Advance Signal Processing Methods for the Estimation of Ground Water Storage Variations in Indus River Basin using GRACE Data

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Outline

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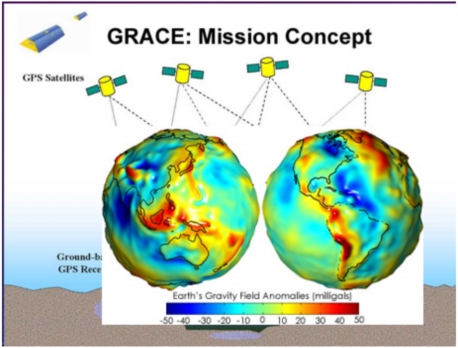
Aims and Goals

- To estimate the averaged ground water storage variations in the Indus river basin (IRB) over a period of 12 years using GRACE data along-wiith GLDAS.
- To develop a framework and toolbox for use and analysis of GRACE data.
- To design optimal localization function for the Indus river basin.

Outline

GRACE Overview



- Gravity Recovery and Climate Experiment.
- Jointly launched by NASA and DLR (German Aerospace Center) in March 2002.
- Provides spatio-temporal variations in the gravity field in the form of Stokes coefficients with monthly temporal resolution.
- The Stokes coefficients provide an (indirect) estimate of terrestrial water storage (TWS) variations.

Estimating surface density change of Earth using GRACE Data

- The surface density change of Earth, as a function of longitude and latitude, can be determined using Stokes coefficients (after de-noising and de-correlating).

$$\Delta\sigma(\theta,\phi) = \frac{a\,\rho_a}{3}\sum_{\ell=0}^{\infty}\sum_{m=0}^{\ell}\frac{2\,\ell+1}{1+k'_\ell}\Big[\Delta\overline{C}_{\ell m}\,X_\ell^m(\theta)\cos\theta + \Delta\overline{S}_{\ell m}\,X_\ell^m(\theta)\sin\theta\Big],$$

  where
  - $\Delta\sigma(\theta,\phi)$: surface density change.
  - a: average radius of the Earth (6371.008 km).
  - ρ_a: average density of the Earth ($5517\ \mathrm{kg/m^3}$).
  - k'_ℓ: load love number as a function of degree ℓ.
  - $X_\ell^m(\theta)$: associated Legendre function.
- The surface density change is proportional to the variations in water storage in the units of equivalent water height.

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Using GRACE Data alonq-with GLDAS Data

GRACE:

- Measures the variations in TWS (includes all forms of water on the surface of the Earth and underground water reservoirs).
- **Major causes of TWS variations:**
  - Precipitation stored as snow.
  - Water penetrated into the ground.
  - Water evaporated or departed the basin as stream flow.
  - Water pumped out from natural underground water reservoirs.

GLDAS:

- Global Land Data Assimilation System.
- Uses advance land surface modeling and data assimilation techniques to generate optimal fields of land surface states (e.g. soil moisture) and fluxes (e.g. evapotranspiration).

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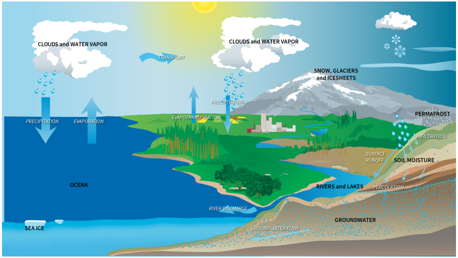

Water Balance Equation:

$$\Delta\mathrm{GWS} \approx \Delta\mathrm{TWS}_{\mathrm{GRACE}} - \Delta\mathrm{SWE}_{\mathrm{GLDAS}} - \Delta\mathrm{SMS}_{\mathrm{GLDAS}}$$

where,

- TWS: terrestrial water storage
- GWS: ground water storage
- SWE: snow water equivalent
- SMS: soil moisture storage

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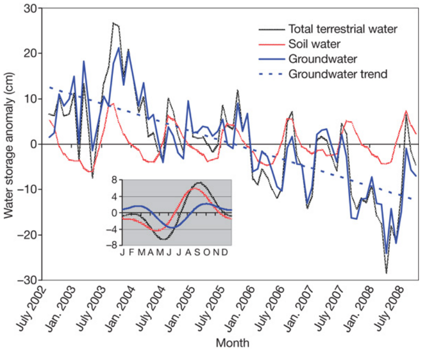
Satellite-Based Estimates of Groundwater Depletion in India



- [1]Measured over Rajasthan, Punjab and Haryana (including Delhi).
- Analyzed yearly variations in GWS from April 2002 to June 2008.
- Uses GRACE data to estimate ΔTWS and GLDAS data estimate soil water storage variations. Then uses water balance equation to estimate ΔGWS.
- **Results:** GWS is being depleted at a mean rate of $4.0 \pm 1.0 \mathrm{cm\,yr}^{-1}$ equivalent height of water.

[1] M. Rodell, I. Velicogna, J.S. Famiglietti, Satellite-based estimates of groundwater depletion in India. Nature, 460(7258), 999–1002, 2009.

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Framework - Methodology

Overview:

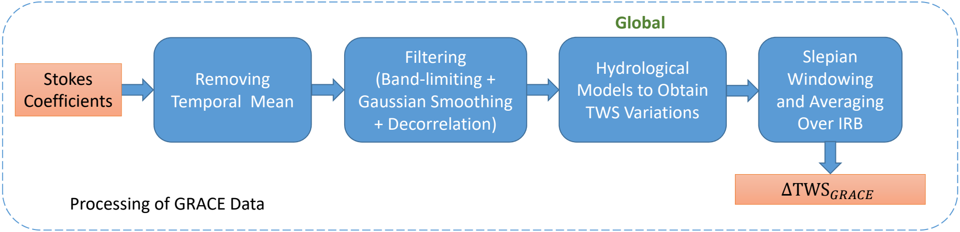

Figure: Framework: Processing of GRACE data

- We used monthly GRACE data from 2005 to 2015.
- First of all the temporal mean is removed from each monthly data of Stokes coefficients to obtain gravitational anomalies.
- Band-limited the Stokes coefficients at spherical harmonic degree $L = 61$.
- Filtered the Stokes coefficients to remove stripping noise (de-correlating filter).

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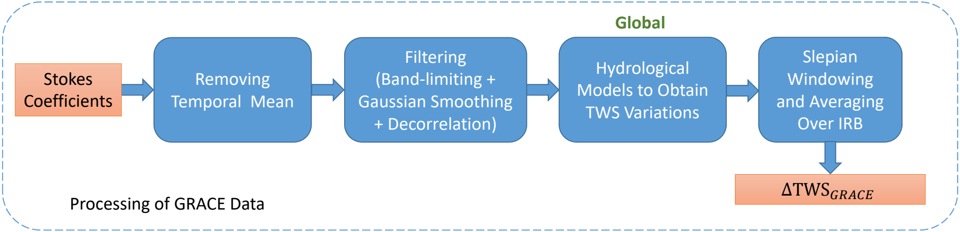

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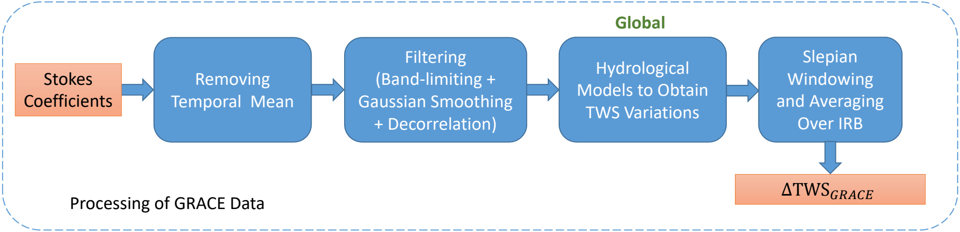


Figure: Framework: Processing of GRACE data

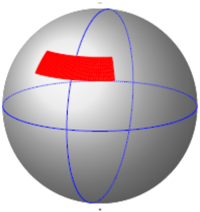
- A Gaussian smoothing filter (800 km radius) is applied.
- The surface density change of Earth can be re-written in terms of spherical harmonics as

$$\Delta\sigma(\theta,\phi) = \frac{a\,\rho_a}{3}\sum_{\ell=0}^{\infty}\sum_{m=0}^{\ell}\frac{2\,\ell+1}{1+k'_\ell}\Delta(f)_\ell^m\,Y_\ell^m(\theta,\phi),$$

where $Y_\ell^m(\theta,\phi)$: the spherical harmonics and $(f)_\ell^m$ are the spherical harmonic coefficients obtained from GRACE.

Framework - Optimal Window Design

- We consider Pakistan map as a region to approximate IRB in our study.
- We design optimal window with simultaneous optimal concentration in spatial and spectral (harmonic) domain.
- **Design**: Solve Slepian spatial-spectral concentration problem.
- Approximate the region with 44 limited colatitude-longitude spatial regions of the form:



- Computed the Slepian functions (band-limited at $L = 61$ and optimally concentrated inside the boundaries of Pakistan) using the analytical formulation for limited colatitude-longitude spatial region developed very recently[2].

[2] A. P. Bates, Z. Khalid and R. A. Kennedy, "Slepian Spatial-Spectral Concentration Problem on the Sphere: Analytical Formulation for Limited ColatitudeLongitude Spatial Region," in IEEE Transactions on Signal Processing, vol. 65, no. 6, pp. 1527-1537, March15, 15 2017.

TWS Variations

- Using the Slepian window, we estimated the mean terrestrial water storage (TWS) variations in the IRB.

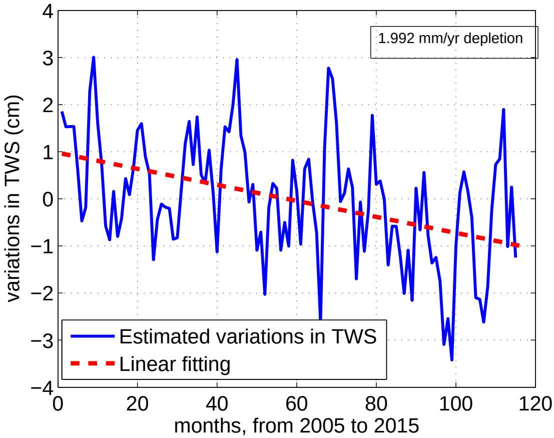
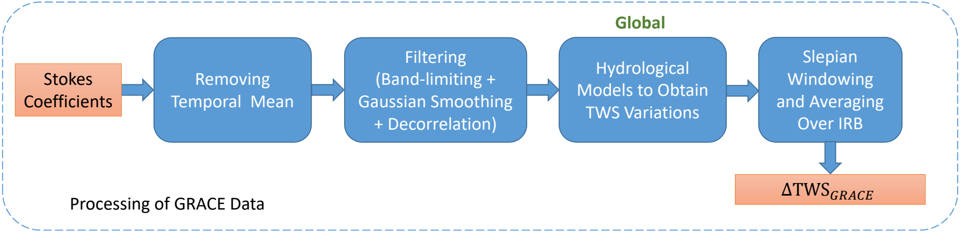
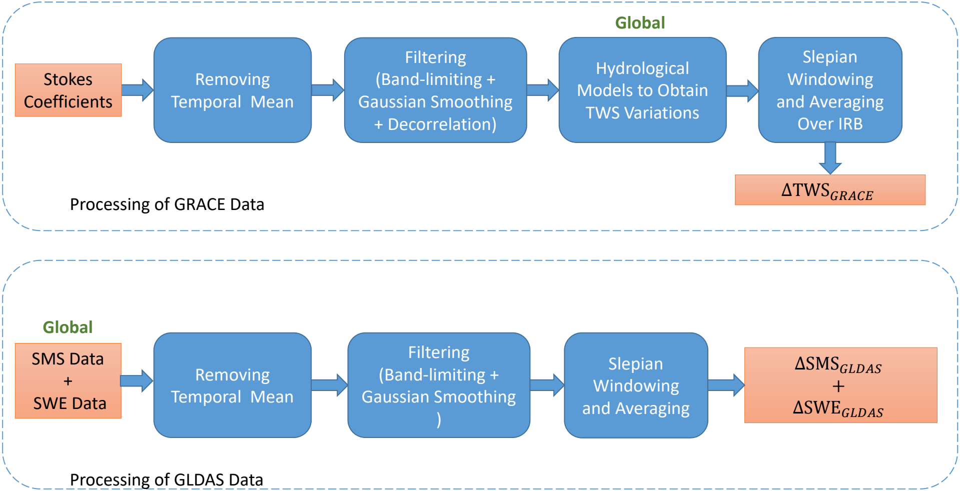


Figure: Estimated variations in TWS in Indus river basin for a period of 10 years (approximately) from 2005 to 2015

GWS Variations using GLDAS Data



GWS Variations using GLDAS Data



$$\Delta GWS = \Delta TWS_{GRACE} - (\Delta SWE_{GLDAS} + \Delta SMS_{GLDAS})$$

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Future Work

- Improving estimation accuracy using ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) Mission data.
- Analysis of satellite laser ranging (SLR) data indicates that the Earths dynamic oblateness (J_2) has undergone significant variations during the past 28 years (Cheng et al.2004).
- In order to increase the accuracy of our results in future works, we will be using another data-set from satellite laser ranging (SLR) to correct the Stokes coefficient $\overline{C}_{20}$ which is showing unreasonable variability.

- Questions?