Drought from top to bottom: Advancing process understanding with GRACE missions

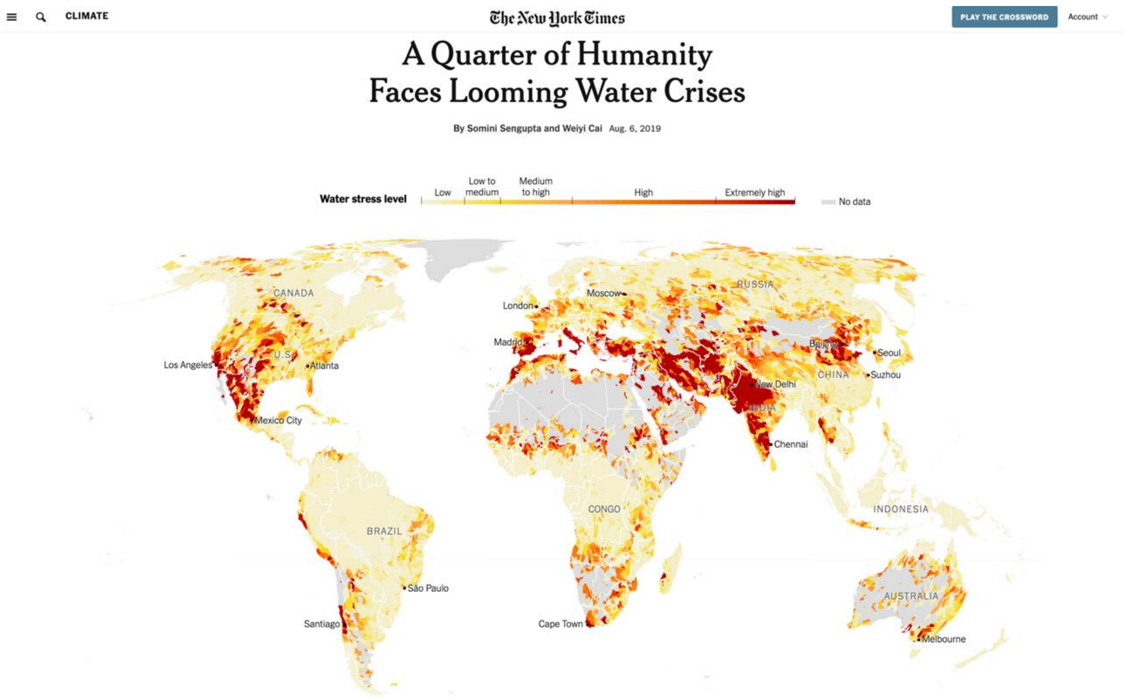
J.T. Reager

2025 GRACE-FO Science Team meeting

Jet Propulsion Laboratory
California Institute of Technology

Why Observe Drought from Space?

- **Droughts** present a large threat to life and livelihoods
- **Water insecurity** estimated to cost **$500 billion per year** to global economy (world water forum, 2015)
- These extremes are expected to **increase with climate change**
- Droughts are driven by processes **below the land surface**, so in situ and electromagnetic remote sensing methods are limiting observations for **process understanding**
- Gravity observations that can capture **events and event transitions** are required to enhance our capacity to prepare and respond



CLIMATE

The New York Times

PLAY THE CROSSWORD

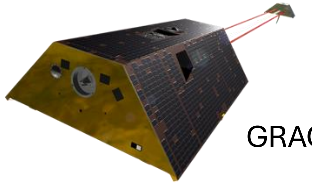
Account

A Quarter of Humanity Faces Looming Water Crises

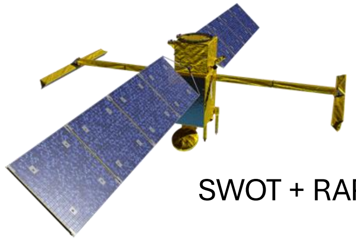
By Somini Sengupta and Weiyi Cai Aug. 6, 2019

Terrestrial water storage anomalies give an integrated drought metric

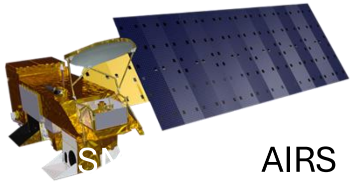
Several missions now lend themselves to drought study



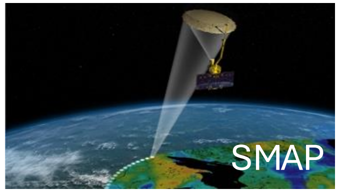
GRACE-FO

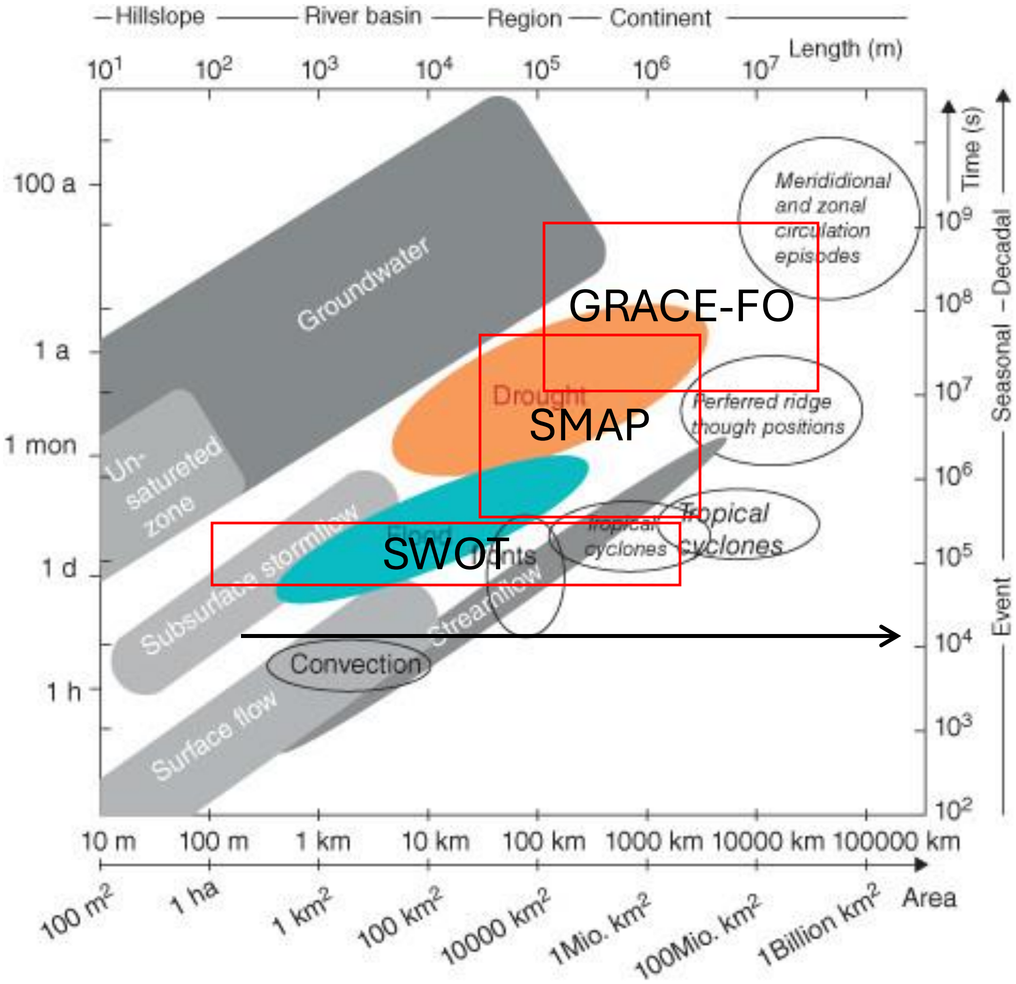


SWOT + RAPID



AIRS





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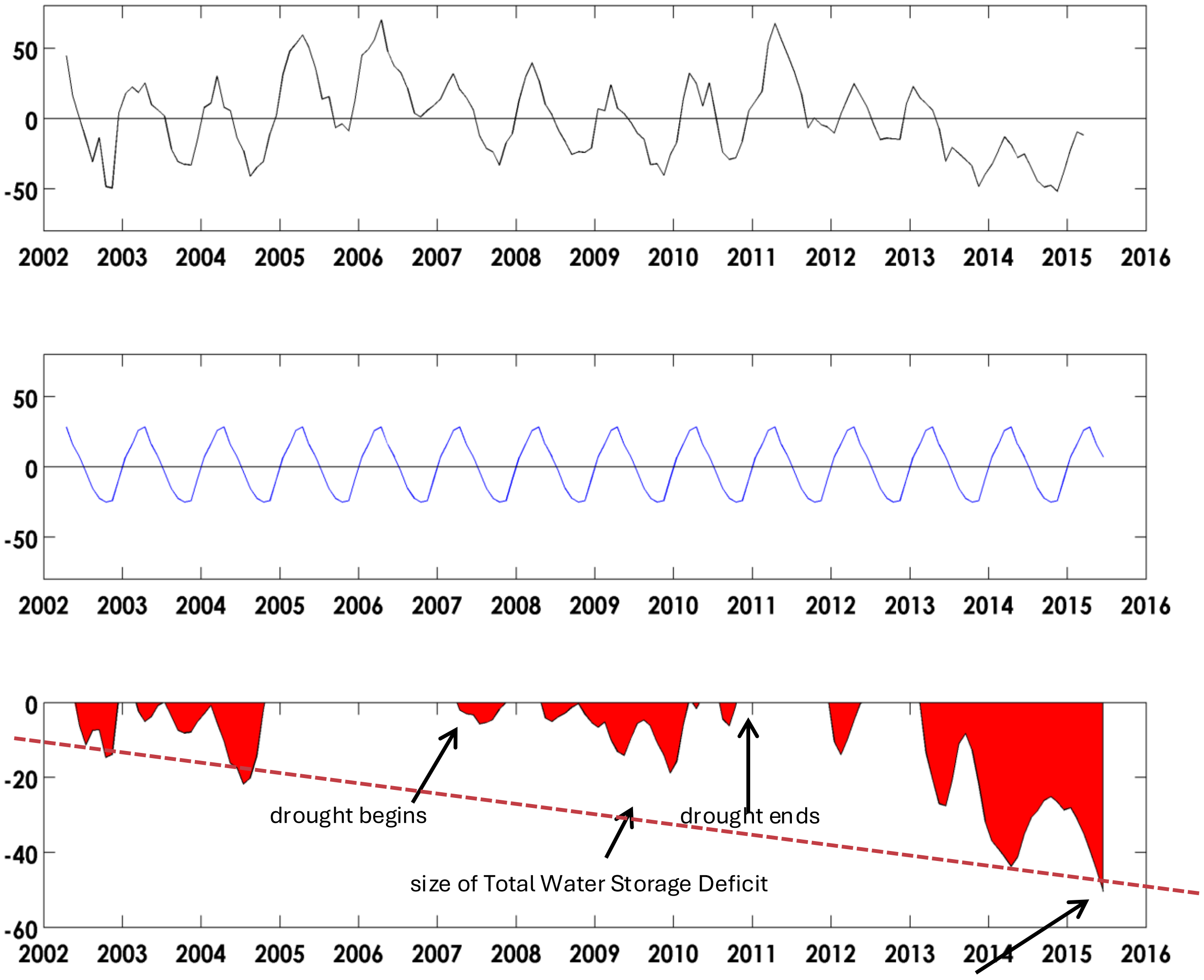
Foundational Advance: *Thomas et al. (2014) Water Storage Deficit Framework*

Actual monthly water storage variations

'Normal' range of monthly water storage variations

Differences from 'normal' dry conditions



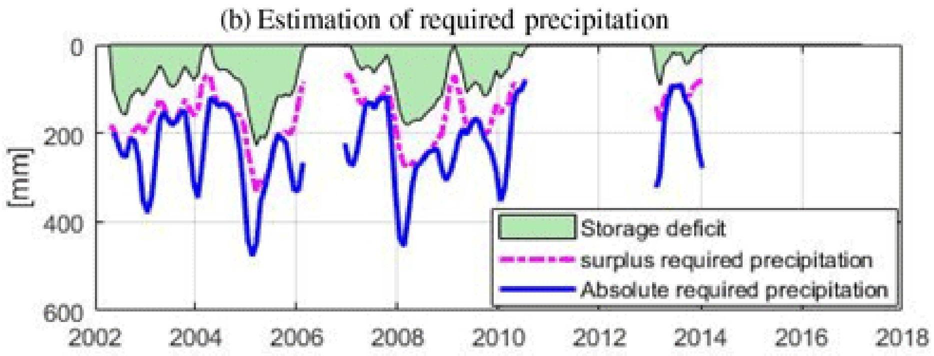
peak Total Water Storage Deficit is 42 km^3 in 2014

- Used GRACE TWSA, defines hydrological drought as missing water (deficit magnitude × duration)
- Demonstrated event severity globally (Amazon, Zambezi, Texas)
- Cross-cutting theme: **Deficit quantification** — a normalized observation-based metric created to compare and relate severity at different locations

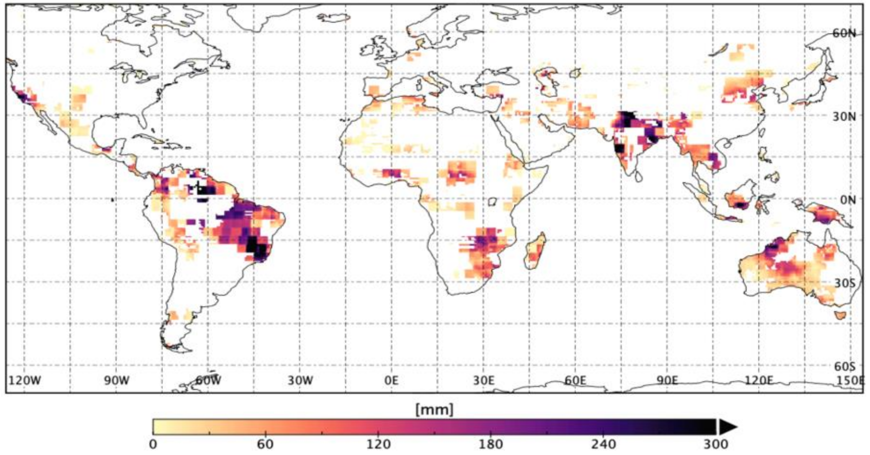
Thomas, Reager et al., 2014

Singh et al (2019): *Precipitation needed for drought recovery*

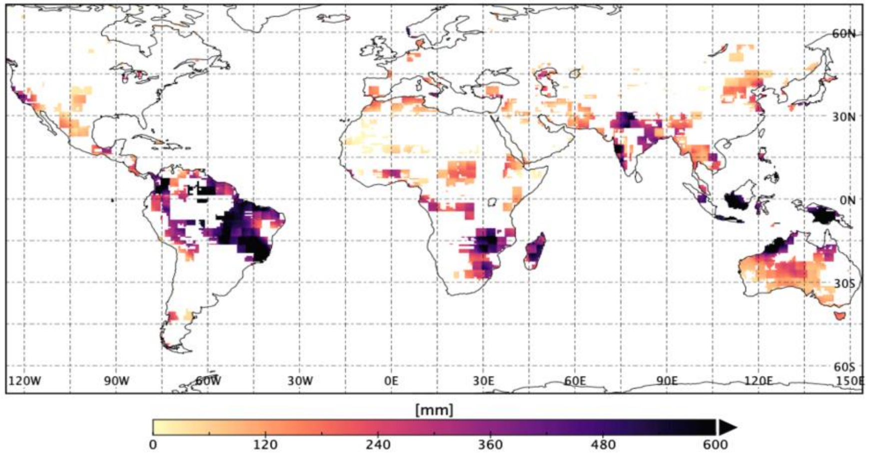
- Established linear relationship between GRACE TWSA and cumulative precipitation anomalies
- Framework to estimate how much and how long precipitation required for recovery
- Highlights seasonal gating — recovery constrained by timing of wet season
- Cross-cutting theme: **Recovery metrics** — bridging diagnostics with predictability



(a) Storage deficit

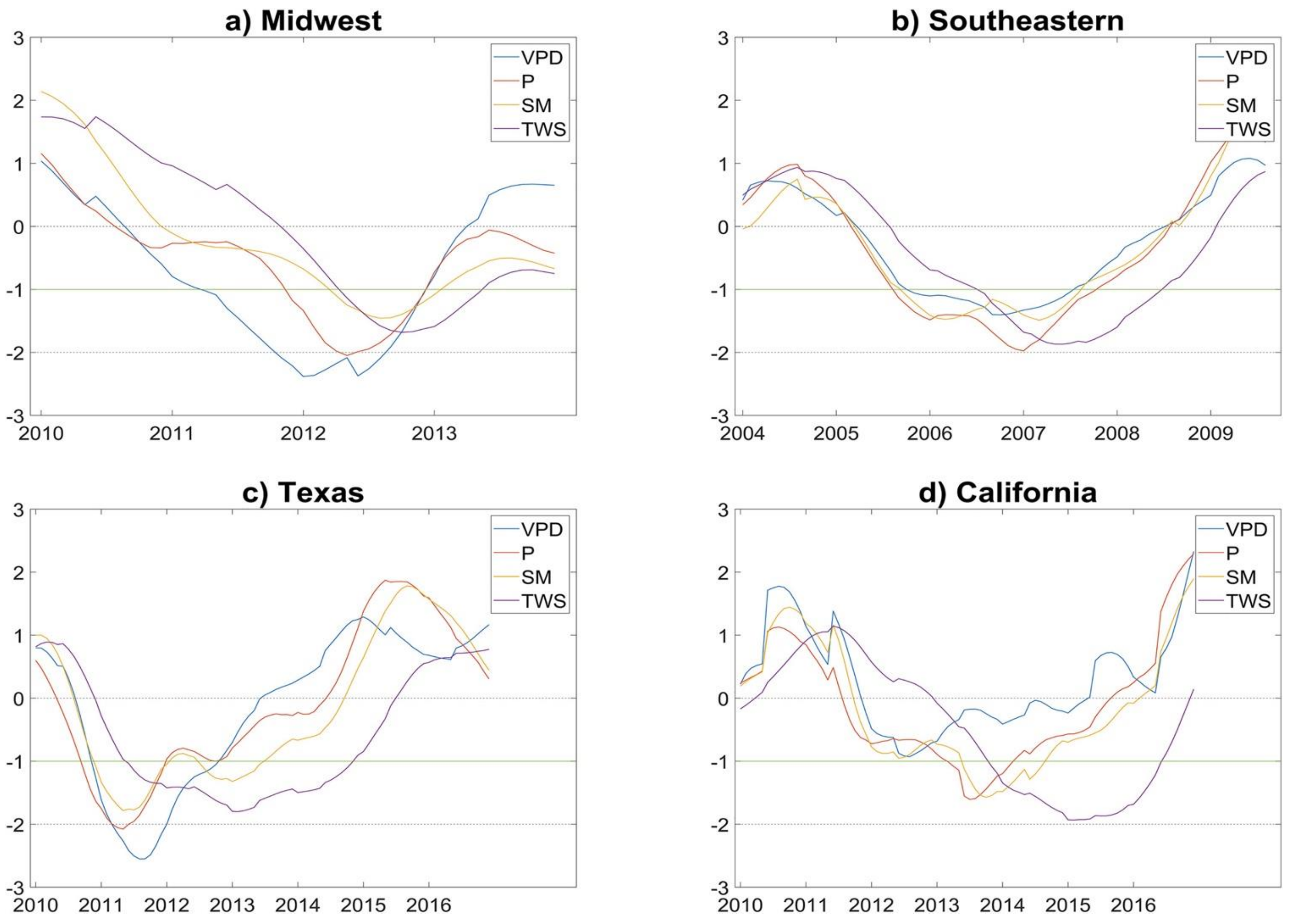


(b) Required precipitation



Farahmand et al (2021): *Introducing the concept of Drought Cascades*

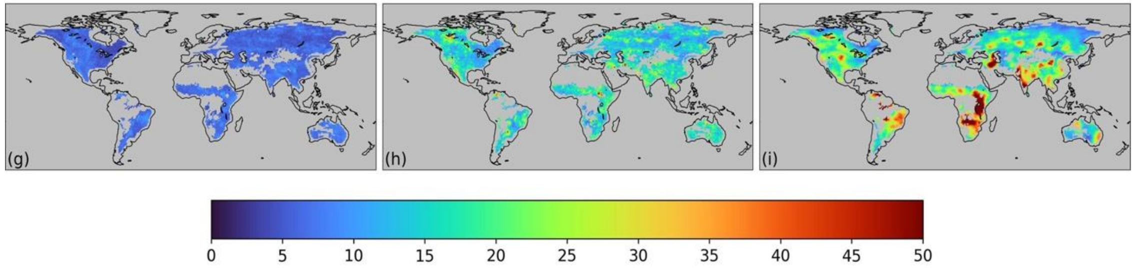
- Introduced *cascade framework*: precipitation → soil moisture → TWS
- Typical lags: ~2.5 months (SM), ~8 months (TWS)
- Cross-cutting theme: **Cascade dynamics** — quantifying delay and attenuation through the profile



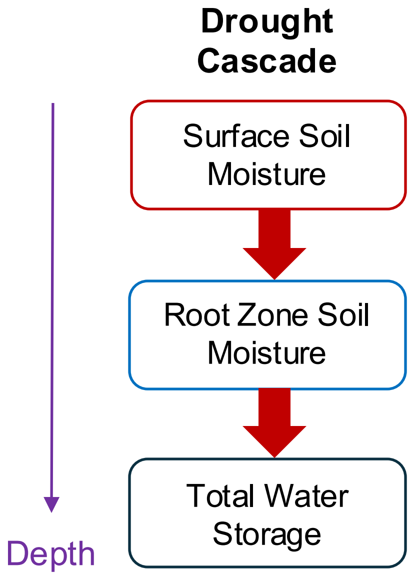
Blank et al. (2025): *Daily GRACE & Depth-Dependent Recovery*

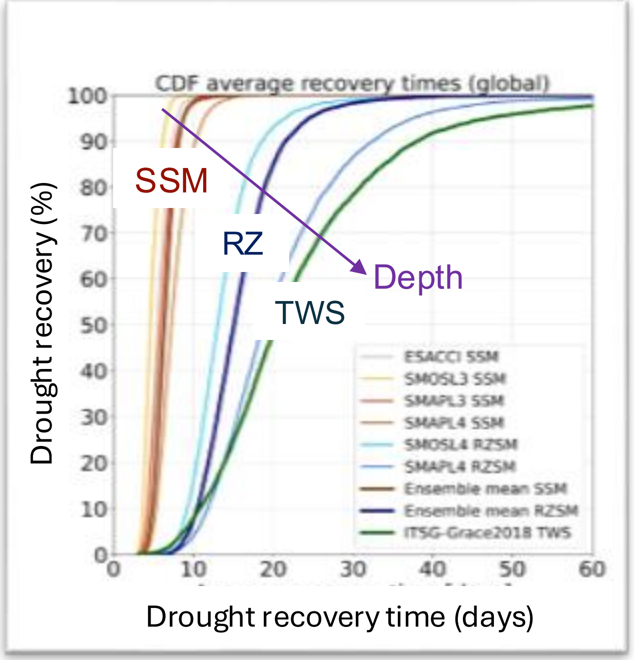
Drought recovery time increases with depth of the drought

Surface soil moisture *Rootzone soil moisture* *Total Water Storage*



Recovery time (days)





Key Findings:

- **Depth matters:** Drought signals dampen and delay as they propagate downward
- Combined daily **GRACE/GRACE-FO** product with **SMAP**, **SMOS**, and **ESA CCI** soil moisture to study drought propagation from surface to subsurface globally (2015–2022)
- Found **clear cascading behavior**:
  - **Surface soil moisture** (SSM): fast drying/quick recovery (~3–5 days)
  - **Root zone soil moisture** (RZSM): slower recovery (~12–15 days)
  - **Total water storage** (TWS): slowest response (~17–21 days)

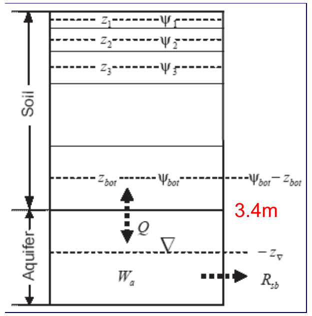
Major Takeaways:

- GRACE-FO, SMAP data explain why **groundwater and deeper storage take years to recover**, informing drought adaptation strategies
- Demonstrates the unique societal value of **multi-sensor integration** across soil layers for understanding drought cascades

Blank, D., Eicker, A., Reager, J.T., & Güntner,A.(2025).Revisiting sub-surface drought cascades with daily satellite observations of soil moisture and terrestrial water storage. Water Resources Research, 61, e2024WR039321

Houborg et al. (2012): *Model Assimilation and Drought Indicators*

- Assimilated GRACE into CLSM (EnKF smoother) to derive drought percentiles
- Improved alignment with U.S. Drought Monitor deep-layer categories
- Cross-cutting theme: **Operational integration** — merging observation and modeling for decision support
- The representation of accurate soil storage is important in runoff generation and in the representation of groundwater dynamics
- Getting the total drainable storage in the soil column is important to understand storage-runoff links



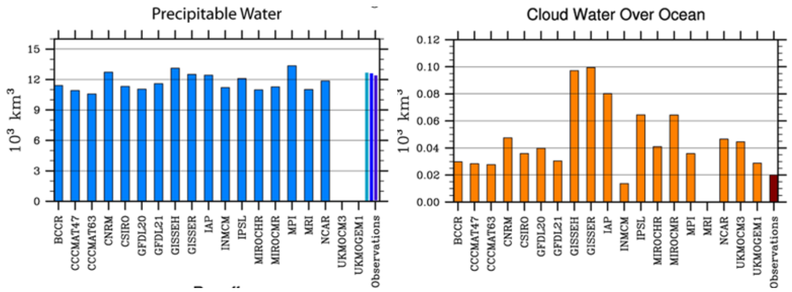
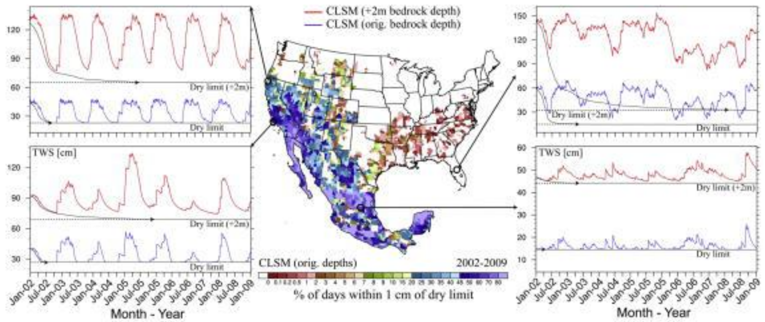


Figure 1: Time mean values of predicted precipitation (*left*) and soil moisture (*right*) from CMIP3 ensemble members in coupled climate simulations.

Waliser et al. (2010)



Houburg et al. (2014)

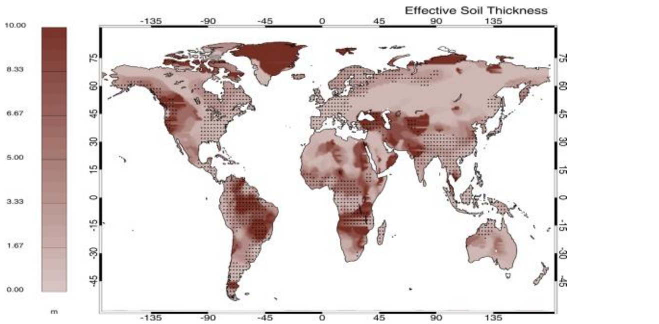
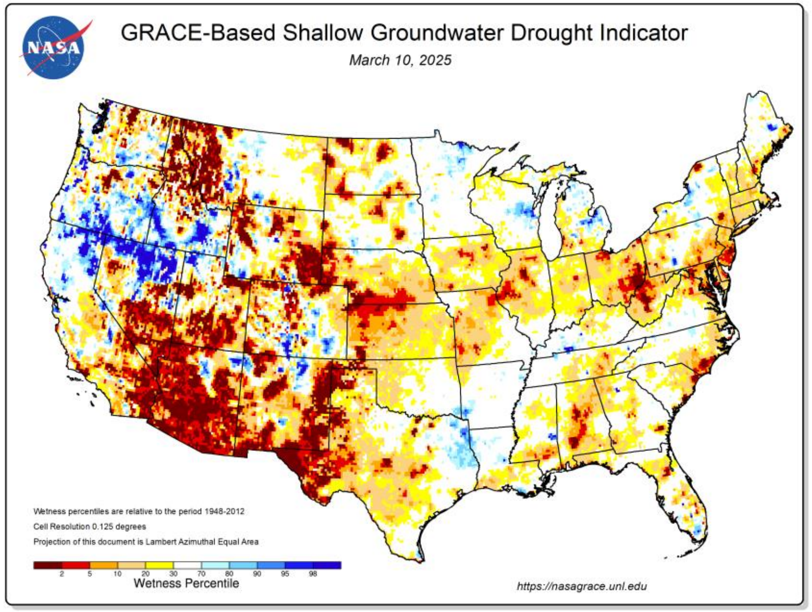


Figure 11. Optimal CLM soil thickness parameter (m). Value at each gridcell is taken from the ZBOT simulation giving the smallest rmsd between GRACE and CLM TWS.

Swenson and Lawrence (2015)

Operational implementation: *GRACE-FO used in the US Drought Monitor to illustrate drought extent*

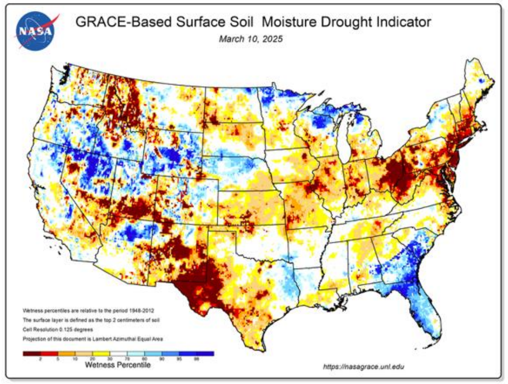
https://nasagrace.unl.edu/



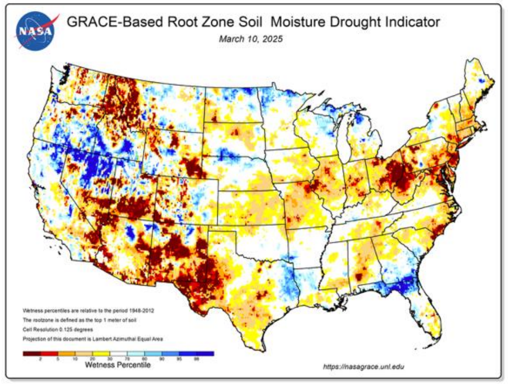
NLDAS model assimilated GRACE observations on 1/8-degree grids, available for download as NLDAS output fields

Ref: Houborg et al (2012)

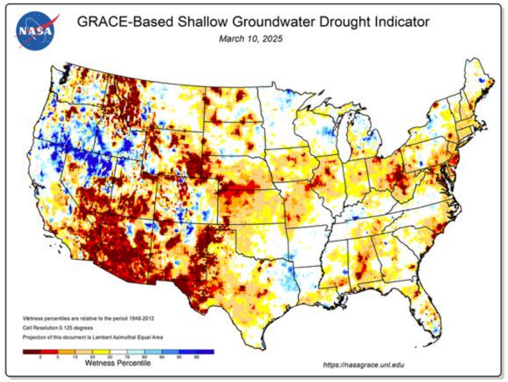
Surface



Root zone



Shallow groundwater



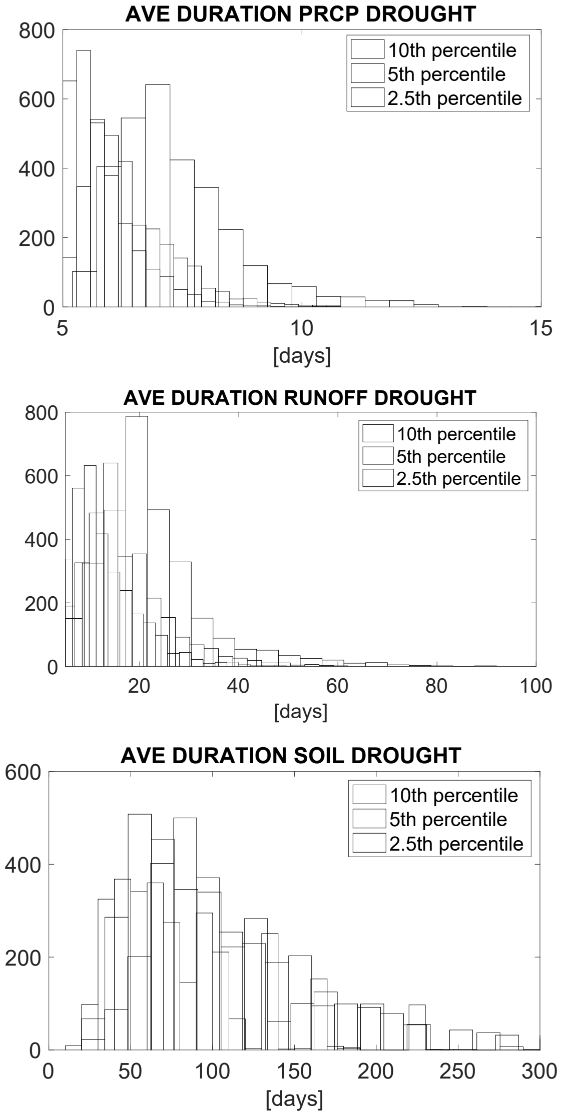
Evolution of GRACE Drought Science

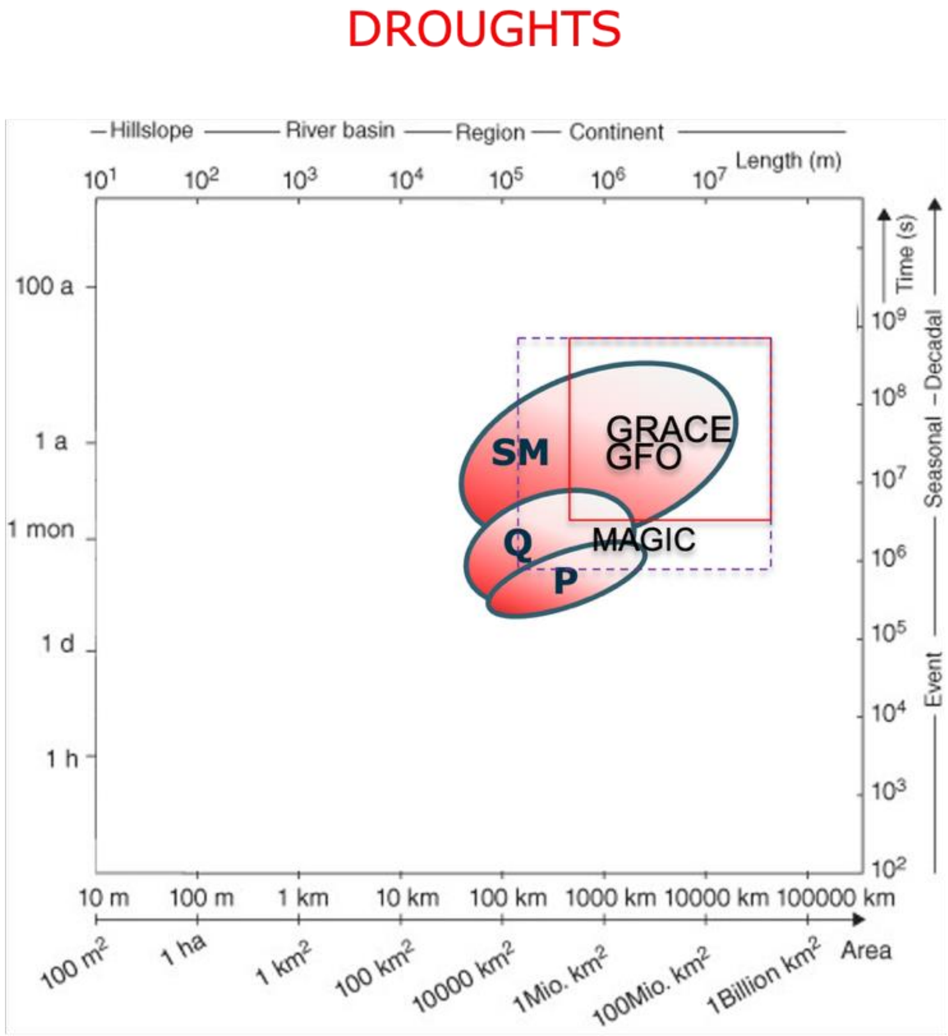
- **2014**: Deficit quantification (Thomas et al., foundation)
- **2021**: Propagation (Farahmand), Recovery (Singh)
- **2025**: Depth-resolved cascades (Blank et al.)
- ***Parallel***: Operational pathway (Houborg et el., 2012)

Cross-cutting themes

- Deficit Quantification — objective drought metrics
- Cascade Dynamics — onset and depth-dependent delay
- Recovery Metrics — storage and precipitation closure
- Operational Integration — toward actionable monitoring

Future directions and opportunities: *multiple pair and increased resolution*





- GRACE-FO continuity; need for GRACE-C and MAGIC
- Fusion with SMAP/SWOT/ECOSTRESS for multi-layer coupling
- Linking storage anomalies to vegetation rooting depth and socio-economic drought impacts

M. Pascolini-Campbell and J. T. Reager, An Investigation of the spatial and temporal characteristics of dry and wet extreme events across NLDAS-2 models, 2023, *Journal of Hydrometeorology,*

Summary and Discussion

- GRACE-missions have transformed drought science: from static deficits to dynamic, layered processes
- Multi-sensor integration across soil layers and depth for understanding drought cascades and layered recovery
- Remaining frontier: connecting physical storage recovery with ecological (plant resilience) & human impacts
- All of these methods could be combined into a next-generation global drought observatory