Hydro-Geodesy

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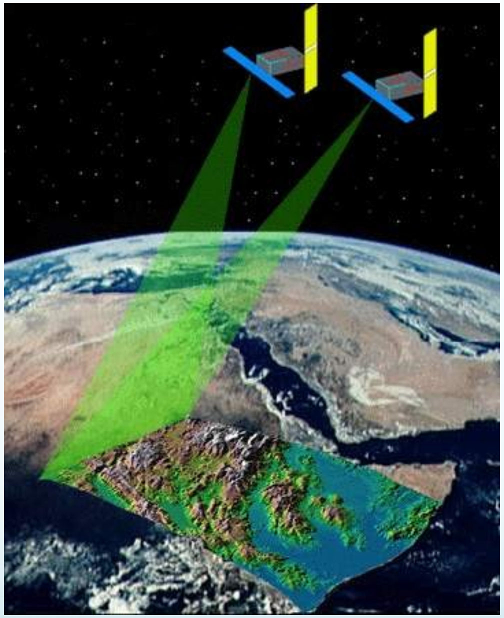
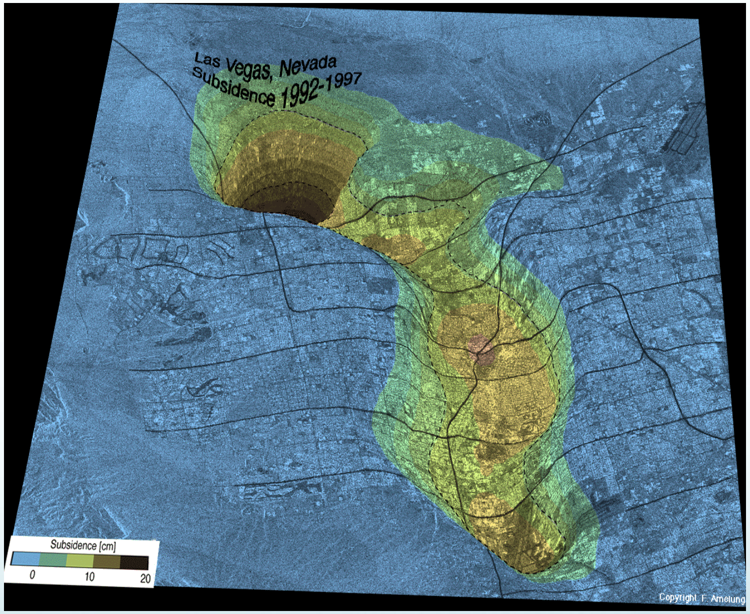
University of Miami



Geodetic observations



Hydrological interpretations

Lecture content

- Introduction
  - The water cycle
  - Geodetic observations – examples
- Geodetic techniques used in hydro-geodesy
  - Altimetry – Rivers and Lakes
  - GRACE – Regional water budgets
  - InSAR – Surface flow, ground water, soil moisture, wetlands
  - Others techniques: GPS, Lidar
- Hydro-Tectonic
  - Improving tectonic observations
  - A new mode of postseismic deformation
- Summary

Why study Hydrology

- Water is one of the most basic requirements for life on planet Earth.
- Human society depends on accessibility water resources.
  - There is a need to monitor the resources and manage them in a sustainable manner.
  - Increasing human population and changing climate stress the available water resources.
- Natural environments (wetlands, streams …) also depend on accessibility to sustainable water resources.
- Water related hazards are threat to the society
  - Too little water - Drought
  - Too much water - Flood

It is extremely important to manage the water resources, mitigate associated hazards and integrate knowledge into water authorities decision process.

The water cycle

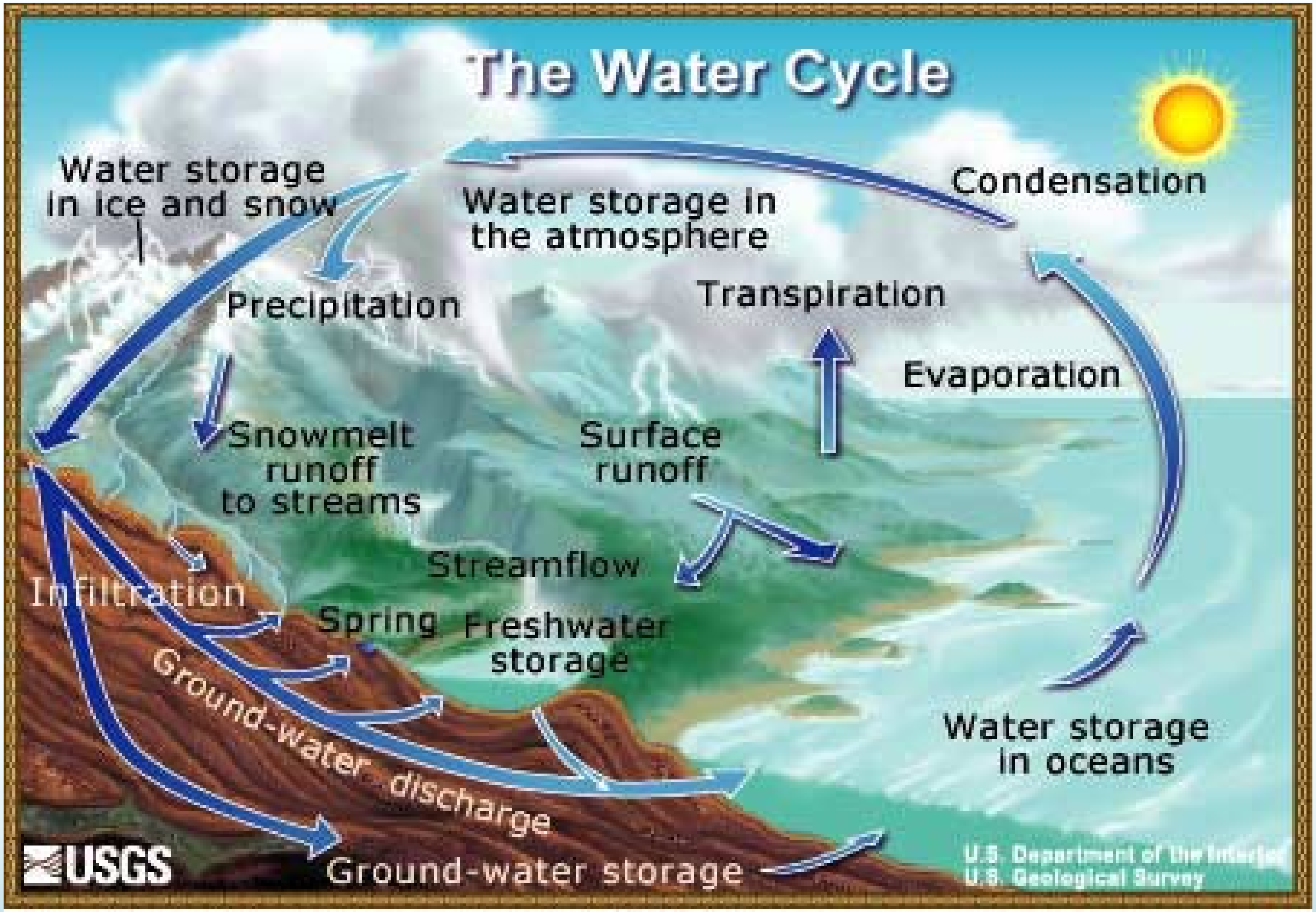
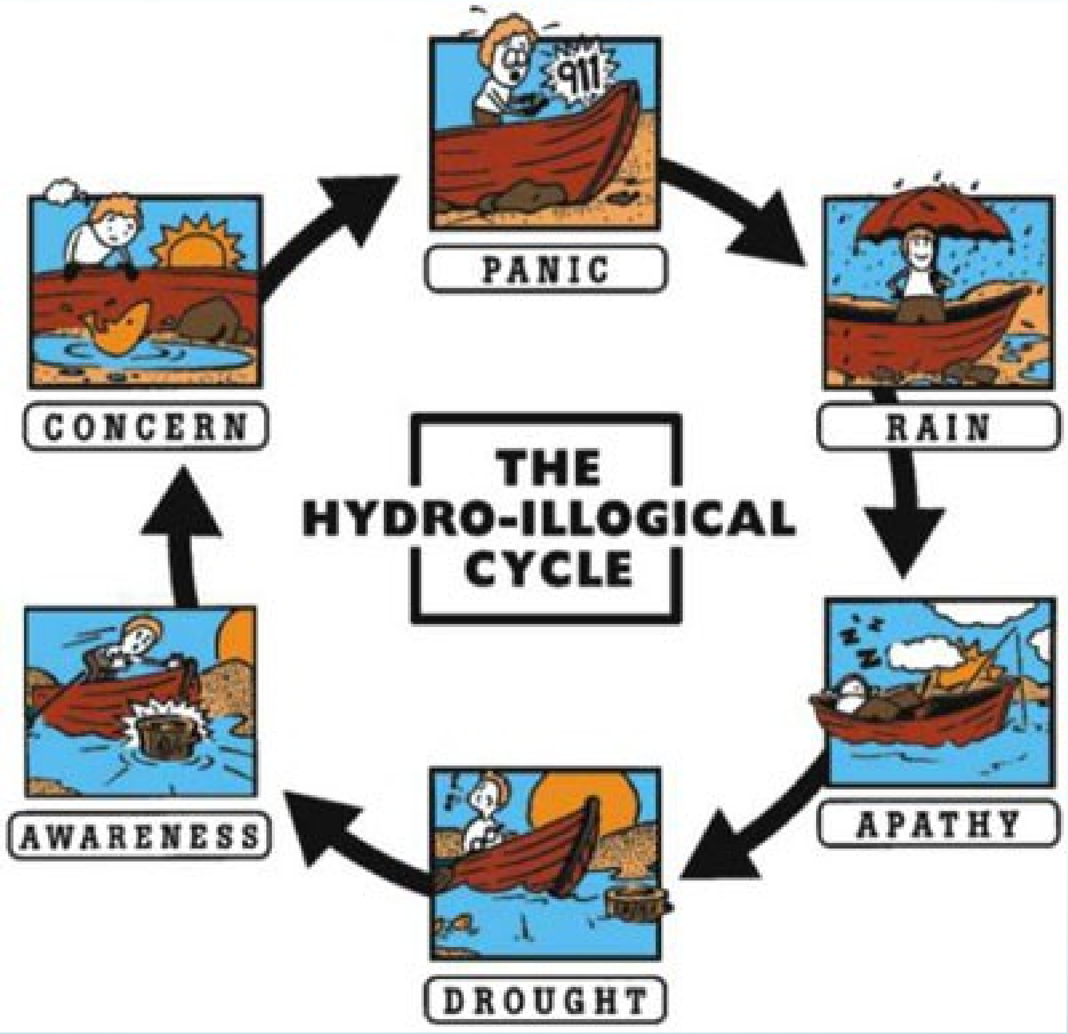


Illustration by John M. Evans, Colorado District, USGS

Atmospheric moisture, snow pack & glaciers, surface water, soil moisture, and groundwater.

The hydro-illogical cycle



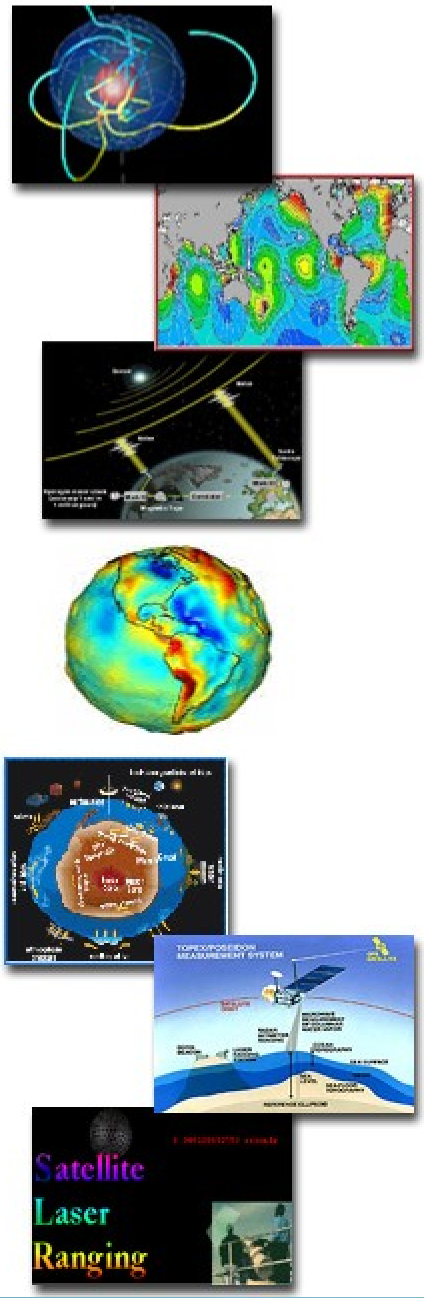
Grand Challenges in Hydrology

The terrestrial hydrologic cycle:

- Atmospheric moisture, groundwater, surface water, soil moisture, snow pack, and glaciers

1. What are the contributions of each component of the water cycle on the global fresh water budget?
2. How do natural and anthropogenic processes redistribute water in both space and time?
3. How can we manage the water resources, mitigate associated hazards and integrate decision support?

- Securing fresh water for
  - increasing human population
  - sustainable natural environments (wetlands, streams …)
- Getting adjusted to the changing climate



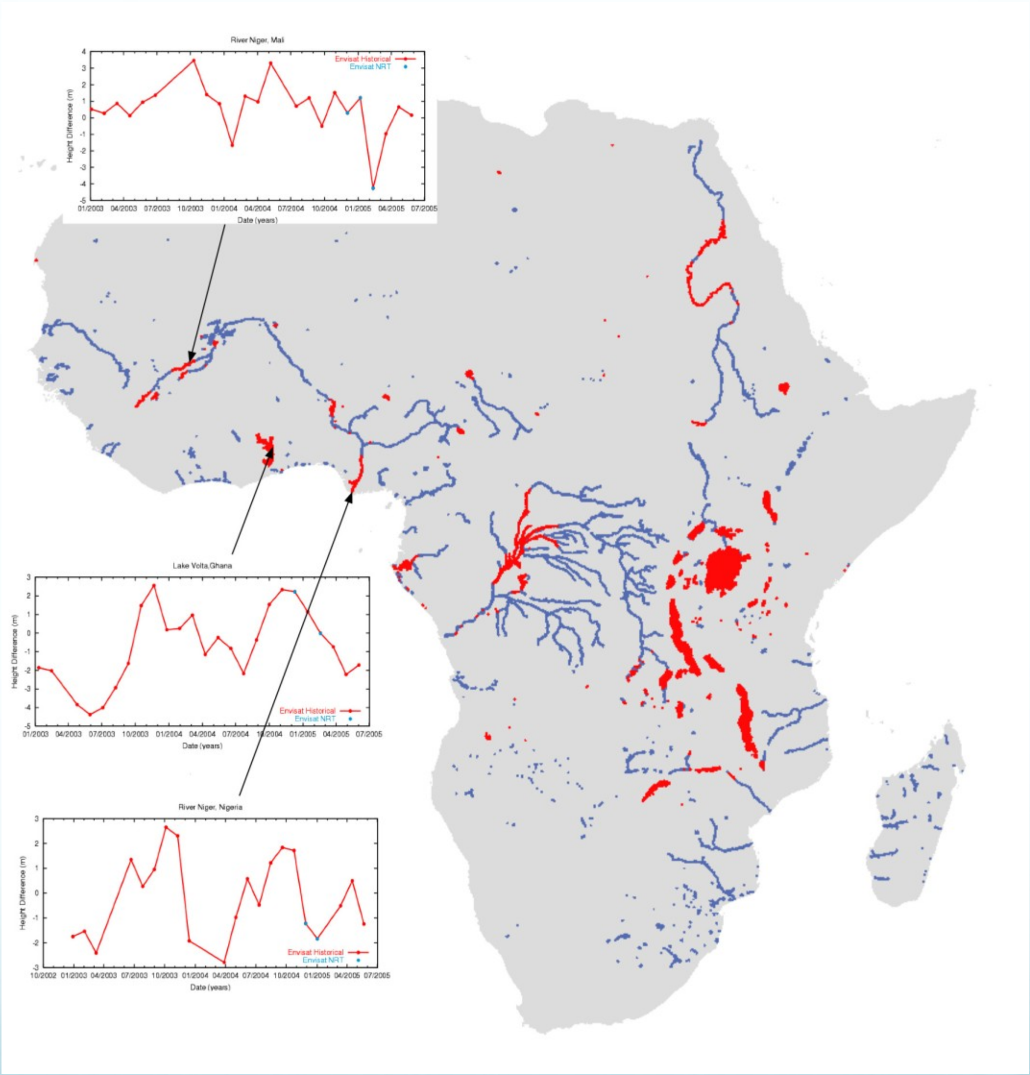
Space technologies

- Positioning techniques (GPS)
- Altimetry (radar & laser)
- Interferometric Synthetic Aperture Radar (InSAR)
- Gravity missions

Terrestrial geodetic technologies

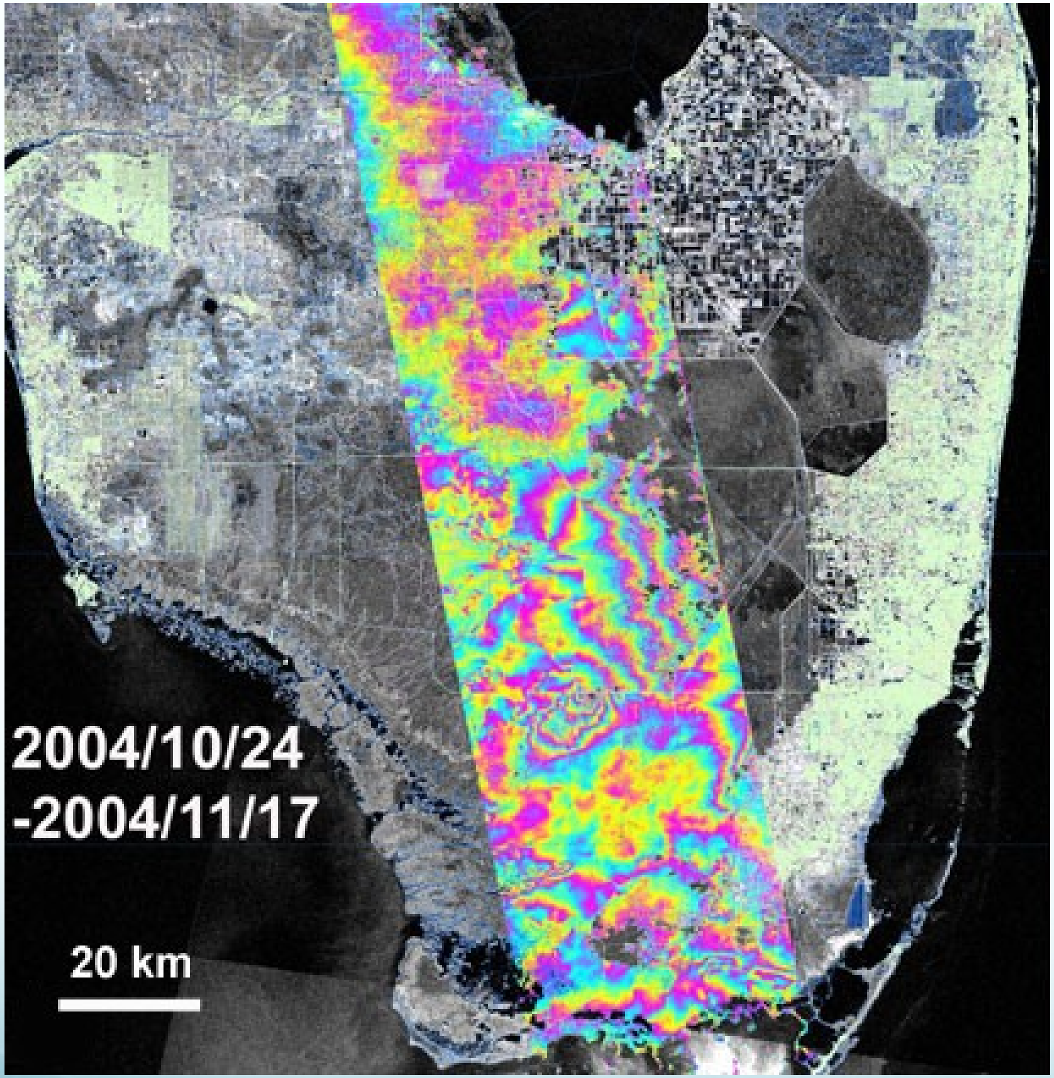
- **Airborne LiDAR**
- **Tripod LiDAR (TLS)**
- **UAVSAR**
- **Surveying techniques (i.e., leveling)**

Surface water level -Radar Altimetry



Remote monitoring of rivers and lakes water levels

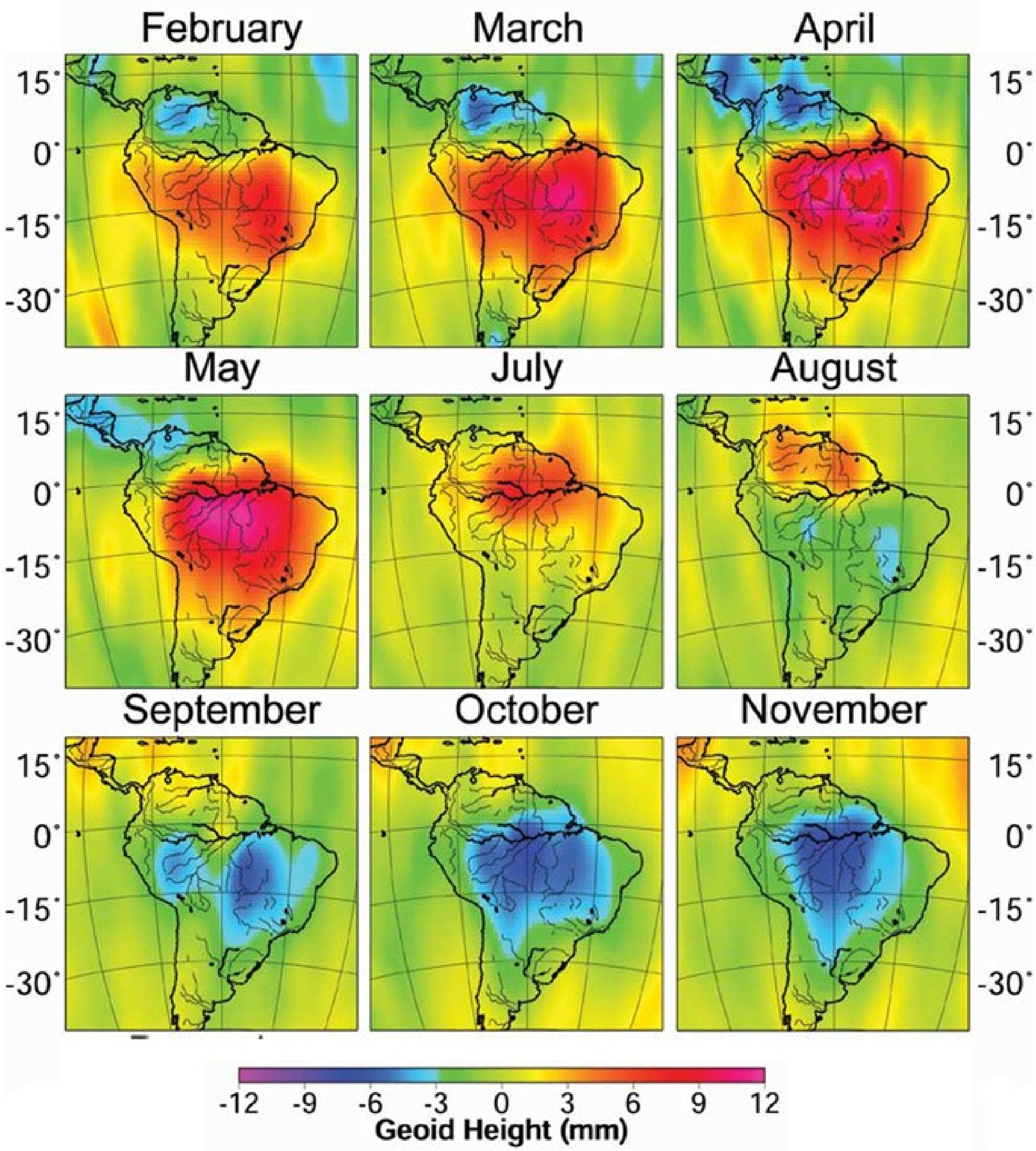
Wetland surface water level changes



Wetlands are fragile and important ecosystem that depends on sufficient water supply.

InSAR monitoring of water resources (Everglades, south Florida)

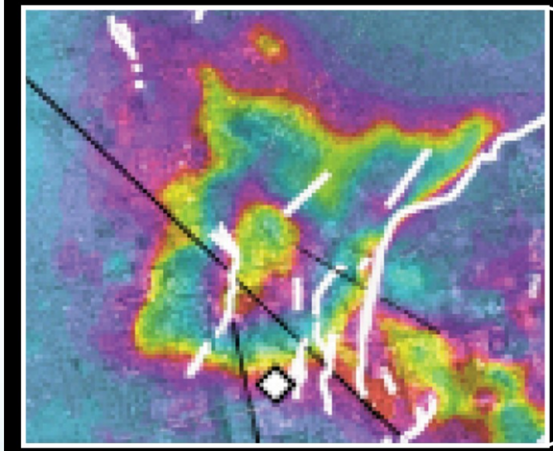
Integrated water budget – GRACE

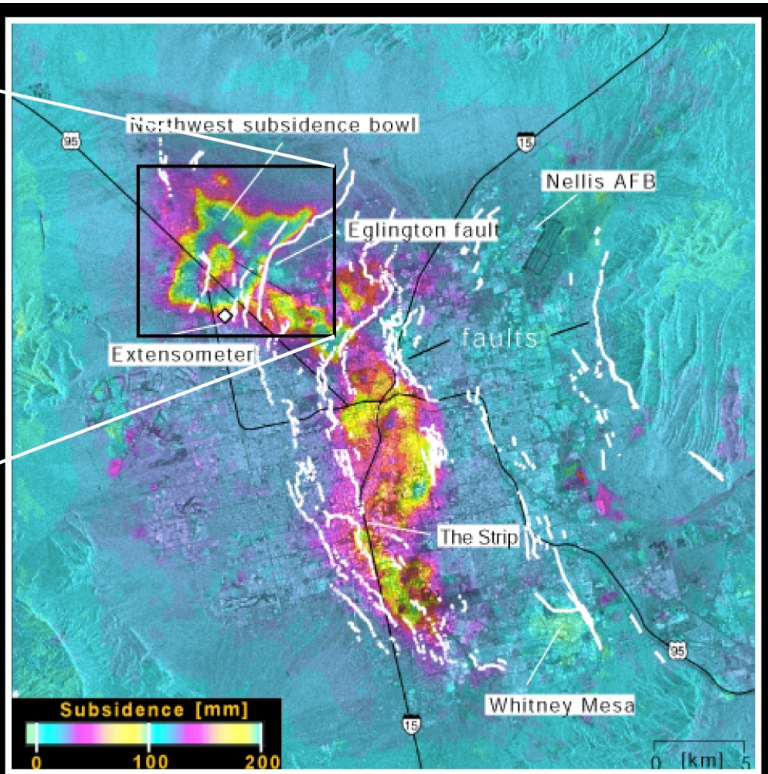


Monthly mean integrated water storage change w.r.t a reference mean field over the Amazon basin.

Subsidence due to groundwater withdrawal – InSAR

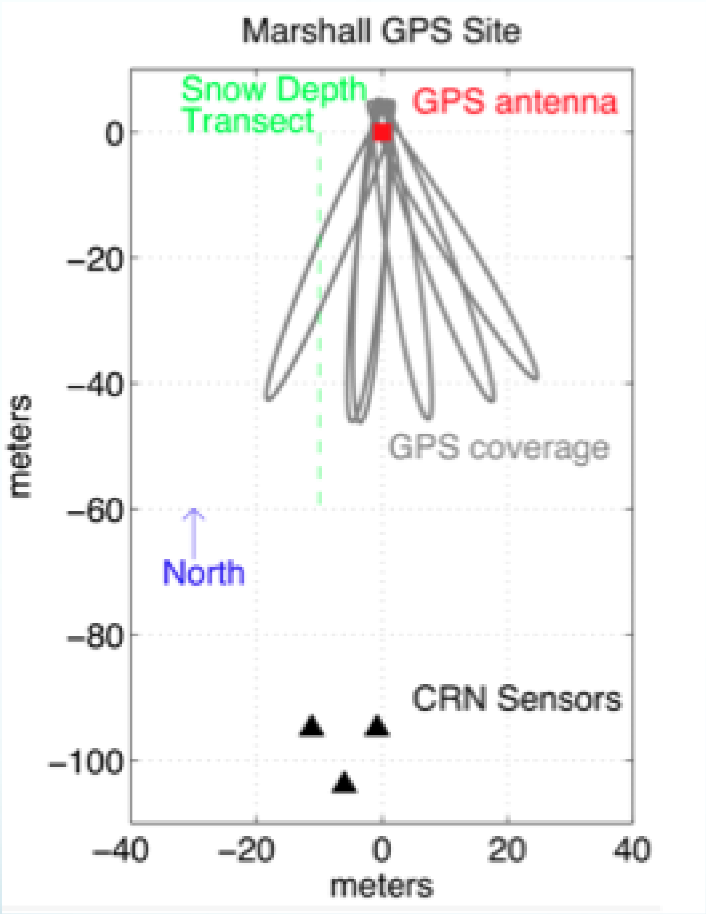
Differential Subsidence across the Eglington fault (Las Vegas)



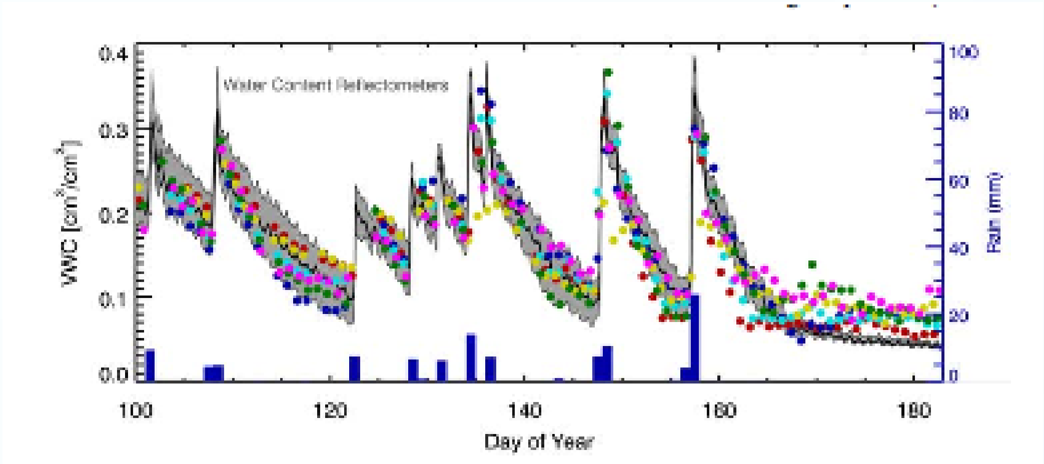


pubs.usgs.gov/of/ 2005/1428/

Soil Moisture – GPS monitoring



Larson (2008)



- Based on multipath observations.
- High temporal resolution.
- L-band – represents the upper 10-20 cm.
- Average moisture value of circular area with radius of ~40 m (standard tensiometers are point measurements).
- The method works also for snowpack monitoring

Hydro-Geodesy Applications

Atmospheric Moisture
InSAR
CGPS

Snow Pack/Avalanche
InSAR/UAVSAR
LiDAR - Airborne/Tripod

Surface water
SAR/InSAR
LiDAR – Airborne/Tripod
CGPS/RTK GPS
Altimetry – Radar/Laser
Gravity - GRACE

Cryosphere
SAR/InSAR
LiDAR
Altimetry

Soil Moisture
SAR/InSAR
CGPS

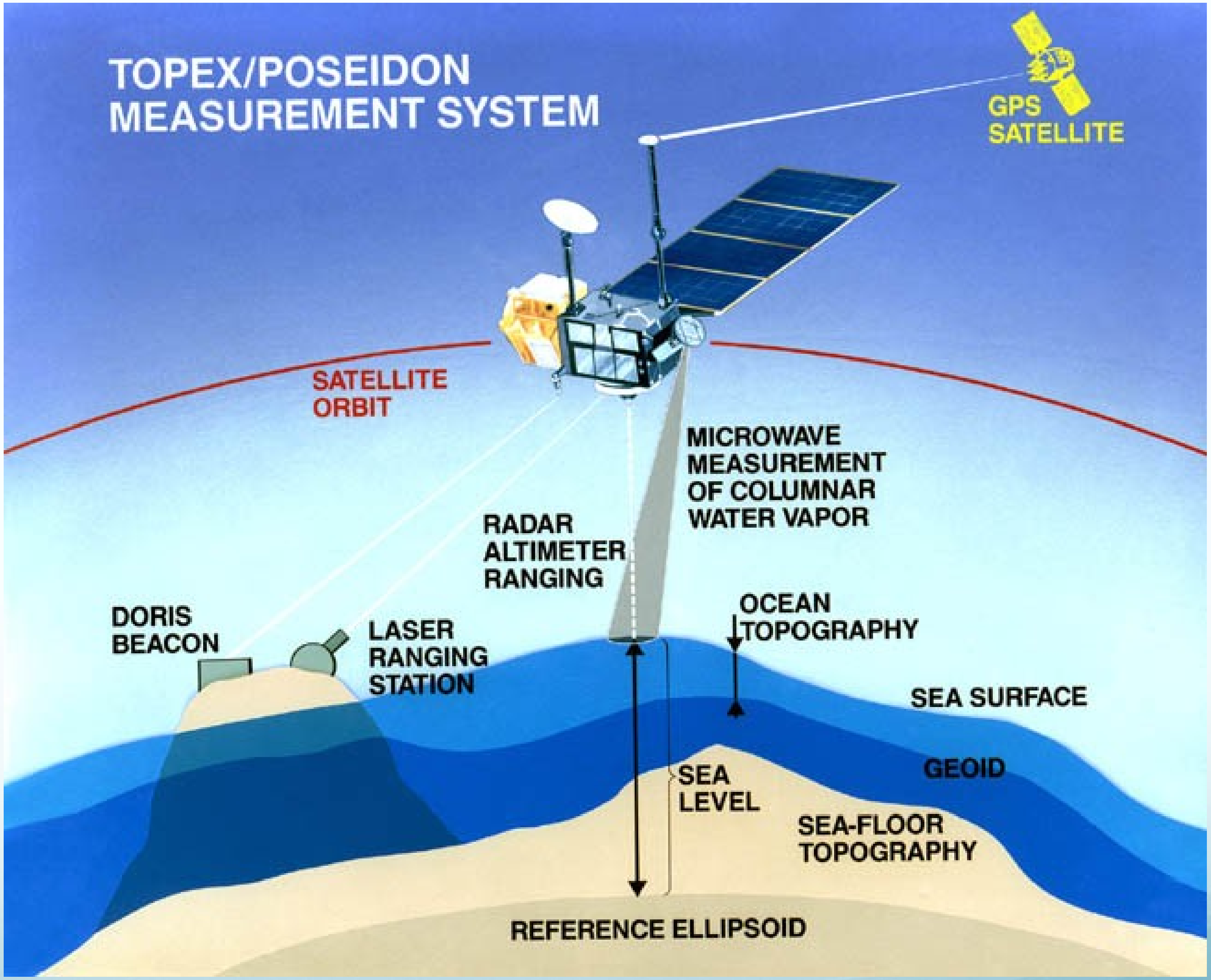
Groundwater
GRACE
InSAR
LiDAR – Airborne/Tripod
Leveling
GPS - all forms

Space geodetic techniques

Radar Altimetry

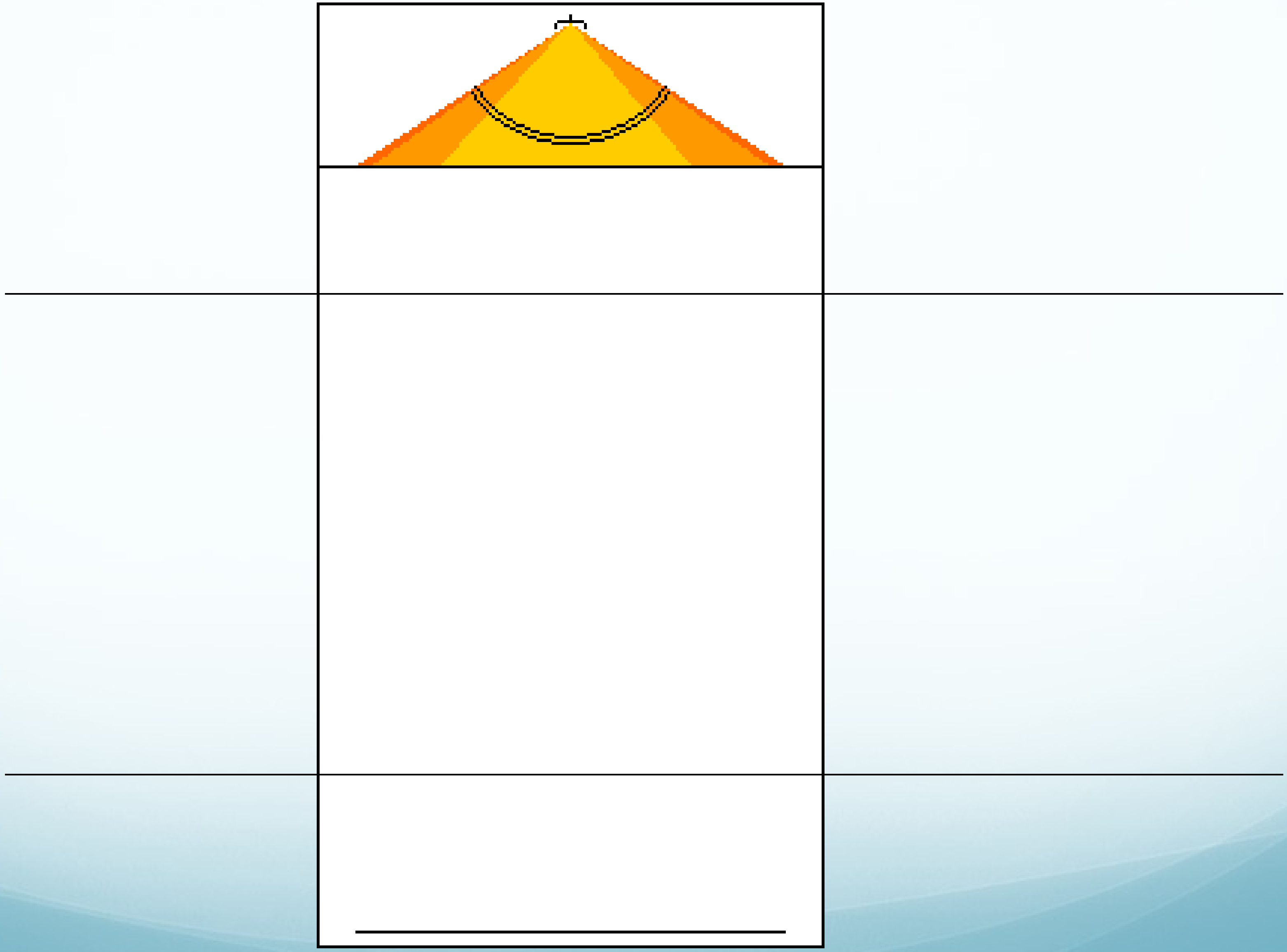
What is satellite altimetry?

By means of a nadir looking radar we measure the reflection of short pulse in the footprint. This footprint is about 4 to 8 kilometer in diameter.



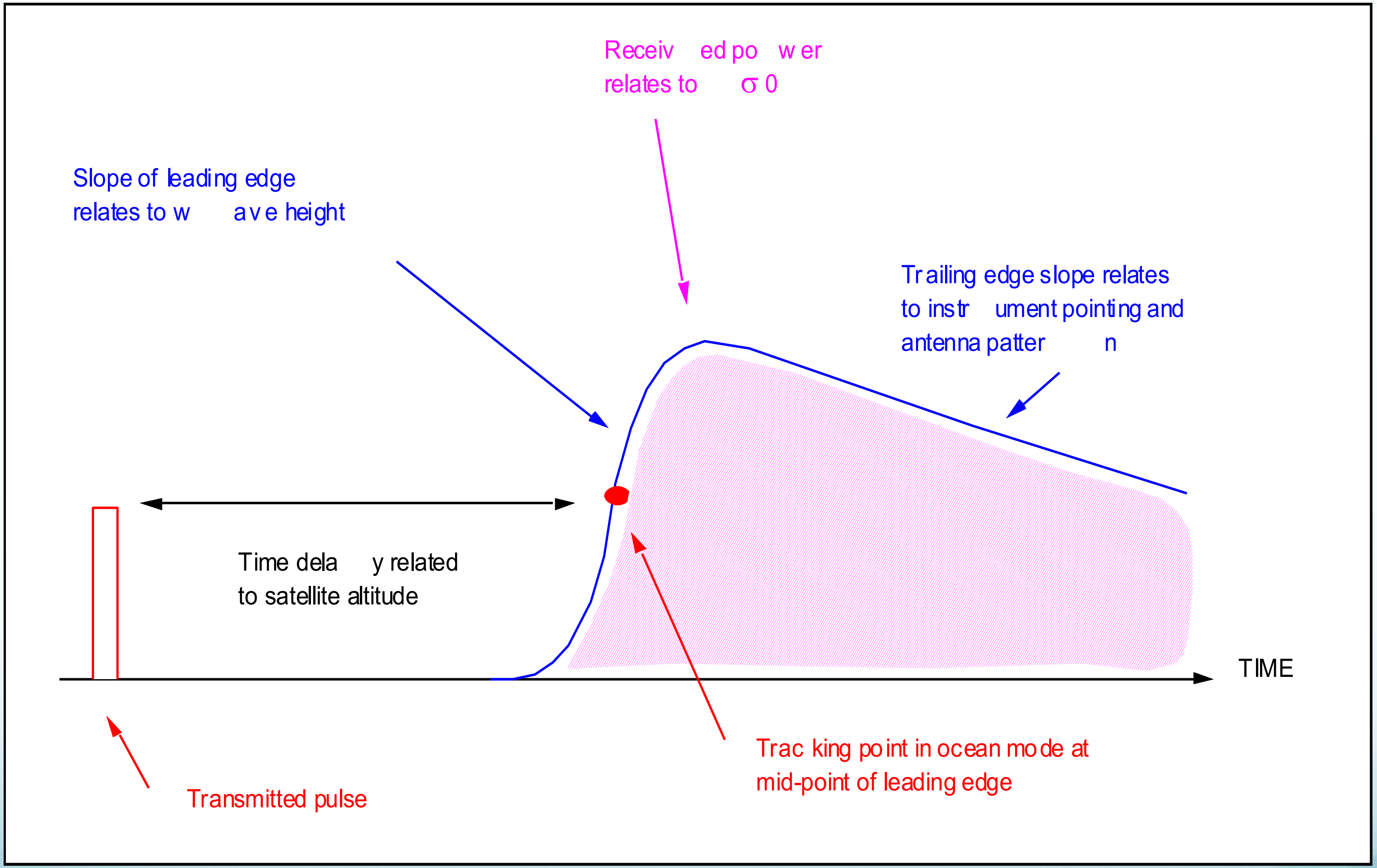
Source: JPL

Radar Altimetry Principle

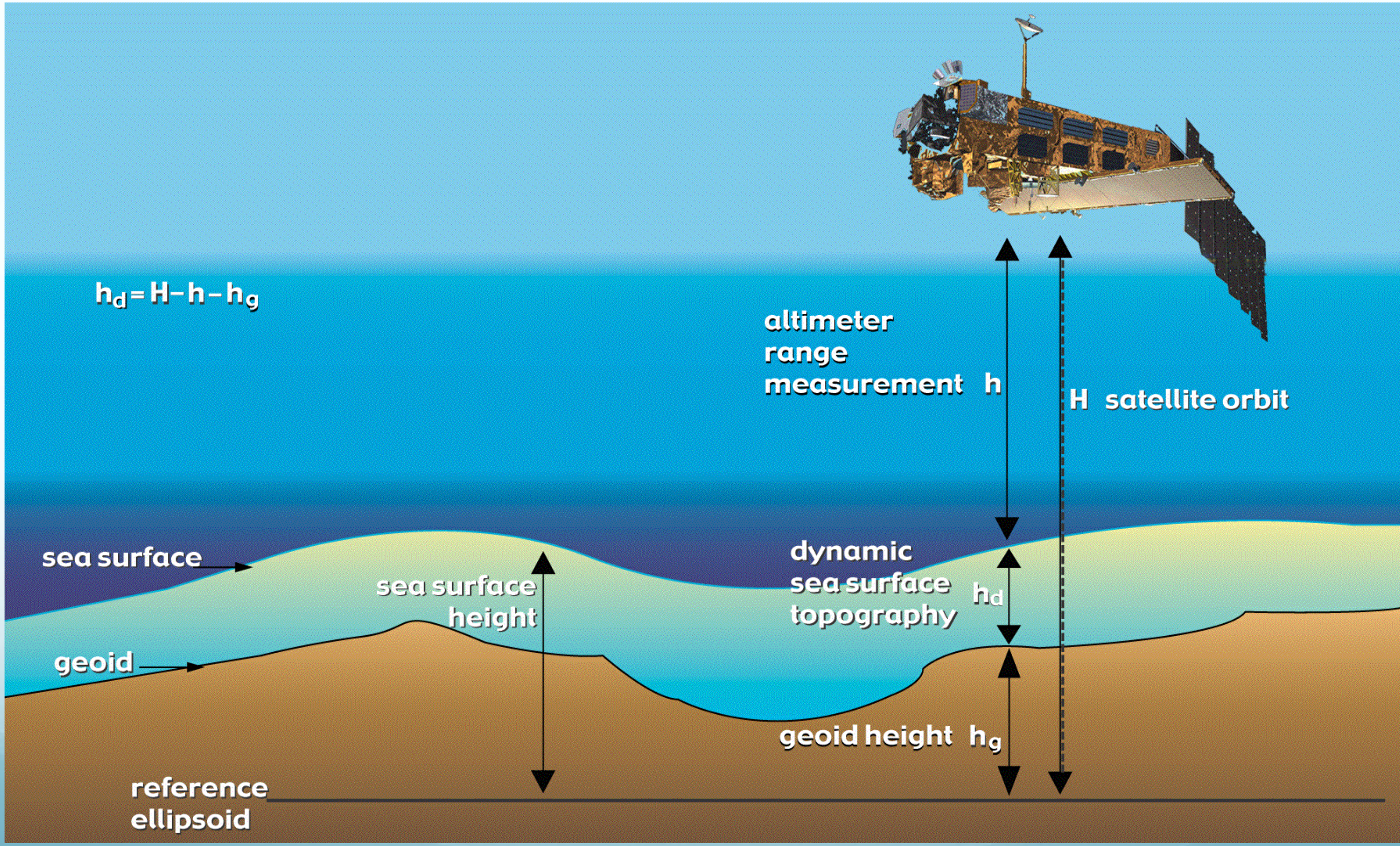


This is an animation

Return Power Waveform



Radar Altimetry Principle



Vertical Datum Applications

- H_i (sea level over ellipsoid) = Horbit - Hrange + E_r

  $= S_g + S_s + S_v + S_t + E_o + E_r$

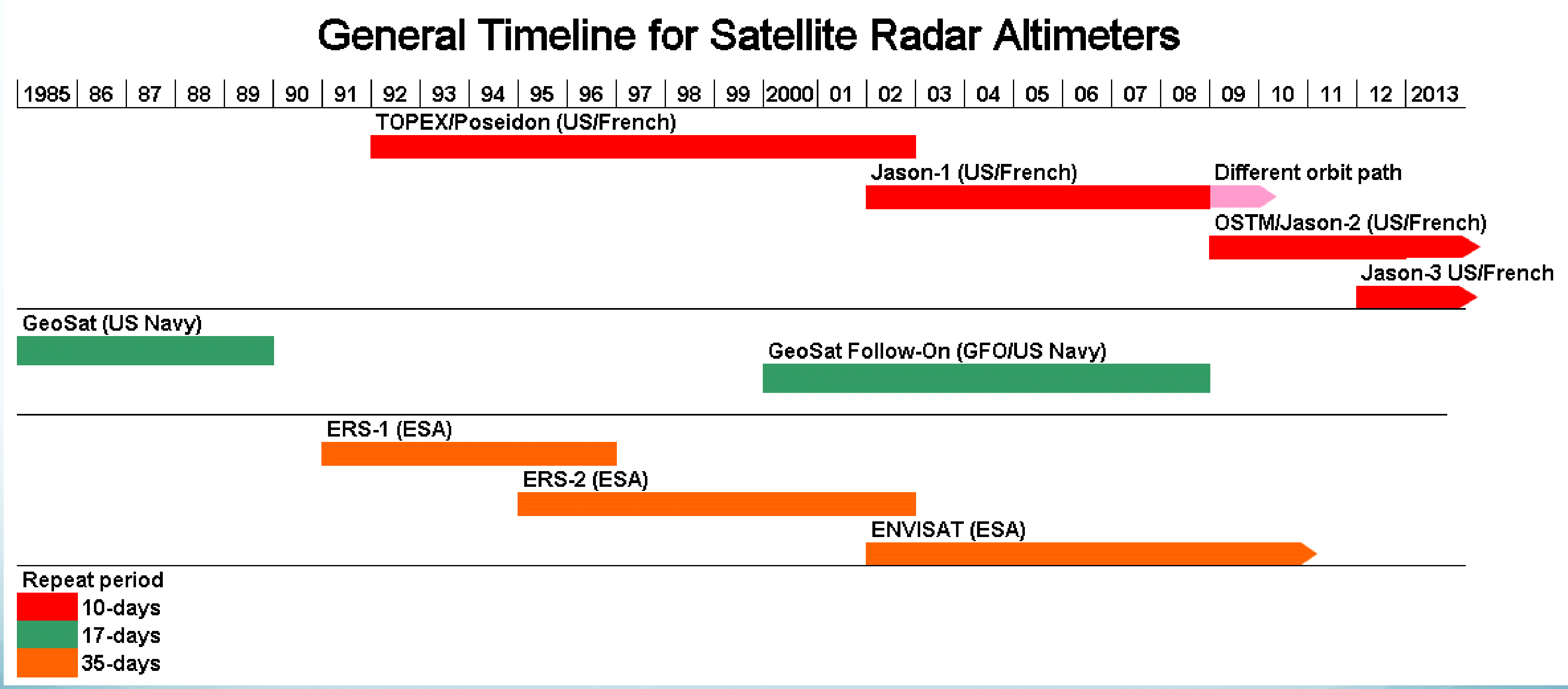
  with S_g = Geoid signal
  S_s = Stationary signal
  S_v = Variability
  S_t = tides signal
  E_0 = Orbital error
  E_r = remaining errors and corrections
  (solid tides, loading effect, inverse barometer effect,...)

- Leads to different types of oceanographic analysis:
  - Meso-scale dynamic topography (currents, eddies, kinetic energy, ...)
  - Large scale topography/large scale variability (basin gyres, strong currents, mean sea level, mean sea level rise?!,...)
  - stationary signal (mean reference surface, estimation of the stationary dynamic topography)
  - tides study (hydrodynamic models constrained by altimetric data)
  - Assimilation to dynamic models of the oceanic circulation

Vertical Datum Applications

- Glaciology
  - DEM, Delta-DEM
  - Input data for forcing, initialisation or test of ice flow dynamic models
  - Long term monitoring of the topography for seasonal or secular variations.
  - Sea-ice thickness
- Land topography
  - Global DEM obtained from the full 336 days of the ERS-1 geodetic phase (most accurate Global DEM)
- Rivers and Lakes level
  - Long term, global, surface water monitoring
  - Study of the response of lakes to climate for water resources management, fisheries, water quality and conservation

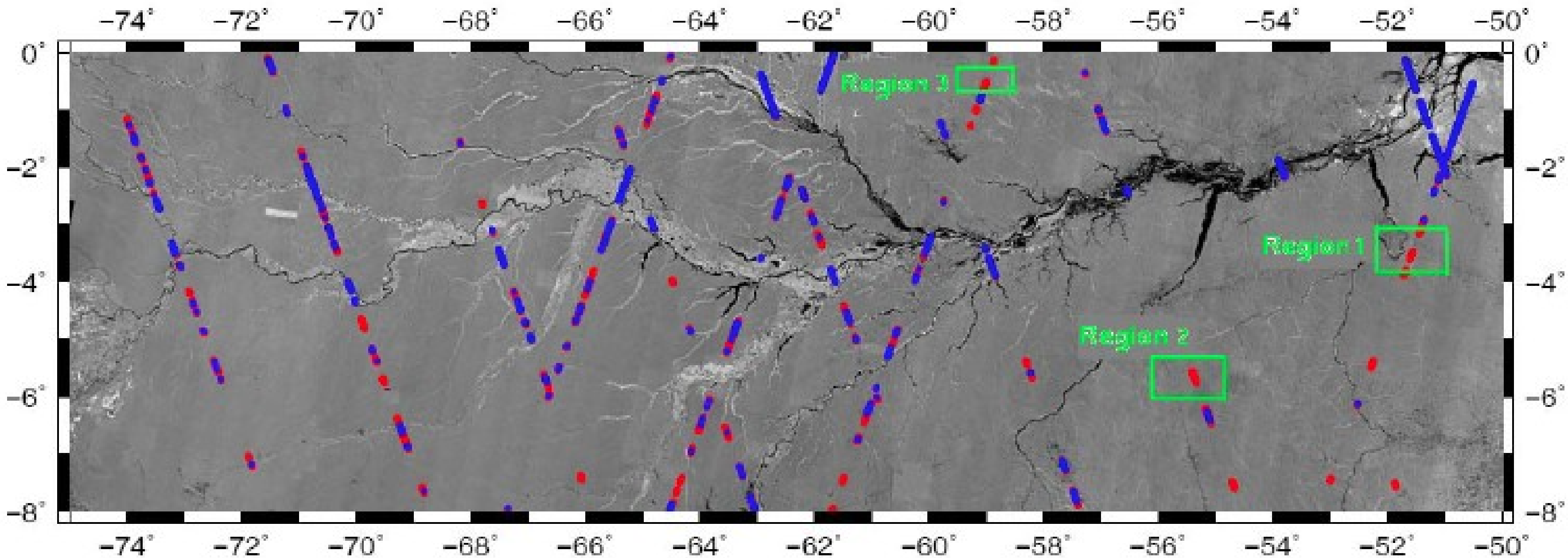
Past and Current altimeter satellites



Past and Current altimeter satellites

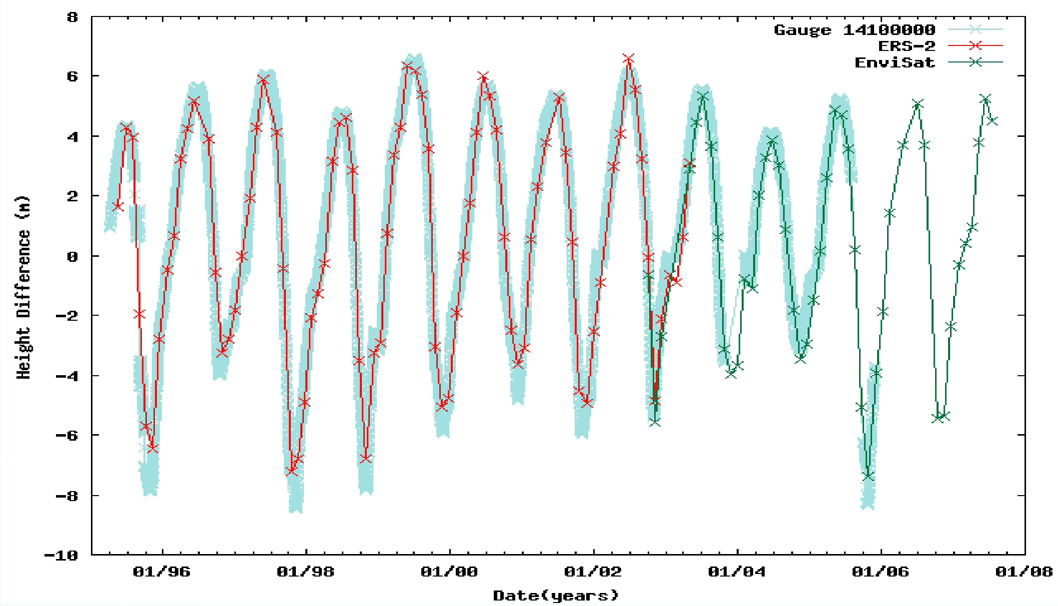
Satellite	Years	Organisation	Accuracy
SKYLAB	1972	NASA	20 m
GEOS-3	1975-1978	NASA	3 m
SEASAT	1978	NASA	2 m
GEOSAT	1985-1990	US Navy	30 cm
ERS-1	1991-1996	ESA	4-10 cm
ERS-2	1995-2006	ESA	4 cm
T/P	1992-2005	NASA/CNES	2 .. 3 cm
GFO	2000-	US Navy	2 .. 5 cm
JASON	2001-	NASA/CNES	2 .. 3 cm
ENVISAT	2002-	ESA	2 .. 3 cm

Altimetry tracks



Amazon basin

Validation over Amazon basin



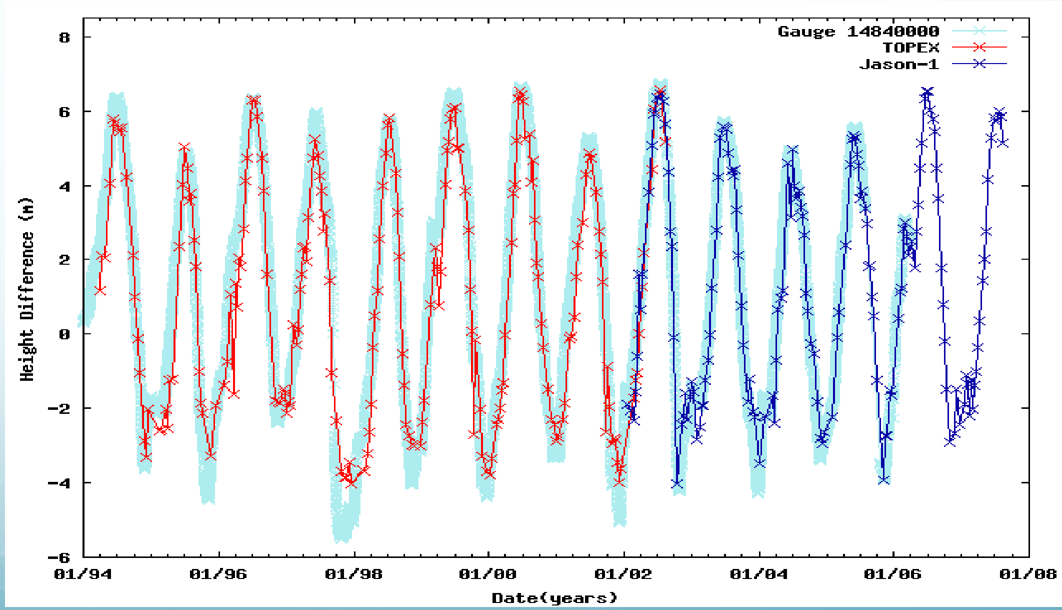
ERS-2 (red): RMS against Gauge: 0.6269m,
Correlation: 0.9878

EnviSat:(green) RMS against Gauge: 0.4724m,
Correlation: 0.9905

- Gauge data plotted in grey-blue

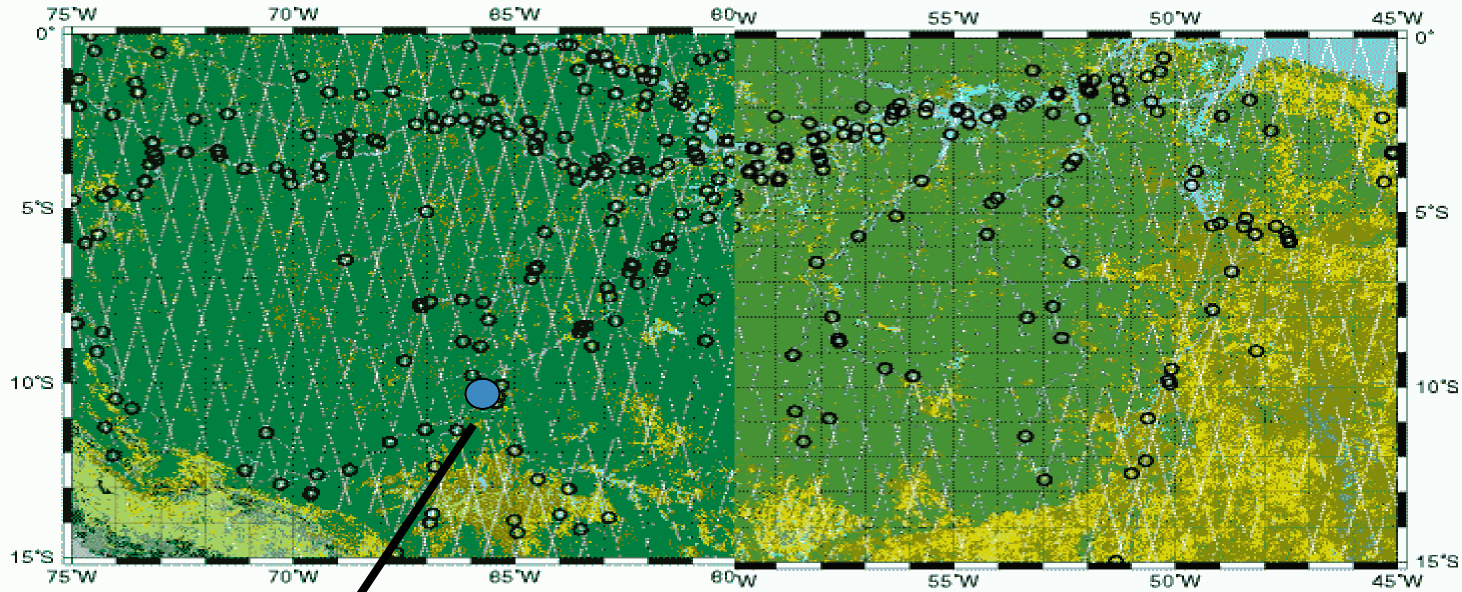
TOPEX (red): RMS against Gauge : 1.8376m,
Correlation: 0.8611

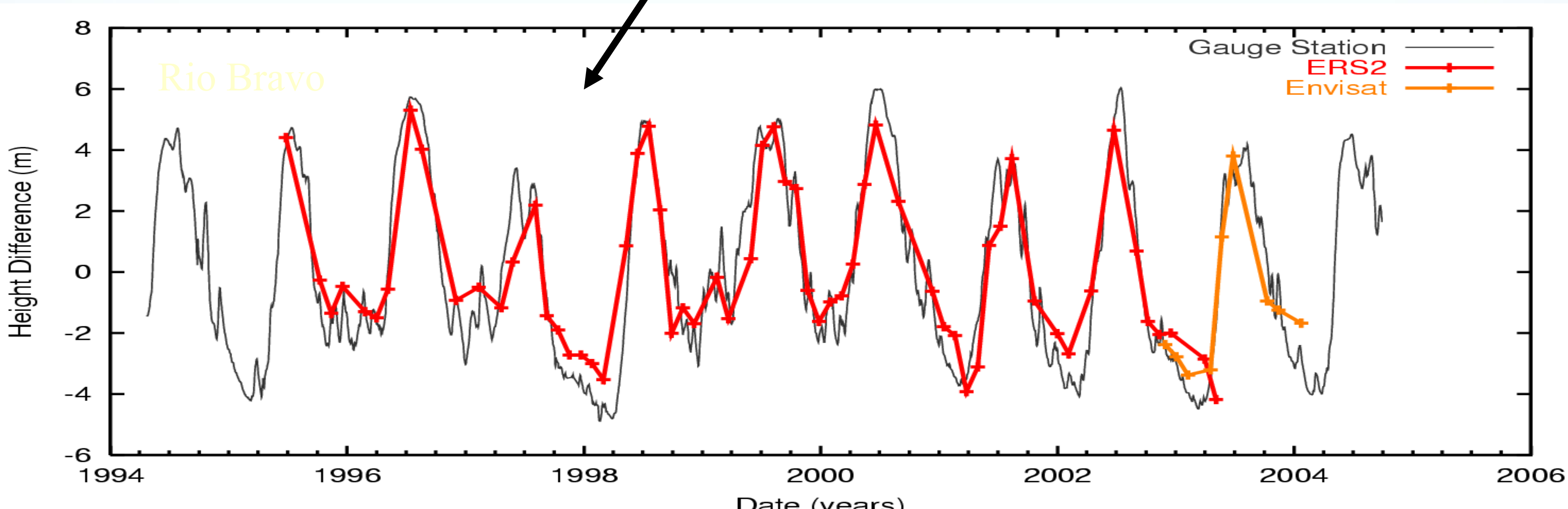
Jason-1 (dark blue): RMS against Gauge:1.2198m,
Correlation: 0.9283



Altimetric Time-Series

192 time series with 95% temporal coverage in the Amazon.
Interpolate to 10 days sampling





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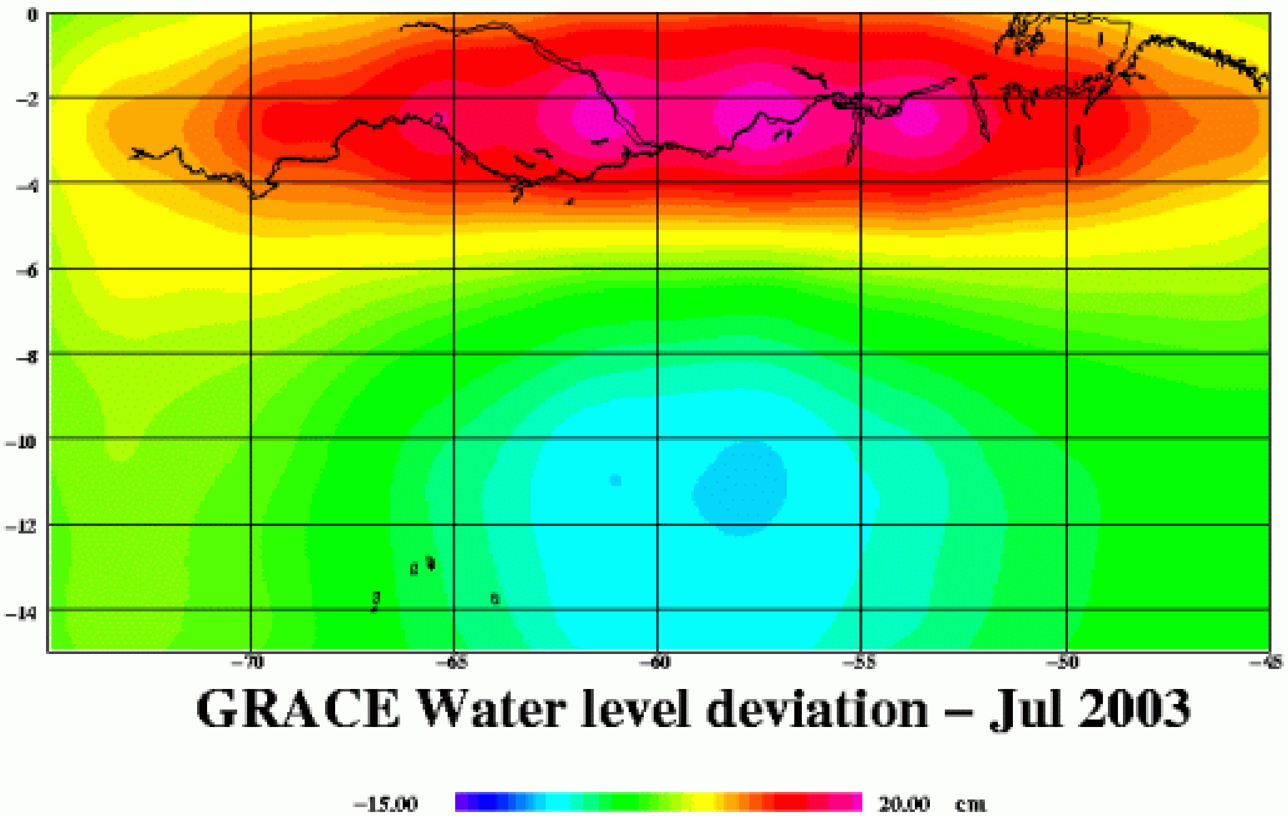
Water level time-series from GRACE



This is an animation

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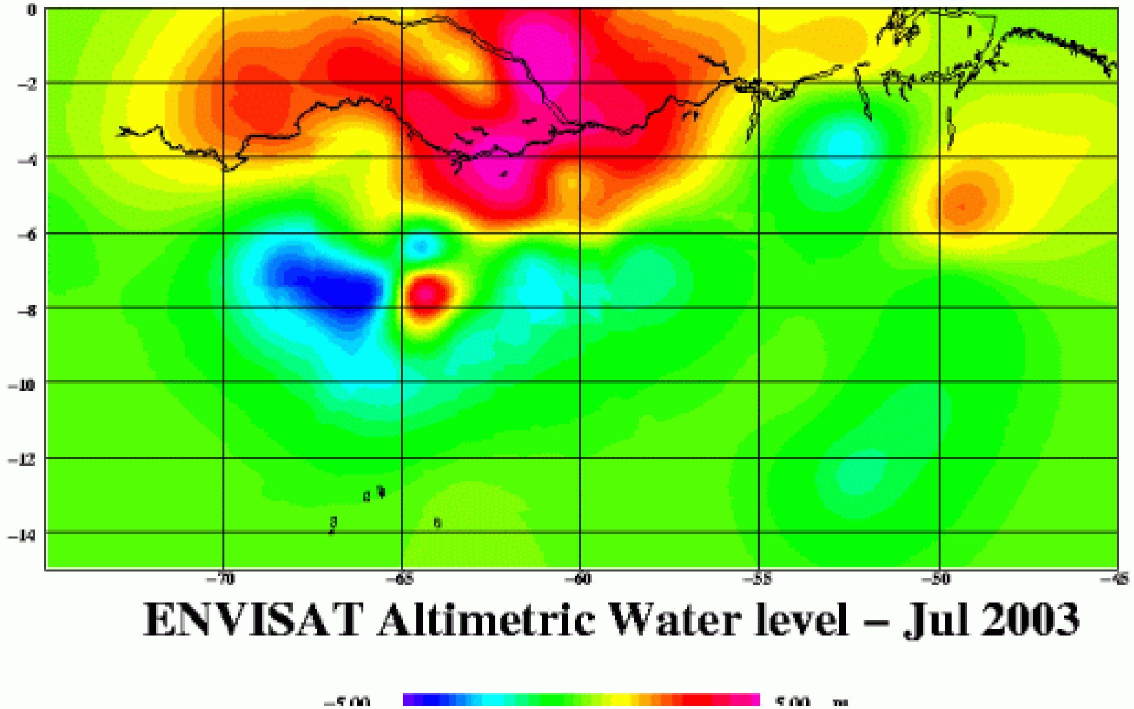
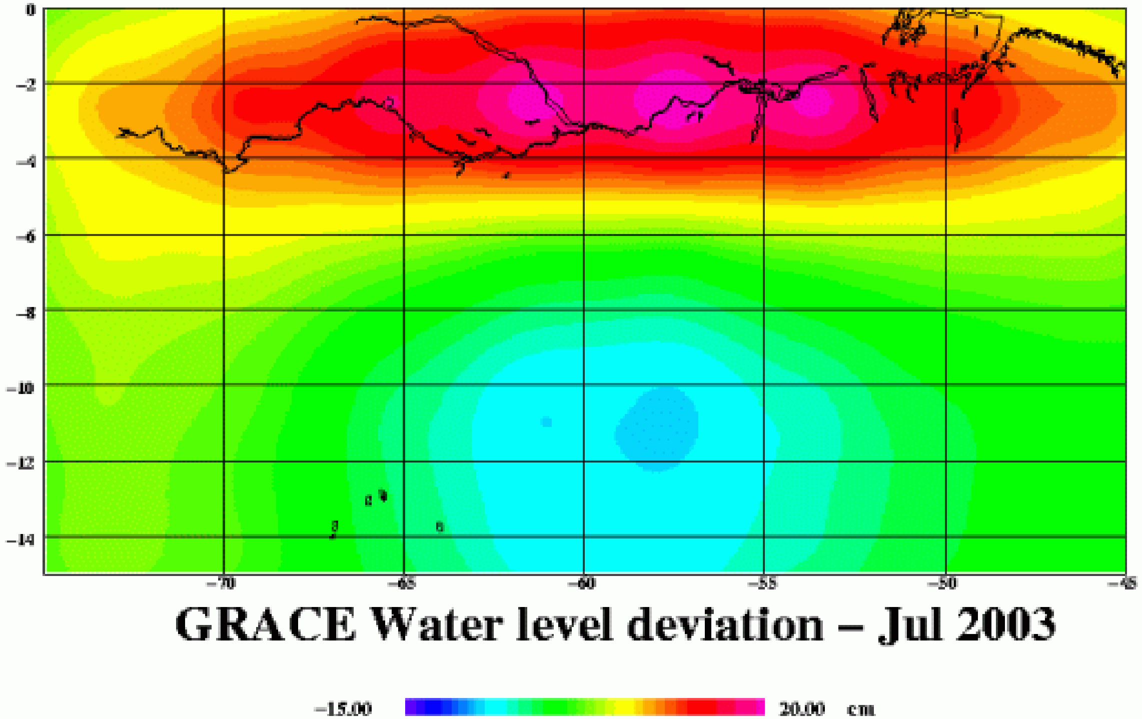
- ERS
- ENVISAT

This is an animation

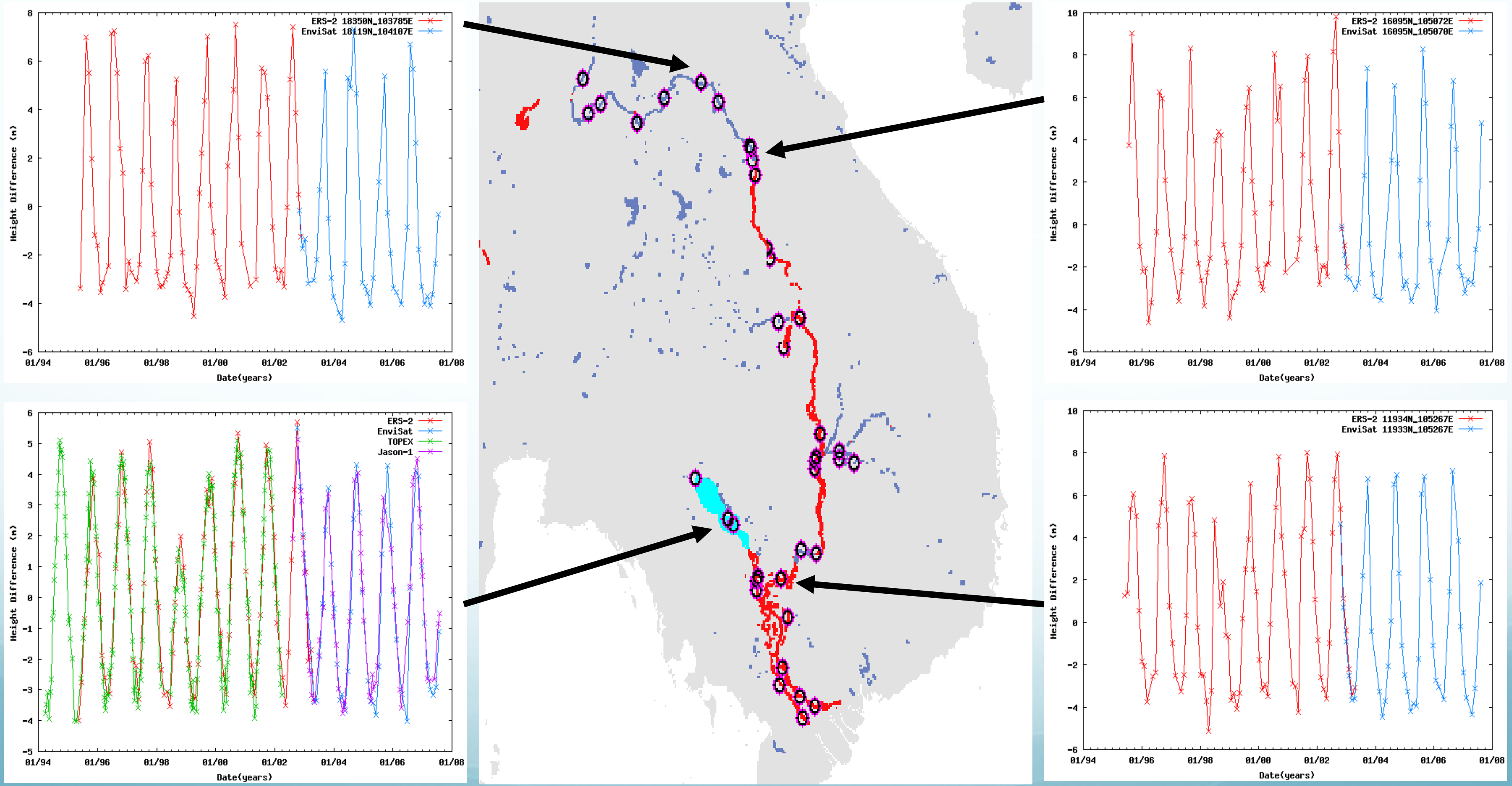
- GRACE





Mekong and Tonle Sap

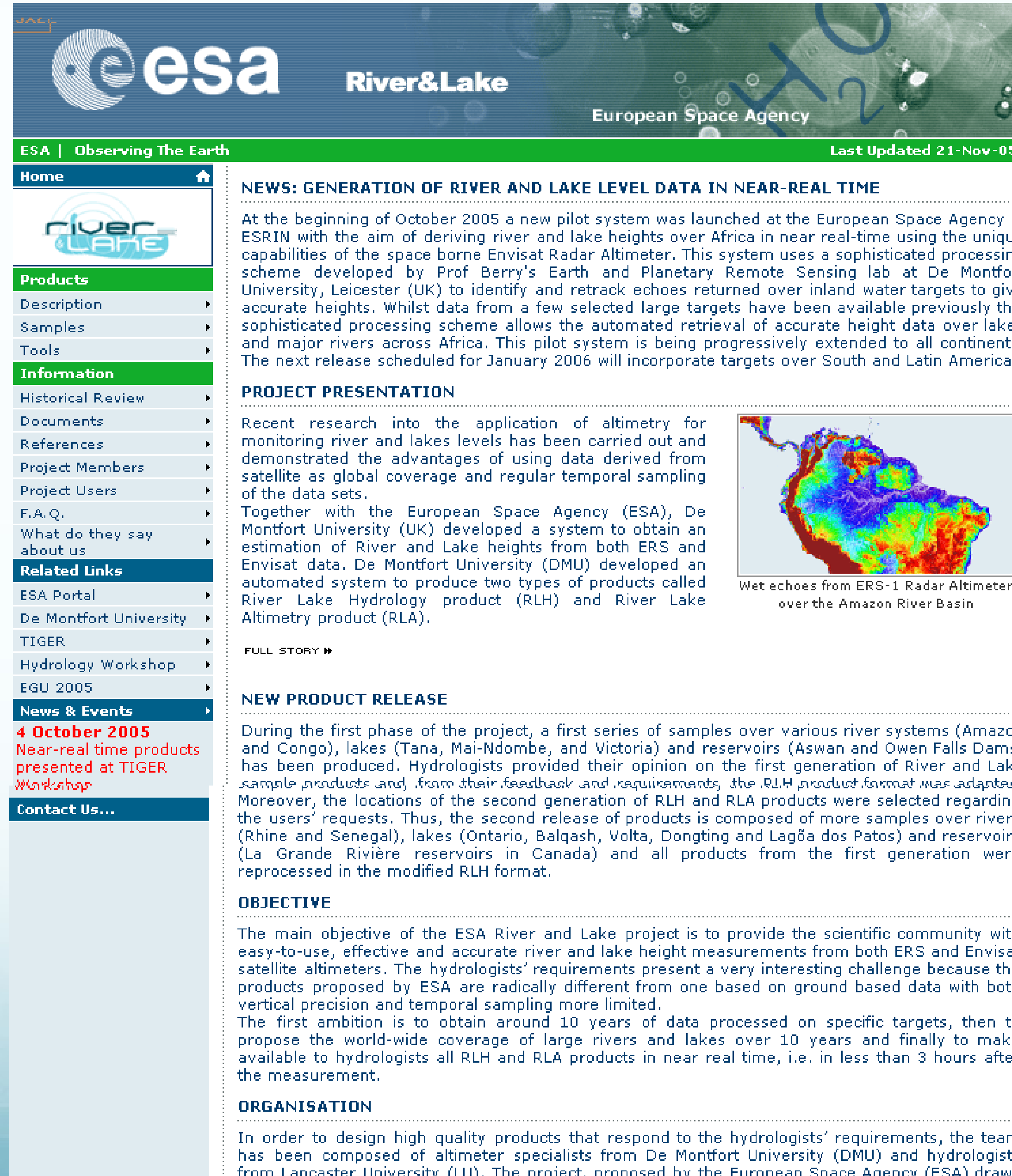
Multi-mission data over Tonle Sap (ERS-2 + Envisat + TOPEX + Jason-1) and on Mekong (ERS-2 + Envisat: each circle is time series)



"River & Lake" Website

Information and Data Products Request:

http://earth.esa.int/riverandlake


esa River&Lake European Space Agency

ESA | Observing The Earth Last Updated 21-Nov-05

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- De Montfort University
- TIGER
- Hydrology Workshop
- EGU 2005

News & Events

4 October 2005
Near-real time products presented at TIGER Workshop

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NEWS: GENERATION OF RIVER AND LAKE LEVEL DATA IN NEAR-REAL TIME

At the beginning of October 2005 a new pilot system was launched at the European Space Agency in ESRIN with the aim of deriving river and lake heights over Africa in near real-time using the unique capabilities of the space borne Envisat Radar Altimeter. This system uses a sophisticated processing scheme developed by Prof Berry's Earth and Planetary Remote Sensing lab at De Montfort University, Leicester (UK) to identify and retrack echoes returned over inland water targets to give accurate heights. Whilst data from a few selected large targets have been available previously this sophisticated processing scheme allows the automated retrieval of accurate height data over lakes and major rivers across Africa. This pilot system is being progressively extended to all continents. The next release scheduled for January 2006 will incorporate targets over South and Latin America.

PROJECT PRESENTATION

Recent research into the application of altimetry for monitoring river and lakes levels has been carried out and demonstrated the advantages of using data derived from satellite as global coverage and regular temporal sampling of the data sets.
Together with the European Space Agency (ESA), De Montfort University (UK) developed a system to obtain an estimation of River and Lake heights from both ERS and Envisat data. De Montfort University (DMU) developed an automated system to produce two types of products called River Lake Hydrology product (RLH) and River Lake Altimetry product (RLA).

Wet echoes from ERS-1 Radar Altimeter over the Amazon River Basin

FULL STORY

NEW PRODUCT RELEASE

During the first phase of the project, a first series of samples over various river systems (Amazon and Congo), lakes (Tana, Mai-Ndombe, and Victoria) and reservoirs (Aswan and Owen Falls Dams) has been produced. Hydrologists provided their opinion on the first generation of River and Lake sample products and, from their feedback and requirements, the RLH product format was adapted. Moreover, the locations of the second generation of RLH and RLA products were selected regarding the users' requests. Thus, the second release of products is composed of more samples over rivers (Rhine and Senegal), lakes (Ontario, Balqash, Volta, Dongting and Lagõa dos Patos) and reservoirs (La Grande Rivière reservoirs in Canada) and all products from the first generation were reprocessed in the modified RLH format.

OBJECTIVE

The main objective of the ESA River and Lake project is to provide the scientific community with easy-to-use, effective and accurate river and lake height measurements from both ERS and Envisat satellite altimeters. The hydrologists' requirements present a very interesting challenge because the products proposed by ESA are radically different from one based on ground based data with both vertical precision and temporal sampling more limited.
The first ambition is to obtain around 10 years of data processed on specific targets, then to propose the world-wide coverage of large rivers and lakes over 10 years and finally to make available to hydrologists all RLH and RLA products in near real time, i.e. in less than 3 hours after the measurement.

ORGANISATION

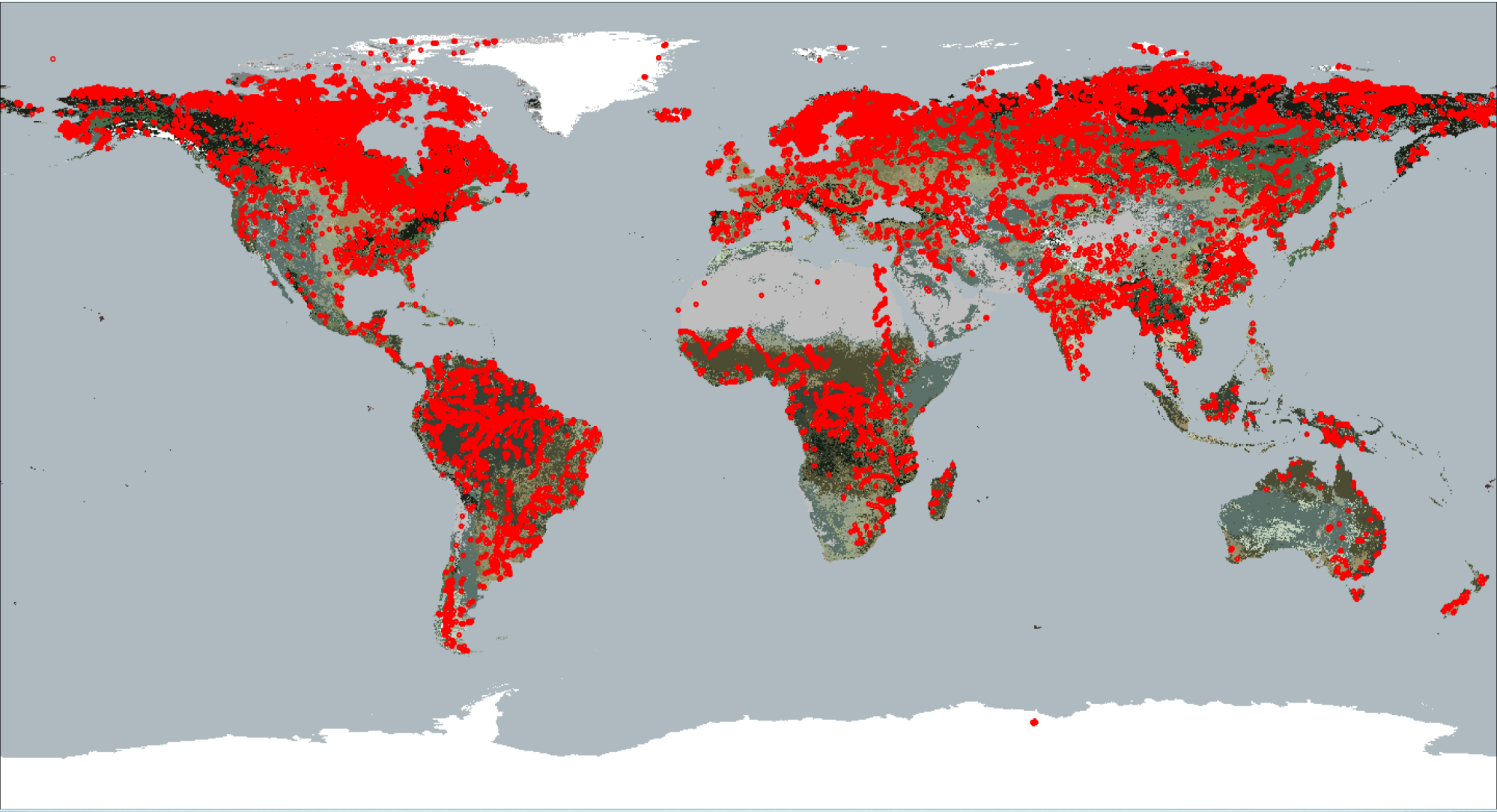
In order to design high quality products that respond to the hydrologists' requirements, the team has been composed of altimeter specialists from De Montfort University (DMU) and hydrologists from Lancaster University (LU). The project, proposed by the European Space Agency (ESA) draws

ESA's current capabilities

So what can the current generation of altimeters recover over inland water?

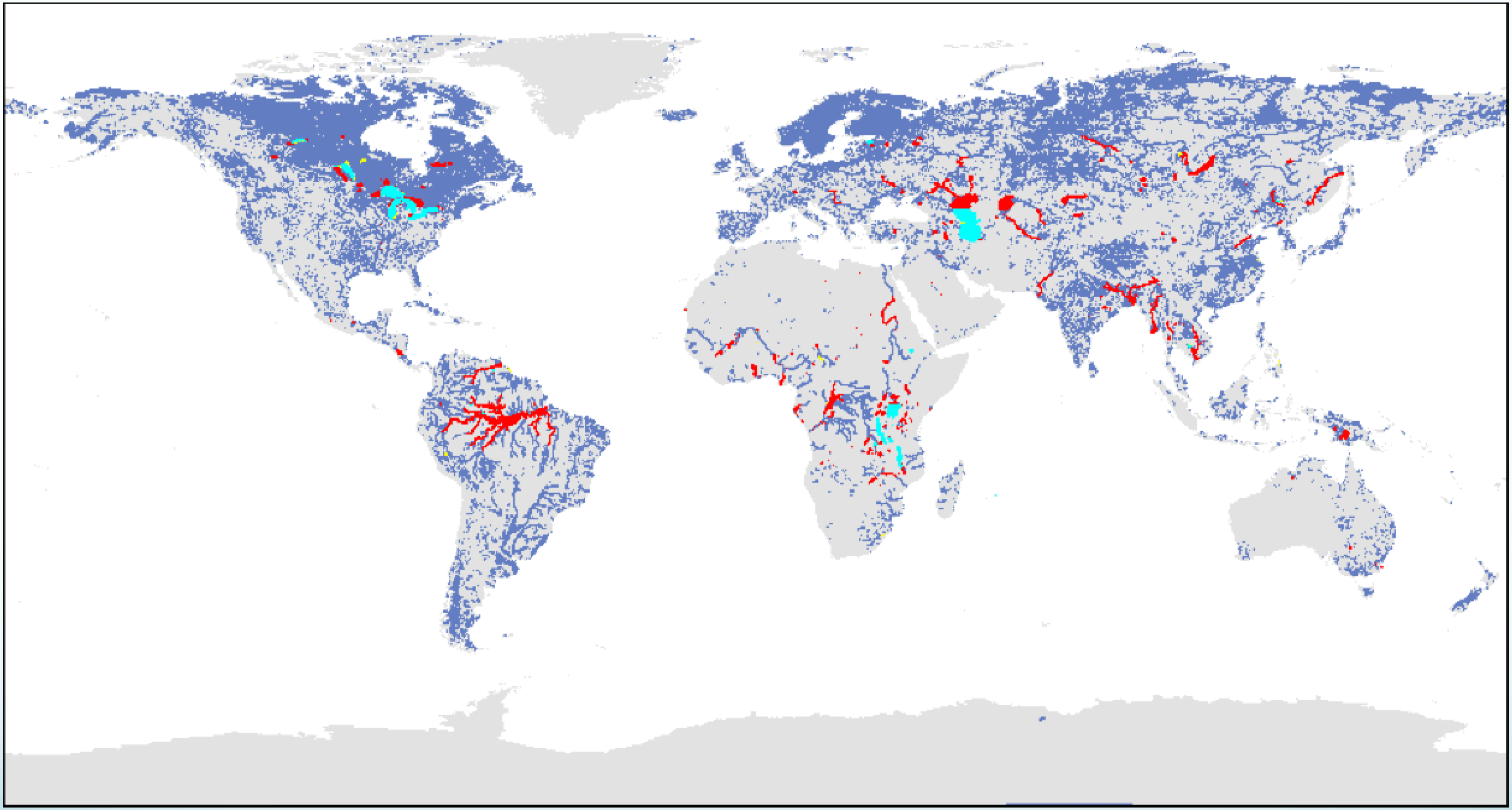
- Huge global analysis carried out of waveform recovery over inland water from ERS-2, TOPEX Jason-1 and Envisat.
- Every location where at least 80% of cycles have valid waveforms over the targets was identified and flagged
- Next slides show global plots for TOPEX, ERS-2 and Envisat with one red dot for each crossing flagged.

Envisat Global Targets



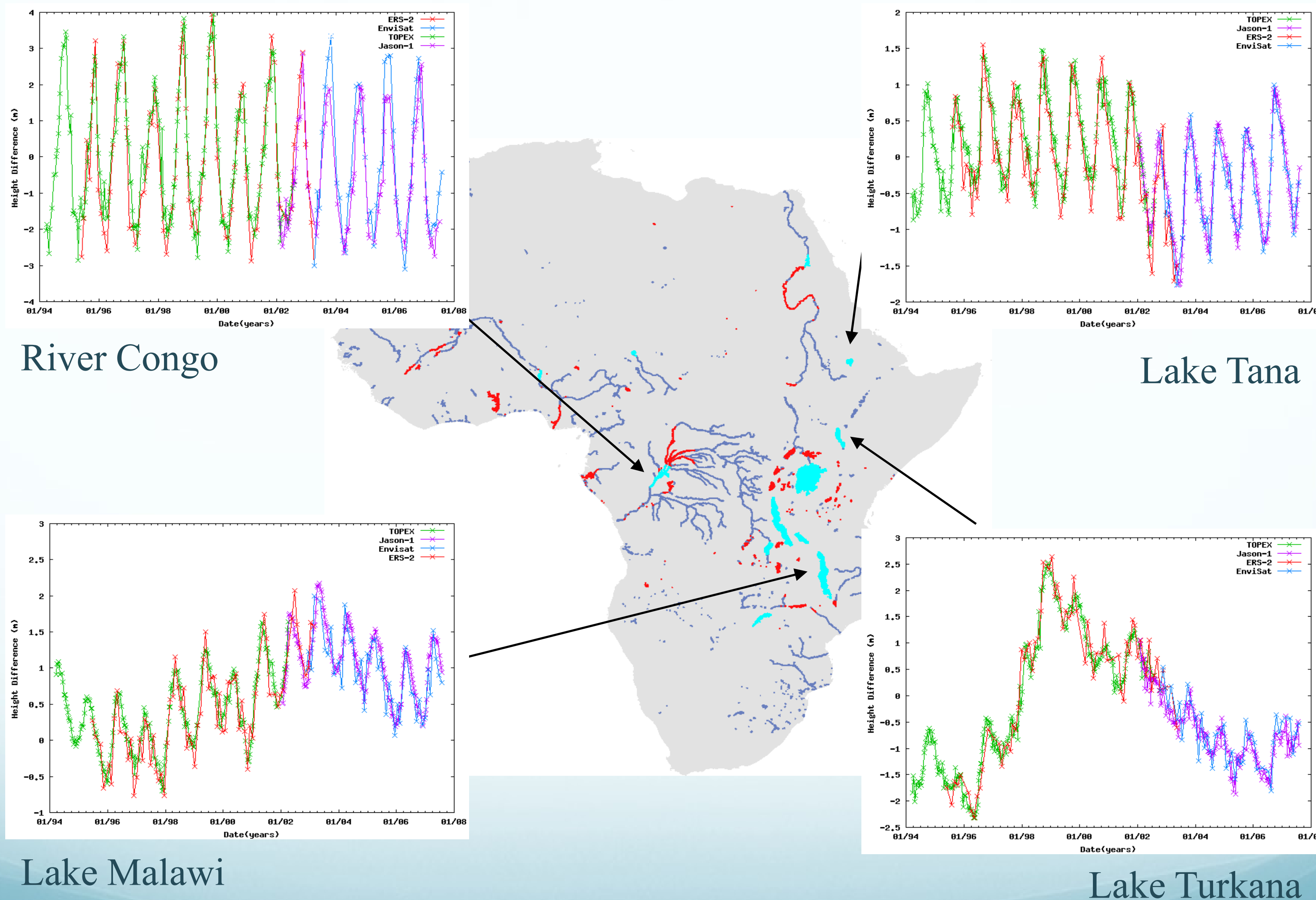
- Even more targets overall, although more 'drop-out' of waveforms
  (the self-adaptive tracker is mostly in high-resolution mode)

Global Mask for NRT RA-2 & Jason-1

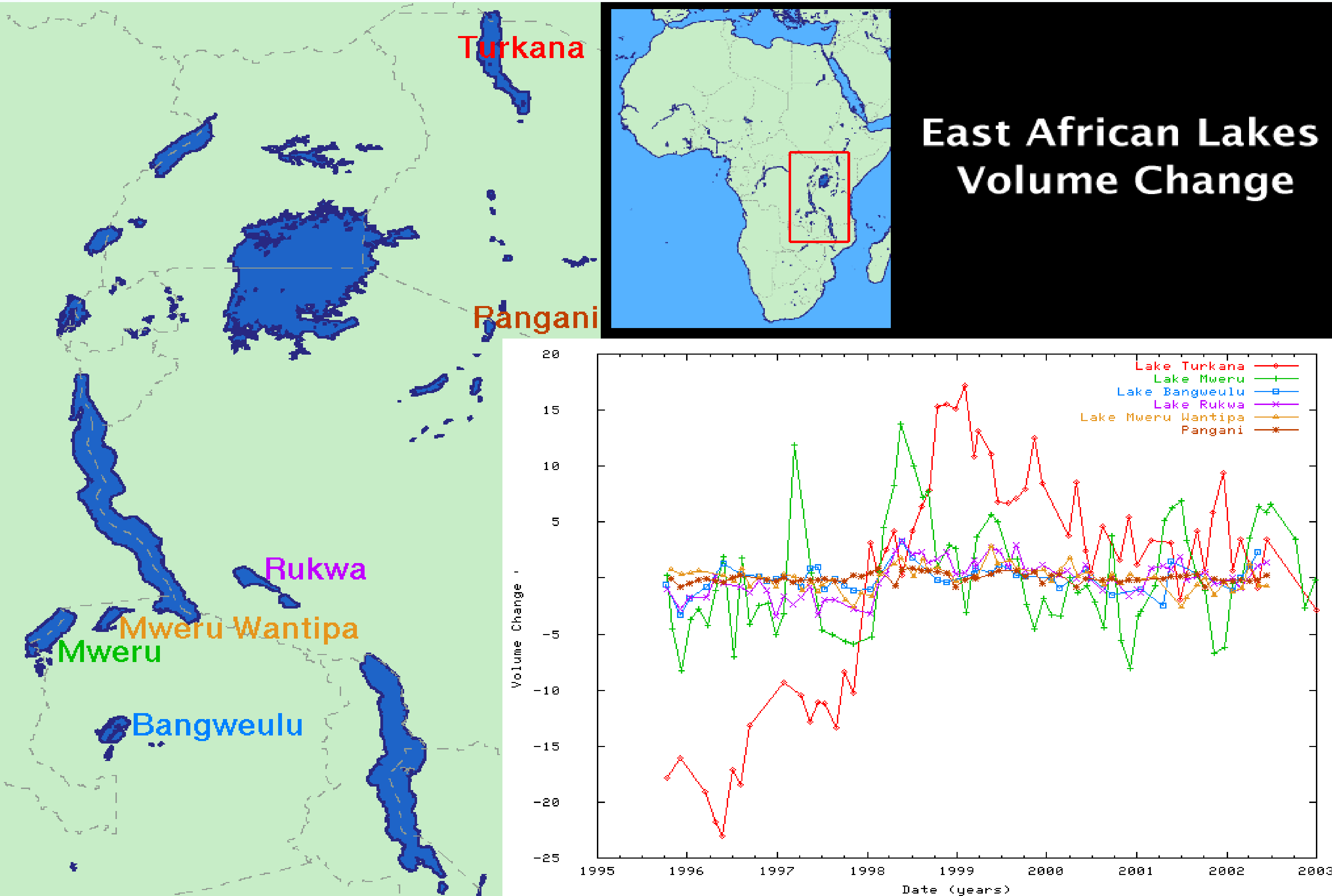


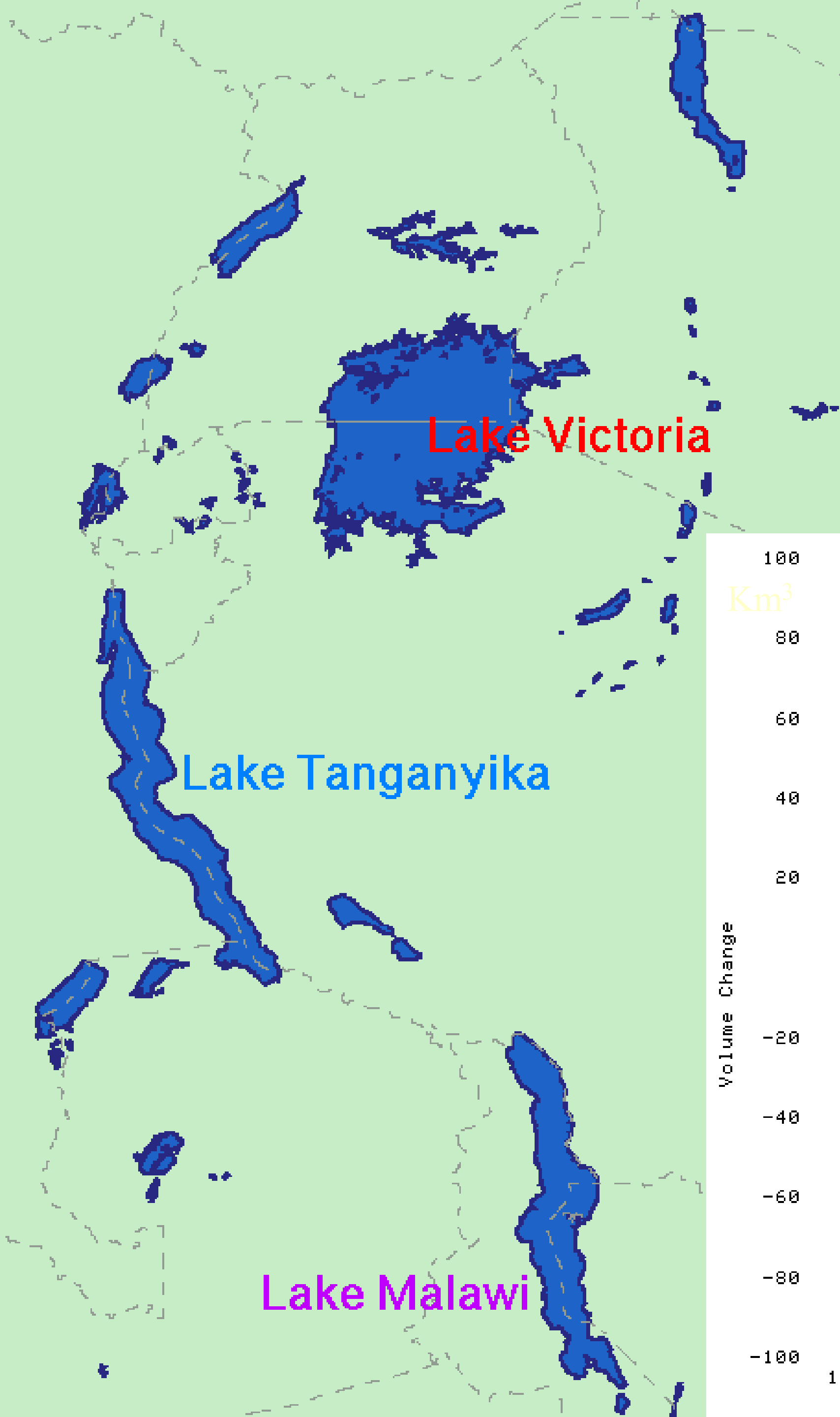
- NRT RA-2 targets red, RA-2 & Jason-1 targets turquoise, potential targets grey-blue. Note: all targets acquired by Jason-1 also seen by RA-2 (better time sampling with both).

New NRT mask over Africa

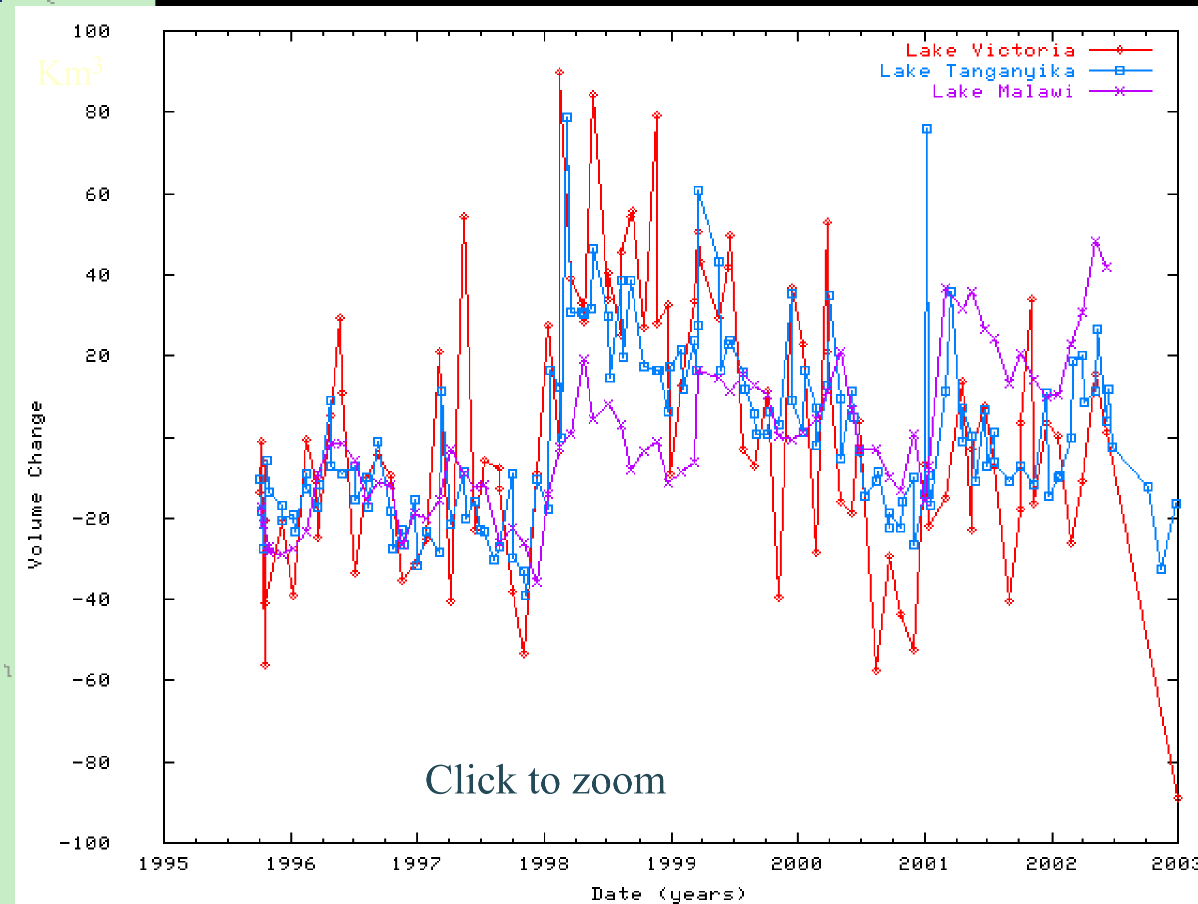


Lake Volume Variation (km^3)

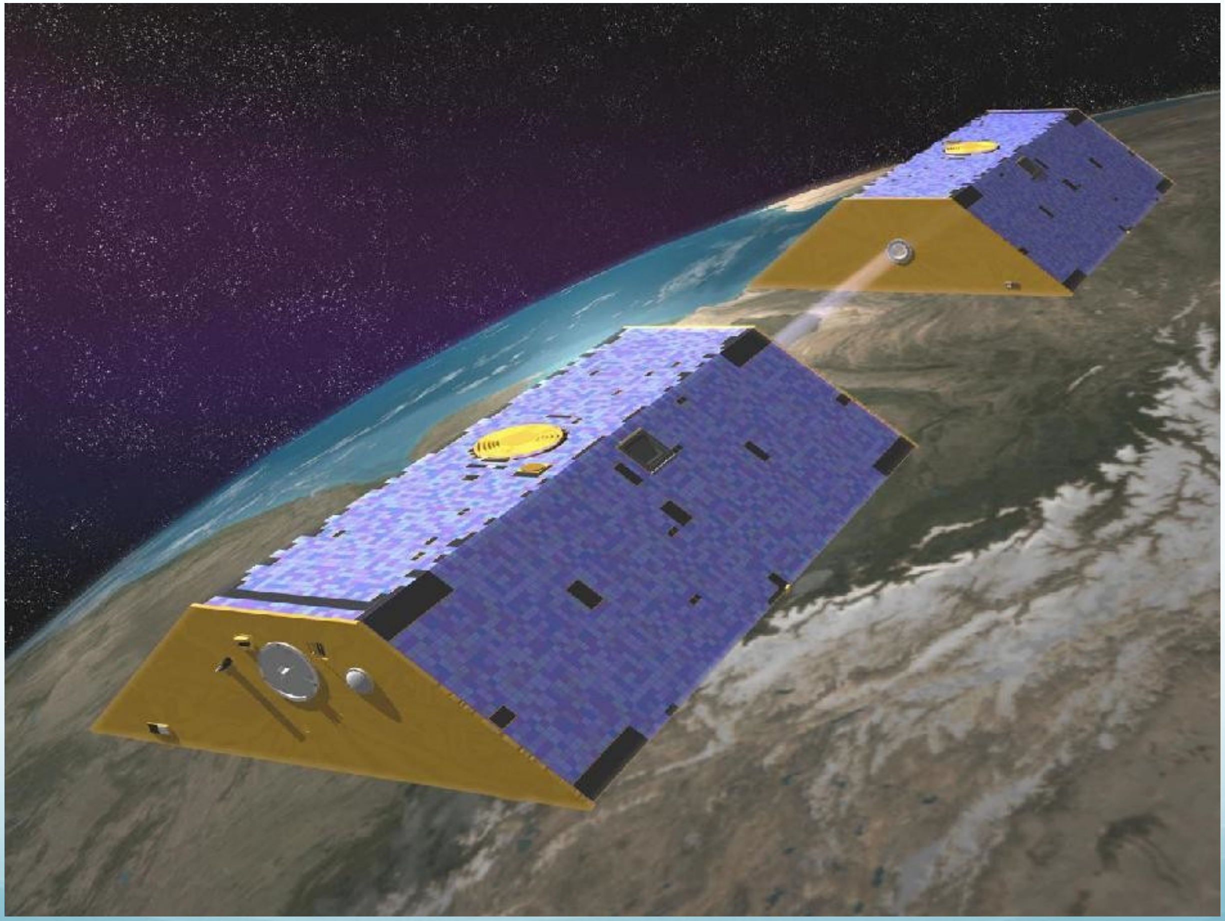




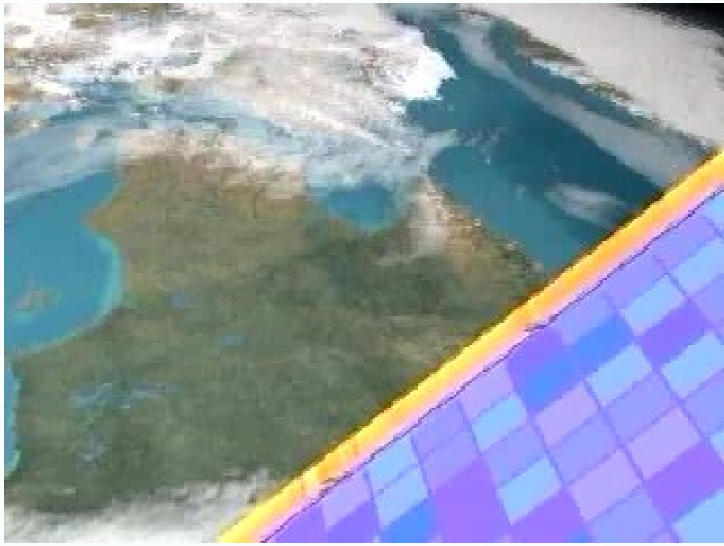
East African Lakes Volume Change



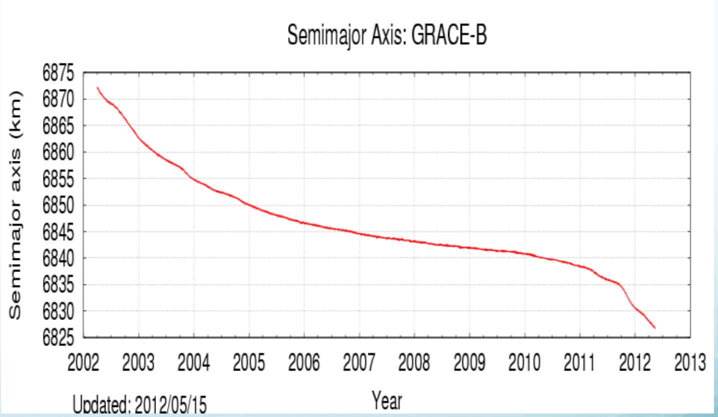
Recovery and Climate Experiment (GRACE) Mission



Mission overview

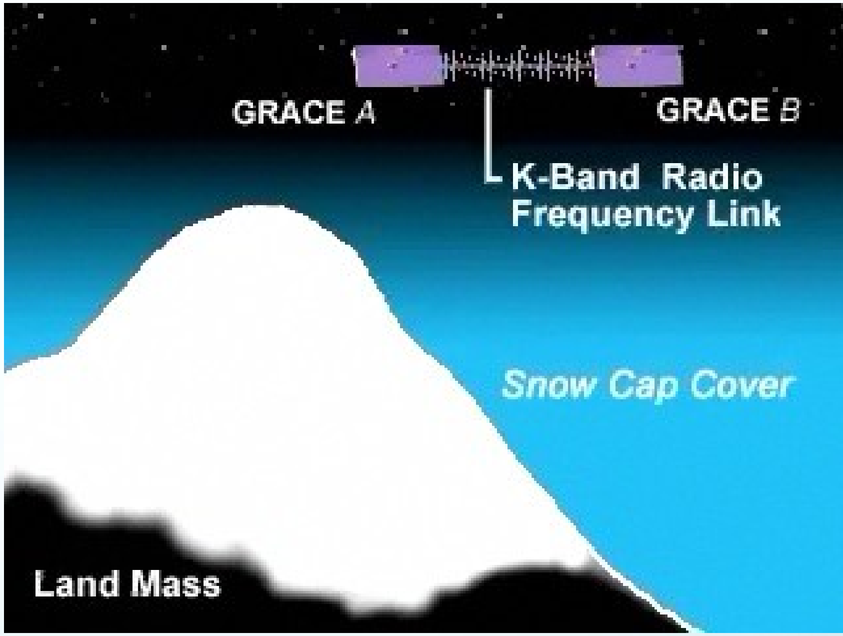


- Observational goals: Measure Earth’ s time-variable gravity field
- Science goals: **Study surface mass redistribution impacted by climate, geodynamic processes, and humans**
- Launched March 17, 2002
- Two co-orbiting vehicles, nominal 210-km separation
- 5-yr lifetime extended multiple times
- 1.6-hr, near-polar orbit,
- Altitude steadily decaying (right)



Inter-satellite ranging

- Dual one-way ranging: Each satellite transmits K-band microwave signal and receives the signal from the other
- Combination of phases yields an estimate of the inter-satellite *range rate* (RR)
- RR nominal accuracy 20 μ /s
- RR is sensitive to location on surface and size of surface mass



Gravity recovery

Estimation of gravity from RR is a multistep process:

- A "background" gravity model represents the known accelerations on the GRACE satellites
- Non-gravitational forces include solar radiation, solar pressure, drag
- Equations of motion for GRACE satellites are integrated using these force models to determine *a priori* RR values
- The *a priori* RR are used to calculate RR residuals
- RR residuals from 30-day combined in a single least-squares solution to estimate gravity parameters:
  - Stokes coefficients up to degree and order 60; or
  - Mascons (tiles of surface mass density)

Contributions to background model

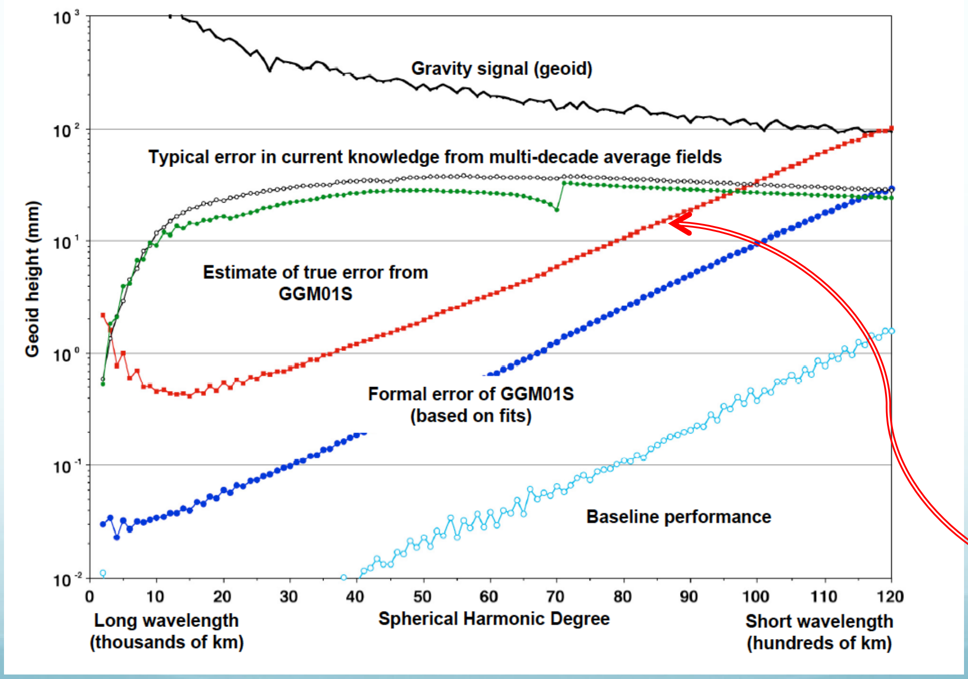
Contribution	Source	Order of magnitude
Spherical Earth		1
Ellipticity/oblateness	Satellite tracking	10^{-3}
Higher-order variations		$\leqslant 10^{-6}$
Low-degree secular variability		$\leqslant 10^{-11}\ yr^{-1}$
Solid-Earth tides	Planetary ephemerides DE-405, IERS anelastic Earth model	10^{-9}
Ocean tides	FES2004 modified for long-period tides	$\leqslant 10^{-10}$ (?)
Pole tide (solid Earth and ocean)	IERS anelastic Earth model	10^{-9}
N-body perturbations	Planetary ephemerides DE-405	

Spherical harmonic representation of gravity field

- Solution to Laplace's equation in spherical coordinates involves expansion by trigonometric polynomials of latitude and longitude
- The polynomials are characterized by the degree n and order m
- Rule of thumb: A spherical harmonic of degree n has a wavelength of 40,000 km / n

GRACE Errors

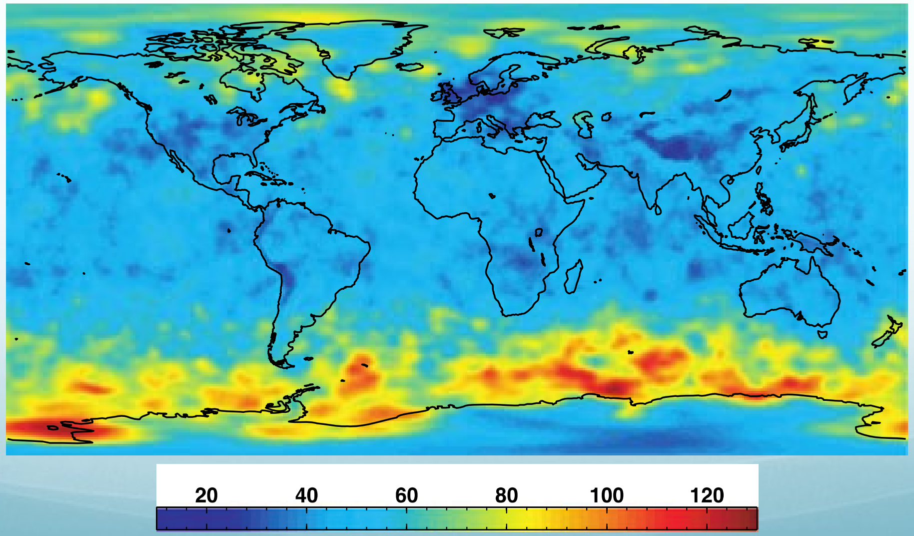
"Baseline error:" Error increases with increasing spherical harmonic degree (i.e., increases with decreasing wavelength)



Typical GRACE error spectrum

Aliasing

- Errors in the numerical oceanic and atmospheric models lead to "aliasing"
- Example: Uncertainties of ECMWF surface pressure values (Pa); *ECMWF - European Center for Medium range Weather Forecasting*

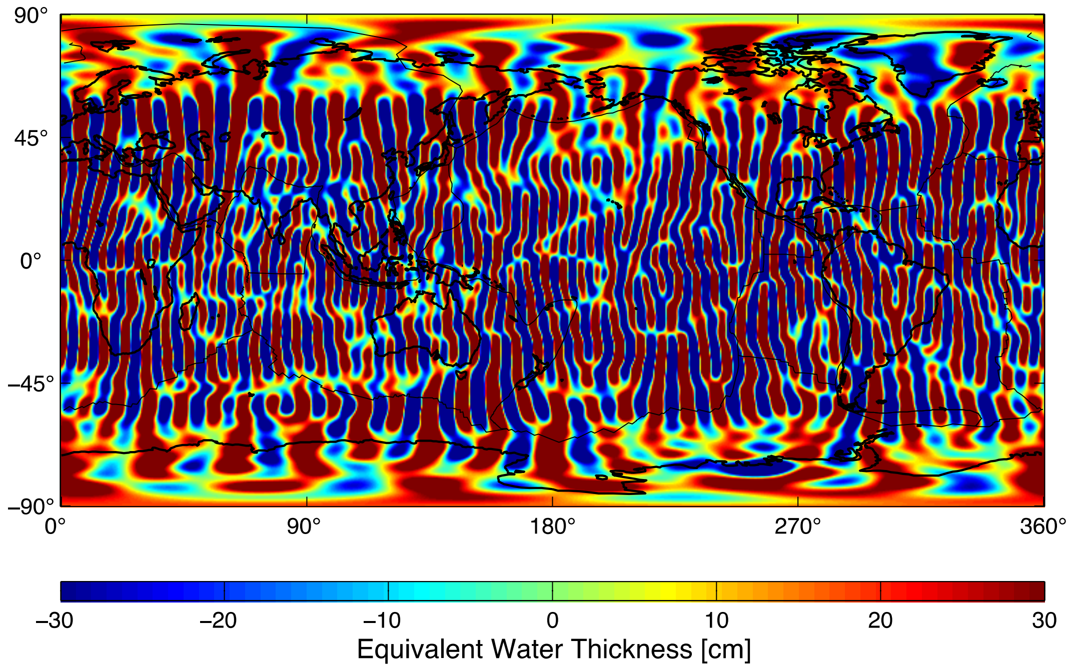


Zenner *et al.* [2010]

Correlated systematic error

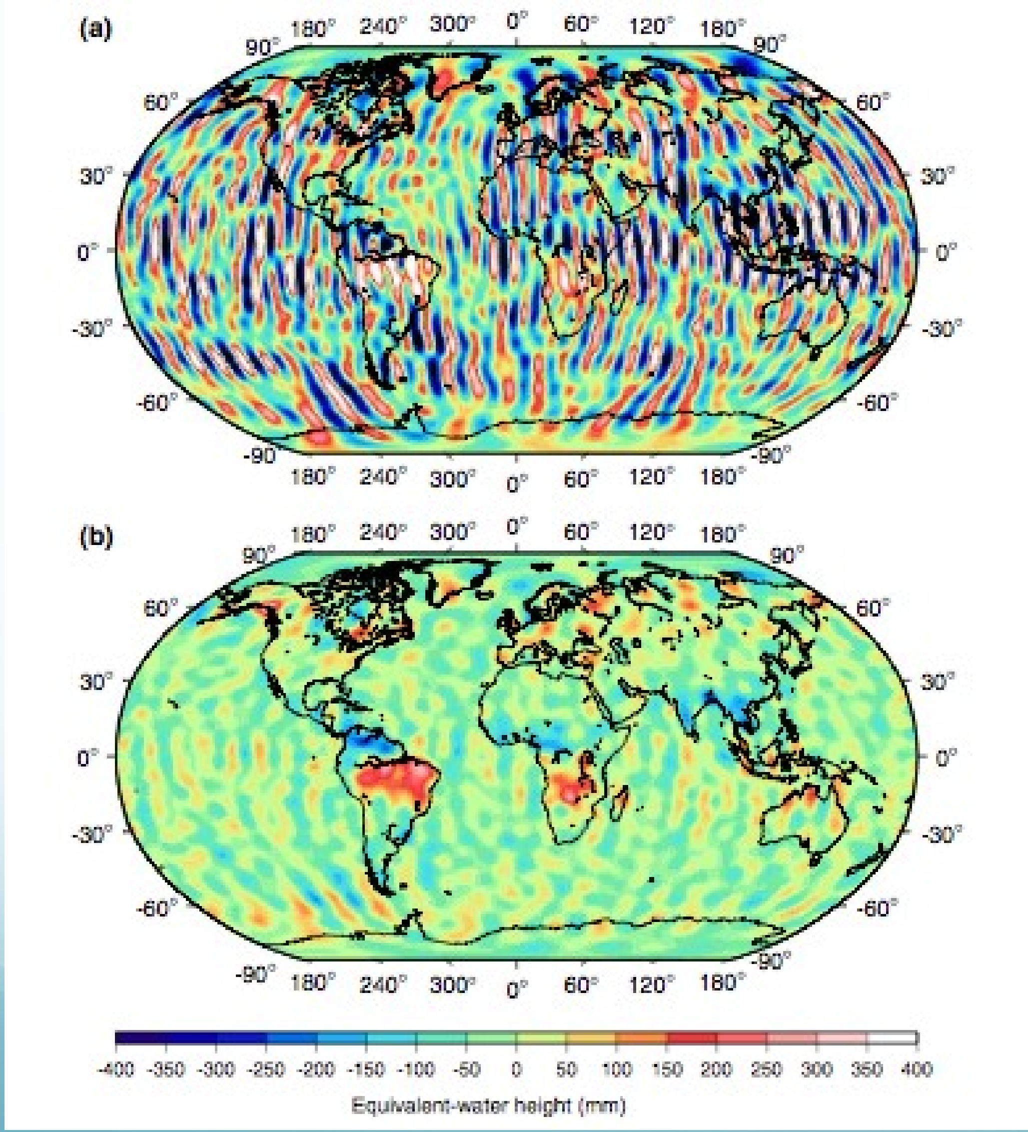
- GRACE orbits are nearly north-south
- The RR represents change of the GRACE inter-satellite distance in the N-S direction
- Small errors in the background gravity model (aliasing) can lead to large E-W gravity gradients
- These errors are known as "stripes"

Example: Raw monthly gravity field



From Lei Wang

Example: Filtered monthly gravity field

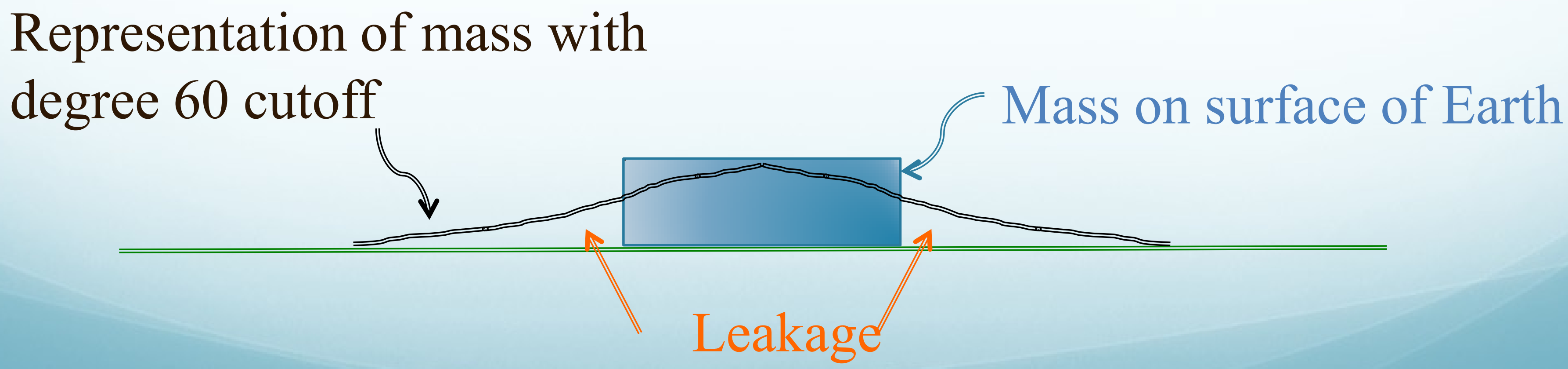


Footprint – 500 km

Ramillien et al. (2008)

Leakage

- Due to increasing error with increasing degree, monthly GRACE fields are cut off at degree 60
- This causes mass model to be "smeared," thereby "leaking" into nearby areas



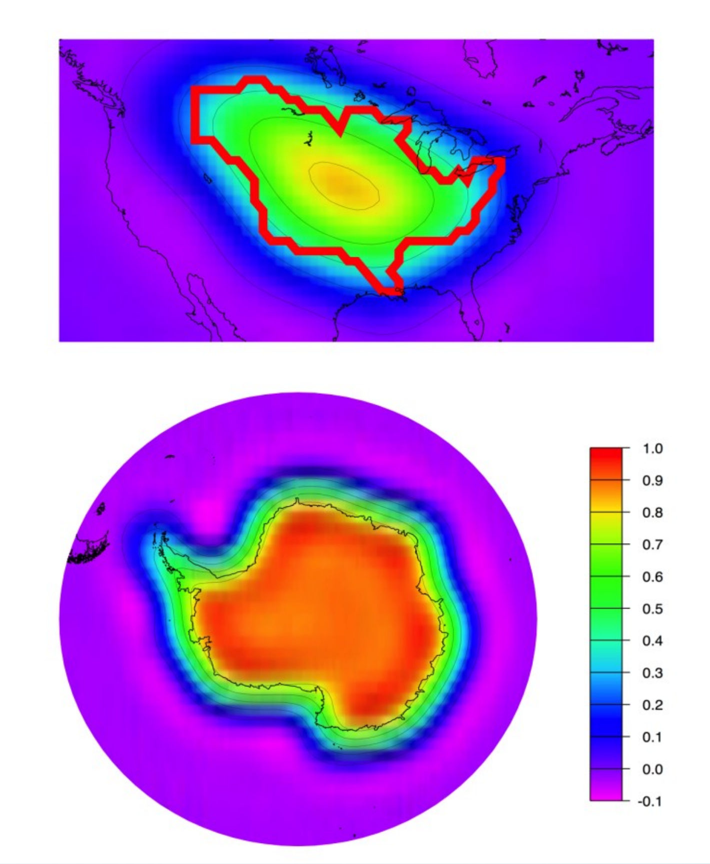
Representations of gravity

1. **Equivalent water depth**: Thickness of surface mass having density of water
2. **Geoid height:** Height relative to ellipsoid of equipotential surface nearly coinciding with mean sea level
3. **Free-air gravity anomaly:** Difference from reference value of gravity acceleration on geoid

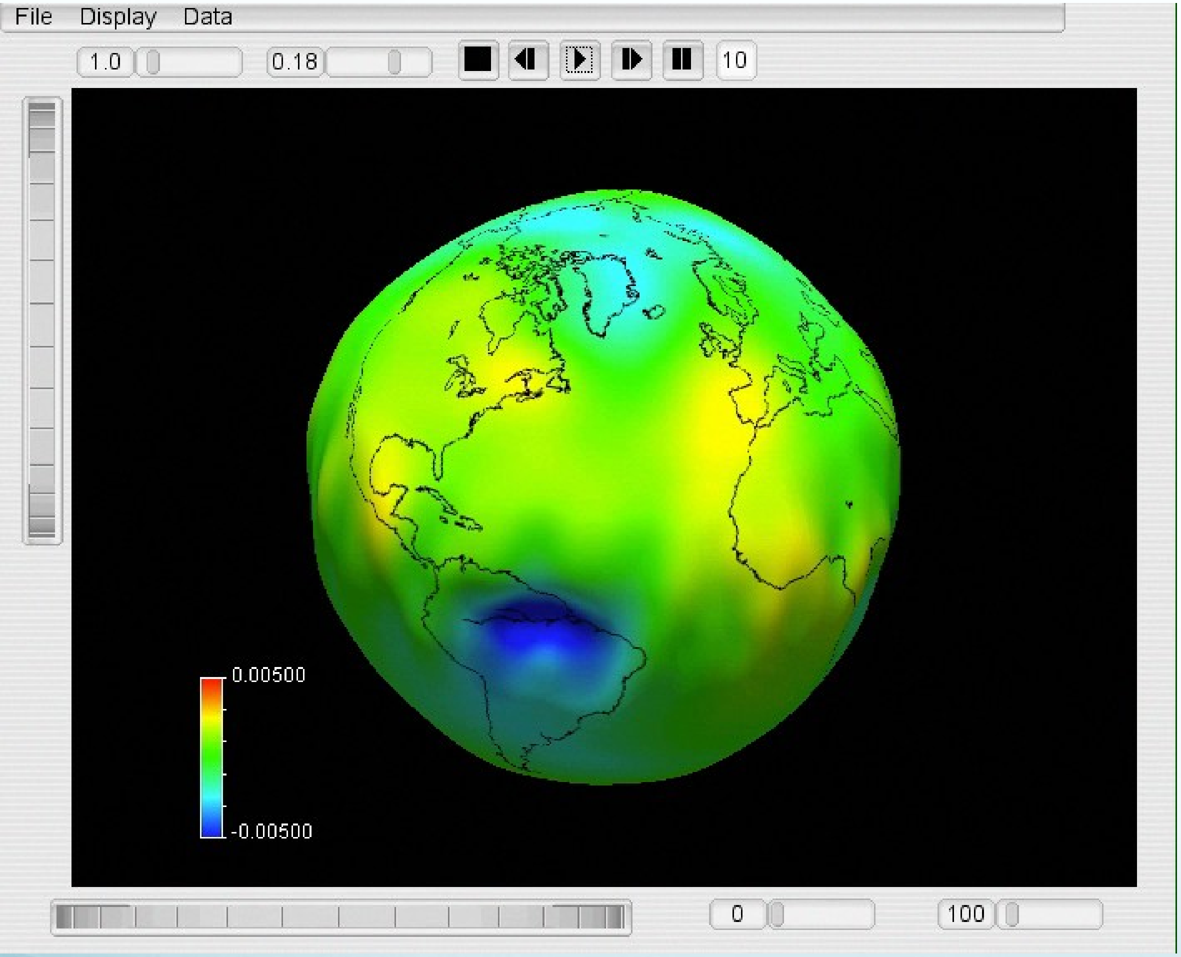
Analysis of GRACE gravity fields

- **Destriping:** Removal of correlated errors to remove “stripes”
- **Smoothing:** Fields smoothed with Gaussian filter of radius ≥250 km to reduce random errors at high degree
- **Regional integration**: To calculate mass variability over specific regions, fields integrated using smoothed averaging functions (right)
- **Hydrology:** Effects of continental water storage removed using hydrology models
- **Glacial isostatic adjustment:** Effects of GIA removed using models

- When spatially integrated, mass changes may be reported in
  - Mass (Gt)
  - Equivalent average water height
  - Equivalent sea-level change
  - Volume (cubic-km of ice @ 910 kg/m^3)

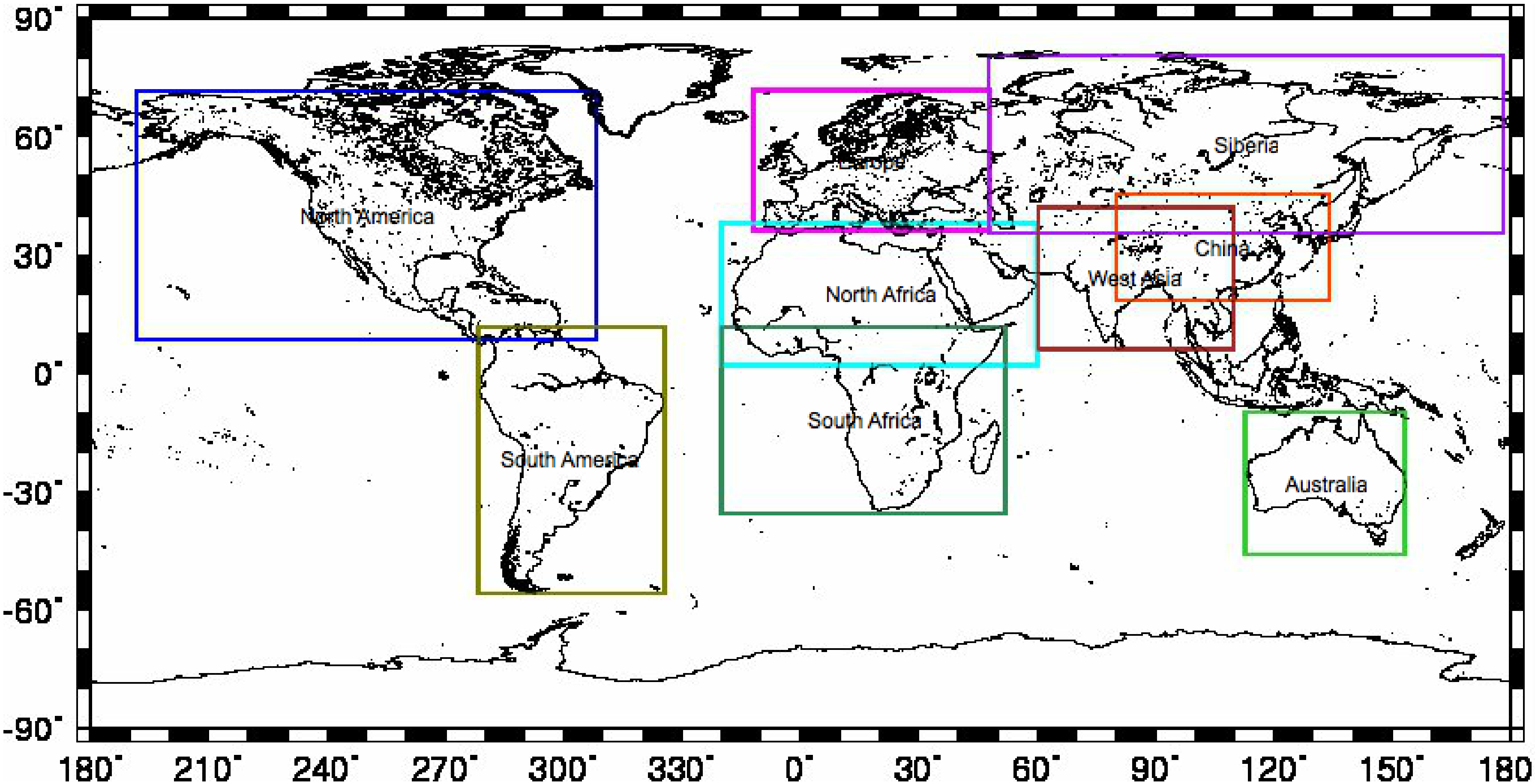


Averaging functions for the Mississippi River basin and Antarctica [*Wahr*, 2009]


File
Display
Data
1.0
0.18
10
0.00500
-0.00500
0
100

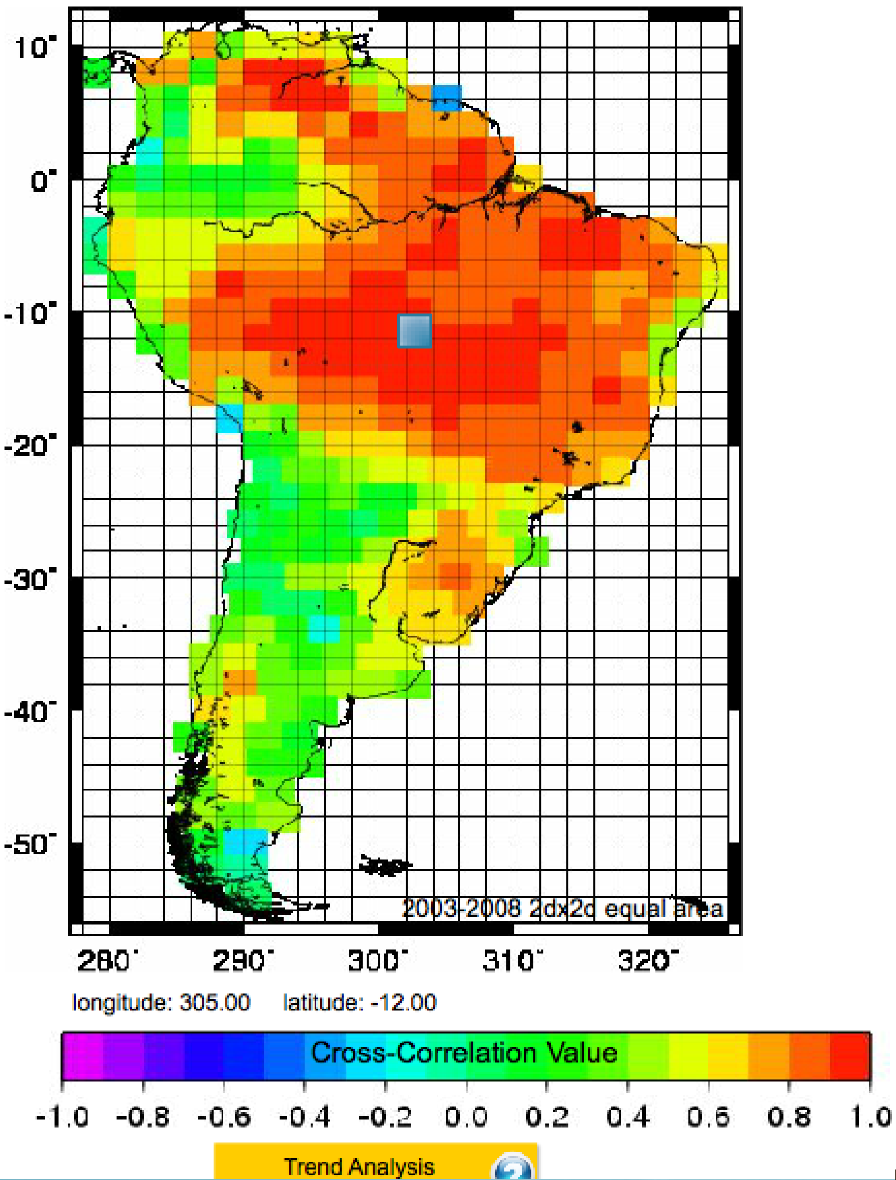
Grace – results

Please click a continent to see the details



http://grace.sgt-inc.com/V2/Global.html

Grace – results

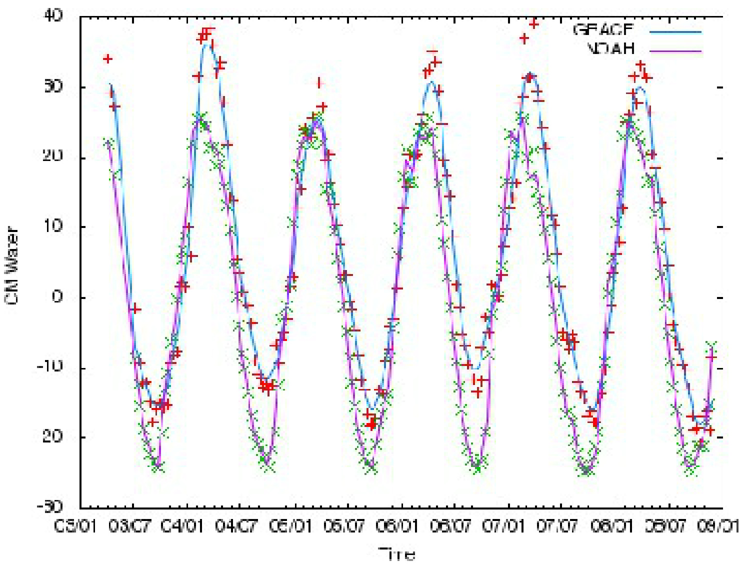


Show all South America data

MASCON value at (305.00,-12.00) Click to expand

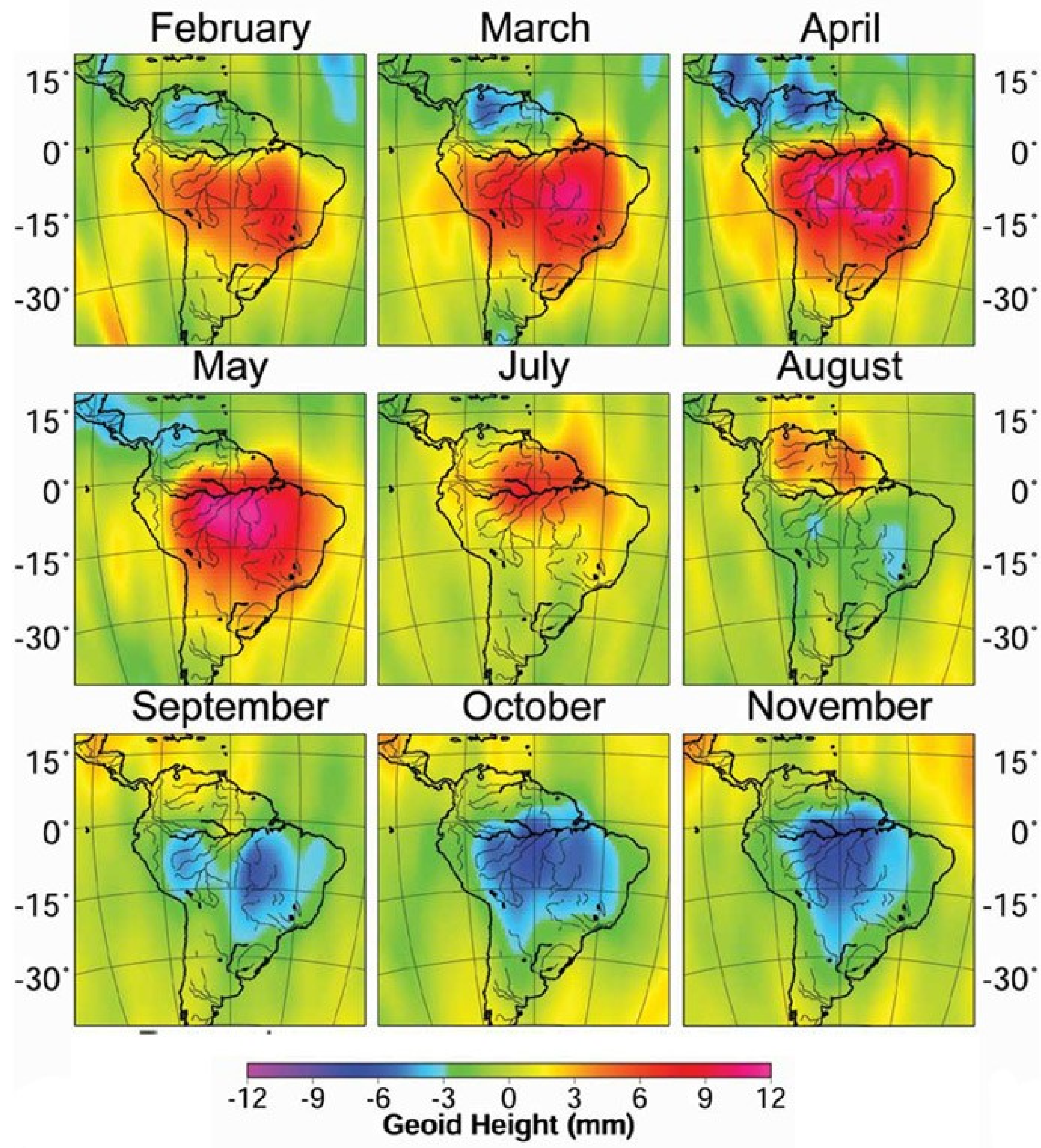
DATE	LON	LAT	GRACE	NOAH	NOAHNORM	SMOOTH
20030406	305.000	-12.000	34.051	671.14	22.338	30.685
20030416	305.000	-12.000	29.293	664.90	21.714	30.128
20030426	305.000	-12.000	27.163	622.20	17.444	29.569
20030706	305.000	-12.000	-1.596	362.43	-8.533	-7.053
20030716	305.000	-12.000	-8.799	325.90	-12.186	-8.326
20030726	305.000	-12.000	-9.420	292.17	-15.559	-9.730
20030806	305.000	-12.000	-12.210	261.53	-18.623	-11.358
20030816	305.000	-12.000	-12.000	240.29	-20.747	-12.792
20030826	305.000	-12.000	-14.667	226.07	-22.169	-14.024
20030906	305.000	-12.000	-17.696	214.58	-23.318	-14.955
20030916	305.000	-12.000	-15.966	206.91	-24.085	-15.322
20030926	305.000	-12.000	-14.976	207.61	-24.015	-15.258
20031006	305.000	-12.000	-14.965	253.50	-19.426	-14.799
20031016	305.000	-12.000	-15.791	316.46	-13.130	-13.883
20031026	305.000	-12.000	-15.181	342.02	-10.574	-12.397
20031106	305.000	-12.000	-9.333	385.24	-6.252	-10.081
20031116	305.000	-12.000	-8.243	393.16	-5.460	-7.495

Cross-Correlation at (305.00,-12.00) Click to expand



http://grace.sgt-inc.com/V2/Sa.html

Amazon Basin

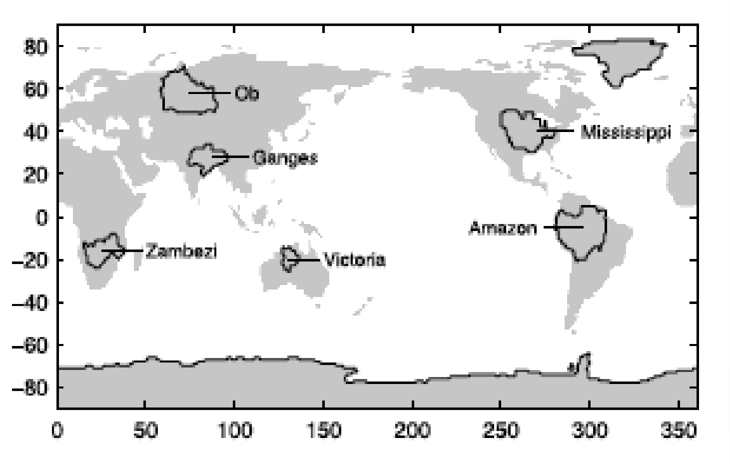


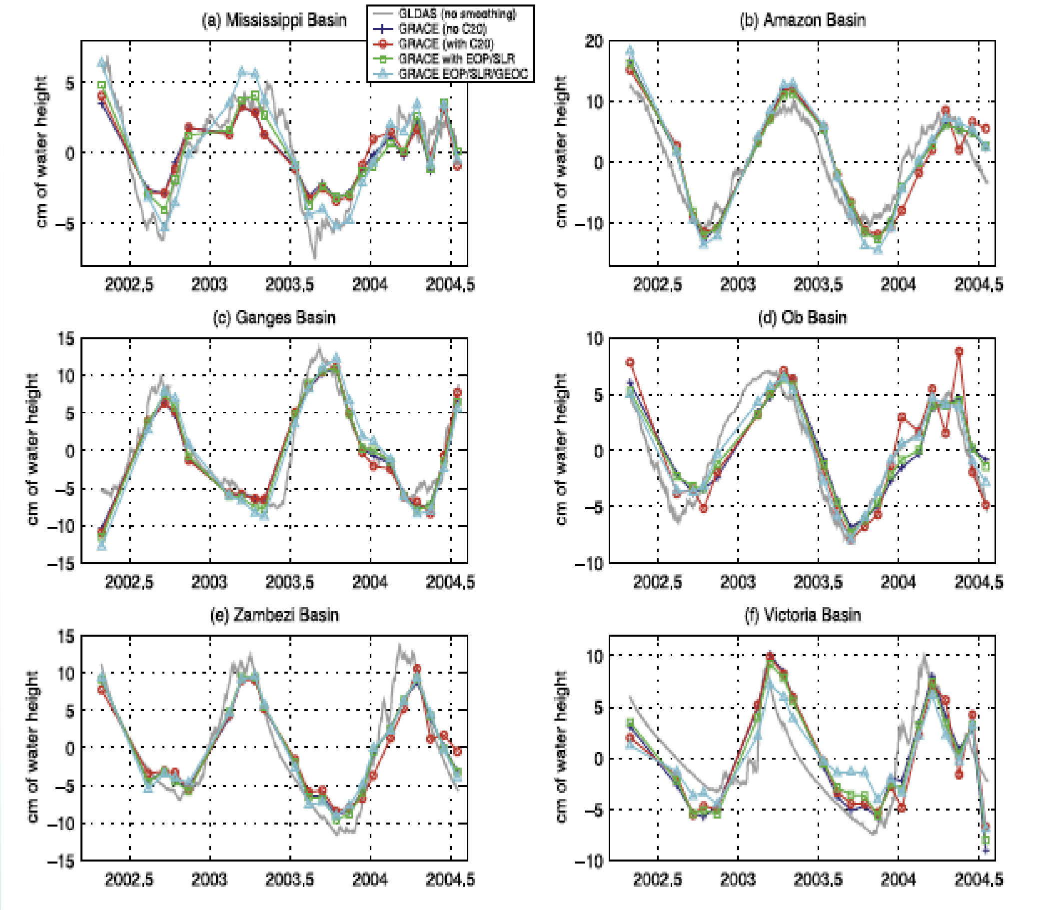
Monthly mean soil water storage change w.r.t a reference mean field.

Low degree spherical harmonic influences on Gravity Recovery and Climate Experiment (GRACE) water storage estimates

J. L. Chen,[1] Matt Rodell,[2] C. R. Wilson,[3] and J. S. Famiglietti[4]

Received 11 March 2005; revised 13 May 2005; accepted 14 June 2005; published 30 July 2005.





Constrained Regional Recovery of Continental Water Mass Time-variations from GRACE-based Geopotential Anomalies over South America

G. L. Ramillien · L. Seoane · F. Frappart · R. Biancale ·
S. Gratton · X. Vasseur · S. Bourgogne

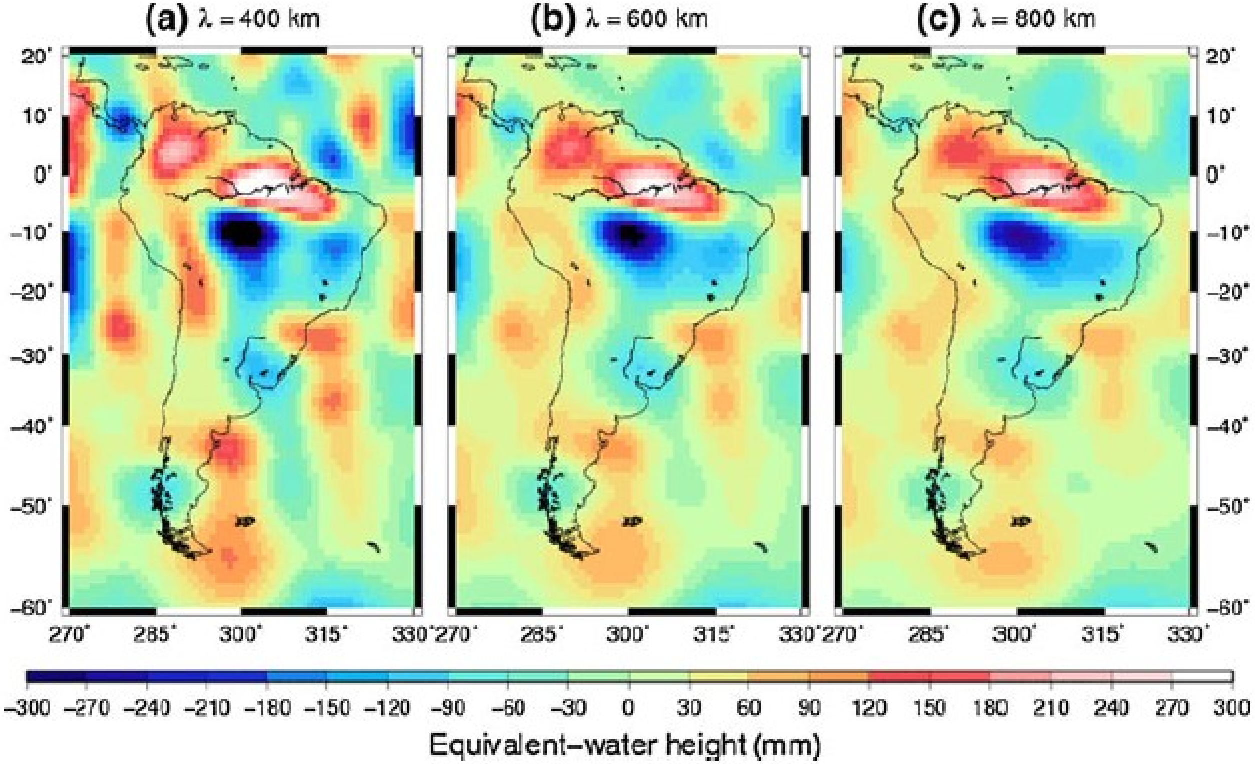
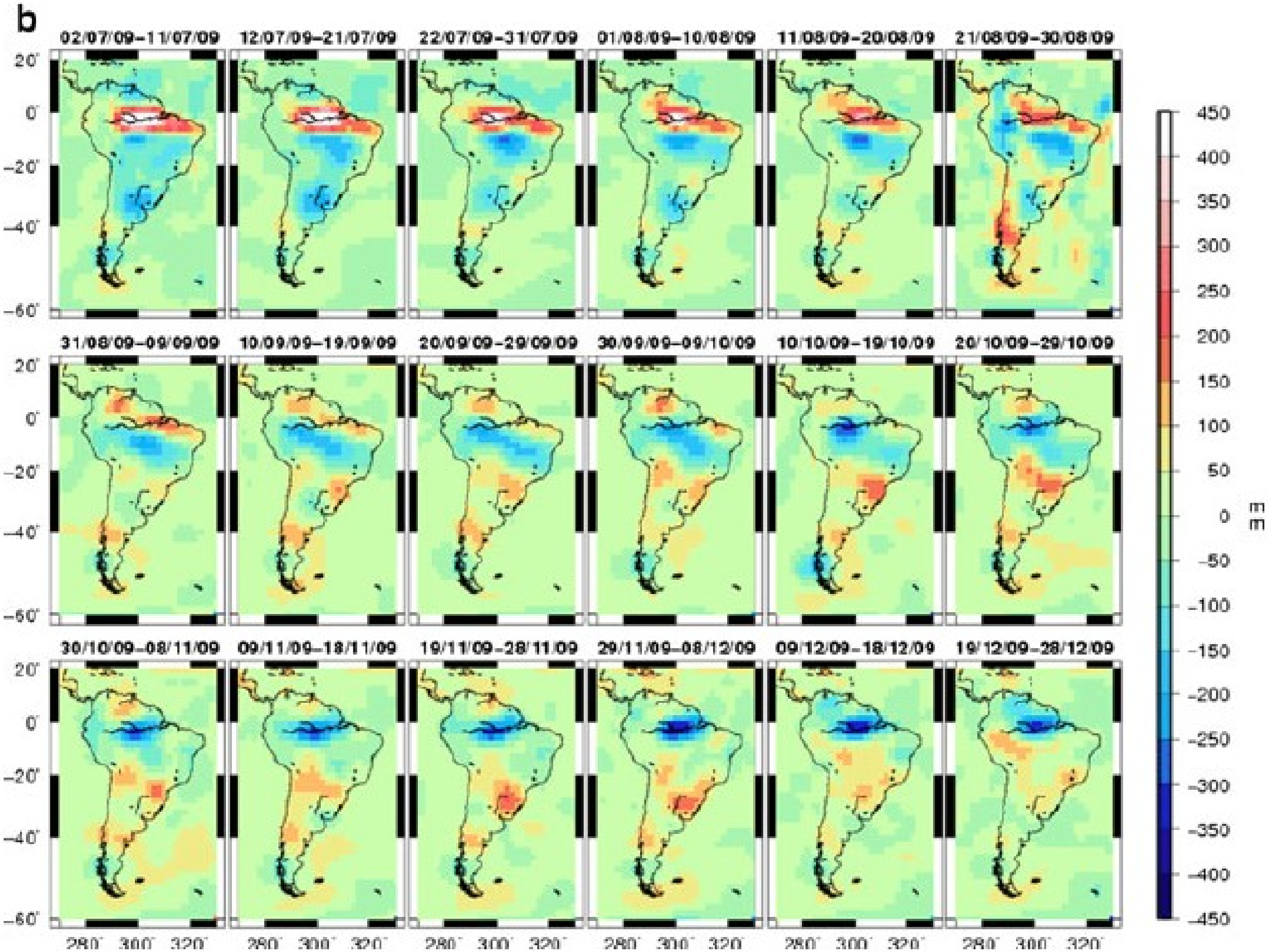


Fig. 2 1-degree regional solutions computed with different lengths of correlation: **a** 400 km, **b** 600 km, **c** 800 km. Note the important smoothing (i.e. loss of short-wavelength details) as the correlation radius increases

Constrained Regional Recovery of Continental Water Mass Time-variations from GRACE-based Geopotential Anomalies over South America



Satellite-based estimates of groundwater depletion in India

Matthew Rodell[1], Isabella Velicogna[2,3,4] & James S. Famiglietti[2]

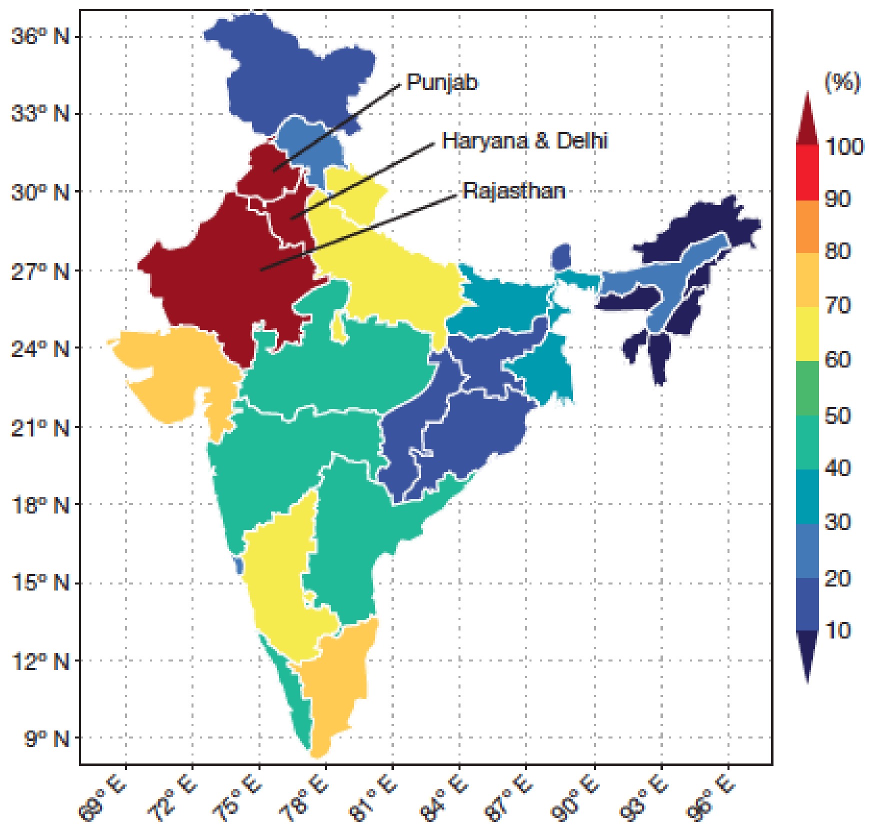


Figure 1 | Groundwater withdrawals as a percentage of recharge. The map is based on state-level estimates of annual withdrawals and recharge reported by the Indian Ministry of Water Resources[2]. The three states studied here are labelled.

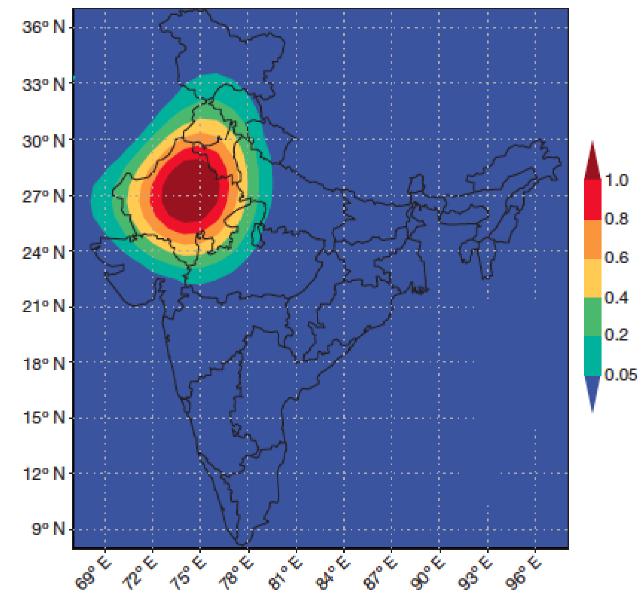
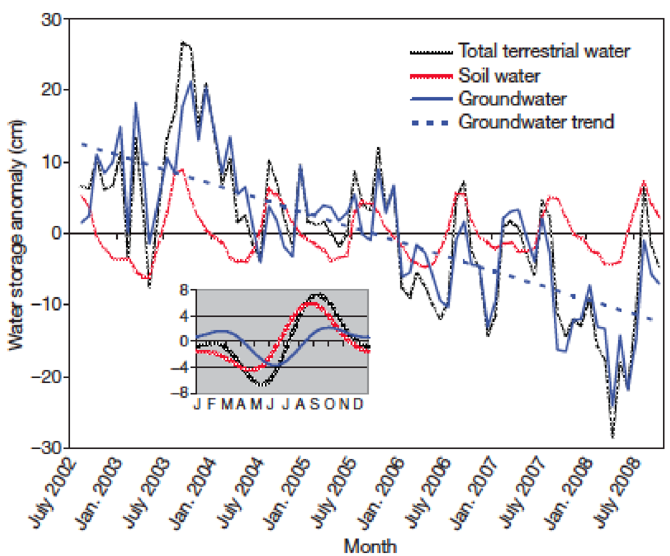
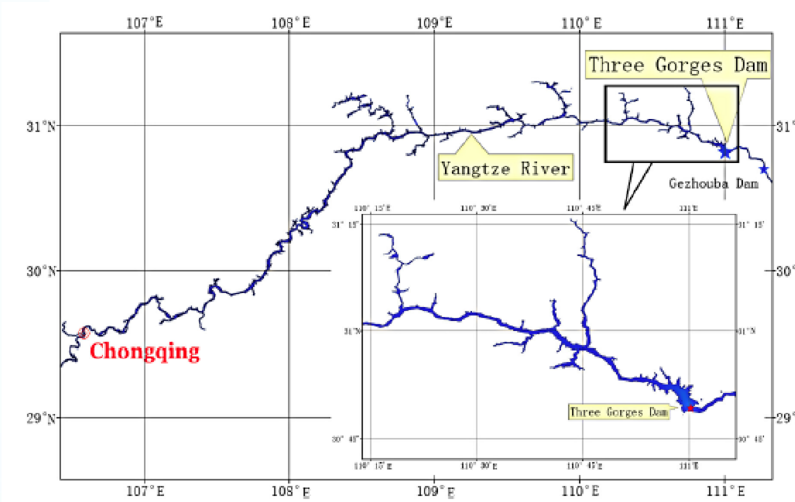


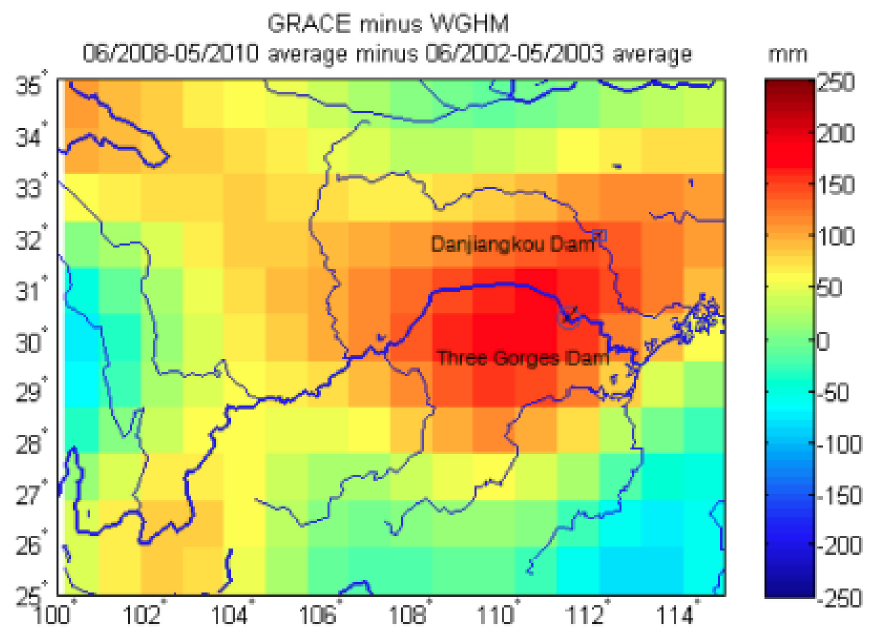
Figure 2 | GRACE averaging function. The unscaled, dimensionless averaging function used to estimate terrestrial water storage changes from GRACE data is mapped.

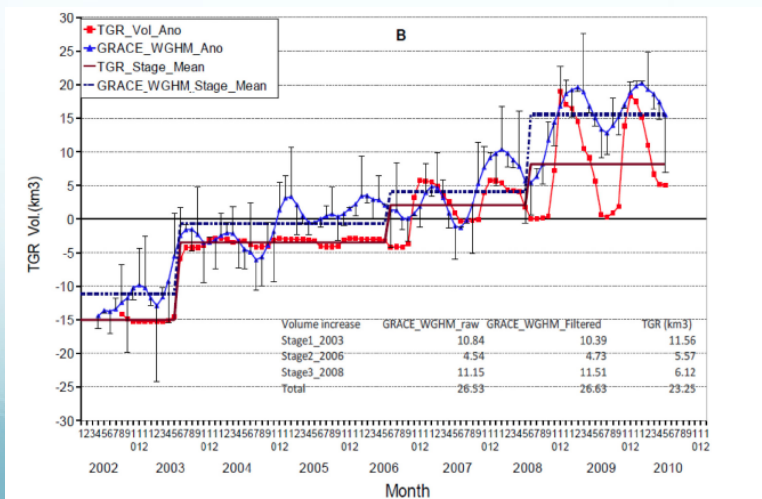


Gravity Recovery and Climate Experiment (GRACE) detection of water storage changes in the Three Gorges Reservoir of China and comparison with in situ measurements

Xianwei Wang,[1,2] Caroline de Linage,[2] James Famiglietti,[2,3] and Charles S. Zender[2]







Analysis of terrestrial water storage changes from GRACE and GLDAS

Tajdarul H. Syed,[1] James S. Famiglietti,[1] Matthew Rodell,[2] Jianli Chen,[3] and Clark R. Wilson[4]

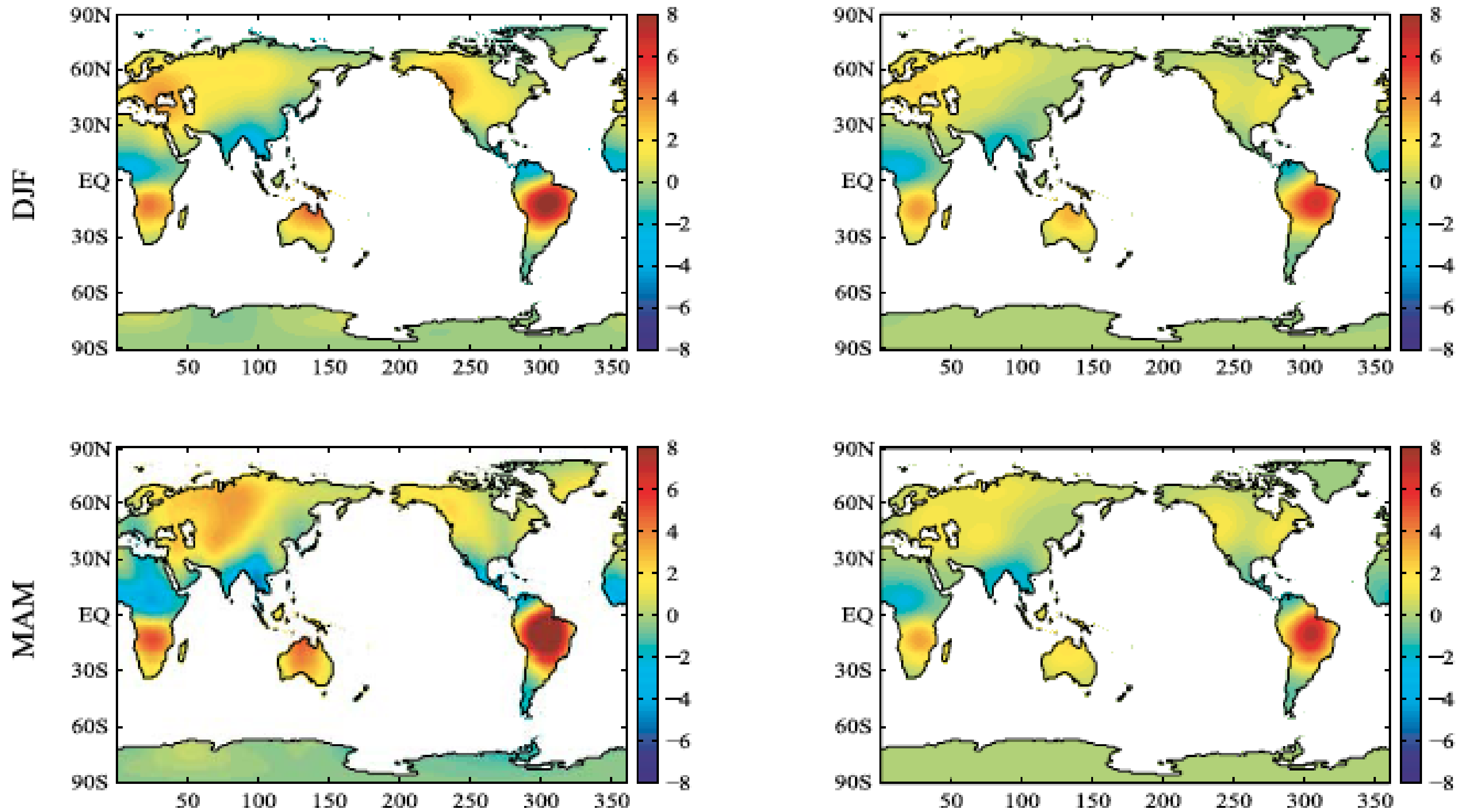


Figure 4. Spatial patterns of seasonally averaged TWSC (cm/month) from GRACE and GLDAS. On the basis of the seasonal averages computed for the period of April 2002 till July 2004.

GLDAS - Global Land Data Assimilation System

Comparison of seasonal terrestrial water storage variations from GRACE with groundwater-level measurements from the High Plains Aquifer (USA)

Gil Strassberg,[1] Bridget R. Scanlon,[1] and Matthew Rodell[2]

Received 25 March 2007; revised 18 May 2007; accepted 6 June 20

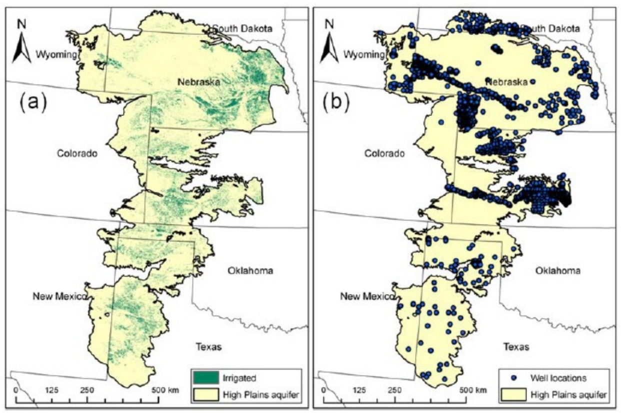


Figure 1. (a) Location of irrigated areas over the High Plains aquifer [*Qi et al.*, 2002] and (b) location of wells where seasonal water-level changes were calculated (total of 2,719 wells).

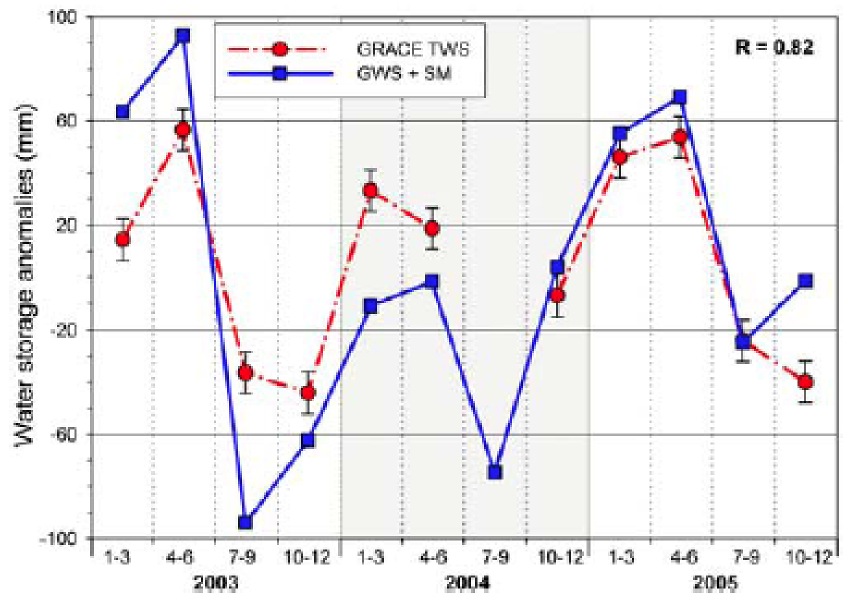
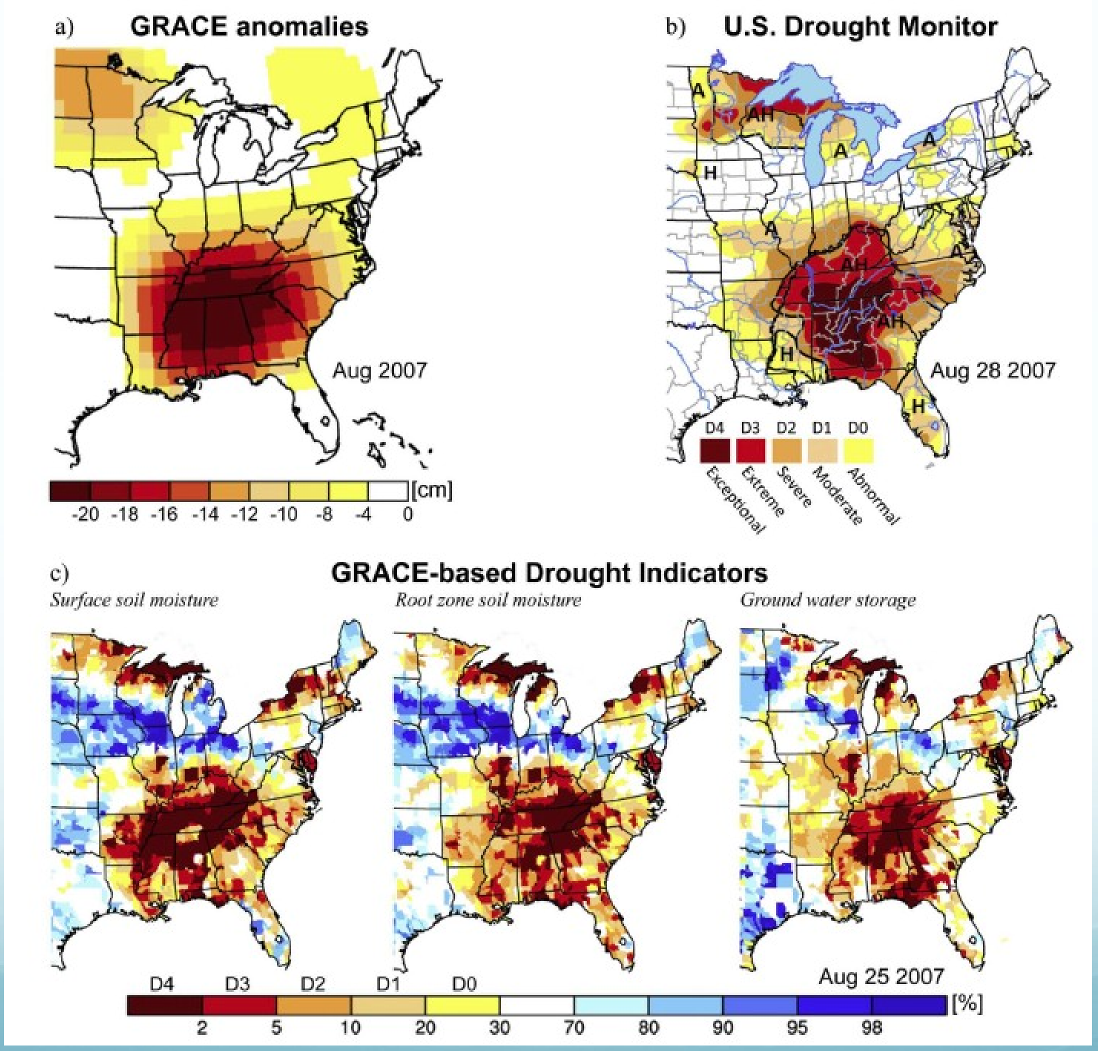


Figure 3. GRACE-derived TWS and combined GWS (from GW-level measurements) and SM (simulated) for the High Plains aquifer. Data are shown as anomalies relative to the mean for the analysis period (2003–2005) and units represent equivalent thickness of water (mm). Error bars represent TWS uncertainties.

Drought indicators based on model-assimilated Gravity Recovery and Climate Experiment (GRACE) terrestrial water storage observations

Rasmus Houborg,[1,2] Matthew Rodell,[3] Bailing Li,[2,3] Rolf Reichle,[3] and Benjamin F. Zaitchik[4]

Received 17 August 2011 ; revised 1 June 2012; accepted 12 June 2012; published 28 July 2012.

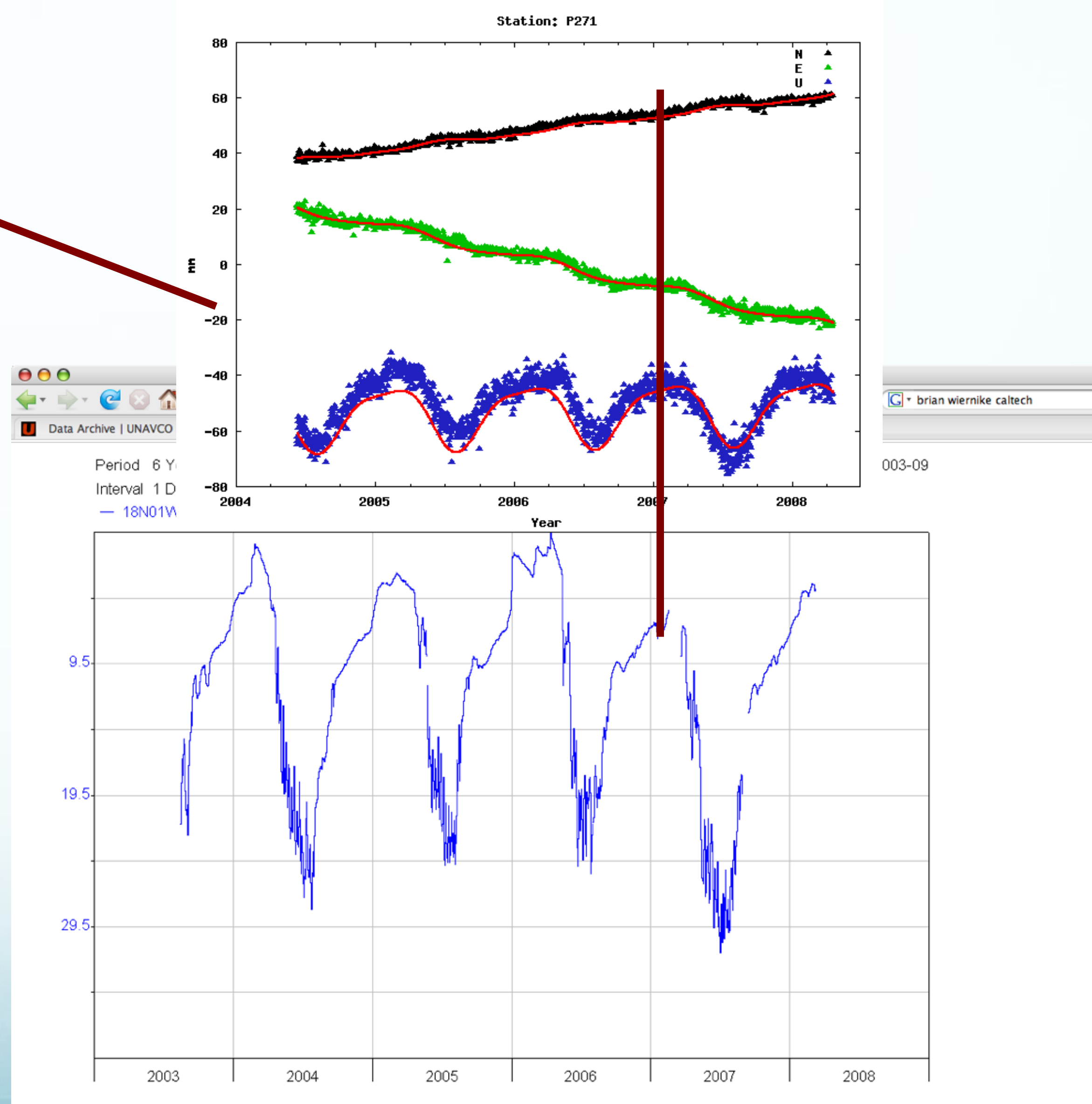


Additional geodetic techniques

- GPS
- Lidar

GPS monitoring of Groundwater Pumping

Central Valley (California)



Deep-drilled braced GPS monument in sediments (valley). Peak annual signal in March - in phase with water table height.

(Meerten)

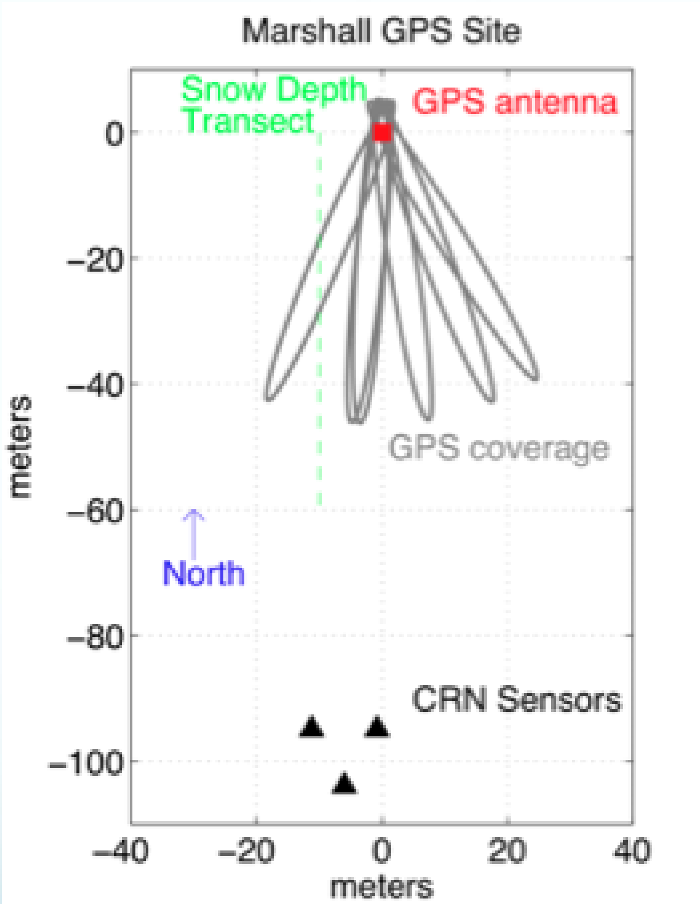
GPS hydrologic monitoring

Branco River Stage Gradient Determination Using GPS Water Level Measurements

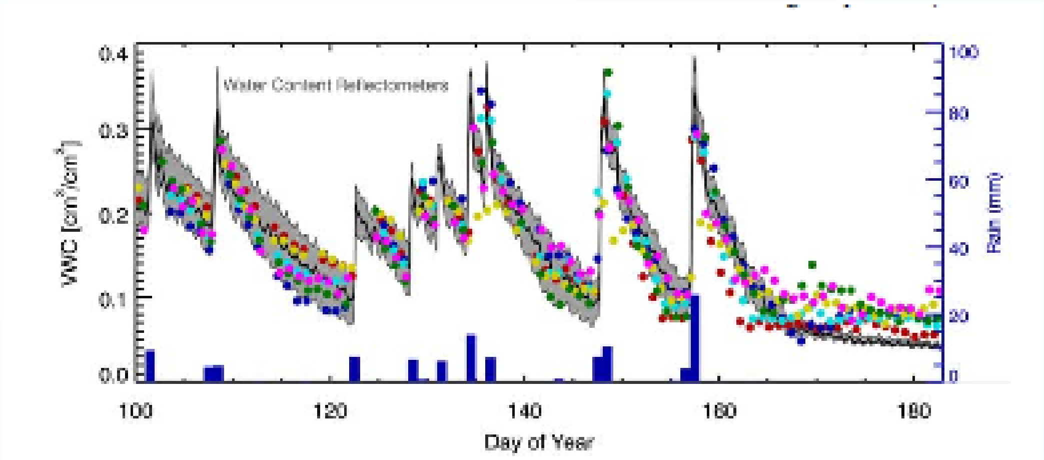
Cheng et al (2009)

Dam monitoring

Soil Moisture – GPS monitoring



Larson (2008)



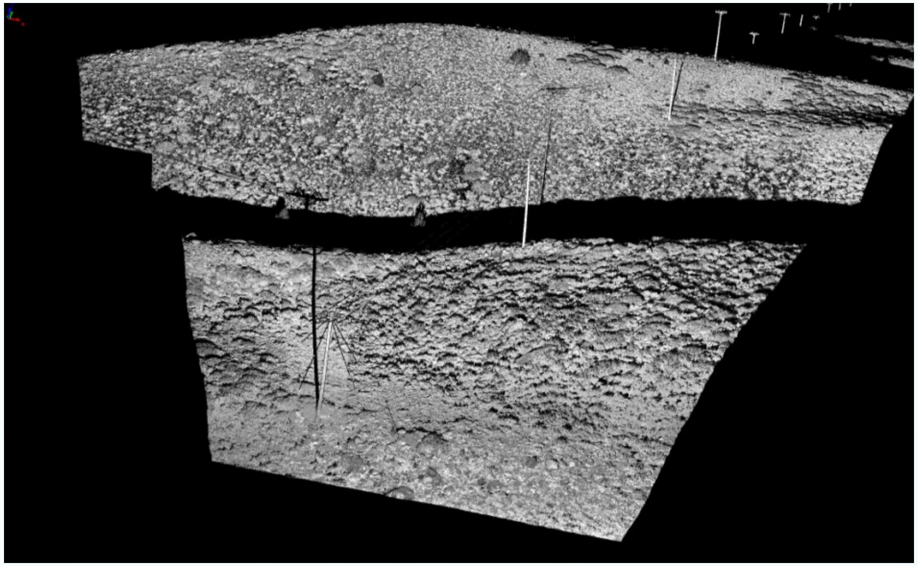
- Based on multipath observations.
- High temporal resolution.
- L-band – represents the upper 10-20 cm.
- Average moisture value of circular area with radius of ~40 m (standard tensiometers are point measurements).
- The method works also for snowpack monitoring

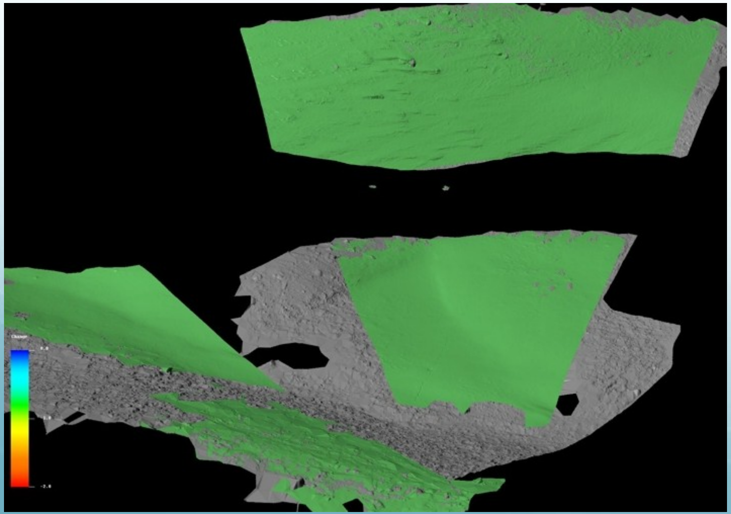
Terrestrial Laser Scanning – LiDAR

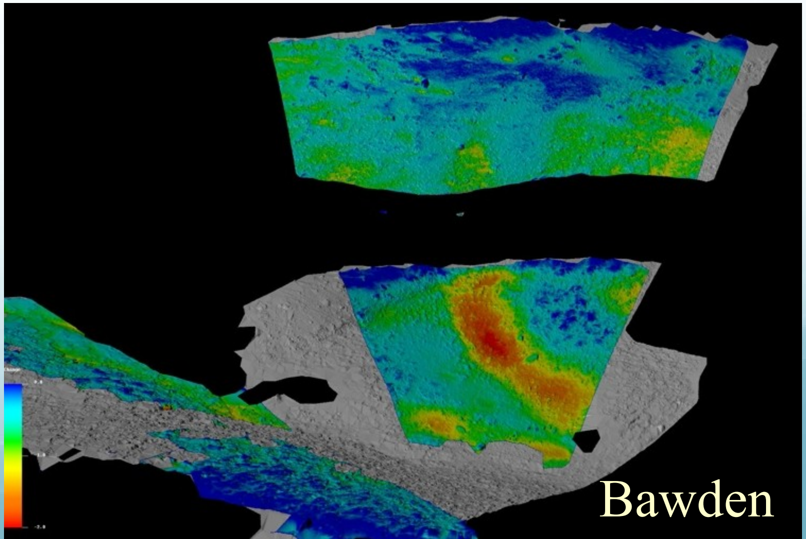
- **LiDAR** = Light Detection And Ranging
- Range is determined by measuring the time delay between transmission and detection of the reflected signal
- Ground-based LiDAR
  - Terrestrial Laser Scanning (TLS)
  - Laser scanner mounted on tripod
  - Surface models generated from point clouds

Snow Pack – Tripod LiDAR

T-LiDAR time-series at Conway Summit, CA



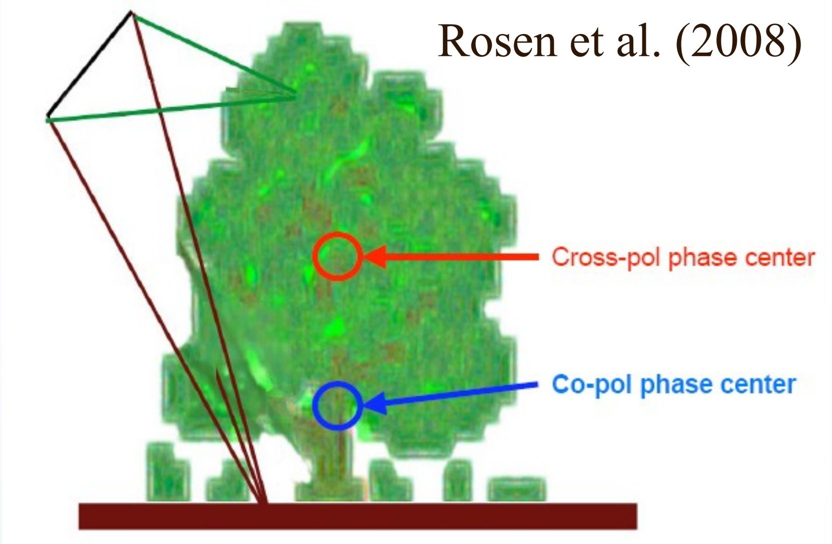




Hydro-Ecology

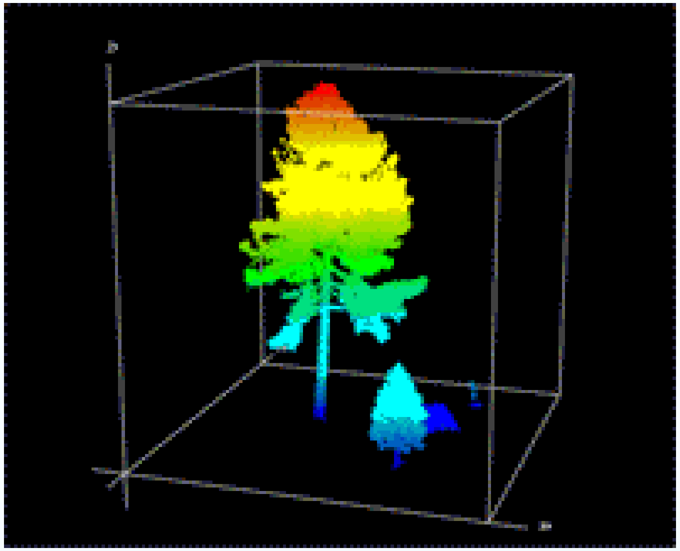
Studying the relations between water and vegetation

Polimetric-InSAR/UAVSAR



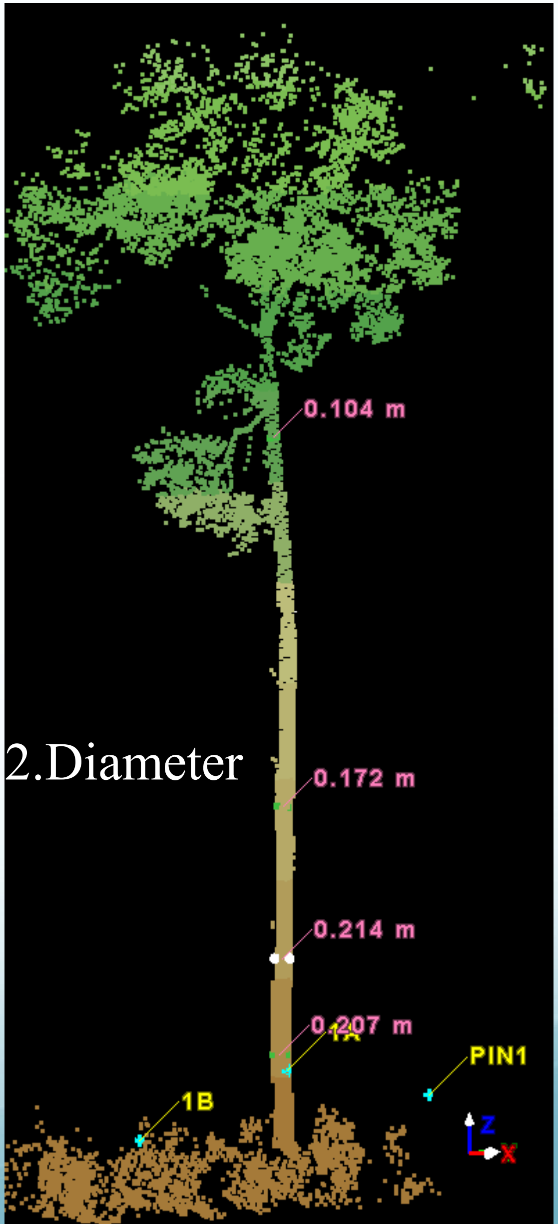
Rosen et al. (2008)

Lidar – Airborne/Tripod



- Vegetation structure characterization
- Above ground biomass
- Catastrophic events – Hurricanes, Fires
  estimated destruction and recovery

Hydro-ecology



Cypress Site