The change of terrestrial water storage in North China observed by GRACE

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Outline

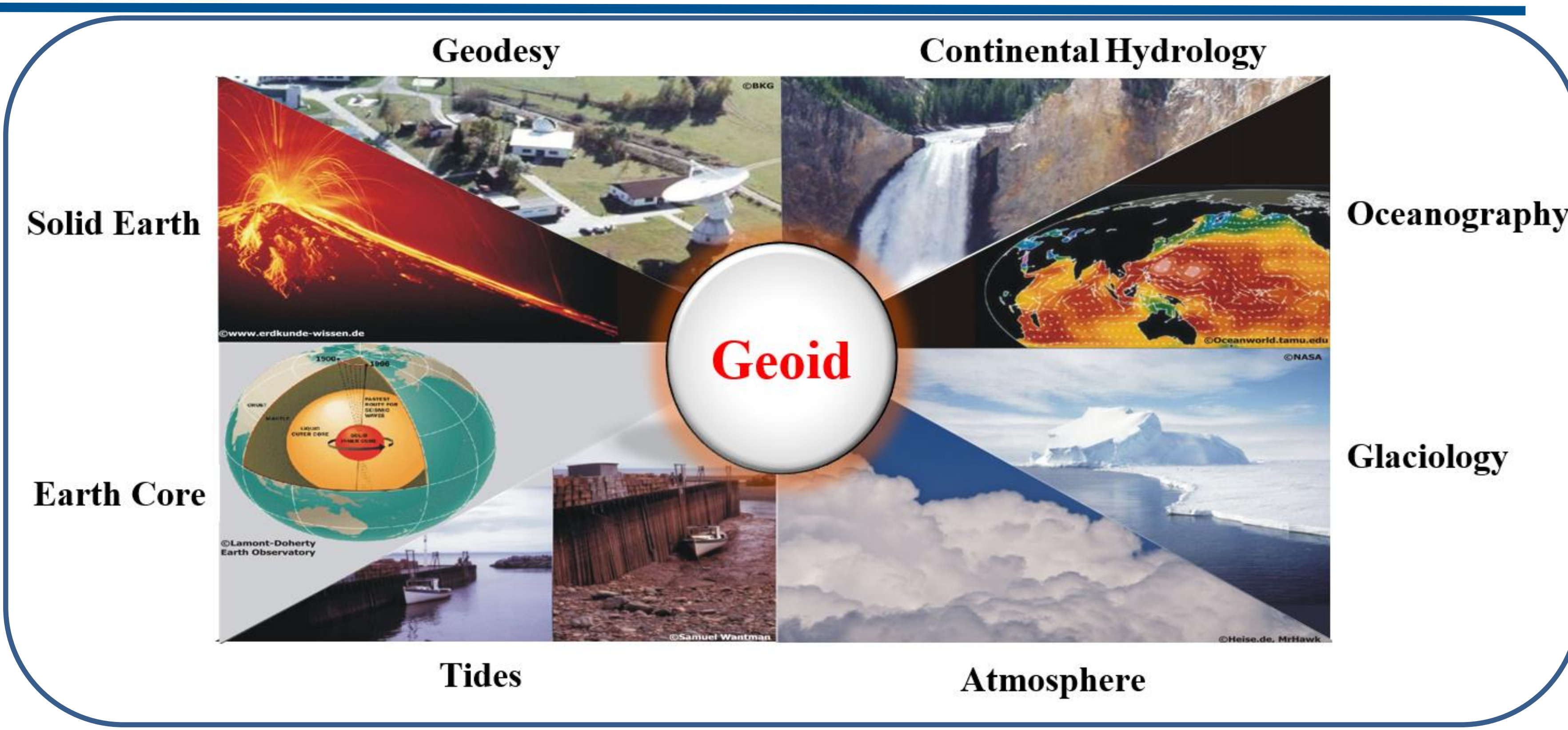
1. Introduction

2. The variation of terrestrial water storage from GRACE Mission

3. An example of TWS change in North China

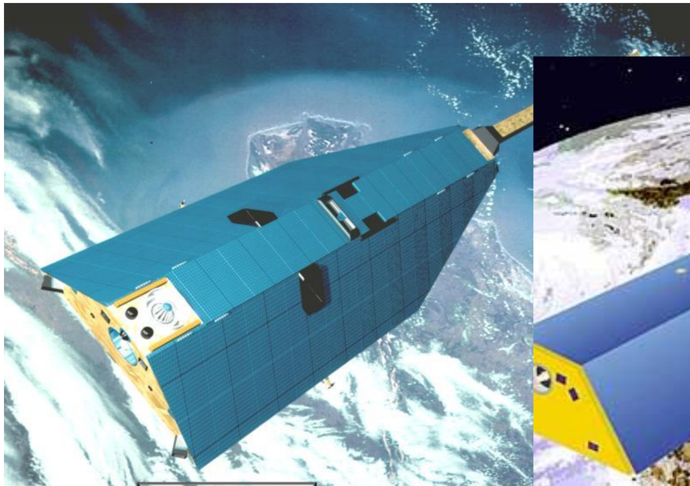
4.Conclusions

Earth’s gravity field

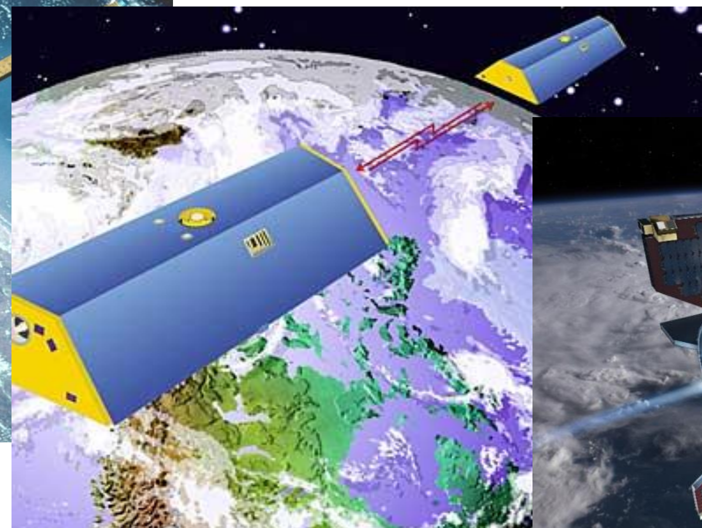


The Earth’s gravity field is reflection of space distribution and redistribution of the earth mass, for which transportation and redistribution in the earth system is important for world climate change, economy development and human society.

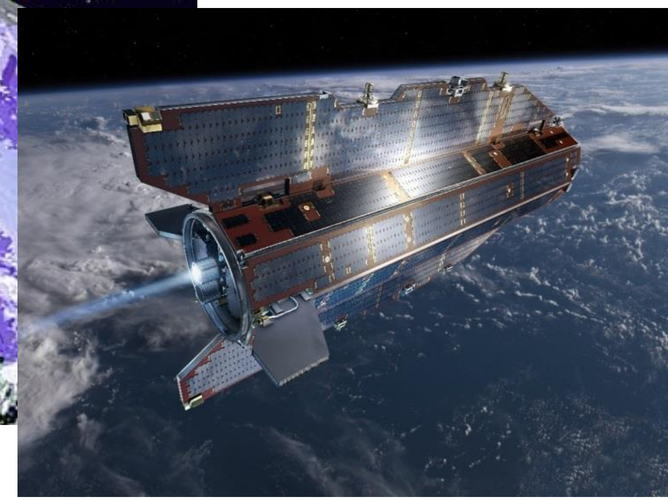
Gravity satellites



CHAMP



GRACE



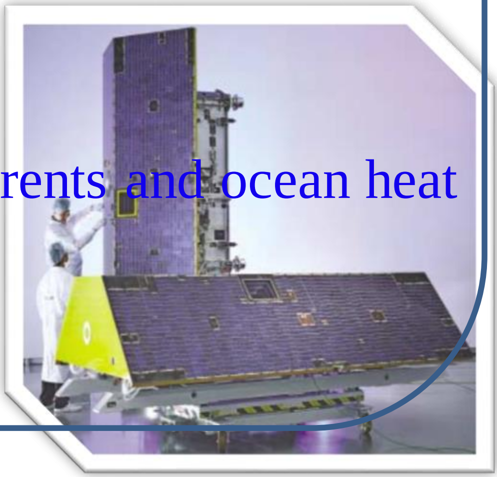
GOCE

The successful launches of the dedicated satellite gravity mission CHAMP (2000), GRACE (2002) and GOCE (2009) have revolutionized the mapping of the Earth's gravity field by space-borne observation techniques on a global scale.

The GRACE Mission

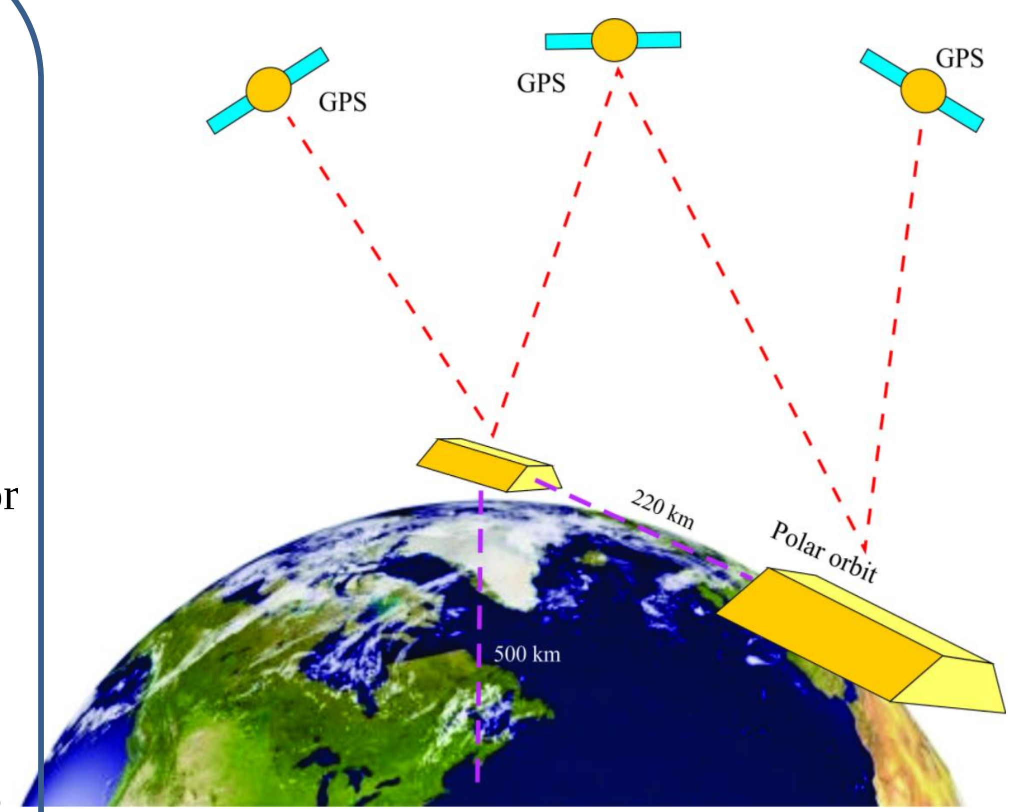
The Gravity Recovery And Climate Experiment（GRACE） objectives：

- To monitor changes in the storage of water and snow on the continents
- To measure changes in the sea-floor pressure
- To measure the mass balance of ice sheets and glaciers
- To study ocean mass changes
- To enable a better understanding of ocean surface currents and ocean heat transport



GRACE Overview

- Mission for gravity field determination (NASA+GFZ)
- Orbit altitude ca. 500 km
- Orbit inclination ca. 89°
- **Distance measurements between the satellites:K-band < 5 μ m, distance ca. 220 km**
- **GPS receiver** and **SLR reflector** for orbit determination
- **Accelerometers:** non-conservative forces (air drag, solar radiation pressure)
- **Orbits give information about the gravity field**



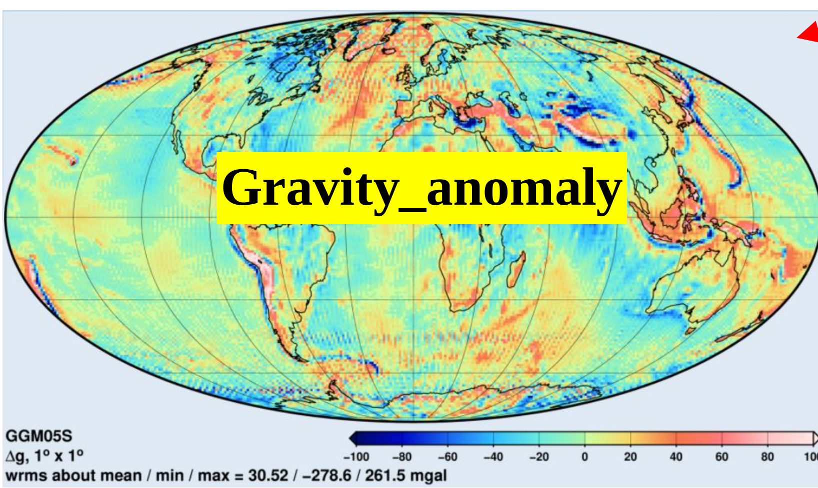
Overview of the GRACE satellite

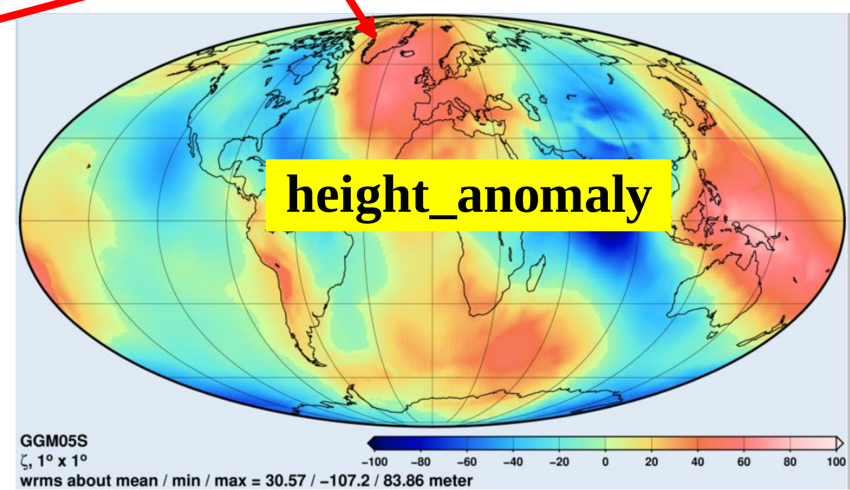
GRACE Main Products

- Time-variable gravity field solutions at approximately monthly intervals.
- In forms of fully normalized spherical harmonics C_{lm} and S_{lm} with degree l and order m up to 96.
- From three processing centers, CSR, GFZ, and JPL.

Include the short term (monthly and weekly) and static gravity field

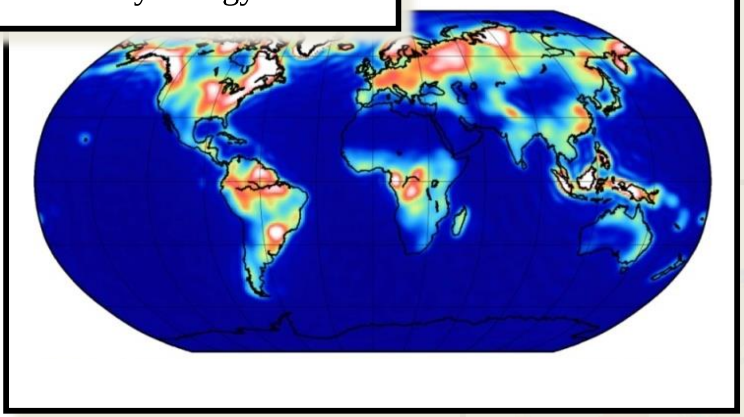
- Main data products（Level-0 、 Level-1, ……, Level-5 ）
- Long-term mean gravity fields from GRACE (e.g., GGM05S, ITU_GRACE16,…).



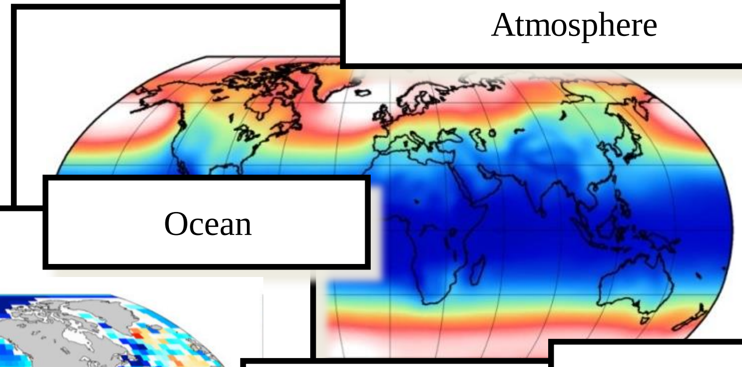


GRACE Applications

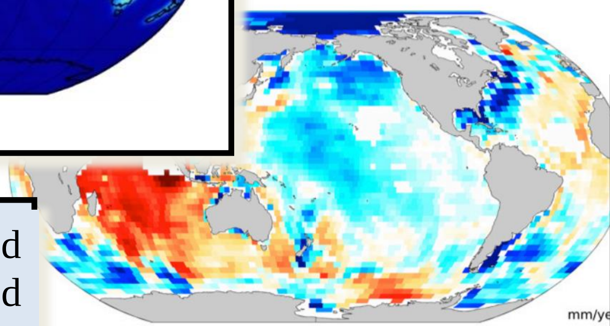
Hydrology



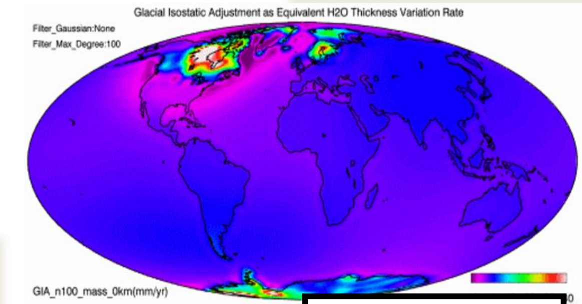
Atmosphere



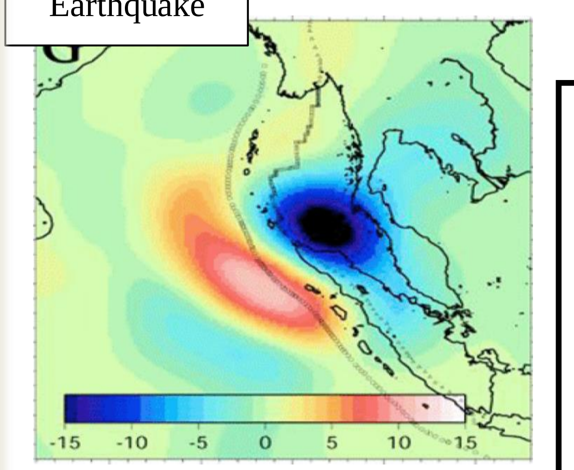
Ocean



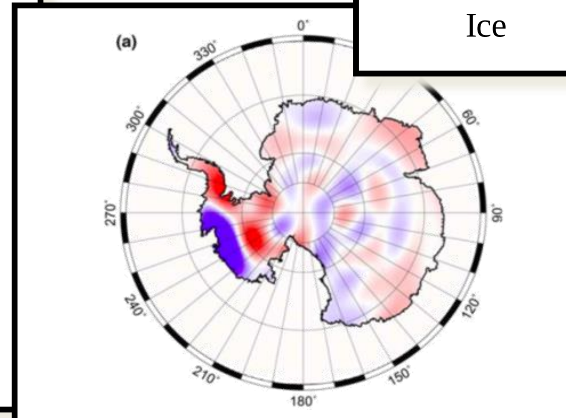
GIA



Earthquake

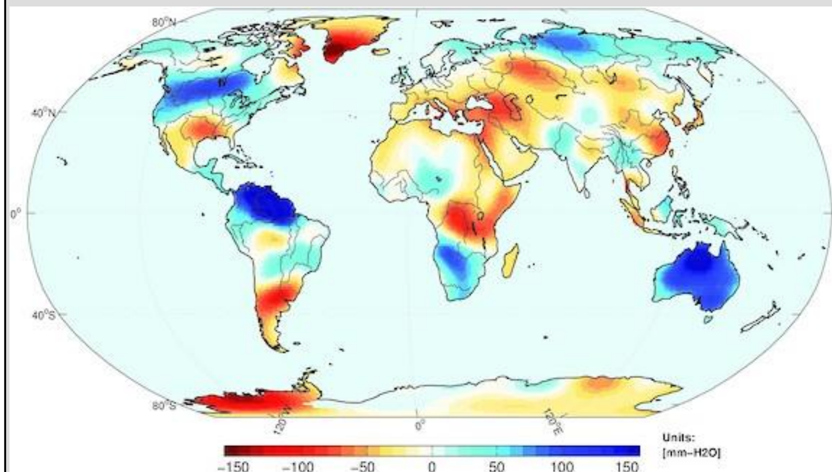


Ice



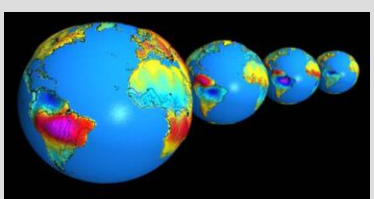
In addition to solid Earth, Atmosphere, and oceanography applications of the data, the relevance of GRACE for hydrology studies is abundant and expanding. GRACE is being used to estimate large-scale aquifer dynamics, improve drought and flood monitoring, and constrain regional hydrological estimates by assimilating GRACE terrestrial water storage observations into hydrological models.

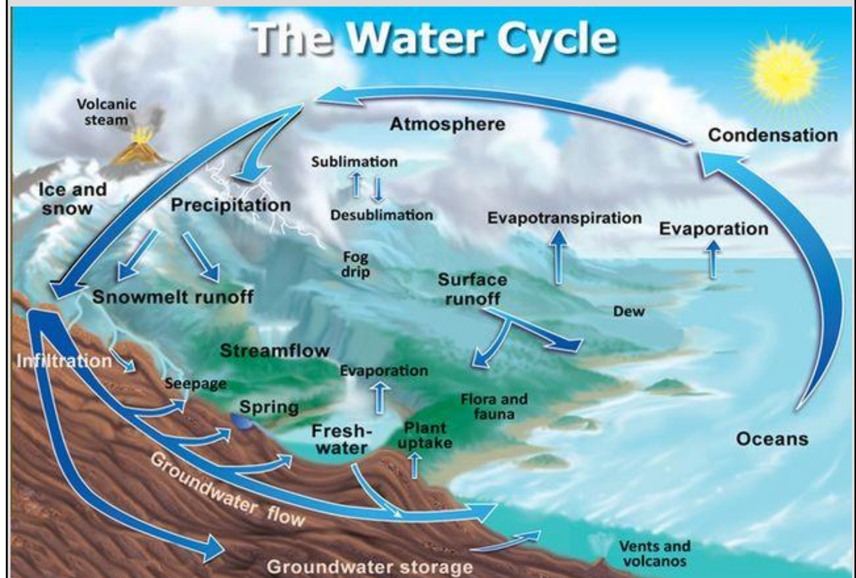
Water storage Changes from GRACE time-variable gravity



- Temporal variations of the gravity field of the Earth

- Water mass variations on the continents after removal of other mass components





ΔS = P - Q - E

ΔS:	**Water storage change**
P:	Precipitation
E:	Evaporation
Q:	Runoff

Only integrative and large-scale measurement of ΔS for hydrology

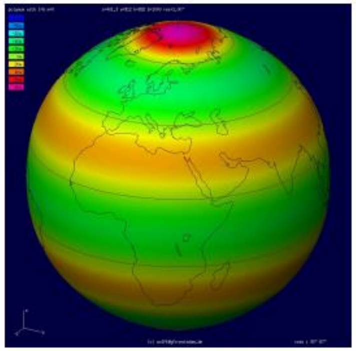
Change of gravity potential

Gravity potential often expressed in **Spherical Harmonics** $(\Delta C_{lm}, \Delta S_{lm})$

$$V(r,\theta,\lambda)=\frac{GM}{r}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\left(\frac{a}{r}\right)^{l}\overline{P}_{lm}(\cos\theta)[\Delta C_{lm}\cos(m\lambda)+\Delta S_{lm}\sin(m\lambda)]$$

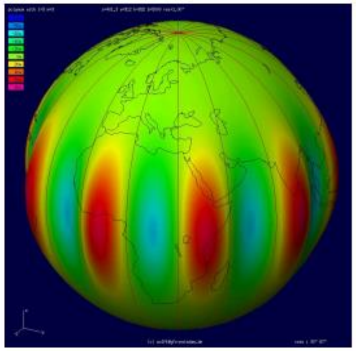
r, ***θ*** and ***λ*** are the radius, colatitude, and longitude coordinates
G, M are the gravitational constant and the mass of the Earth
a is the reference radius of the earth (6371 km)
l and **m** are spherical harmonic degree and order
$\overline{P}_{lm}(\cos\theta)$ is are normalized associated Legendre Polynomials

Zonal



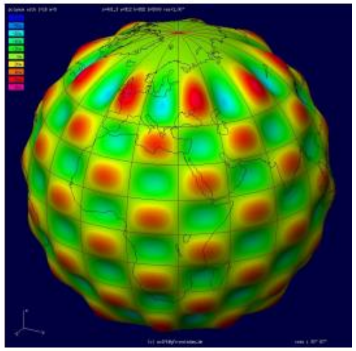
$(m=0)$

Sectorial



$(l=m)$

Tesseral



$(l \neq m \;\&\; m \neq 0)$

Surface Mass Density

- Geopotential at a fixed location is variable in time as masses move and are exchanged between the Earth system components
- With GRACE we assume the mass variation occurs in a thin layer

$$\Delta\sigma(\theta,\lambda) = \int_{thin\ layer} \Delta\rho(r,\theta,\lambda)dr$$

$\sigma(\theta, \lambda)$ is the surface mass density (typically expressed in cm w.e.)
1 cm water equivalent equal to 1 g/cm^2 (ρw = 1 g/cm^3)

- Changes in surface loads deform the underlying solid Earth:
  - Leads to a density anomaly at depth (not in thin layer)
  - Need to compensate for the elastic deformation of the Earth
  - Load Love number for degree l: k_l

$$\begin{Bmatrix} \Delta C_{lm}^{solid\ Earth} \\ \Delta S_{lm}^{solid\ Earth} \end{Bmatrix} = k_l \begin{Bmatrix} \Delta C_{lm}^{surface\ mass} \\ \Delta S_{lm}^{surface\ mass} \end{Bmatrix}$$

- Set of spherical harmonics from a surface mass density field:

$$\begin{Bmatrix} \Delta C_{lm} \\ \Delta S_{lm} \end{Bmatrix} = \frac{3\rho\omega}{4\pi a\rho_E}\frac{1+k_l}{(2l+1)}\int \Delta\sigma(\theta,\lambda)\bar{P}_{lm}(\cos\theta)\begin{Bmatrix} \cos(m\lambda) \\ \sin(m\lambda) \end{Bmatrix}\sin\theta d\theta d\lambda$$

Equations Relating Surface Mass to Gravity

- Equation below relates the change in surface mass density $\Delta\sigma(\theta,\lambda)$ from changes ΔC_{lm} and ΔS_{lm} in the geoid coefficients when expressed in spherical surface functions [Wahr et al., 1998]:

$$\Delta\sigma(\theta,\lambda)=\frac{a\rho_{ave}}{3}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\overline{P}_{lm}(\cos\theta)\frac{2l+1}{1+k_l}[\Delta C_{lm}\cos(m\lambda)+\Delta S_{lm}\sin(m\lambda)]$$

- Surface mass changes can be expressed in equivalent water thickness (EWH):

$$\Delta H(\theta,\lambda)=\frac{\Delta\sigma(\theta,\lambda)}{\rho_w}=\frac{a\rho_{ave}}{3\rho_w}\sum_{l=0}^{\infty}\sum_{m=0}^{l}\overline{P}_{lm}(\cos\theta)\frac{2l+1}{1+k_l}[\Delta C_{lm}\cos(m\lambda)+\Delta S_{lm}\sin(m\lambda)]$$

the density of water, 1000kg/m³

the average density of earth, 5517kg/m³

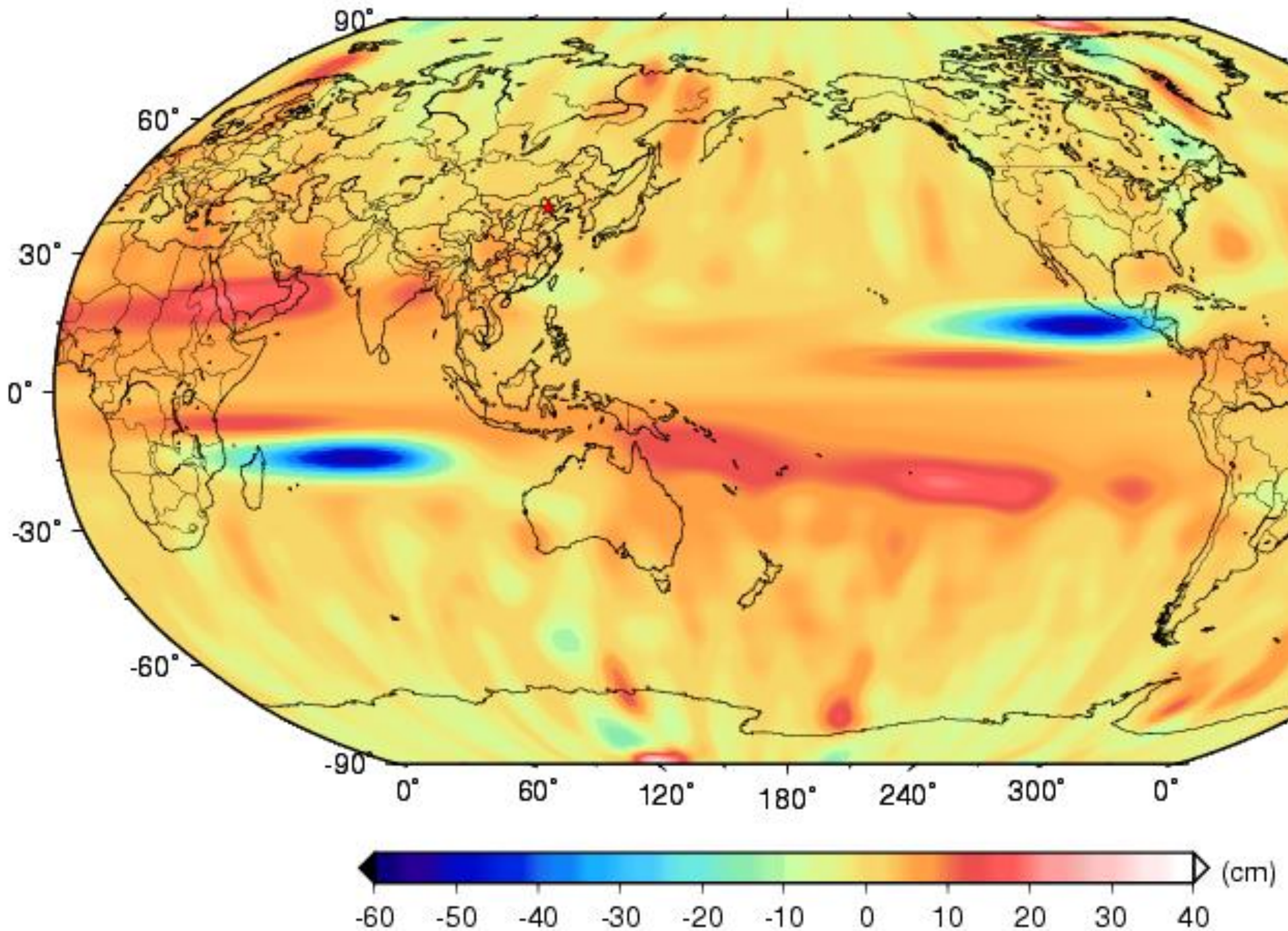
the fully-normalized Legendre

Load Love number of degree

Love number	
l	k_l
0	+0.000
[illegible]	+0.027
[illegible]	+0.303
3	-0.194
4	-0.132
5	-0.104
……	……

EWH derived from the GRACE products provides 'total water storage(TWS)'changes. Therefore, TWS is defined as the sum of all available water storage on and below the surface of the earth.

Technology: Filter



2011-07

Technology: Filter

Gauss-Filter

$W_{lm} = W_l$:

l – degree

$$W_l = \frac{1}{\sqrt{2l+1}} \int_0^{\pi} W(\alpha) \overline{P}_{l0}(\cos\alpha) \sin\alpha \, d\alpha$$

$$W(\alpha) = \frac{b}{2\pi} \frac{\exp[-b(1-\cos\alpha)]}{1-e^{-2b}}$$

$$b = \frac{\ln(2)}{(1-\cos(r/a))}$$

$$W_0 = \frac{1}{2\pi}$$

$$W_1 = \frac{1}{2\pi}\left[\frac{1+e^{-2b}}{1-e^{-2b}} - \frac{1}{b}\right]$$

...

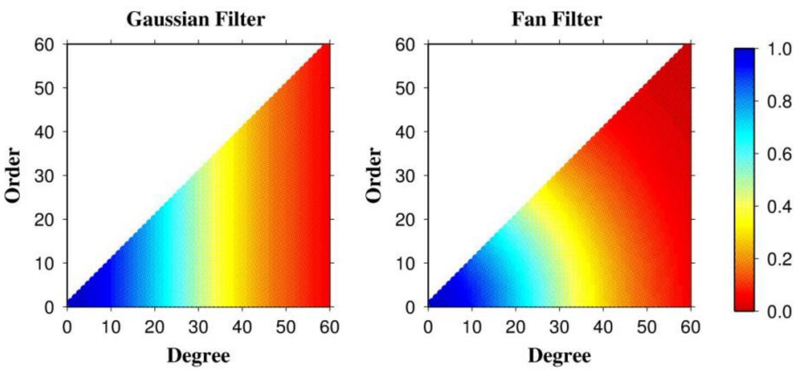
$$W_{l+1} = -\frac{2l+1}{b} W_l + W_{l-1}$$

Fan-Filter

Reduce high-frequency error:
Non-isotropy

$W_{lm} = W_l \cdot W_m$:

l – degree; m – order



Decorrelatted-Filter

Reduce system error:

when $m > N$,
$\Delta C_{l-4,m}, \Delta C_{l-2,m}, \Delta C_{l,m}, \Delta C_{l+2,m}, \Delta C_{l+4,m}$:

$$\Delta C_m(l) = a_0 + a_1 l + a_2 l^2 + a_3 l^3$$

$$\begin{cases} \Delta \hat{C}_{l,m} = \Delta C_{l,m} - \Delta C_m(l) \\ \Delta \hat{S}_{l,m} = \Delta S_{l,m} - \Delta S_m(l) \end{cases}$$

$$\Delta H(\theta,\lambda) = \frac{a\rho_{ave}}{3} \sum_{l=0}^{\infty} \frac{2l+1}{1+k_l} W_l \sum_{m=0}^{l} \overline{P}_{lm}(\cos\theta) \times W_m (\Delta \hat{C}_{lm} \cos(m\lambda) + \Delta \hat{S}_{lm} \sin(m\lambda))$$

Outline

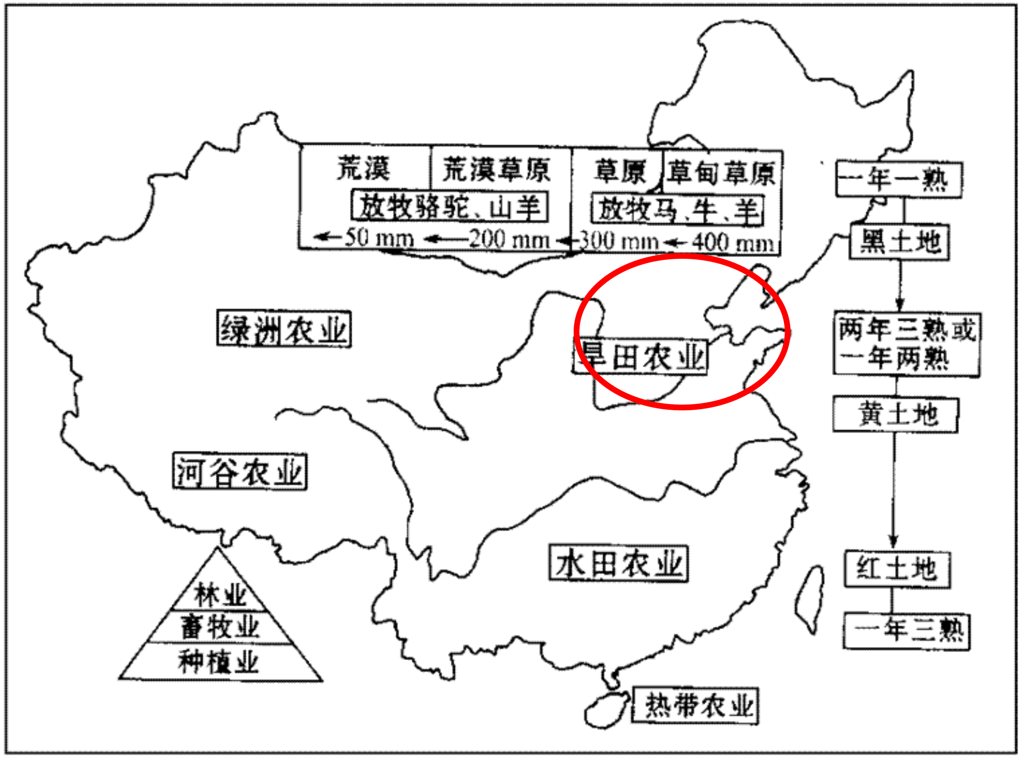
1. Introduction

2. The GRACE Mission and its Applications

3. The formulae for the water storage calculation

4. The water storage in North China

Importance of water storage in North China



- **Groundwater overexploitation**

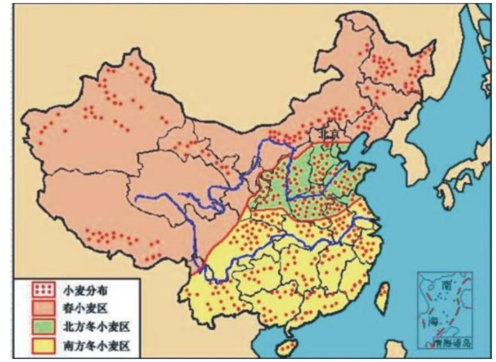
  Population density

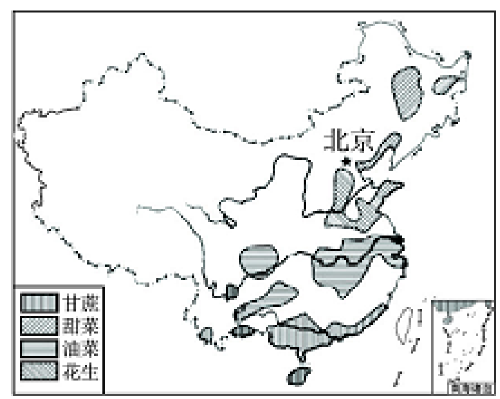
  Industrial water

  Crops demand (can be detected by GRACE)

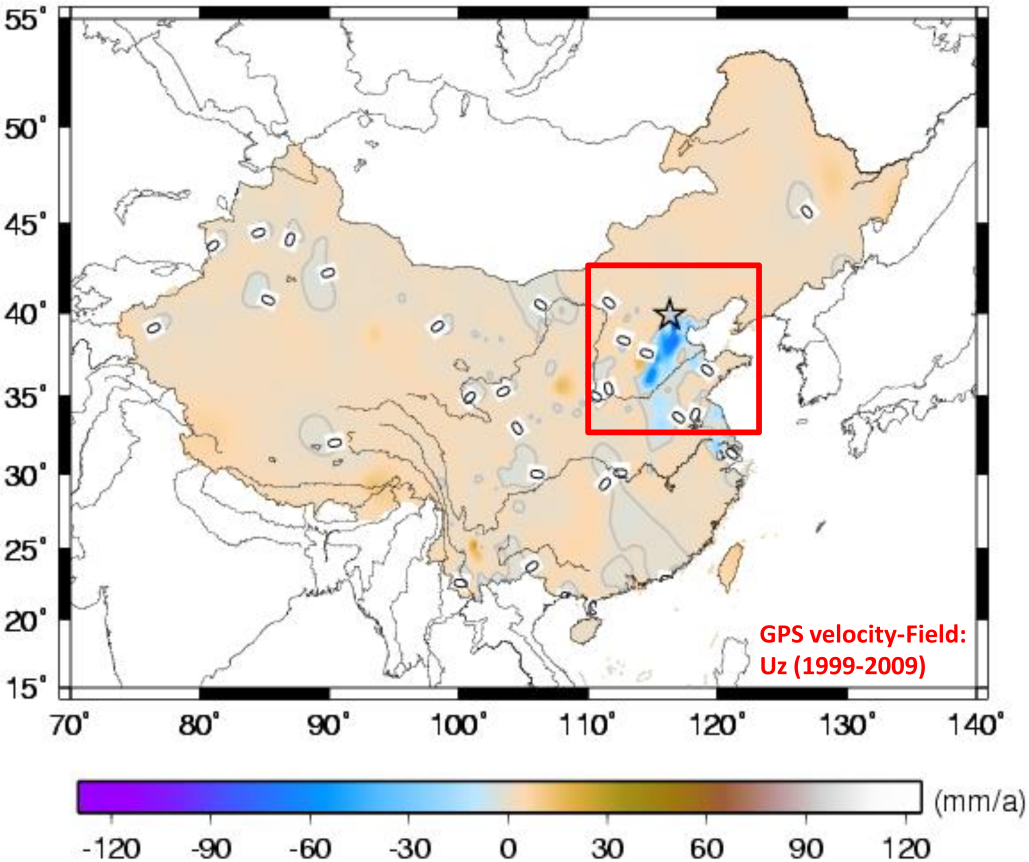
- **Reduced precipitation**

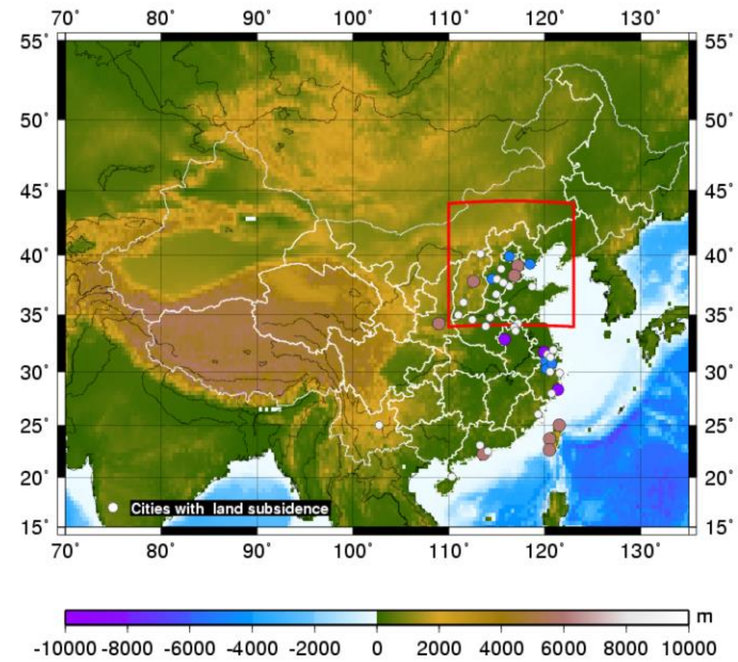
----Drought in North China

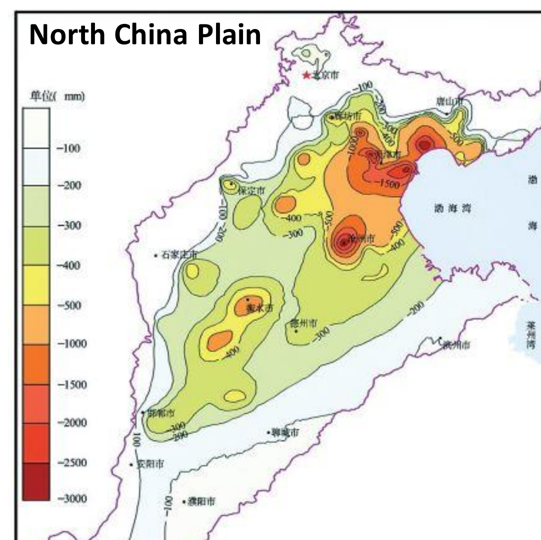




Cities with land subsidence in China







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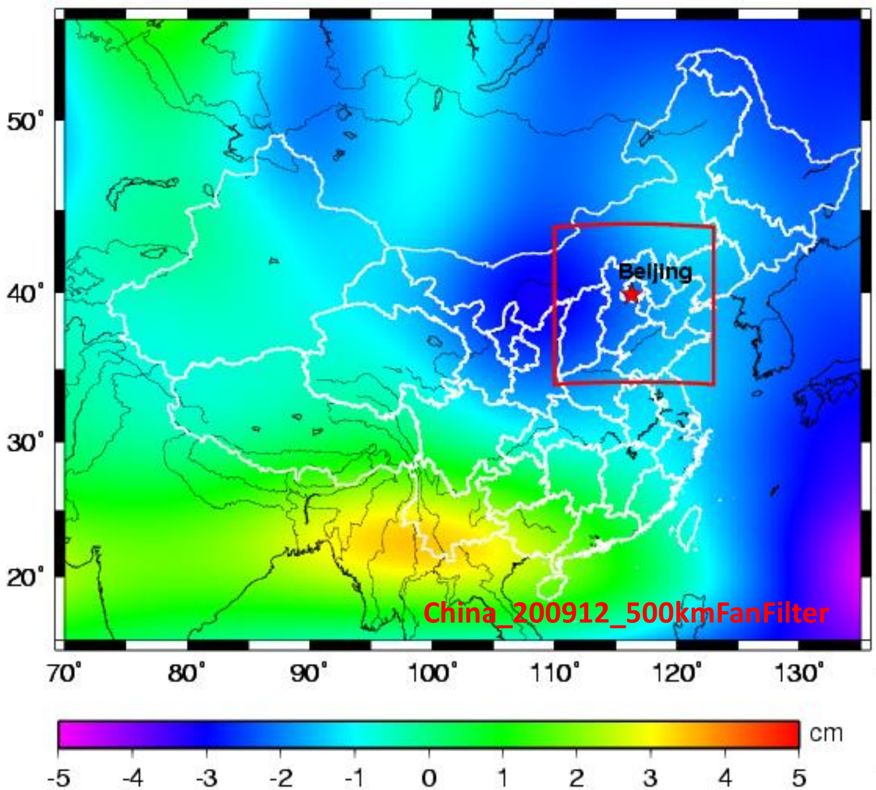
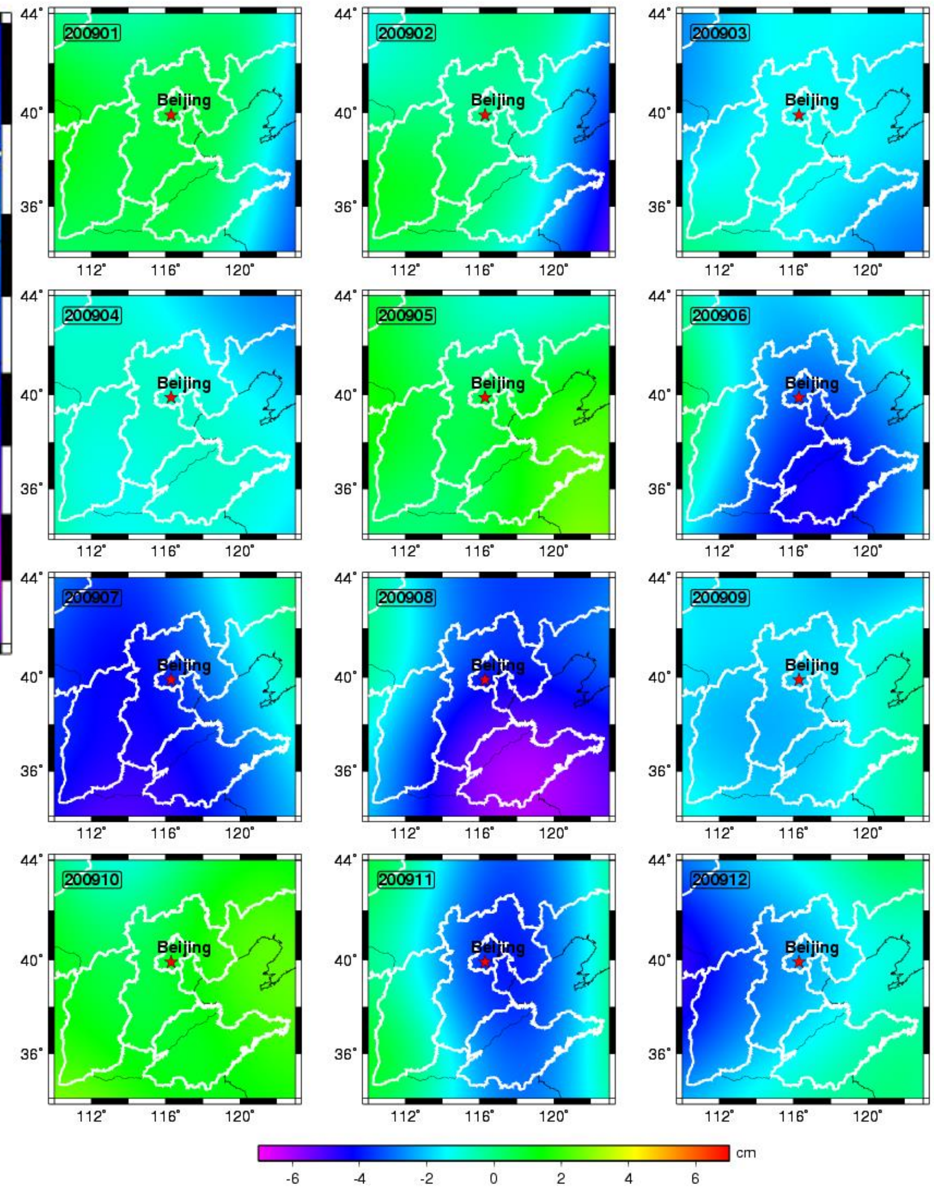
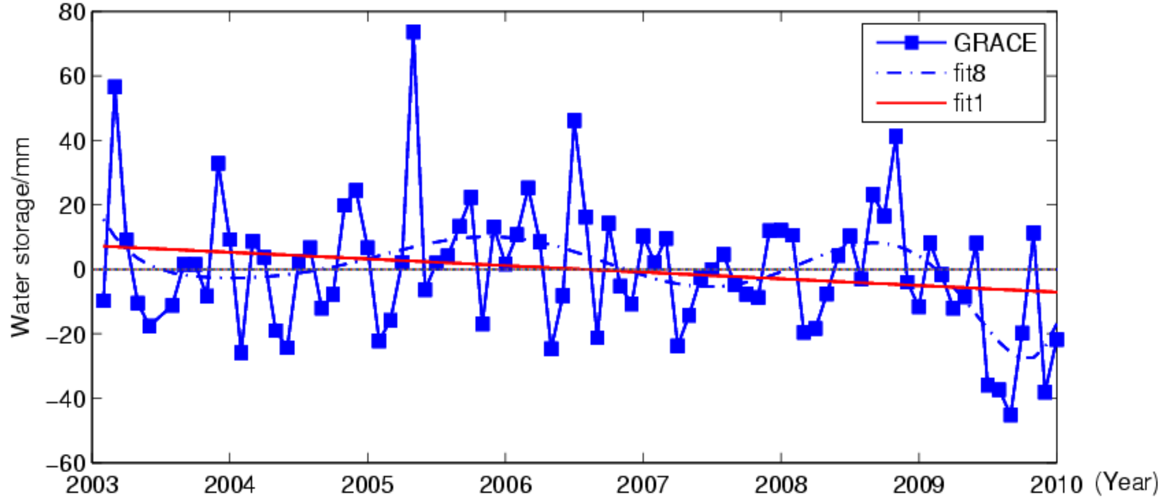
Monthly water storage variations inversed by GRACE data

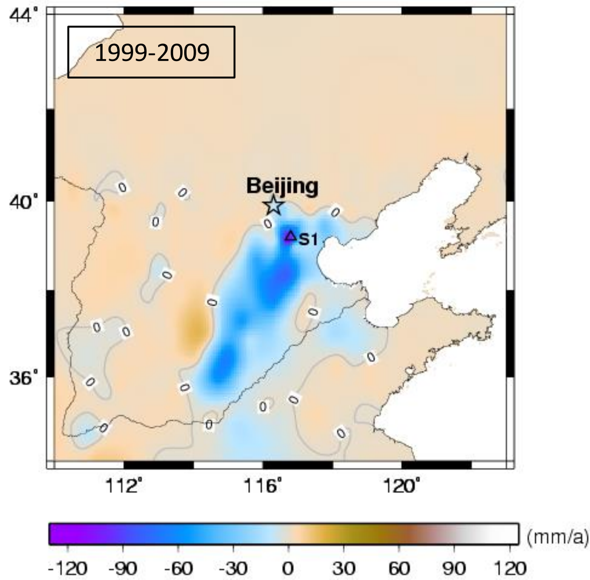


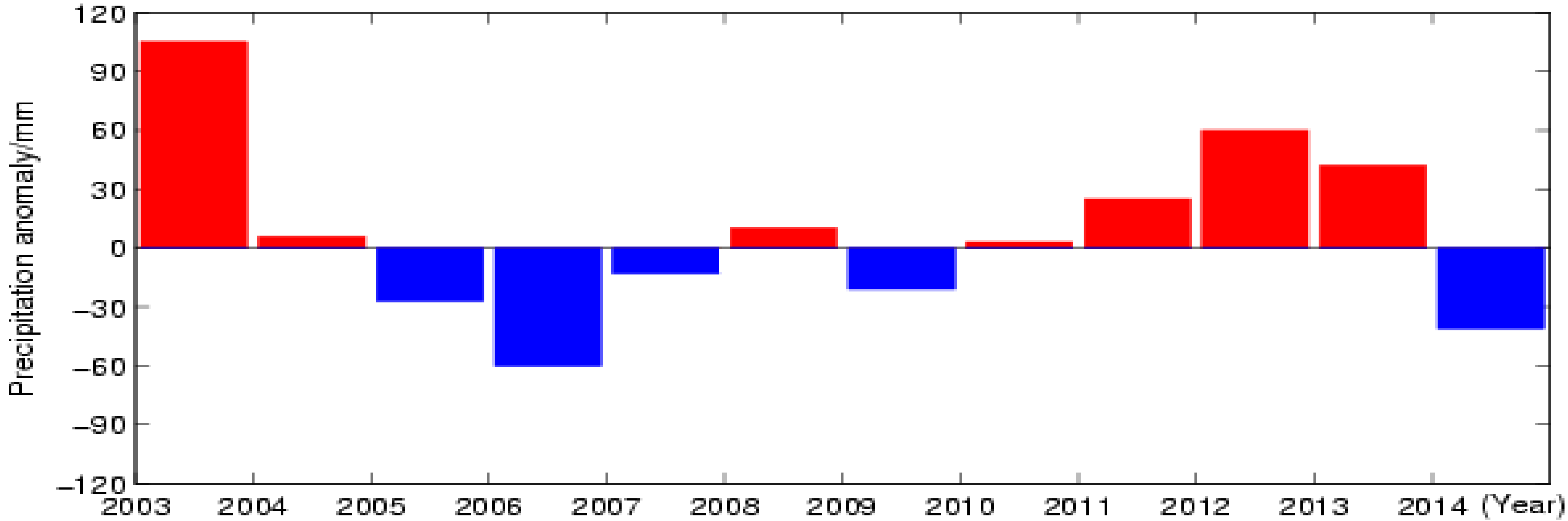


GRACE：Jan.2003-Dec.2009
For the whole country, 500km Fan-Filter
For local area, 350km Fan Filter
2009: severe drought

Water storage trend of S1 inversed by GRACE data







Near big subsidence, S1 selected to show the trend. 2004-2009 drought

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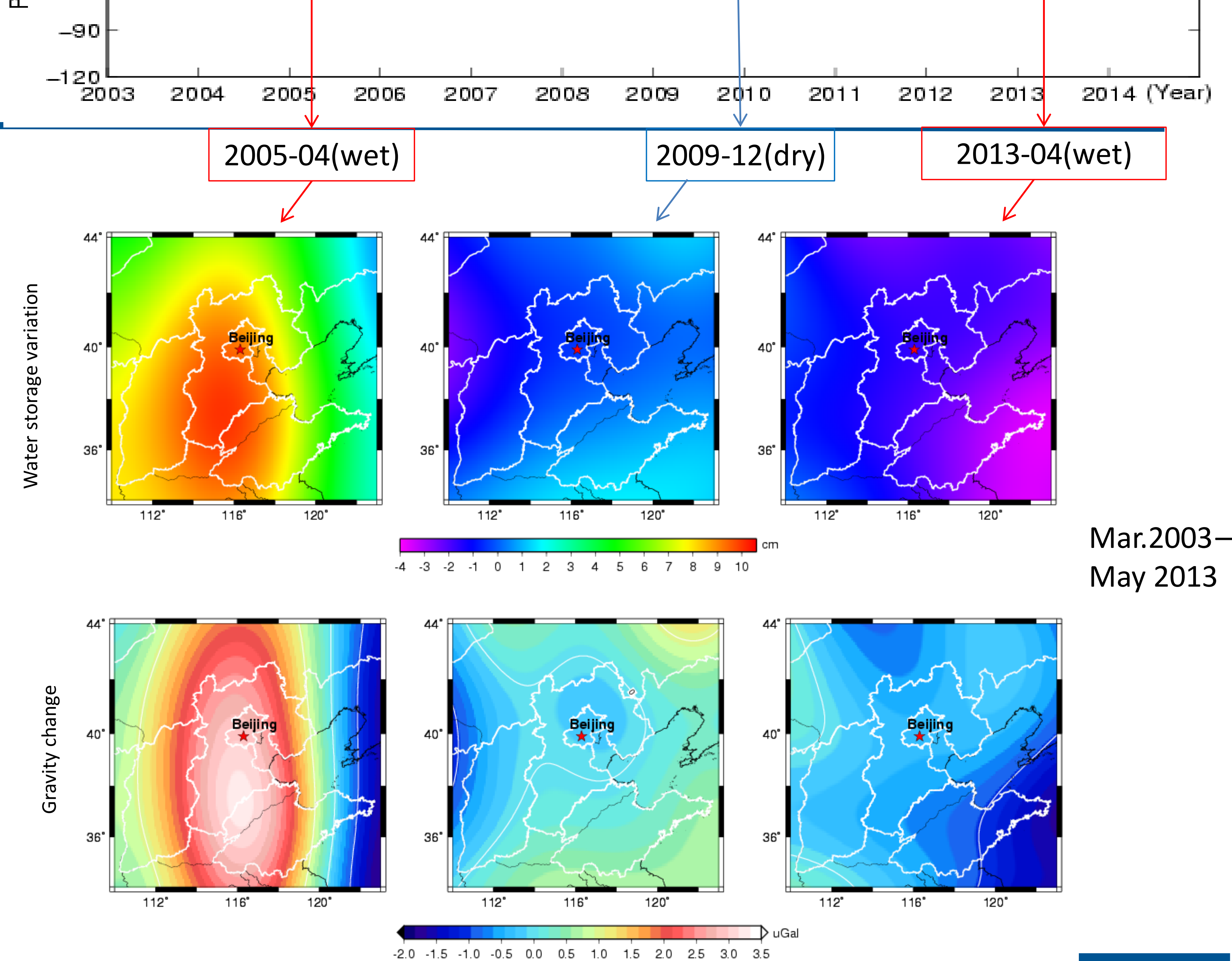
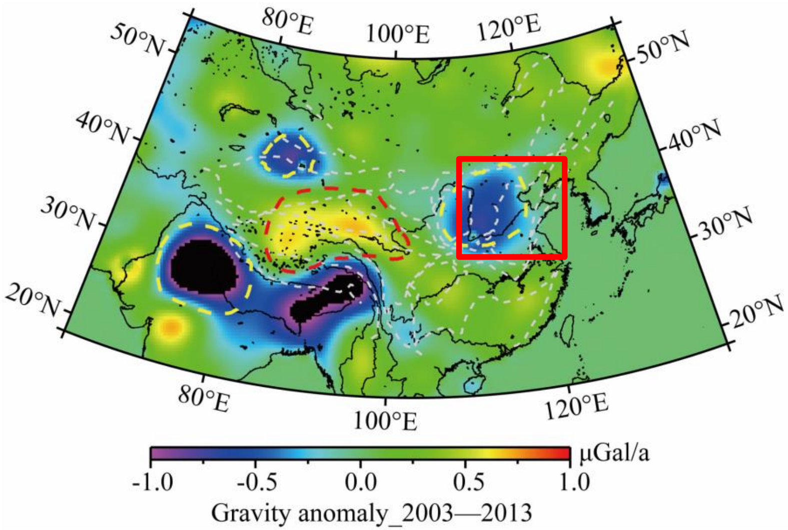
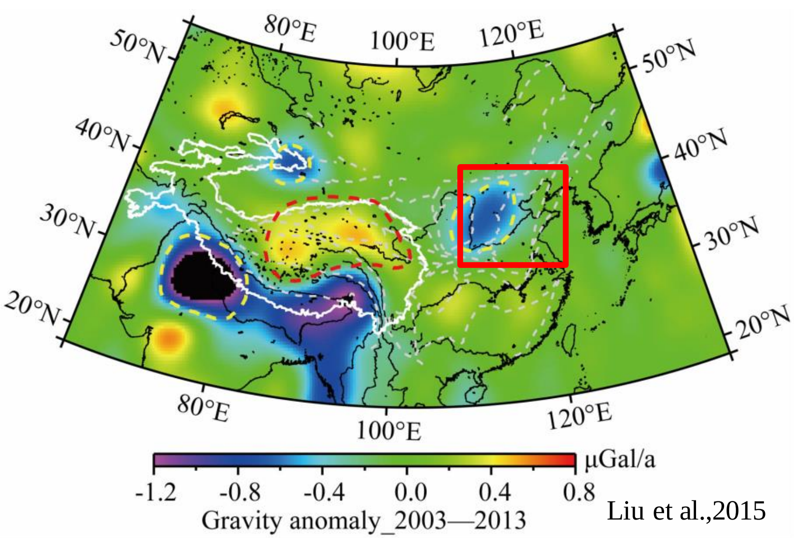

-90
-120
2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 (Year)
2005-04(wet)
2009-12(dry)
2013-04(wet)
Water storage variation
Gravity change
Beijing
44° 40° 36°
112° 116° 120°
cm
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10
uGal
-2.0 -1.5 -1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
Mar.2003–
May 2013

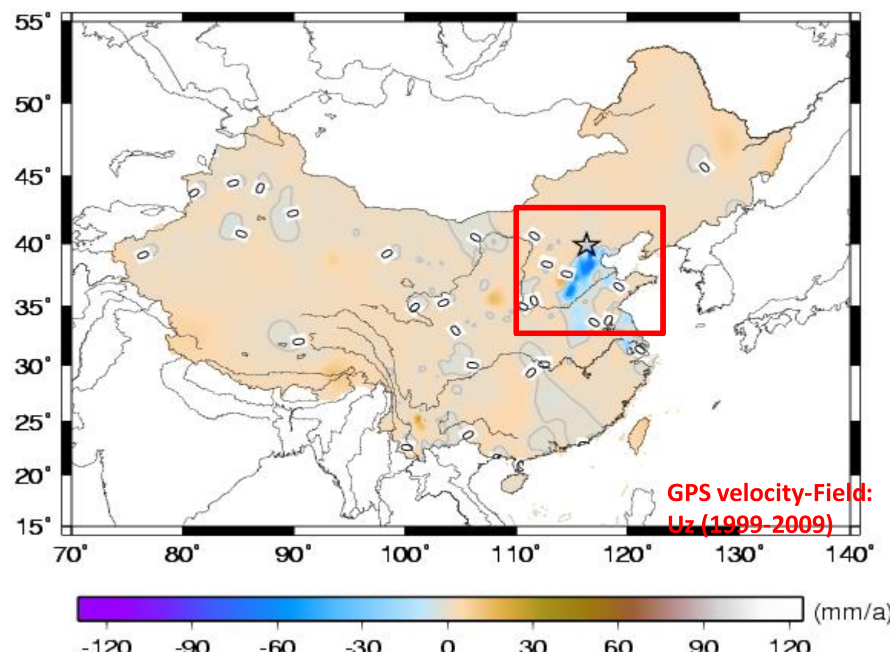
Gravity Anomaly in China (2003-2013)



Secular trends of gravity anomaly in China and adjacent area from GRACE solutions



Secular trends of gravity anomaly in China and adjacent area after the deduction of soil moisture and GIA effects from GRACE solutions



North China:
1. Water storage reduction is the main cause of gravity change.
2. The Land subsidence is also caused by the water storage reduction.

Upleft: Change of gravity anomalies
Downleft: Water storage reduction is the main cause of gravity change.
2. The Land subsidence is also caused by the water storage reduction.

Conclusions and Outlook

Conclusions:

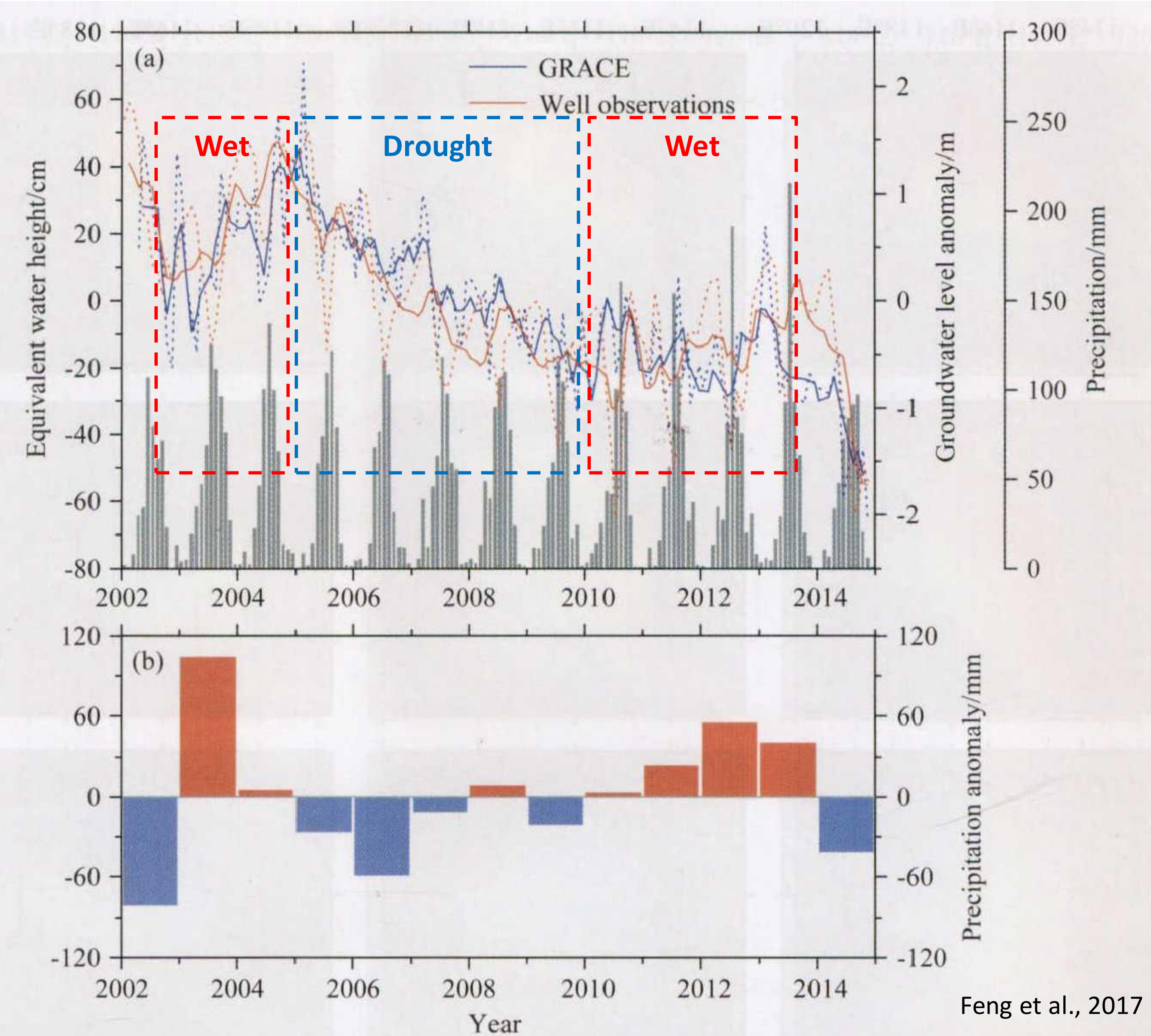
- GRACE can be used to derive the gravity change, the water storage, mass migration
- North China with serious land subsidence
- Precipitation reduce (2004-2009) and with a strong seasonal influence —Water Storage Reduction in North China

Outlook:

- The quantitative of the land subsidence of North China .
- How much the gravity change caused by the land susidence?

Thank you
for your attention!

Groundwater storage variations in North China Plain



Feng et al., 2017

1. Significant groundwater storage (GWS) long-term depletion in North China Plain(NCP);

2. The large GWS depletion in the confined aquifers of NCP;

3. Interannual storage variation are detected by GRACE and related to precipitation anomalies.