# Groundwater storage variations in the North China Plain from GRACE and ground observations

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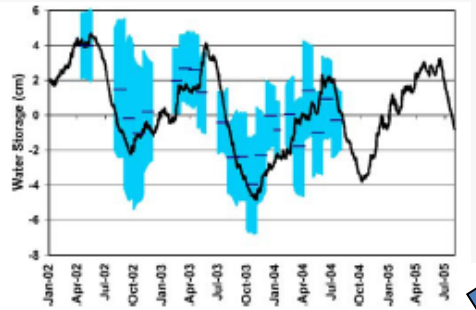
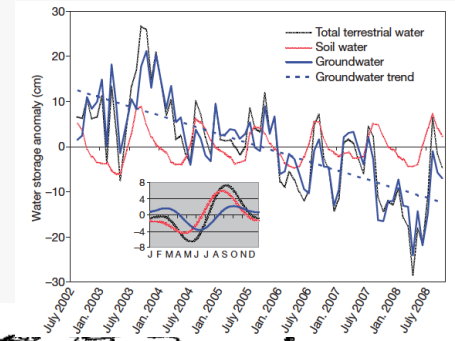
# Motivation




17.7 km$^3$/yr, 54 km$^3$/yr, 14 km$^3$/yr

**North India and Pakistan**

**Rodell [2009]**

**Tiwari [2009]**

**Long [2016]**

**North China Plain??**

**Mississippi rive basin**

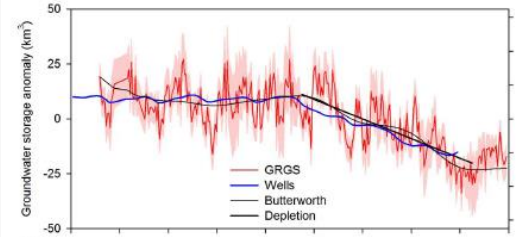
**Rodell [2007],**

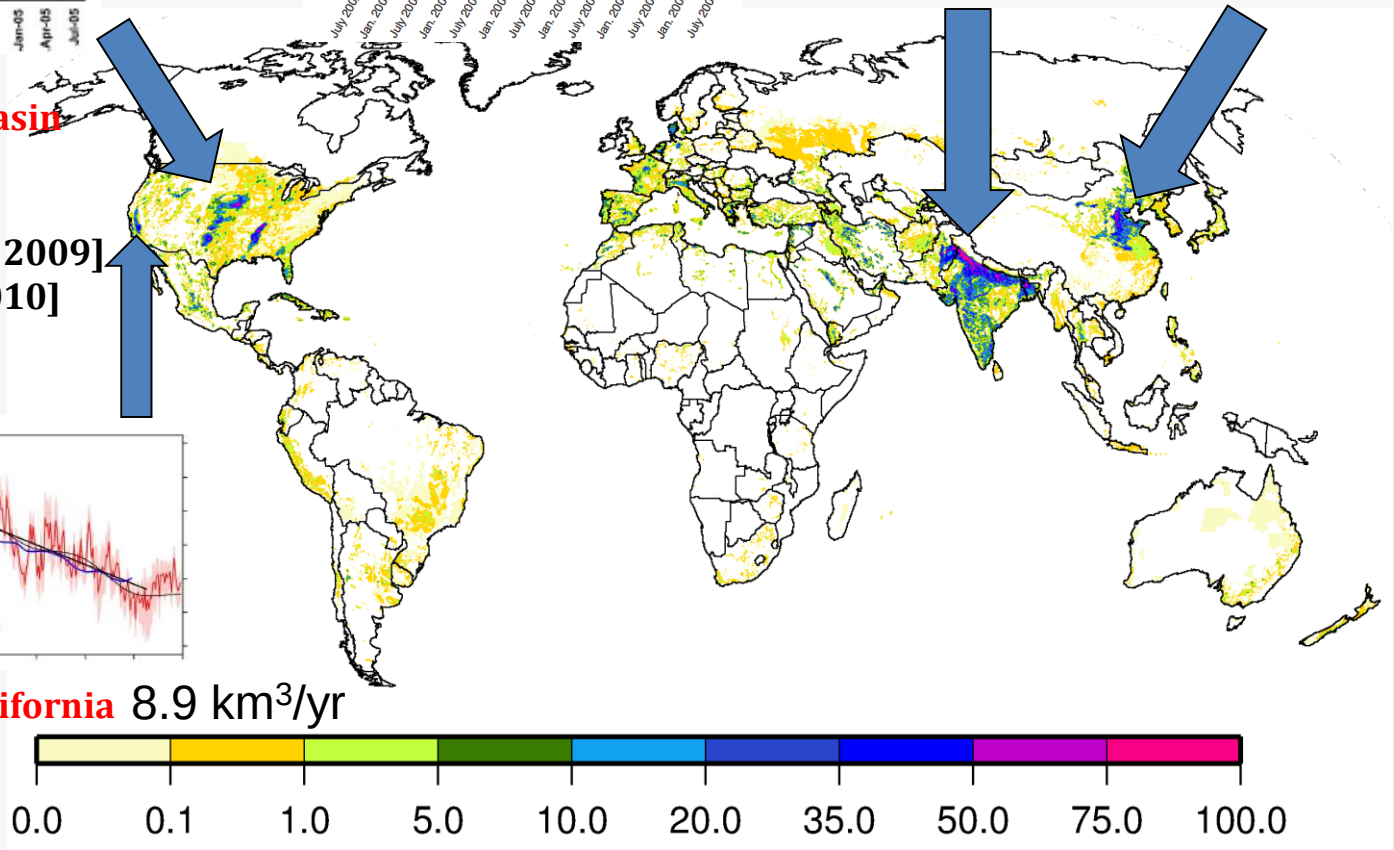
**High Plains**

**Strassberg [2007, 2009]**

**Longuevergne [2010]**

~9 km$^3$/yr




**Central Valley, California** 8.9 km$^3$/yr

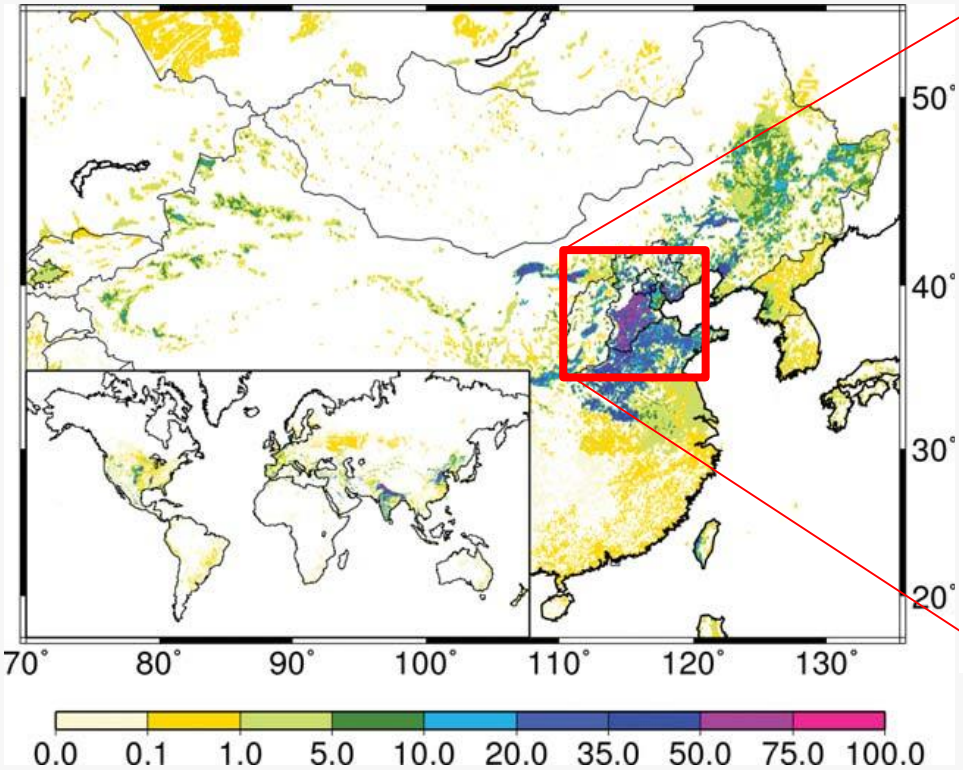
**Famiglietti [2011]**

**Scanlon [2012]**

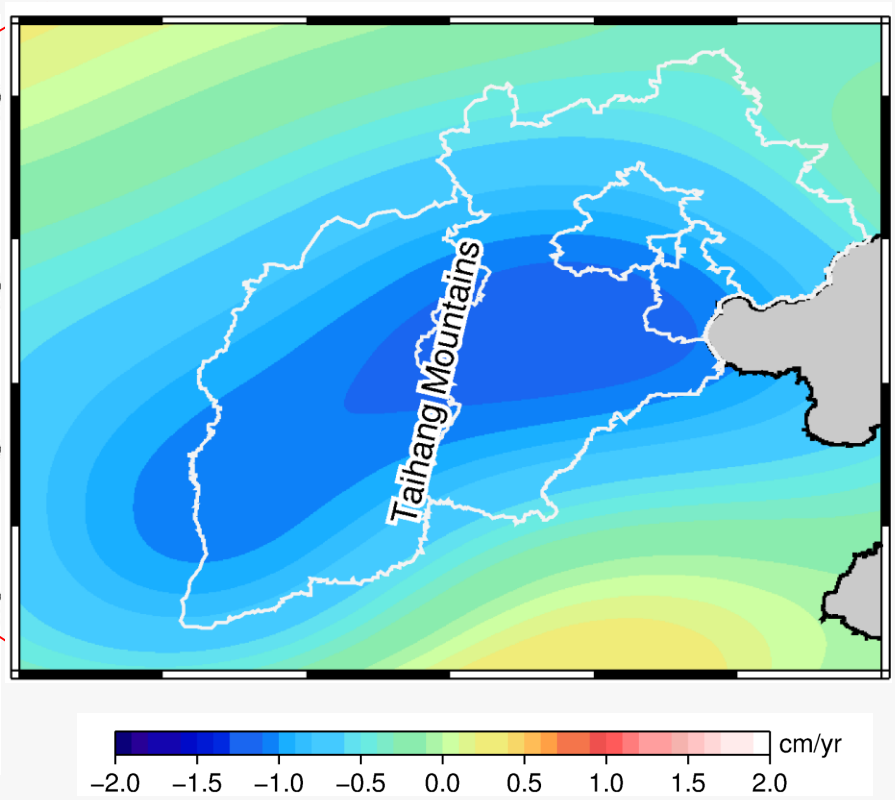
**Percentage of grid cell area equipped for irrigation with groundwater, *Siebert [2010]***

# Motivation

- linear GWS decline during 2003-2010




**Percentage of grid cell area equipped for irrigation with groundwater, *Siebert [2010]***




**Trend map of groundwater storage changes from GRACE-SM**

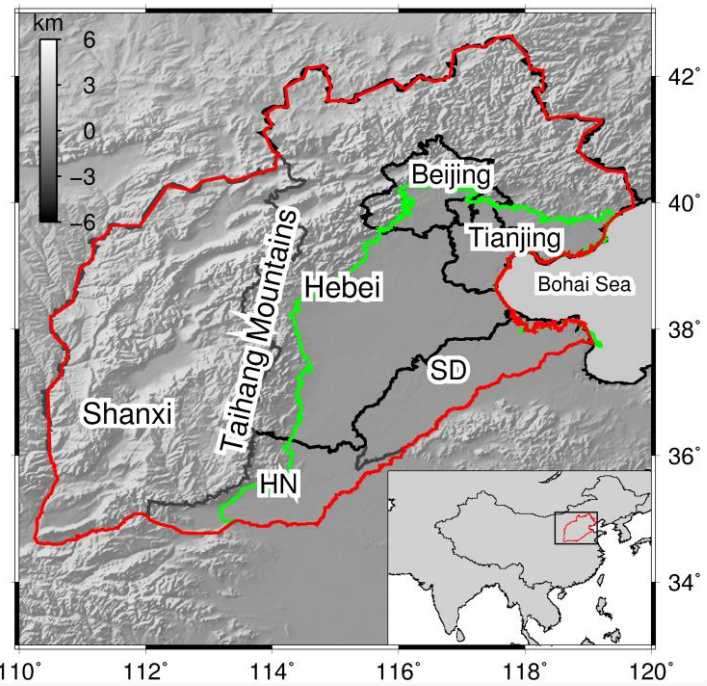
Feng et al. *Water Resources Research*, 2013

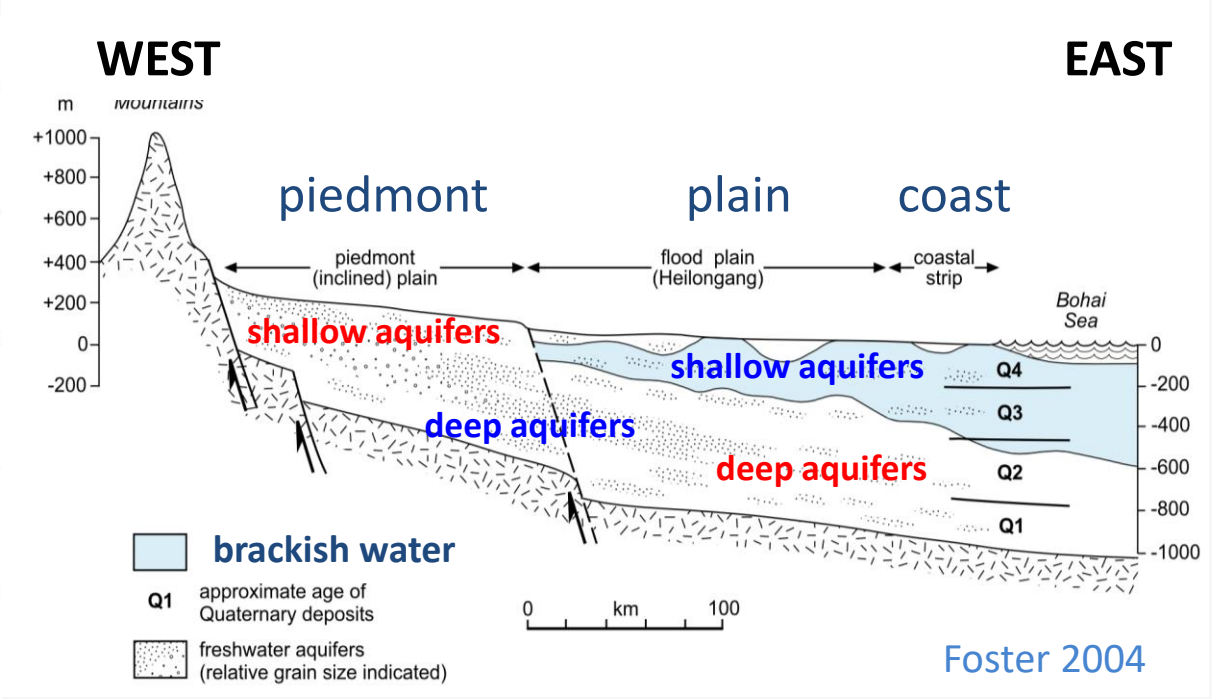
# Motivation

- Previous study
  - Linear GWS depletion in the NCP (2003-2010)

- **Questions**
  - Seasonal and inter-annual GWS variations in the NCP
  - Causes of these GWS variations: anthropogenic vs. natural ?
  - Comparison with other space and ground geodetic observations (GPS, InSAR, & ground gravity observations?)

# North China Plain



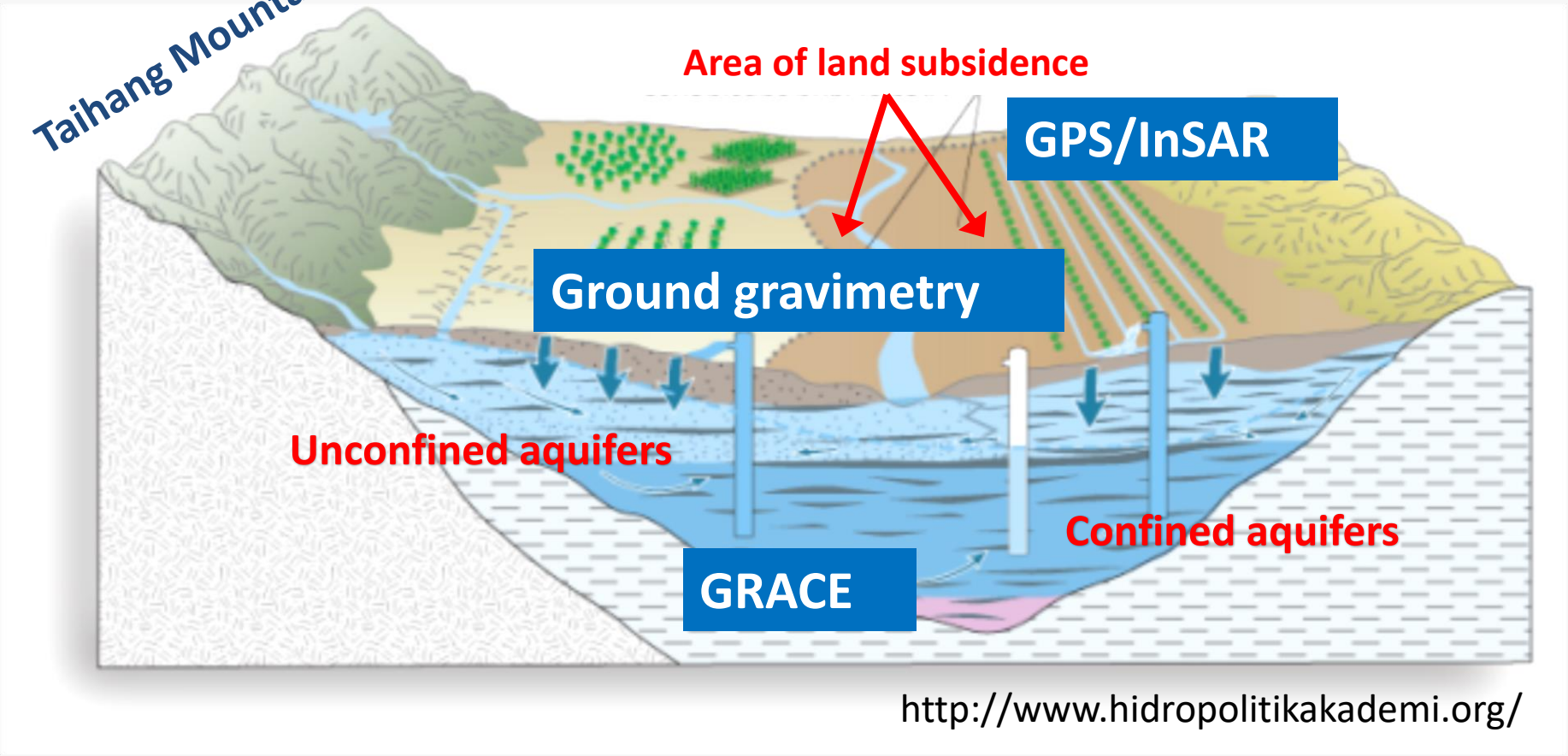

North China Plain
(140,000 km$^2$)

Our study region
(434,000 km$^2$)

**Cross-section of the NCP showing the general hydrogeological structure**

# North China Plain

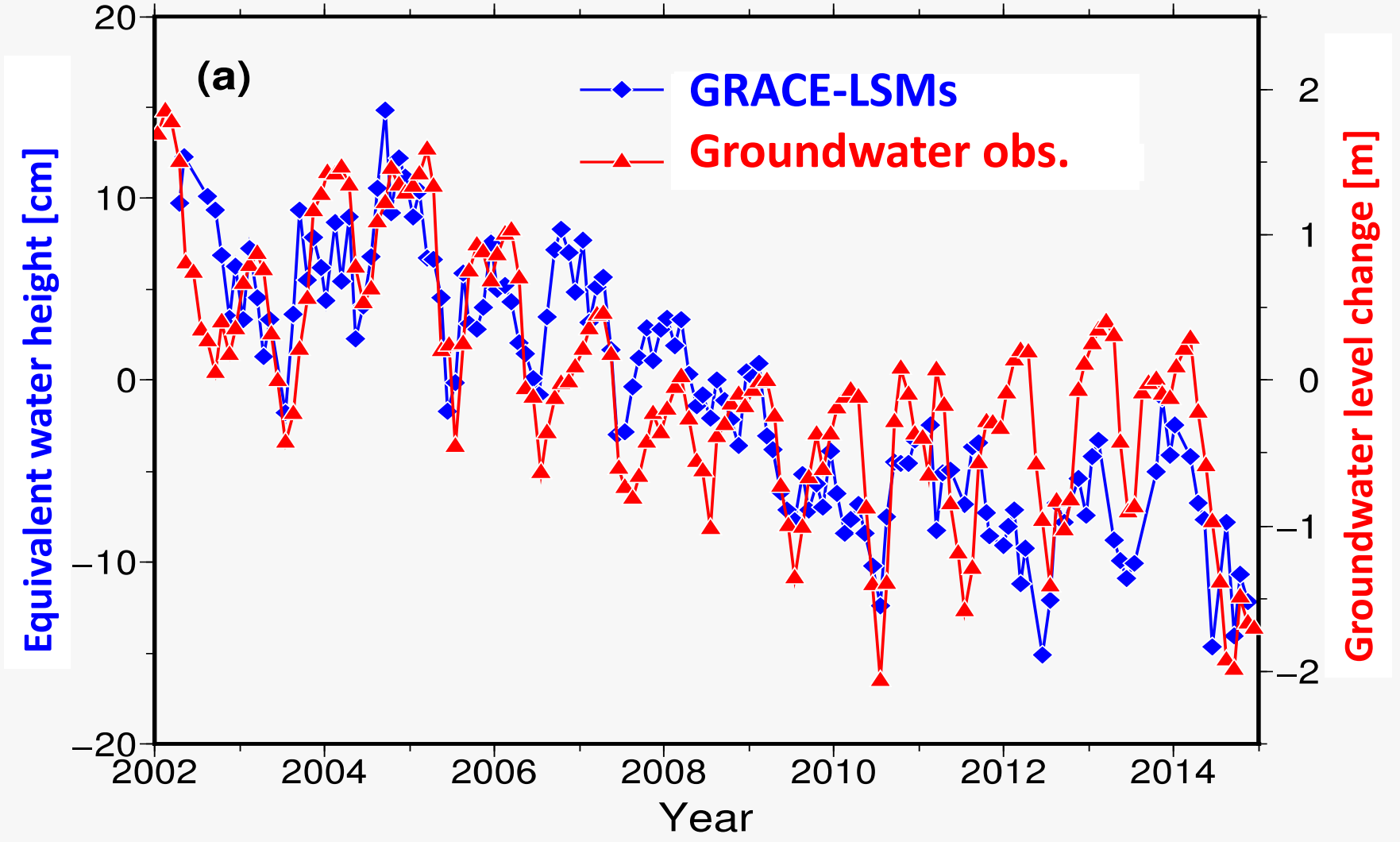
- GWS depletion and land subsidence




http://www.hidropolitikakademi.org/

# GWS variations in the NCP

- GRACE vs. Groundwater observations

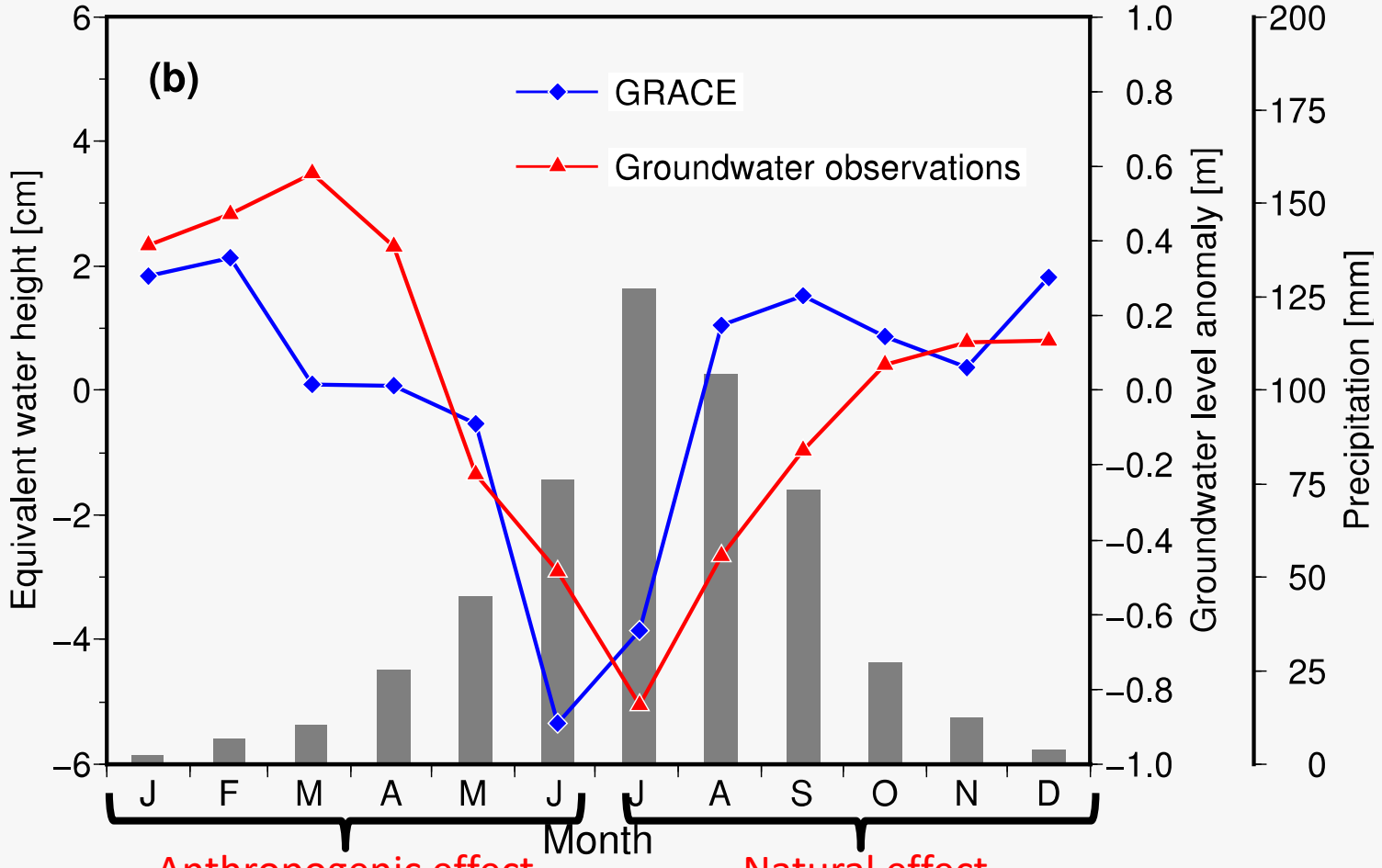


# Estimation of GWS variations based on well observations

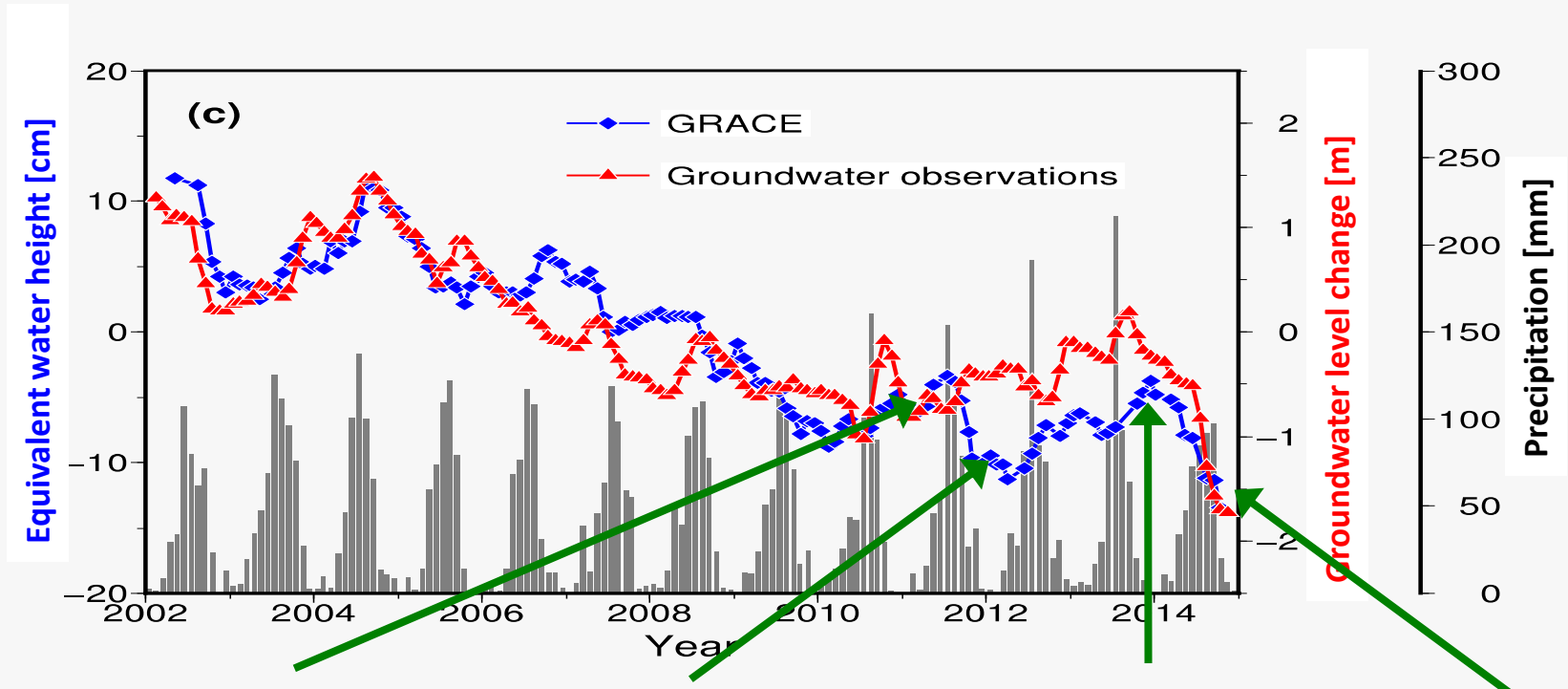
- For shallow aquifers (unconfined)
  - Groundwater level changes * specific yields (0.06 in NCP)
- For deep aquifers (confined)
  - Elastic storage change of GW (recoverable)
    - Groundwater level changes * storage coefficients (0.00125 in NCP)
  - *Inelastic storage change of GW*, compaction of aquifers (unrecoverable, related to land subsidence (GPS/InSAR), potentially significant)

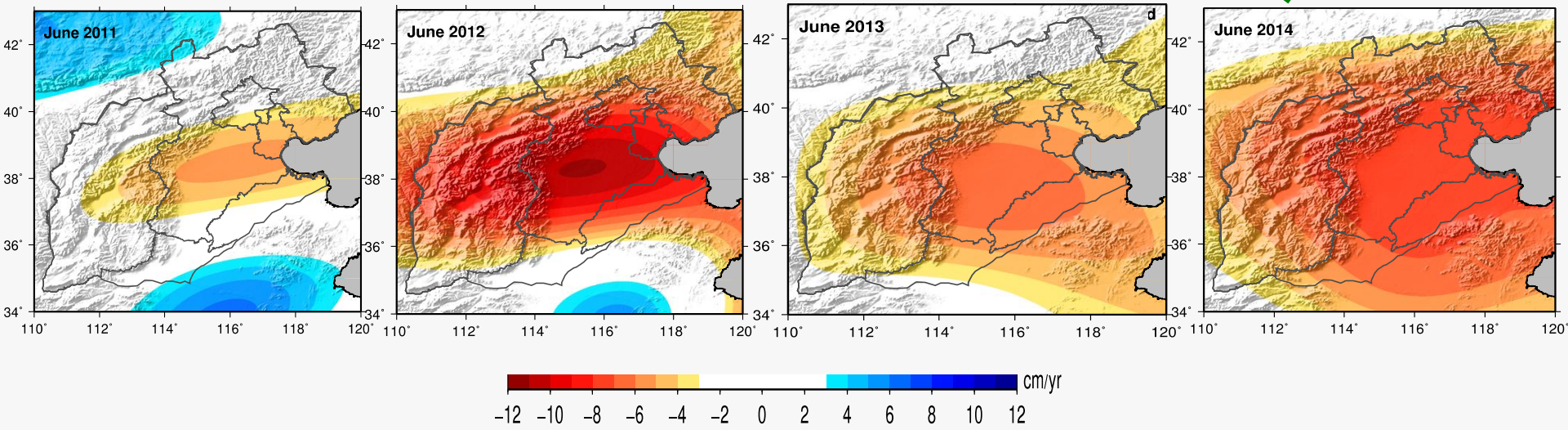
# Climatological GWS vs. Precipitation variations

- **anthropogenic** + **natural** effect

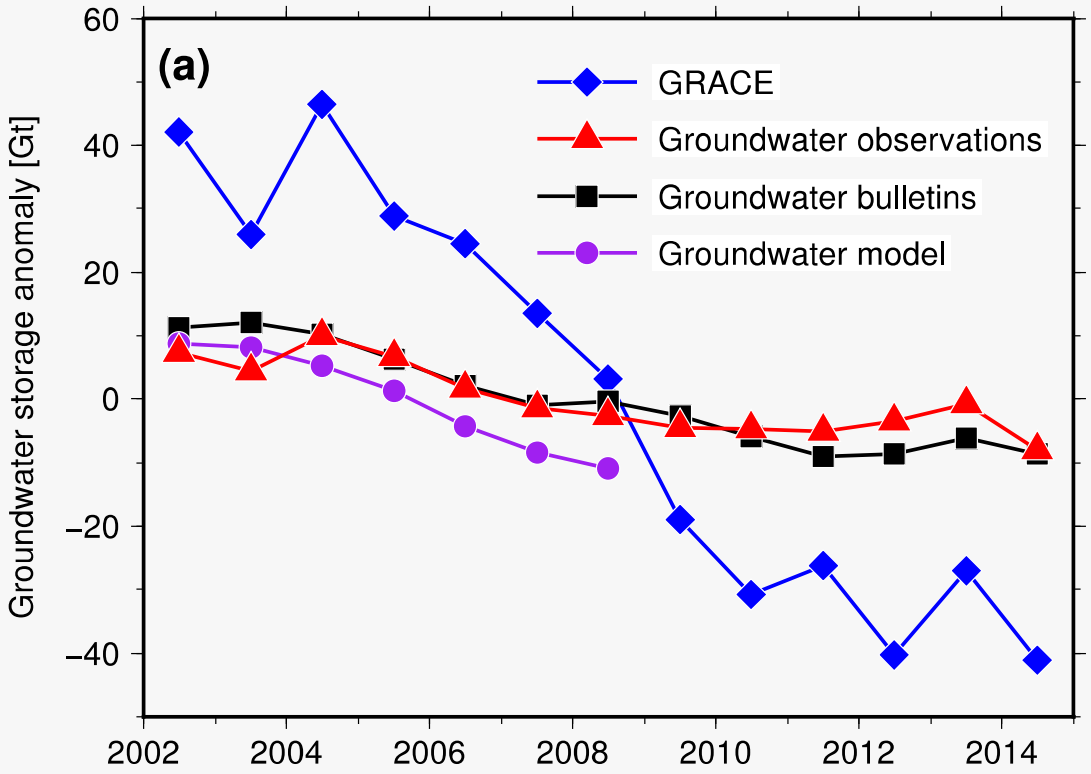


# Interannual GWS variations



# Long-term GWS trends

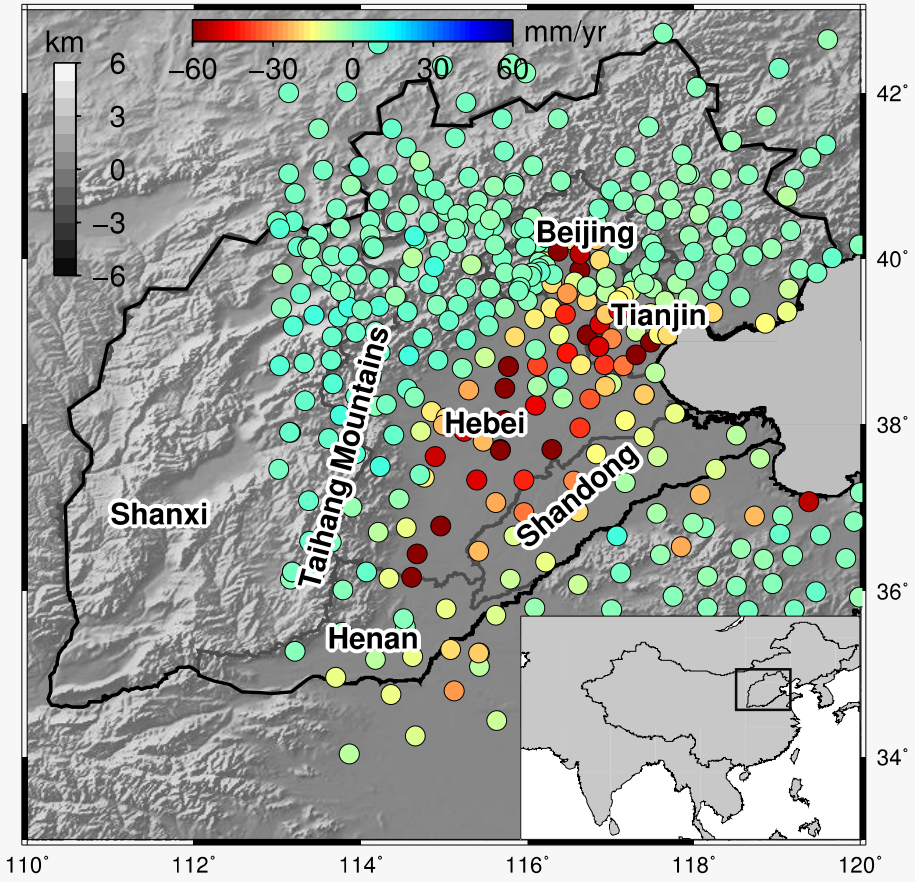



**km³/yr**

| | GW observations | GW bulletins | GW model | GRACE |
|---|---|---|---|---|
| **2002-2014** | **-1.2 ± 0.1** | **-1.9** | **--** | **-8.4 ± 1.0** |
| **2002-2008** | **-1.8 ± 0.2** | **-2.5** | **-4.0** | **-5.0 ± 1.8** |

# GWS depletion rate estimation from GPS (*missing part*)

**Linear trends of vertical deformation from GPS (2002-2014)**



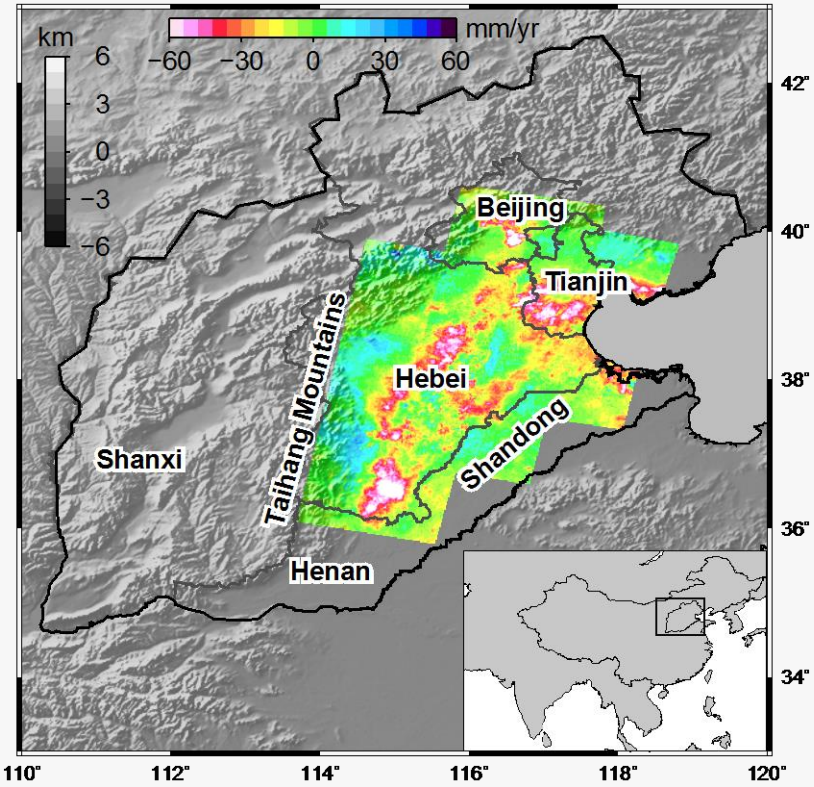

Observed subsidence rate: **-3.2** km$^3$/yr

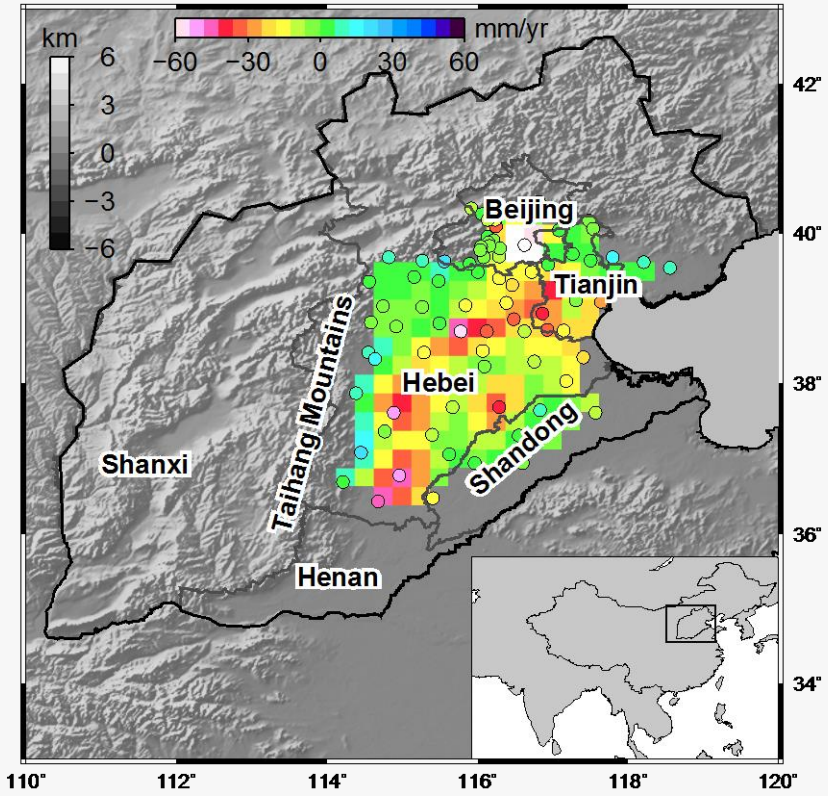
Underestimation effect **~2.0 times**

"Real" subsidence rate: **-6.4** km$^3$/yr

# Underestimate effect estimated from InSAR

## Linear trends of vertical deformation from InSAR (2012-2014)




"Real" signal from InSAR

**18.87 mm/yr**

~2.0 times

Simulated signal from sparse GPS

**9.47 mm/yr**

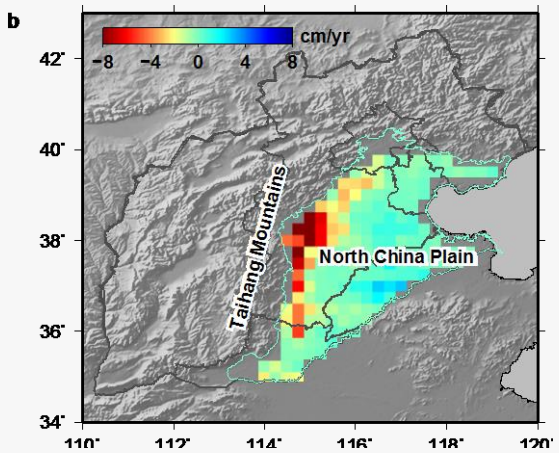
*InSAR data from Dr. ZHANG Yonghong*

# GWS budget in the North China Plain

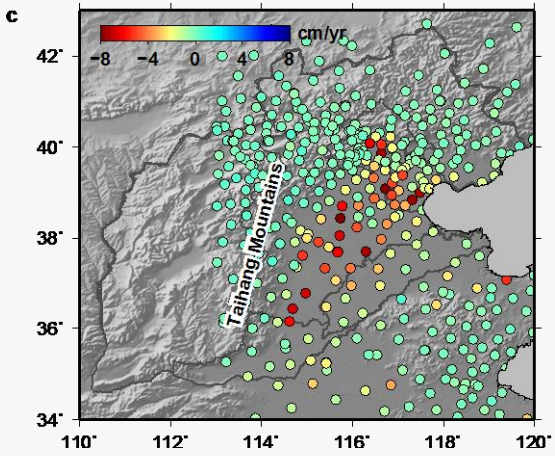
## GWS budget can be closed based on GRACE and GPS

| 2002-2014 | GWS depletion rate ($km^3/yr$) |
|---|---|
| Unconfined (GW obs./Bulletins) | -1.2 ~ -1.9 |
| Confined (GPS) | -6.4 |
| Total (GW obs./Bulletins + GPS) | **-7.6 ~ -8.3** |
| Total (GRACE) | **-8.4** ± 1.0 |

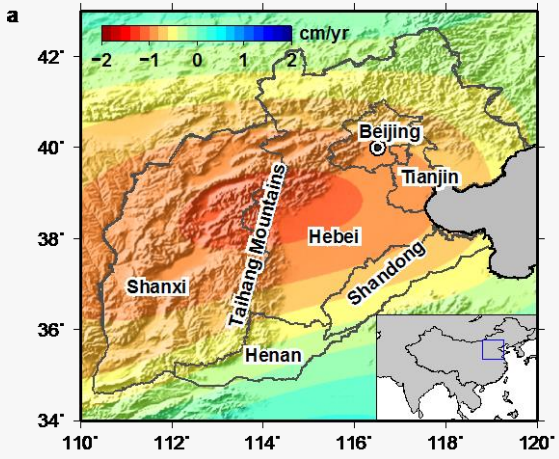
**GWS obs.**




**GPS**




**GRACE**

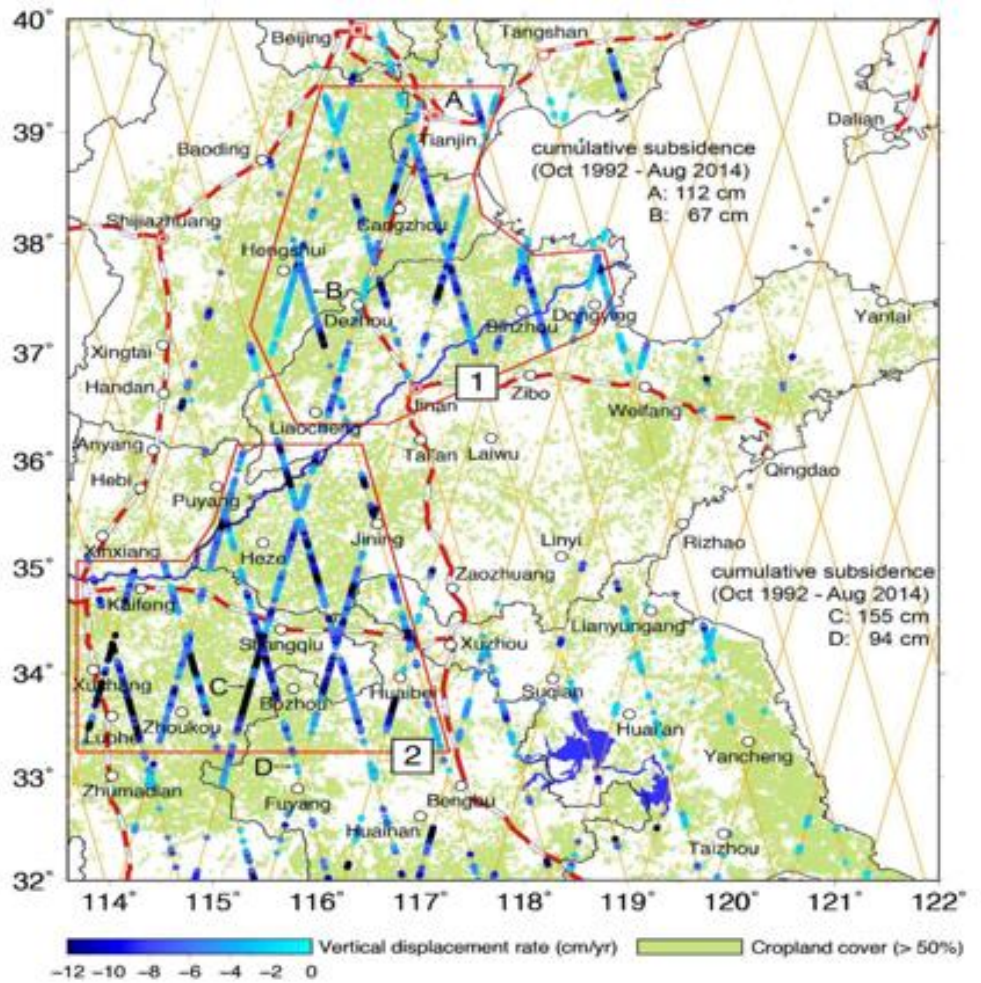


# Summary & Outlook

- On *seasonal* timescales, GRACE-derived GWS variations are well explained by the combined effect of groundwater abstraction due to *anthropogenic* irrigation activities and groundwater recharge from *natural* precipitation.
- On *seasonal* timescales, GRACE-derived GWS variations are dominated by groundwater changes in shallow *unconfined* aquifers.
- On *long-term* trend, the GRACE-derived GWS depletion rate is -8.4 $\pm$ 1.0 $km^3$/yr (i.e., -1.7 $\pm$ 0.2 cm/yr in equivalent water height) during 2002-2014, three quarters of which can be well explained by groundwater changes in deep *confined* aquifers observed by GPS.

# Summary & Outlook

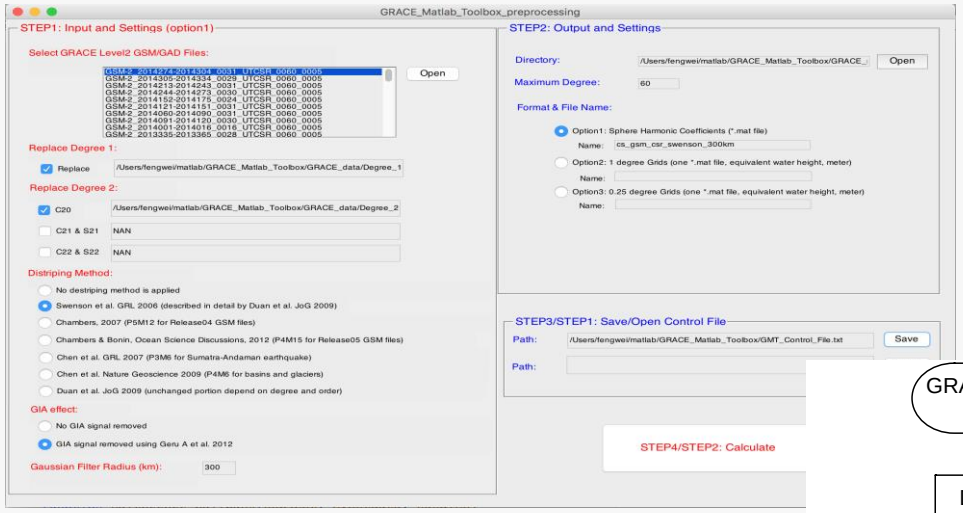
Land surface deformation from radar altimeter (Hwang et al. 2016)



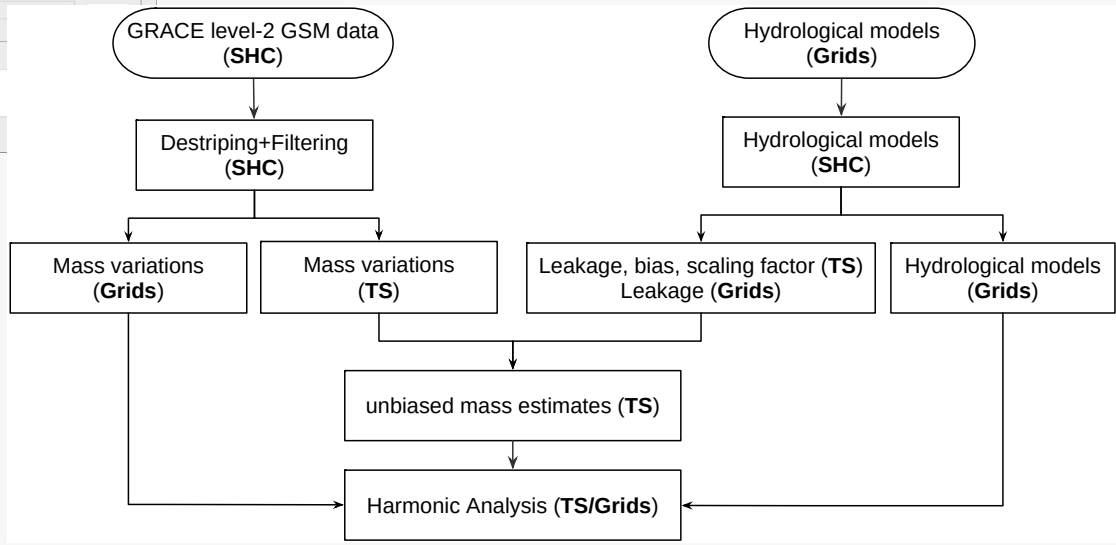

**Vertical displacement rates from ENVISAT**

# GRACE Matlab Toolbox

https://github.com/fengweiigg/GRACE_Matlab_Toolbox




Matlab GUIs to process GRACE level-2 products




Schematic workflow of GMT