GRACE/GRACE FO for Monitoring Hydrological Extremes and Groundwater

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WWAO Connecting the Drops Webinar

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Outline

1) Update on the hydrological extreme study using GRACE/FO

(Rodell & Li, 2023; Li & Rodell, 2023)

Total intensity indicates intensification of hydrological extremes

2) GRACE/FO data assimilation for global groundwater estimates (GLDAS2.2)

(Li et al., 2019)

Validation results; Tools for accessing data

3) Future gravity measuring missions

The Gravity Recovery and Climate Experiment (GRACE, 2002-2017) and GRACE-Follow-on (FO, 2018-present) missions

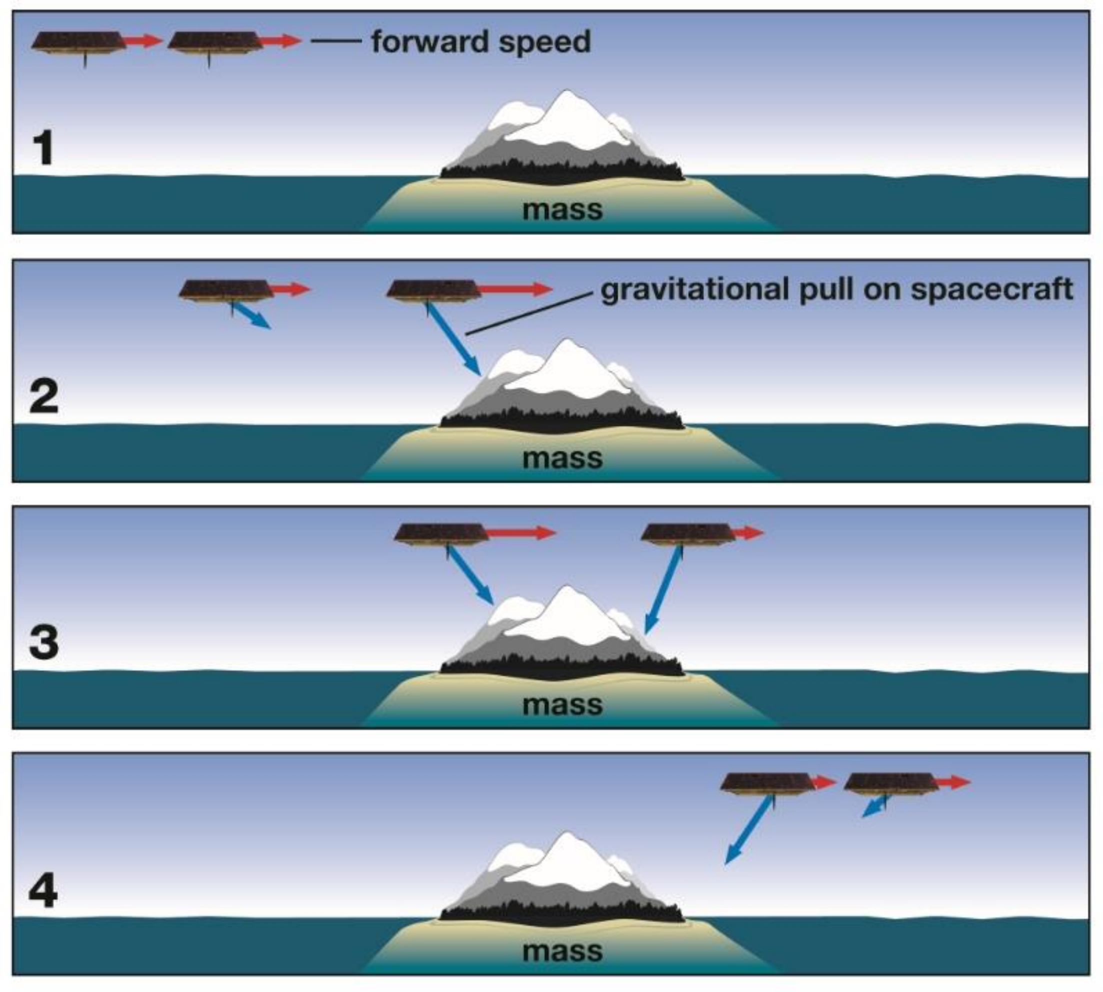


Image source: NASA

- The satellite systems measure gravity
- GRACE/FO TWS represents integrated observations: soil moisture, groundwater, snow and surface water
- Coarse spatial resolution: 150,000 km^2
- Monthly mass changes

1. GRACE/FO for examining changes in hydrological extremes

Motivation

Erftstadt-Blessem, Germany, 2021

Sao Paulo, Brazil, 2015

Limitations of gauge data:

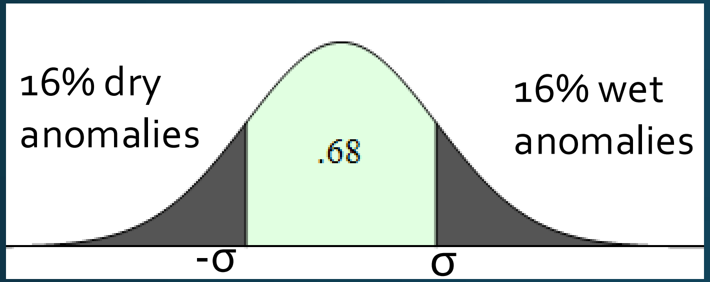
- Limited in number and spatial distribution (more in developed countries); various density across watersheds
- Inadequate to reflect depth and extent of severe extremes
- Difficult to draw global conclusions
  - IPCC AR5&AR6 :regional changes; low confidence on global scale changes

Benefits of GRACE/FO observations:

- Global coverage and nearly continuous record since 2002
- Reflect changes in all water compartments affected by hydrological extremes

Identifying extreme events

Define wet and dry anomalies at grid cells



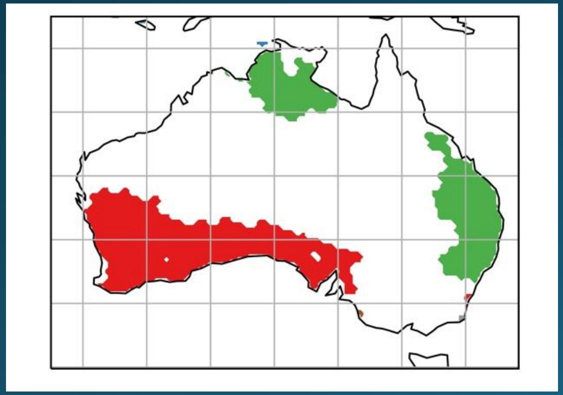
3-D dry or wet anomalies

ST-DBSCAN
Spatial and temporal clustering

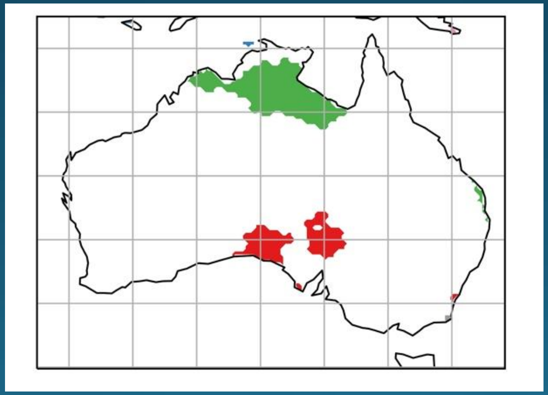
Event 1

Event 2

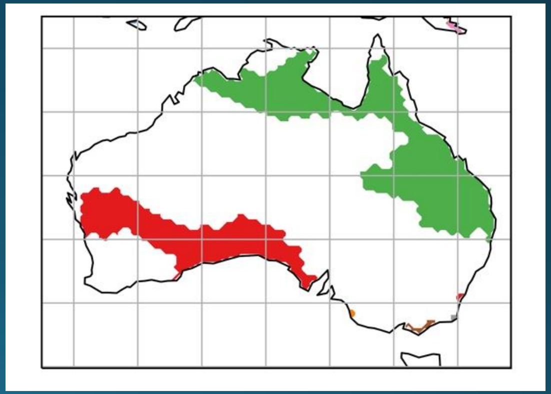
Month 1



Month 2



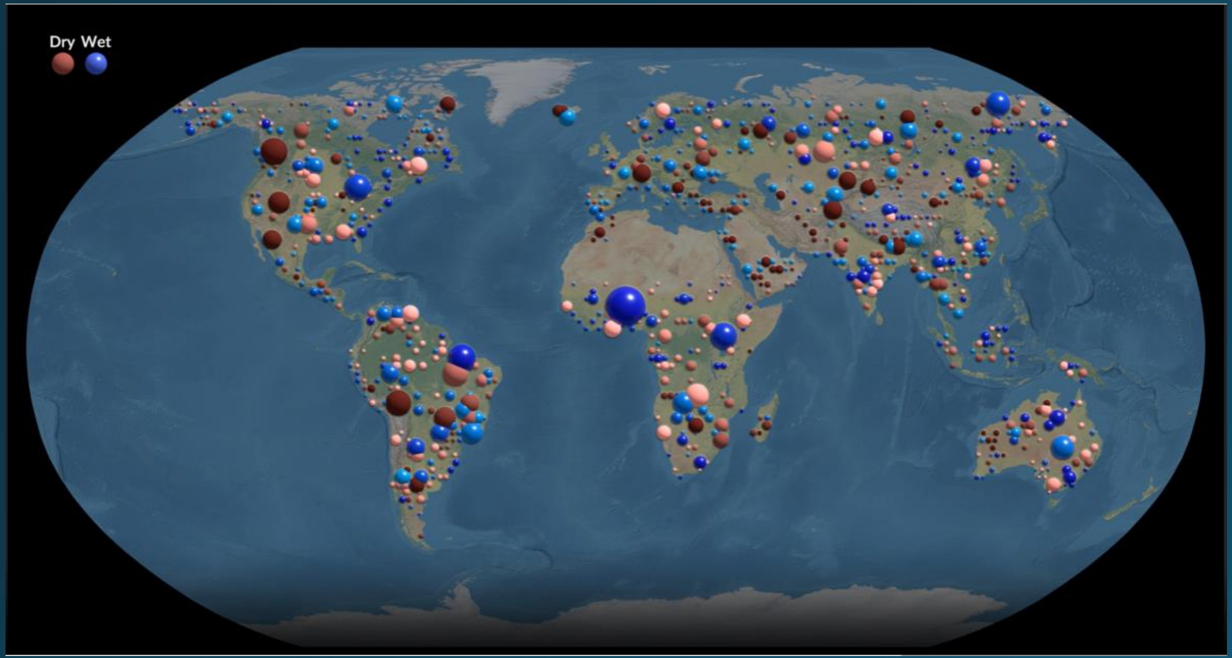
Month 3



Shaded areas represent TWS anomalies

Hydrological extremes derived from GRACE/FO data (2002-2024)

Spatial distribution of 1229 events



Events occurred in each year

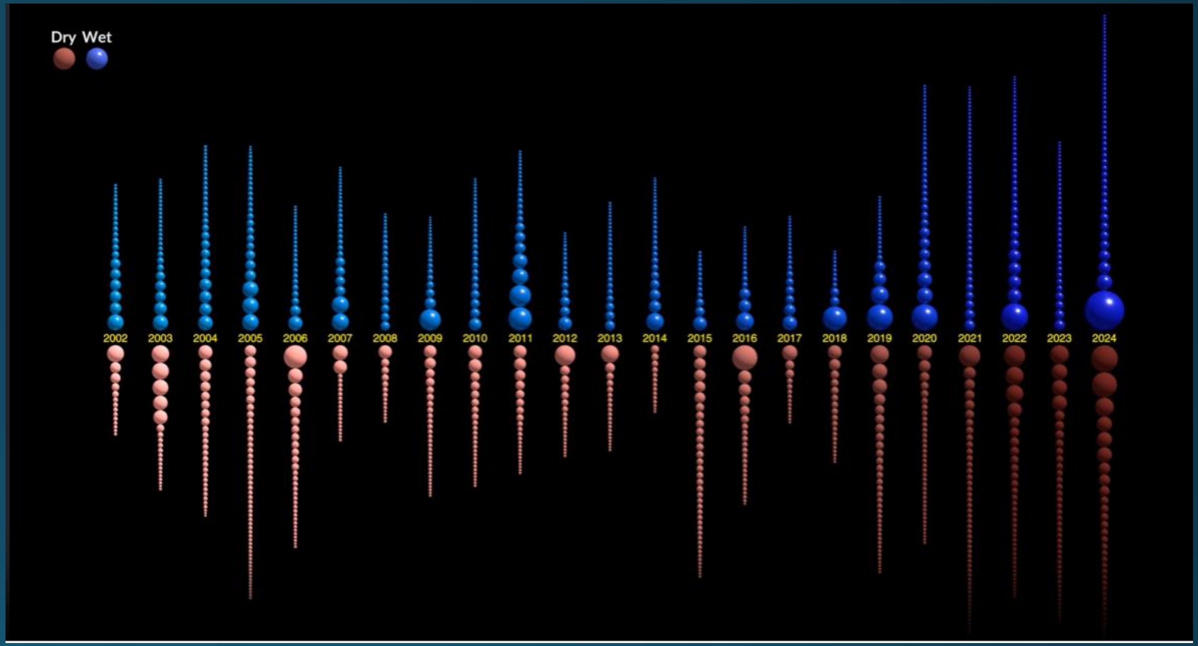


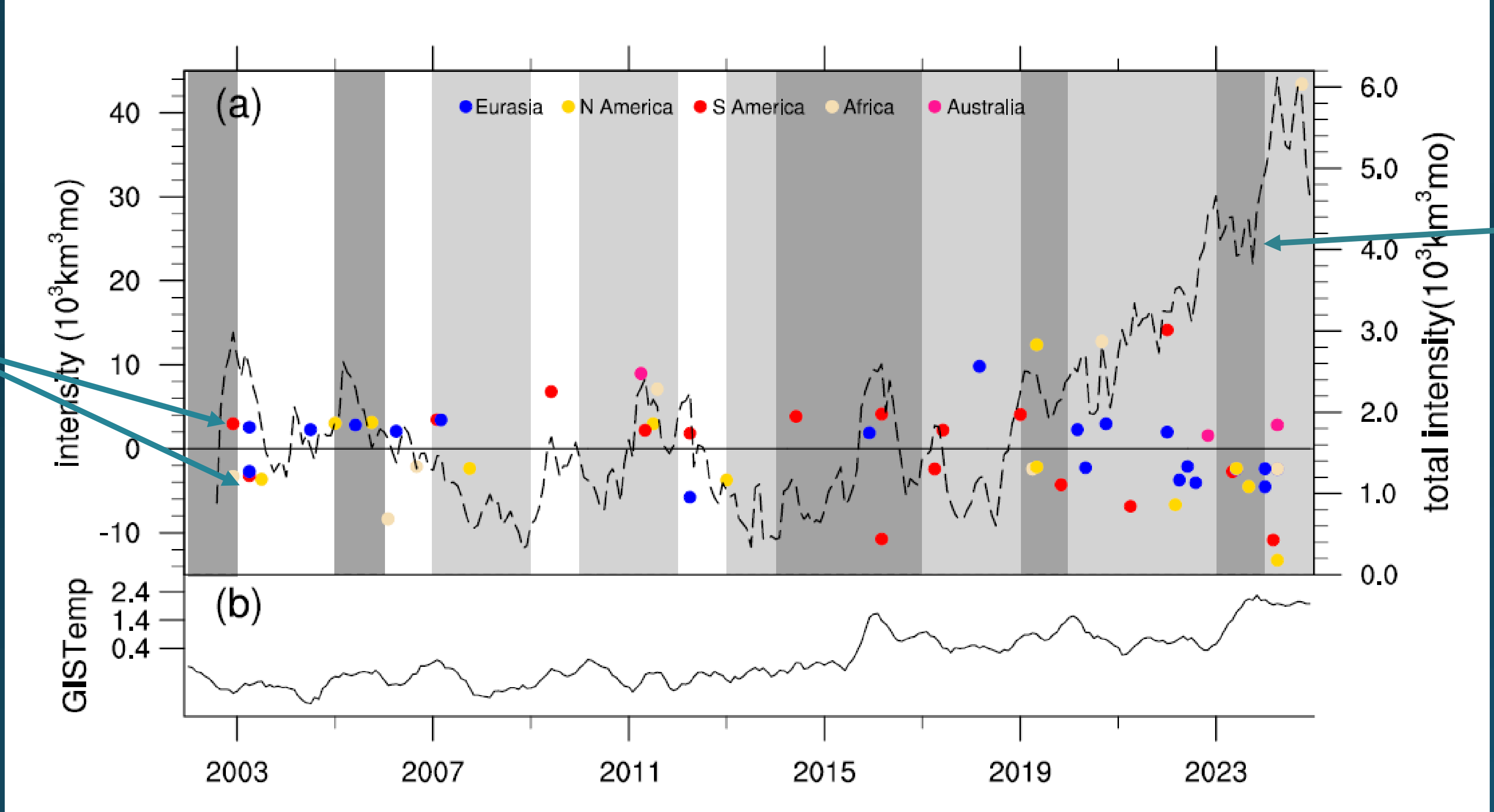
Image source: NASA Scientific Visualization Studio

- The diameter of spheres is proportional to intensity, $\sum_S \sum_T TWS\ anomalies$
- The color keys for the spheres are provided in the right figure.
- Watch animation of these events at: https://svs.gsfc.nasa.gov/5565/

Characteristics of extremes: frequency of occurrence, extent, duration, severity and intensity

Intensification of hydrological extremes

Colored dots represent top 30 wet and top 30 dry events



Total intensity: sum of monthly intensities of all wet and dry extremes

- Consistent with increases in extreme precipitation and prolonged dry spells
- reflect changes in all aspects of hydrological extremes (severity, frequency of occurrence, duration and extent)

Rodell & Li, 2023; Li & Rodell, 2023

2. Global GRACE/FO data assimilation for groundwater estimates

Purposes:

- Separate TWS into components
- Constrain model simulation
- Spatial and temporal downscaling

The Catchment land surface model (CLSM)

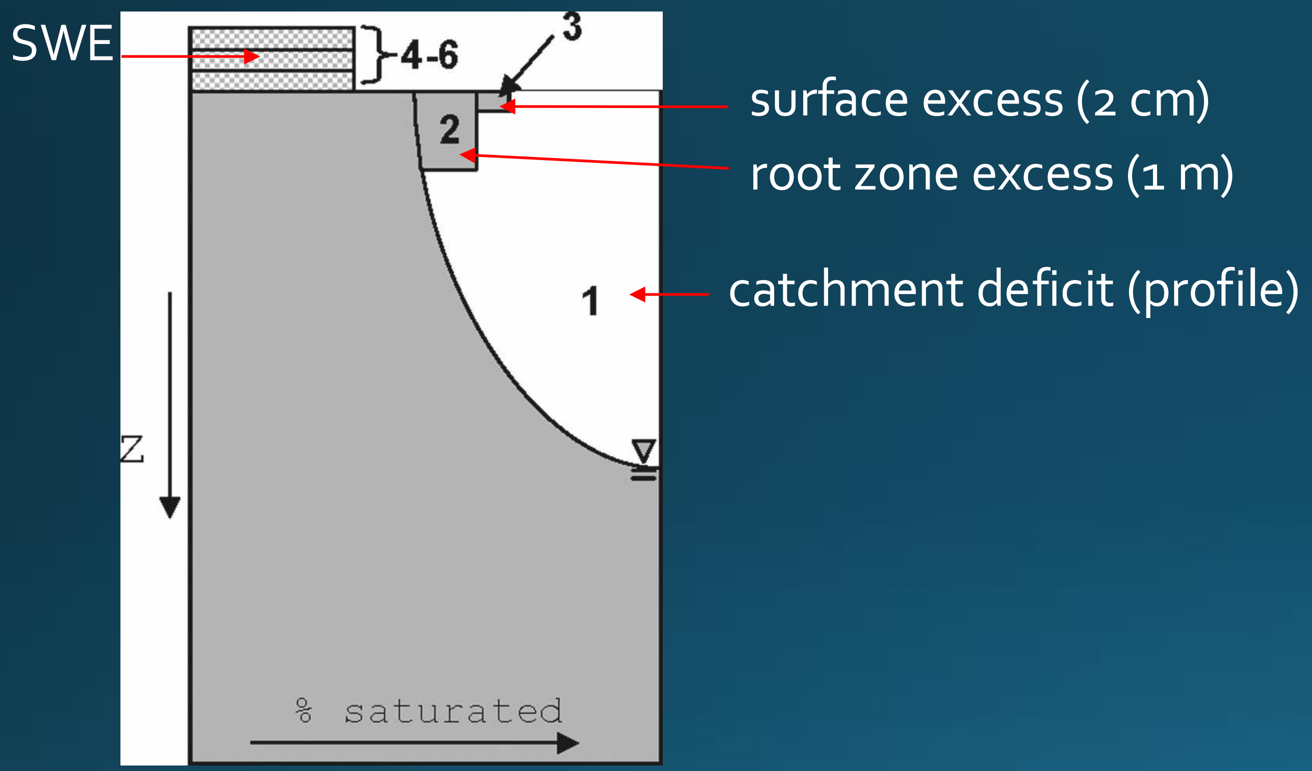


Image source: Zaitchik et al. 2008

Advantages:

- More realistic representation of near surface processes
- Global application
- Computational efficiency

Limitations:

- No surface water and groundwater withdrawals

CLSM TWS = SMC+GWS+SWE

The ensemble Kalman filter for assimilating GRACE/FO data

X: soil moisture, groundwater, SWE simulated by the model at finer spatial and temporal resolutions

Ensemble update equation

GRACE obs

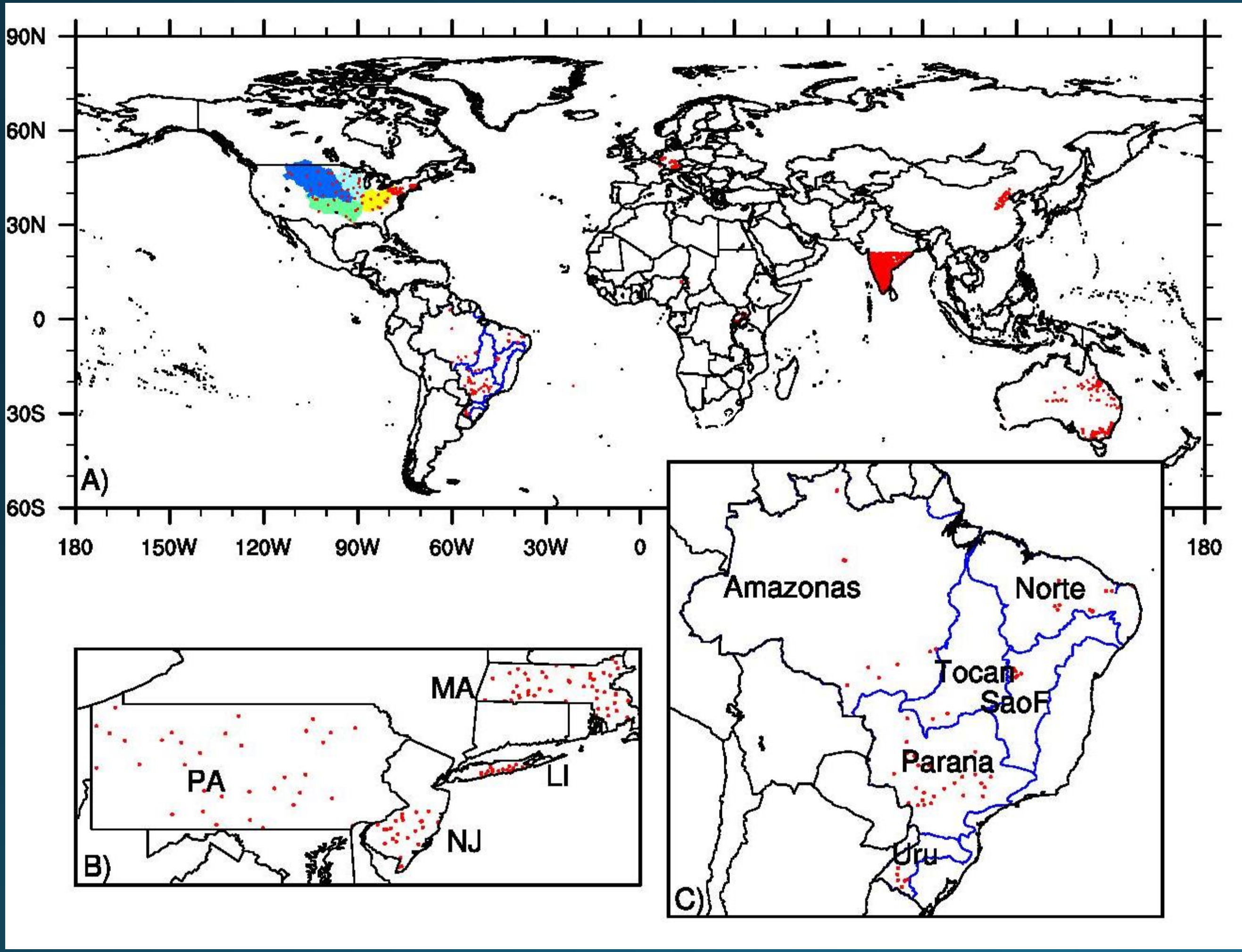
Predicted obs

$$X^a = X^f + K(Y - H(X))$$

Kalman gain matrix

- Model mean TWS is added to GRACE TWS anomalies before assimilation
- The Kalman gain matrix depends on relative errors between the model and observations
- Model errors are represented by ensemble spreads

Global evaluation results using nearly 4,000 wells



Average statistics over 22 regions

	GRACE DA	OL	
RMSE(cm)	4.3	6.7	down 36%
correlation	0.65	0.56	up 16%

Well selection criteria:

- Unconfined aquifers
- Not impacted by pumping or injection
- >5 years of data

See Li et al. 2019 for details

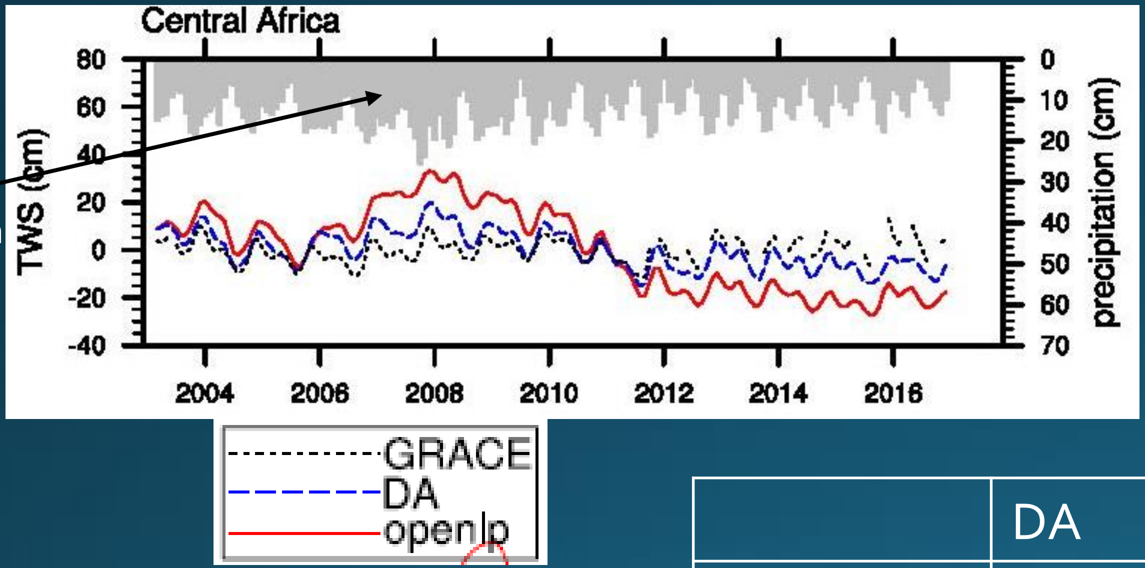
TWS and groundwater storage anomalies in central Africa

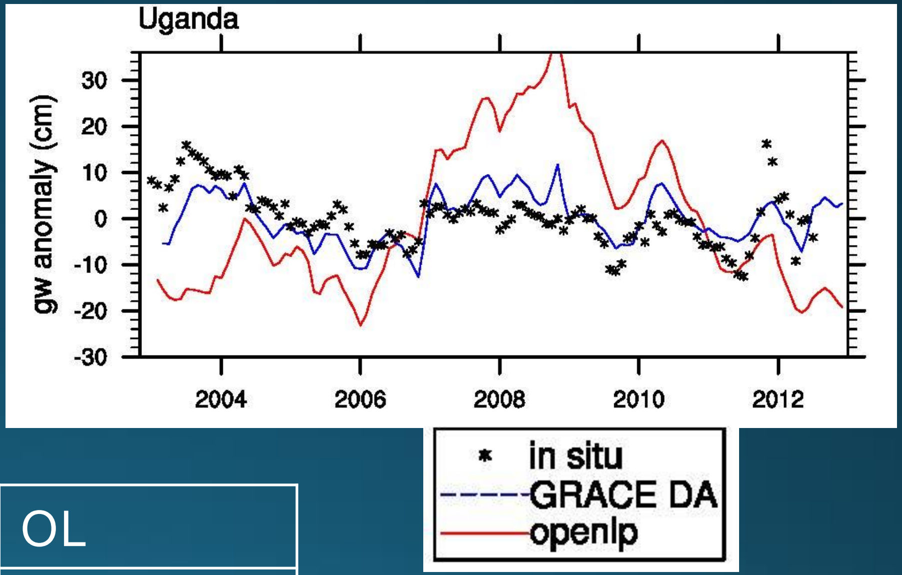
11 wells

TWS for the blue rectangular region

Groundwater storage

precipitation

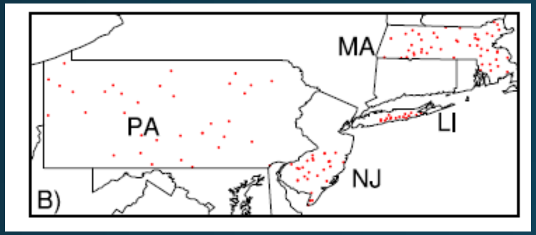


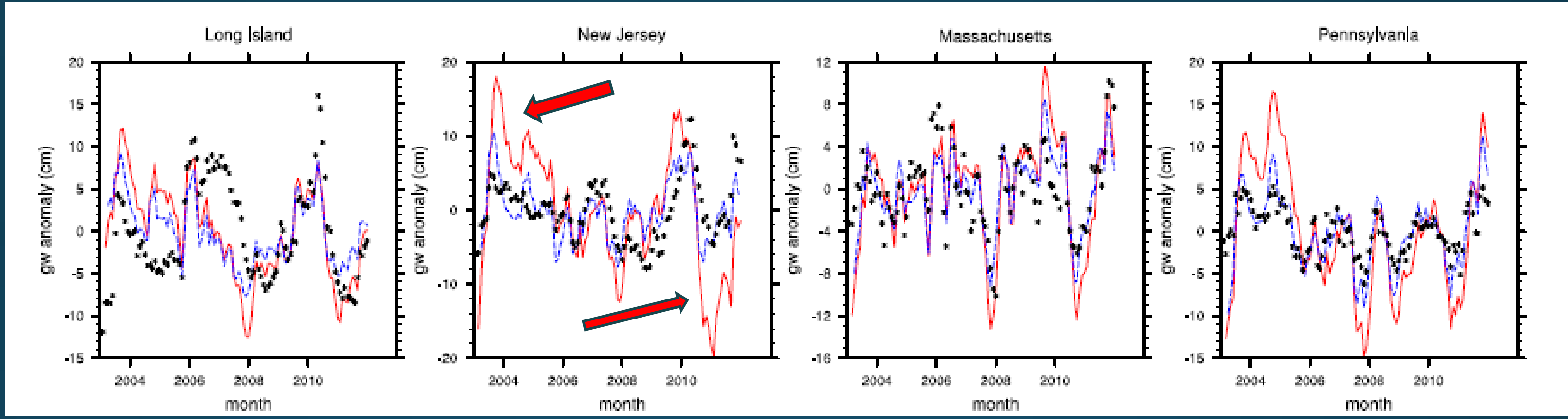


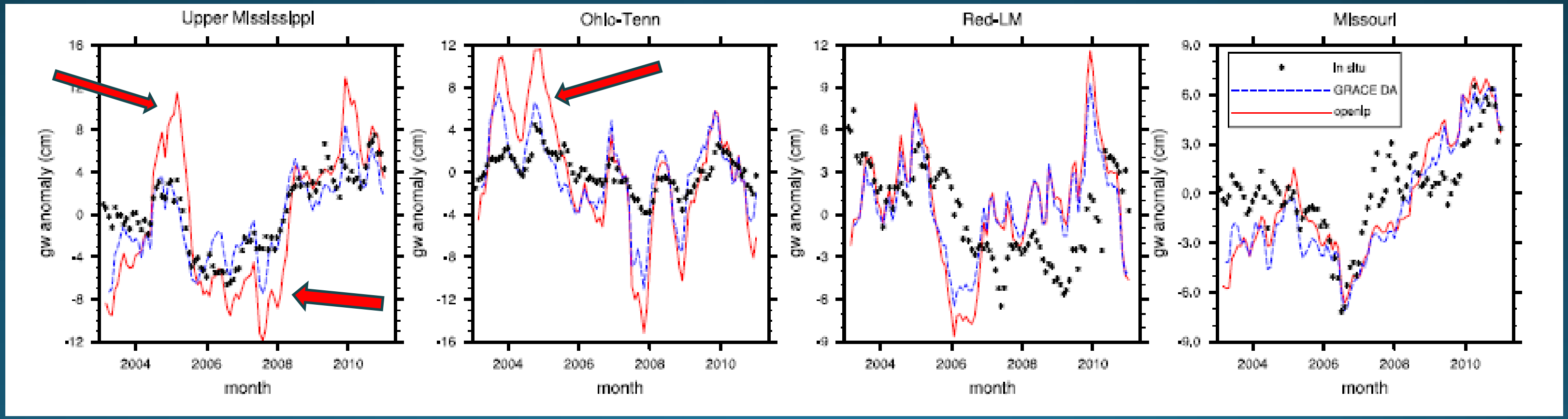
	DA	OL
RMSE(cm)	5.34	17.2
correlation	0.56	-0.05

Evaluation results using USGS wells in the Northeast US and Mississippi basin

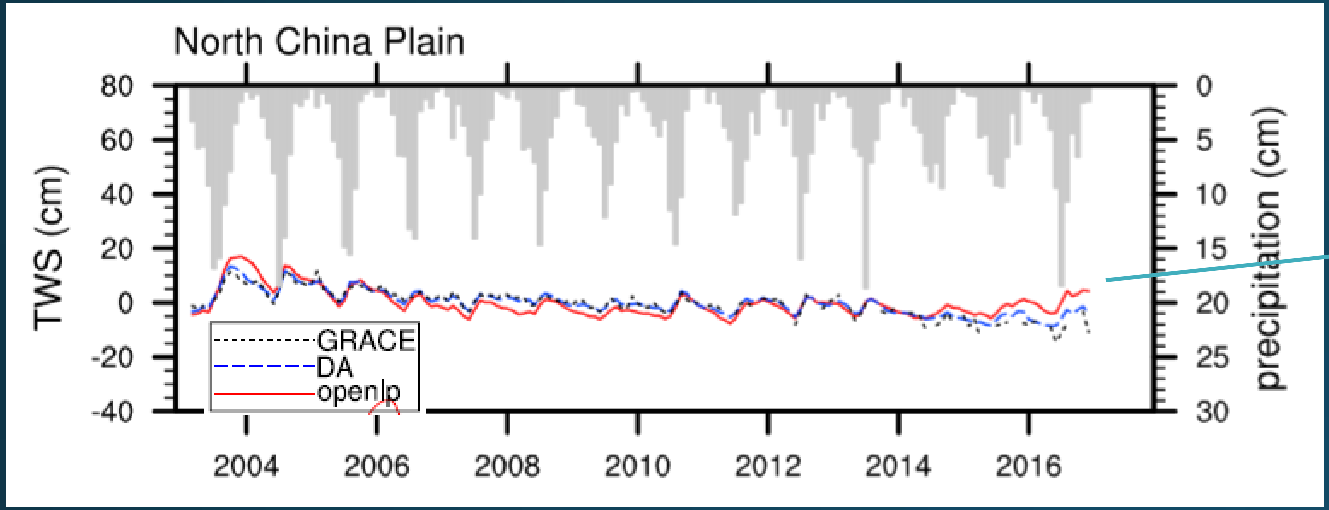
Well locations

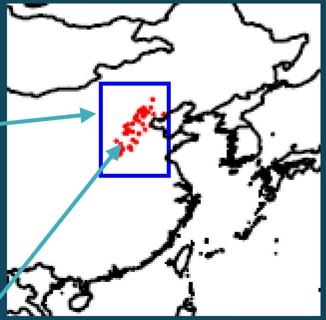




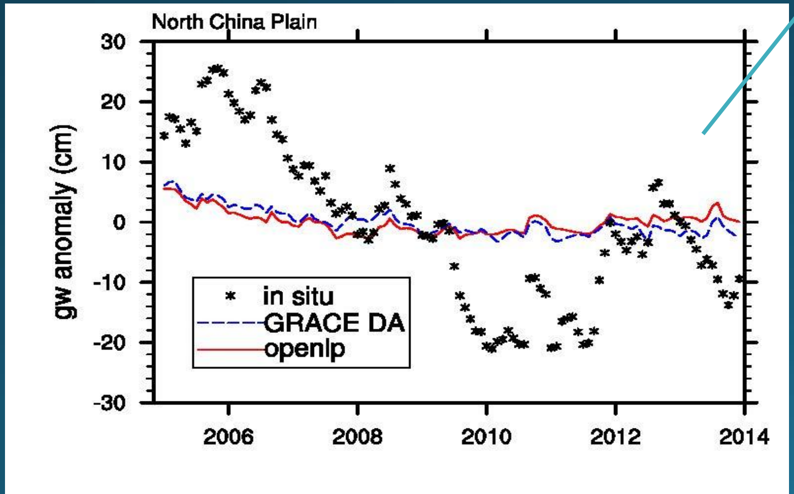


TWS and groundwater storage anomalies in the North China Plain





50 wells in North China Plain

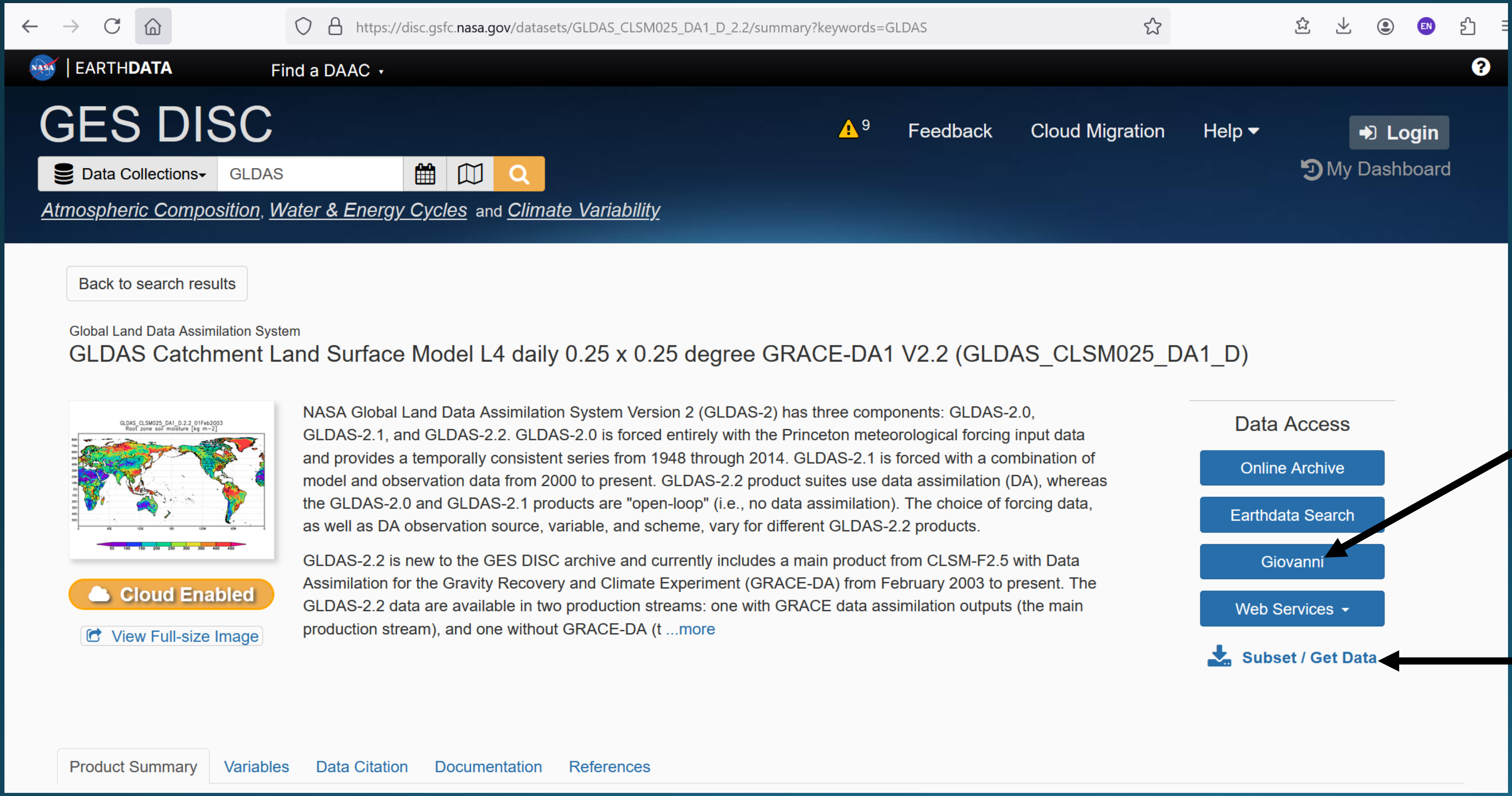


GRACE DA GWS is unable to stimulate the large dynamics in well data because CLSM does not simulate groundwater withdrawals.

	DA	OL
RMSE (cm)	11.32	12.09
Correlation	0.83	0.61

GLDAS2.2 at GES DISC

(https://disc.gsfc.nasa.gov/datasets/GLDAS_CLSM025_DA1_D_2.2/summary?keywords=GLDAS)

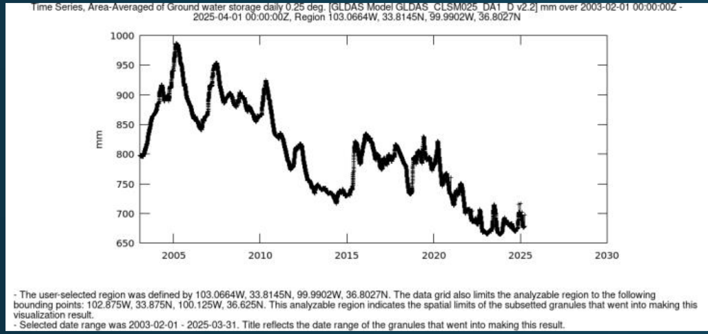


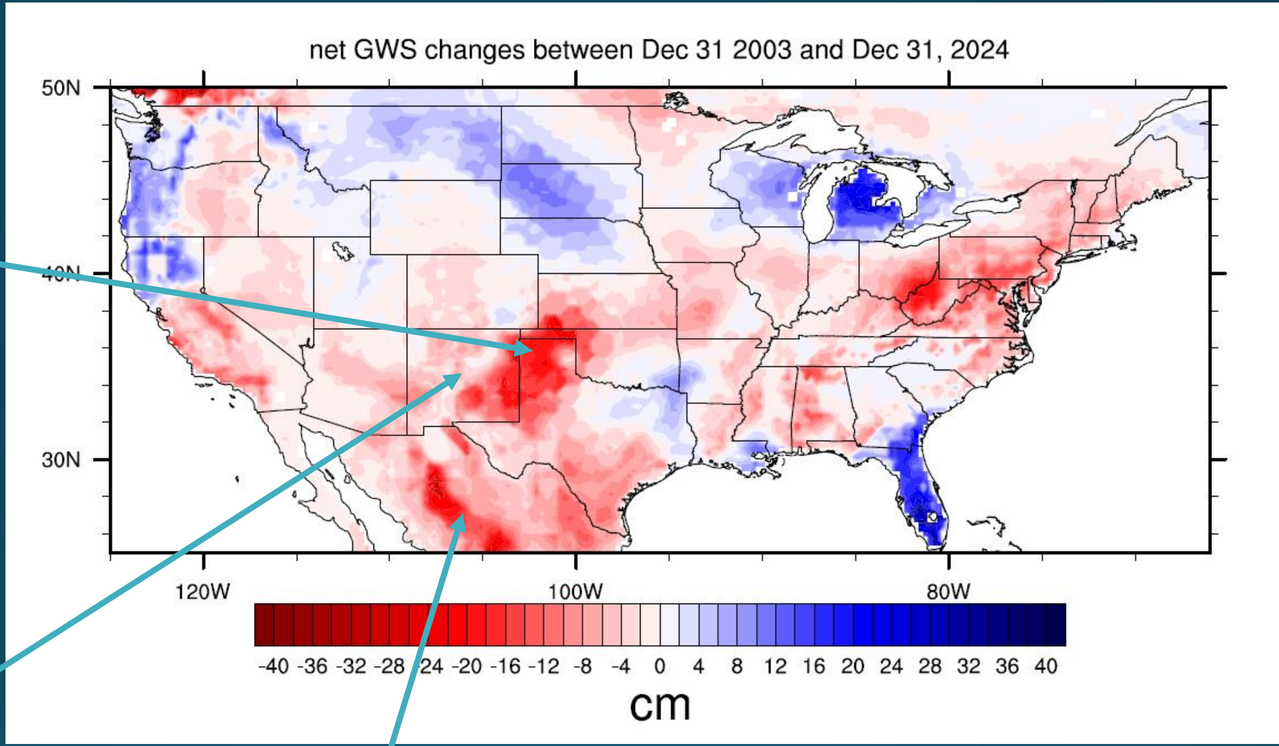
Interactive data visualization and analysis tools

Subsetting, extracting and downloading data

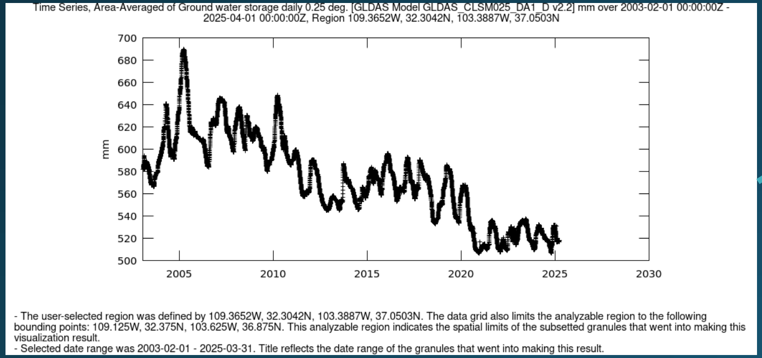
Analyzing groundwater storage changes using GES DISC tools

Texas Panhandle



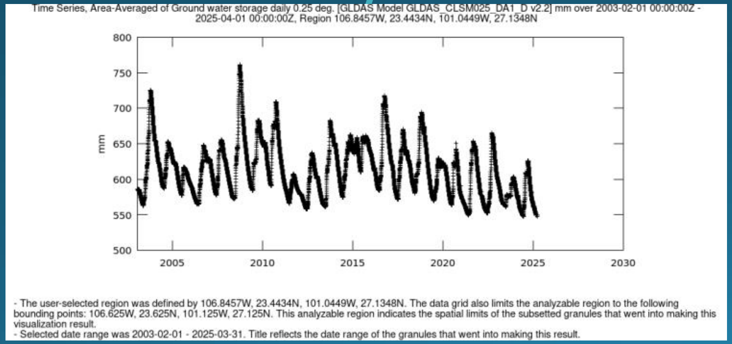


New Mexico



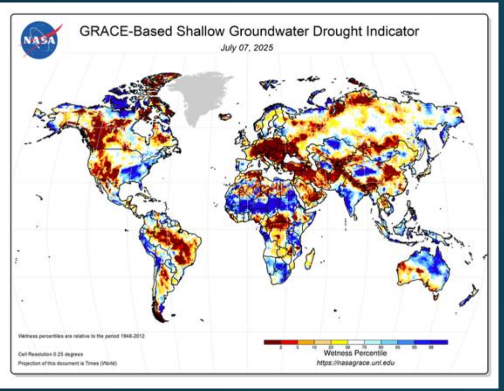
- Climate analysis
- Model evaluation

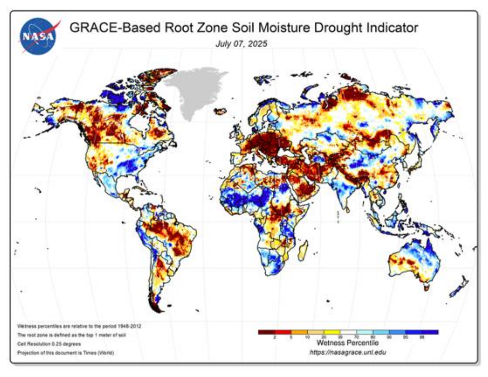
Central Mexico

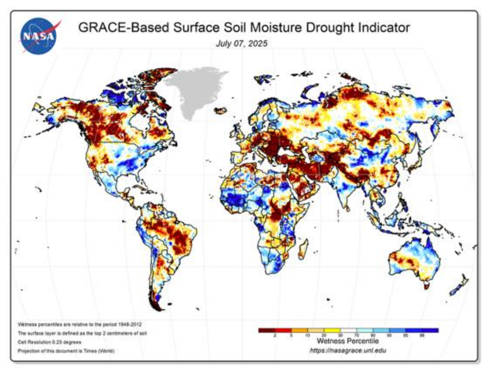


- Full quantities of GWS have no physical meaning.
- Use anomalies and changes over a time period.

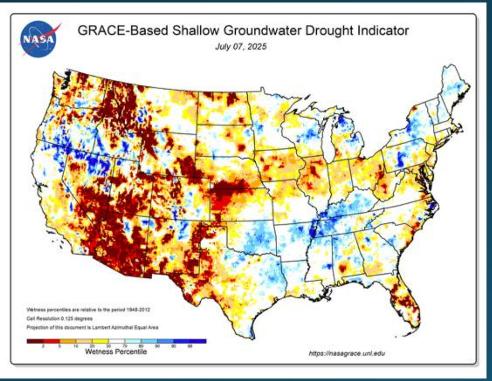
GRACE-based wetness percentile maps (https://nasagrace.unl.edu/)

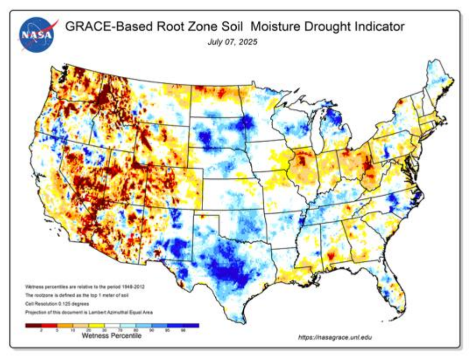


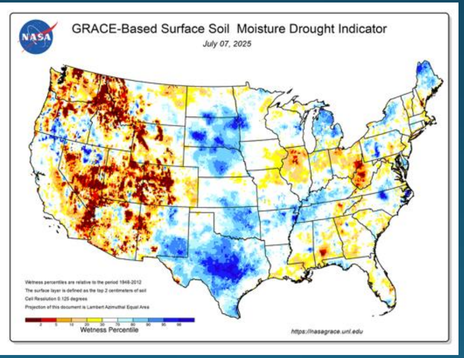




Driven by ECMWF forcing data at 0.25 resolution







Driven by NLDAS-2 forcing data at 0.125 resolution

GES DISC product IDs: GRACEDADM_CLSM025GL_7D_3.0, GRACEDADM_CLSM0125US_7D_4.0

3. Future gravity measuring missions

1. GRACE-C is in the administration's FY26 budget and will launch in 2028
    - Similar design as GRACE/FO

2. Next generation gravity missions: a second pair of satellites is actively under study and is planned for launch in 2032 to improve spatial and temporal resolutions of measurements. See additional info at: https://www.esa.int/Applications/Observing_the_Earth/FutureEO/The_future_of_gravity_is_MAGIC

Conclusions

1. GRACE/FO data are valuable for studying and monitoring changes in hydrological extremes
   - groundwater losses & thawing of permafrost
2. GRACE/FO data assimilation is an effective tool for constraining large-scale groundwater simulation
   - There are limitations with the model and the ensemble Kalman filter
   - Evaluation is key to gain better understanding
     - Convert water levels to groundwater storage using the specific yield

References

Li B. and M. Rodell. 2023. "How have hydrological extremes changed over the past 20 years?." *Journal of Climate* [10.1175/jcli-d-23-0199.1].

Rodell M. and B. Li. 2023. "Changing intensity of hydroclimatic extreme events revealed by GRACE and GRACE-FO." *Nature Water* **1 (3)**: [Full Text] [10.1038/s44221-023-00040-5].

Li B., M. Rodell, S. Kumar, et al. 2019. "Global GRACE data assimilation for groundwater and drought monitoring: Advances and challenges." *Water Resour. Res.* **55 (9)**: 7564-7586 [10.1029/2018wr024618].

Media reports

The Guardian, Nasa data reveals dramatic rise in intensity of weather events, https://www.theguardian.com/world/2025/jun/17/nasa-data-reveals-dramatic-rise-in-intensity-of-weather-events.

Rethinking resilience: Howe a new era of extremes is changing how utilities invest: https://www.globalwaterintel.com/documents/rethinking-resilience.