Modeling deformation induced by seasonal variations of continental water in the Himalaya region: sensitivity to Earth elastic structure

K. Chanard[1], J.P. Avouac[1], J. Genrich[1] & G. Ramillien[2]
[1] Tectonics Observatory, California Institute of Technology, Pasadena, California, USA
[2] Géophysique Environnement Toulouse, FRANCE

> Abstract

Strong seasonal variations of horizontal and vertical positions are observed on GPS times series from stations located in Nepal, India and Tibet (China). We demonstrate that this geodetic deformation is induced by seasonal variations of continental water storage driven by the Monsoon. For this purpose, we use satellite data from the Gravity Recovery and Climate Experiment (GRACE) to determine the time evolution of surface loading. We compute the expected geodetic deformation assuming a perfectly elastic Earth model. We consider Green's functions, describing the surface deformation response to a point load, for an elastic homogeneous half-space model and for a layered non-rotating spherical Earth model based on the Preliminary Reference Earth Model (PREM) and a local seismic velocity model. The amplitude and phase of the seasonal variation of the vertical and horizontal geodetic positions can be jointly adjusted only with the layered Earth model while an elastic half-space appears to fail. The study emphasizes the importance of using a realistic Earth elastic structure to model surface displacements induced by surface loading. The study also shows that the modeling of geodetic seasonal variations provides a way to probe the Elastic structure of the Earth, even in the absence of direct measurements of surface load variations.

> GPS and GRACE data

1. GPS dataset

- 26 continuous GPS stations (IGS China & India, Nepal network),
- Daily station positions computed with GAMIT/GLOBK processing software,
- GMF model for tropospheric mapping function and tropospheric gradients,
- 12 reference stations to obtain a loosely constrained regional solution,
- Time series detrended by removal of best fitting linear trend.

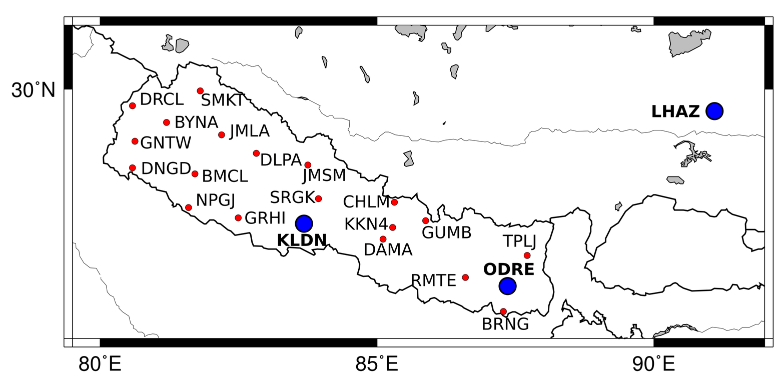

FIG. 1: Location of cGPS in Nepal used in this study (Blue dots show cGPS stations for which time series are plotted in FIG. 4 and 7)

2. Continental water mass derived from GRACE Level-2 solutions

Global mapping of gravity field variations

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Access to redistributions of surface water mass (atmosphere, oceans, continental water storage)

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Gravitational contributions of known time-varying phenomena removed

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Conversion into geoid and continental water mass coefficients (expressed in mm of equivalent-water height)

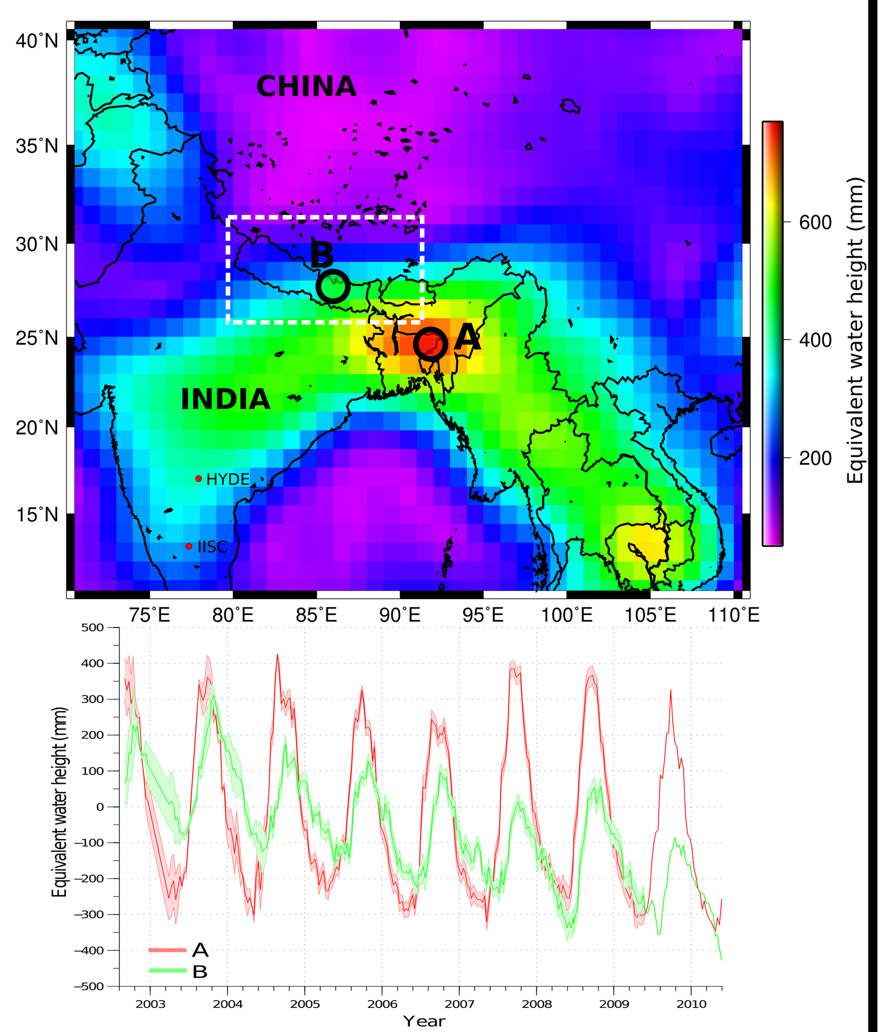

FIG. 2: Peak to peak surface load variations derived from GRACE (2007). A and B: location of the surface load time-series plotted

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> Modeling of seasonal ground deformation induced by surface load variations

THE "TRAMPOLINE" EFFECT

SUMMER WINTER

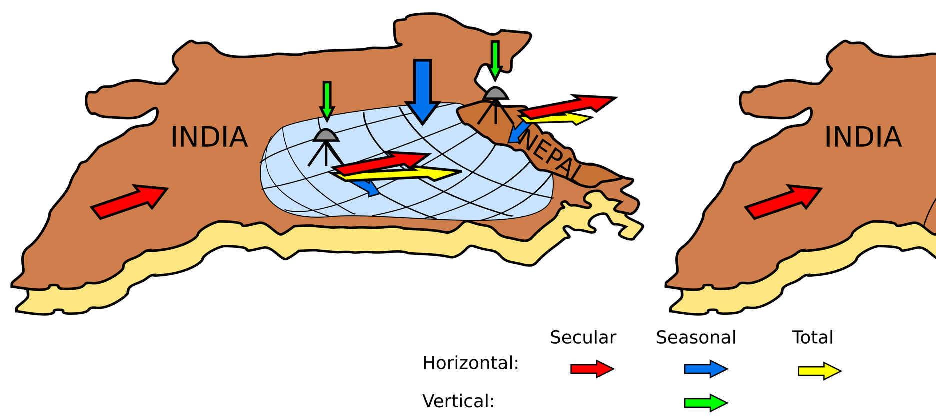

FIG. 3: Effect of water loading and unloading in the Ganges basin on geodetic displacements

PURELY ELASTIC MODEL

Convolution of the load distribution with the Green's functions

$$U_i(M,t) = \rho \int_S h(m,t) G_i(M-m)\, dm$$

- $U_i(M,t)$, time varying geodetic displacement $U_i(M,t)$, i=1,3 at point M
- ρ, water density
- G_i, Green's functions ⇒ geodetic displacement at M due to a single point load
- $h(m,t)$, equivalent water thickness (GRACE)

1. HOMOGENEOUS ELASTIC HALF-SPACE EARTH MODEL: difficult to fit (1) phase and (2) amplitudes for horizontal and vertical components using the same model

BOUSSINESQ'S SOLUTION:

$$u_R(R,0) = \frac{-F(1-2\nu)(1+\nu)}{2\pi E R}$$

$$u_\theta(R,0) = 0$$

$$u_z(R,0) = \frac{-F(1-\nu)(1+\nu)}{\pi E R}$$

- F, point load force,
- ν, Poisson's coefficient,
- E, Young's modulus,
- R, distance between application and observation points.

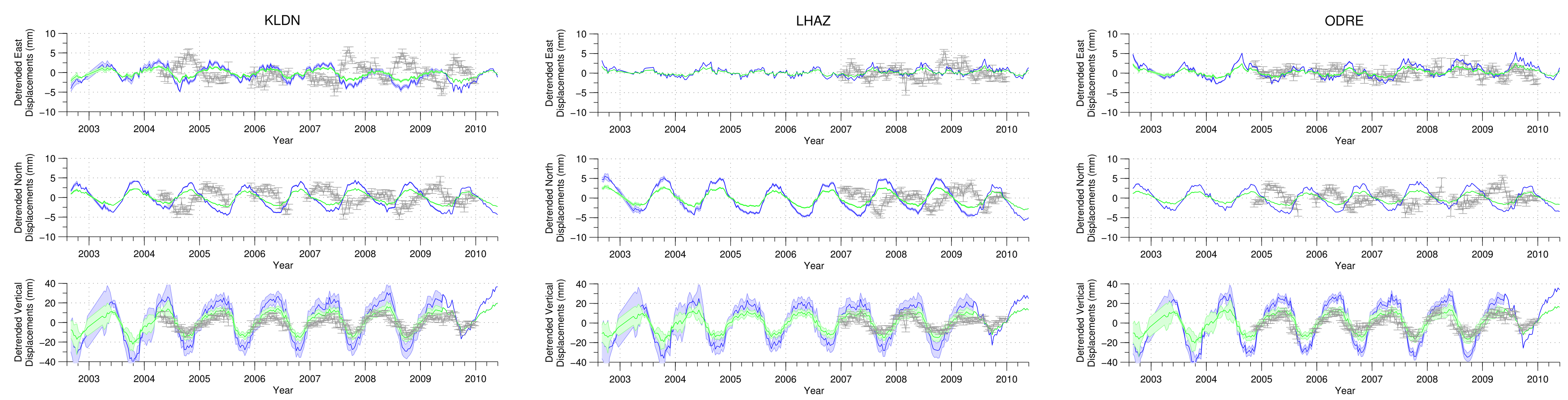

FIG. 4: Detrended geodetic positions, 10-days averaged, ODRE, KLDN and LHAZ cGPS (gray, 1-σ uncertainties). Blue & Green lines: elastic half-space models with E=90GPa and E=170GPa, respectively best overall fit to horizontal and vertical components. ν=0.25

2. COMPARISON OF GREEN'S FUNCTIONS for an elastic spherical, layered and an homogeneous half-space Earth models

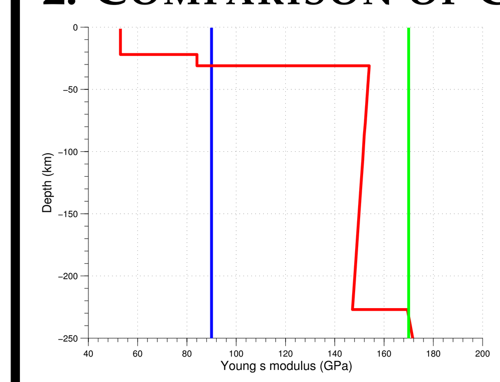

FIG. 5: E=90GPa, E=170GPa and E=PREM-modified model

$$u_r = \frac{R}{M} \sum_{n=0}^{\infty} h'_n P_n(\cos\theta)$$

$$u_\theta = \frac{R}{M} \sum_{n=0}^{\infty} l'_n \frac{\partial P_n(\cos\theta)}{\partial\theta}$$

- $P_n(\cos\theta)$, Legendre polynomials of the n'th degree,
- θ, angular distance application and observation point,
- l'_n, harmonic coefficients vertical displacements,
- h'_n, harmonic coefficients of horizontal displacements.

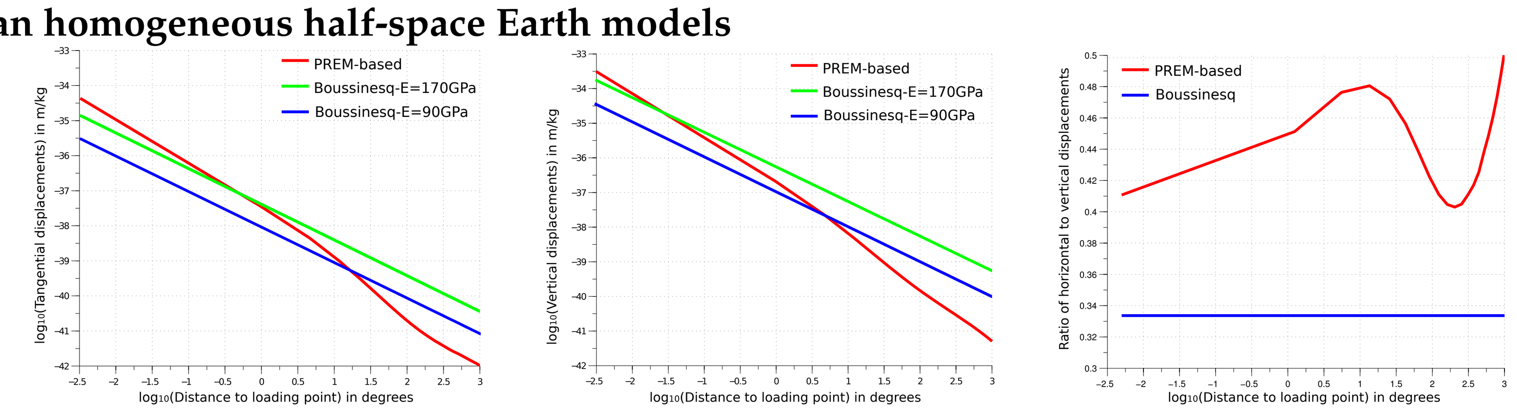

FIG. 6: Comparison of Green's functions of surface horizontal and vertical displacements and their ratio of an elastic homogeneous half-space and an elastic spherical and layered models

3. ELASTIC SPHERICAL AND LAYERED EARTH MODEL: reconciles phase and amplitudes for horizontal and vertical components

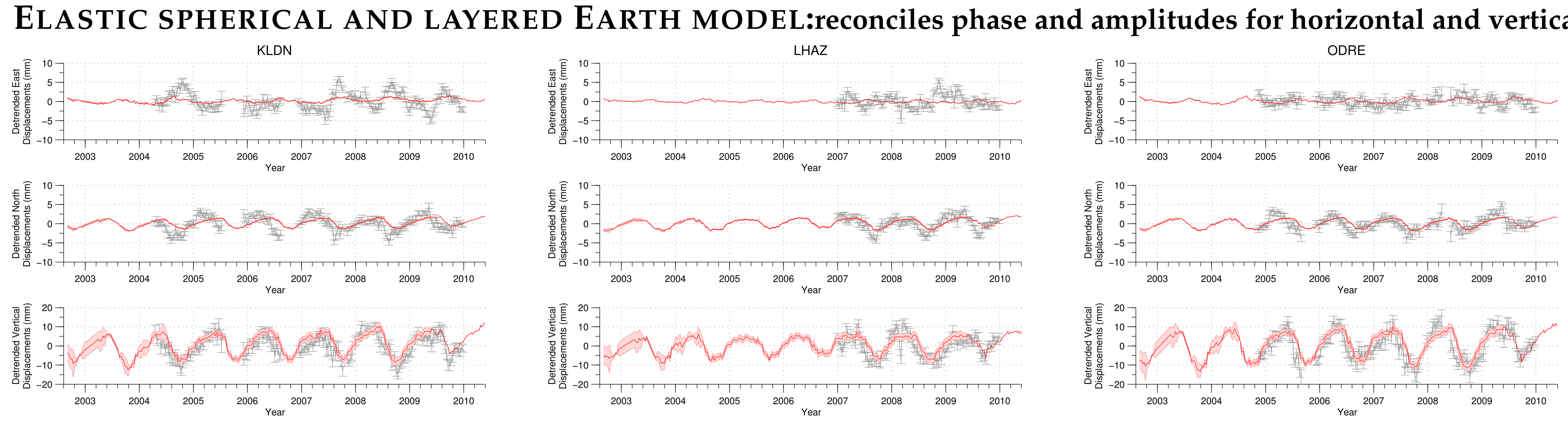

FIG. 7: Detrended geodetic positions, 10-days averaged, ODRE, KLDN and LHAZ cGPS (gray, 1-σ uncertainties). Elastic, spherical and layered model in red

χ_r^2	Horizontal	Vertical	Horizontal and Vertical
Half-space (E=90 GPa)	27.2	29.0	28.1
Half-space (E=170 GPa)	38.4	7.03	22.7
PREM-based	11.5	4.43	7.97

TAB. 1: Reduced Chi-squares χ_r^2 obtained from the inversion of the geodetic time-series, using the Boussinesq half-space approximation and χ_r^2 using a direct model based on PREM

> Implications and Conclusions

- Horizontal and vertical seasonal strains in the Himalaya are primarily due to surface load variations induced by continental hydrology,
- Comparison between an homogeneous elastic half-space and the modified-PREM models shows that vertical displacements are reflecting the crustal Earth elastic properties while horizontal displacements are reflecting properties at shallower depths. Amplitudes of vertical an horizontal components cannot be simultaneously adjusted by this model,
- Importance of using a realistic model of the elastic Earth structure, problems solved using PREM-based model for Earth,
- Residuals remain larger than uncertainties on average (Table 1): heterogeneities of surface load distribution at a scale not resolved by GRACE or non-optimal elastic Earth structure?
- Modeling of seasonal geodetic strain might be a way to constrain regional variations of elastic properties of the the Earth at depths typically shallower than about 150km,
- Implications for detection of transient deformation events which requires proper identification and modeling of non-tectonic sources of surface deformation.