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Space Gravimetry Applications and Needs for Drought Monitoring, Water Resource Assessment and Regional Climate Monitoring

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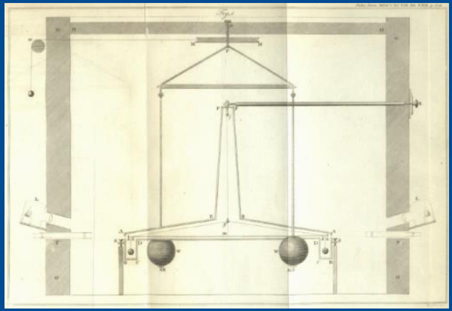
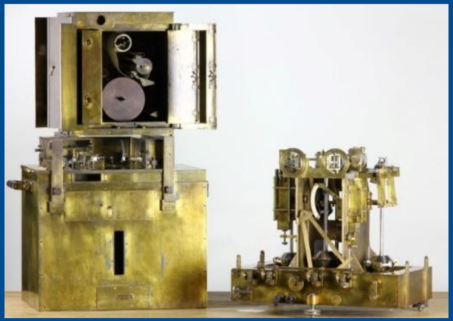
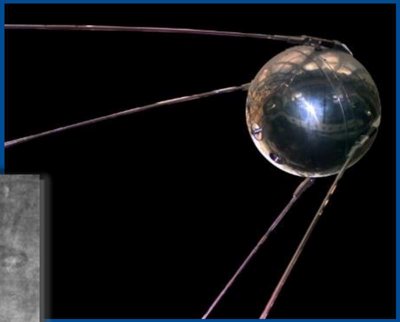
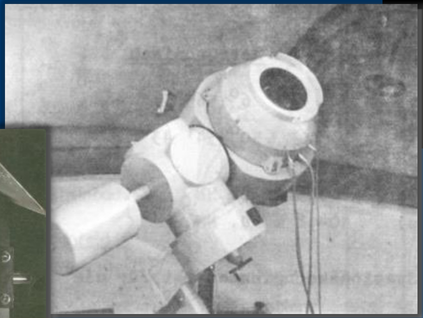
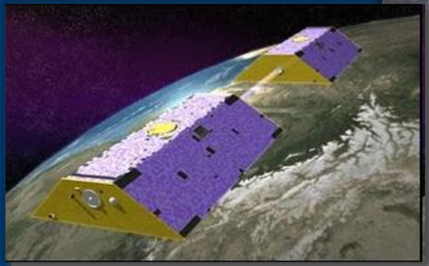
Gravity research, how one thing led to another





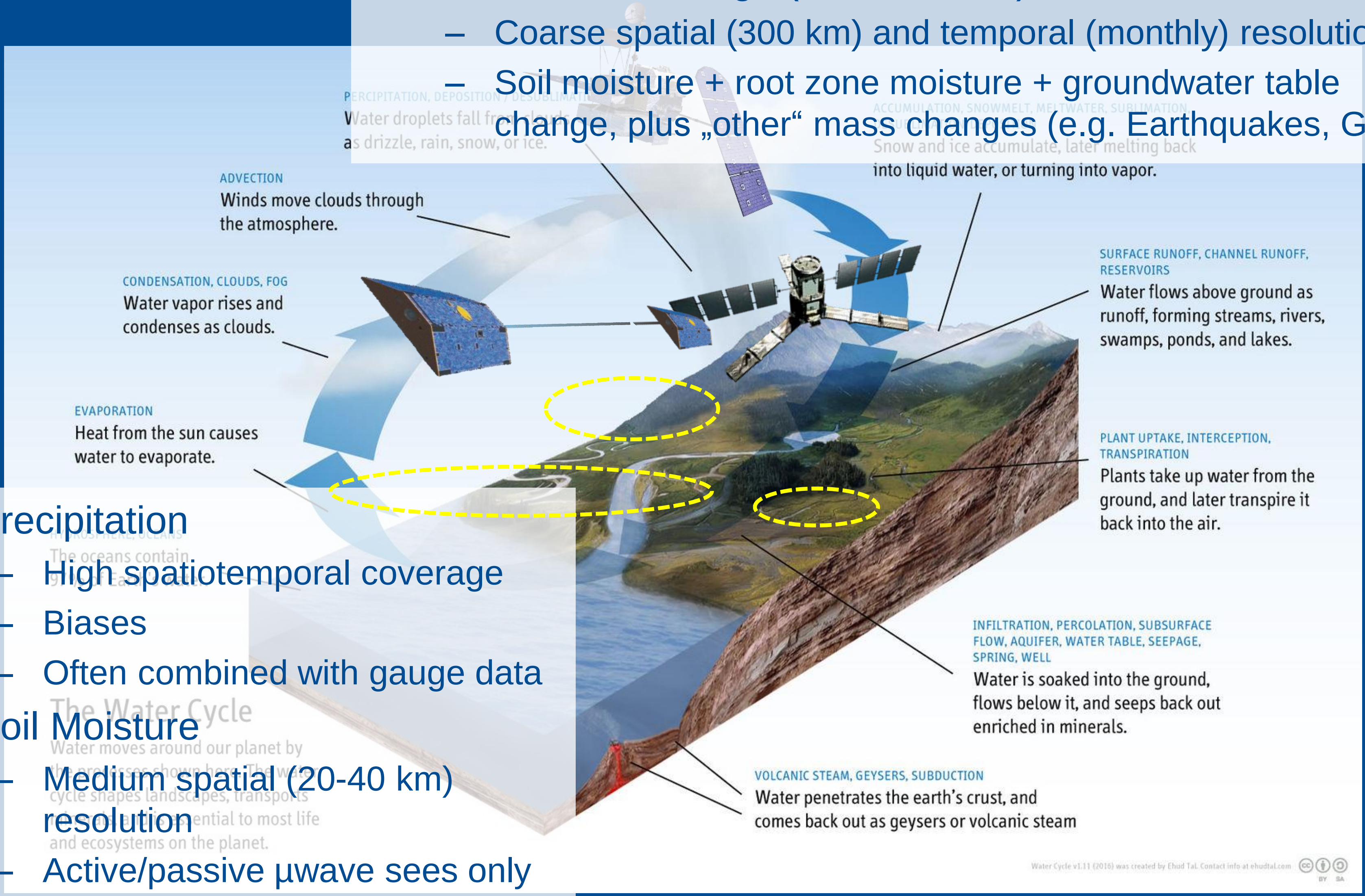






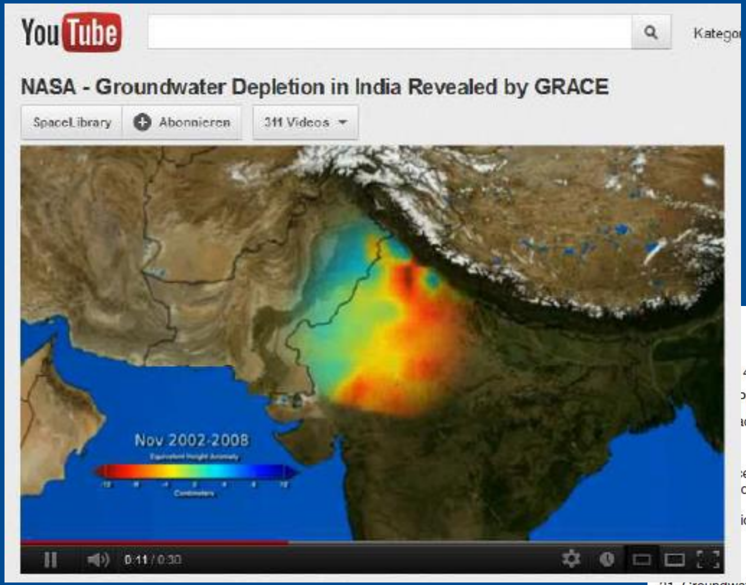
GRACE w.r.t other water cycle satellite sensors

- Total Water Storage (GRACE/-FO)
  - Coarse spatial (300 km) and temporal (monthly) resolution
  - Soil moisture + root zone moisture + groundwater table change, plus „other“ mass changes (e.g. Earthquakes, GIA)

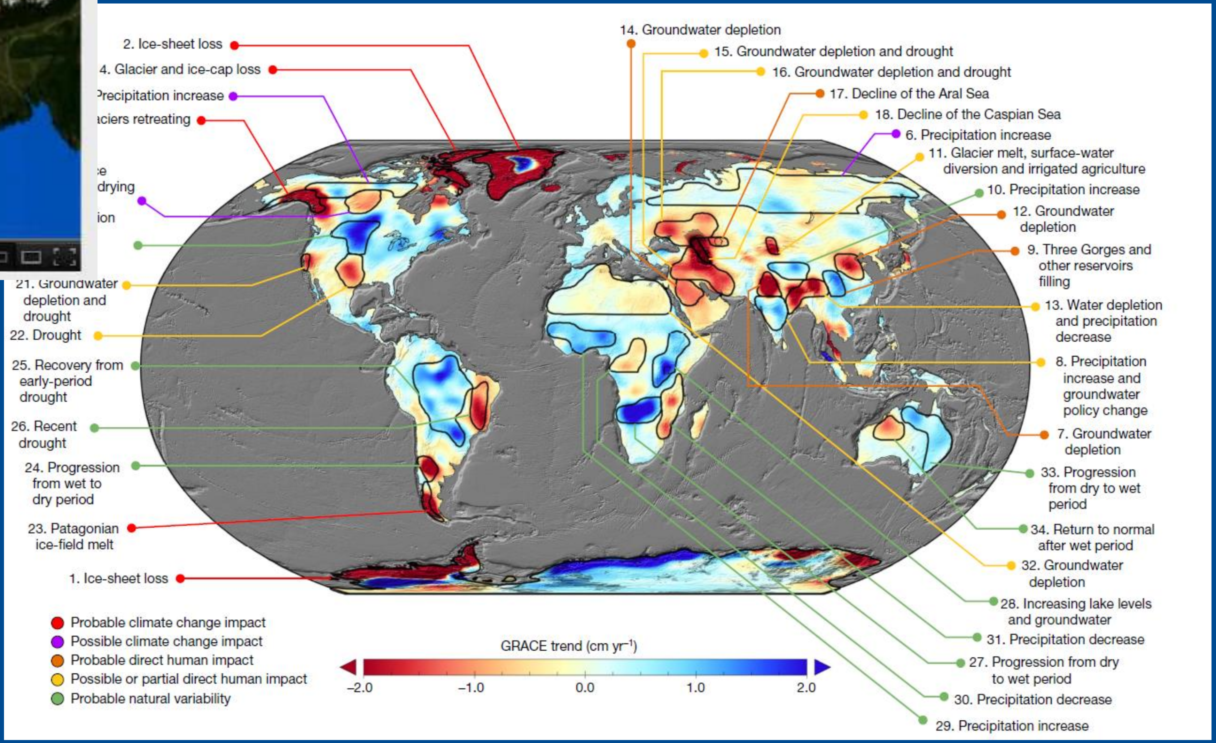


- Precipitation
  - High spatiotemporal coverage
  - Biases
  - Often combined with gauge data
- Soil Moisture
  - Medium spatial (20-40 km) resolution
  - Active/passive µwave sees only few cm

GRACE/-FO and watercycle



Rodell et al

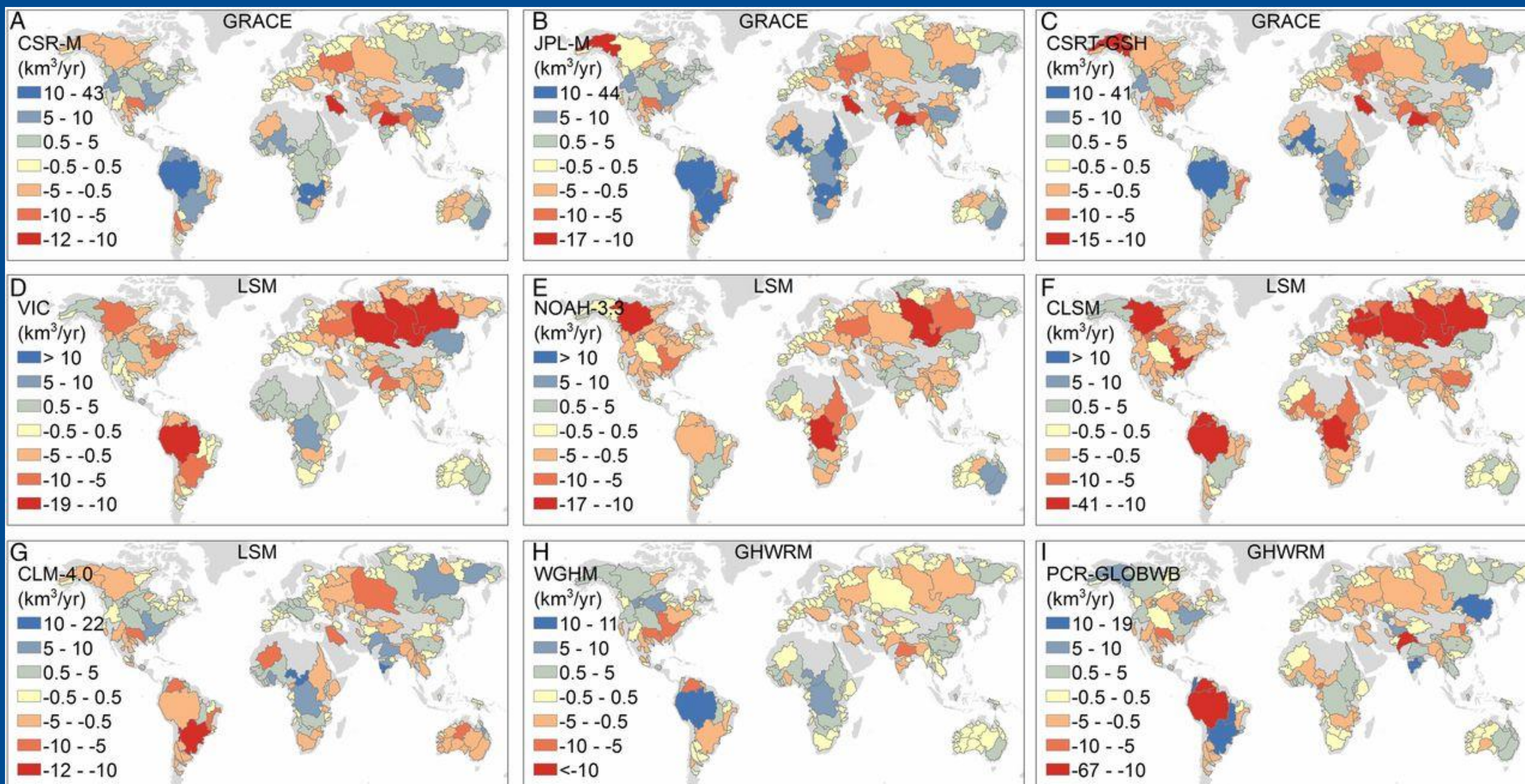


GRACE/-FO have demonstrated problems with hydrological and land surface models at longer timescales (Scanlon et al., 2018)

Suspected reasons are forcing data biases, limitations in representing anthropogenic processes, limitations in representing soil processes, …

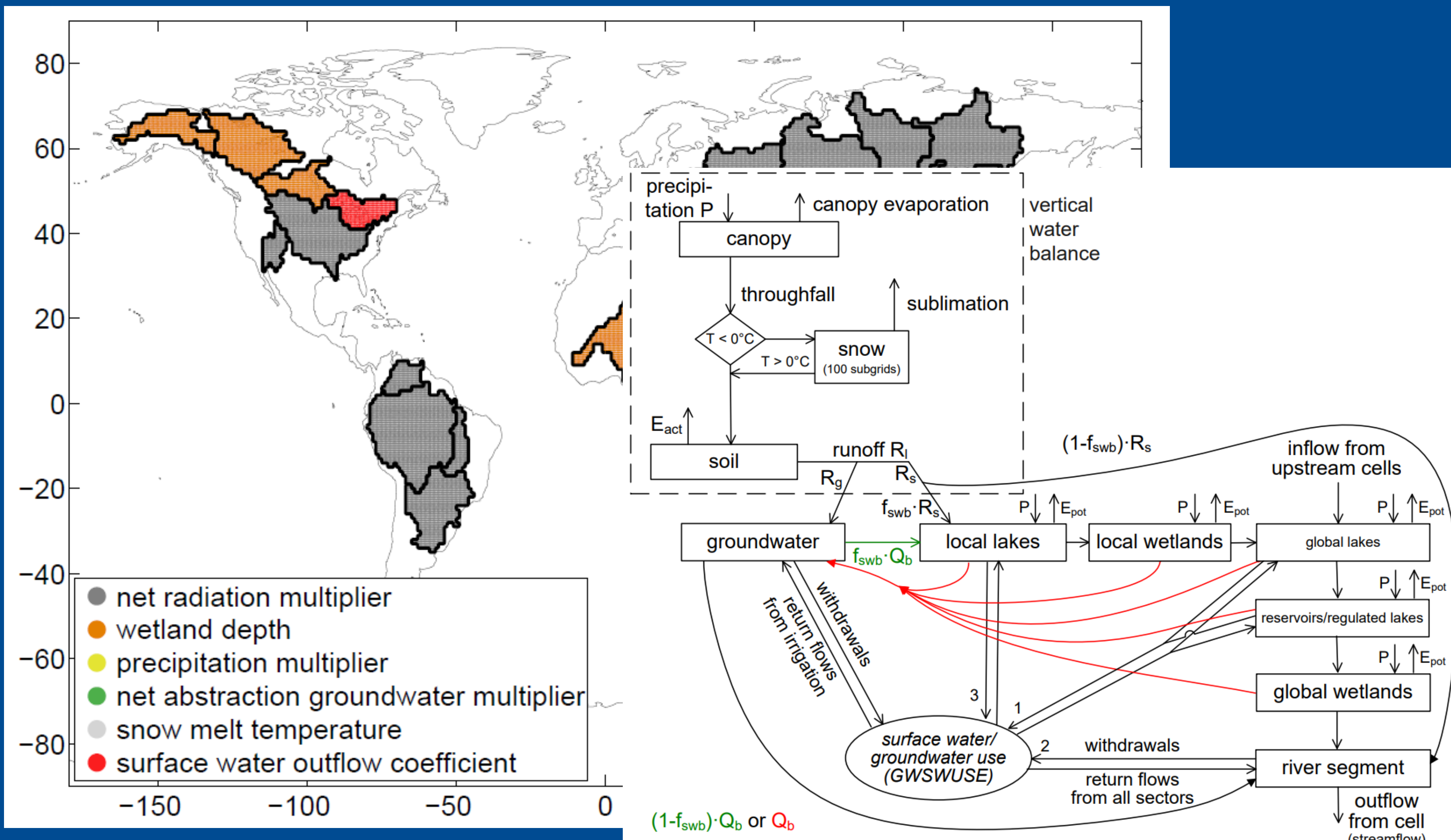
OBSERVED

MODELLED

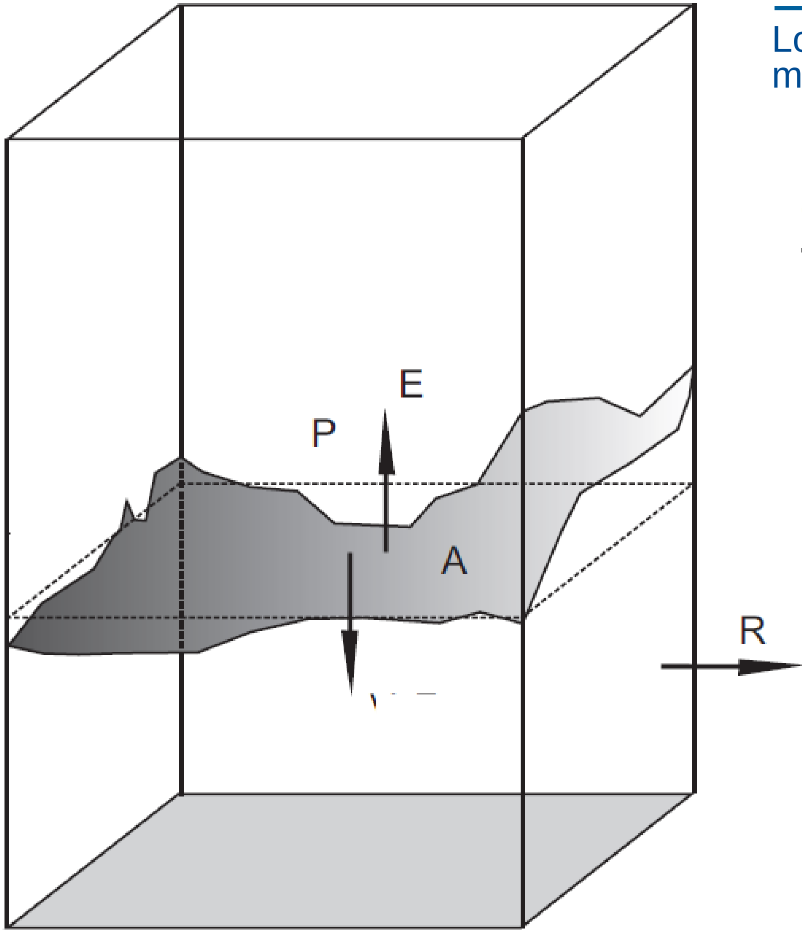


How can GRACE/-FO improve modelling?

Schumacher et al 2018: Parameters in WaterGAP model most sensitive towards calibration with TWSA



GRACE/-FO data have been used to evaluate fluxes in atmosphere models



Column-integrated

Local atmospheric moisture change

Horizontal moisture flux divergence

$$\frac{\partial W}{\partial t} = E - P + \int_A \boldsymbol{\nabla} \cdot \boldsymbol{Q} \, d\sigma$$

$$P - E = \frac{\partial S}{\partial t} + R$$

(Springer et al., 2017) Evaluation of the water cycle in COSMO-REA6 using GRACE (+ GRDC discharge)

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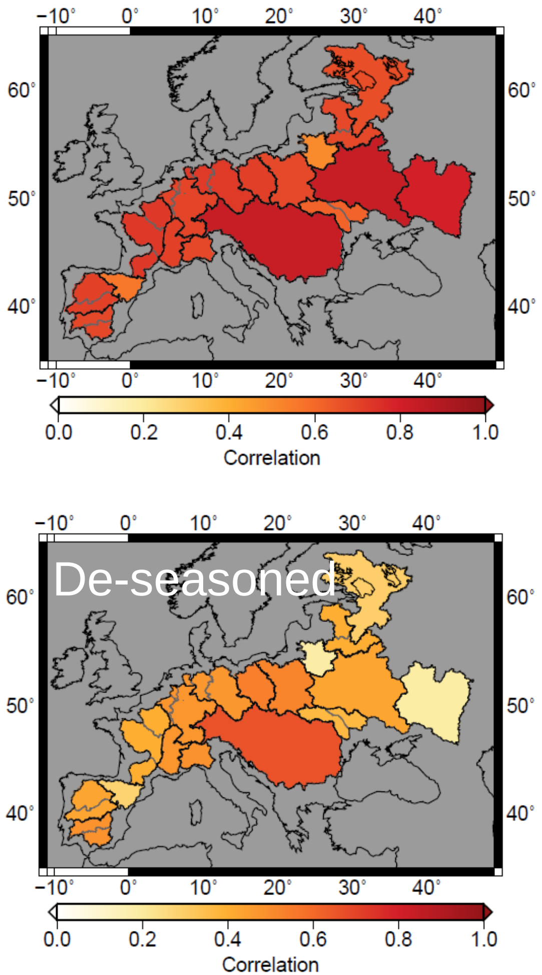
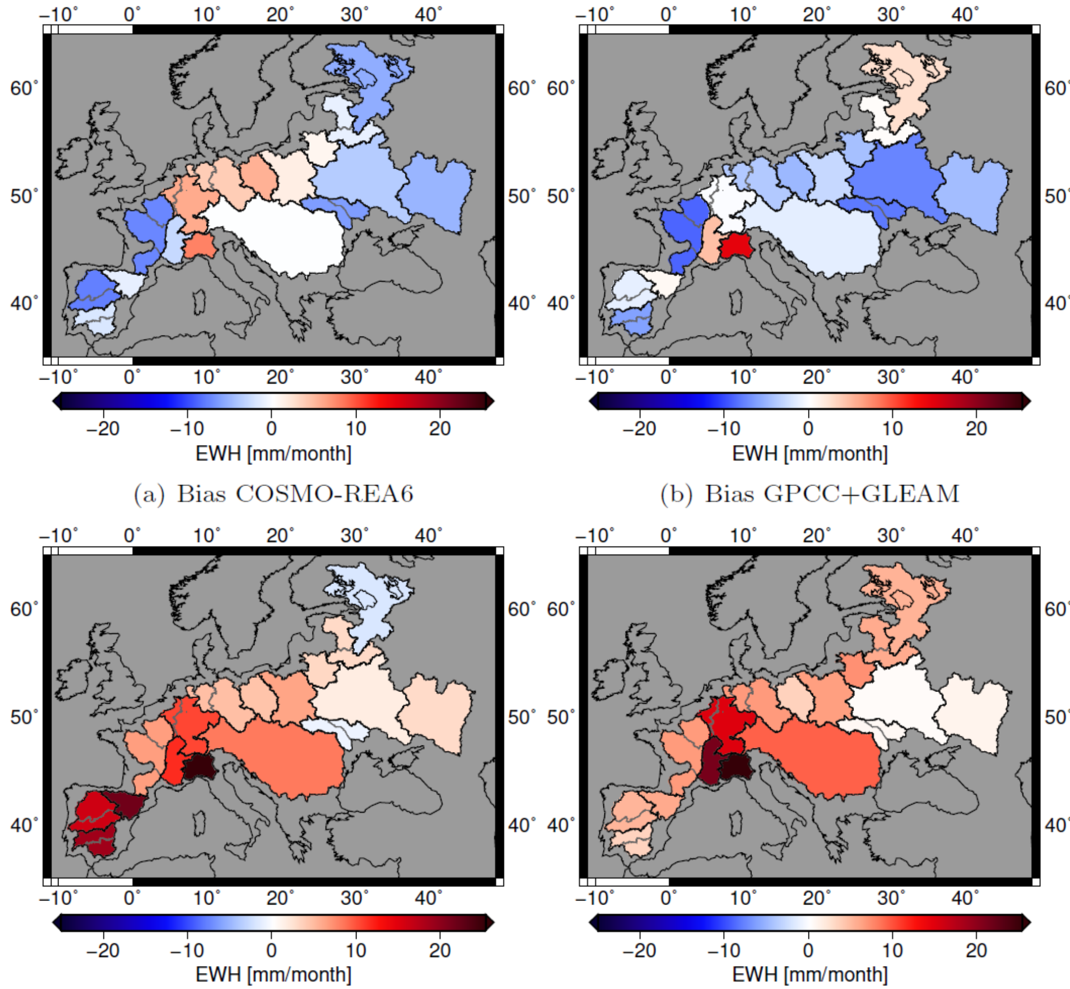


Correlation P-E



(a) Bias COSMO-REA6

(b) Bias GPCC+GLEAM

(c) Bias ERA-Interim

(d) Bias MERRA-2

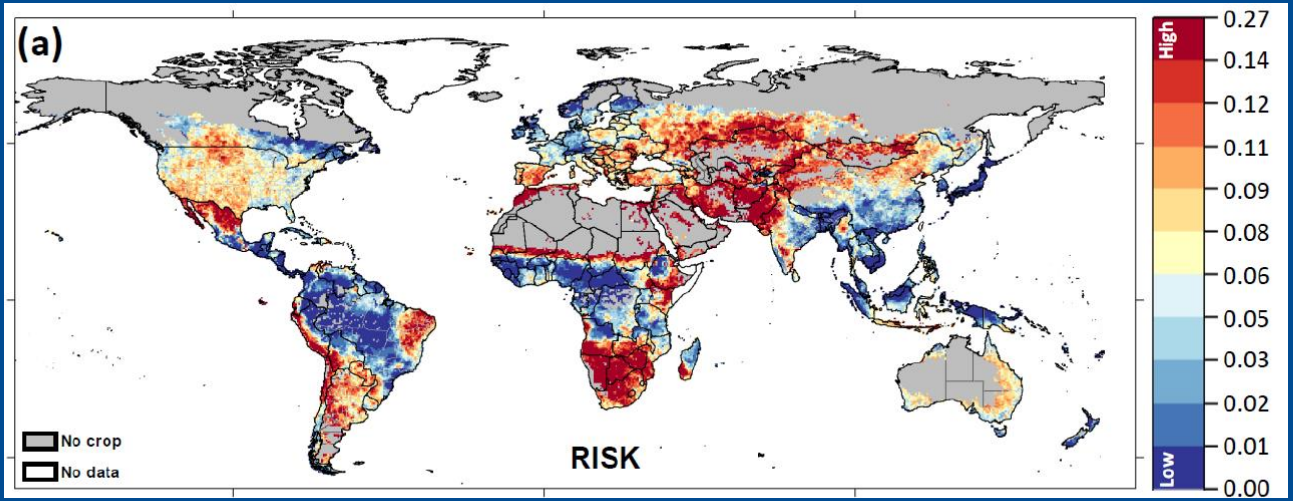
Bias P-E

Globedrought project (https://grow-globedrought.net/, funded by BMBF)

Objectives - develop a web-based integrated drought information system:

- past droughts and drought risks on global scale
- detailed analysis for selected regions
- (composite) drought indicators
- impact on food trade flow
- WGHM + Crop model + GRACE + …

Example (Meza et al., 2019)



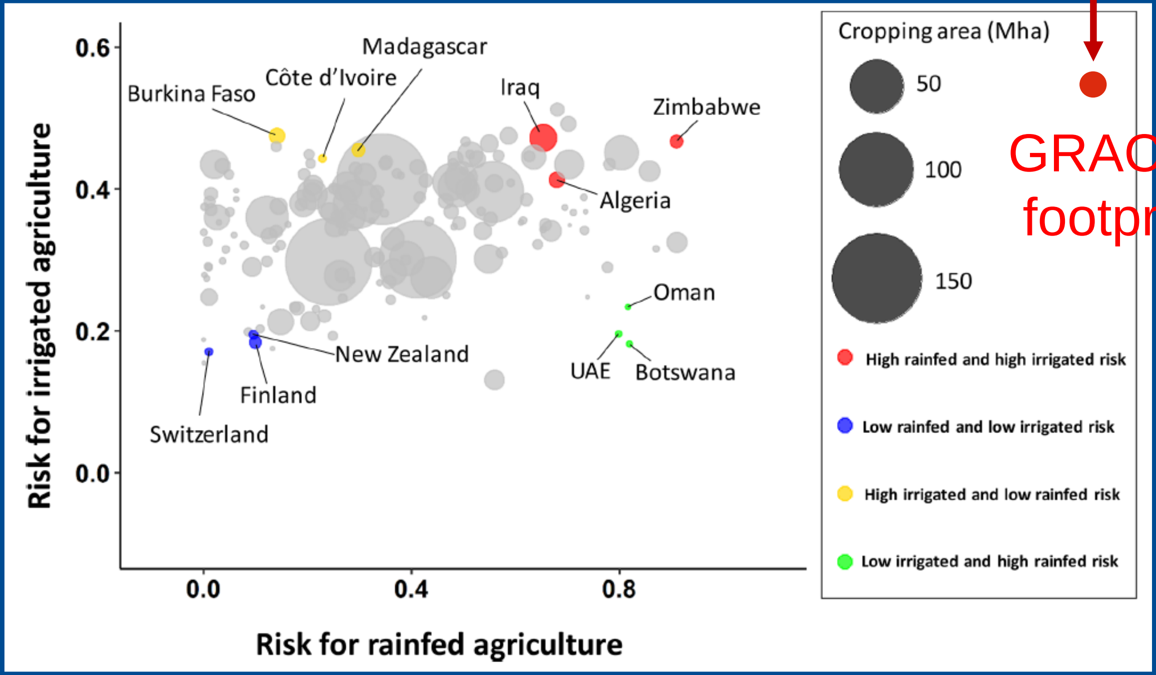
Assessment w remote sensing but w/o GRACE

Country-level: observable with GRACE/-FO?

RISK =

HAZARD * EXPOSURE

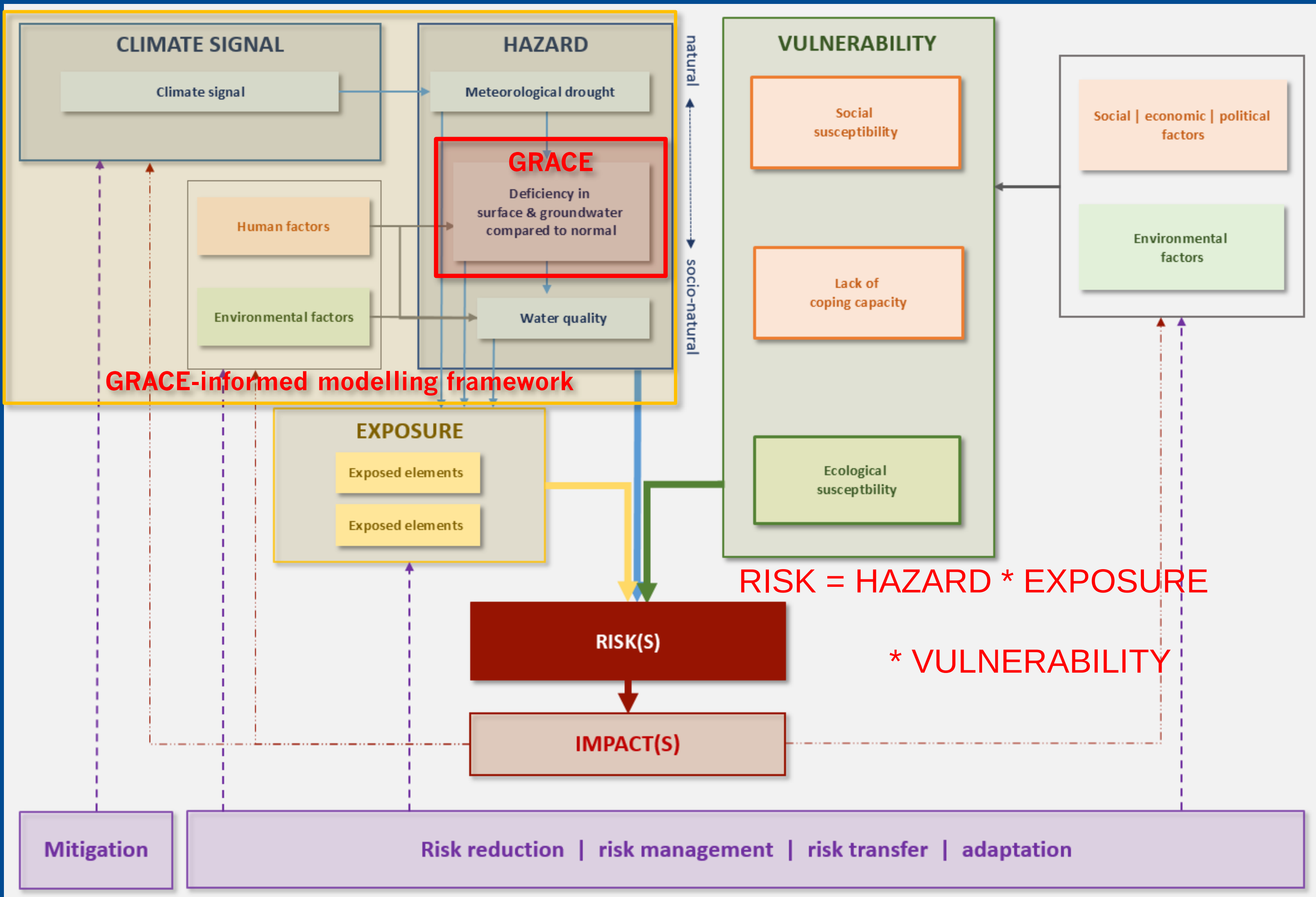
* VULNERABILITY



GRACE footprint

Conceptual drought risk framework (based on IPCC 2014, Birkmann et al 2013): Risk = Hazard x Exposure x Vulnerability

How GRACE can inform risk assessment

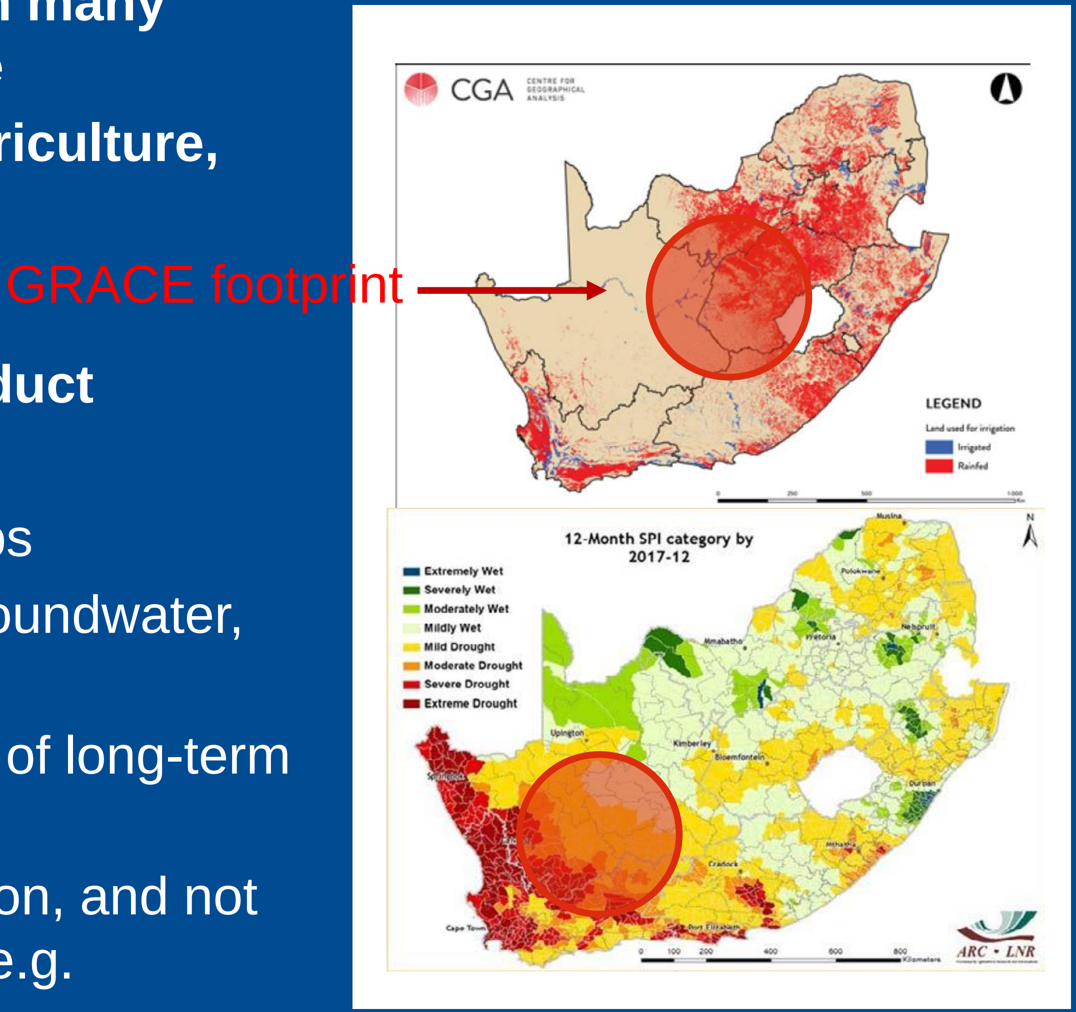


Meza et al., 2019

What is required for a more widespread use of space gravimetry?

Drought conditions depend on many factors at small (few km) scale

- **rainfall, soil, vegetation, agriculture, irrigation, …**

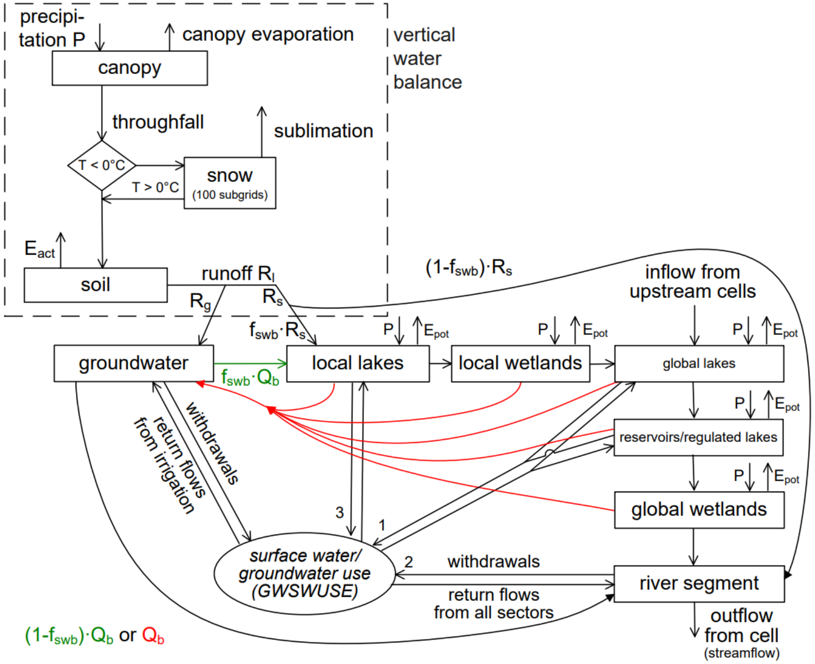


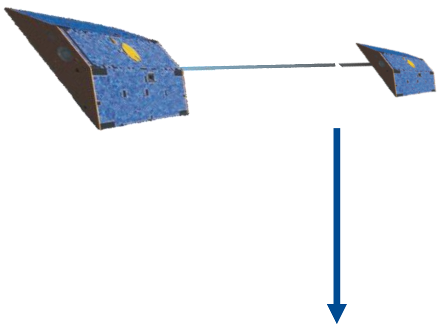
Current GRACE/-FO „footprint“

What is needed from data product

- Higher resolution!
- Operational coverage, no gaps
- TWSA maps partitioned in groundwater, surface water etc.
- Long time series and capture of long-term changes of mean conditions
- Data must be usable in addition, and not instead, of established data (e.g. precipitation, streamflow)
- Key is model-data assimilation

Data Assimilation





$$\mathcal{J}(\mathbf{z}_0) = (\mathbf{z}_0 - \mathbf{z}_0^*)^T \mathbf{C}_{\mathbf{z}_0^*\mathbf{z}_0^*}^{-1} (\mathbf{z}_0 - \mathbf{z}_0^*) + \sum_i (H_i(\mathbf{z}_0) - \mathbf{y}_i)^T \mathbf{C}_{\mathbf{e}_i\mathbf{e}_i}^{-1} (H_i(\mathbf{z}_0) - \mathbf{y}_i)$$

Data Assimilation – Scenarios

- **Multi-data full state DA in coupled modelling**
  - Realtime („analysis“) requires very low latency, data must fit operational DA systems (not likely unless NGGM community proves value for NWP)
  - Models resolve diurnal cycle (15min timesteps)

  - Use of space gravimetry in „climate monitoring“ and reanalyses?

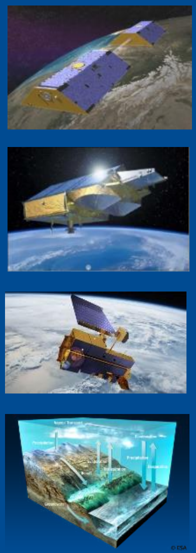
- **Reanalysis of single (TWSA) or multi-sensor data (soil moisture, snow, …) in offline modelling**
  - So far with offline hydrological/LSMs
  - Spectacular improvements have been documented: Zaitchik et al 2008, Li et al (2012), Houborg et al. (2012), Eicker et al., 2014, Girotto et al. 2016, 2017, 2019, 2021, Schumacher et al., 2016, 2018
  - Most based on Ensemble Kalman filters
  - Models typically at daily timestep

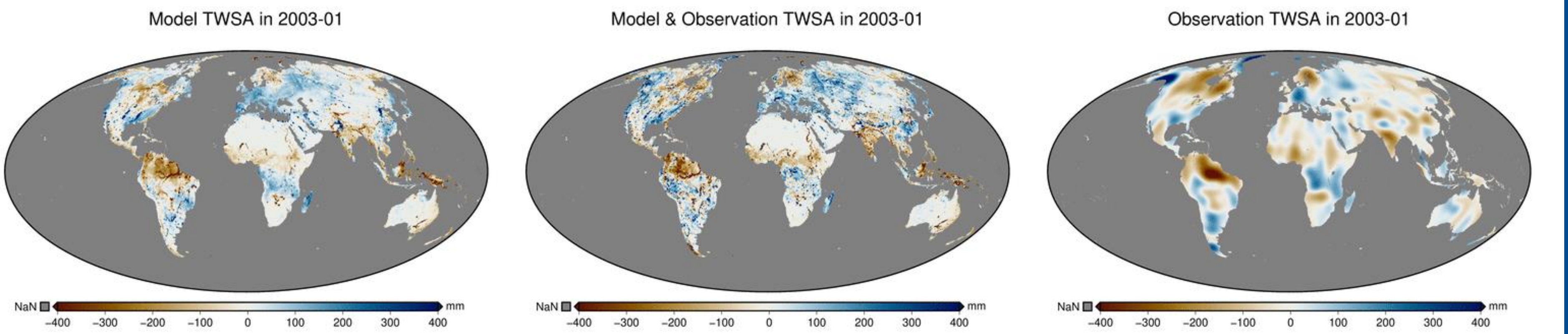
  - Can also be viewed as physically consistent downscaling of TWSA
  - Downscaled/disaggregating TWSA data set to confront climate modelling

Caveat: DA always needs uncertainty assessment!

GlobalCDA project (http://globalcda.de/)

Improved quantitative understanding of the freshwater system by integrating GRACE/-FO and remote sensing with conceptual hydrological modelling (WaterGAP)





Total water storage from model (left), GRACE (right) and model-GRACE assimilation (center)

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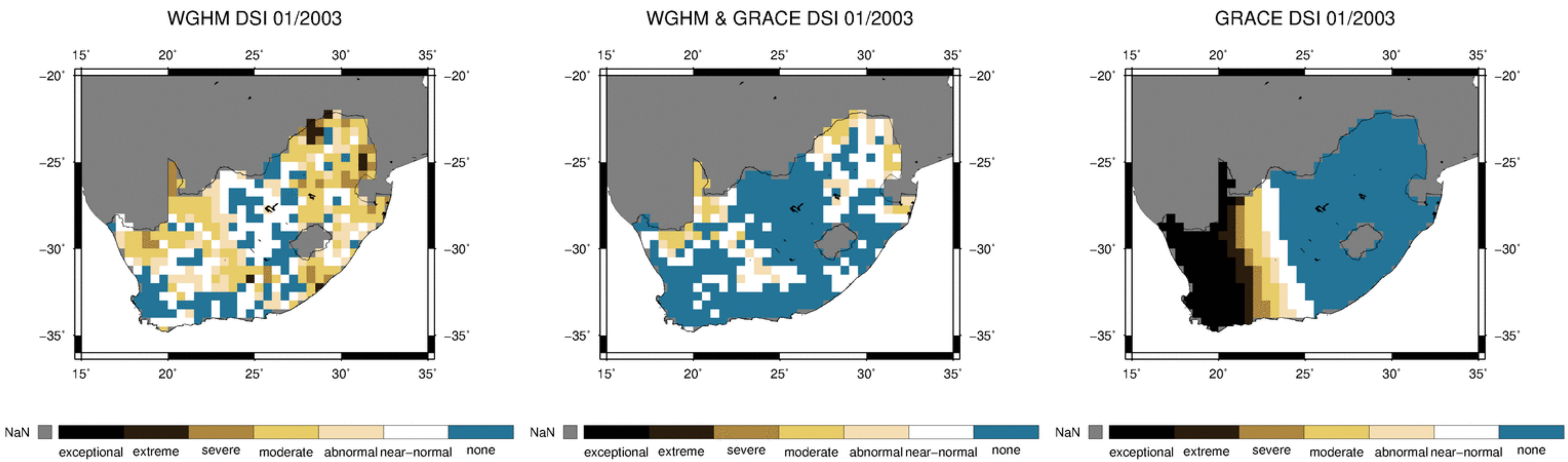
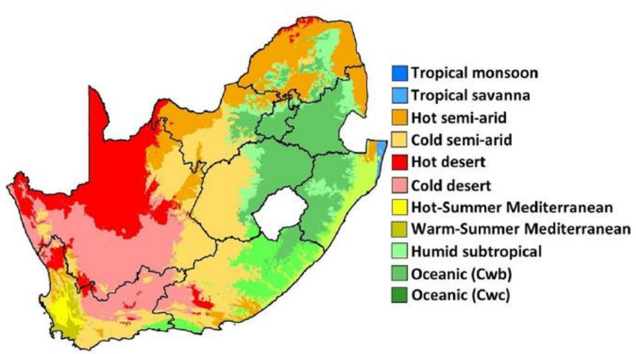
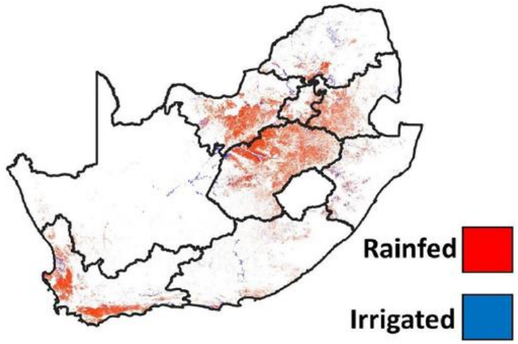
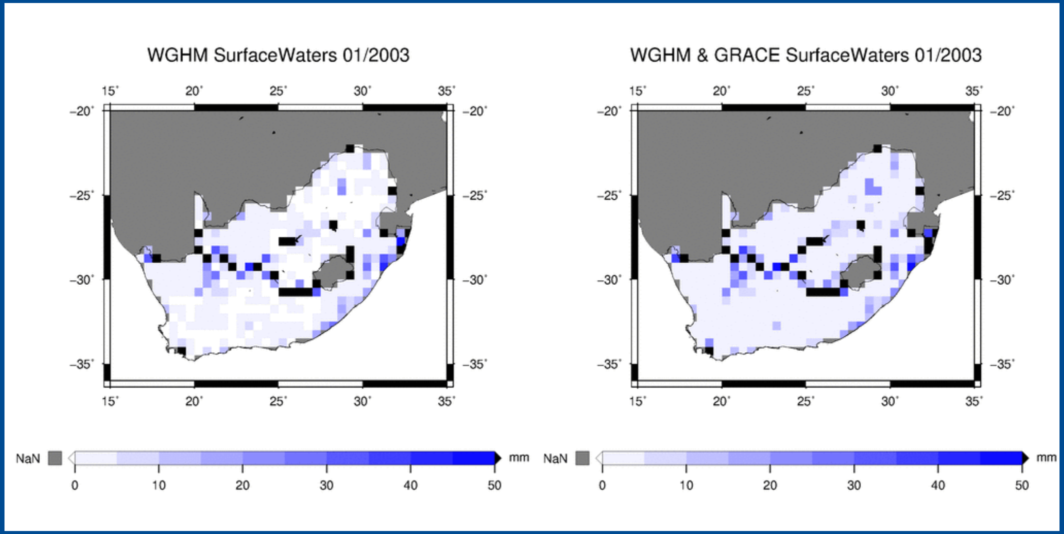
DA provides a physically consistent downscaling of GRACE to model resolution (here 50 km)
Gerdener et al., in prep.





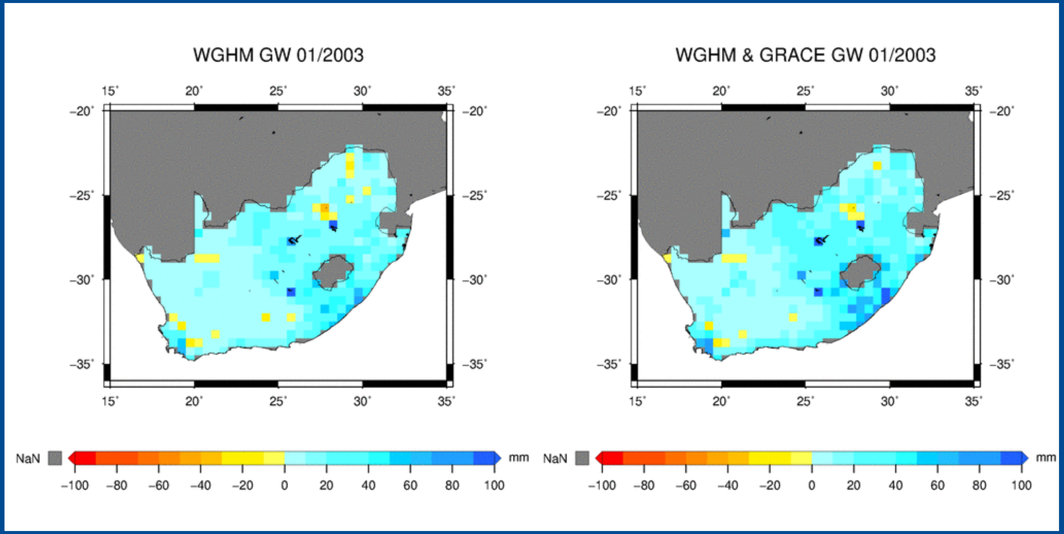




Vertical disaggregation:

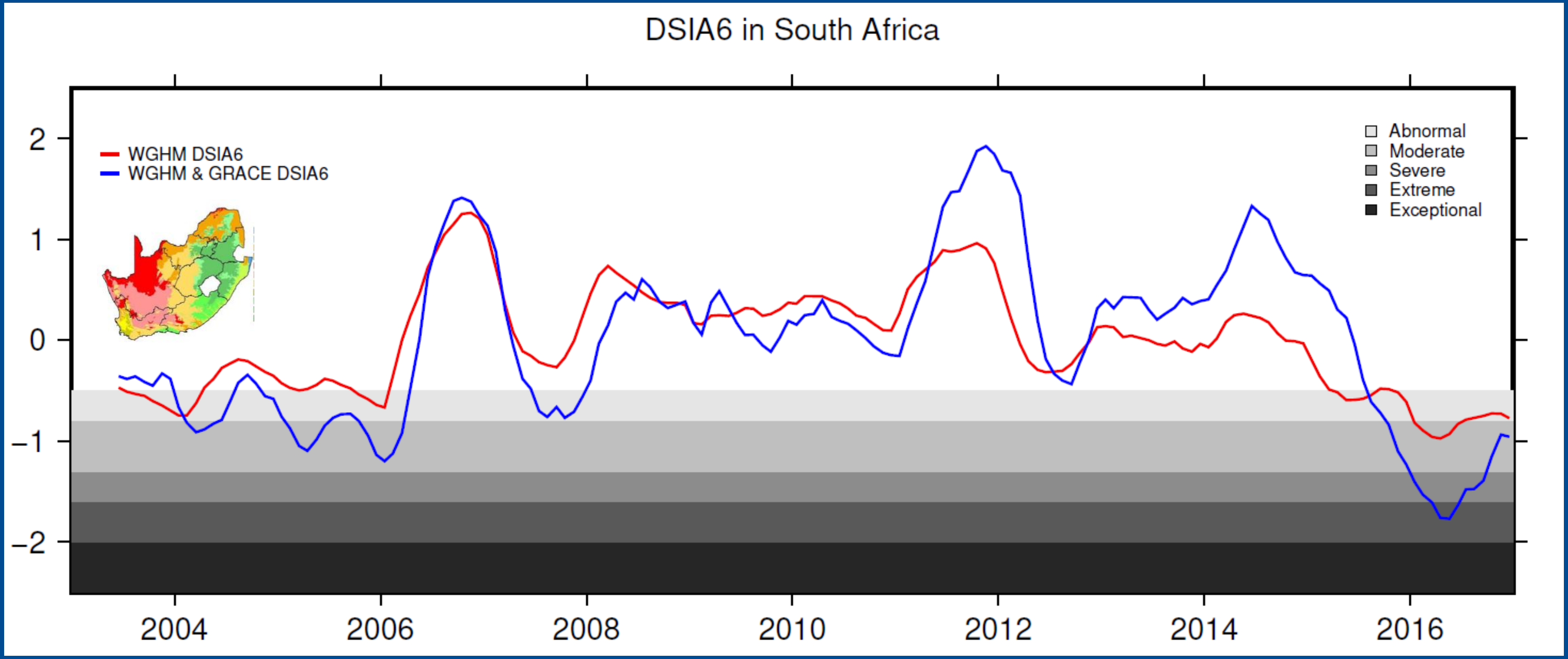
Adding GRACE has little impact on surface water but…

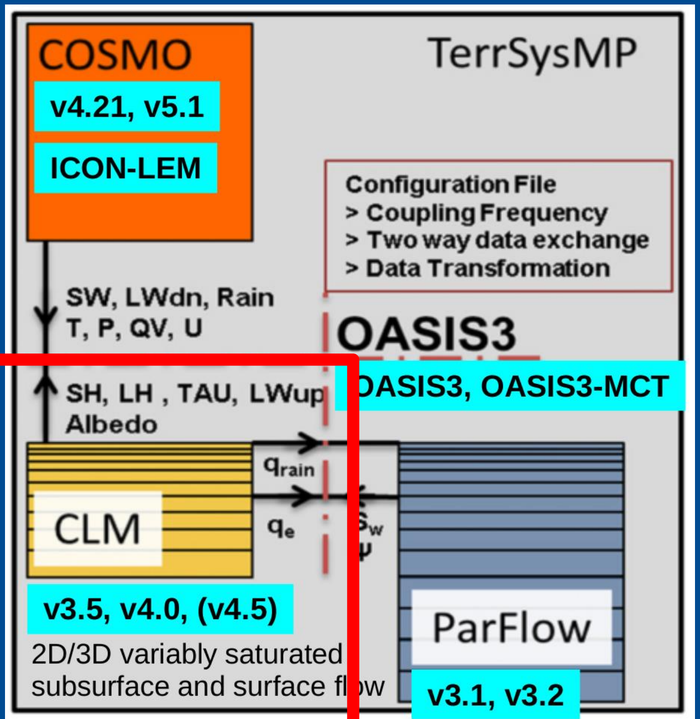
…large impact on groundwater

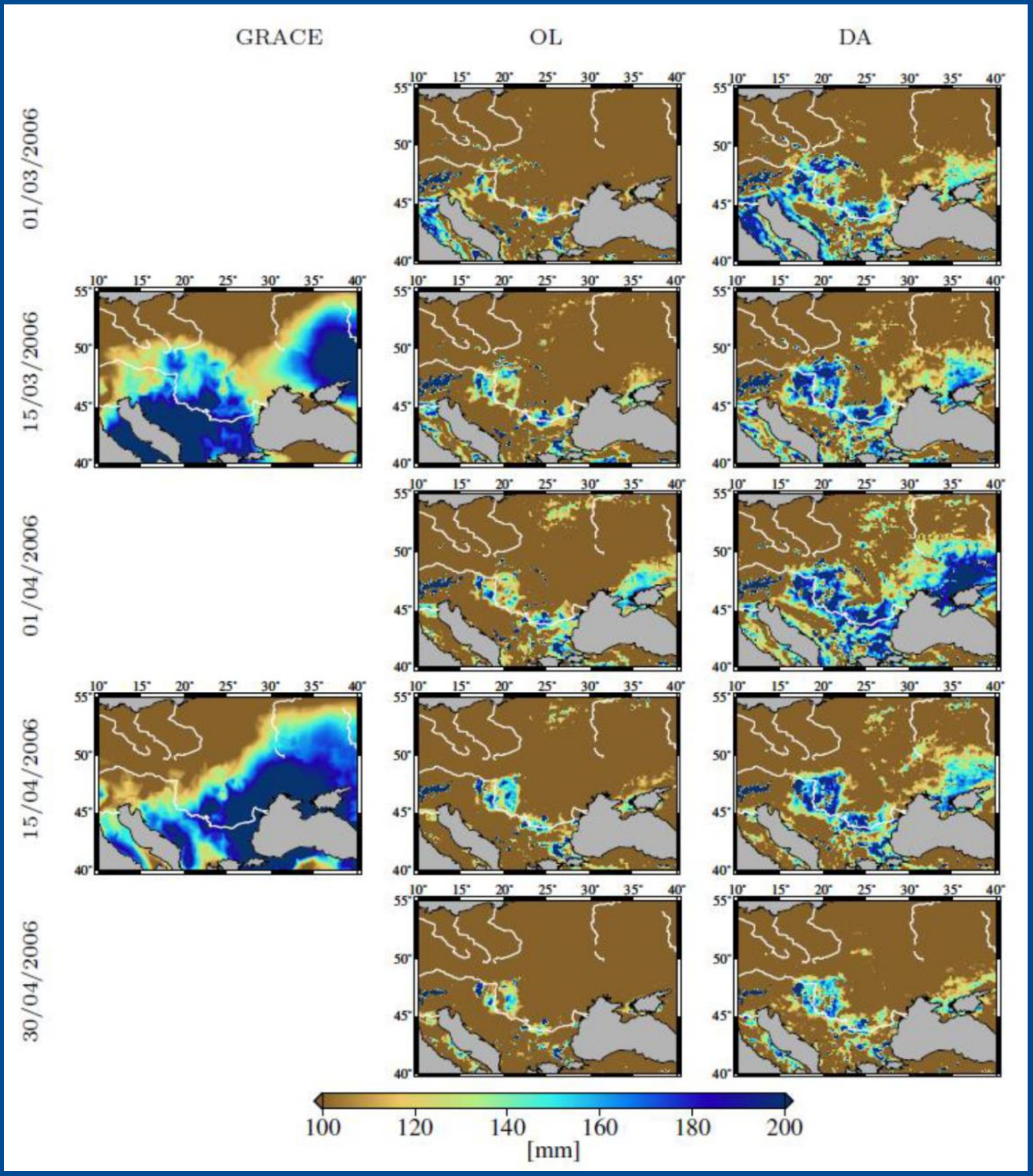


Country-averaging. Here: groundwater storage drought indicator (DSI6 = DSI 6-months averaged, Gerdener et al., 2020)

Adding GRACE improves the sensitivity

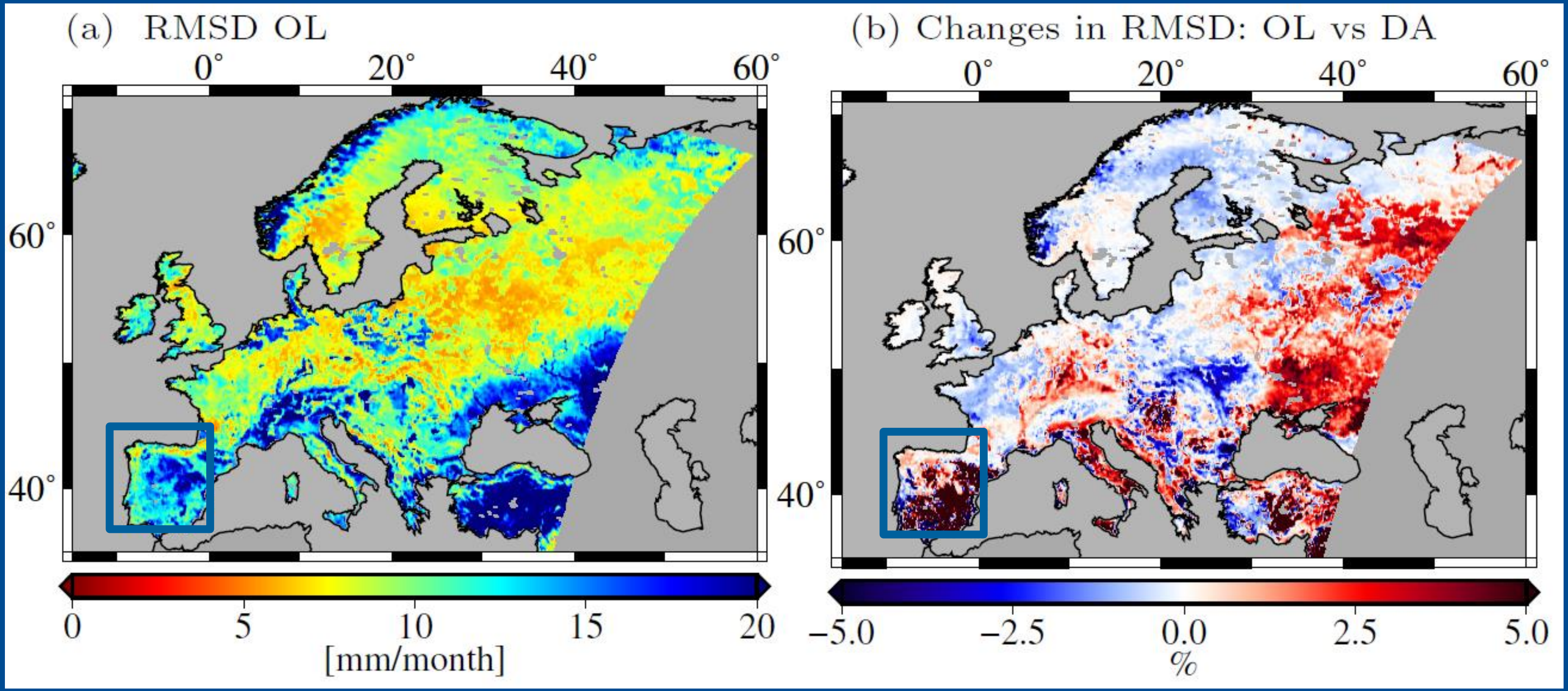






Danube flood 2006 as seen by GRACE (left), CLM (center), assimilation (right)

Springer (2019), Springer et al. (2019)



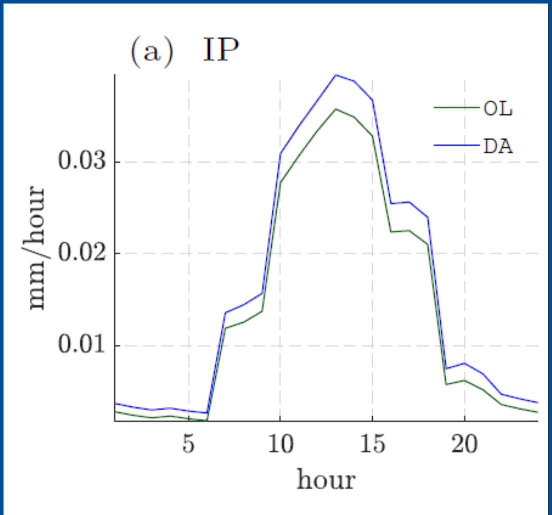
Evaporation

Top left – CLM open-loop vs. MPI Jena ML-based fluxnet product

Top right – OL vs DA

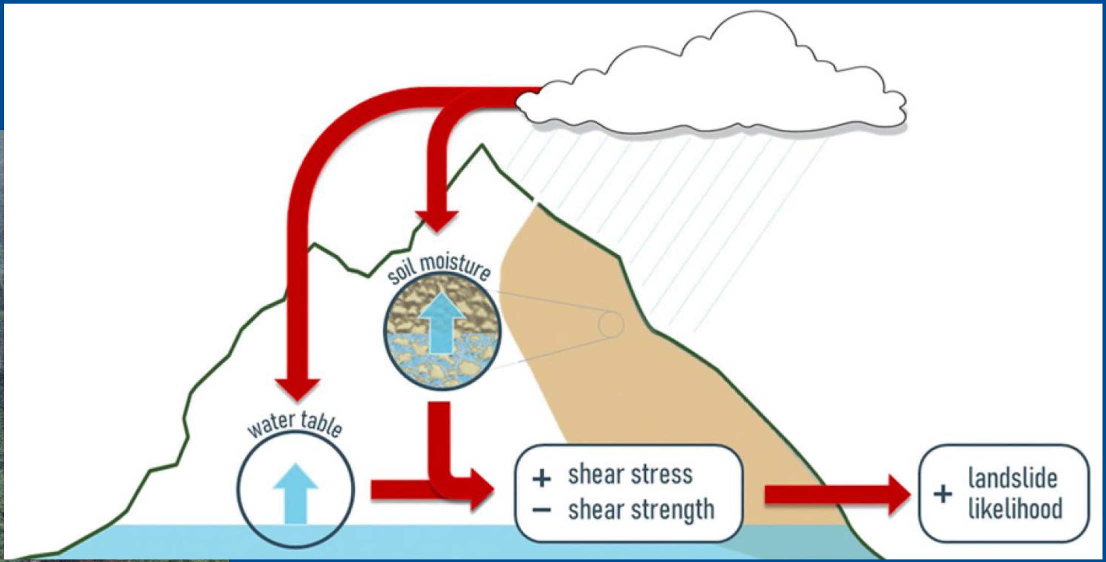
Bottom: diurnal cycle Iberian peninsula, August 2005

Springer (2019)



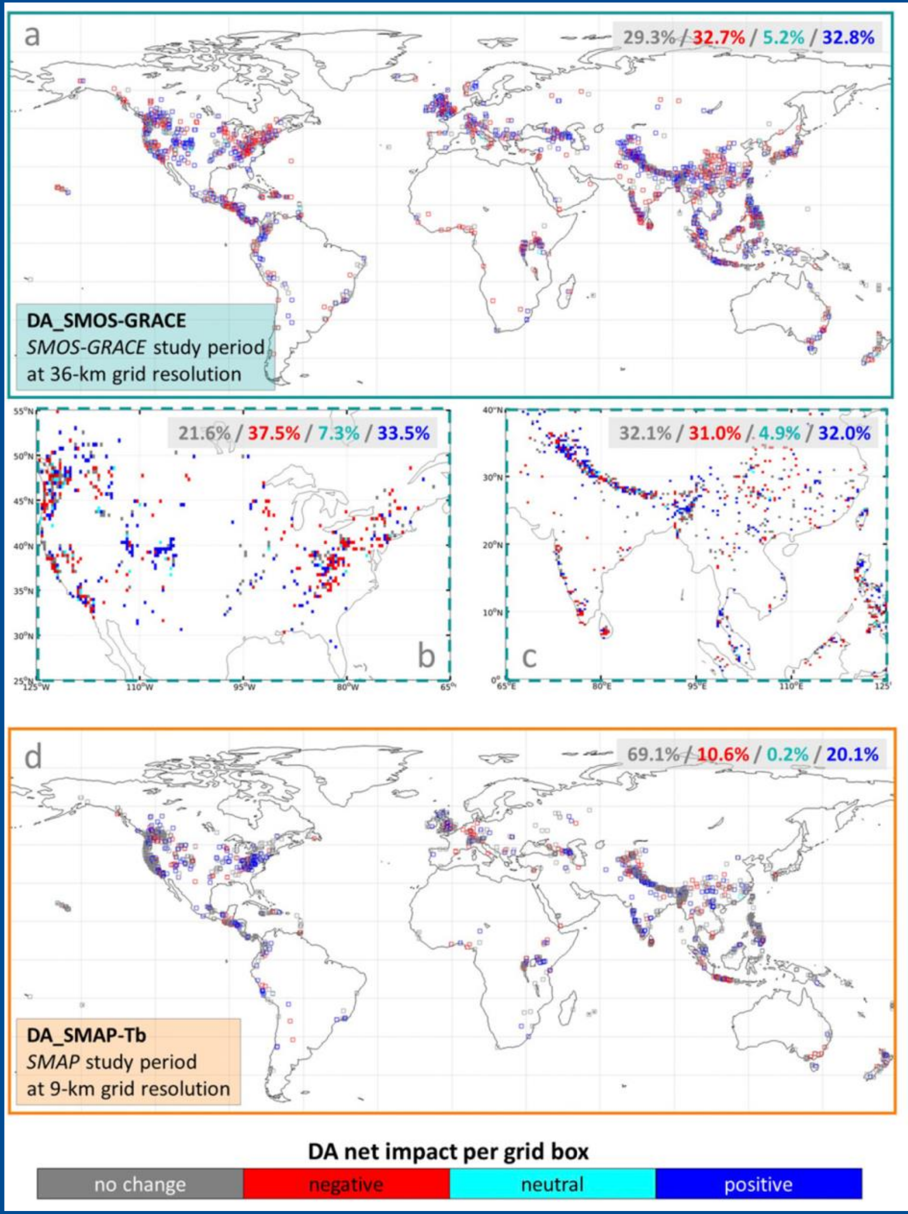
Soil water estimates as landslide predictors (Felsberg et al., 2021)

- Landslide predictors typically based on rainfall only
- Joint assimilation of GRACE and satellite soil moisture (SMAP, SMOS) into CLSM land surface model improves soil moisture profiles
- Inform physically based landslide models (36km/9km)



Freetown 2017 (Photo M Stedman, CC BY 2.0)

Soil water estimates as landslide predictors (Felsberg et al., 2021)



Neither GRACE nor SMAP or SMOS alone would be of use due to coverage and resolution.

Adding GRACE, SMOS, SMAP can improve the ability of CLSM to distinguish „stable slope“ and „landslide“ condition in terms of soil water

- GRACE has revolutionized water cycle research

- Limitations that prevent further use are related to spatial resolution
- Data assimilation could be the way out

- Geodesists are often afraid of combining their precious data with „models“
- There is no reason for this.