Advances in GPS Techniques for Measuring Vertical Coastal Motion

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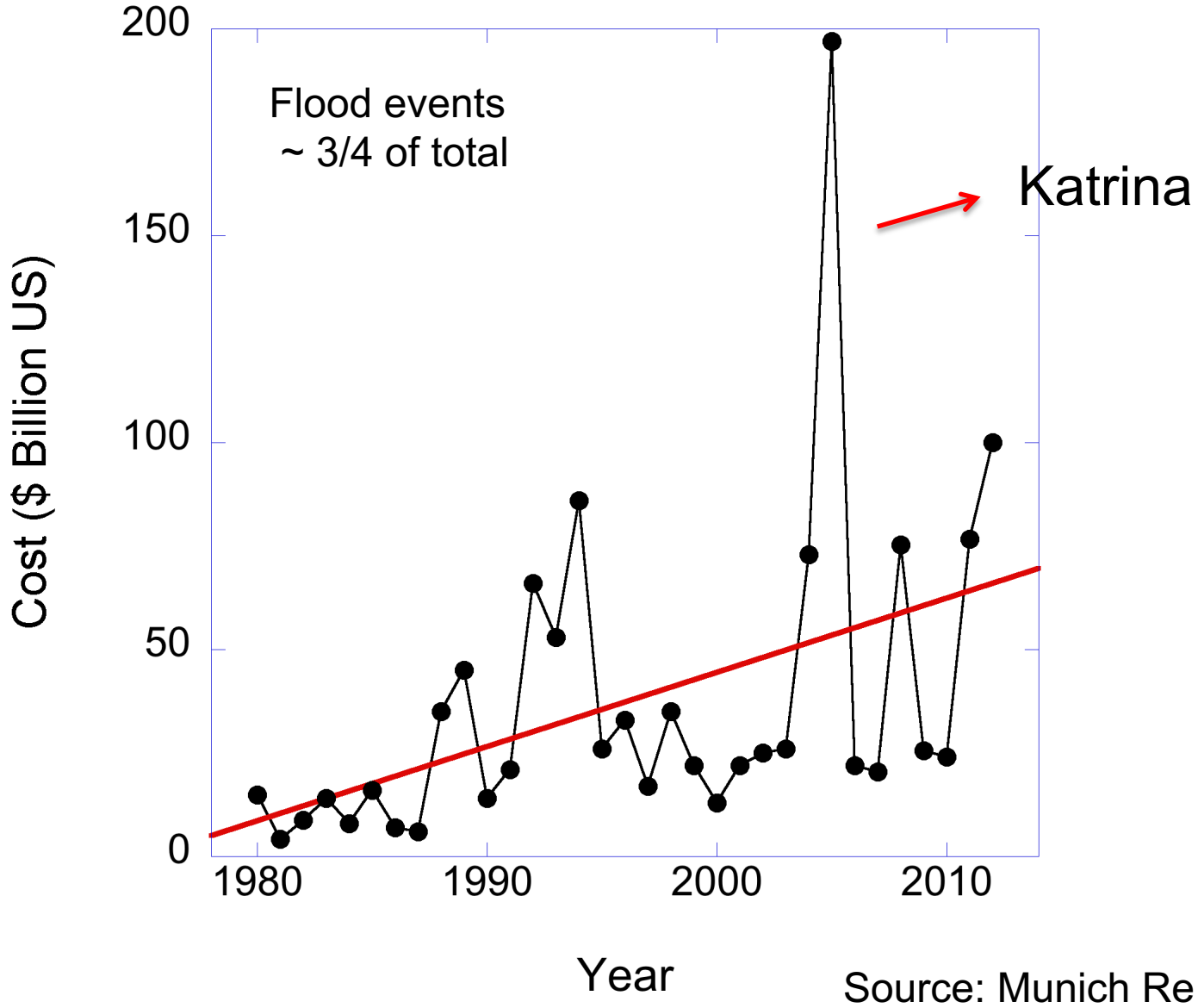
Hurricane Katrina, 2005, ~$160 B in losses (noaa)

Harvey & Irma (2017, ~$75 B)

Natural Disasters, Cost vs Time

US only, insured + uninsured



"Sunny-day" or "nuisance" flooding in Miami Beach

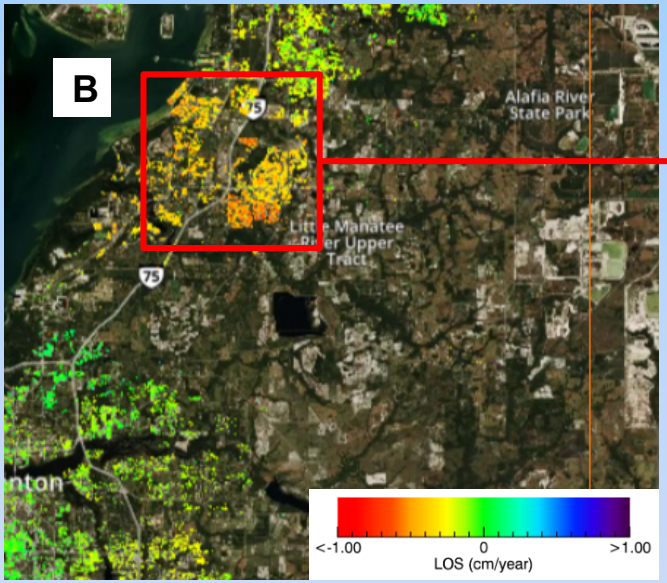
Not considered a disaster, but has costs, and shows future flood potential from SLR

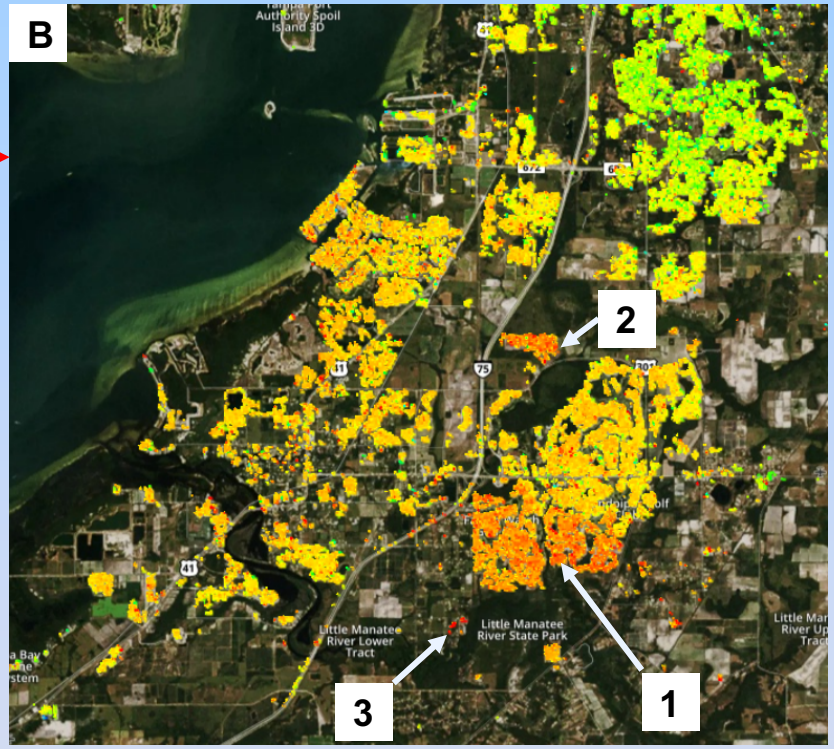
Because of its low elevation & long coastline, coastal Florida is "ground zero" for problems related to sea level rise

Nuisance flooding

- Does not make "top ten" disaster lists, but cumulative economic losses are high
- Parts of the US eastern seaboard & Gulf Coast are subsiding, exacerbating flood hazard from Sea Level Rise
- "Canary in the coal mine" for what other low lying areas will experience in the future
- Combination of human and natural causes
  - Glacial Isostatic Adjustment (GIA)
  - Ground water extraction
  - Compaction of artificial fill

Tampa Bay - surface displacement from SBAS, Sentinel





- InSAR can show policy makers long-term hazard of continued housing development in filled wetlands.

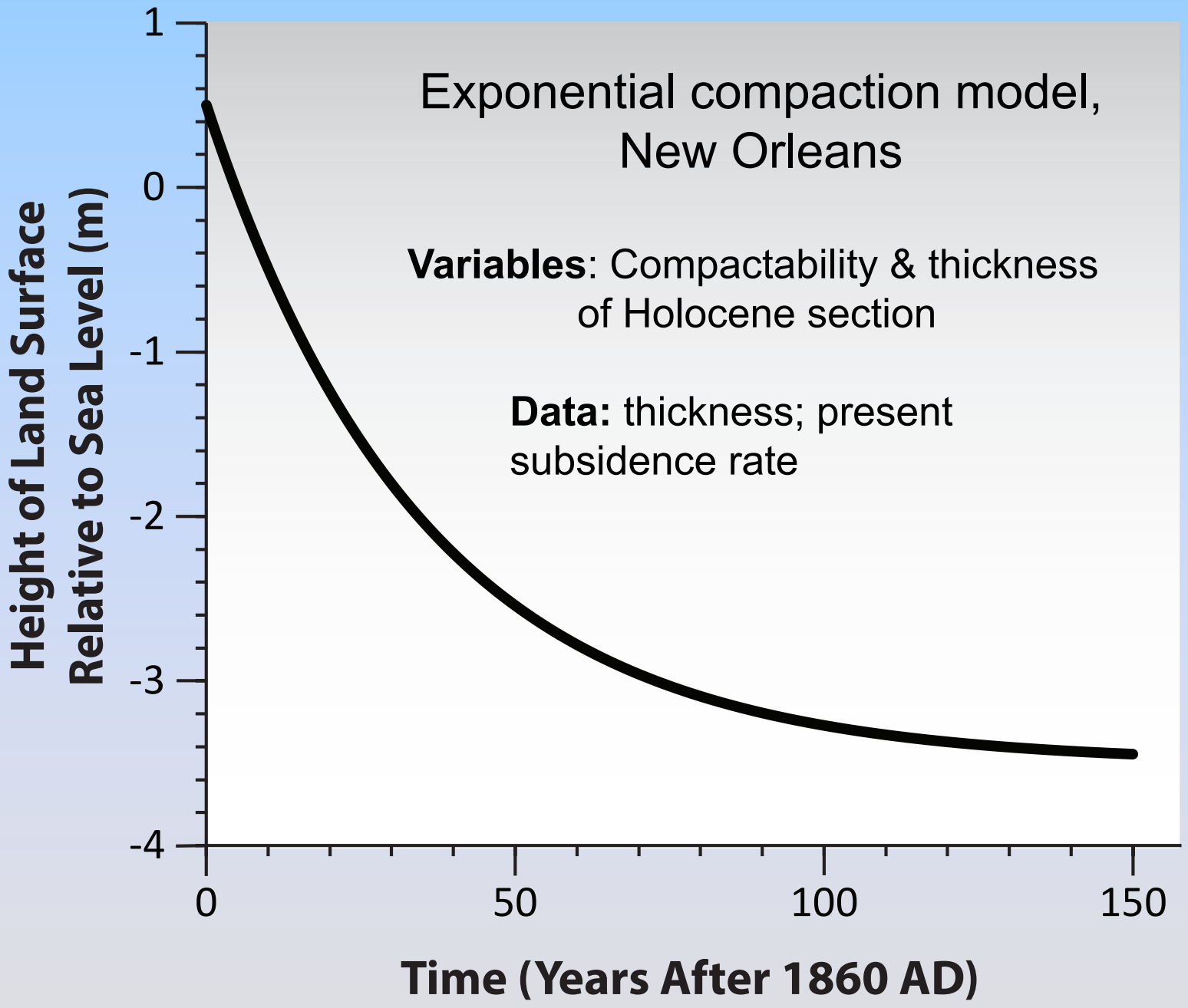
- Current subsidence at 1.3 cm/yr leads to 30 - 60 cm lowered elevation in 50 yrs depending on age of construction (exponential compaction model)

Average displacement velocity

- **1 : -1.28 cm/year**
- **2 : -0.91 cm/year**
- **3 : -1.24 cm/year**

St Pete example – 1950's development now routinely floods during high tides or high rainfall

High rainfall events cause flooding because of reduced drainage gradient


Exponential compaction model,
New Orleans
Variables: Compactability & thickness of Holocene section
Data: thickness; present subsidence rate
Height of Land Surface Relative to Sea Level (m)
1
0
-1
-2
-3
-4
0
50
100
150
Time (Years After 1860 AD)

Importance of subsidence in future flood hazard still not widely appreciated

- Construction on artificial fill, destruction of wetlands continues in many states
- Explanations for flooding in popular press usually omit this factor

Scientific American, 2015

“Virginia Islanders Could Be U.S. First Climate Change Refugees”

“Scientists have labeled the area from the Carolinas to Boston a sea-level rise “hotspot,” where rates are higher than the global average partly because of a slowing of Atlantic Ocean circulation tied to melt from the Greenland ice sheet.”

- For flood susceptibility, more important to consider total subsidence since settlement, rather than focus on current subsidence rates

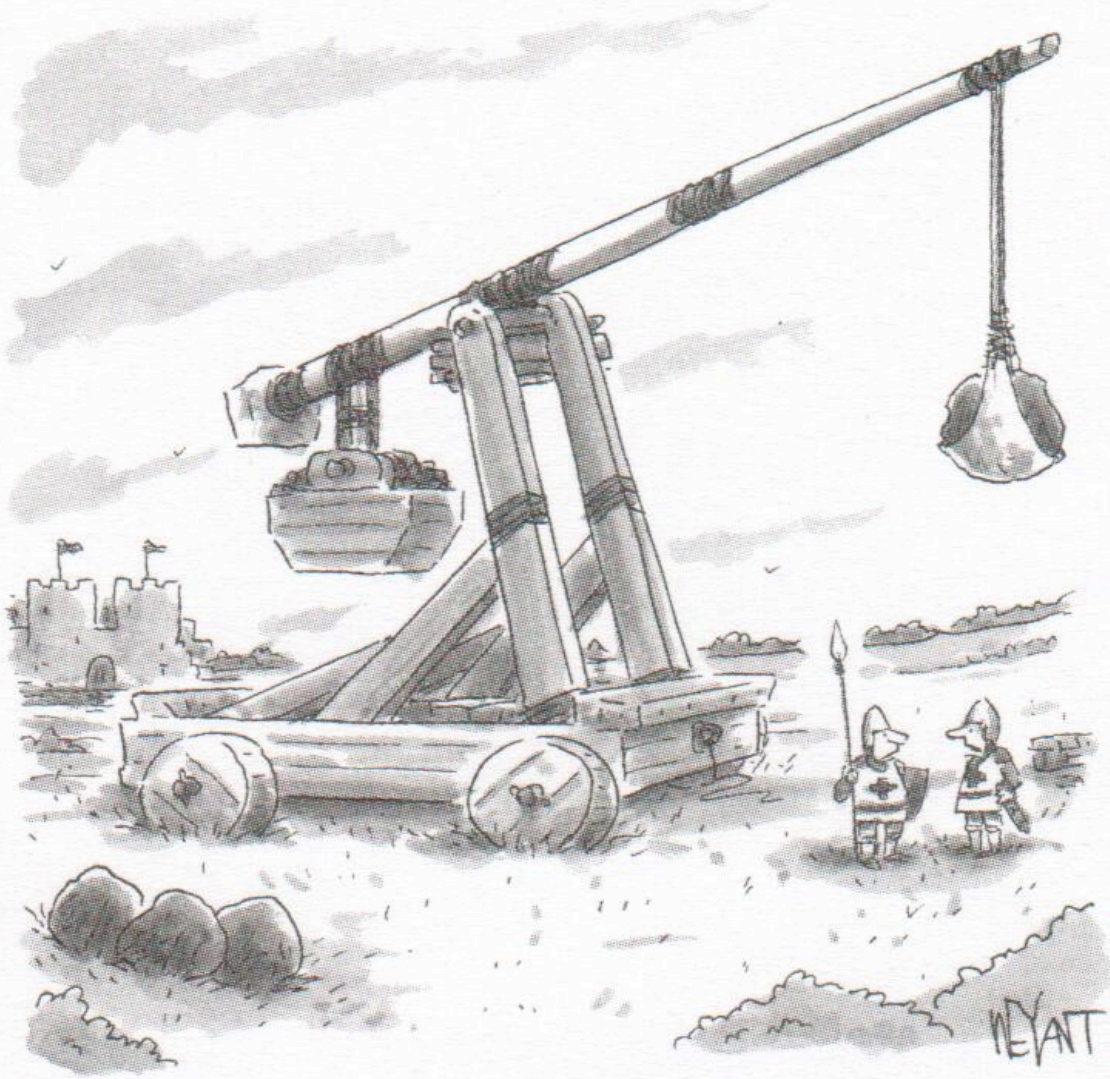
Compare relative height change from subsidence vs oceanographic sea level rise for Tangier Island

Tangier Island settled by 1700

From GIA: 315 yrs x 1.3 mm/yr = 409.5 mm ~ 41 cm

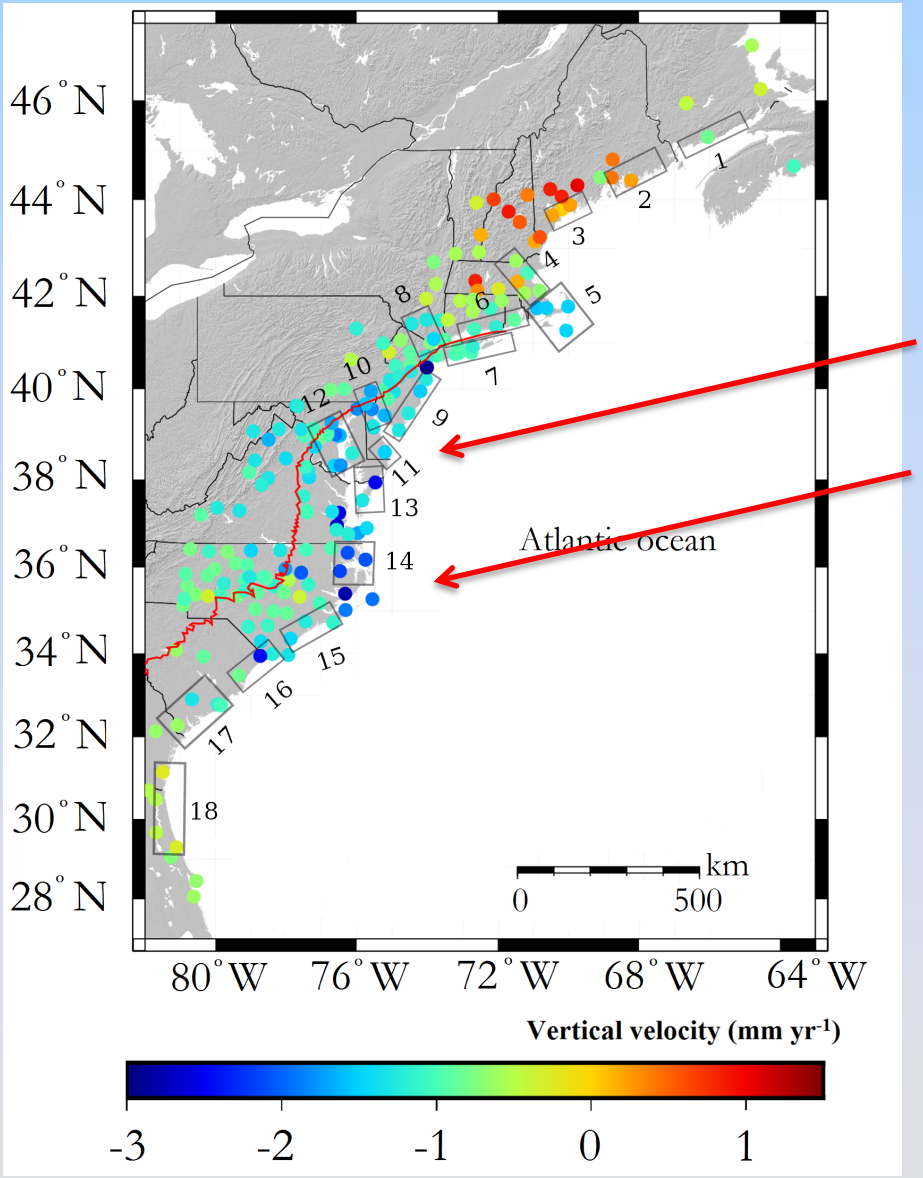
From ocean effects:

Period	Sea Level Rise
• 1700 – 1890:	0
• 1890-1990: 1.8 mm/yr x 100 years =	180 mm
• 1990 – 2015: 3.3 mm/yr x 25 years =	82.5 mm
• Total:	262.5mm ~ 26 cm



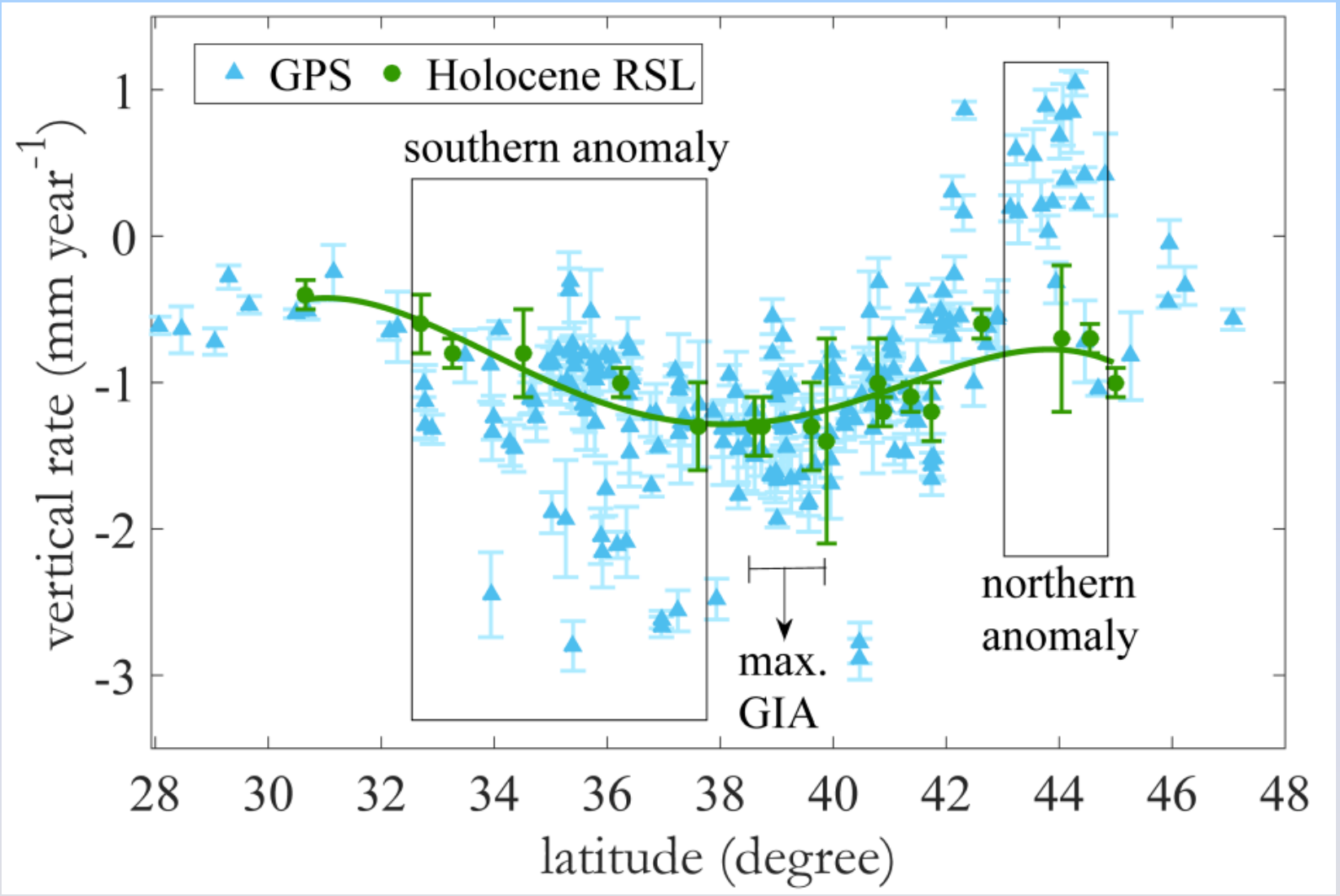
"When your only tool is a trebuchet, every problem looks like a siege."

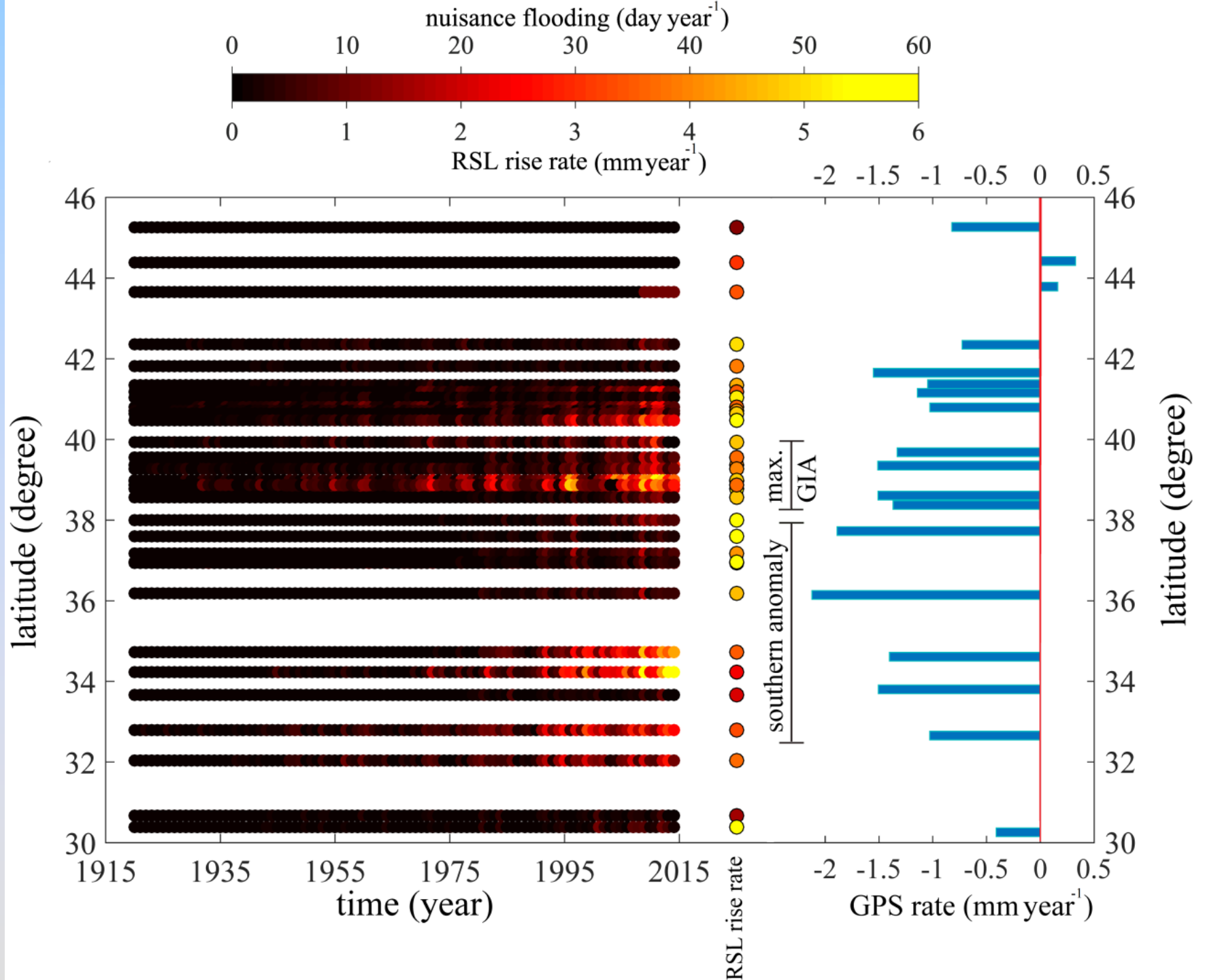
GPS Measurement of Coastal Subsidence



Collapse of peripheral bulge

Groundwater Extraction


GPS
Holocene RSL
southern anomaly
northern anomaly
max. GIA
vertical rate (mm year-1)
latitude (degree)
1
0
-1
-2
-3
28
30
32
34
36
38
40
42
44
46
48

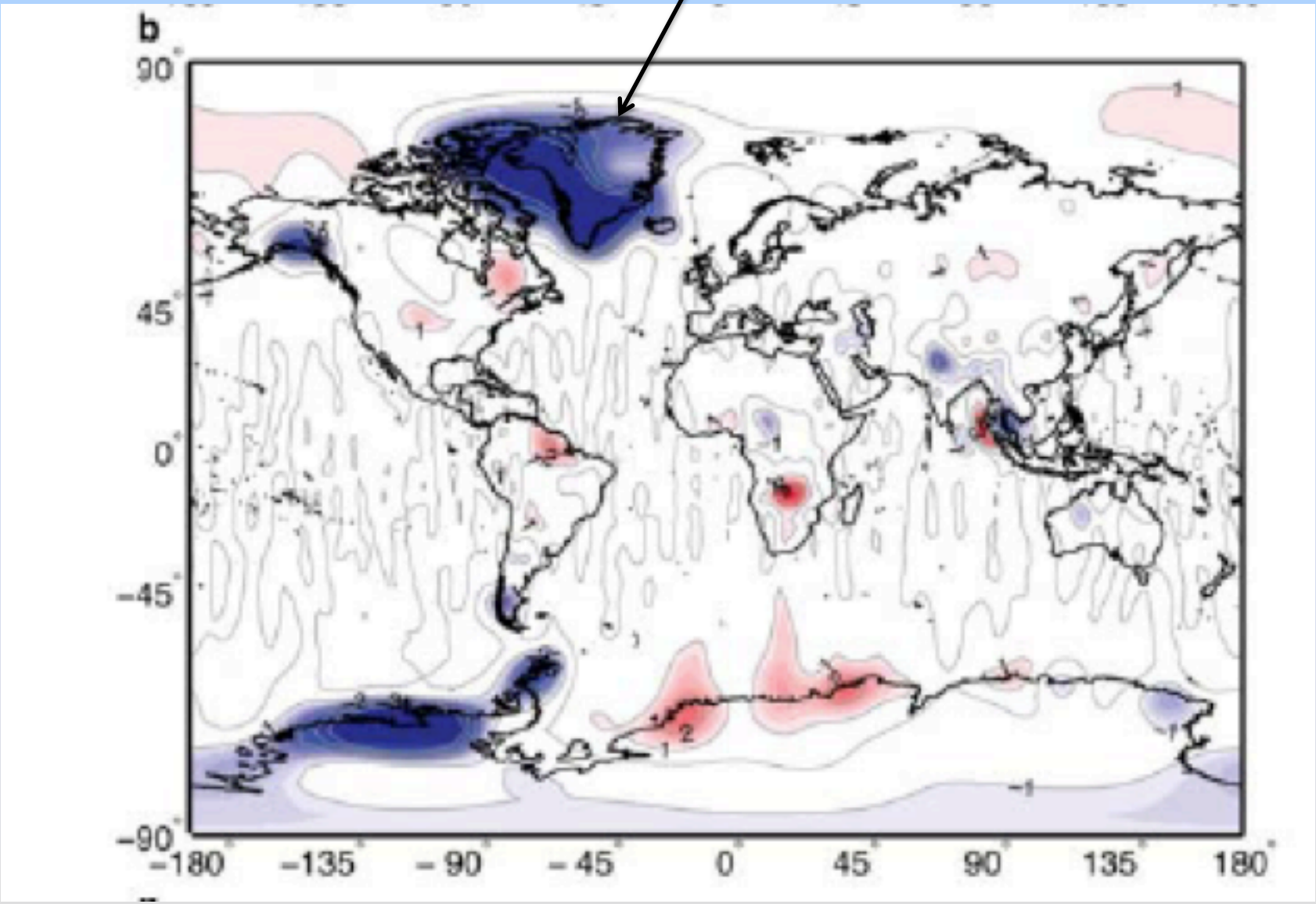

nuisance flooding (day year-1)
0 10 20 30 40 50 60
0 1 2 3 4 5 6
RSL rise rate (mm year-1)
-2 -1.5 -1 -0.5 0 0.5
46 44 42 40 38 36 34 32 30
latitude (degree)
1915 1935 1955 1975 1995 2015
time (year)
max. GIA
southern anomaly
RSL rise rate
-2 -1.5 -1 -0.5 0 0.5
GPS rate (mm year-1)

Importance of Greenland

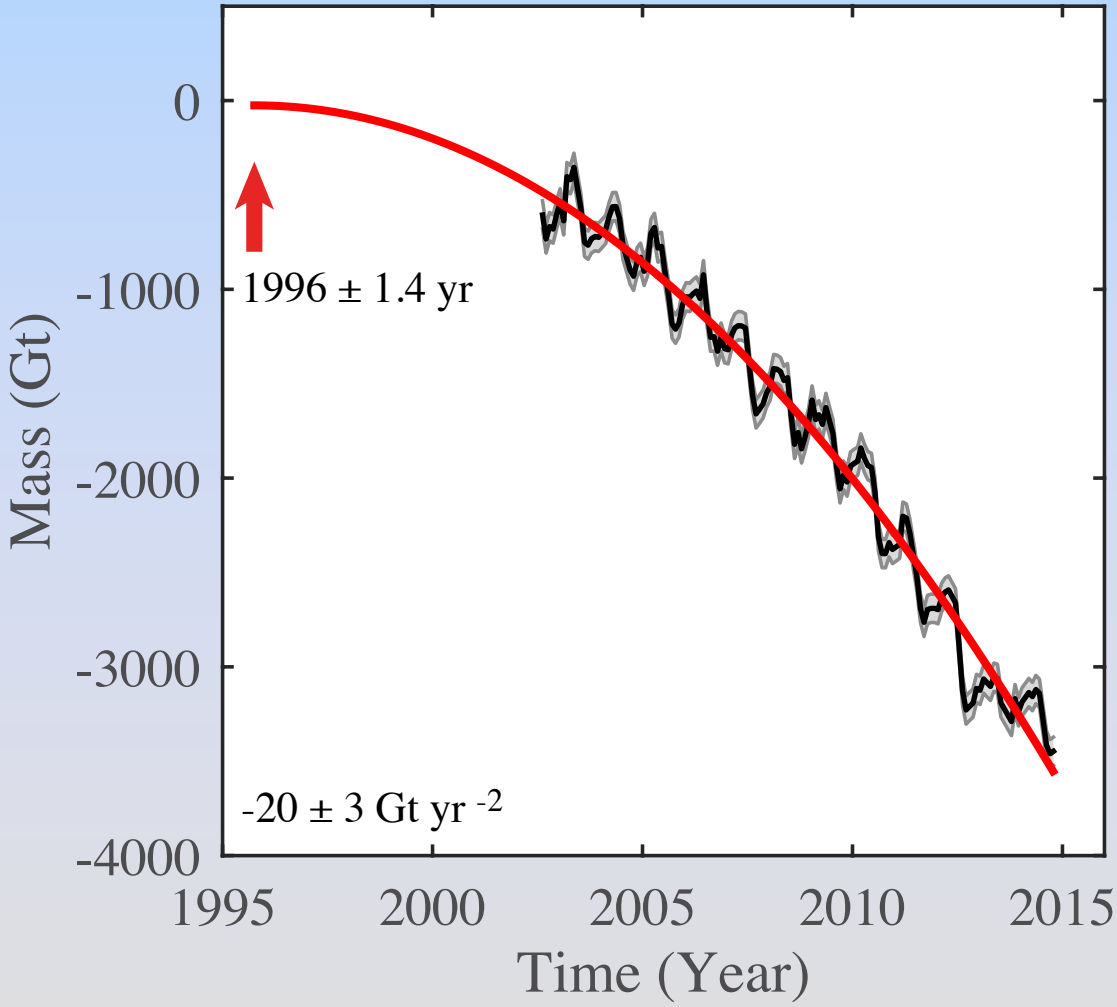
- **What happens in Greenland does not stay in Greenland**
- **Impacts both sea level and global ocean circulation**
- **“Teachable moments” for mid- and low latitude citizens**
- **Provides great visuals – scientists at work; calving glaciers**

GRACE Results, 2002-2012

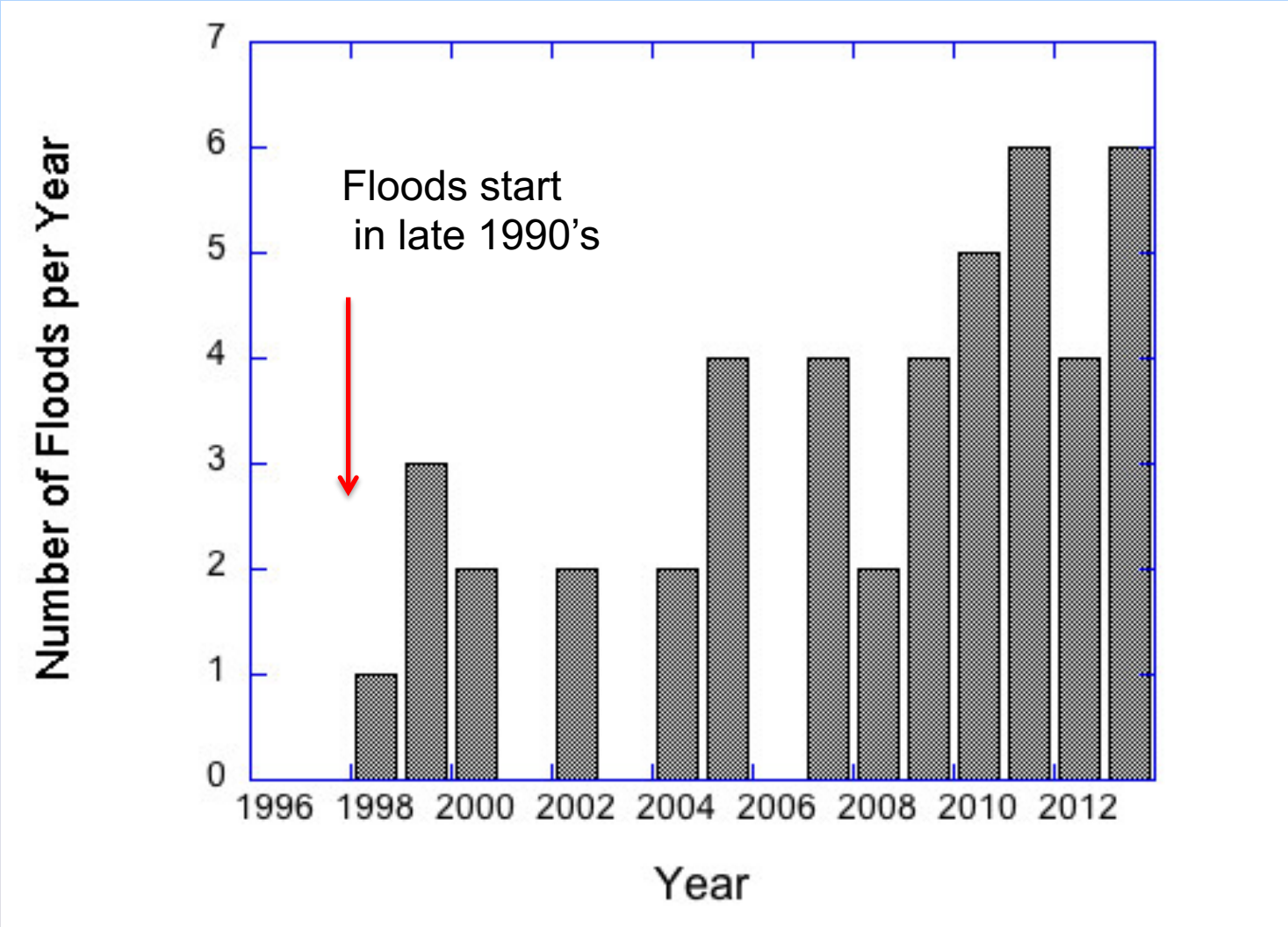
Greenland: world's biggest "loser"



*Average loss for Greenland ~250 GT/yr (1 GT= 1 km^3)
*Curvature shows acceleration (2015 loss ~ 400 GT/yr)
*Fit to data (assuming constant acceleration) constrains timing of recent acceleration – began in mid- late-1990's



Miami nuisance flooding accelerates after 1998



Future flooding: global warming vs other human factors

- Increased ocean mass from melting of Greenland and other glaciers
- Increased ocean volume from thermal expansion
- Increased high rainfall events from warmer atmosphere
- Increase intensity of hurricanes from warmer ocean water

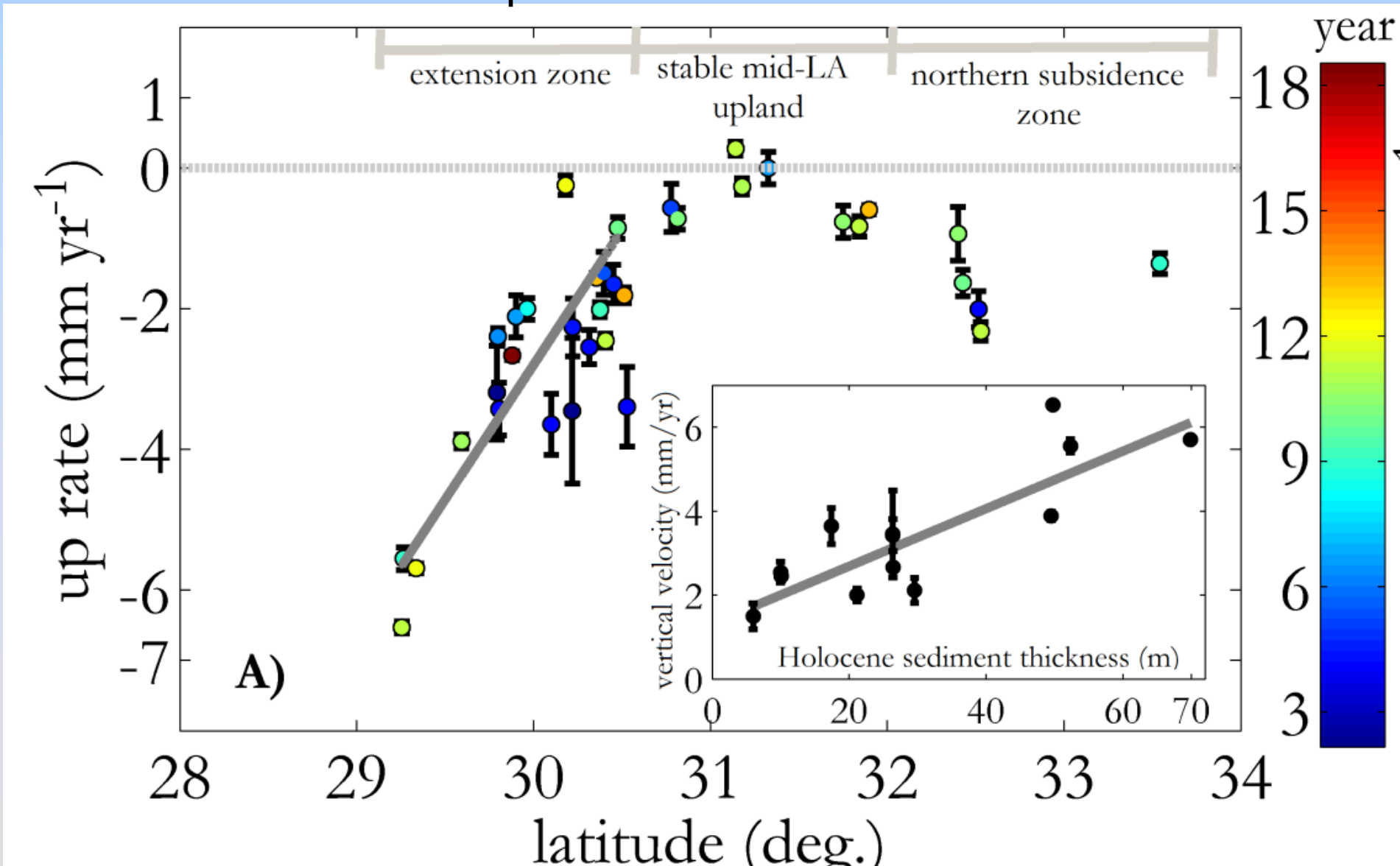
- Building styles, zoning:
  - "hardscape" increases flooding from high rainfall events
  - Increased coastal development, loss of natural protection (dunes, mangroves)
  - Low elevation construction, artificial fill

New Orleans and Hurricane Katrina example (all of the above factors apply)

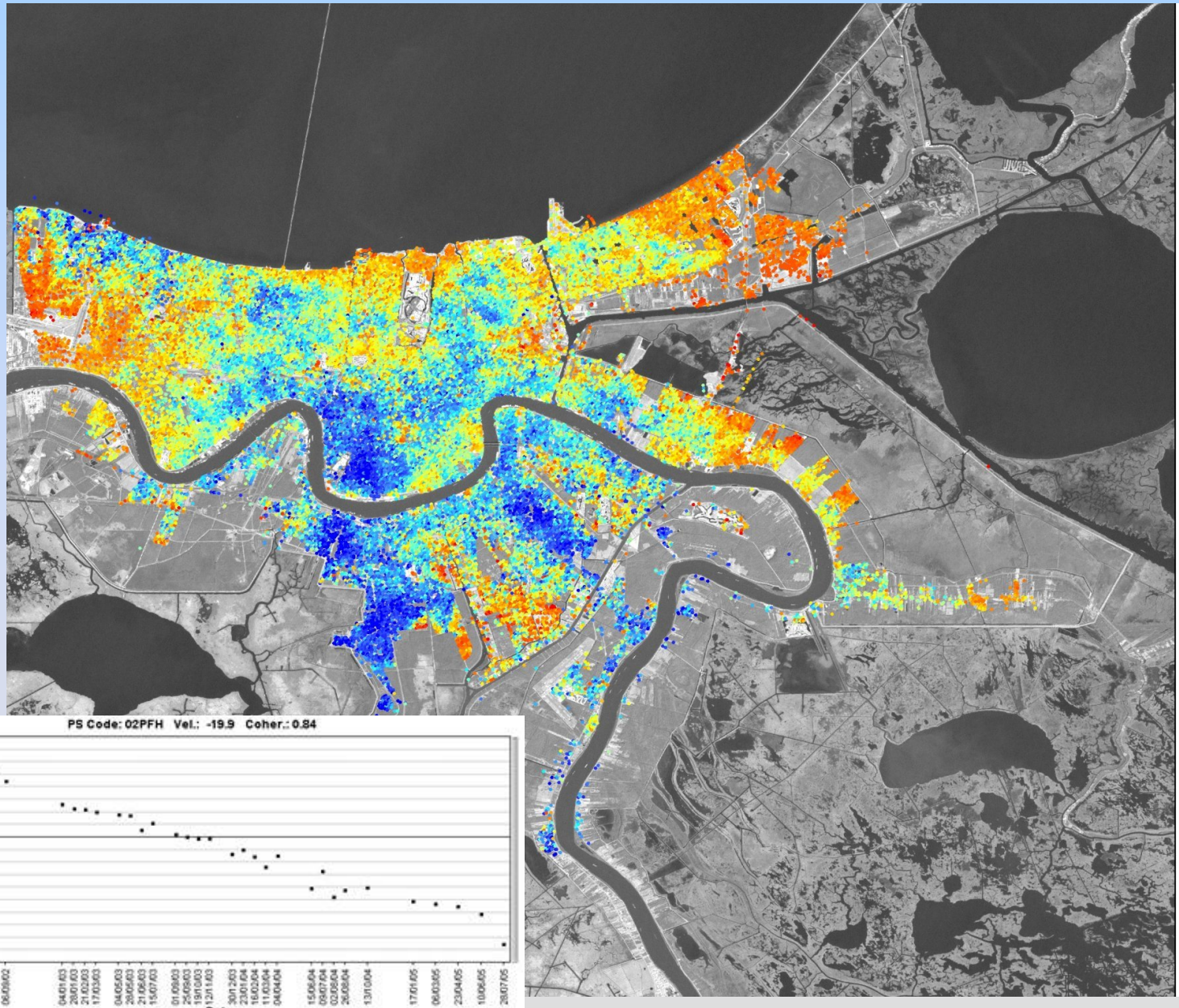
- New Orleans is especially vulnerable to flooding because it is built on a subsiding delta with restricted supply of new sediment

- Holds important lessons for other coastal cities around the world – what New Orleans experiences now, other coastal cities will experience in the future

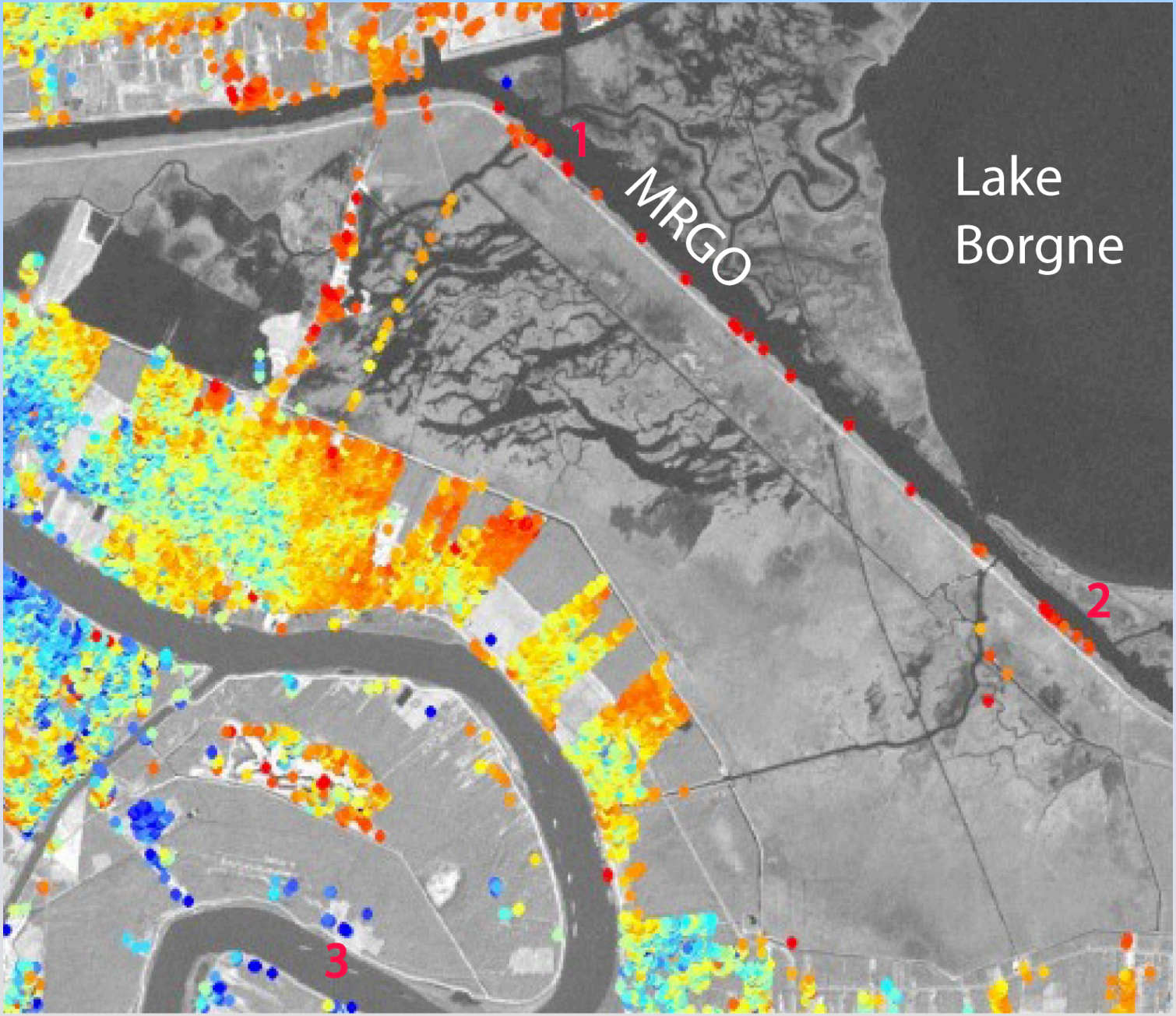
- GPS shows Mississippi Delta is subsiding
- Most of this motion reflects natural sediment compaction
- Does GPS capture full subsidence?



SAR Image of Subsidence in New Orleans



Close up of St. Bernards Paris and levees



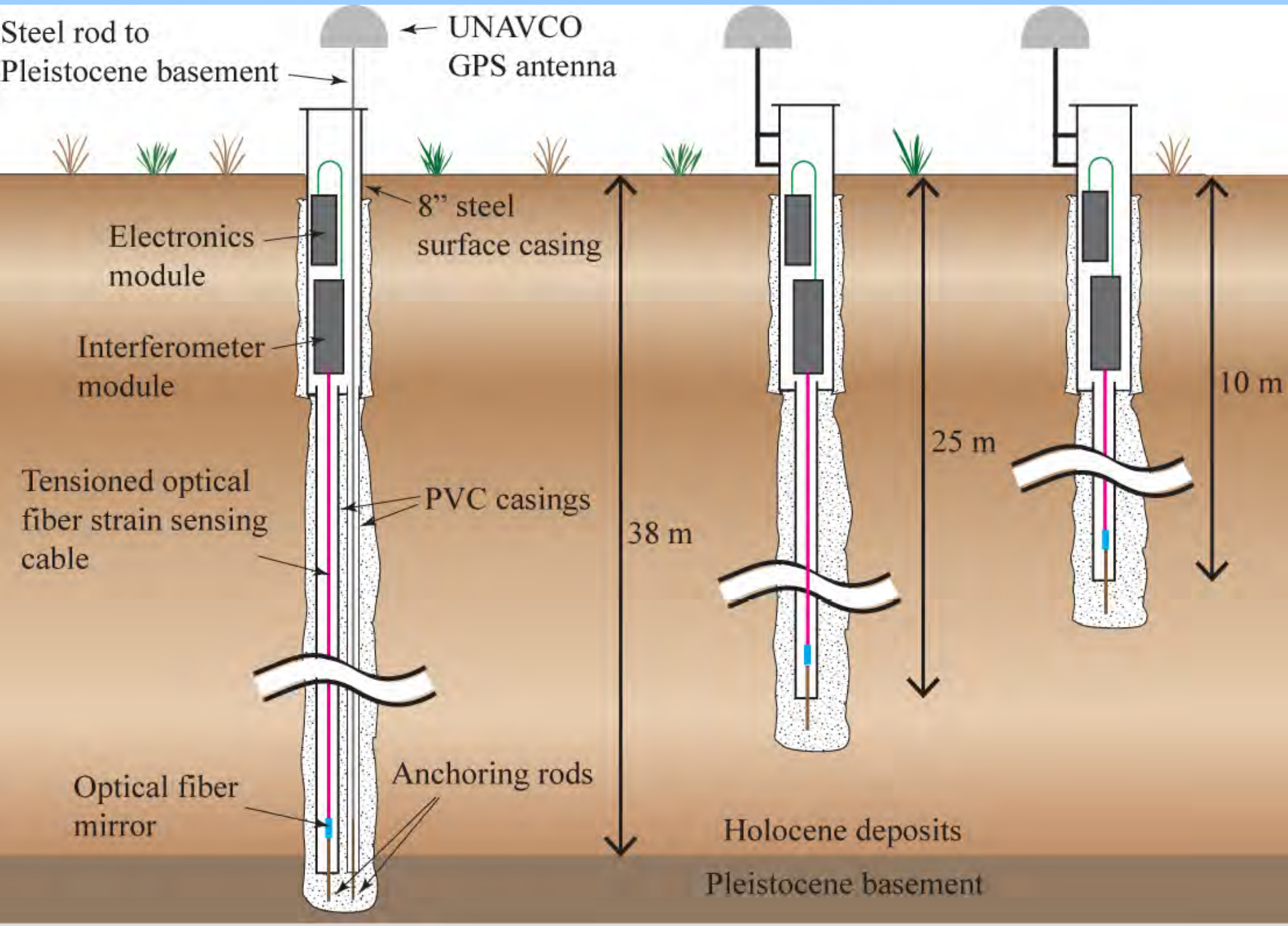
St. Bernards Parish:
Levee system post Katrina damage assessment

Source: http://www.freerepublic.com/focus/f-news/1489838/posts

Mississippi Delta “Super Site”

In typical delta site, what proportion of total subsidence is due to Holocene sediment compaction vs deeper processes (eg loading)?

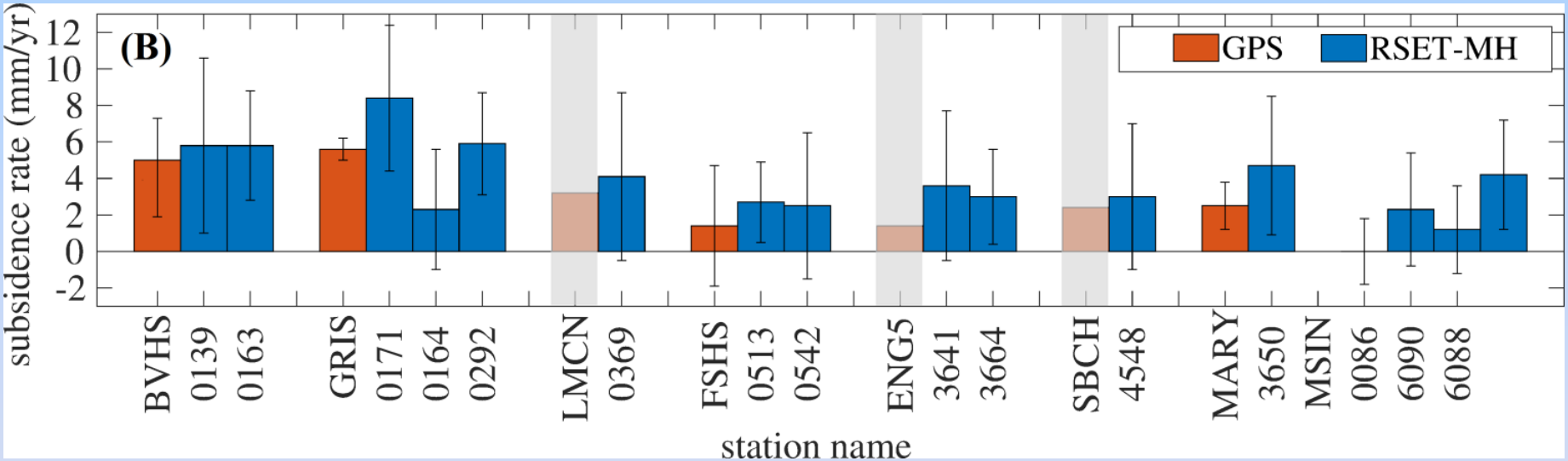
Install vertical borehole strainmeters & GPS anchored to various depths, and compare results


Steel rod to
Pleistocene basement
UNAVCO
GPS antenna
8" steel
surface casing
Electronics
module
Interferometer
module
Tensioned optical
fiber strain sensing
cable
PVC casings
38 m
25 m
10 m
Anchoring rods
Optical fiber
mirror
Holocene deposits
Pleistocene basement

Initial results (~ 2 yr time series) imply
~ 1 mm/yr of deep-seated subsidence

Are we adequately capturing shallow subsidence?

Comparison to RSET: suggests GPS under-estimates shallow subsidence at some sites



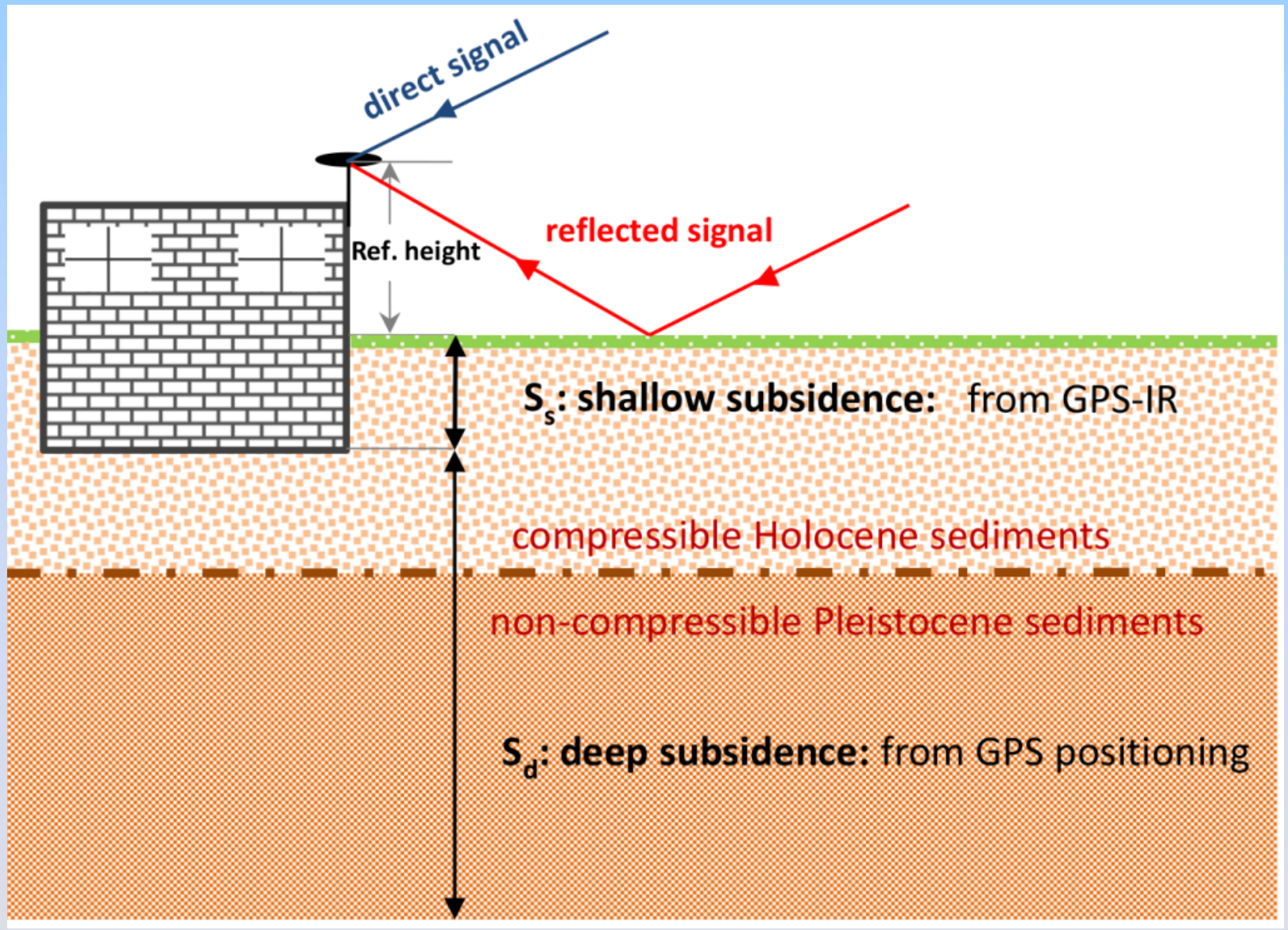
RSET-MH: Rod Surface-Elevation Table-Marker Horizon

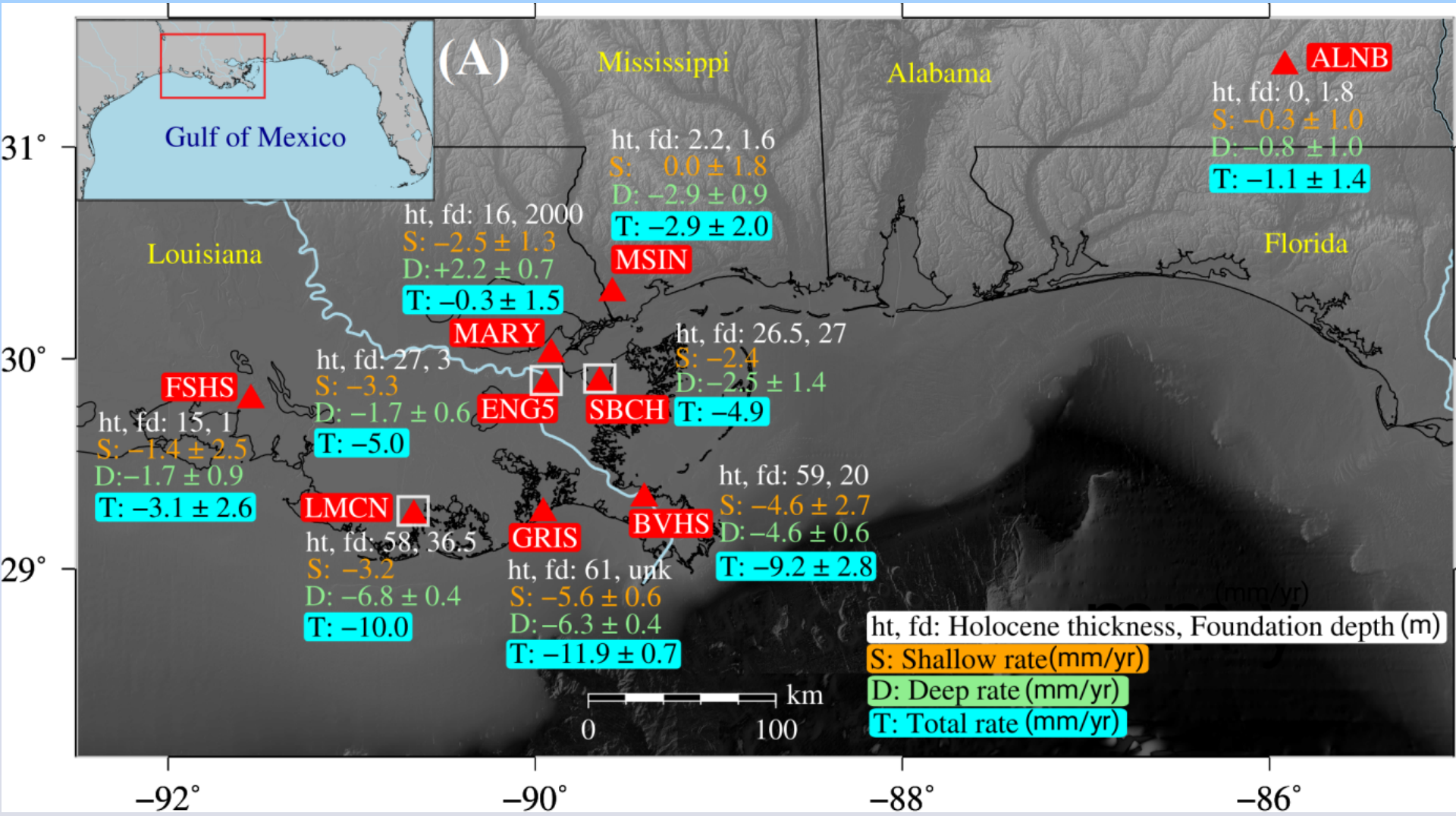
Land Loss vs Subsidence

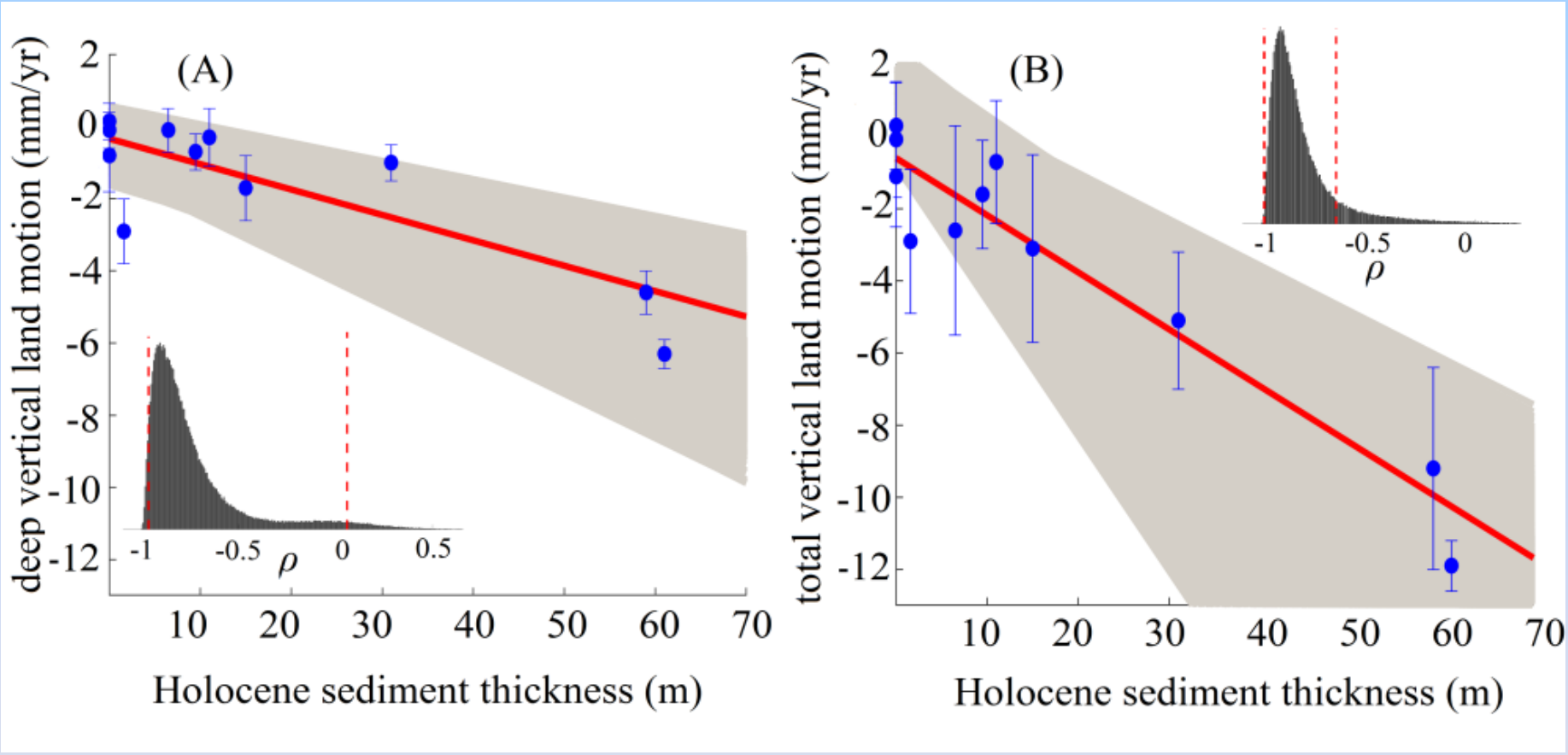
For Mississippi Delta and some other low lying coasts with thick Holocene sections, rates of land loss are higher than expected

Could we be under-estimating modern subsidence rates in these areas?

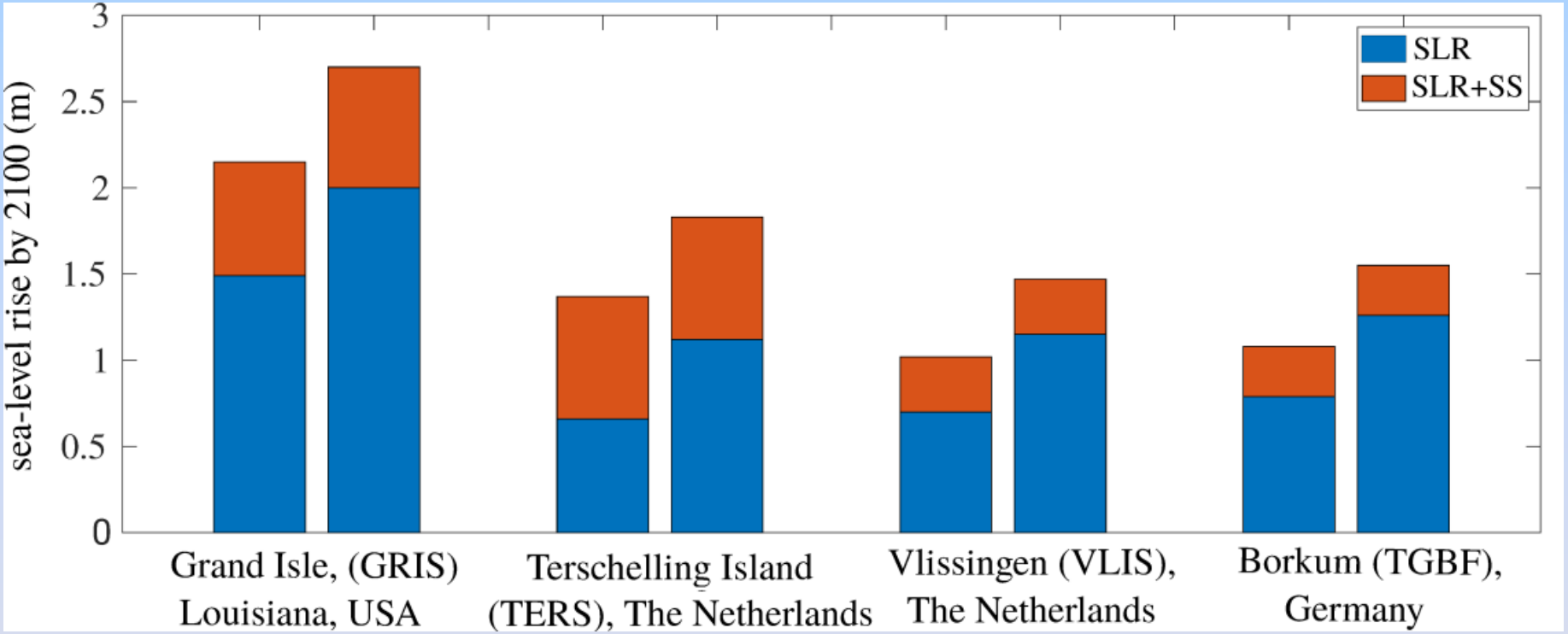
GPS measures subsidence at base of anchor, not necessarily equal to surface motion – compaction of upper few meters is missed, depending on anchor type


direct signal
reflected signal
Ref. height
S_s: shallow subsidence: from GPS-IR
compressible Holocene sediments
non-compressible Pleistocene sediments
S_d: deep subsidence: from GPS positioning


(A)
Gulf of Mexico
Mississippi
Alabama
Florida
Louisiana
ALNB
ht, fd: 0, 1.8
S: −0.3 ± 1.0
D: −0.8 ± 1.0
T: −1.1 ± 1.4
ht, fd: 2.2, 1.6
S: 0.0 ± 1.8
D: −2.9 ± 0.9
T: −2.9 ± 2.0
MSIN
ht, fd: 16, 2000
S: −2.5 ± 1.3
D: +2.2 ± 0.7
T: −0.3 ± 1.5
MARY
ht, fd: 26.5, 27
S: −2.4
D: −2.5 ± 1.4
T: −4.9
ENG5
SBCH
ht, fd: 27, 3
S: −3.3
D: −1.7 ± 0.6
T: −5.0
FSHS
ht, fd: 15, 1
S: −1.4 ± 2.5
D: −1.7 ± 0.9
T: −3.1 ± 2.6
ht, fd: 59, 20
S: −4.6 ± 2.7
D: −4.6 ± 0.6
T: −9.2 ± 2.8
BVHS
LMCN
GRIS
ht, fd: 58, 36.5
S: −3.2
D: −6.8 ± 0.4
T: −10.0
ht, fd: 61, unk
S: −5.6 ± 0.6
D: −6.3 ± 0.4
T: −11.9 ± 0.7
(mm/yr)
ht, fd: Holocene thickness, Foundation depth (m)
S: Shallow rate(mm/yr)
D: Deep rate (mm/yr)
T: Total rate (mm/yr)
km
0
100
31°
30°
29°
−92°
−90°
−88°
−86°


(A)
deep vertical land motion (mm/yr)
2
0
-2
-4
-6
-8
-10
-12
-1
-0.5
ρ
0
0.5
10
20
30
40
50
60
70
Holocene sediment thickness (m)
(B)
total vertical land motion (mm/yr)
2
0
-2
-4
-6
-8
-10
-12
-1
-0.5
0
ρ
10
20
30
40
50
60
70
Holocene sediment thickness (m)

Total SLR by 2100 (Mean & 95th Percentile)



Conclusions

Subsidence in some coastal areas equals or exceeds rates of modern oceanographic sea level rise, and needs to be considered in flood hazard assessment.

In regions with thick Holocene deposits, compaction of the upper few meters has likely been underestimated.

Thanks!