



The GHYRAF (Gravity & HYdrology in AFrica) experiment: first results on land water storage changes

Jacques Hinderer & the GHYRAF team

J. Hinderer^{a,*}, C. de Linage^{a,i}, J.-P. Boy^{a,j}, P. Gegout^a, F. Masson^a, Y. Rogister^a, M. Amalvict^a, J. Pfeffer^a, F. Littel^a, B. Luck^a, R. Bayer^b, C. Champollion^b, P. Collard^b, N. Le Moigne^b, M. Diamant^c, S. Deroussi^c, O. de Viron^c, R. Biancale^d, J.-M. Lemoine^d, S. Bonvalot^e, G. Gabalda^e, O. Bock^f, P. Genthon^g, M. Boucher^g, G. Favreau^g, L. Séguis^g, F. Delclaux^g, B. Cappelaere^g, M. Oi^g, M. Descloitres^h, S. Galle^h, J.-P. Laurent^h, A. Legchenko^h, M.-N. Bouin^k

^a Institut de Physique du Globe de Strasbourg (UMR 7516 CNRS/Université de Strasbourg), 67084 Strasbourg, France

^b Géosciences Montpellier (UMR 5243 CNRS/Université Montpellier 2), 34095 Montpellier, France

^c Institut de Physique du Globe de Paris (UMR 7154 CNRS/IPGP/Université Paris 7), 75252 Paris, France

^d Dynamique terrestre et planétaire (UMR 5562 CNRS/Université Paul Sabatier), 31400 Toulouse, France

^e Laboratoire des Mécanismes et Transferts en Géologie (UMR 5563 CNRS/IRD/Université Paul Sabatier), 31400 Toulouse, France

^f Laboratoire de Recherche en Géodésie/IGN, 77455 Marne la Vallée, France

^g Hydrosiences Montpellier (UMR 5569 CNRS/IRD/Université Montpellier 2), 34095 Montpellier, France

^h Laboratoire d'étude des Transferts en Hydrologie et Environnement (UMR 5564 CNRS/INPG/IRD/Université Joseph Fourier), 38041 Grenoble, France

ⁱ University of California, Irvine, Department of Earth System Science, Croul Hall, Irvine, CA 92697-3100, USA

^j NASA GSFC Planetary Geodynamics Laboratory, Greenbelt, MD 20771, USA

^k CNRM/Centre de Météorologie Marine, 29604 Brest, France

GHYRAF: A pilot study

to investigate the water cycle in Africa from Sahara to equatorial monsoon zone with ground and satellite-derived gravity and GPS.

Target:

- Comparison between hydrology models and multi-disciplinary observations (gravity, geodesy, hydrology, meteorology...) of seasonal water storage changes.

Corollary:

- Ground “validation” of space derived gravity (GRACE)

Project characteristics:

- AG repeated campaigns (FG5+A10) at 4 reference sites
- SG (GWR) continuous monitoring at one site
- Micro-gravimetry repetition at hydrology sensors in vicinity of FG5
- Continuous precise GPS measurements at each site
- In-situ measurements of hydrological parameters + MRS (magnetic resonance sounding) at each site for modeling local contributions to gravity
- GRACE time-variable gravity field.

The GHYRAF team

EOST/IPGS, Strasbourg
Geosciences Montpellier

IRD/IPG Paris

CNES/GRGS, Toulouse

IGN

IRD/Hydrosiences Montpellier

LTHE Grenoble

FG5-206, GWR-SG, GPS

FG5-228, GPS

A10

GRACE

GPS

Hydrology, MRS, EM

Hydrology, MRS, EM

Other collaborations:

IGN Spain FG5 + A10

FGI Finland FG5 (Ghana ?)

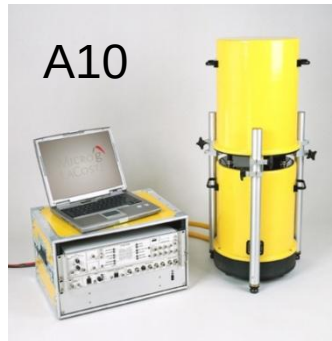
Uni. Luxemburg FG5 (Algeria)

African Water Authorities + Niamey, Cotonou

FG5



A10



SG

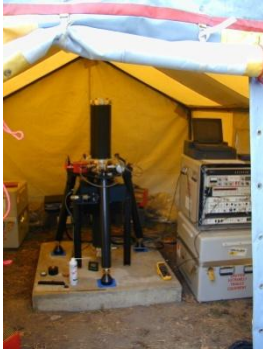


CG5



GHYRAF actions in gravimetry

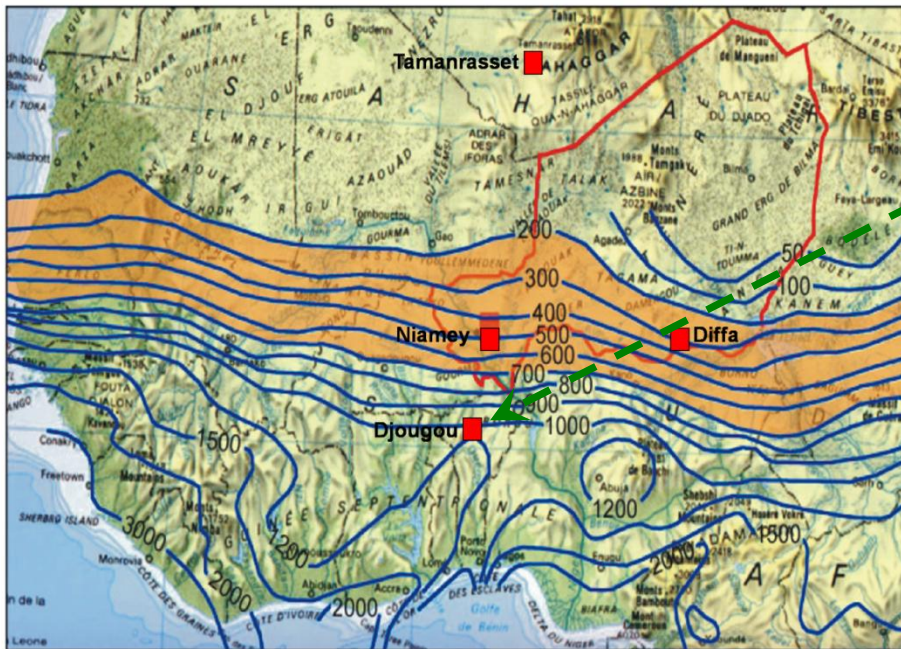
AG



- absolute gravity measurement (FG5) campaign every 3 months at 4-5 stations (2008-2010) + complementary measurements (A10, Scintrex)
- continuous monitoring of relative gravity measurements (field SG) at Djougou

SG

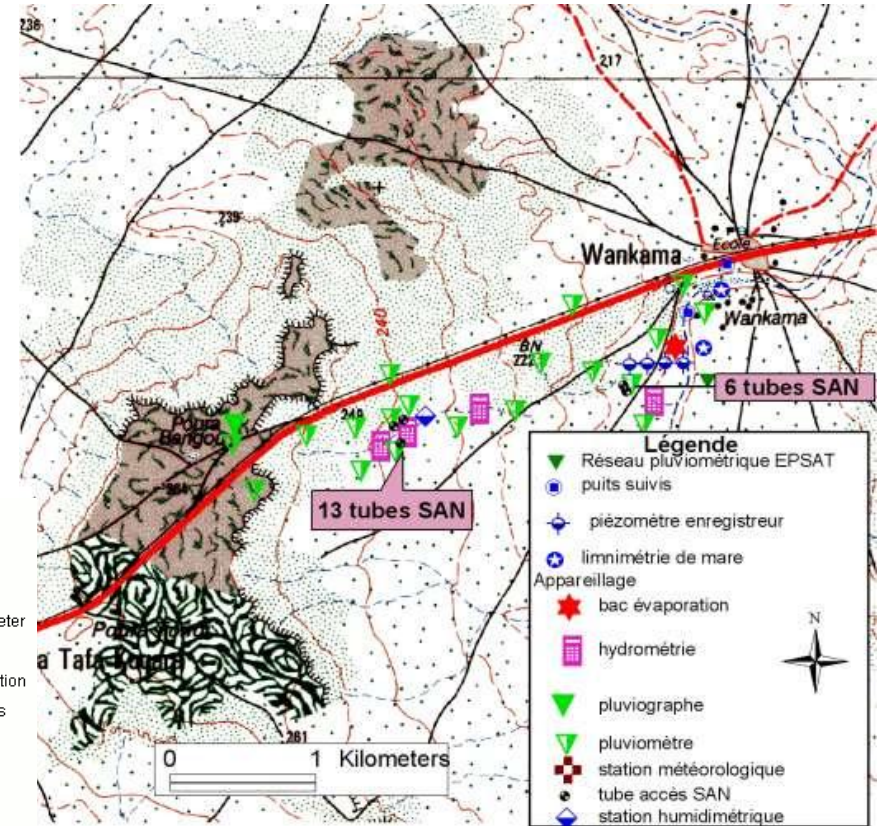
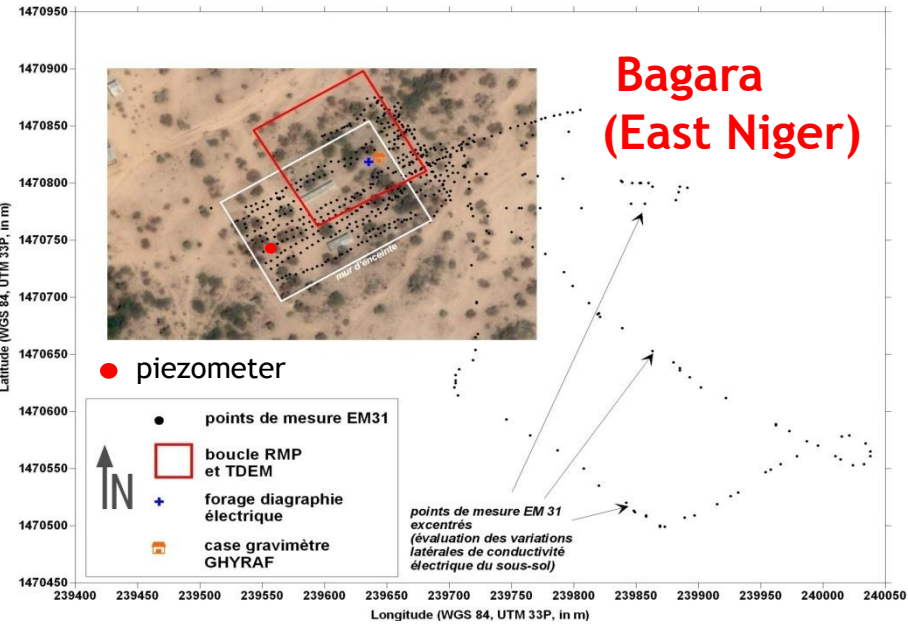
FIELD SUPERCONDUCTING GRAVIMETER
Superconducting Gravimetry for remote field sites!



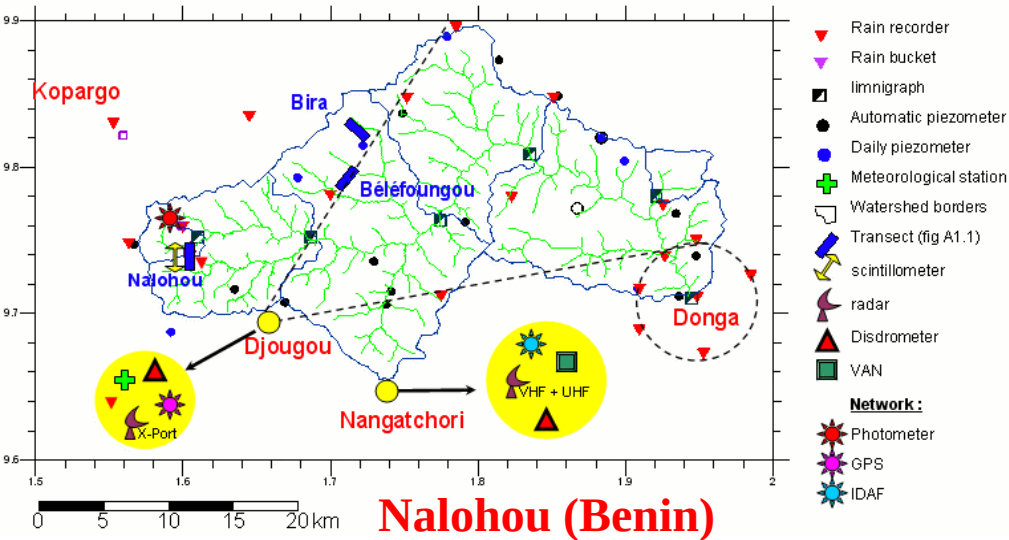
- Tamanrasset: 20 mm/yr (Sahara)
-> **null test**
- Diffa: 300 mm/yr (Sahara-Sahel transition, lake Chad)
- Niamey: 560 mm/yr (Sahel, Niger basin)
- Djougou: 1200 mm/yr (monsoon zone, Benin)

Average annual precipitations in West Africa (1951-1989) from *L'Hôte & Mahé (1996)*

GHYRAF actions in hydrology

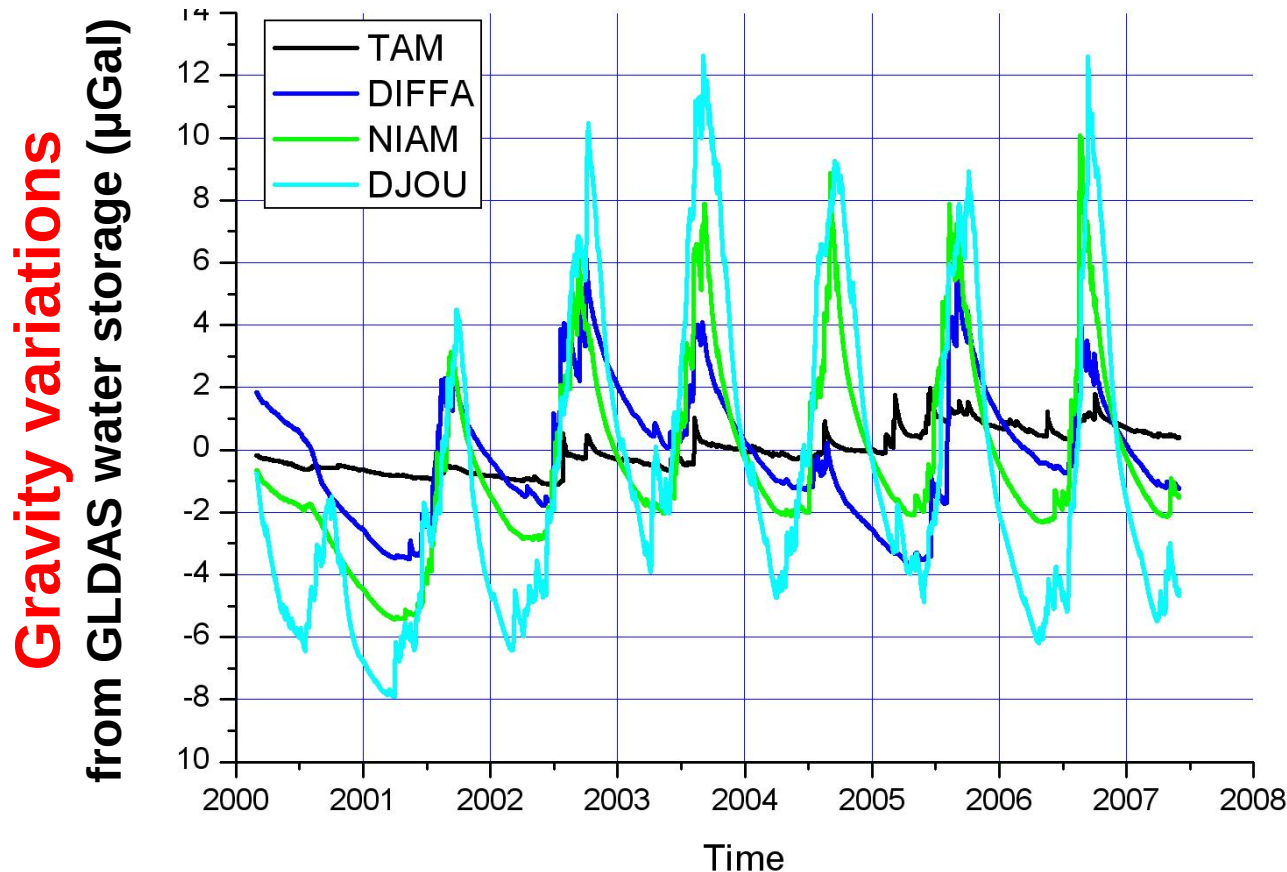


Wankama (West Niger)



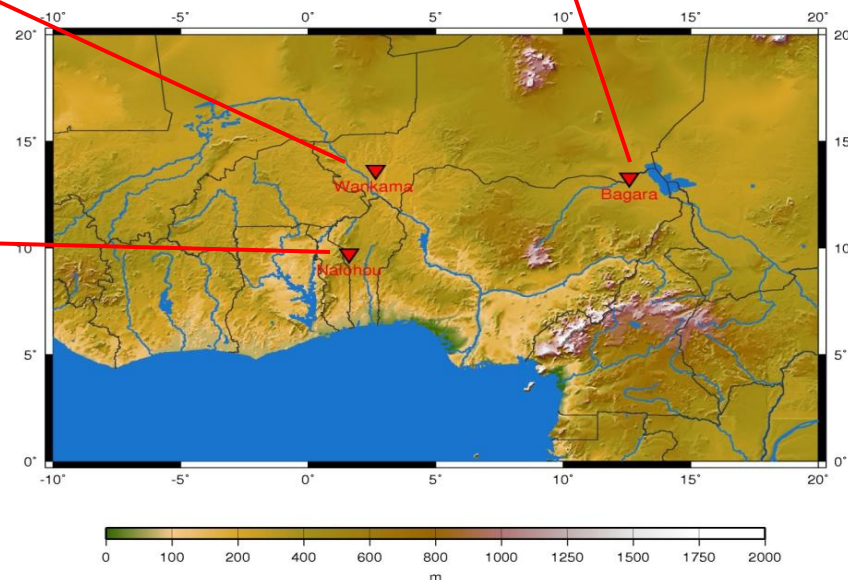
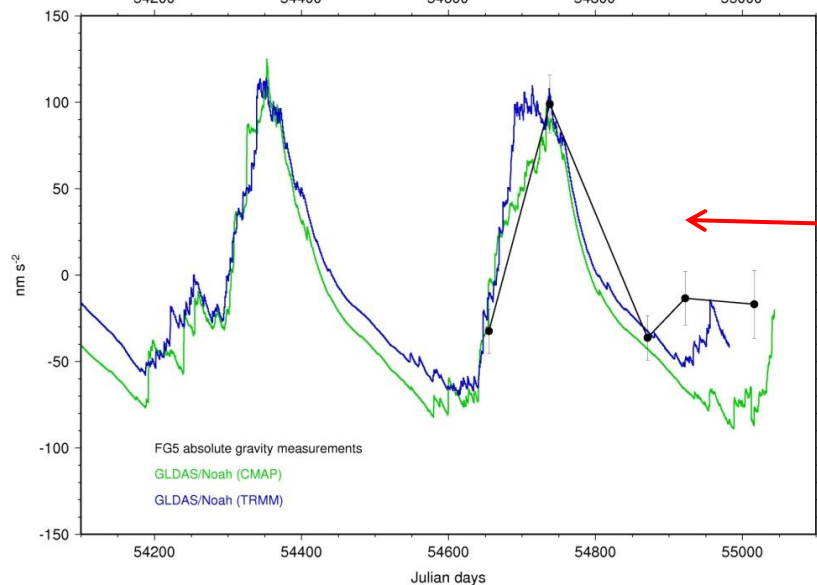
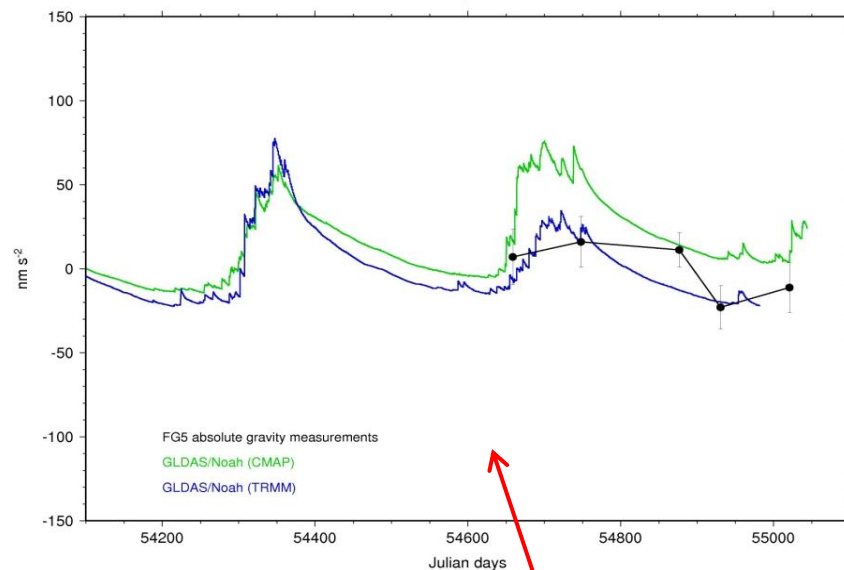
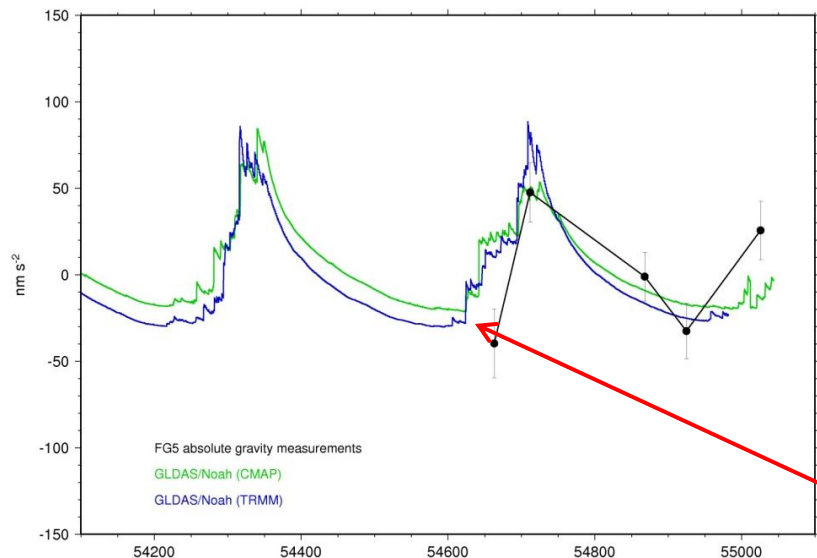
Predicted gravity changes

$$1 \mu\text{Gal} = 1 \cdot 10^{-8} \text{ m.s}^{-2} \\ \sim 10^{-9} \text{ g}$$

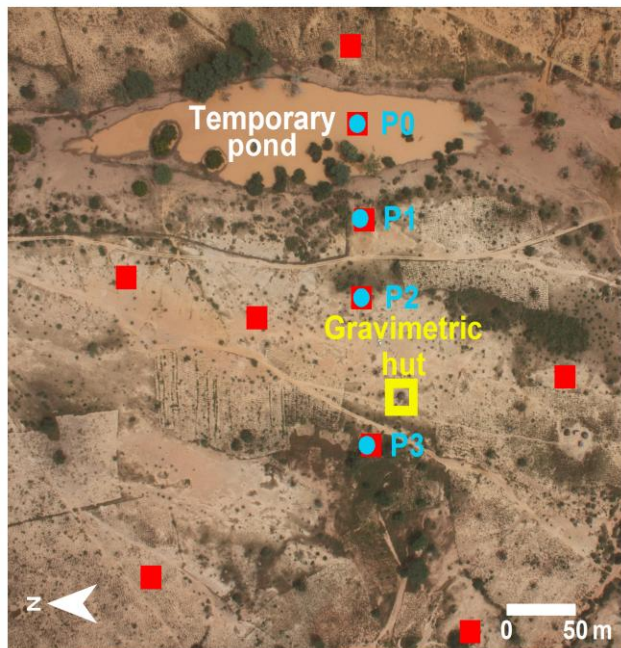


- Amplitude of annual signal **highly variable** depending on location
- stable phase (linked to monsoon occurrence)

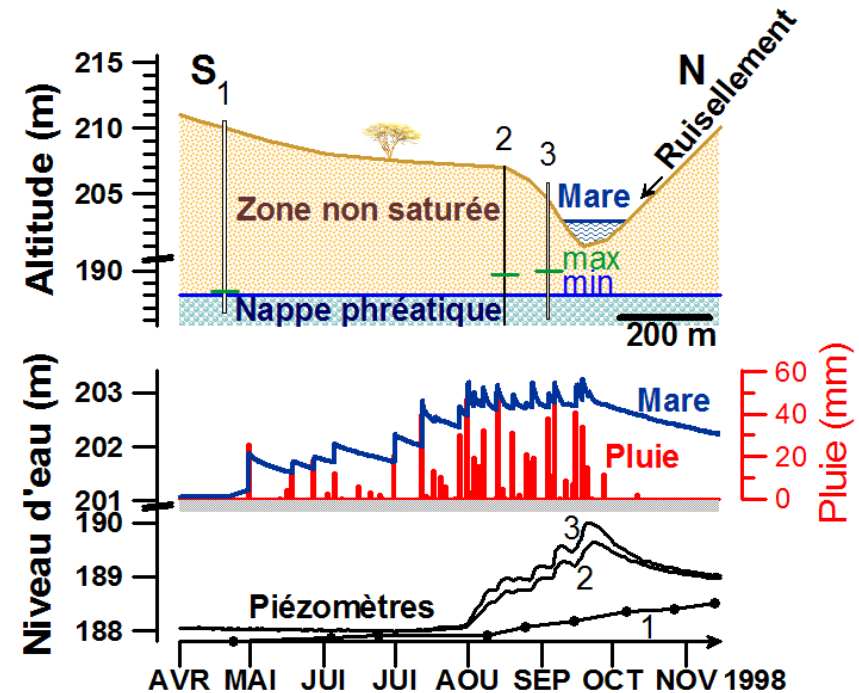
Absolute gravity measurements (July 2008-July 2009)



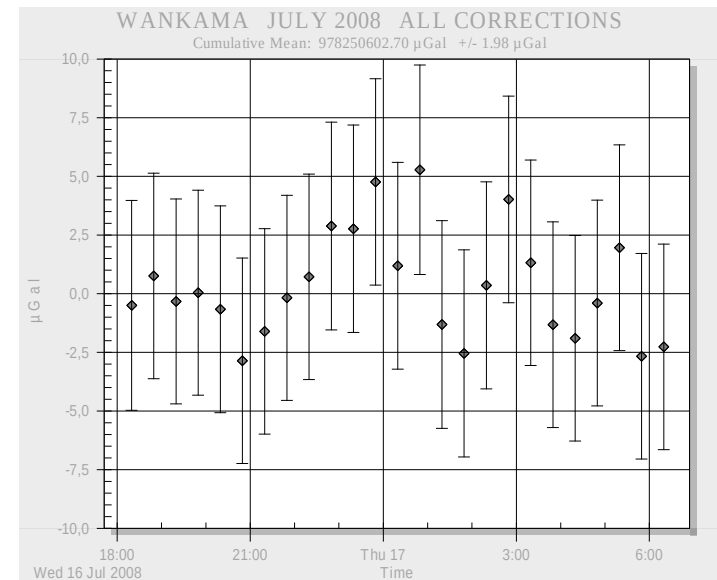
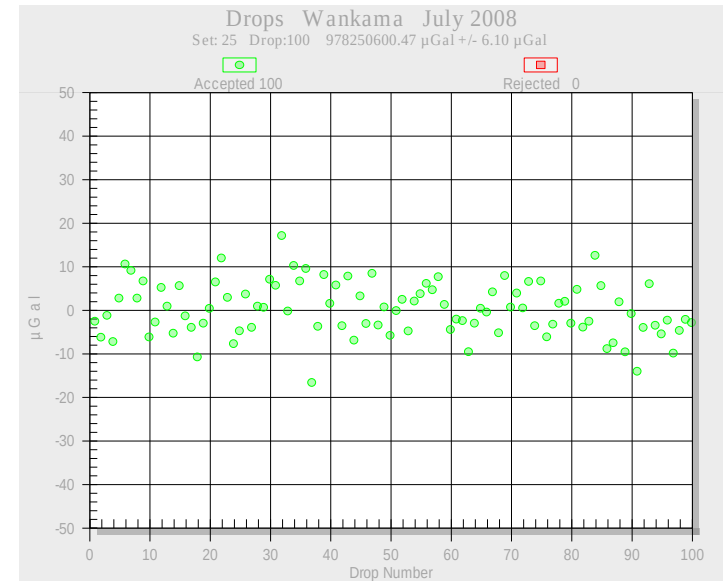
Wankama site (West Niger)



- Relative gravimetric measurement
- Absolute gravimetric measurement
- Piezometer



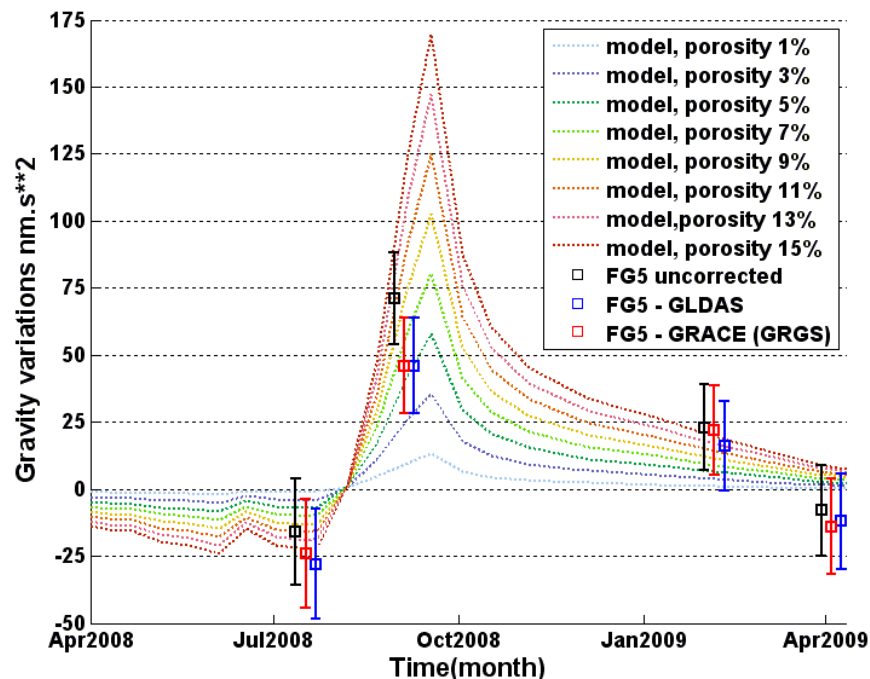
Wankama site (West Niger)



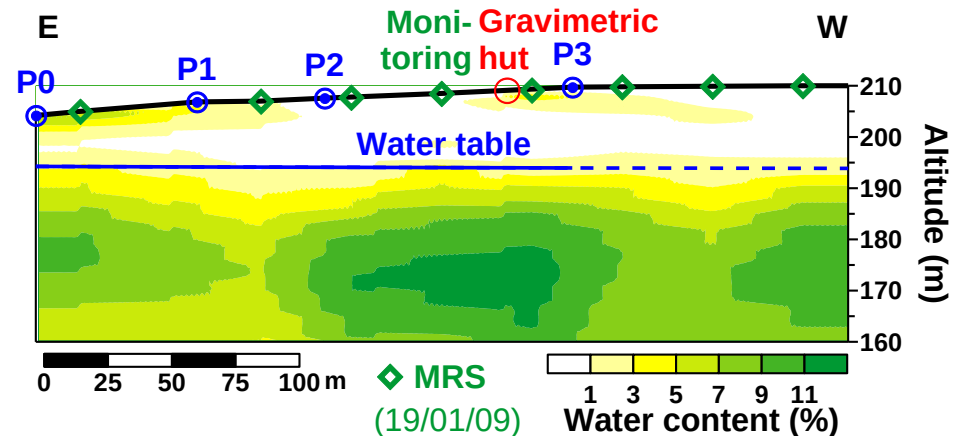
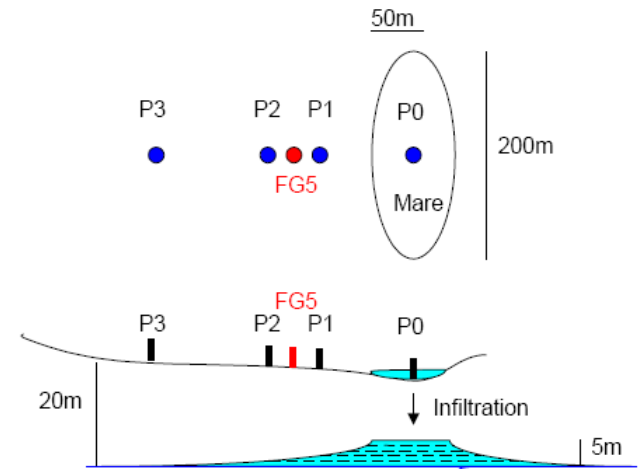
Modeling of local gravity changes at Wankama

Different contributions:

- piezometric level
- temporary pond
- *superficial soil moisture (vadose zone)*



Comparison of corrected FG5 measurements and local gravity variations model (J. Pfeffer)



MRS water content profile
The 19th January 2009 (Marie Boucher)

Microgravimetric campaign in Wankama

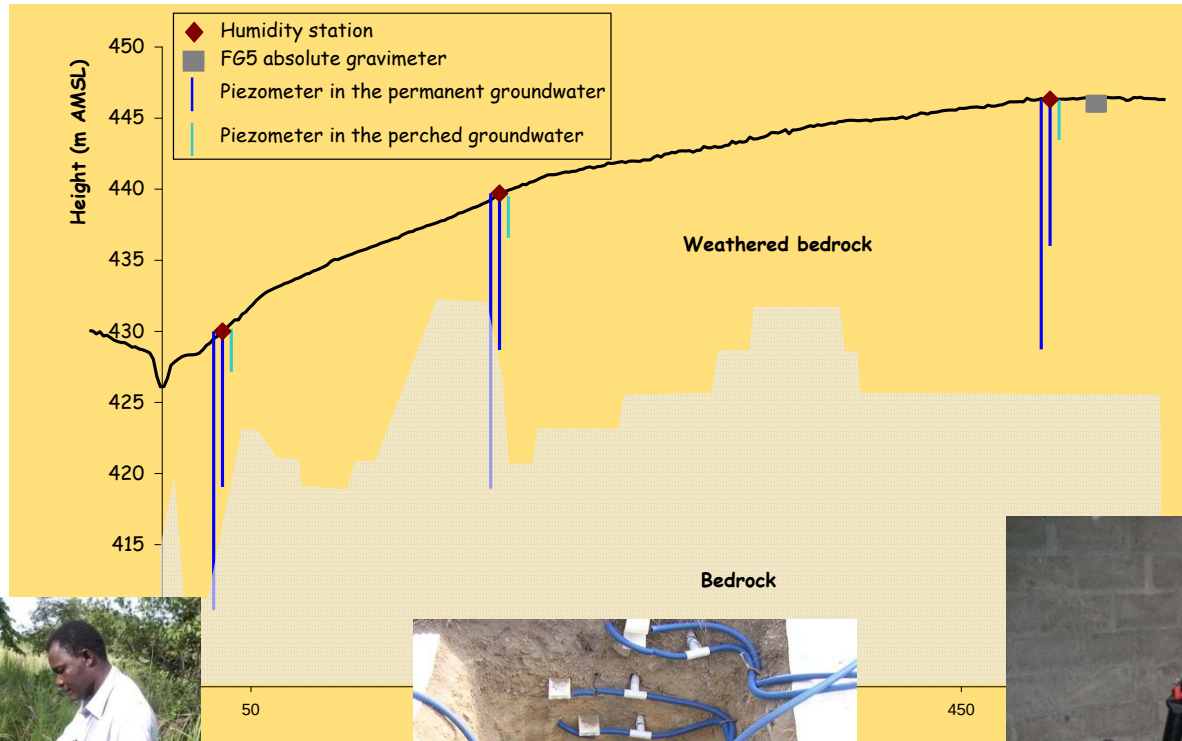
Repetition of a network of 16 points once a week during the rainy season 2009 with 2 microgravimeters CG5

Goal:

- ✓ spatial variations of water storage
- ✓ temporal variations of water storage

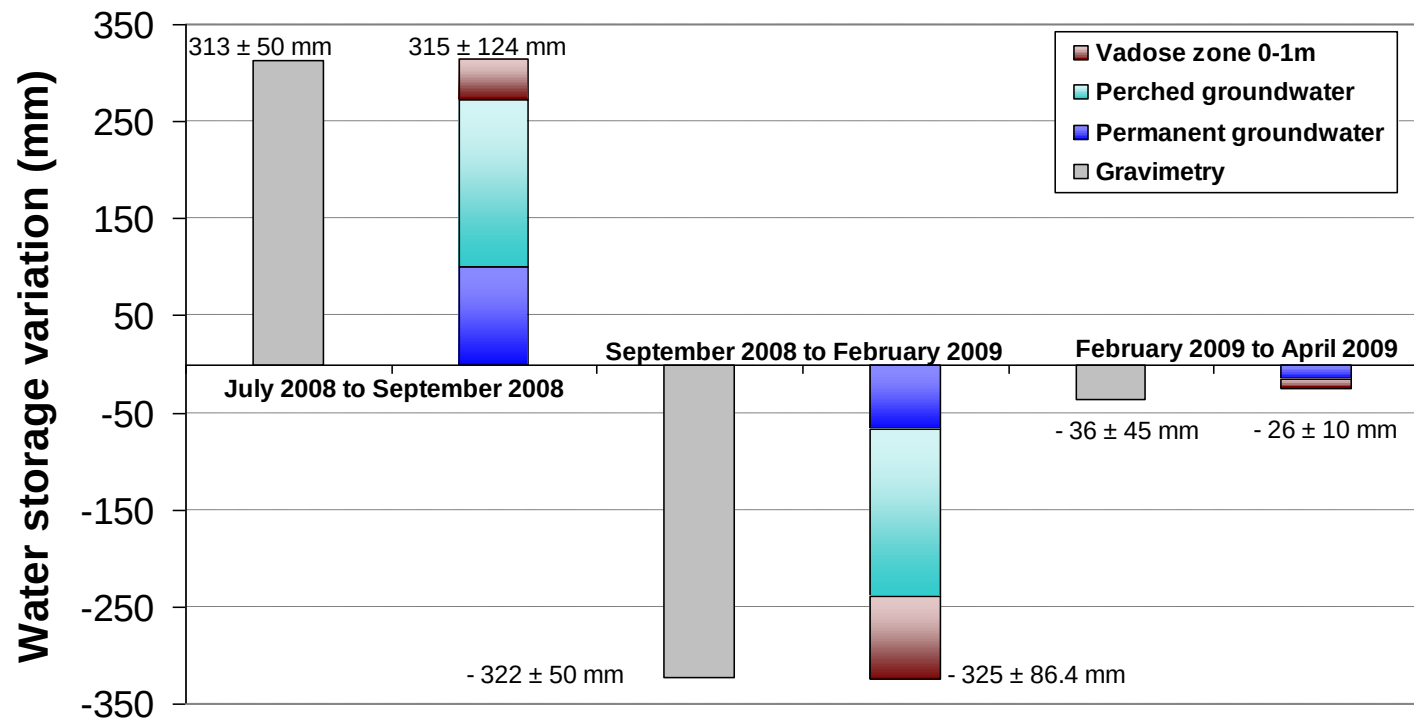


Nalohou site (Bénin)

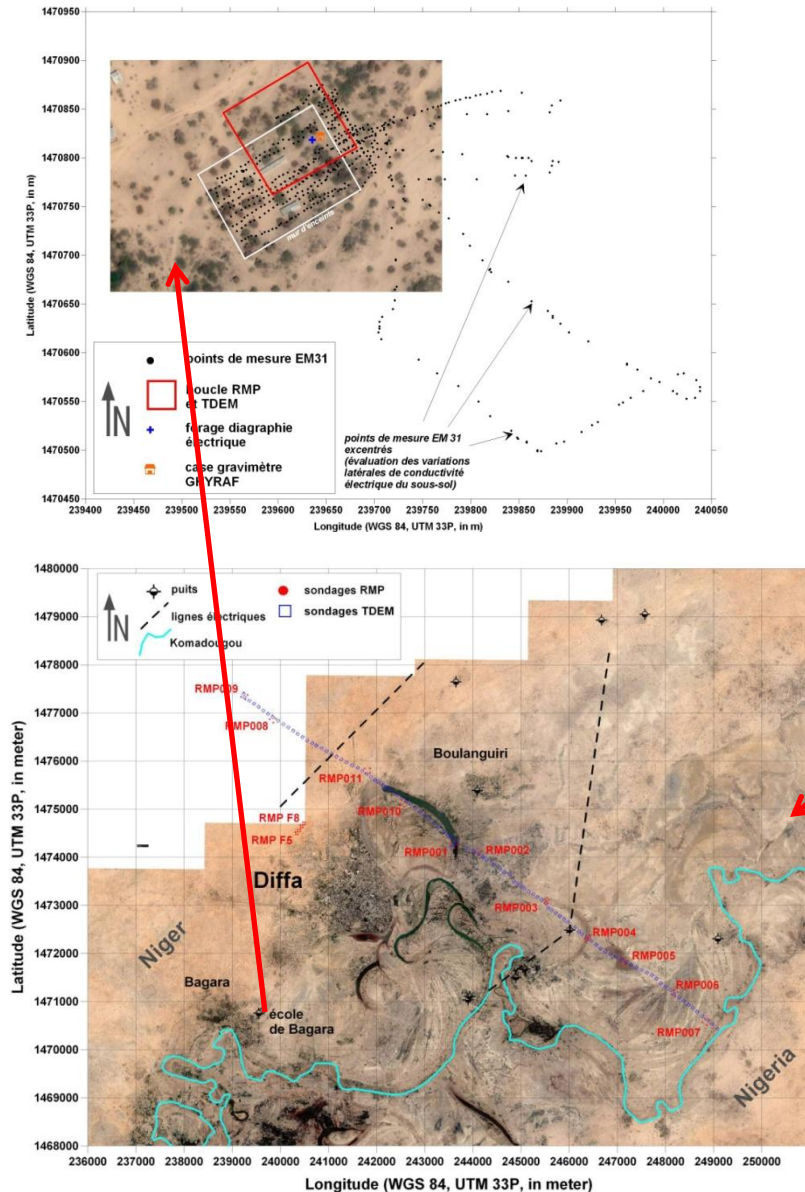


Estimate of water storage (Nalohou site)

Vadose zone	Perched aquifer	Permanent aquifer
TDR probes	Piezometric data	Piezometric data
	Drainage porosity : $20 \pm 5 \%$ (Hg porosimetry)	Drainage porosity : $3 \pm 2 \%$ (MRS)

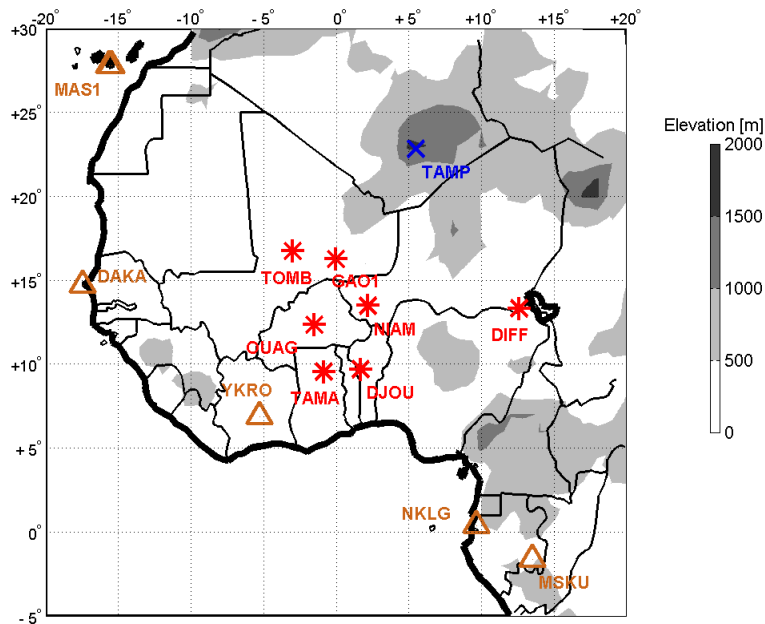


Bagara site (East Niger)



- No effect of lake Chad height changes
- Interactions river Komadougou and aquifer ?
- Poroelastic effects?

GHYRAF actions in GPS

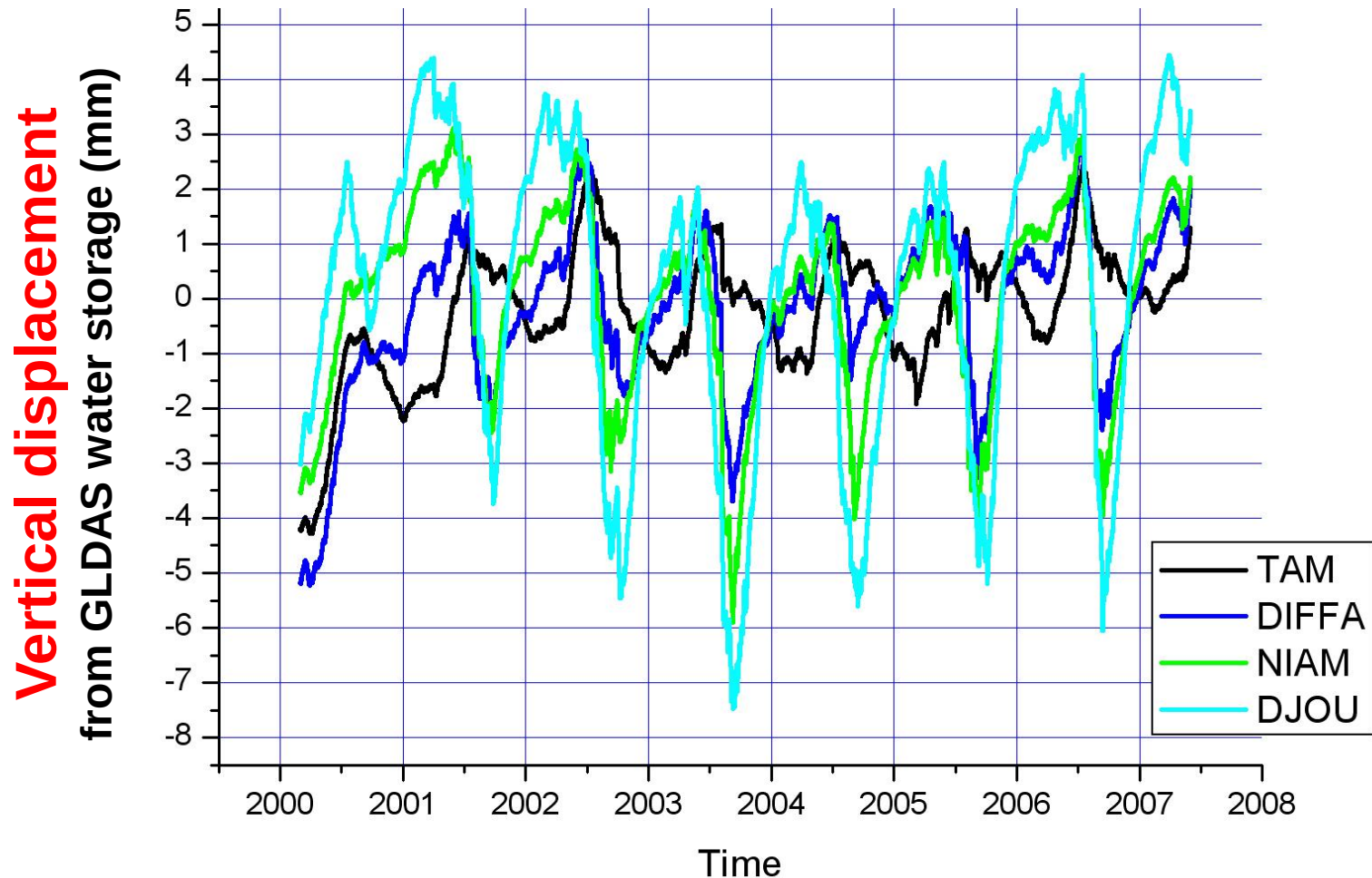


- 6 stations from the **AMMA** experiment;
- 2 of them maintained by EOST since 2009
 - TOMB, OUAG, TAMA
 - DJOU, NIAM, GAO1
- 1 new EOST station
 - DIFF Diffa
 - operational since july 2008
- 1 CRAAG (Algeria) station
 - TAMP Tamanrasset
- nearby IGS stations
 - DAKA, YKRO, NKLG, MSKU, MAS1

O. Bock

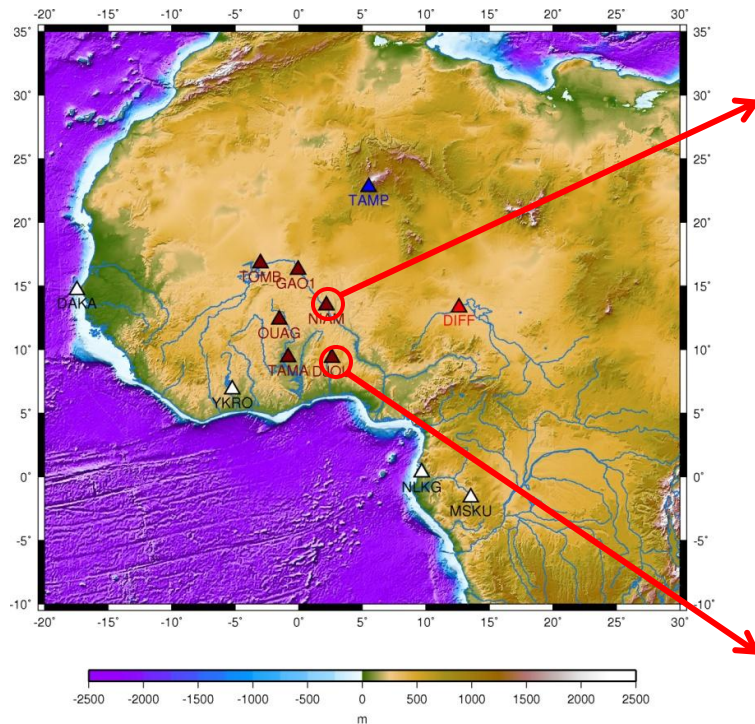


Predicted vertical displacement



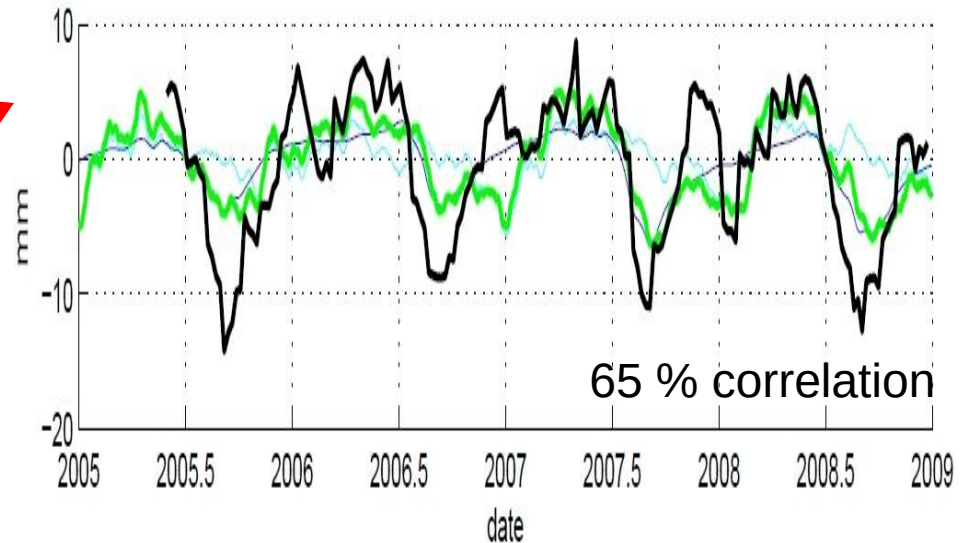
Variable amplitude and phase of the annual component

GPS vertical displacement and loading models



 Atmo + Hydro loads
 GPS residuals

NIAM



DJOU

GHYRAF actions in space gravimetry

GRACE (Gravity Recovery And Climate Experiment) satellite data

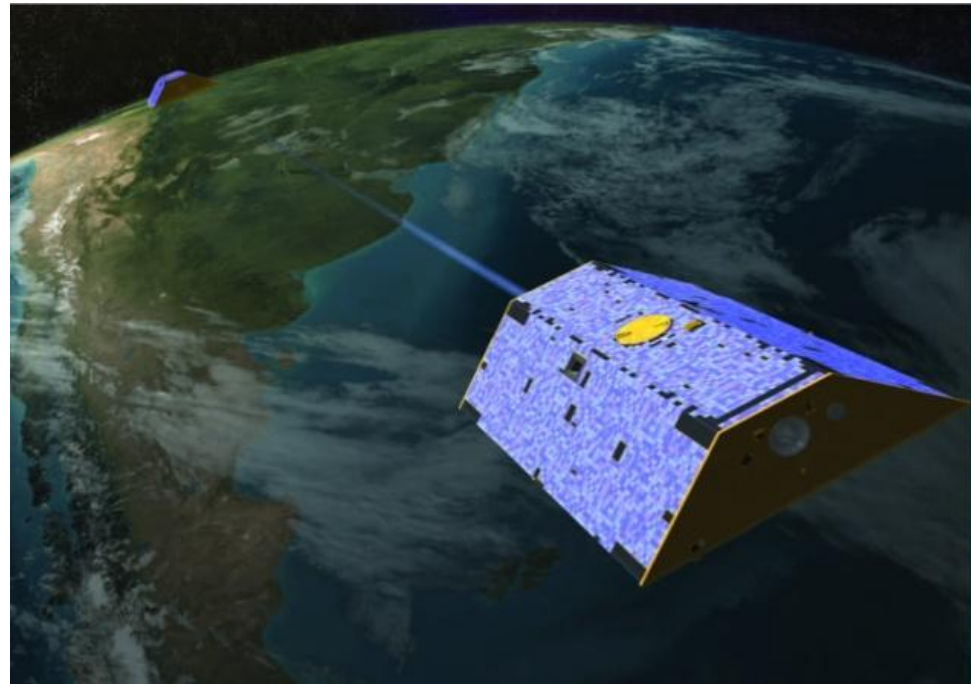
3 main data processing centers:

1. CSR (USA)
monthly solutions
2. GFZ (Germany)
monthly solutions
3. CNES/GRGS (France)
10-day solutions



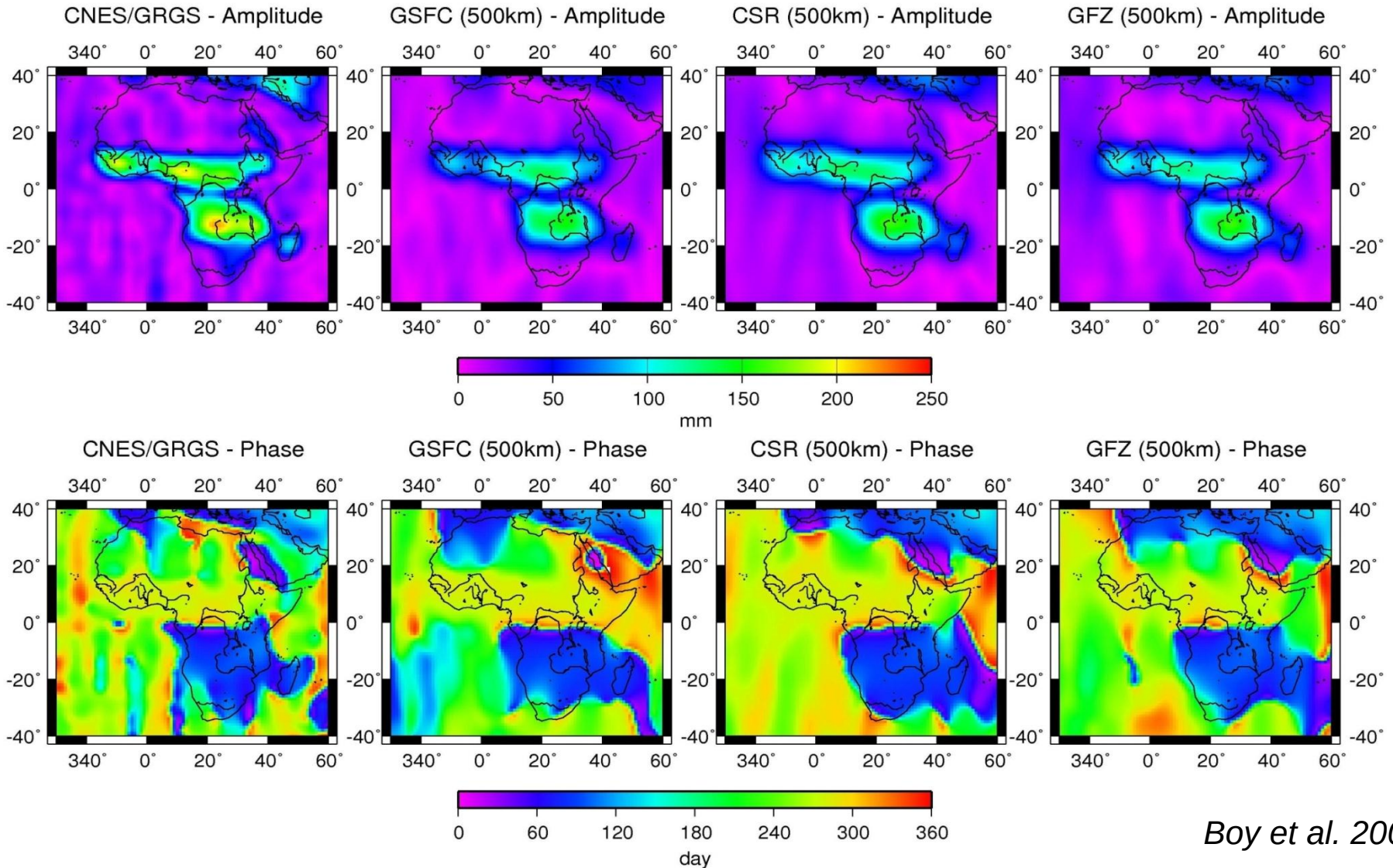
Major impact on:

- co- and post-seismic deformation
- **Continental hydrology**
- Ice melting

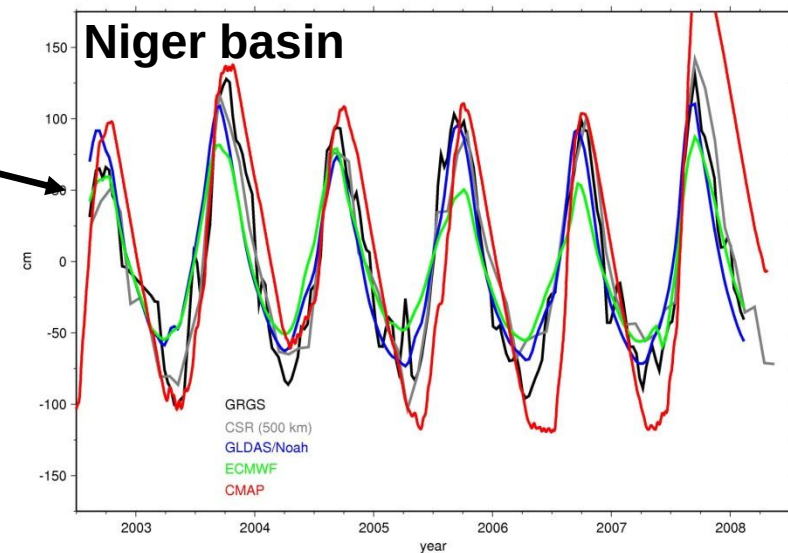
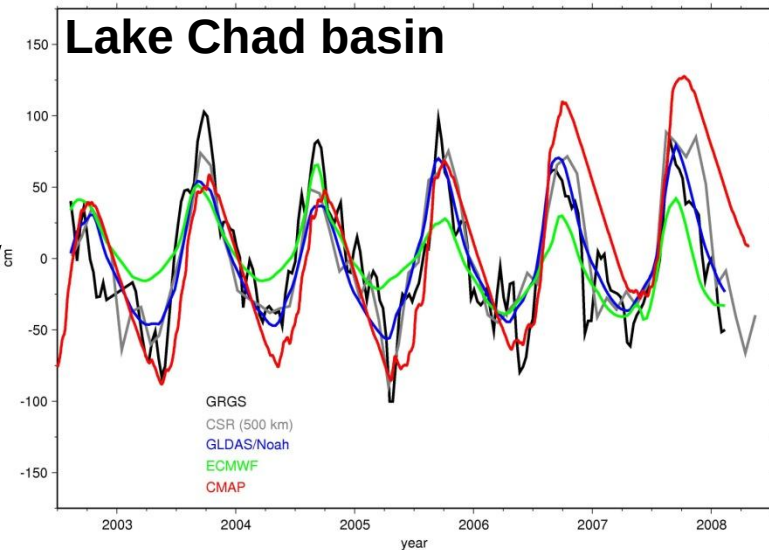
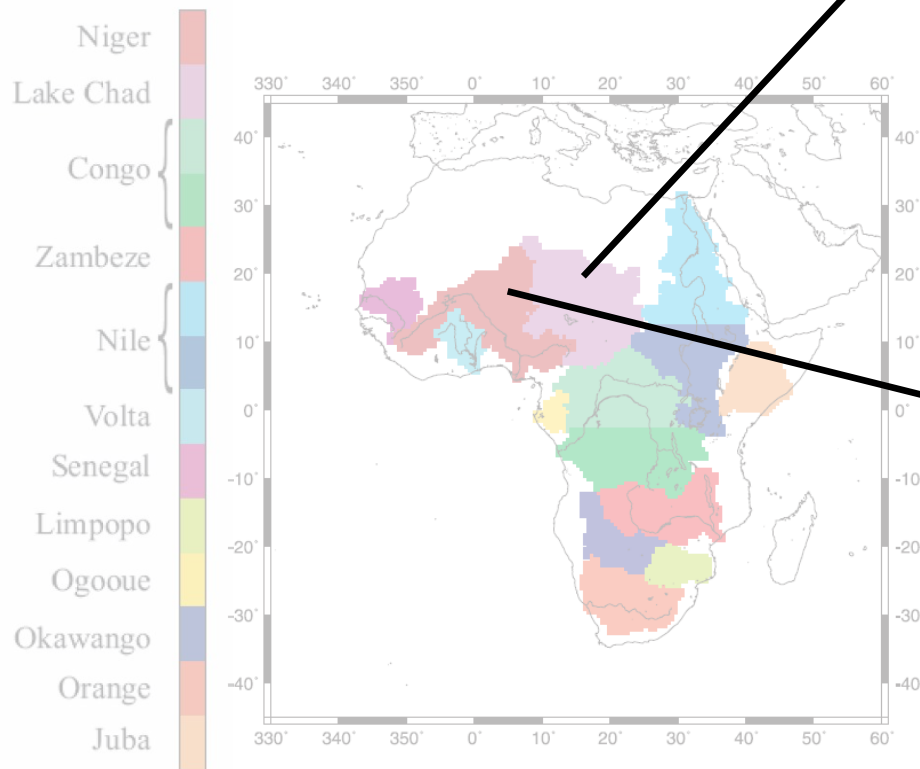


Launched in 2002
Still orbiting

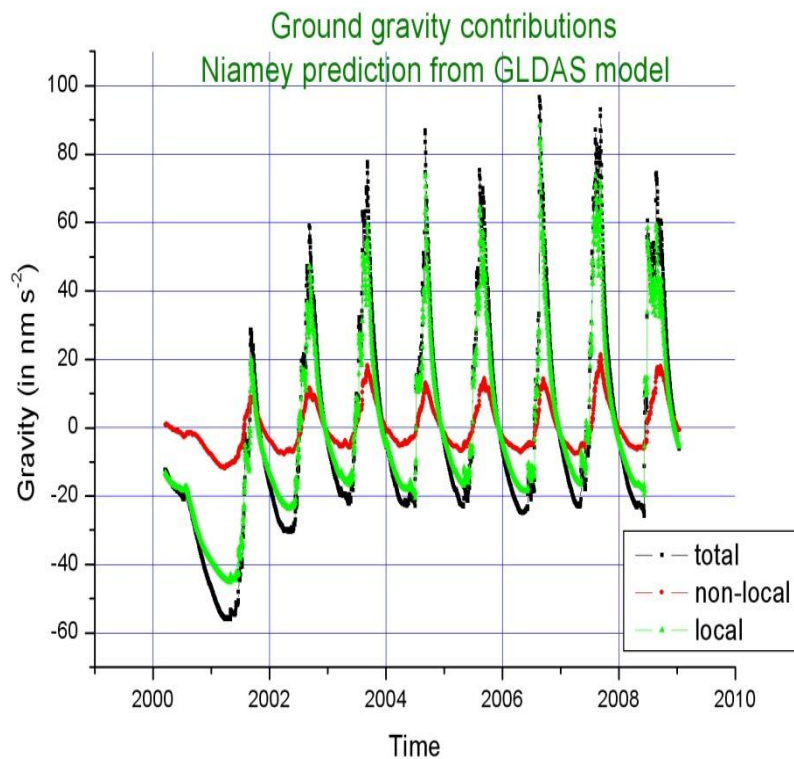
Amplitude of annual term by GRACE



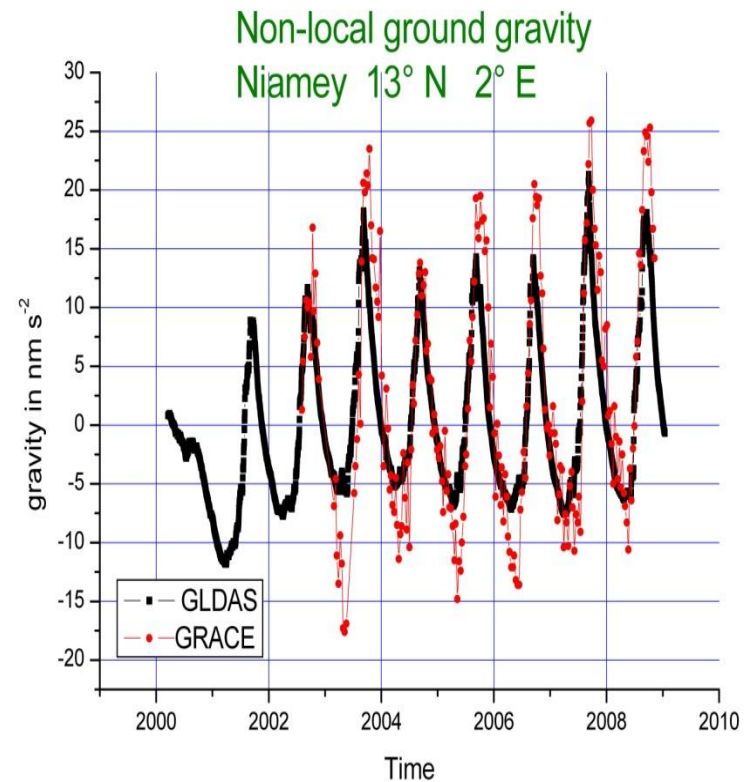
Comparison of GRACE, hydrological models and precipitation estimates



Local and non-local contributions in ground gravity



Dominant part is local (Newtonian)



Non-local part can be retrieved from models or GRACE observations

Time schedule (2008-2011)

Done

- **First exploratory field mission** in March 08 for selecting the gravity and GPS sites
- **Construction of the sites** (concrete pillar, building) in May/June 08
- **Installation of GPS receiver** in Diffa in July 08
- **6 AG (FG5) field campaigns** (Niger + Benin) from July 08 to Sept/Oct 2009
- **MRS** (Magnetic resonance sounding) at all sites + neutron probes monitoring
- Exploratory field mission for the '**desert**' point in Algeria (TAM region) in Jan 09
- **Microgravimetric survey** at Wankama in rainy season 2009
- **First A10 campaign** in Sept/Oct 2009

Future steps of project

- Start gravity measurements in Sahara to do the **‘null test’** experiment (spring 2010)
- Install **superconducting gravimeter** in Nalohou (spring 2010)
- **Densify** gravity measurements around **Nalohou** (Bénin) (summer 2010)
- Obtain **mascons solutions of GRACE data** with better spatial resolution for the zones of interest (ongoing research)

Summary

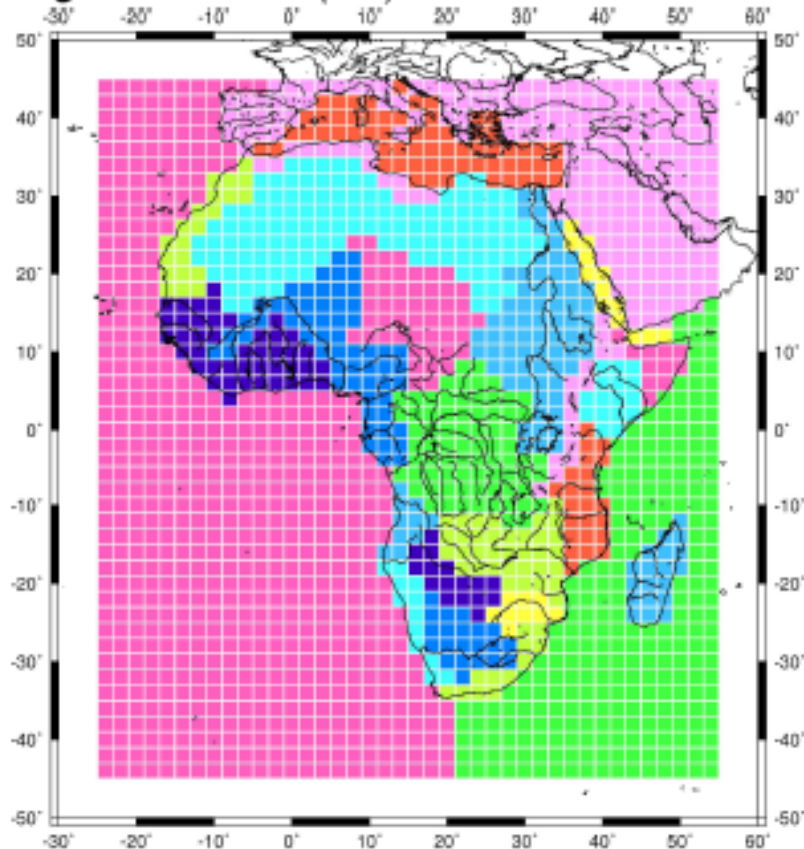
- First cycle of AG measurements demonstrate **feasability of experiment** with low noise observations despite climate, lack of electric power and other logistic problems
- Preliminary processing of GPS vertical motion shows **clear hydrologic signal** related to the monsoon
- Gravity changes in **Wankama** well explained with local piezometry and porosity values inferred from MRS
- Water storage changes in **Nalohou** well explained by gravity and hydrological in-situ observations of soil moisture and piezometry
- Poro-elasticity to be studied at **Bagara** to explain smaller than expected gravity changes
- **GRACE** solutions agree well with hydrology models for the Niger and Chad basins

Merci de votre attention!



New developments in space gravimetry

High resolution (2°) mascon solution



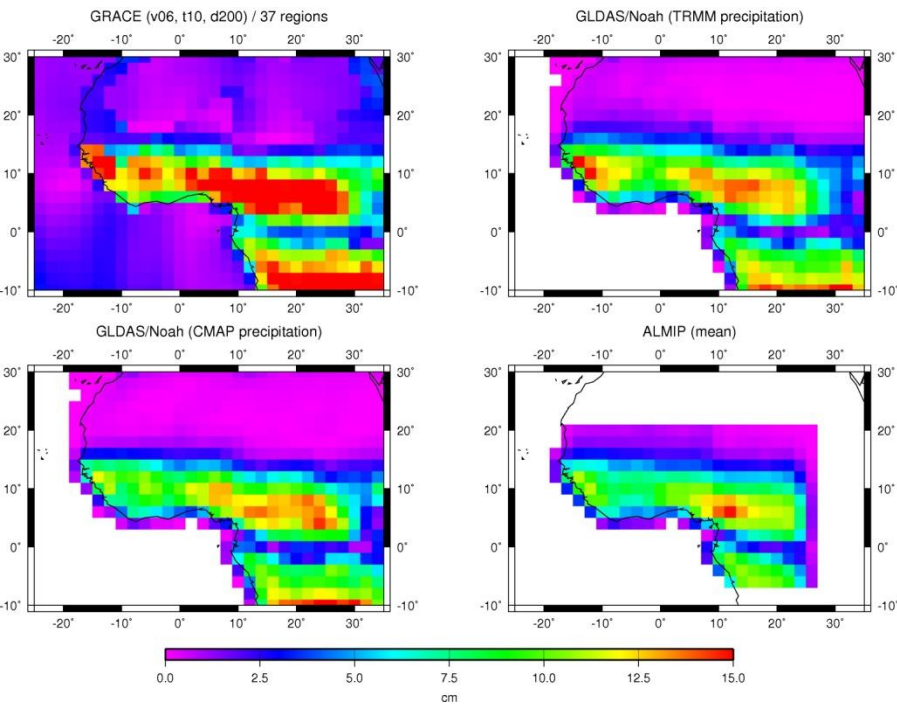
v06 forward modeling:

- 3 hourly ECMWF surface pressure,
- 6 hourly MOG2D barotropic sea surface height,
- 3 hourly GLDAS/Noah.

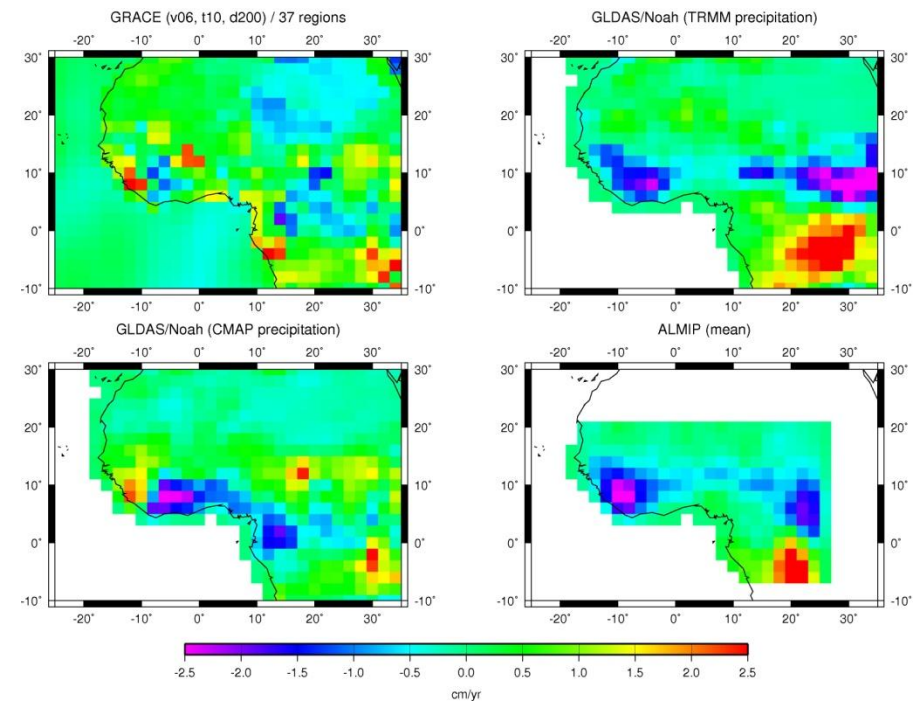
Different temporal & spatial constraints, and relative weights of data vs constraints, (10 & 20 days, 250 km and 10000).

Constraints applied to 37 different regions (river basin defined) or 7 different regions (all Africa cells are tied together).

Comparison of GRACE with Hydrology models (GLDAS & ALMIP)



Annual term in cm



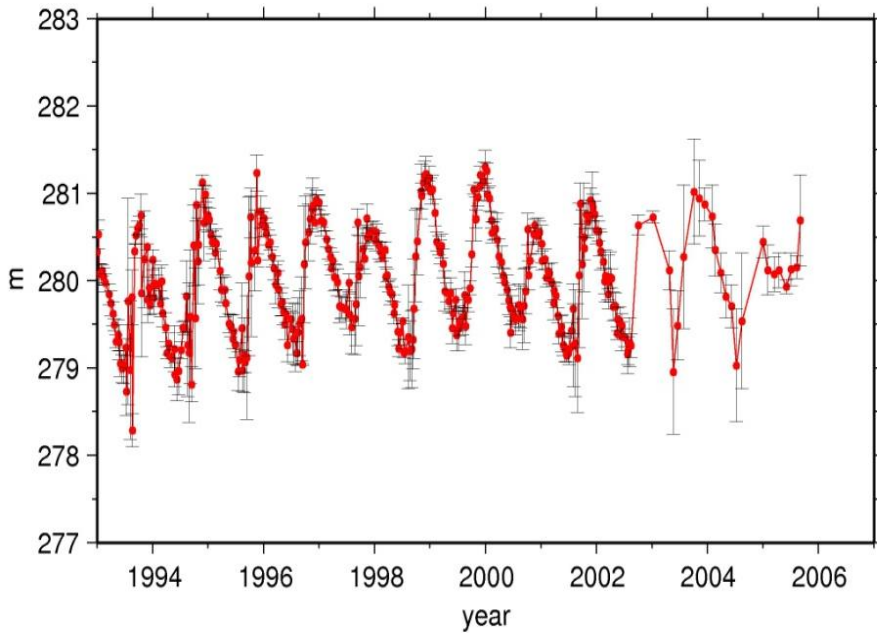
Trend in cm/yr



Construction work at Wankama site (Niger) in May 2008

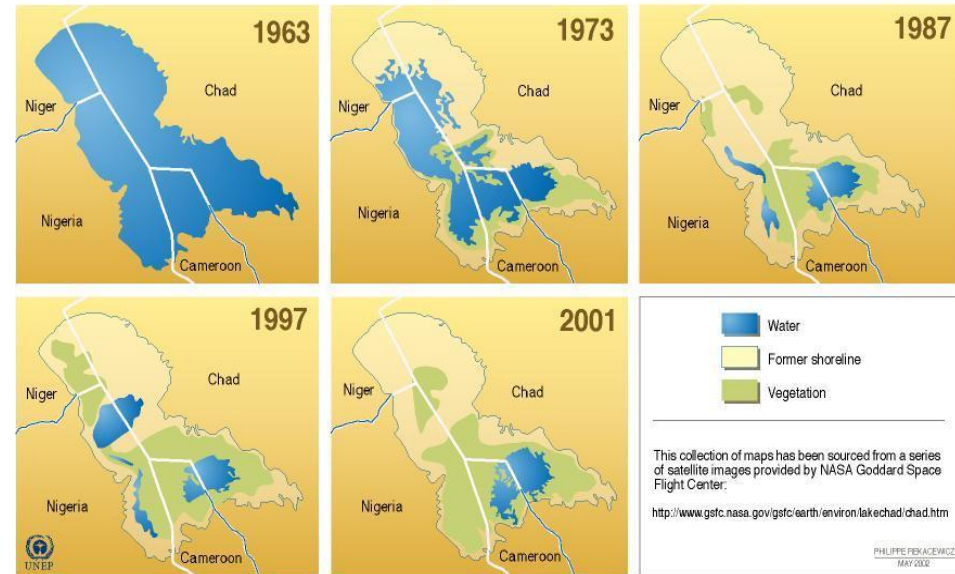


Lake Chad



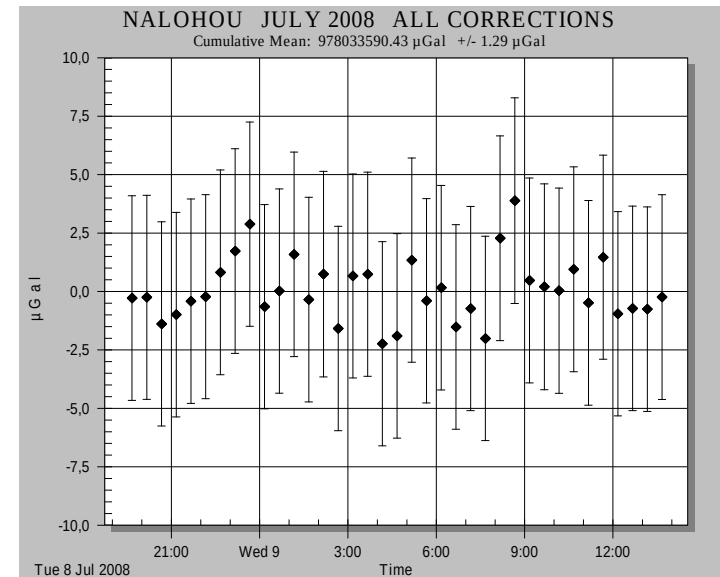
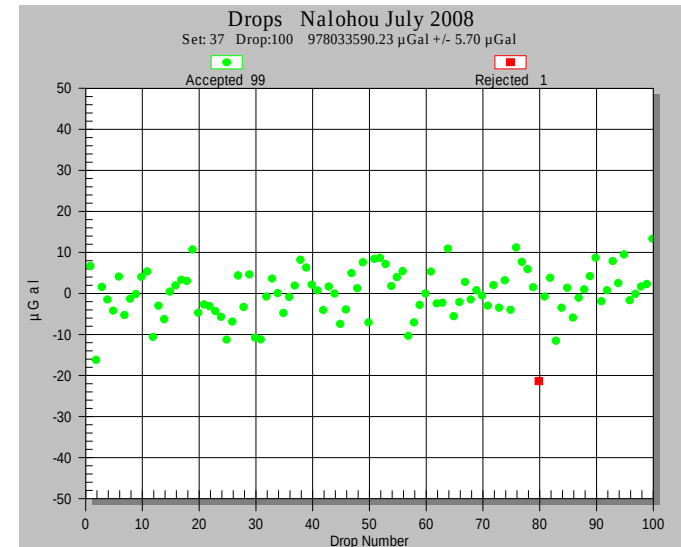
Lake Chad level from Radar altimetry
From *Hydroweb* database (LEGOS, Toulouse, France)

A Chronology of Change Natural and Anthropogenic Factors Affecting Lake Chad

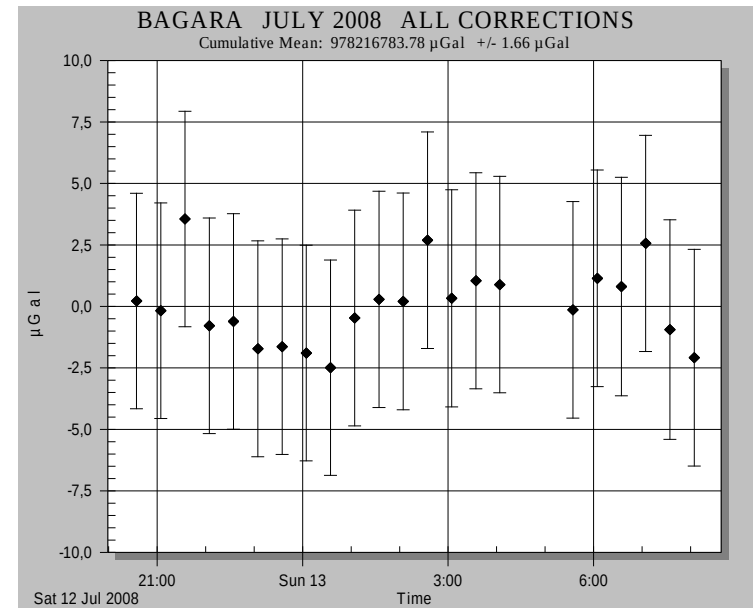
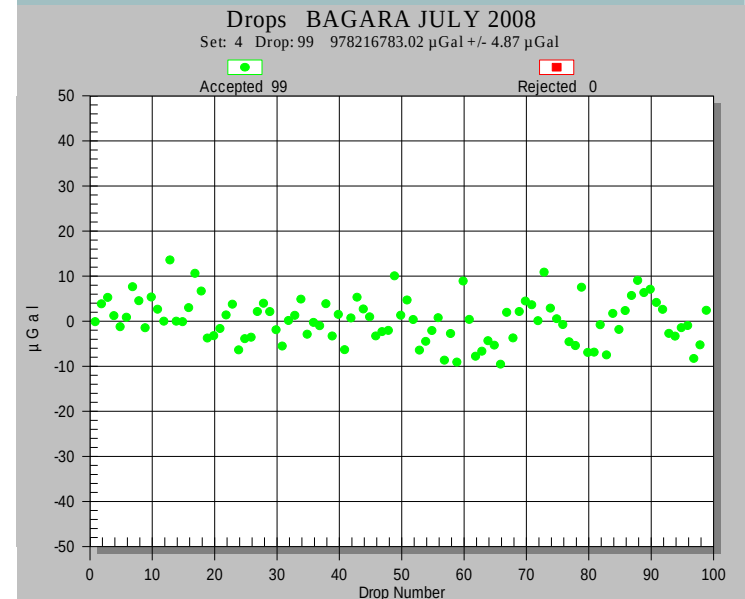


Climatic changes and high demands for agricultural water are responsible for the lake's shrinkage.

Nalohou (near Djougou, Benin)



Bagara (near Diffa, Niger)



Variation annuelle du niveau du lac Tchad et effets géodésiques au sol

Cuvette Nord
5300 km²
0.65 m

Cuvette Sud
7700 km²
1.34 m

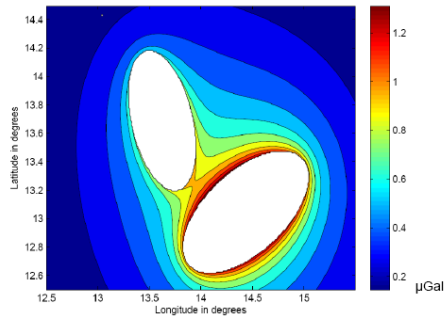


Figure 2 Variation élastique du champ de pesanteur dans la région du Lac Tchad

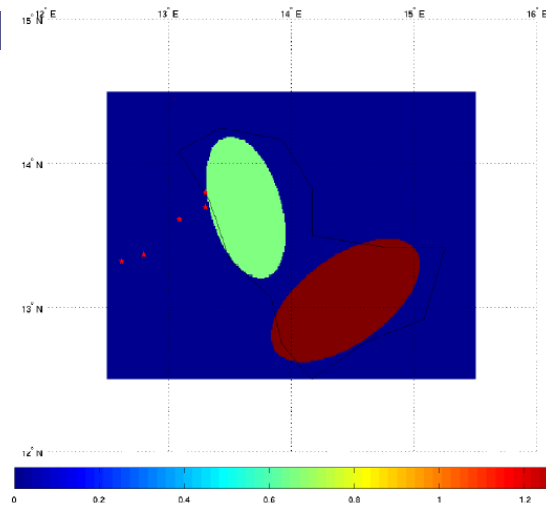


Figure 1 Modélisation de la variation annuelle de lame d'eau du Lac Tchad

Min,max 1999

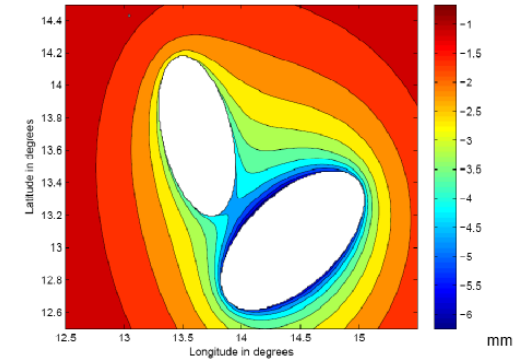


Figure 3 Déplacement vertical dans la région du Lac Tchad



	Unité	Point 1	Point 2	Point 3	Point 4	Point 5
Latitude	degré	13,32	13,37	13,61	13,7	13,8
Longitude	degré	12,62	12,8	13,09	13,3	13,3
Altitude	m	26	20	14	2	0
Distance au lac	Km	82	55	33	2	1
Δg^N	μGal	0,05	0,05	0,07	0,1	0,1
Δg^E	μGal	0,2	0,3	0,4	0,6	0,7
Δg_{tot}	μGal	0,25	0,35	0,47	0,7	0,8
u_r	mm	-1	-1	-2	-3	-3

Rainfall observations (1988-2008)



Sahel hydrology
conditions

Diffa (Niger)



Wankama, near
Niamey (Niger)



Monsoon hydrology
conditions

Djougou (Benin)

