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

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

Gravity_anomaly

height_anomaly
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.
Temporal variations of the gravity field of the Earth

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

\[ \Delta S = P - Q - E \]

\( \Delta S \): Water storage change
P: Precipitation
E: Evaporation
Q: Runoff

Only integrative and large-scale measurement of \( \Delta S \) for hydrology
Change of gravity potential

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

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

- \( r, \theta \) and \( \lambda \) 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**

\( (l \neq m \& m \neq 0) \)
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:

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

\( \sigma(\theta, \lambda) \) is the surface mass density (typically expressed in cm w.e.).

1 cm water equivalent equal to 1 g/cm\(^2\) (\(\rho_w = 1 \text{ g/cm}^3\)).

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 \(l\): \(k_l\)

\[ \begin{bmatrix} \Delta C_{lm}^{\text{solid Earth}} \\ \Delta S_{lm}^{\text{solid Earth}} \end{bmatrix} = k_l \begin{bmatrix} \Delta C_{lm}^{\text{surface mass}} \\ \Delta S_{lm}^{\text{surface mass}} \end{bmatrix} \]

Set of spherical harmonics from a surface mass density field:

\[ \begin{bmatrix} \Delta C_{lm} \\ \Delta S_{lm} \end{bmatrix} = \frac{3 \rho \omega}{4 \pi \rho_E} \frac{1 + k_l}{(2l + 1)} \int \Delta \sigma(\theta, \lambda) \bar{P}_{lm}(\cos \theta) \begin{bmatrix} \cos(m\lambda) \\ \sin(m\lambda) \end{bmatrix} \sin \theta d\theta d\lambda \]
Equations Relating Surface Mass to Gravity

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

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

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

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

- 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.

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<th>Love number</th>
<th>$k_l$</th>
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<td>-0.104</td>
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<tr>
<td>......</td>
<td>......</td>
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</tbody>
</table>
Technology: Filter

### Gauss-Filter

\[ W_l = W_j : \]
\[ l – \text{degree} \]
\[ W_l = \frac{1}{\sqrt{2l+1}} \int_0^\pi W(\alpha) P_l(\cos \alpha) \sin \alpha \, d\alpha \]
\[ W(\alpha) = \frac{b}{2\pi} \exp[-b(1-\cos \alpha)] \frac{1-e^{-2b}}{1-\cos(r/a)} \]
\[ b = \ln(2) \]
\[ W_0 = \frac{1}{2\pi} \]
\[ W_1 = \frac{1}{2\pi} \left[ \frac{1+e^{-2b}}{1-e^{-2b}} - \frac{1}{b} \right] \]
\[ \ldots \]
\[ W_{l+1} = -\frac{2l+1}{b} W_l + W_{l-1} \]

### Fan-Filter

Reduce high-frequency error:
Non-isotropy

\[ W_{lm} = W_l \cdot W_m : \]
\[ l – \text{degree}; m – \text{order} \]

### Decorrelatated-Filter

Reduce system error:

when \( m > N \),

\[ \Delta C_{l-4,m}, \Delta C_{l-2,m}, \Delta C_{1,m}, \Delta C_{l+2,m}, \Delta C_{l+4,m} : \]
\[ \Delta C_m(l) = a_0 + a_1l + a_2l^2 + a_3l^3 \]

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

GPS velocity-Field: Uz (1999-2009)
Monthly water storage variations inversed by GRACE data

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
Water storage variation

Mar. 2003 — May 2013

Gravity change

2005-04 (wet)

2009-12 (dry)

2013-04 (wet)
Gravity Anomaly in China (2003-2013)

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

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

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.

Uplift: 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 subsidence?
Thank you for your attention!
Groundwater storage variations in North China Plain

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.