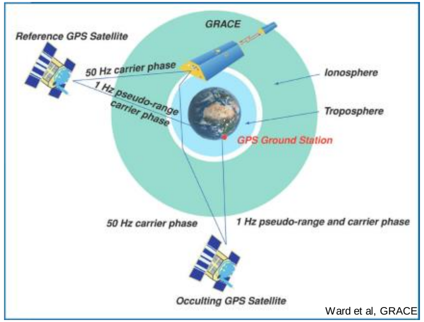


Storage based: TWS Change = SMS Change + GWS Change + SNS Change + INS Change + USS Change

Flux based: TWS Change = P - E - Q

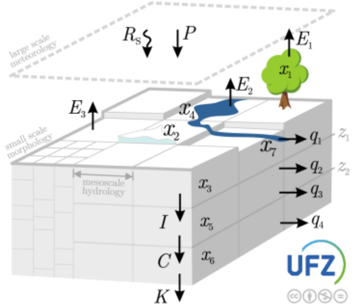
Data

- Grace/Grace-FO derived total water storage (TWS) anomalies 2002 – 2022 from COST-G (Boergens et al, 2020), which is combination of all three official GRACE-TWS solutions



Ward et al, GRACE

- mHM Simulations Casty-CRU-Eobs 1766 – 2022, which is a combination of different meteorological datasets: Casty et al: 1766–1900, which were reconstructed by up-scaling the available station data using principal component regression on the CRU TS dataset 1900 -2015, additional biascorrection and extension with Eobs (Rakovec et al, 2022)



Boergens, Eva; Dobslaw, Henryk; Dill, Robert (2020): **COST-G GravIS RL01 Continental Water Storage Anomalies**. V. 0004. GFZ Data Services. https://doi.org/10.5880/COST-G.GRAVIS_01_L3_TWS

Rakovec, O., Samaniego, L., Hari, V., Markonis, Y., Moravec, V., Thober, S., Hanel, M., & Kumar, R. (2022). **The 2018–2020 Multi-Year Drought Sets a New Benchmark in Europe.** In Earth's Future (Vol. 10, Issue 3). American Geophysical Union (AGU). https://doi.org/10.1029/2021ef002394

Methods
(Total Water) Storage Deficits

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- Total water storage deficits are defined following Thomas et al (2014) *"deviation of regional, monthly terrestrial water storage anomalies from the time series' monthly climatology, where negative deviations represent storage deficits. Monthly deficits explicitly quantify the volume of water required to return to normal water storage conditions"*

- *„The monthly deficit (M) quantifies the **volume of water required to recover from below-normal water storage conditions"** → no standardization!*

- the total water storage includes storages with different reaction times. "*This definition combines agricultural and hydrological droughts and only includes meteorological droughts as long as they result in a negative storage anomaly."* (Teuling et al 2013)

Teuling, A. J., Van Loon, A. F., Seneviratne, S. I., Lehner, I., Aubinet, M., Heinesch, B., Bernhofer, C., Grünwald, T., Prasse, H., & Spank, U. (2013). **Evapotranspiration amplifies European summe drought**. In Geophysical Research Letters (Vol. 40, Issue 10, pp. 2071–2075). American Geophysical Union (AGU). https://doi.org/10.1002/grl.50495

Thomas, A. C., Reager, J. T., Famiglietti, J. S., & Rodell, M. (2014). **A GRACE-based water storage deficit approach for hydrological drought characterization**. In Geophysical Research Letters (Vol. 41, Issue 5, pp. 1537–1545). American Geophysical Union (AGU). https://doi.org/10.1002/2014gl059323

Methods
(Total Water) Storage Deficits

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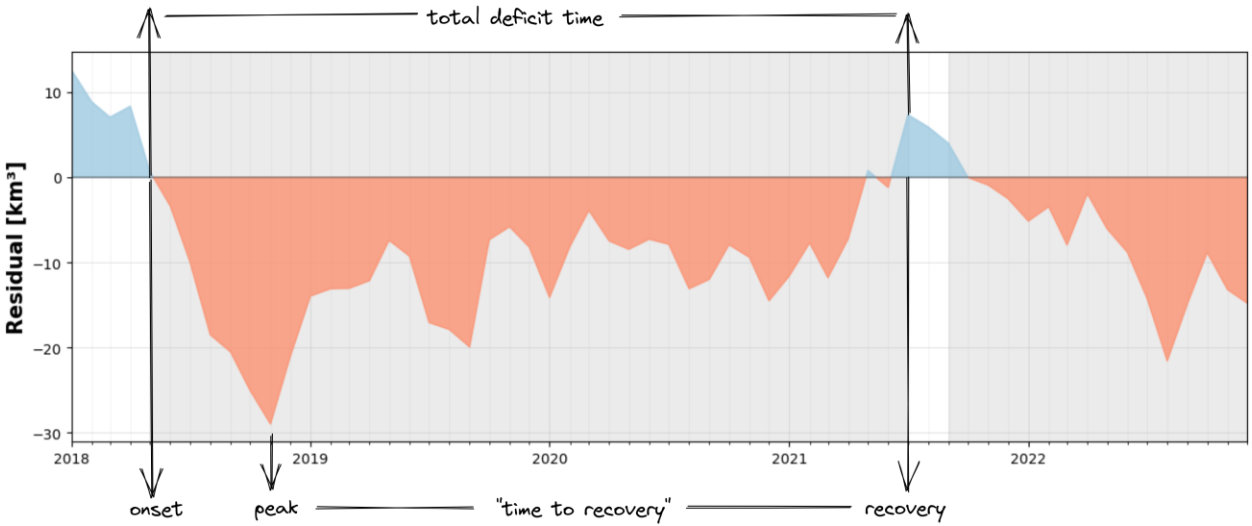
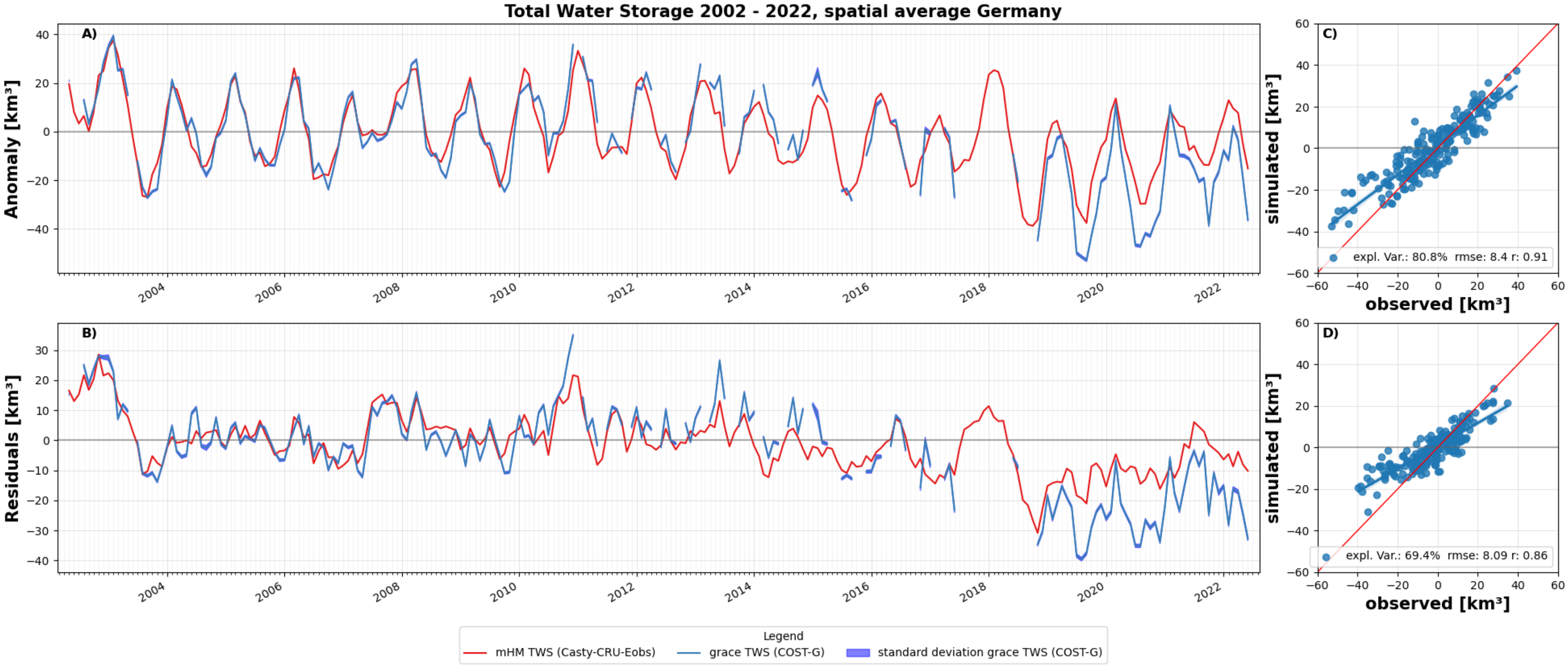


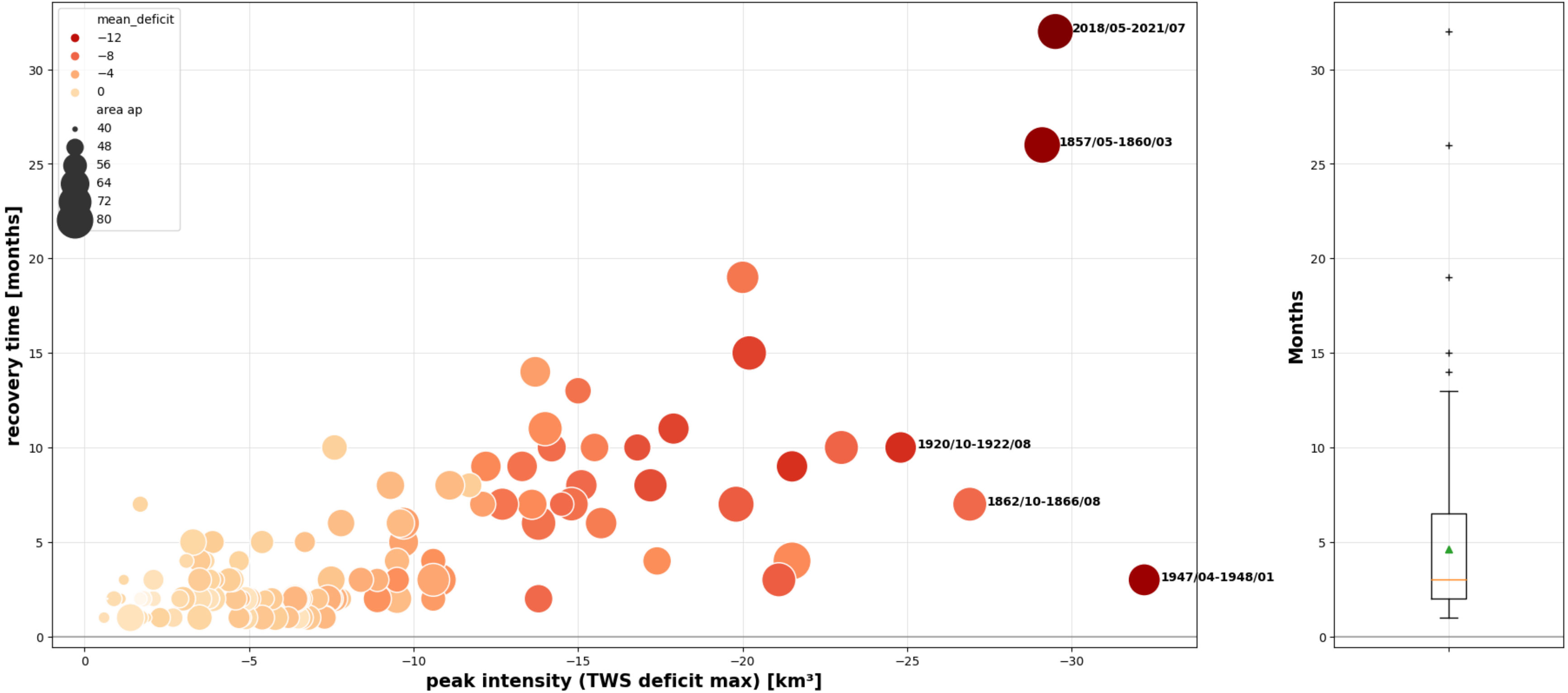
- **deficit** should last for at least *3 months*
- **onset** is defined when TWS negatively departs from climatological average conditions
- **peak** is defined when TWS reaches a minimum during deficit
- **recovery** is defined when deficit reaches climatological average conditions for at least n months (n=2)
- **recovery time** is then defined as the *time from peak to recovery of the deficit*.

Parry, S., Prudhomme, C., Wilby, R. L., & Wood, P. J. (2016). Drought termination. In Progress in Physical Geography: Earth and Environment (Vol. 40, Issue 6, pp. 743–767). SAGE Publications. https://doi.org/10.1177/0309133316652801

Results:
Comparison of TWS estimates from mHM to Grace



Results:
Estimation of recovery times:



Results:
Characteristics of 10 largest storage deficit periods

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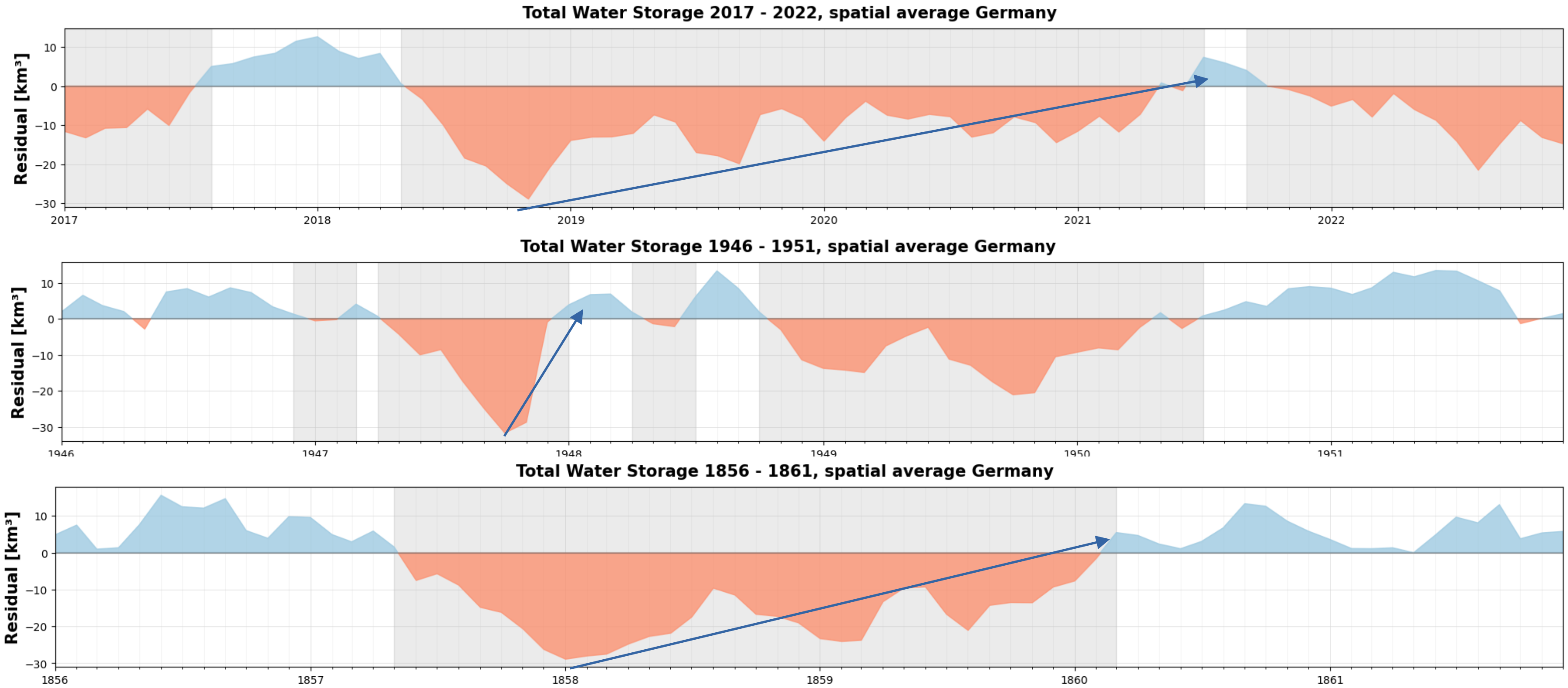
Start	Peak	End	Total Time [months]	Start to Peak [months]	Recovery time [months]	Peak deficit [km³]	Mean deficit [km³]
1947-04-15	1947-10-15	1948-01-15	9	7	3	-32.2	-13.7
2018-05-15	2018-11-15	2021-07-15	38	7	32	-29.5	-15.1
1857-05-15	1858-01-15	1860-03-15	34	9	26	-29.1	-14.1
1862-10-15	1866-01-15	1866-08-15	46	40	7	-26.9	-7.7
1920-10-15	1921-10-15	1922-08-15	22	13	10	-24.8	-10.5
1959-05-15	1959-10-15	1960-08-15	15	6	10	-23.0	-8.0
1948-10-15	1949-10-15	1950-07-15	21	13	9	-21.5	-10.3
2021-09-15	2022-08-15	-	15	12	-	-21.5	-5.8
1971-07-15	1972-03-15	1972-06-15	11	9	3	-21.1	-8.3
1814-03-15	1814-10-15	1816-01-15	22	8	15	-20.2	-9.6

Results:
Three largest deficit periods (with respect to peak deficit)



Results:
Drivers of water balance and recovery times:

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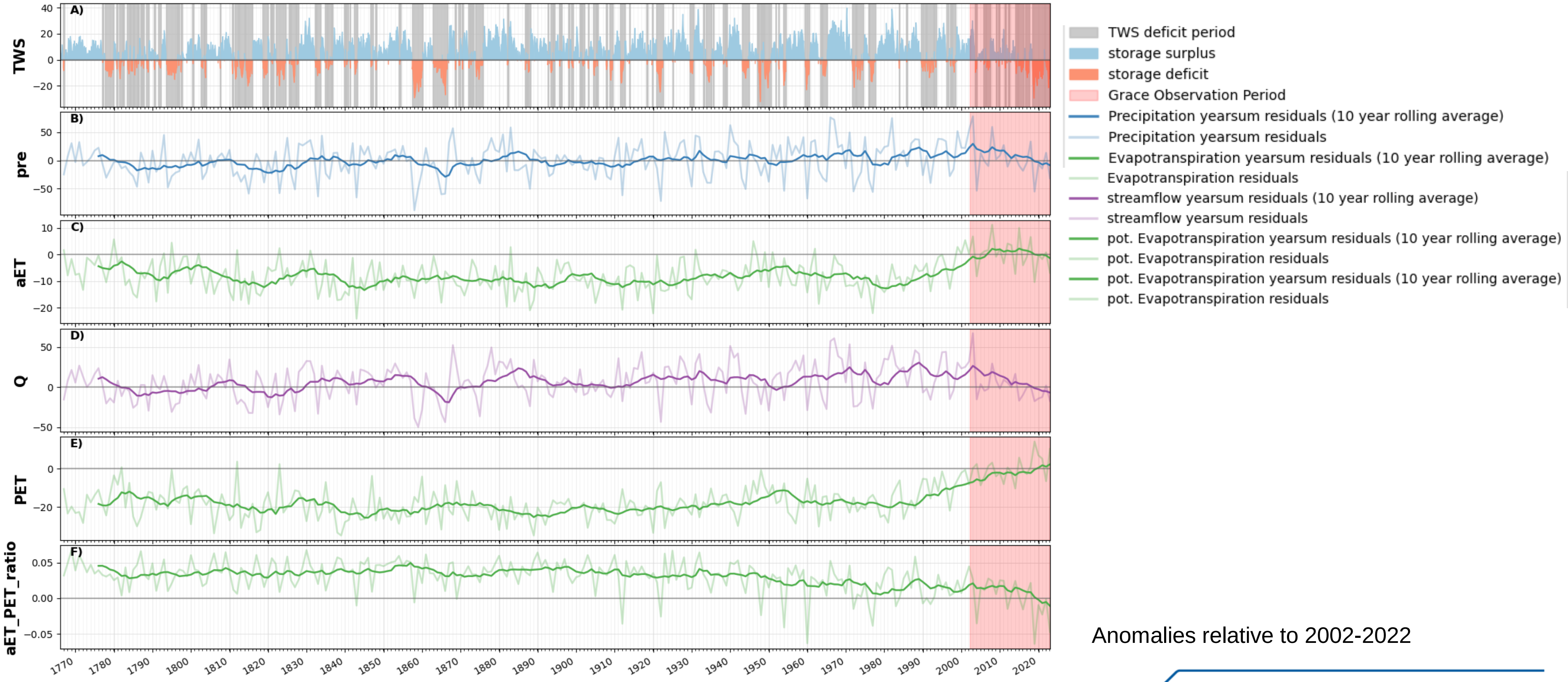

Anomalies relative to 2002-2022

Results/Discussion

- most severe deficit periods are characterized by fast onset to peak and large variability in recovery times (3 month for 1947 event to 32 months for 2018 – 2021 event)

- extremity of recent 2018 – 2021 deficit period with respect to recovery time, exceeded recovery times from past

- 2021 very short recurrent time, followed by ongoing 2022 deficit period (data until 10/2022)

- high precipitation can end total storage deficits in very short amount of time (e.g. 1947 event)

- Increasing influence of above average ET during last 3 decades, less extreme precipitation deficits compared to historic periods

- possible explanations for differences of TWS estimated with GRACE/GRACE-FO versus mHM: anthropogenic influences (GW abstraction) and plant access to groundwater not represented in mHM, signal leakage into germany from glacier loss in alps overestimate the negative trends (Güntner et al, 2023), meteorological forcing uncertainty