Crustal response to the changing climate and anthropogenic activity

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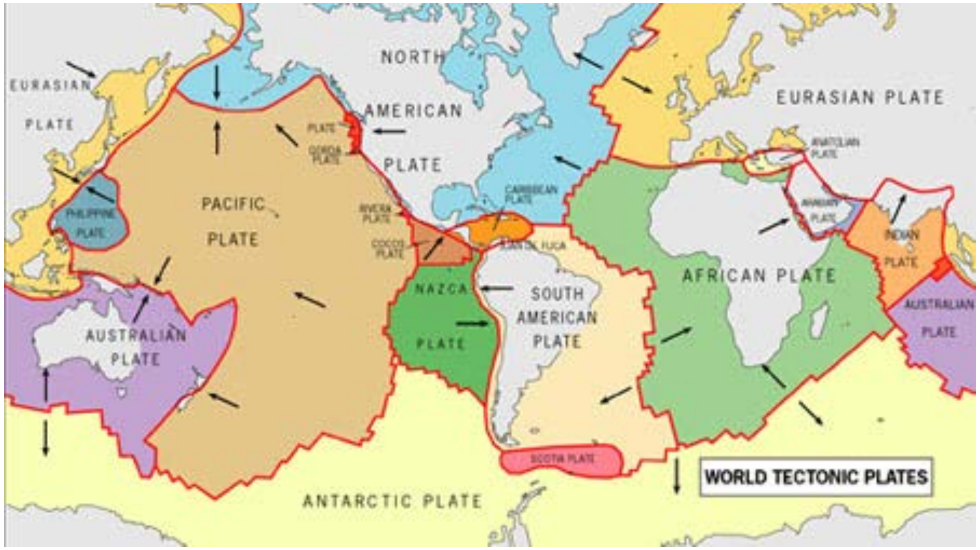
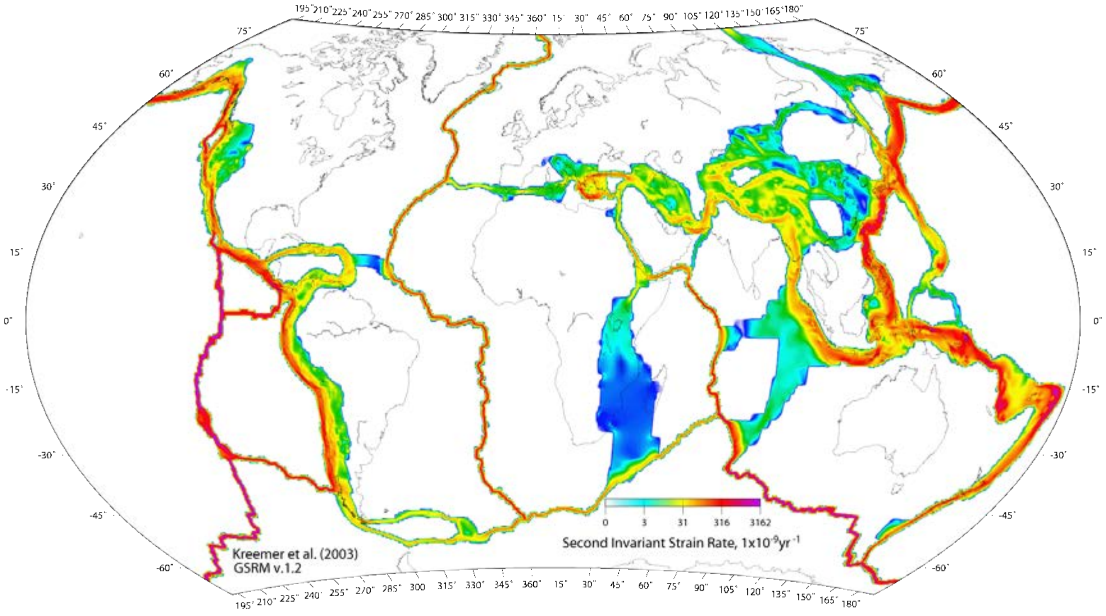
Presentation Content

- Crustal deformation
- Space Geodesy
  - GPS
  - InSAR
  - GRACE
- Response to melting icecaps - Greenland
  - Accelerated uplift
  - Seasonal variations
- Response to groundwater withdrawal
  - Venice
  - Mexico
  - Others – New Orleans, Indonesia
- Summary & acknowledgements

Plate motion and crustal deformation

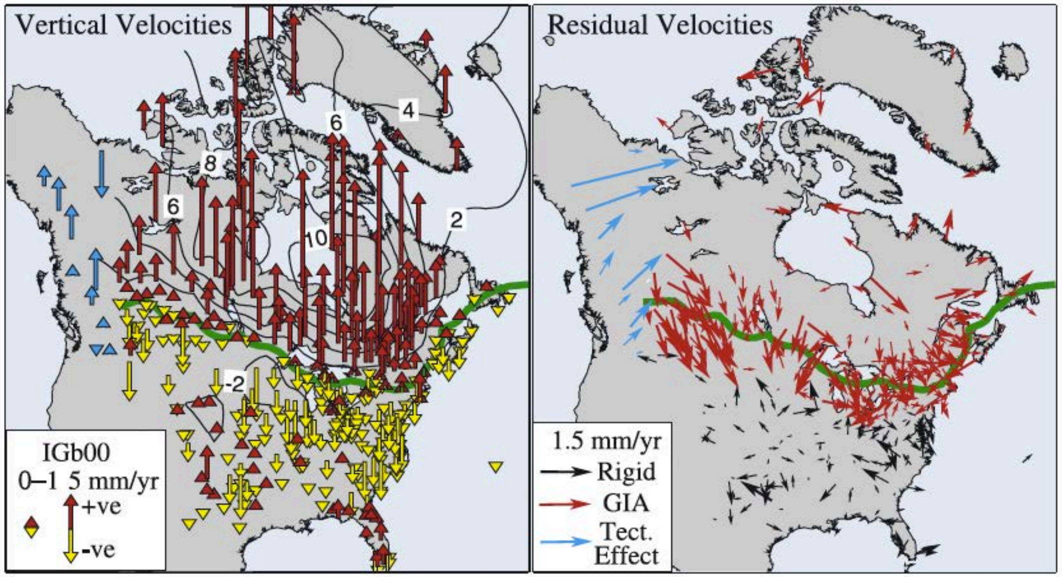


Tectonic plate motion

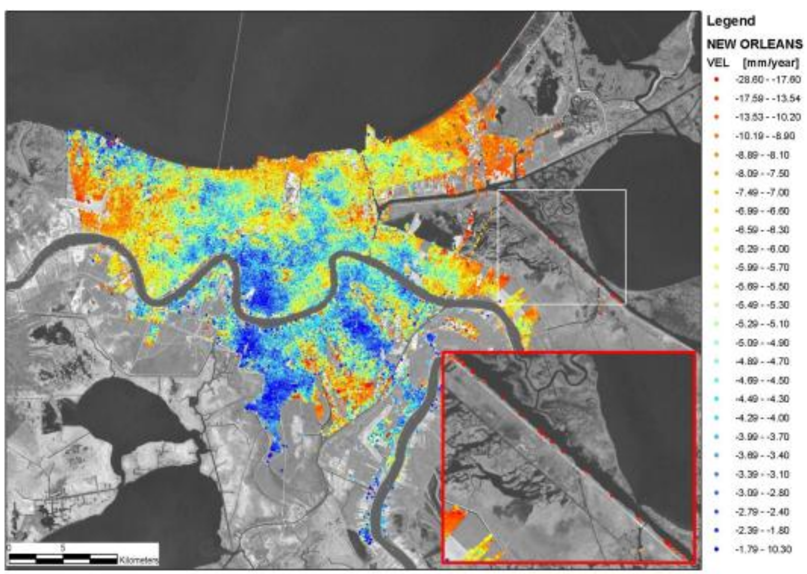


Global
Strain-rate map
(Kreemer, 2004)

Non-tectonic crustal deformation



Glacial Isostatic Adjustment
(Sella et al., 2007)

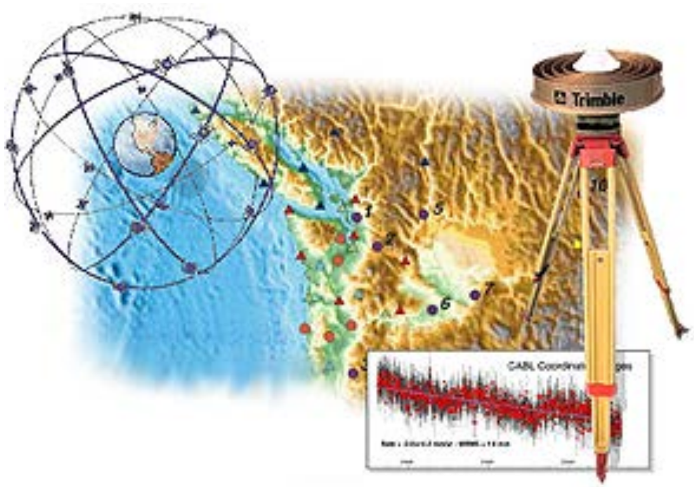


New Orleans subsidence
(Dixon et al., 2004)

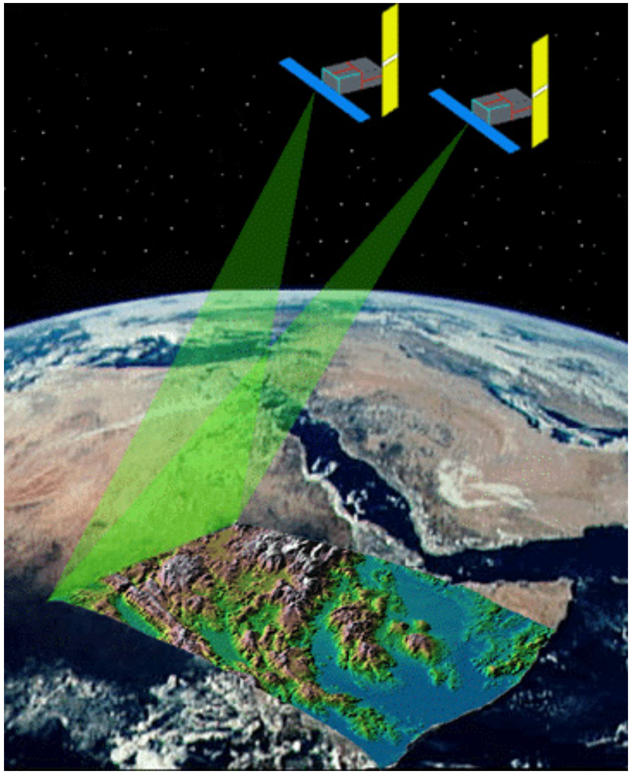
Space geodetic measurements

Global Positioning System - GPS

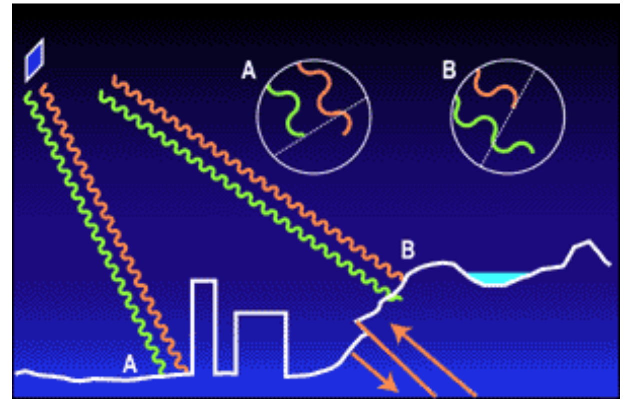
- The Global Positioning System (GPS) is a satellite-based navigation system.
- GPS was originally intended for military applications, but in the 1980s, the government made the system available for civilian use.
- GPS works in any weather conditions, anywhere in the world, 24 hours a day. There are no subscription fees or setup charges to use GPS
- Some civilian uses:
  - Navigation on land, sea, air and space
  - Geophysics research
  - Guidance systems
  - Geodetic network densification
  - Hydrographic surveys



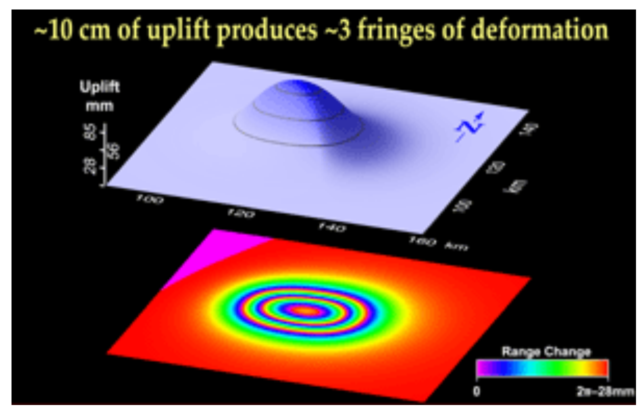
Interferometric SAR - InSAR



Two or more data acquisition of the same area from nearby location (< 1000 m)



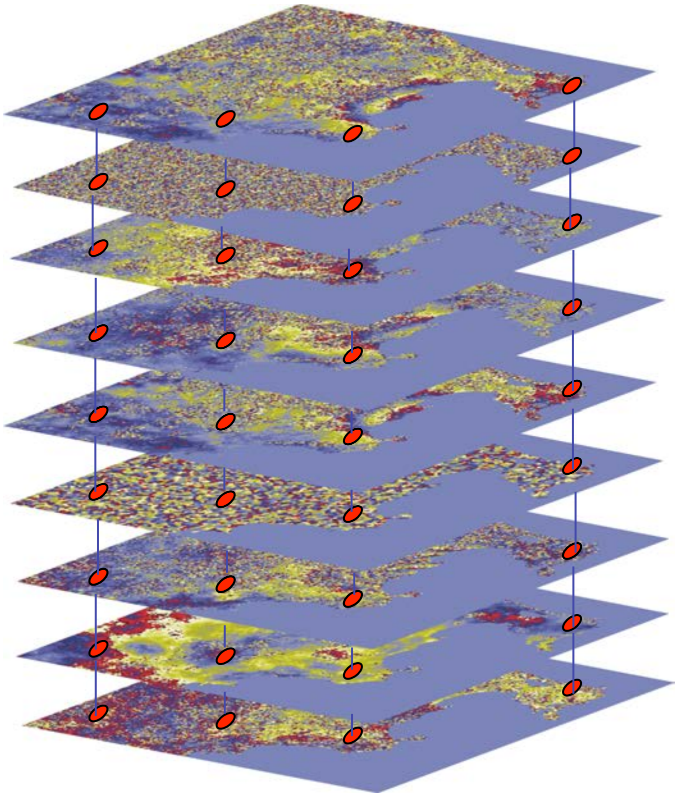
Changes in surface location result in detectable phase changes

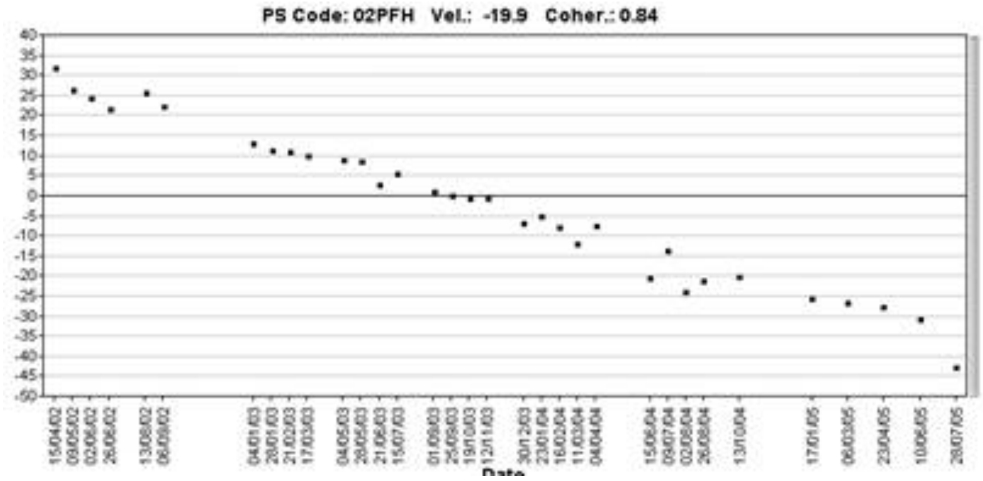


Fringes – 1 cycle (2π) = ½ λ

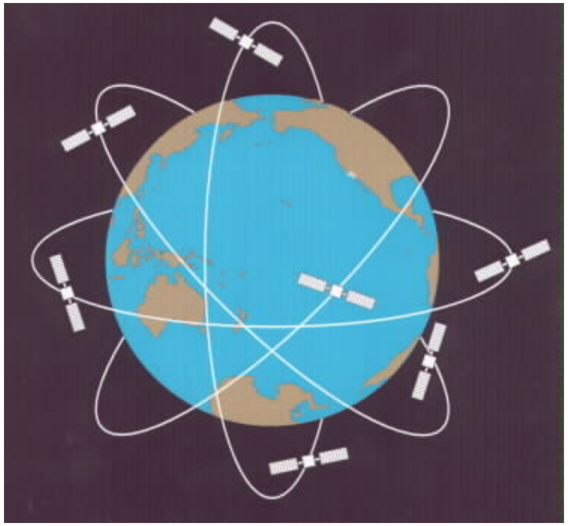
InSAR time series

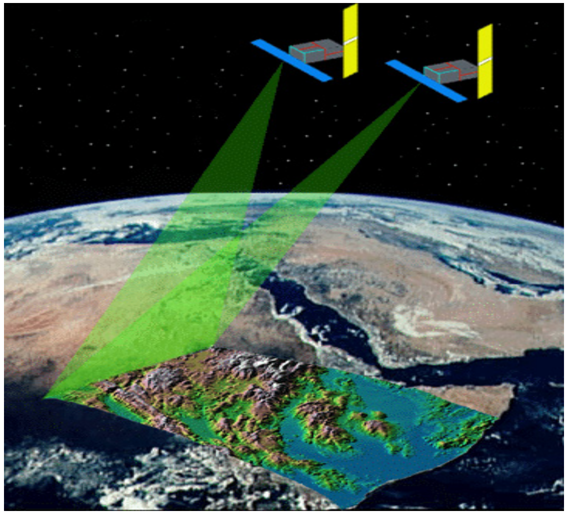
- Subset of reliable scatterers
- InSAR time series
- Low pass filter for removing atmospheric noise





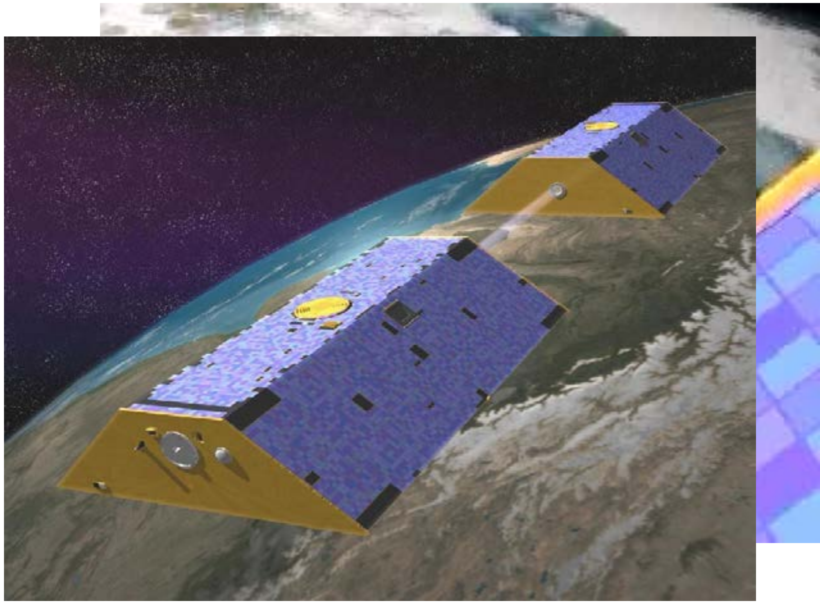
GPS	InSAR
Absolute (3D) displacements	Line of sight displacements
Continuous measurements	Periodic measurements
Almost no artifact	Orbital & atmospheric artifacts
Horizontal resolution - 1mm	Horizontal resolution - 15mm
Vertical resolution - ~ 3mm	Vertical resolution - 2mm
Restricted to receiver sites	Complete spatial coverage
Requires stable monuments	Requires no monuments





Gravity Recovery and Climate Experiment (**GRACE**)

- 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)



Crustal response to the changing climate

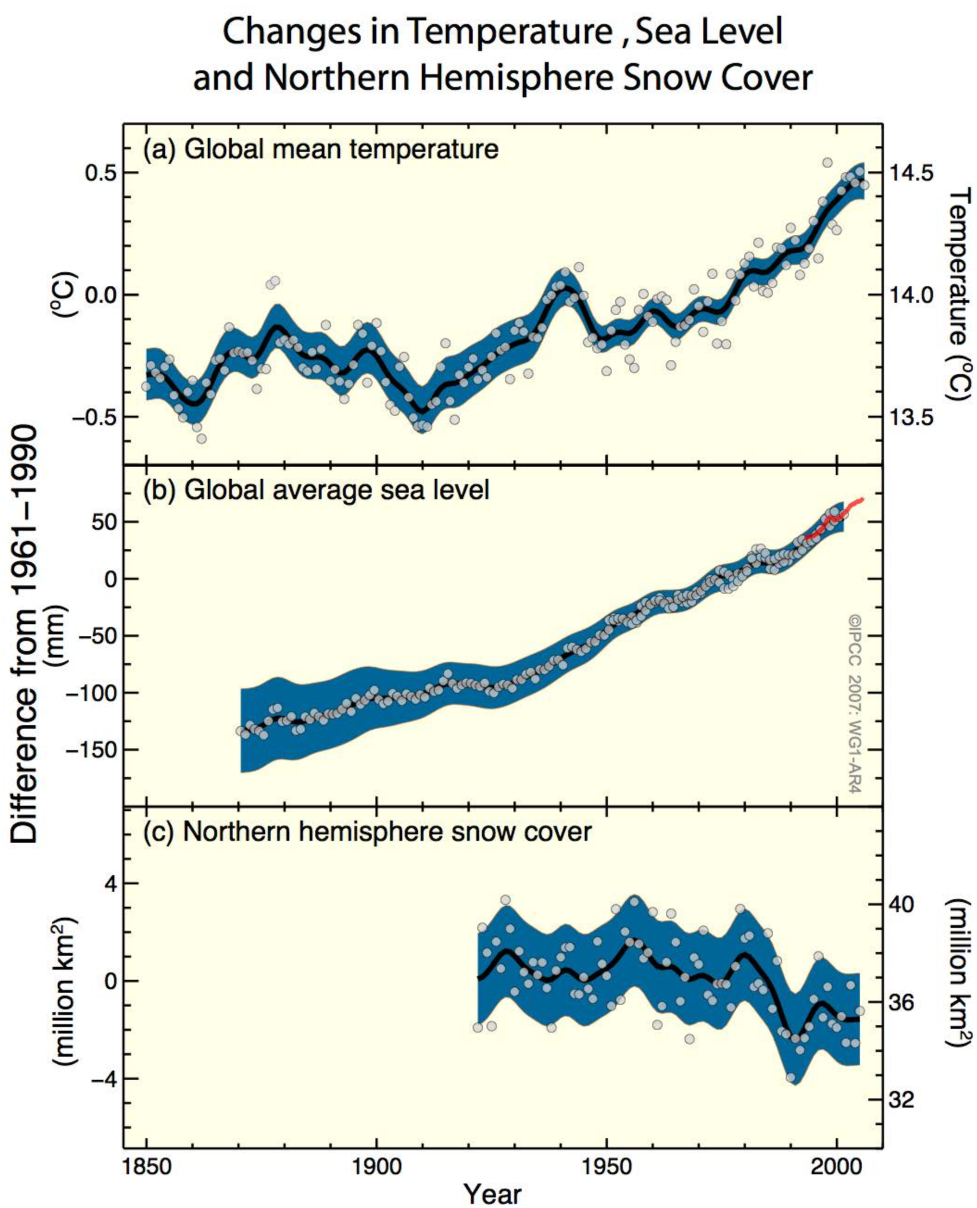
Direct Observations of Recent Climate Change

Gobal mean temperature

Global average sea level

Northern hemisphere Snow cover

IPCC report (2007)

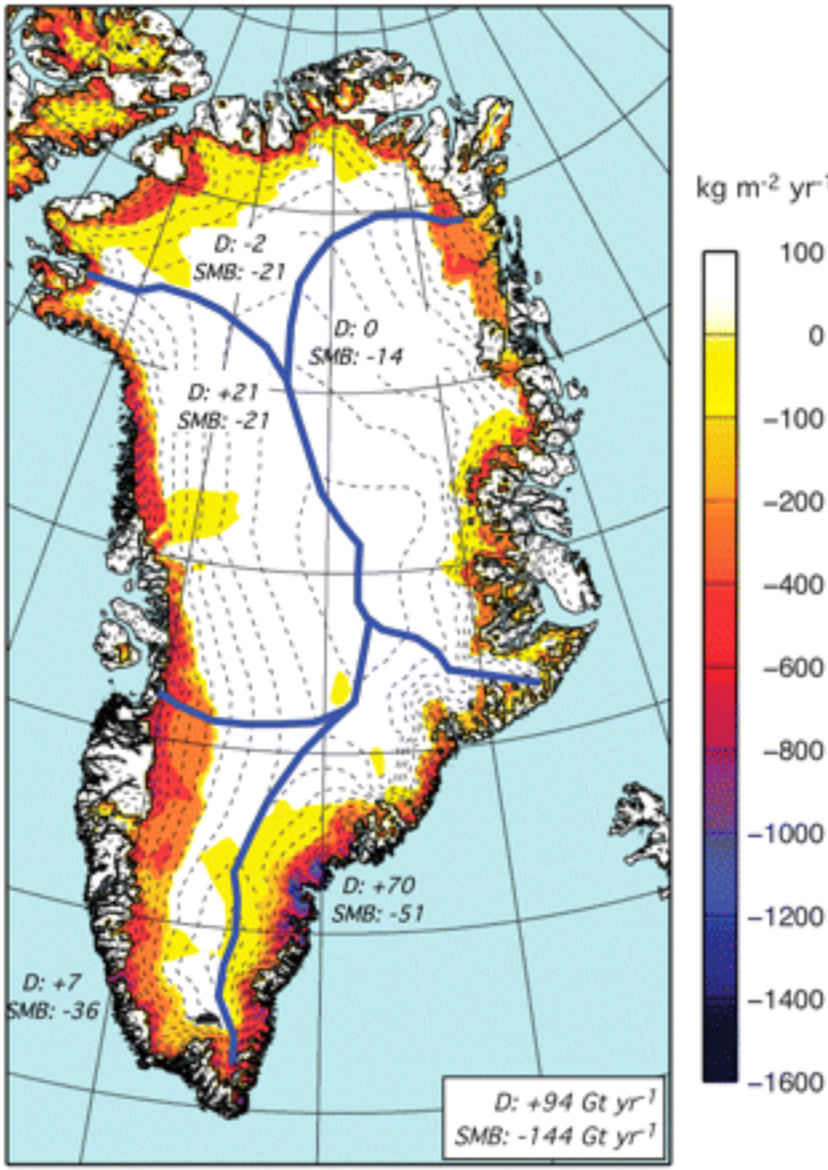


Arctic ice loss

Summer Arctic Sea Ice Decline

Source: NASA & Natural Resources Defense Council

Greenland ice loss



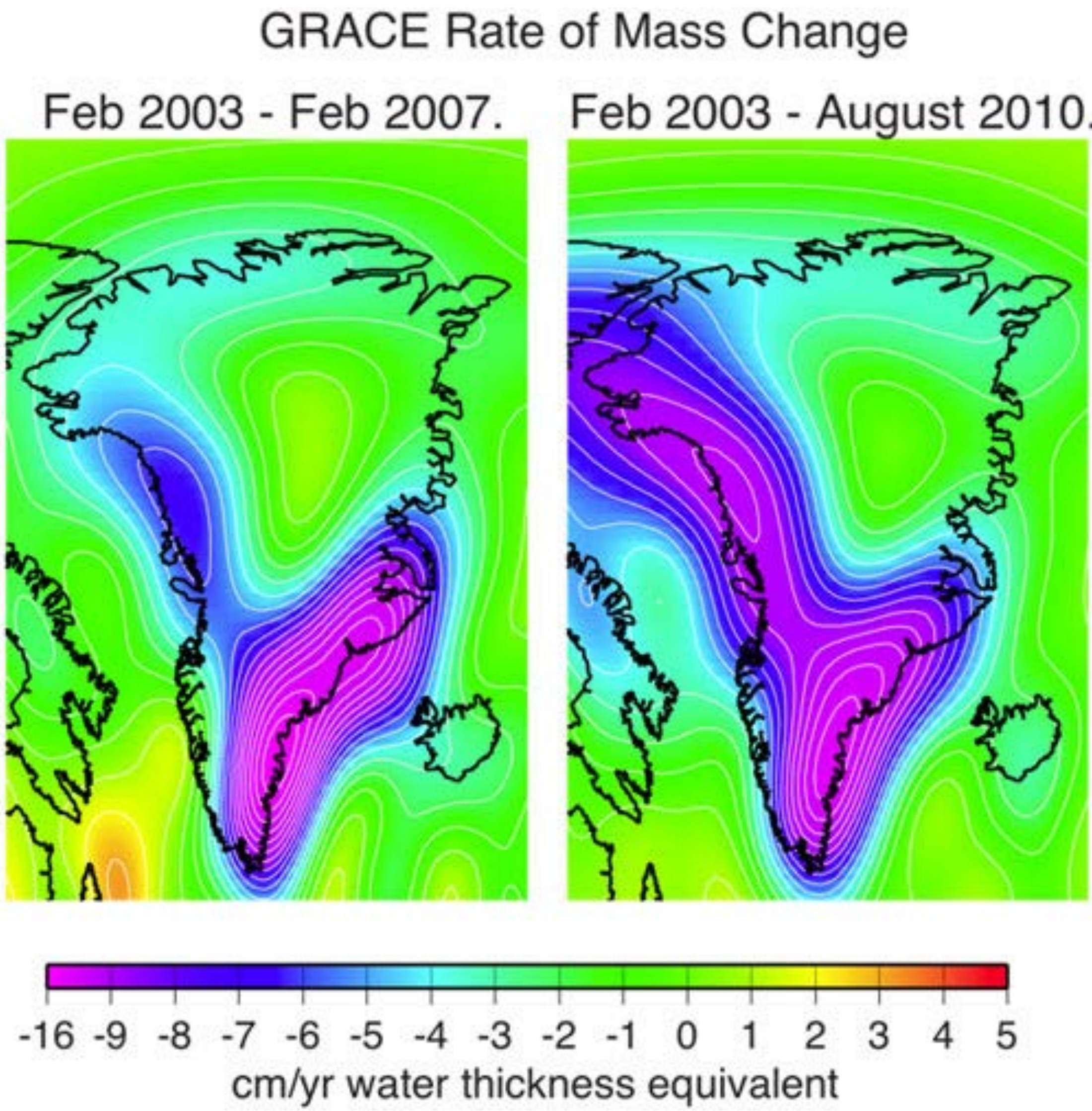
Greenland melting contributed ~ 0.2 - 0.4 mm/yr of sea level rise for period 1990-2000, may increase in future.

Greenland vs Antarctica: Greenland is not at pole, impacted by Gulf Stream (may melt faster)

Sea Level Rise

- Global average ~1.8 mm/yr from 1900-2000
- Composed of ~ 0.3- 0.5 mm/yr from mountain ice, ~0.70 - 1.0 mm/yr from thermal expansion
- Relatively small contribution from Greenland (<0.5 mm/yr)
- Current rate:
  - Roughly double?
  - Difficult to measure directly (large decadal fluctuations)
  - Direct measurement of melt contribution from Greenland, Antarctica is important

Greenland ice loss



Satellite monitoring: GRACE, Lidar, SAR/mass balance

In principle, could also use isostasy (GPS)

Problem: the past haunts us (visco-elastic effects: peripheral bulge from LGM; LIA)

Importance of Glacial Isotatic Adjustment (GIA)

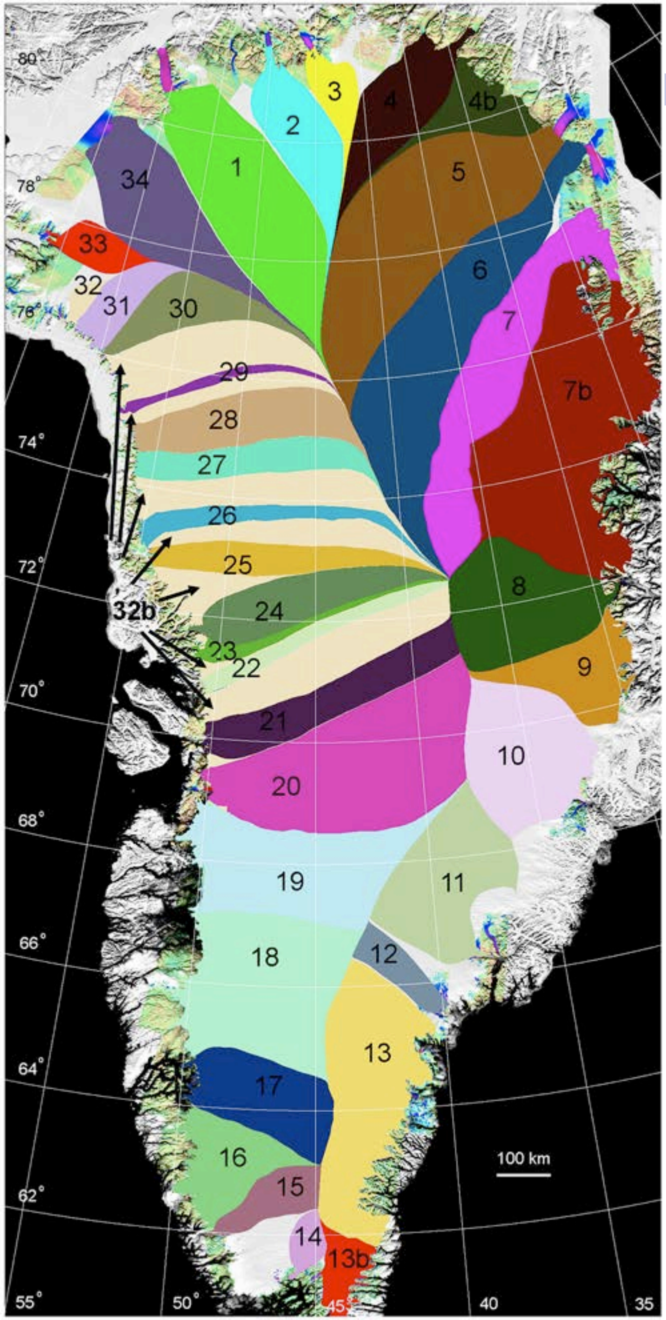
- Both GRACE and Altimetry depend on a model for GIA
- GIA models depend on:
  - Mantle viscosity structure (poorly known)
  - Ice melting history (very poorly known)

Mass Accumulation/Loss Estimates

- Does not depend on GIA
- Requires estimation of interior snow accumulation, peripheral loss by calving and melting
- Done for each drainage basin, then summed

Major Drainage Basins

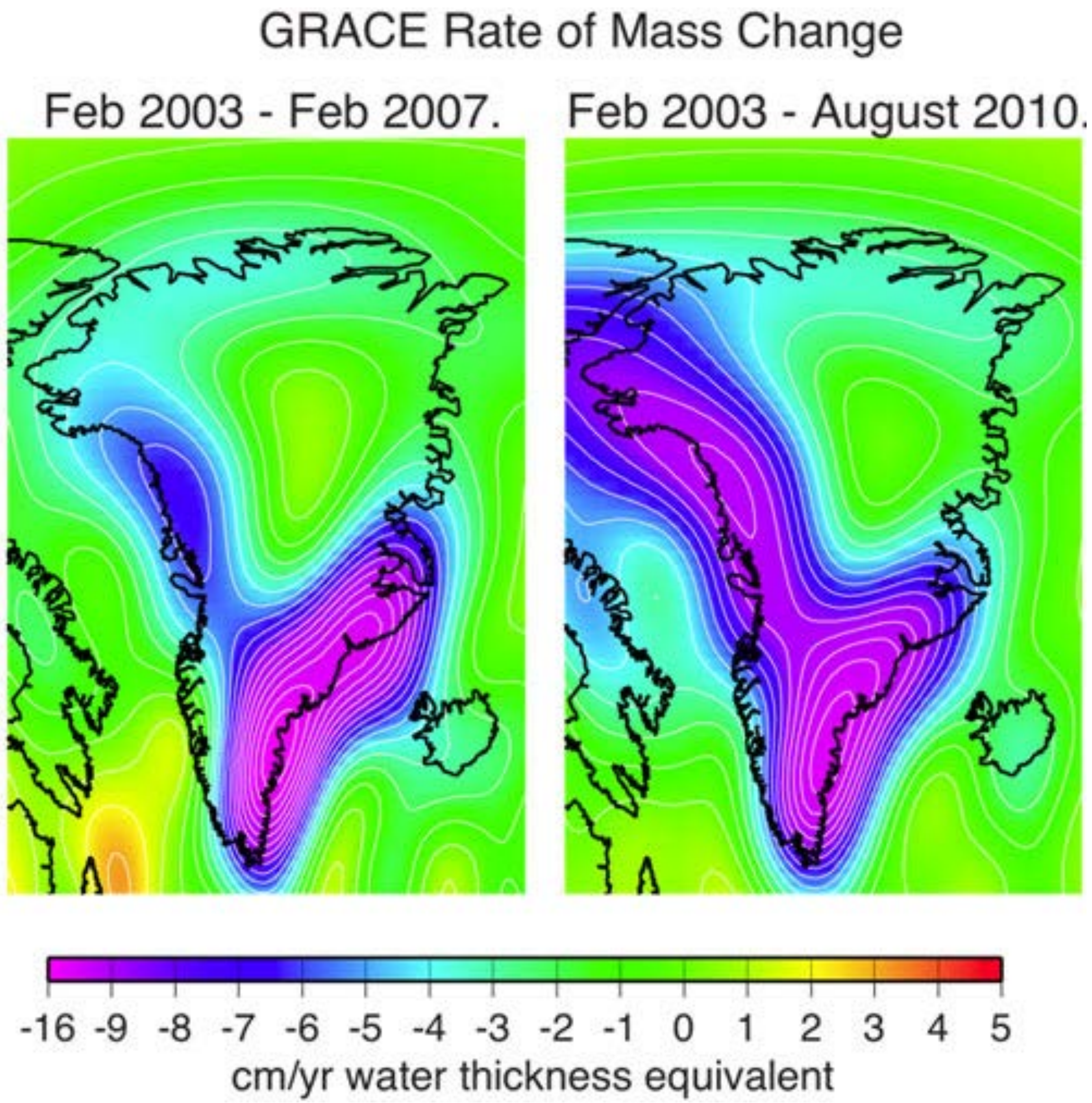
Rignot et al
2008



Mass Accumulation/Loss

- Subtract two large numbers, each with uncertainties, to obtain a small number
- Suggests accumulation rate ~ constant, but increasing loss at margins
- Consistent with GRACE results

GRACE 2003-2008

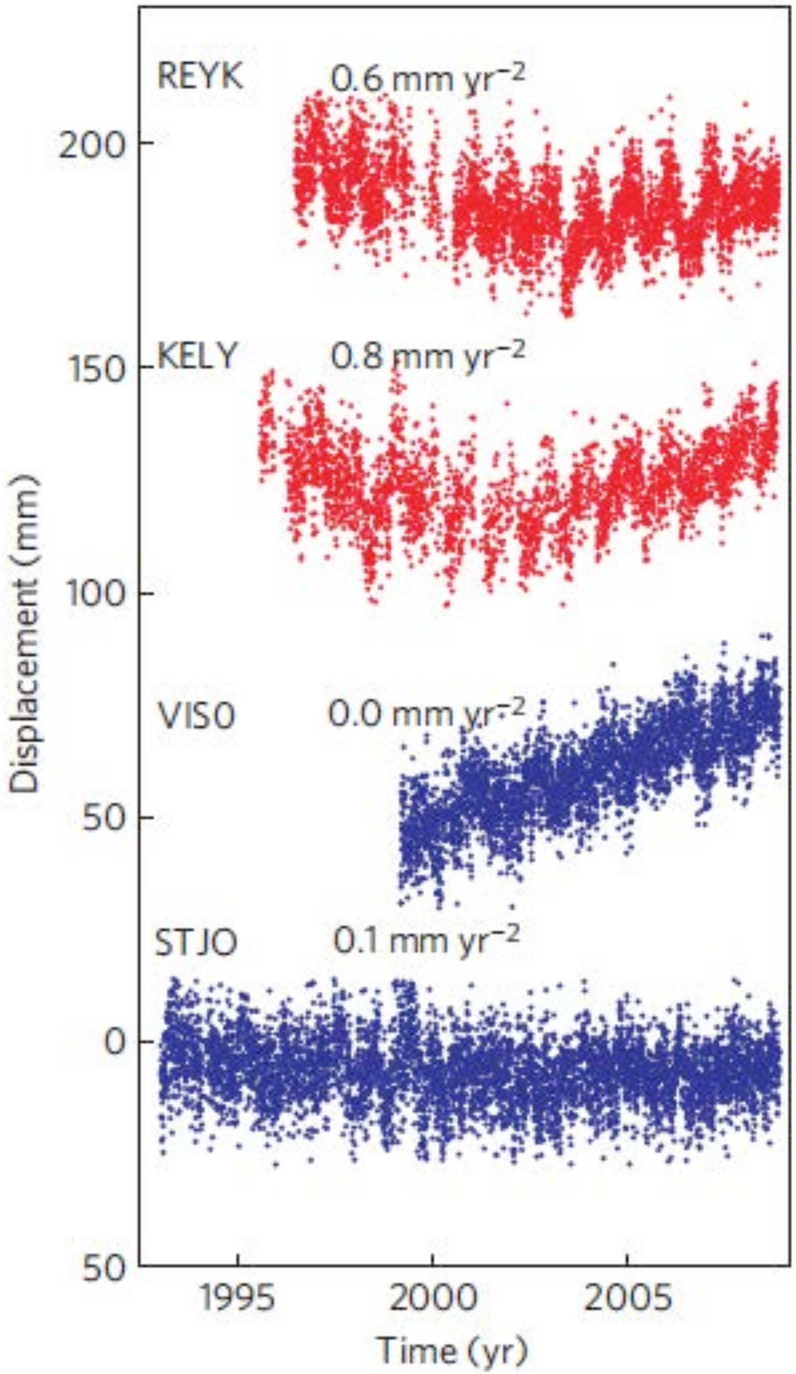


GPS as a Tool for Monitoring Greenland

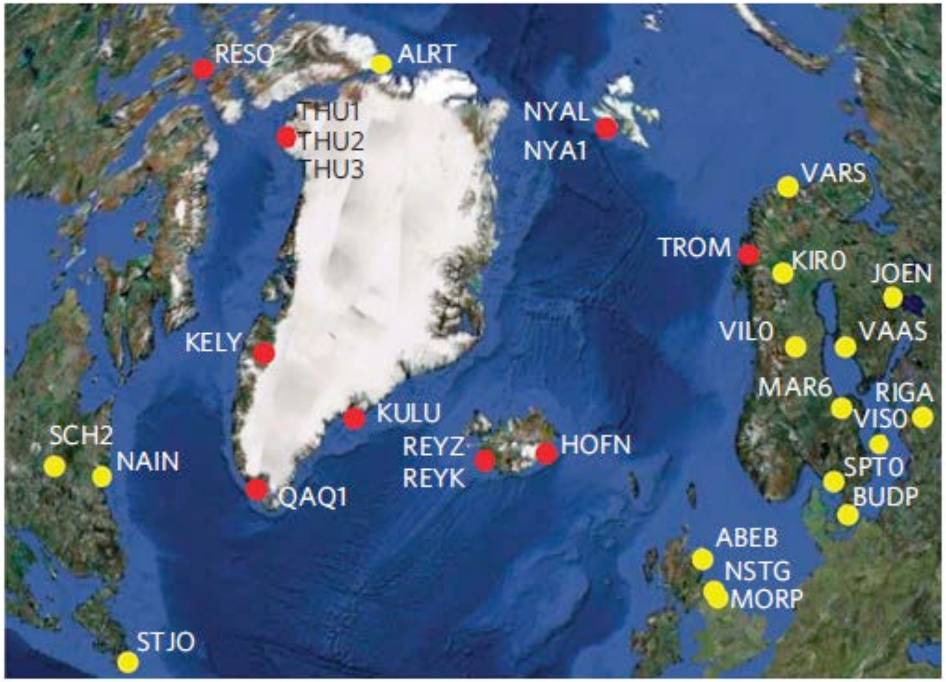
- Restricted to rocky coast (but that is where loss is concentrated)
- MAL studies indicate interior in approximate mass balance (outflow to edges balanced by new snow)
- Need to deal with GIA
- Most GIA models predict that Greenland is subsiding due to peripheral bulge collapse from Laurentide glaciation

“Correcting” for GIA

- GIA models are “noise source” if we want to look at present-day melting
- Focus on perturbations to velocity field (accelerations) rather than velocity field itself

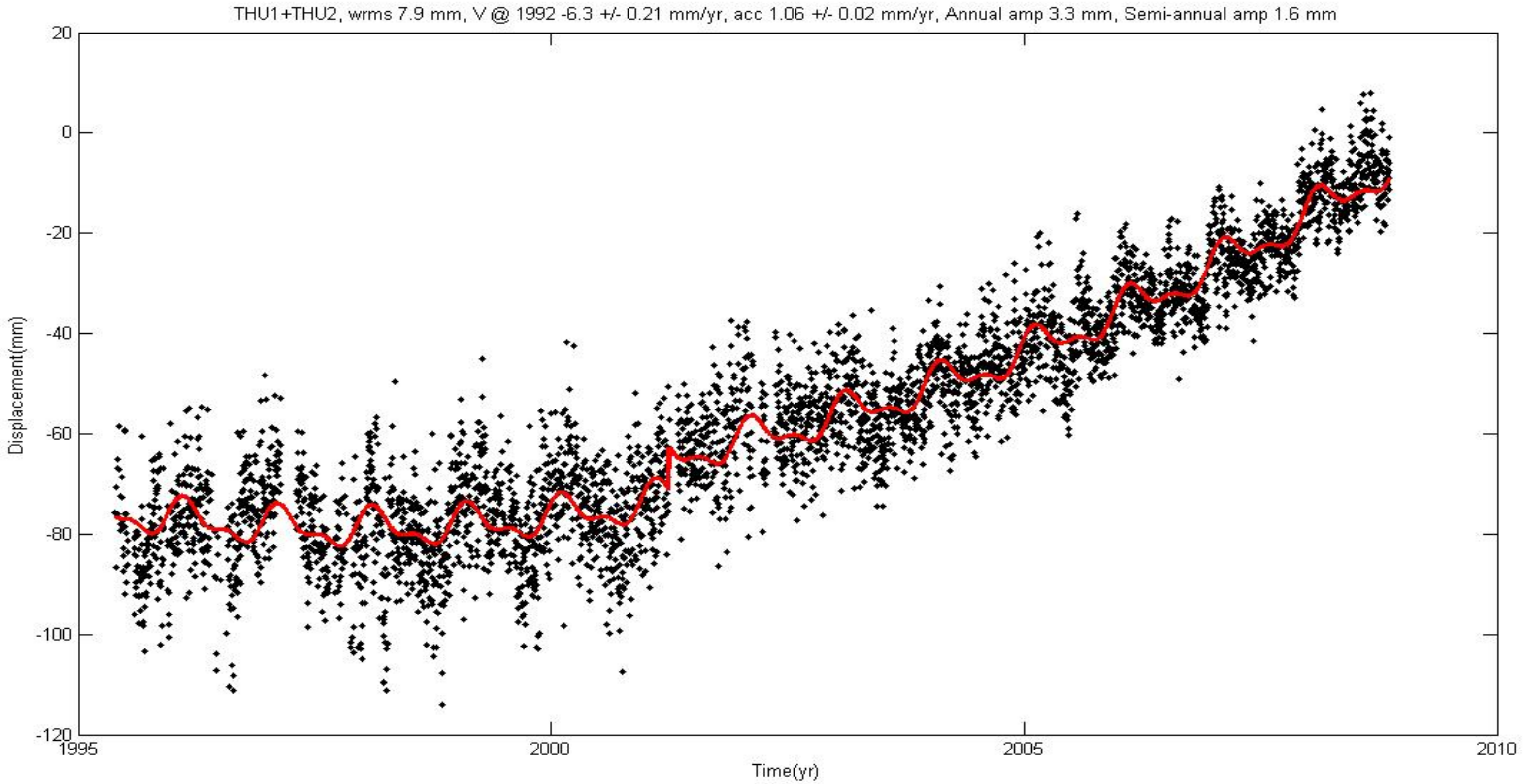


GPS time series Vertical component



GPS Position Time Series

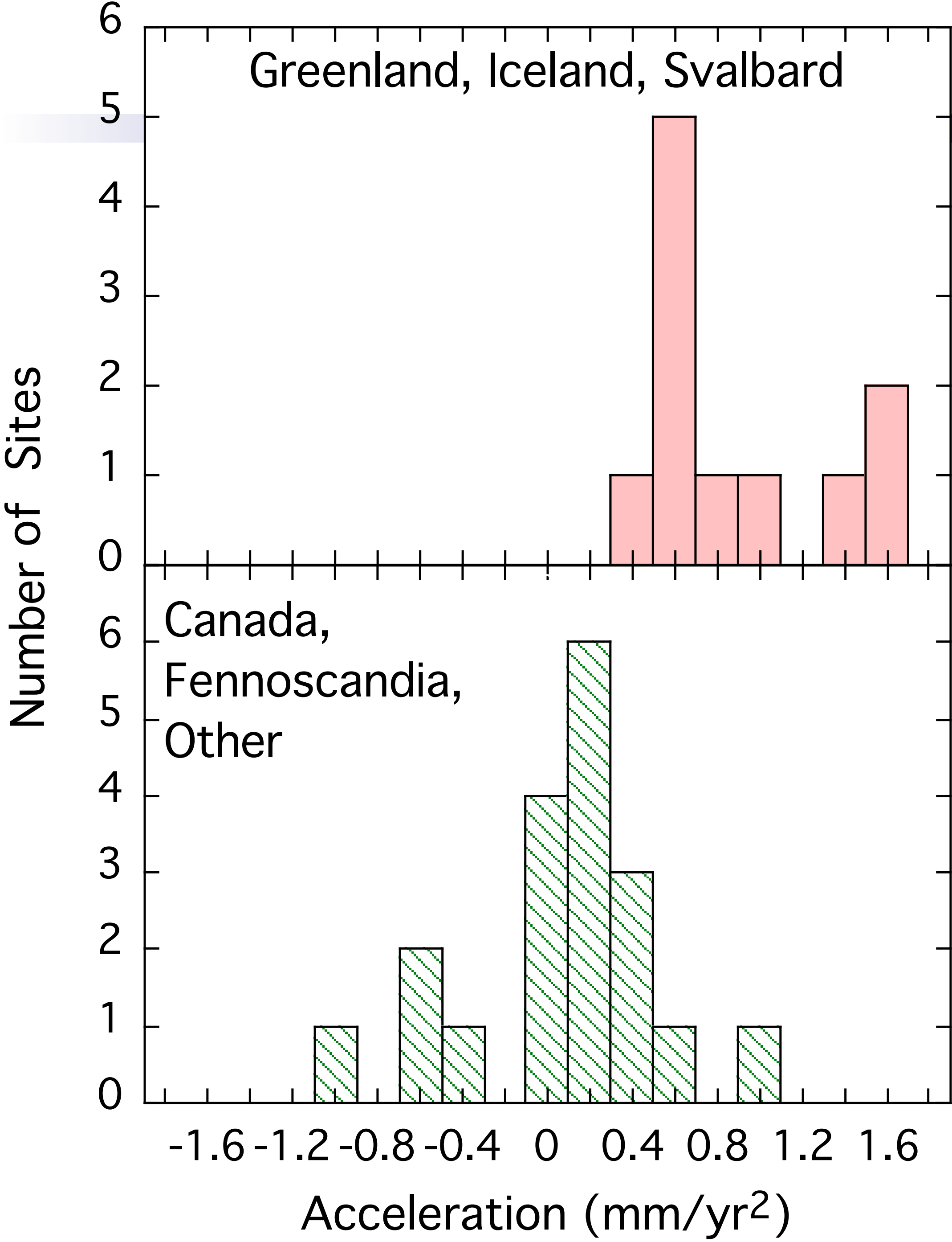
The series account for equipment change, annual variation, and possible rate changes; use 7 parameter model (red line). All Greenland sites show acceleration



Reference Frame Effects

- Previous studies have assumed that deviations from linear trend reflect long term drift of GPS reference frame
- Evaluate via regional comparisons (Fennoscandia, Canada)

Acceleration



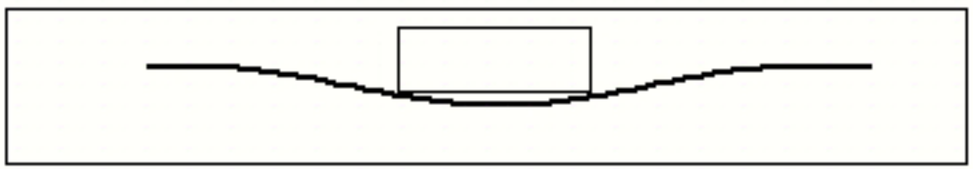
Implications of Accelerating Uplift

- Accelerating uplift implies accelerating ice loss in regions with multi-year land ice
- Unlikely to be reference frame effect (not observed in Fennoscandia or northern Canada
- Time scale implies mainly elastic response to mass unloading
- Evidence from phase of annual term supports elastic response

MODIS
Summer 2006
Western Greenland

Modified 2-D Model:

Finite Width Line Load



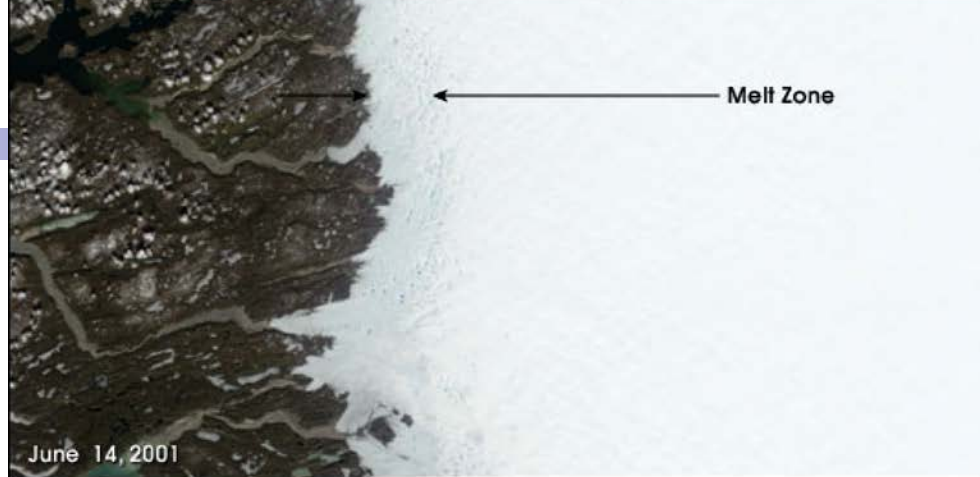
$$U \cong \frac{3.3(1-v)}{\pi G}\left[N_0\right]$$

Jaeger et al., 2007

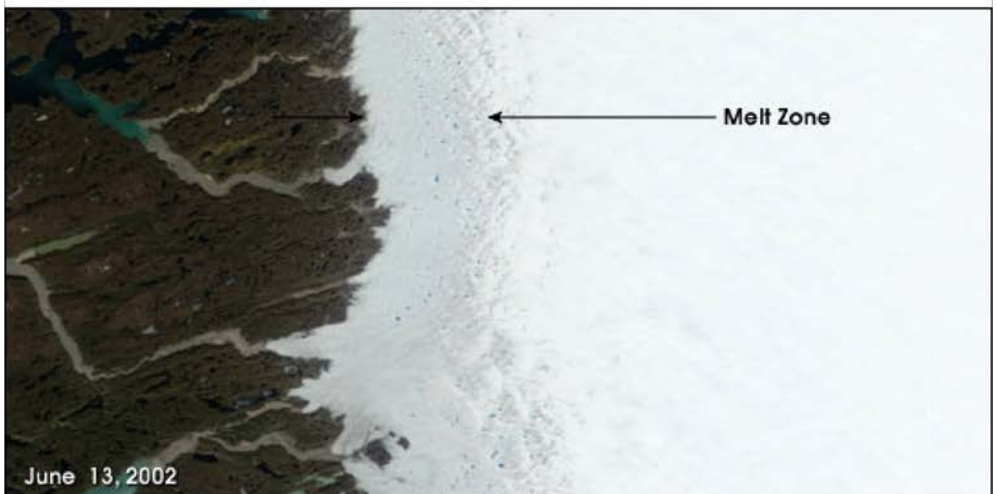
Model results

- Applicable to western and southeastern Greenland, where melting is focused in narrow coastal band
- 1 mm/yr of increased uplift =>load change of ~$5*10^7$ N/m^2
- For 1700 km coastal strip in W Greenland, implies acceleration ~8 GT/yr^2
- Corresponding SE Greenland value ~12 GT/yr^2
- ~ agreement with GRACE result

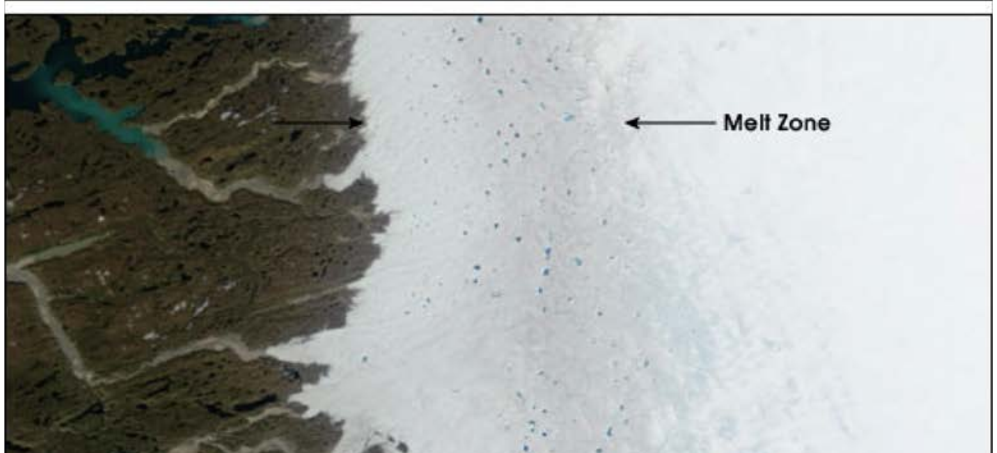
June 2001

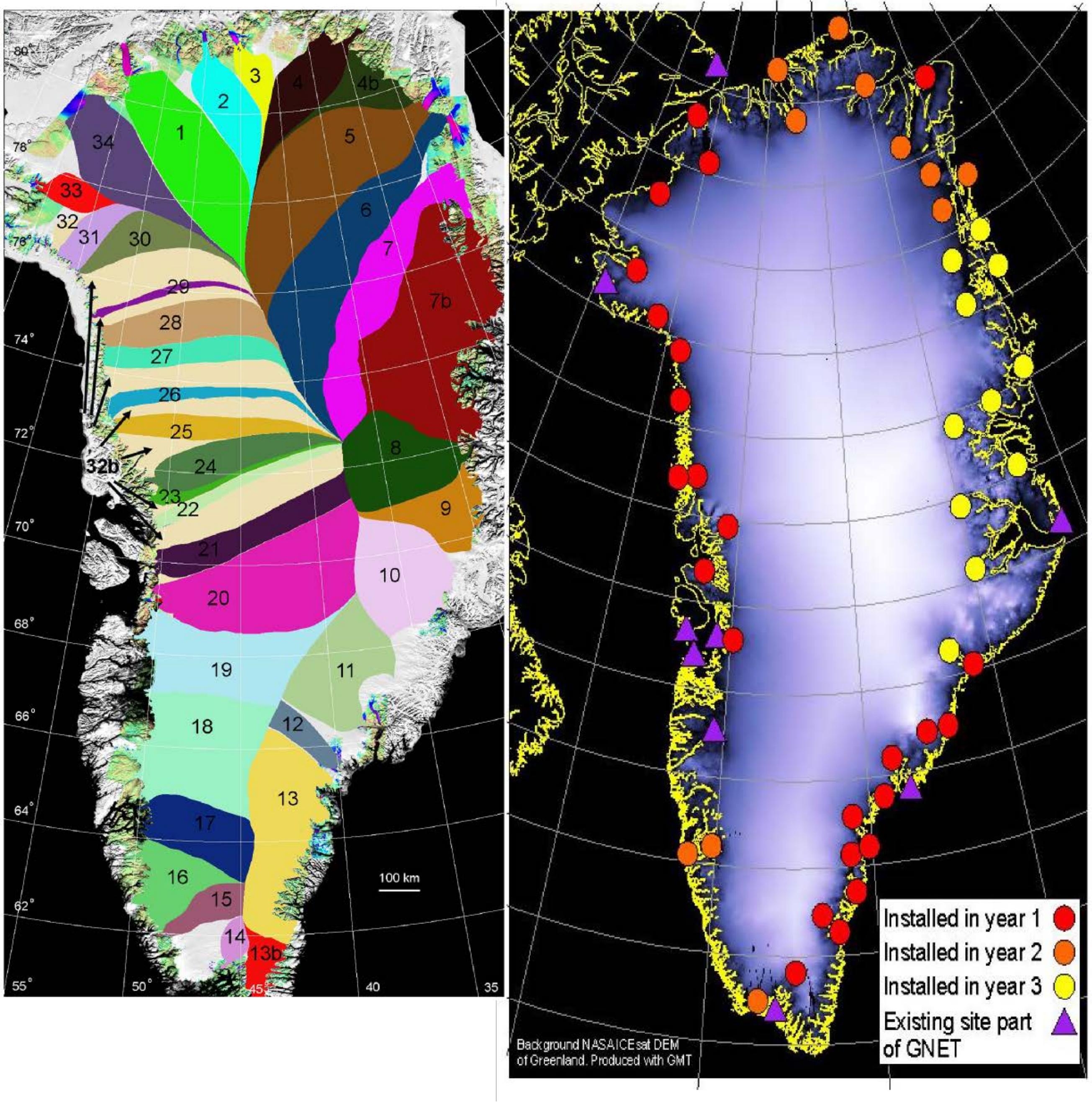


June 2002



June 2003

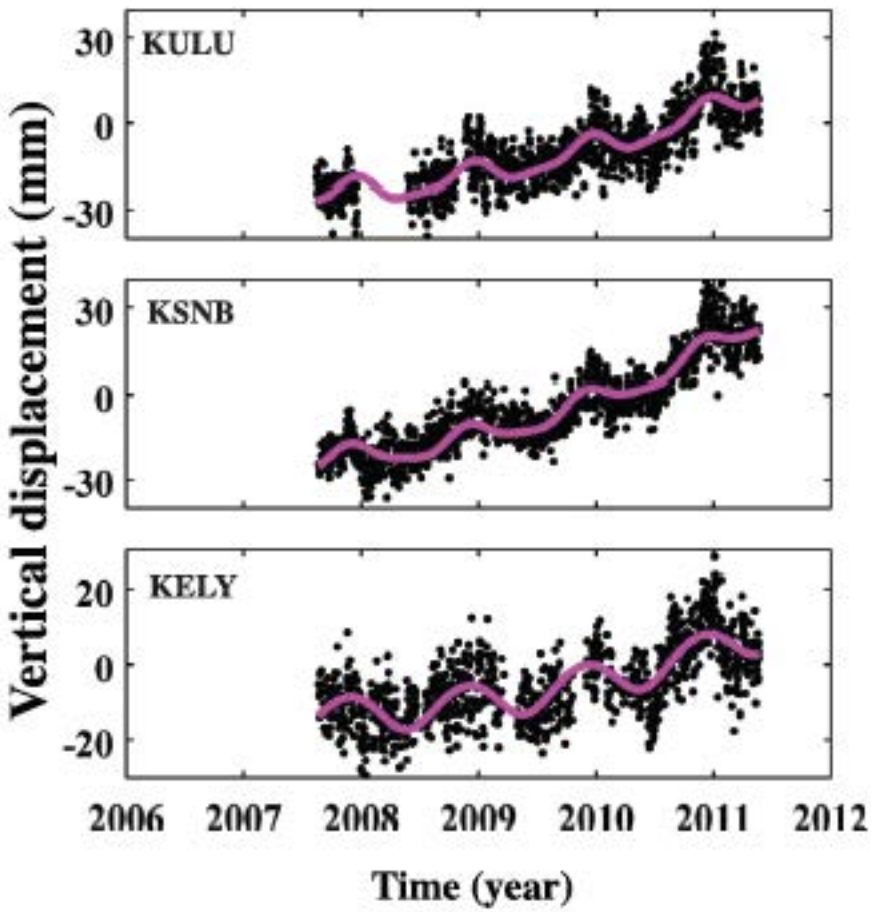




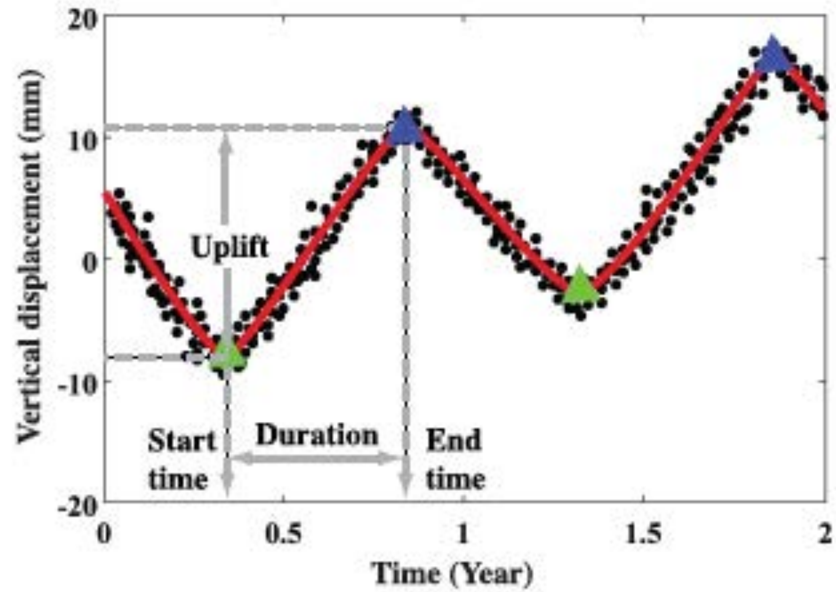
GNET:
will provide basin-by-basin view of ice health

Seasonal signal analysis

GPS time series

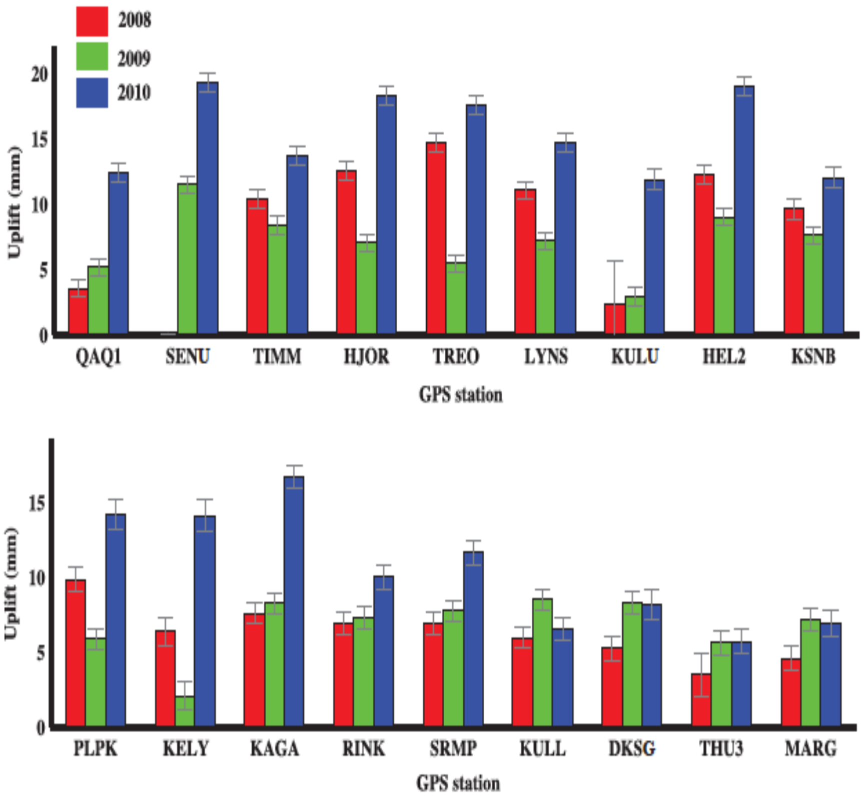


Seasonal parameter estimation

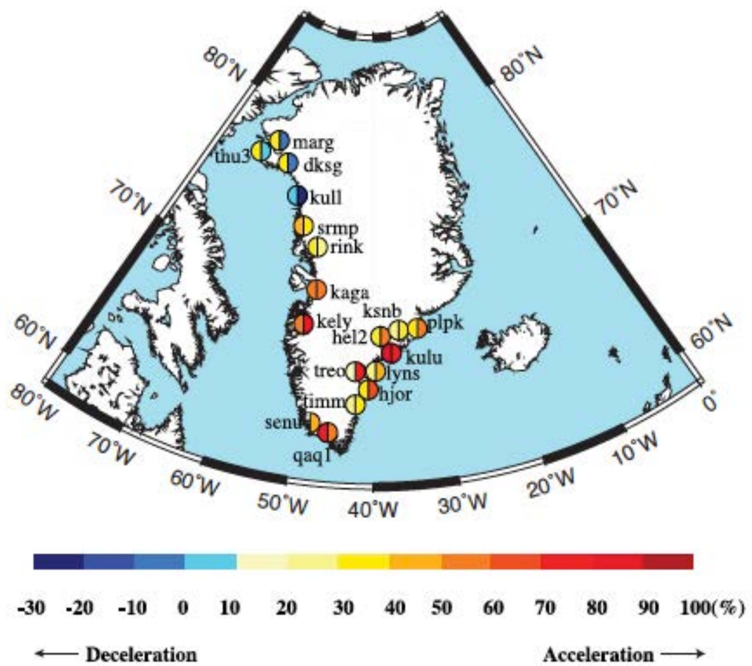


Seasonal signal analysis

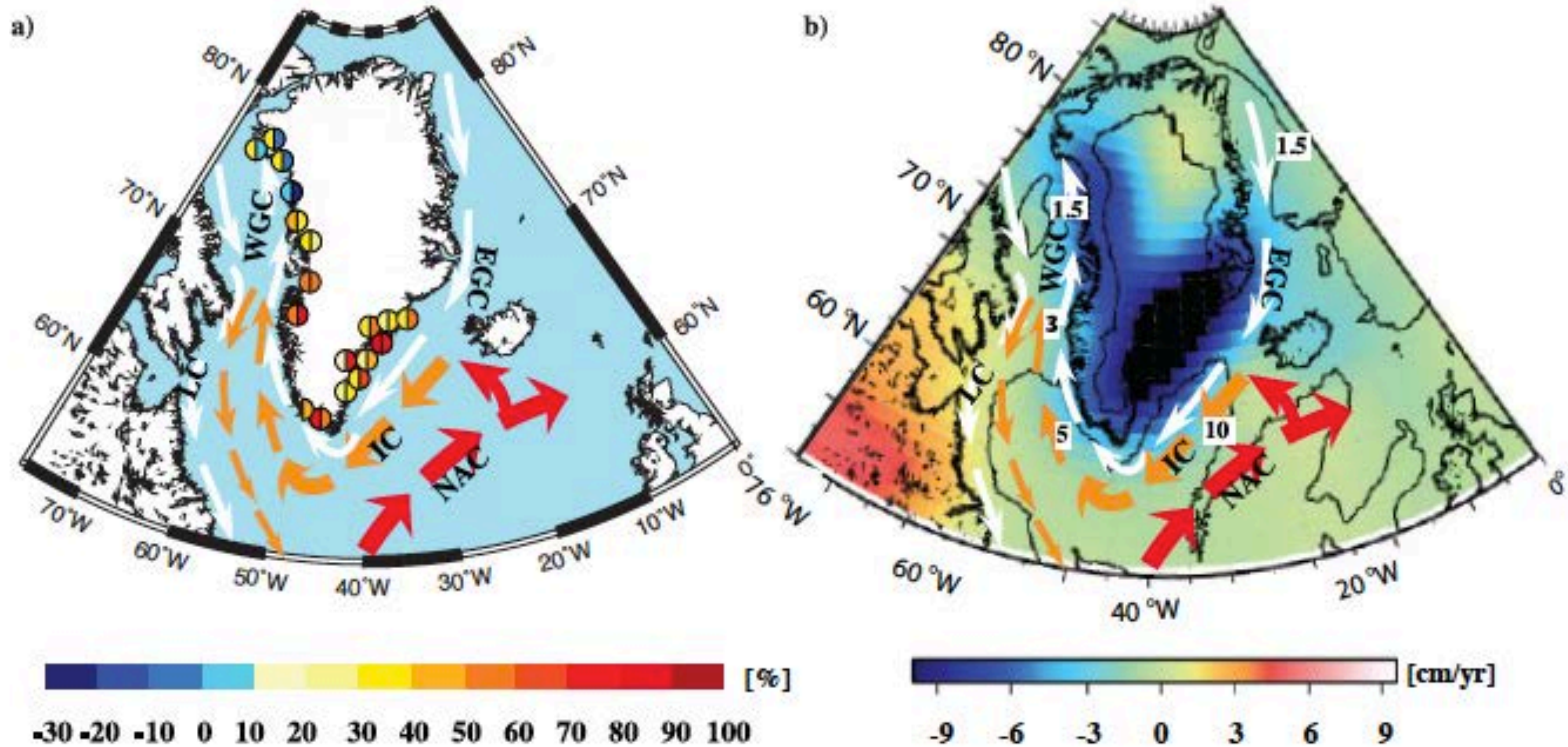
Summer uplift 2008-2010



Uplift



Ocean currents, coastal uplift, and ice mass balance



Red arrows indicate the mean path of the warm North Atlantic Current (NAC); orange arrows indicate Irminger Current (IC), white arrows indicate East Greenland Current (EGC), West Greenland Current (WGC) and Labrador Current (LC).

Conclusions

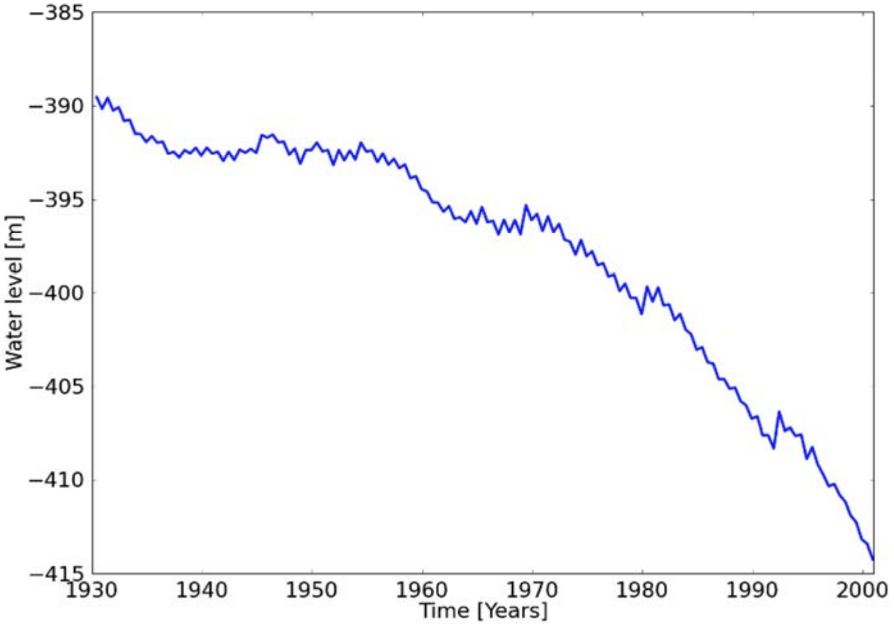
- Perturbations to the vertical velocity field measured by GPS are sensitive to recent land ice melting
- Uplift of Greenland, Iceland and Svalbard is accelerating
- A simple elastic model for coastal melting in Greenland gives ice loss is approximate agreement with other techniques
- Seasonal analysis of GPS time series indicates that the uplift in 2010 was unusual high for southern Greenland
- The unusual 2010 conditions were caused by the warm Irminger water

Crustal response to Anthropogenic activities

Deformation occurs due to

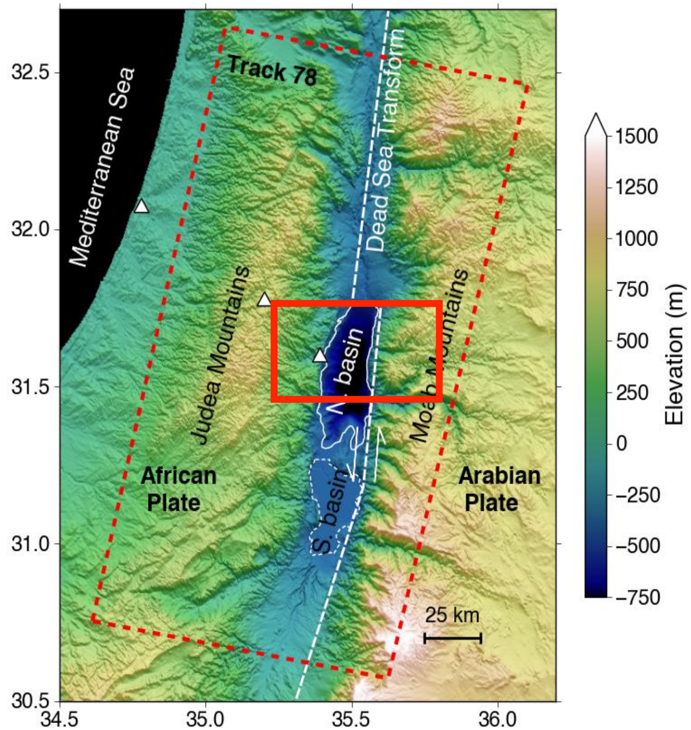
1) Changes in hydrological loads
   - Surface water
   - Ground water
2) Sediment compaction

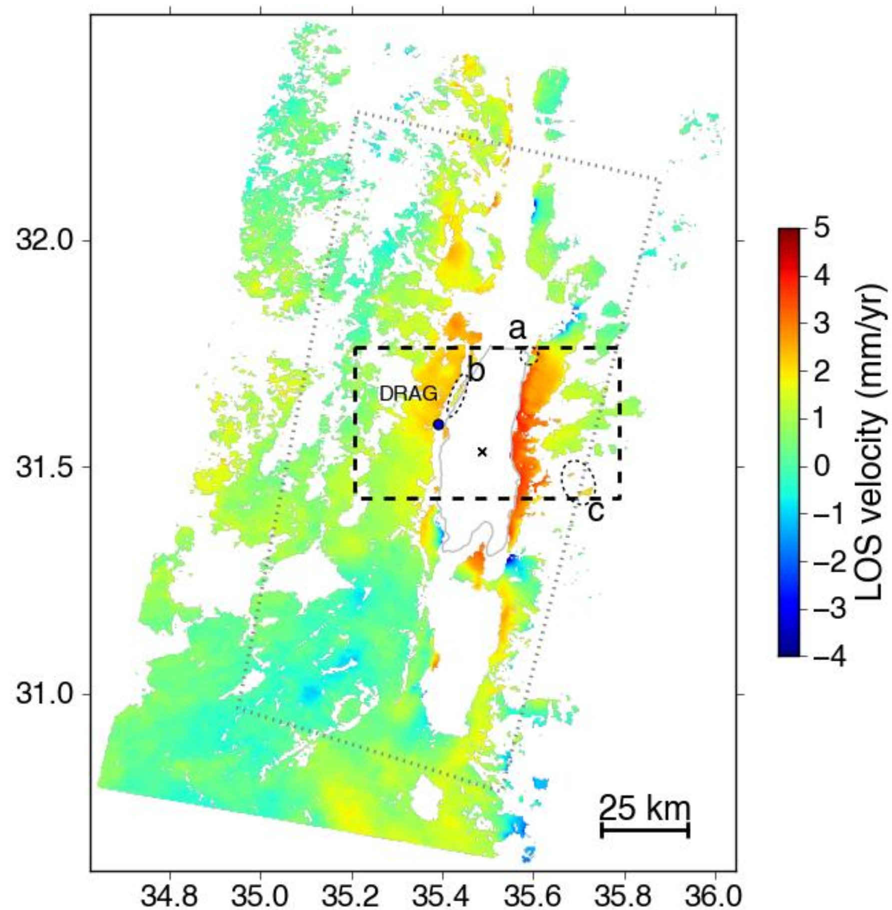
Dead Sea water level drop



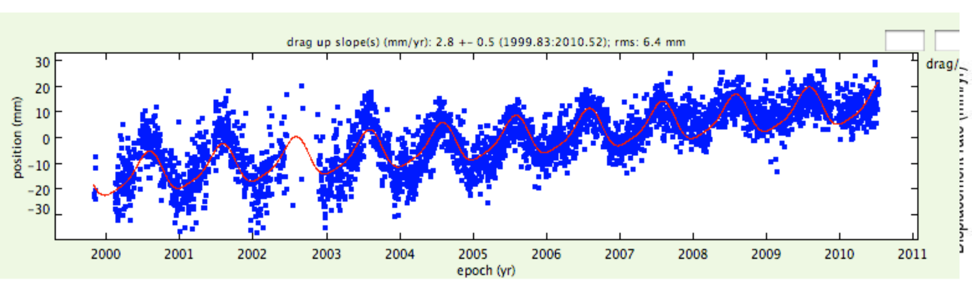
This dock was level with the Dead Sea in 2007.

The lowest place on Earth is rising (Nof et al., 2012)

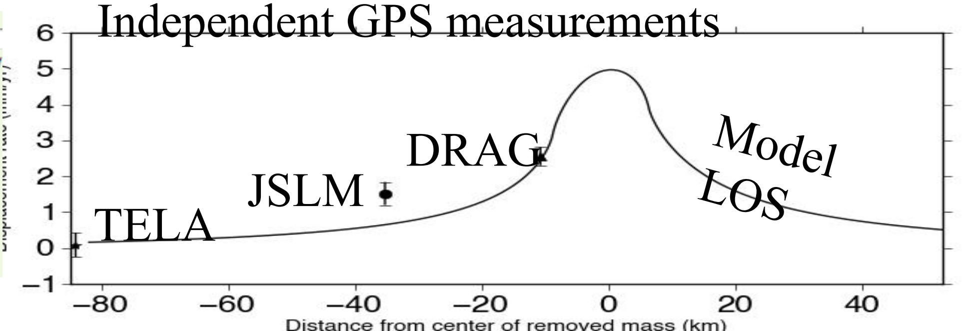




DRAG - 2.8+-0.5 mm/yr



Independent GPS measurements



Satellite-based estimates of groundwater depletion in India

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

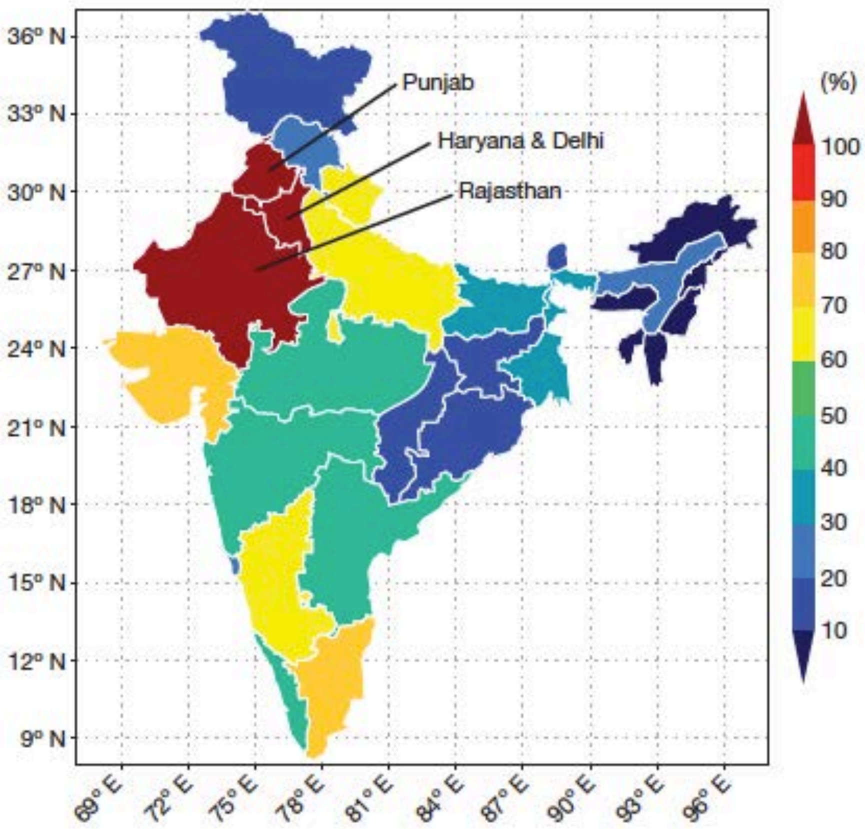


Figure 1 | Groundwater withdrawals as a percentage of recharge. The map is based on state-level estimates of annual withdrawals and recharge reported by the Indian Ministry of Water Resources[2]. The three states studied here are labelled.

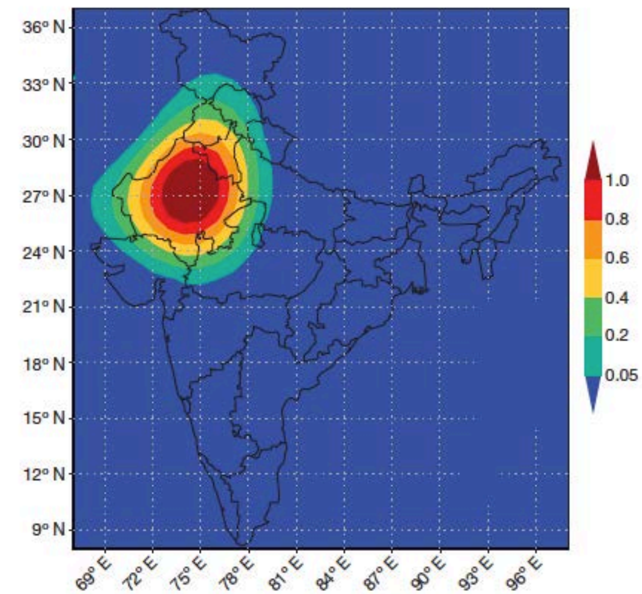
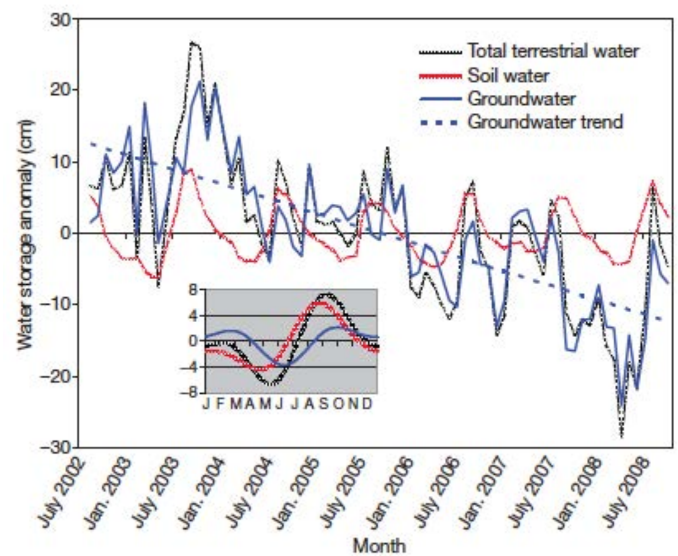


Figure 2 | GRACE averaging function. The unscaled, dimensionless averaging function used to estimate terrestrial water storage changes from GRACE data is mapped.



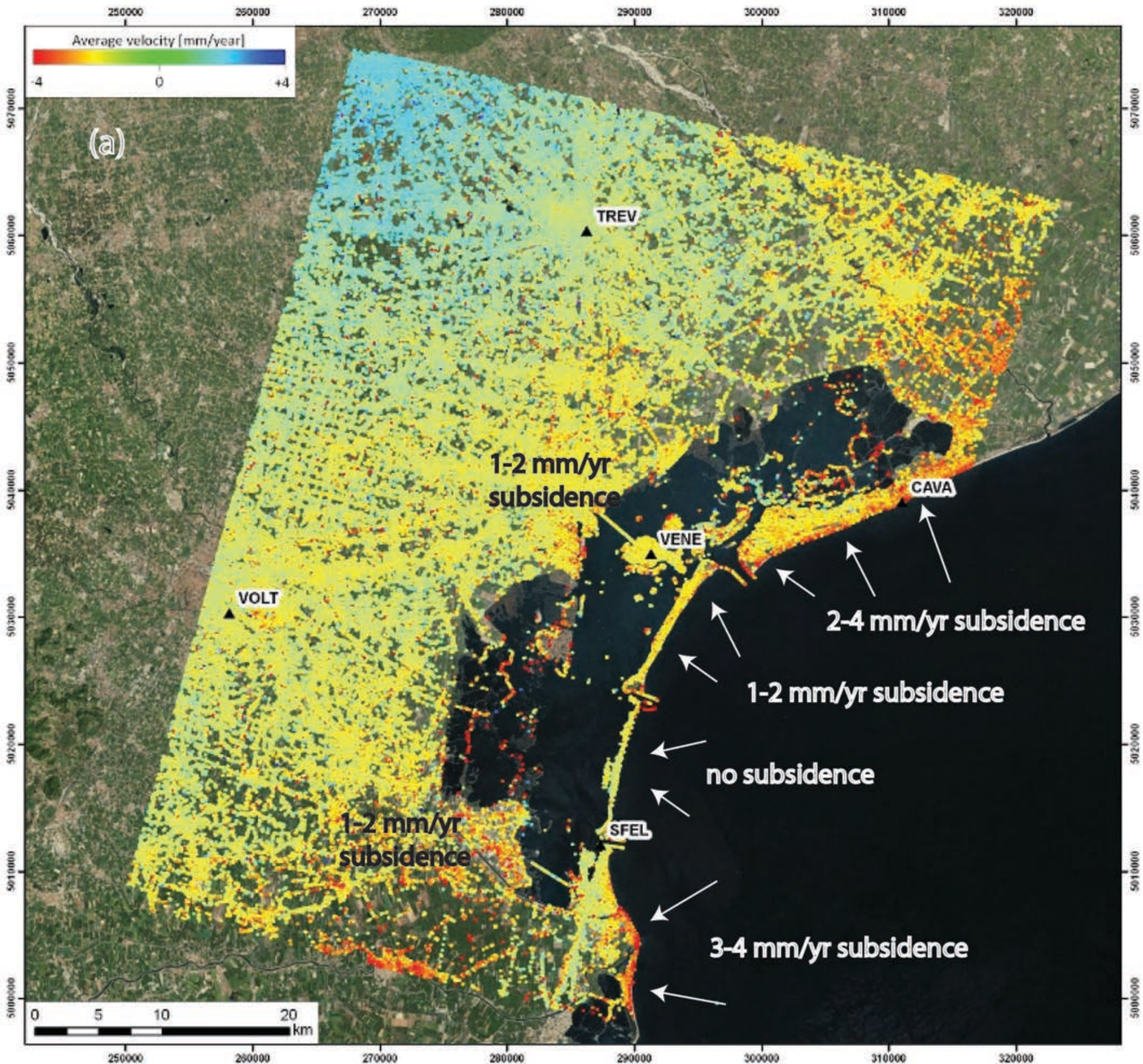
Urban subsidence

Venice subsidence

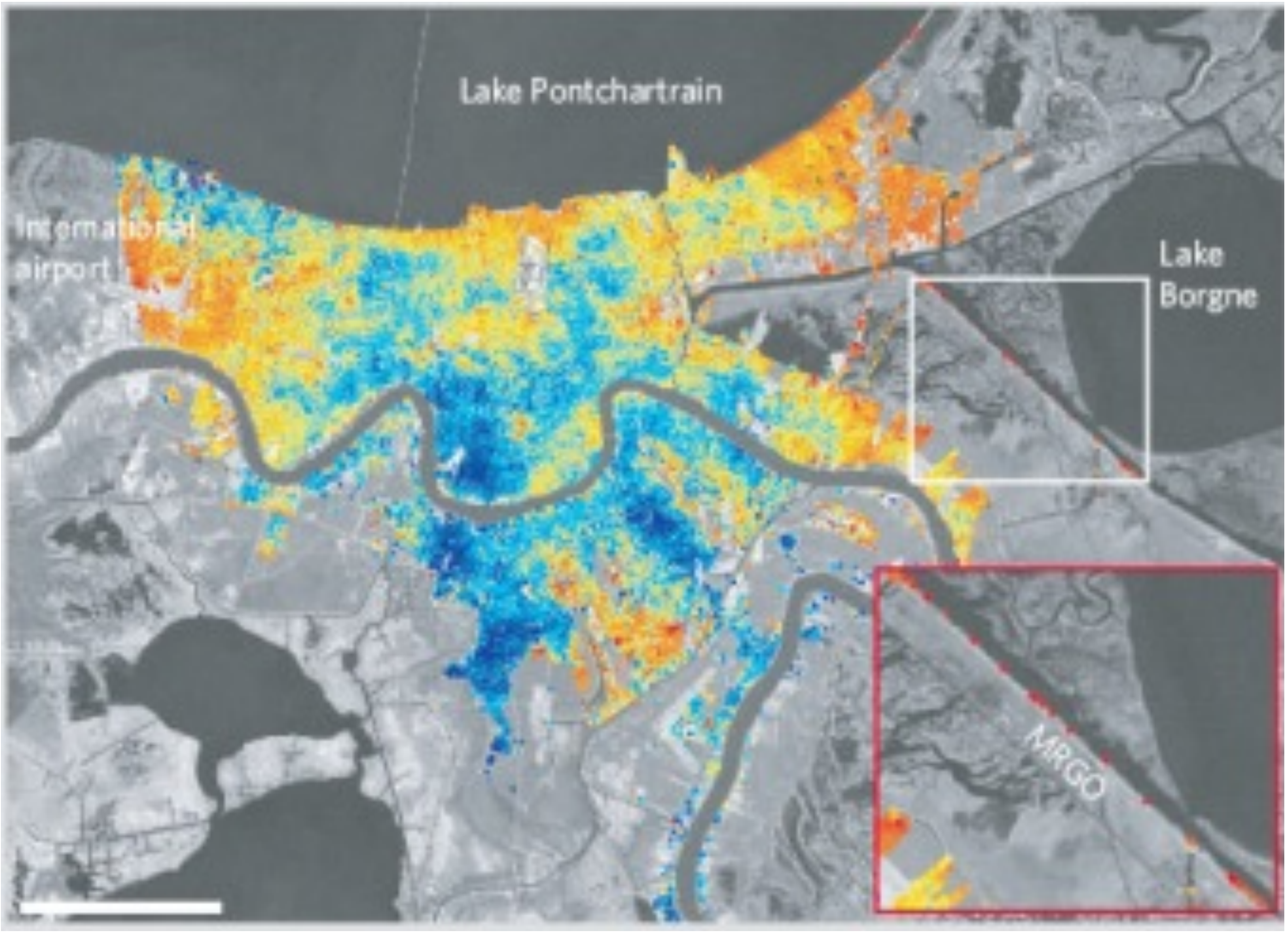
- The city is located within the Venice Lagoon.
- It is located on an archipelago of 128 small islands

Alta Aqua

Venice Lagoon (Bock et al., 2012)

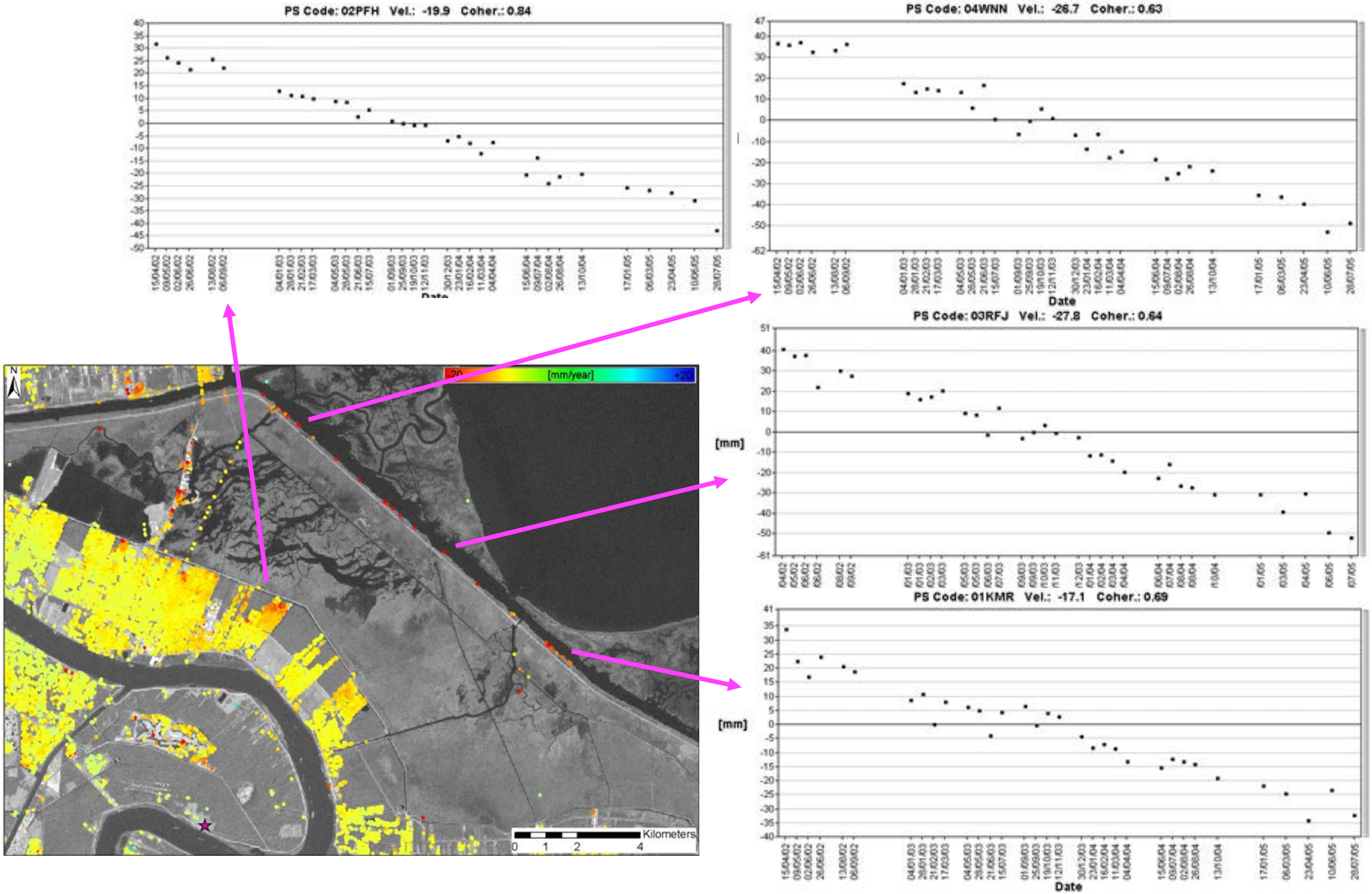


New Orleans Flooding & Subsidence



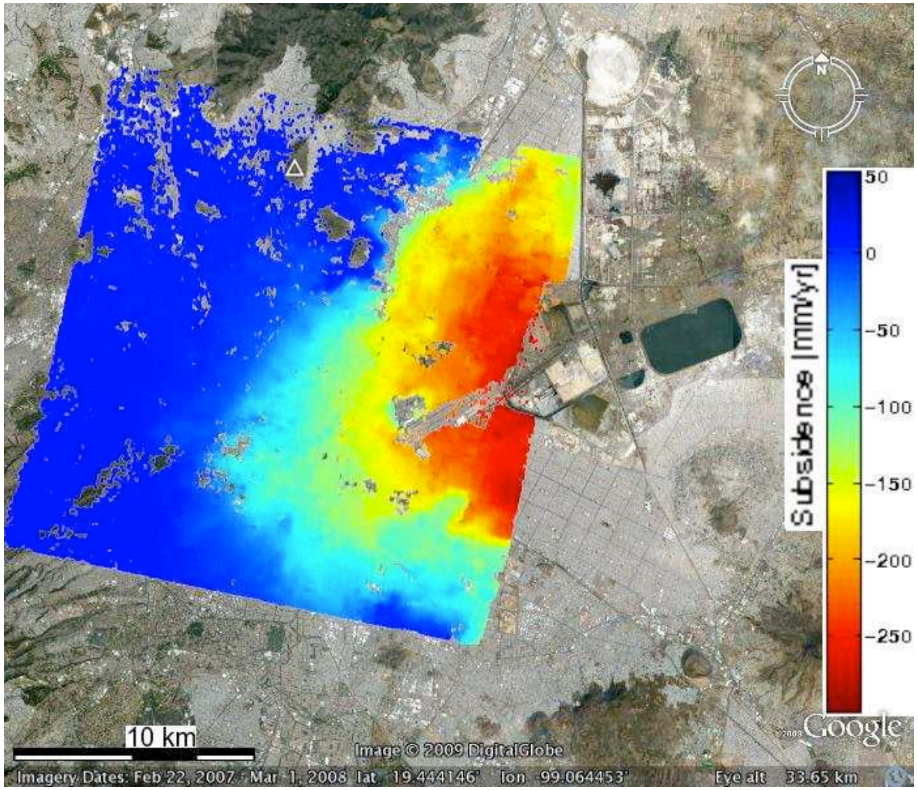
Dixon et al. (2006)

St. Bernards Parish: PS displacement time series in LOS



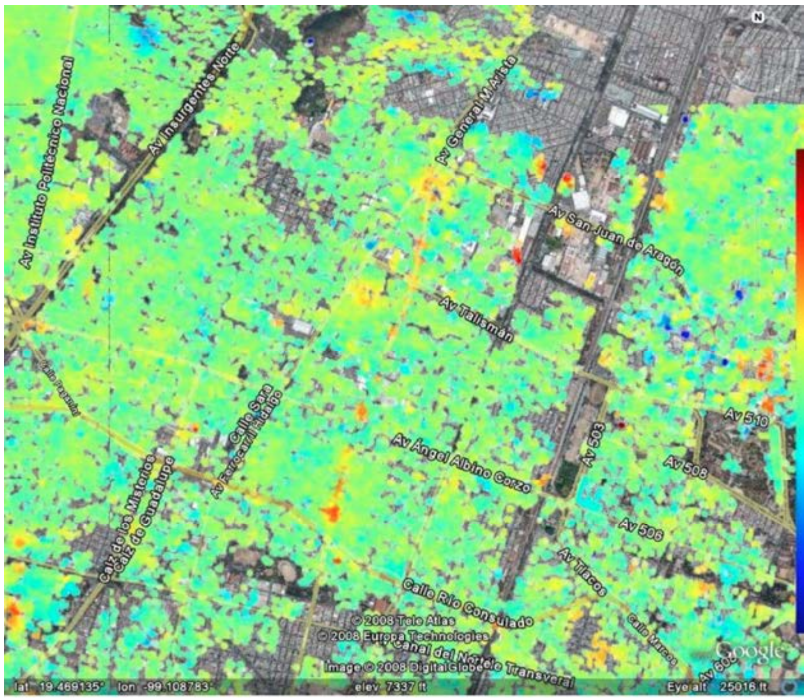
Mexico City

- Mexico City is built on lake deposits
- It subsides at very high rate, up to 25 cm/yr
- The subsidence causes structural damage in many buildings and to the infrastructure



Osmanoglu et al. (2011)

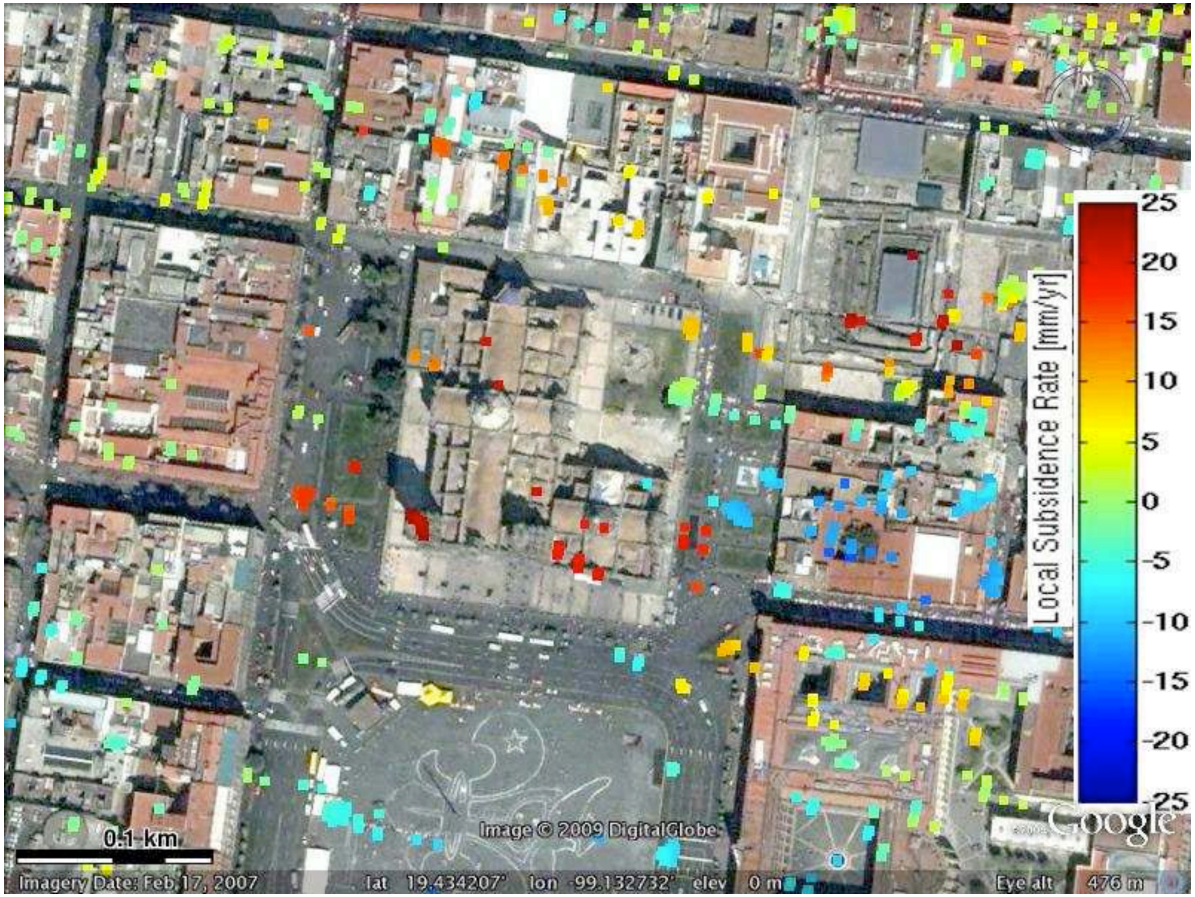
Mexico City



Differential subsidence in Mexico City causes structural damage to building and infrastructure

Osmanoglu et al. (2011)

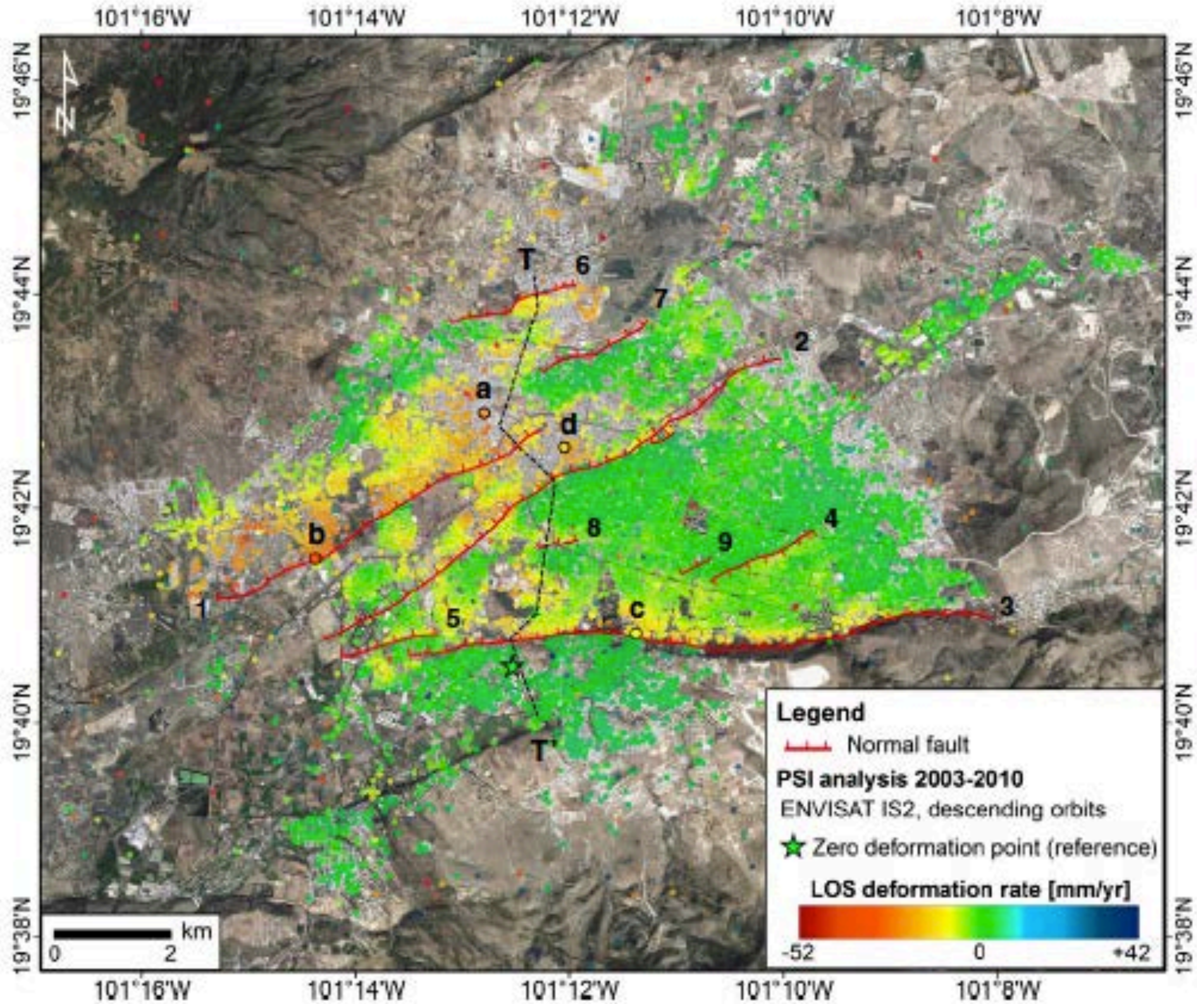
Mexico City



Differential subsidence at the building scale (main Cathedral)

Osmanoglu et al. (2011)

Morelia (Mexico)



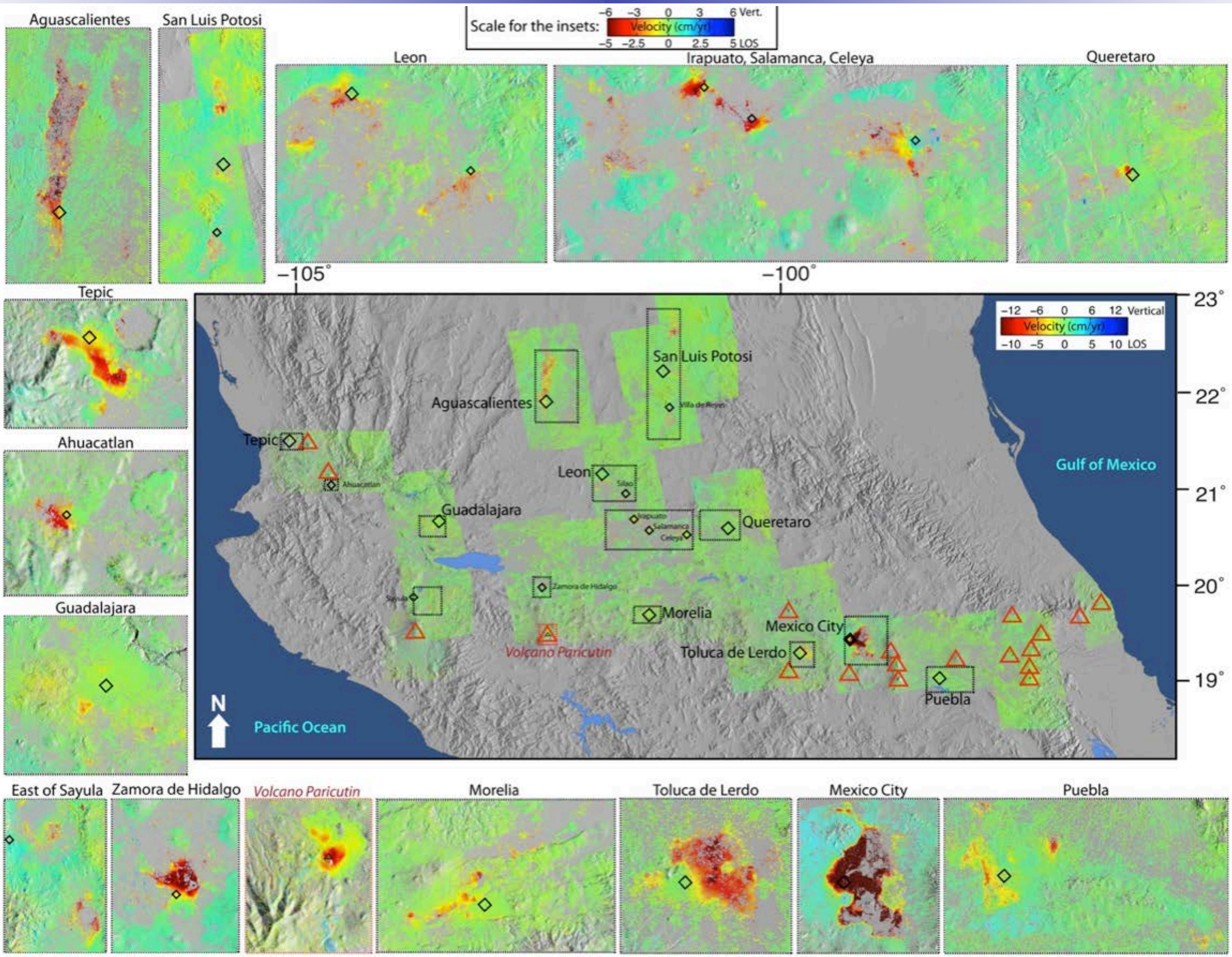
Subsidence is controlled by geological fault

Cigna et al. (2011)

A new NASA project

Applications of InSAR time series imagery for subsidence hazards and water resources exploitation in four Mexican metropolitans

ALOS data processing *(Estelle)*



Conclusions

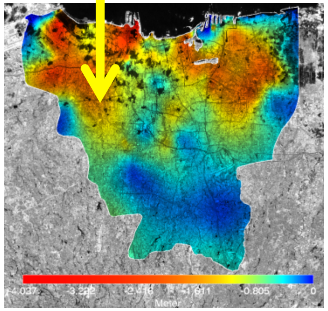
- InSAR, GPS and GRACE are very powerful techniques for monitoring non-tectonic crustal movements
- The observed deformation occurs in response to climatic or anthropogenic changes in hydrological load or sediment compaction
- Our multi-year Greenland study show a noticeable ice melt acceleration since the mid-1990's.
- Our seasonal analysis of the Greenland GPS data indicates unusual high uplift in 2010, most likely due to the influence of the warm Irminger current.
- Land subsidence due groundwater extraction occurs in many urban areas and can cause significant structural damage to buildings and infrastructure.

Land Subsidence around Java Island

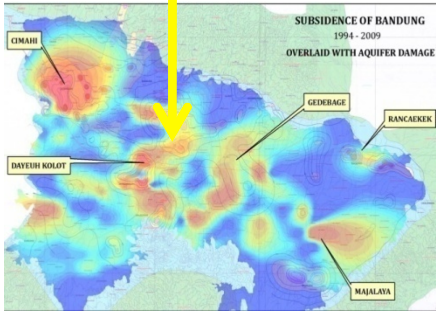
Where are the places of subsidence around Java?

Chaussard et. al 2012

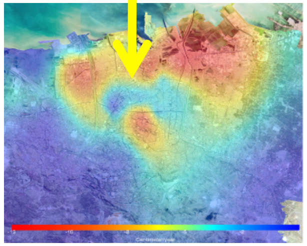
University of Miami



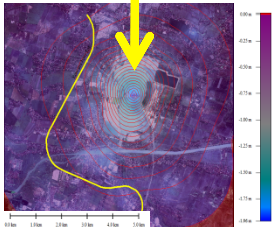
Jakarta area



Bandung area



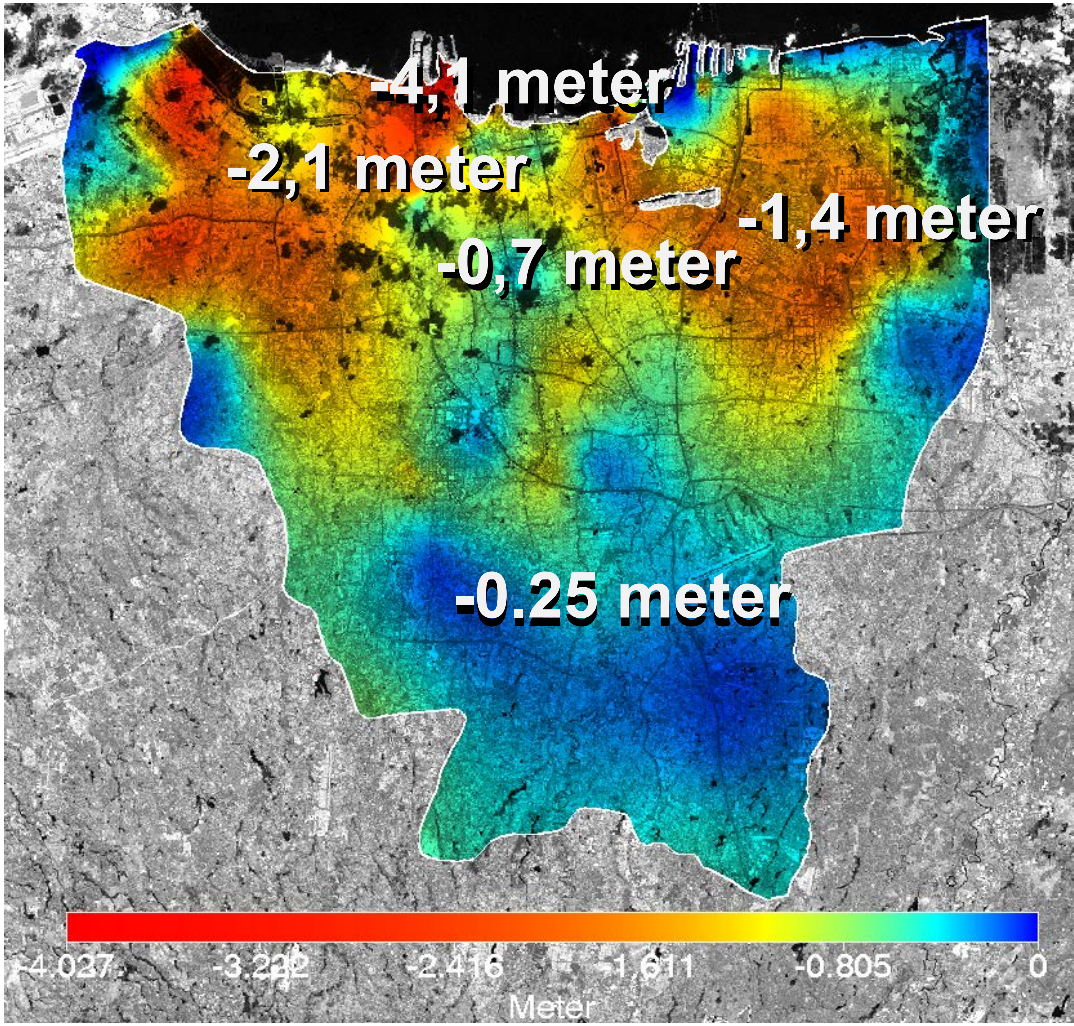
Semarang area



LUSI area

Land Subsidence around Jakarta area

In period of 1974-2010 a significant subsidence happened in Jakarta area. Four meter recorded in the north of Jakarta, two meter in west area, and one and a half in the east. Seventy cm recorded for central part while 25 cm for southern area



Consequences of Jakarta subsidence

"ROB" in northern Part of Jakarta