Sea level rise:
How important is the climate signal compared to human-induced coastal subsidence?

James PM Syvitski

IGBP Chair

CSDMS Director

Thanks to Stephanie Higgins & Tad Pfeffer (INSTAAR)

Components of Sea Level Rise (SLR)

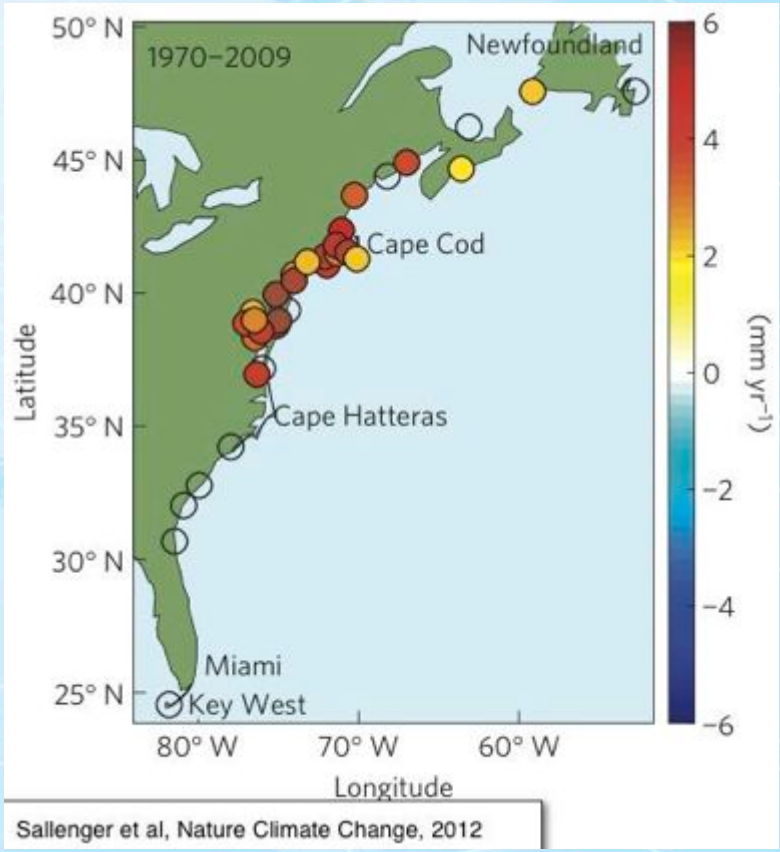
1. Steric (Thermal Expansion)
    a. Upper ocean (top 700 m)
    b. Deep ocean
2. Eustatic (new water)
    a. Antarctica
    b. Greenland
    c. Glaciers and Ice Caps (GIC)
    d. Terrestrial storage
        1. Ground water
        2. Surface water
        3. Reservoir storage

Global

3. Relative
    a. Dynamics (e.g. storm surges, tides)
    b. Gravitational
    c. Tectonics & Isostasy
    d. Coastal subsidence
        1. Peat oxidation
        2. SLR loading
        3. Upstream sediment trapping
        4. Groundwater depletion
        5. Petroleum Mining

Local

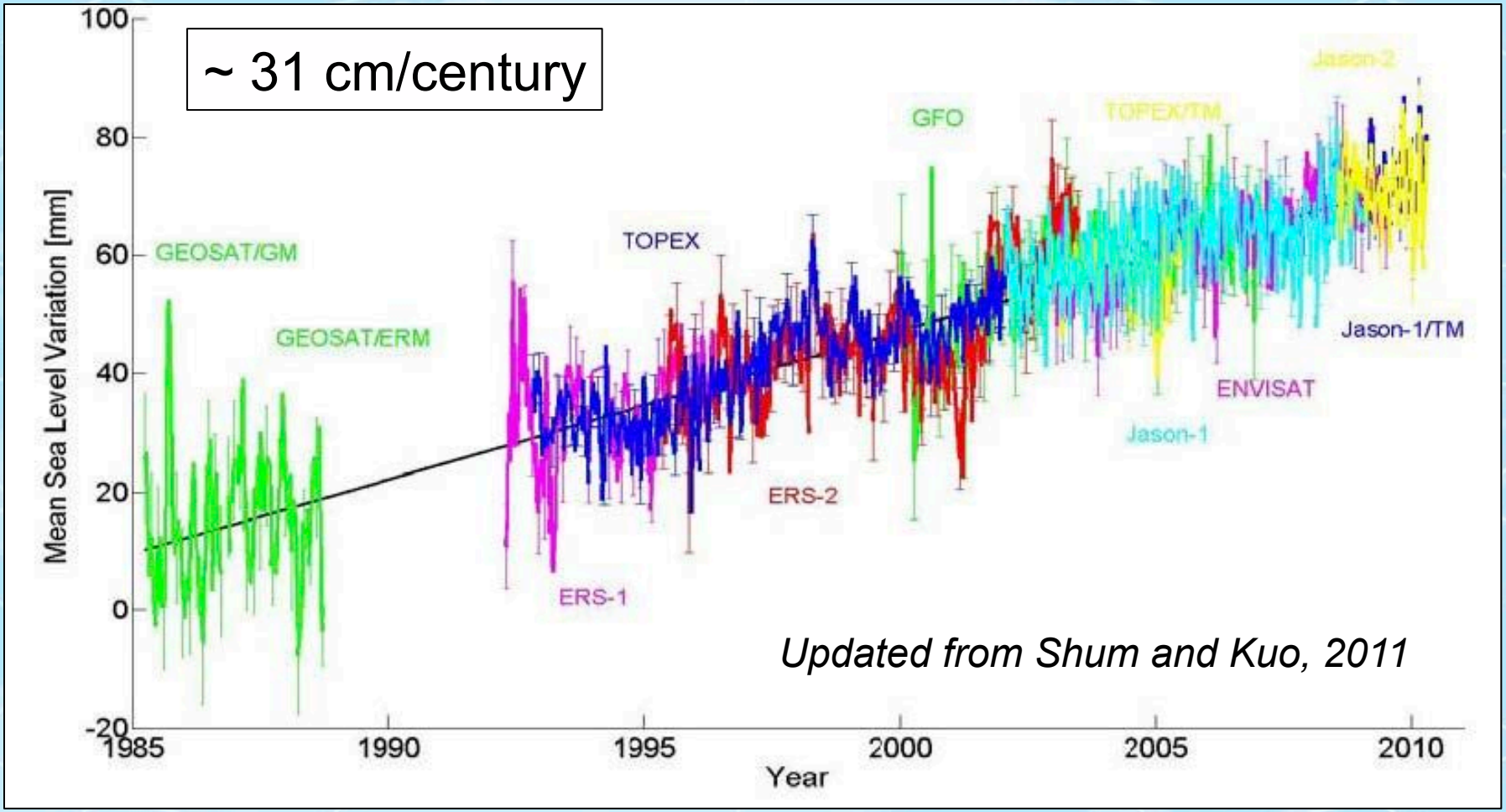
Sea Level Predictions must:
1. Include all sources
2. Forecast on useful time scales
3. Provide meaningful uncertainties
4. Be delivered soon enough to be of use



Relative effects may dominate locally

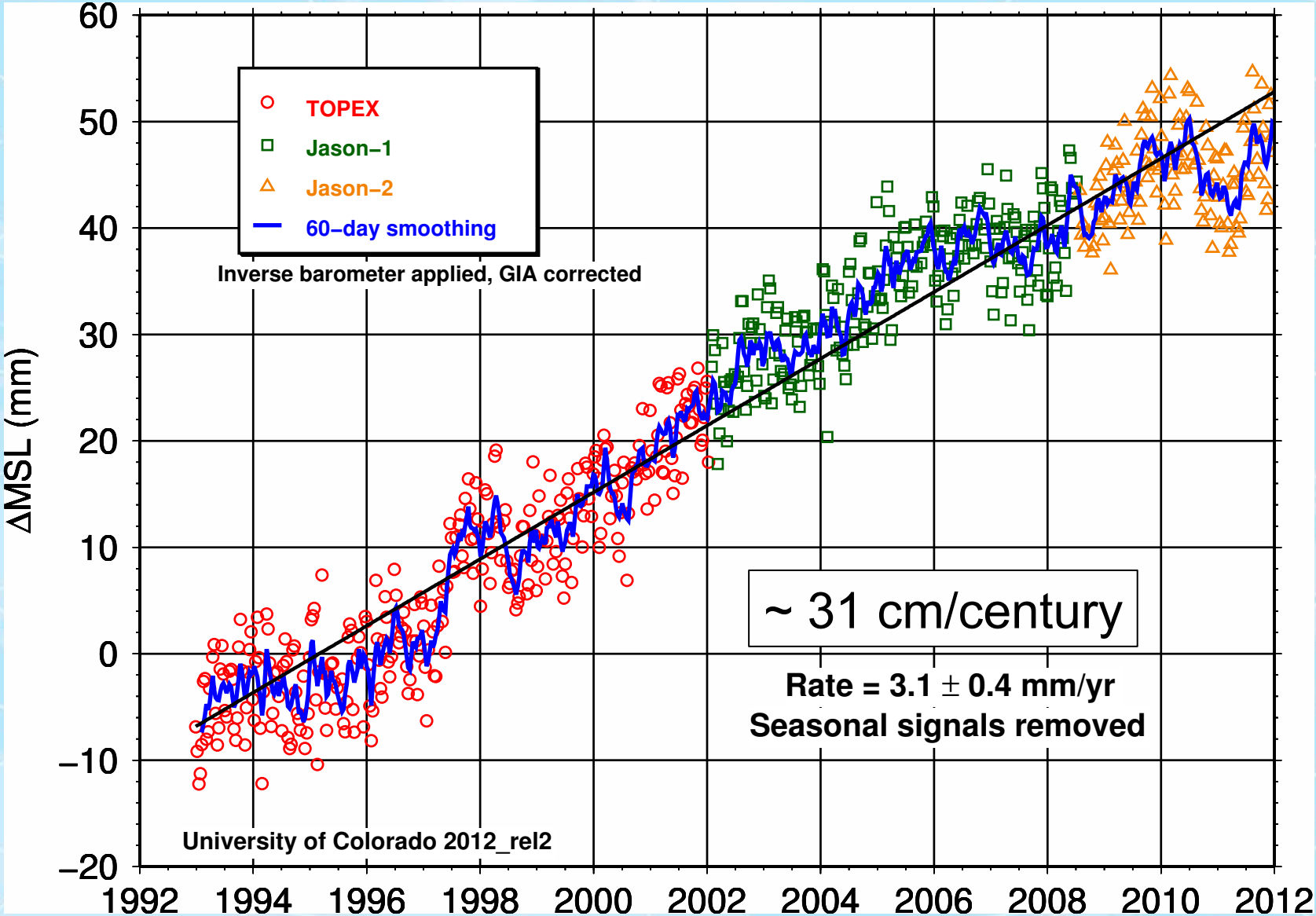
from National Research Council 2012

Comparison of 11 Satellite Altimeter records

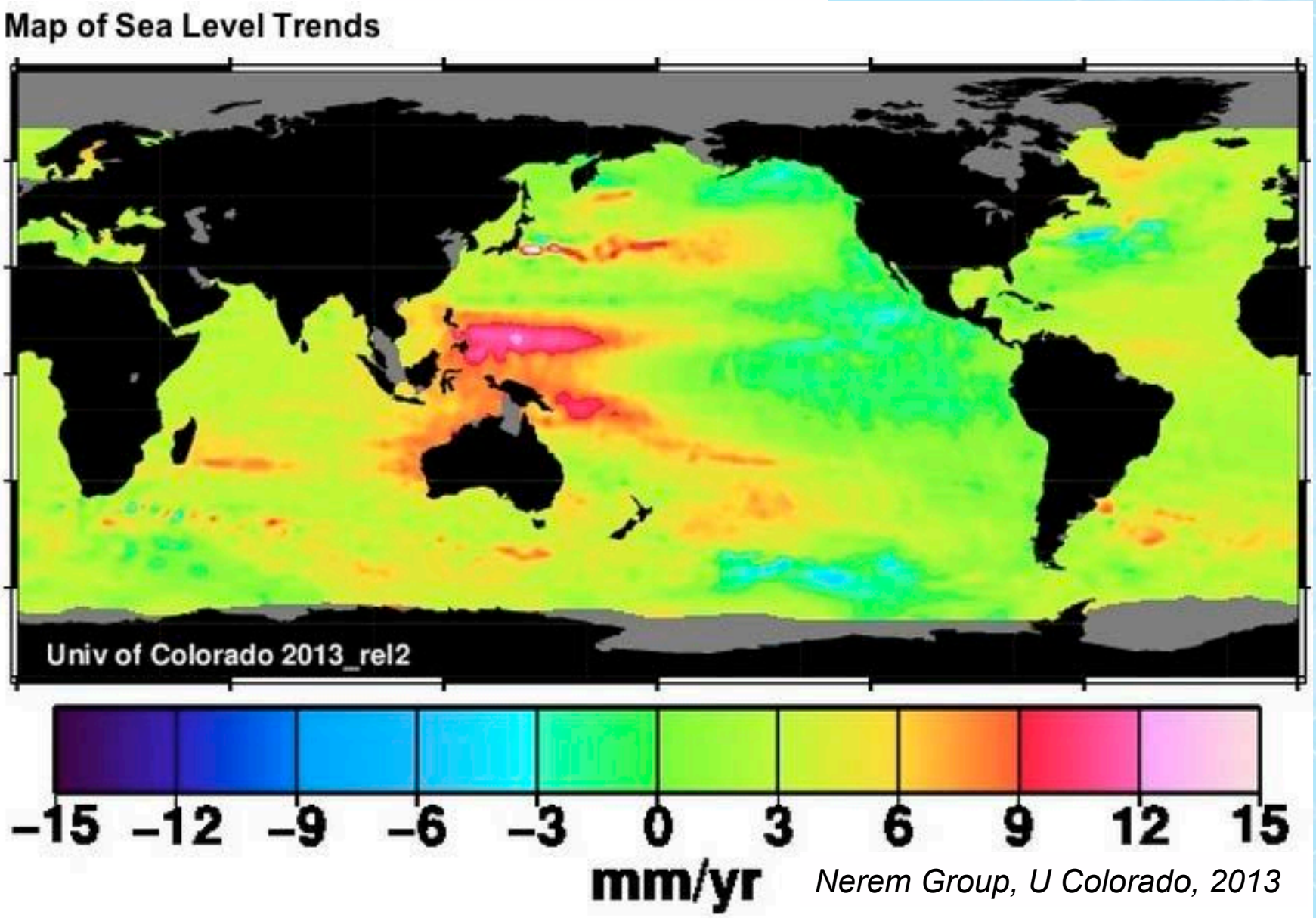


Observed Sea Level Rise from satellite altimetry

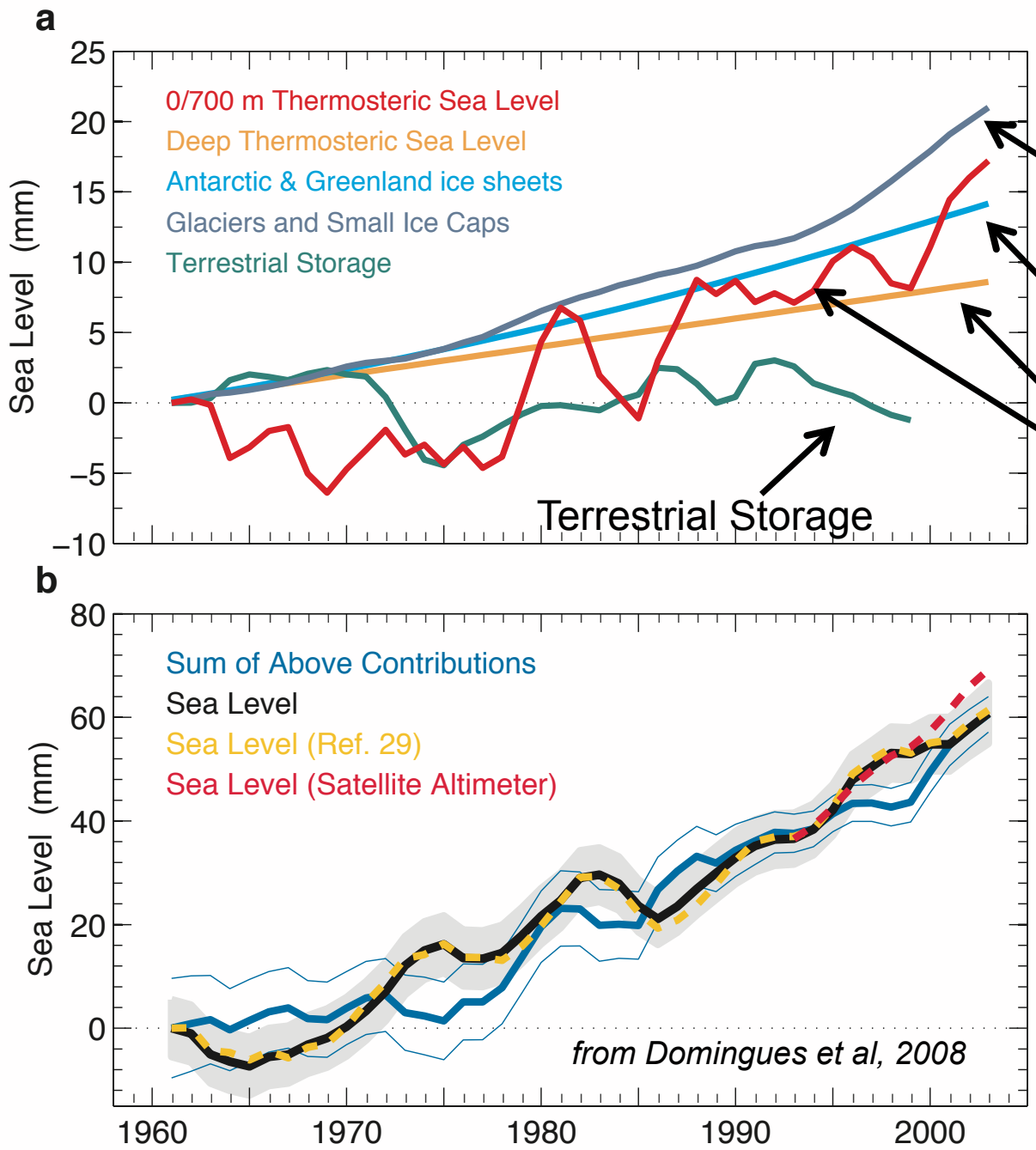
(Nerem Group, Univ. of Colorado)



Variability in rate of SLR 1993-2010



Nerem Group, U Colorado, 2013



Present-day observations

Glaciers

Greenland and Antarctic Ice Sheets

Thermal expansion

Summation of components of SLR compared to direct observation of SLR as of 2008

Syvitski, Switzerland, 2013

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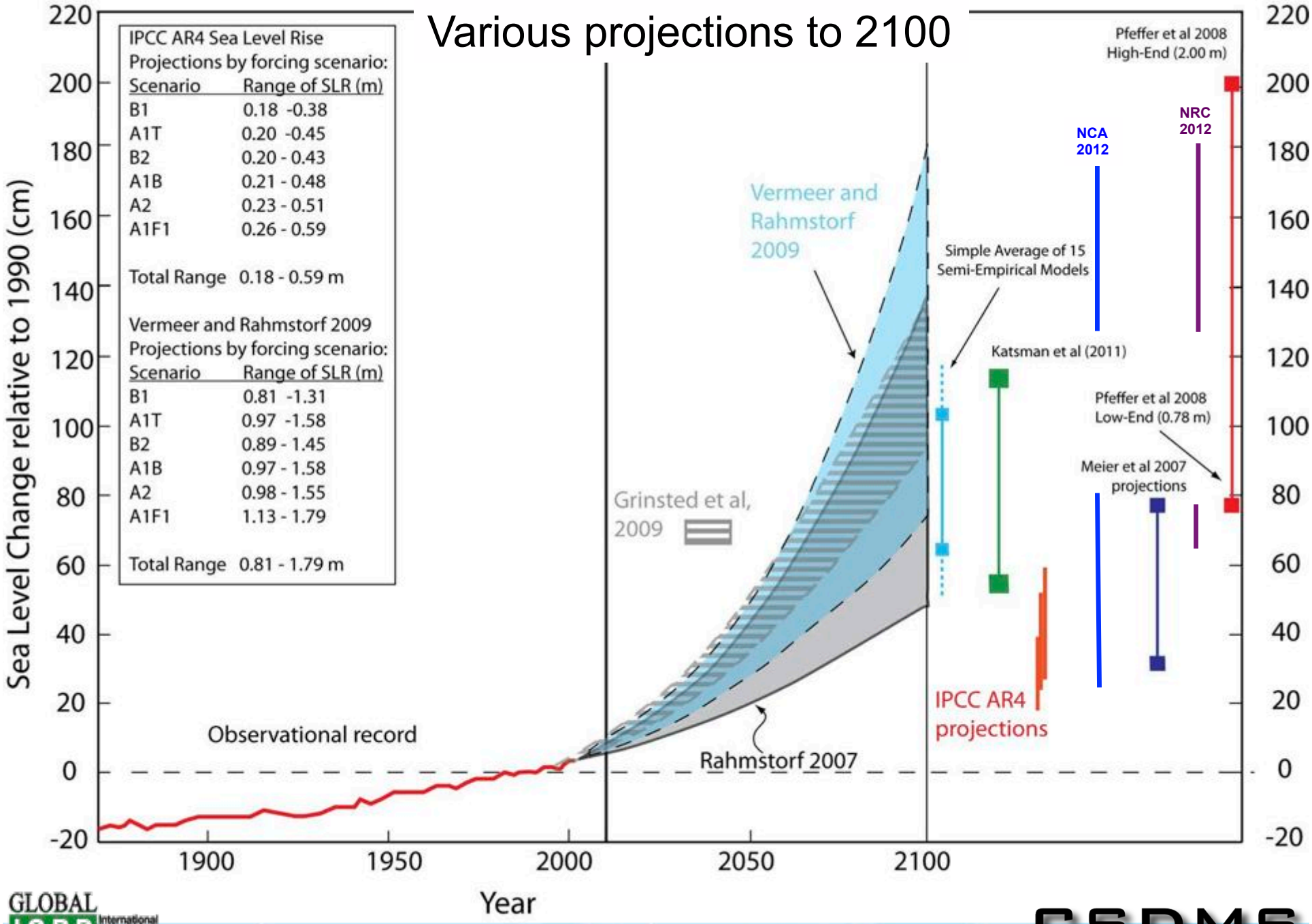
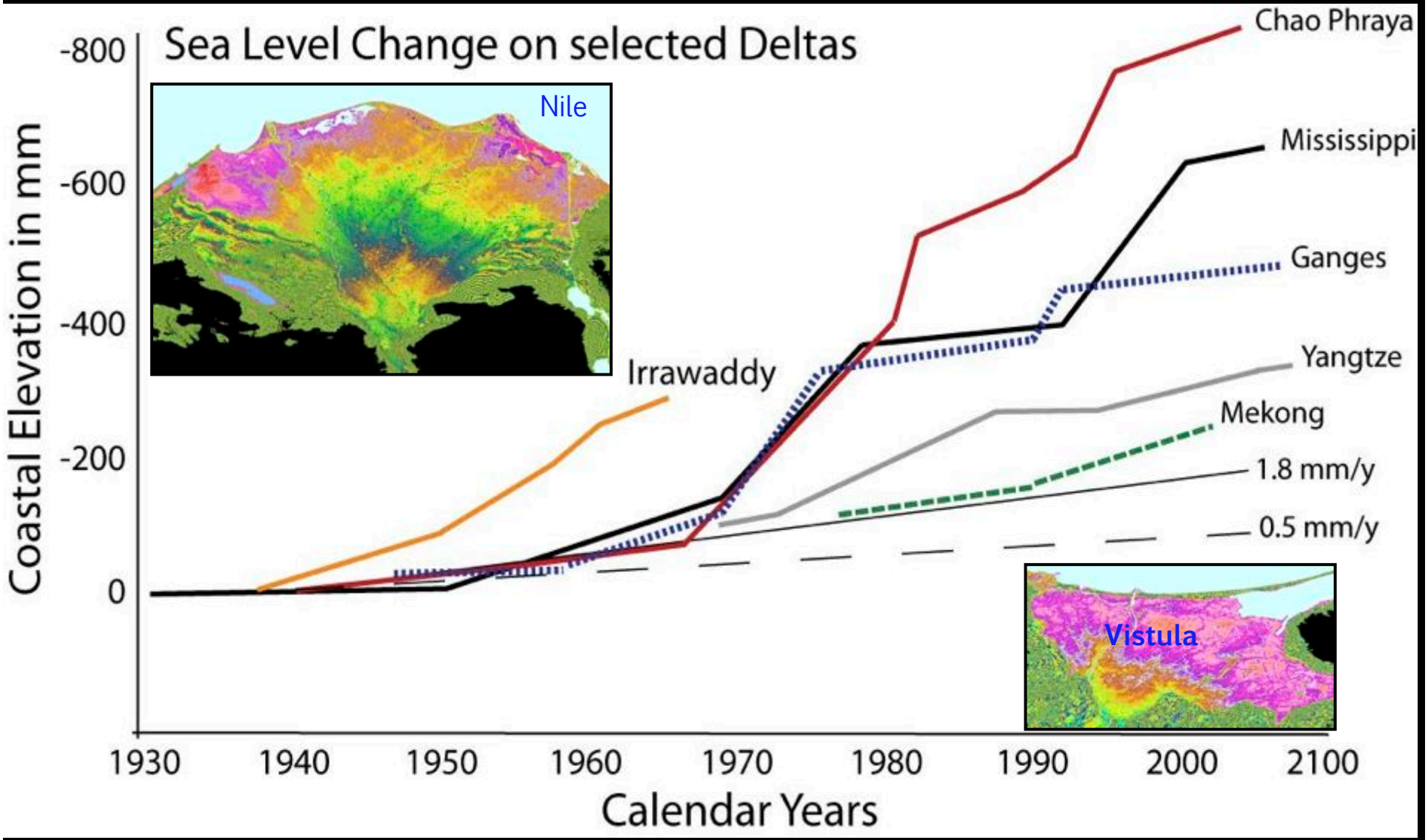
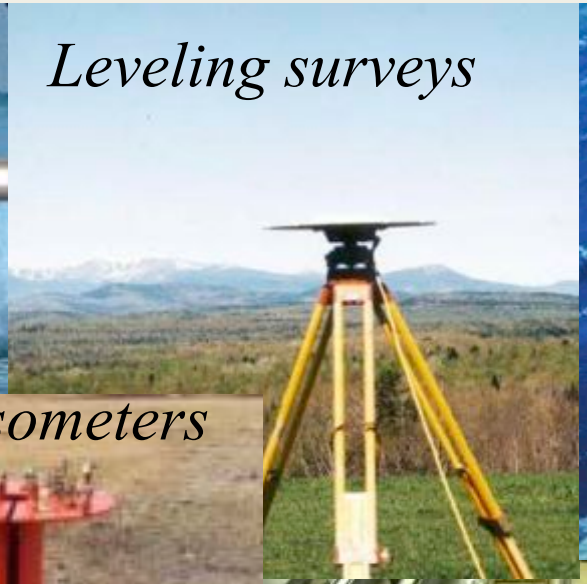
Various projections to 2100

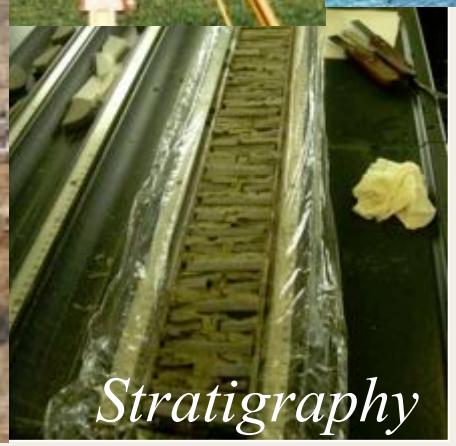


Humans are sinking deltas 4x faster than SL is rising.



How we measure subsidence at the coast



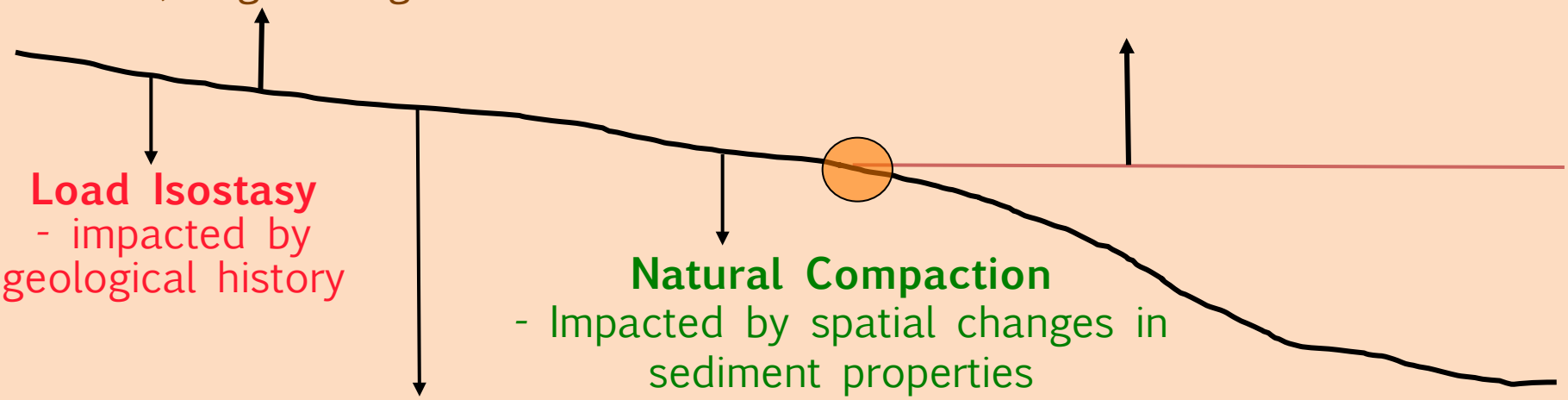


Interferometric Synthetic Aperture Radar (InSAR)
mm-scale measurements on monthly timescales

The Relative Sea Level Budget (Syvitski et al, 2009 Nature Geoscience)

Aggradation – impacted by soil erosion activities, upstream dams, engineering activities

Eustasy – impacted by global warming and changes in terrestrial freshwater storage



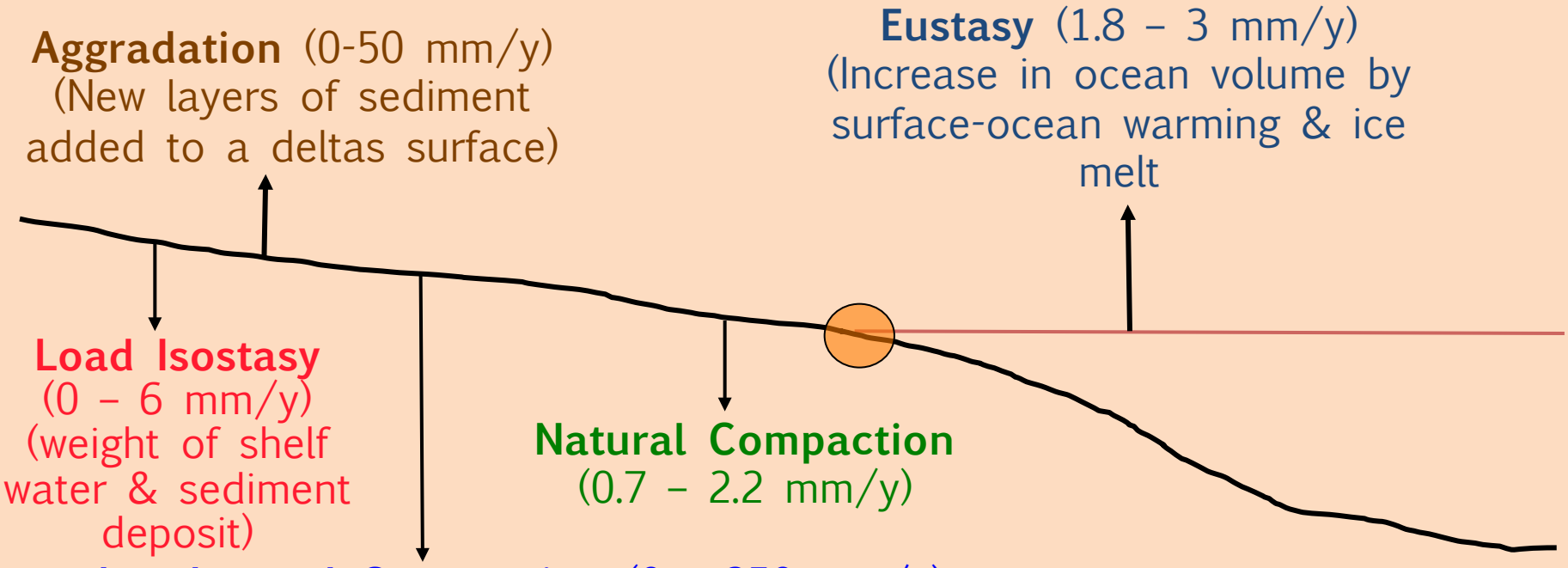
Load Isostasy - impacted by geological history

Natural Compaction - Impacted by spatial changes in sediment properties

Accelerated Compaction – impacted by human occupation and interaction with the environment

Delta Surface Elevation $\Delta_{RSL} = A - \Delta E - C_n - C_A - M$

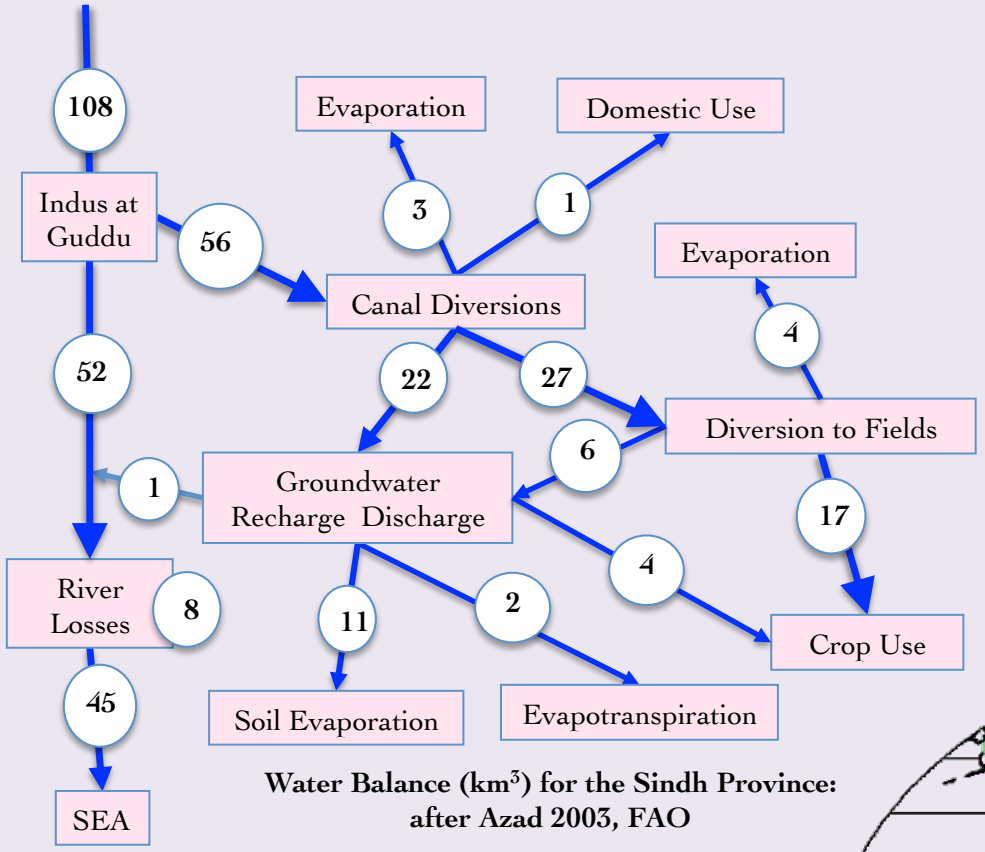
Modern Deltas are in Disequilibrium



Delta Surface Elevation $\Delta_{RSL} = A - \Delta E - C_n - C_A - M$

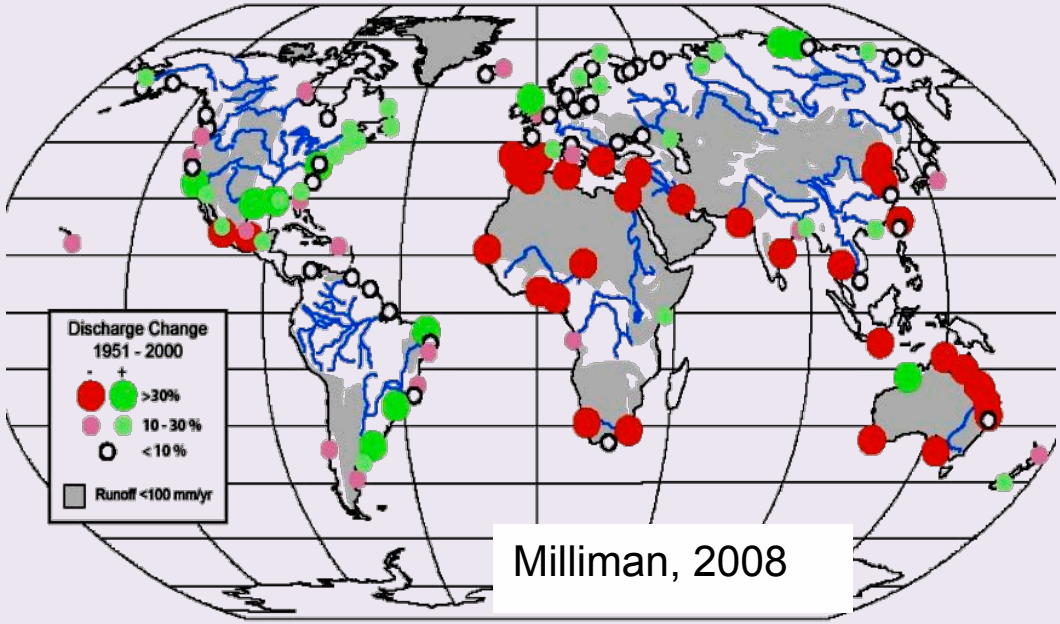
e.g. natural conditions (mm/y) $+5.5 = 10 - 0.5 - 2 - 0 - 2$

e.g. anthropogenic forcing (mm/y) $-15 = 5 - 3 - 2 - 13 - 2$



Water Balance (km^3) for the Sindh Province: after Azad 2003, FAO

For many coastal areas discharge is decreasing.



Milliman, 2008

Syvitski, Switzerland, 2013

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2.3 Gt/y LESS sediment reaches coastal deltas worldwide due to dams and 100's of GT of sediment is stored in our world's reservoirs

Syvitski & Kettner, 2011, Phil Trans Royal Society

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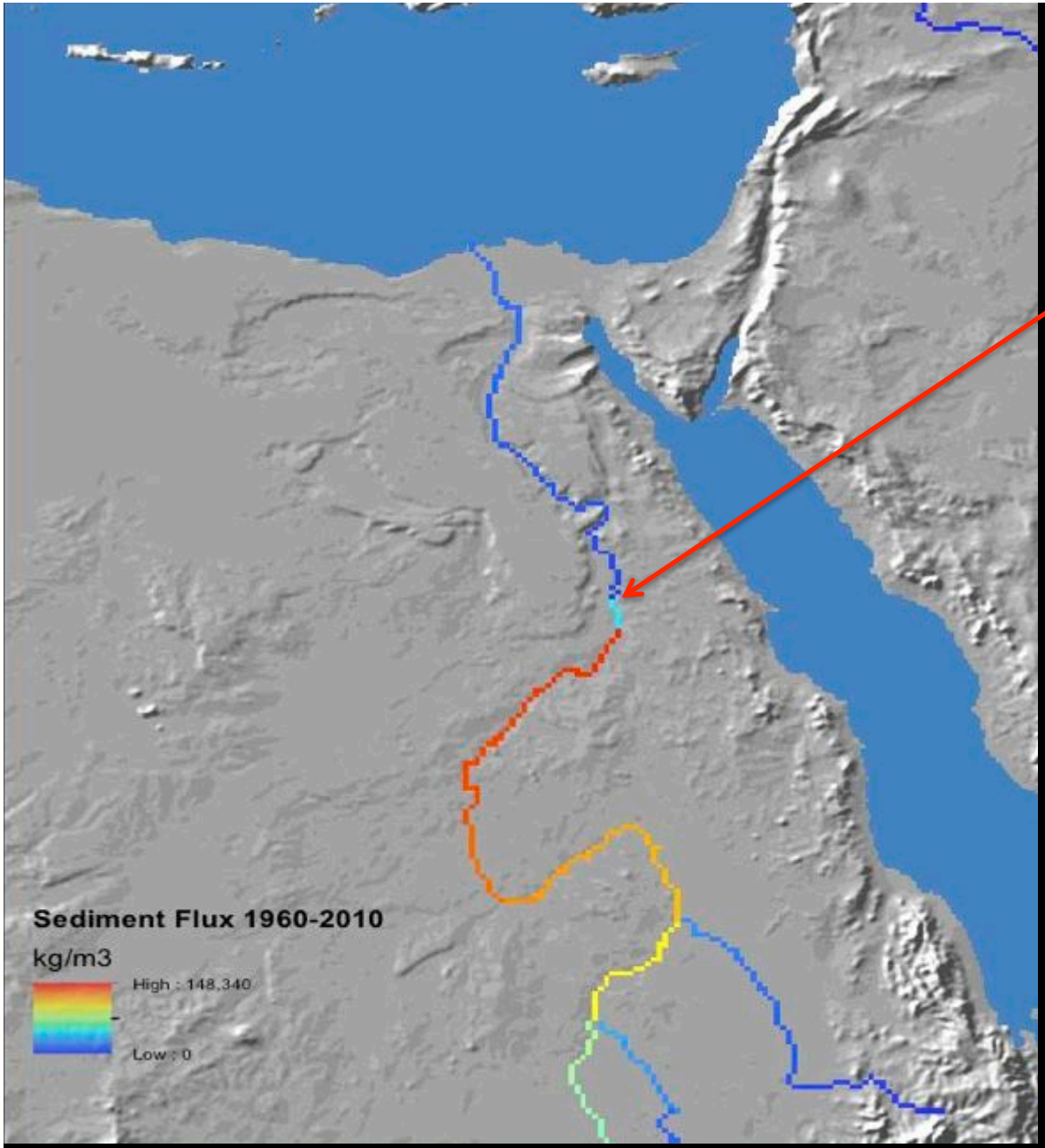
Examples of individual rivers feeding deltas that receive much less water and sediment discharge

Delta Examples	ΔQ_{av} (%)	ΔQ_{mx} (%)	ΔQ_s (%)	ΔC_s (%)
Colorado 1904-23 vs. 1934-63	-76	-90	-100	-100
Ebro 1913-62 vs. 1988-90	-83	-91	-99	-88
Nile 1871-98 vs. 1967-95	-64	-82	-98	-96
Yellow 1950-70 vs. 1961-88	-74	-81	-80	-22
Indus 1931-46 vs. 1979-2003	-77	-84	-69	-38
Krishna 1901-60 vs. 1965-2003	-42	-19	-75	-61
Po 1933-39 vs. 1982-87	-19	-33	-65	-57
Danube 1931-55 vs. 1956-96	0	0	-76	-76
Yangtze 1951-68 vs. 1986-04	0	0	-37	-36
Mississippi 1940-60 vs. 1961-90	0	-2	-65	-65
Mekong 1962-92 vs. 1993-00	5	4	-19	-28



Hydrological models like *WBMsed* now incorporate sediment sequestration behind large dams, e.g. the Aswan Dam on the Nile River

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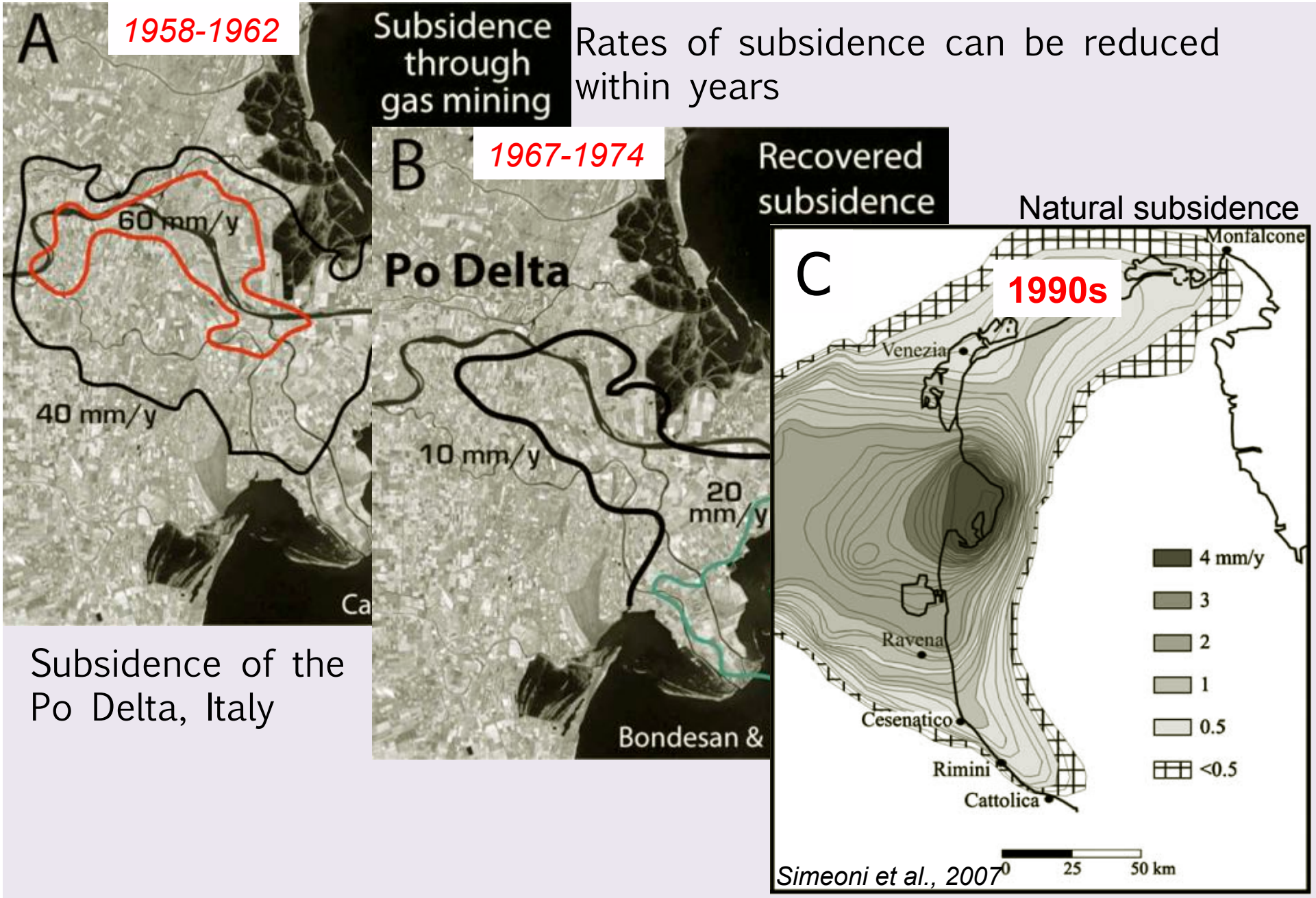
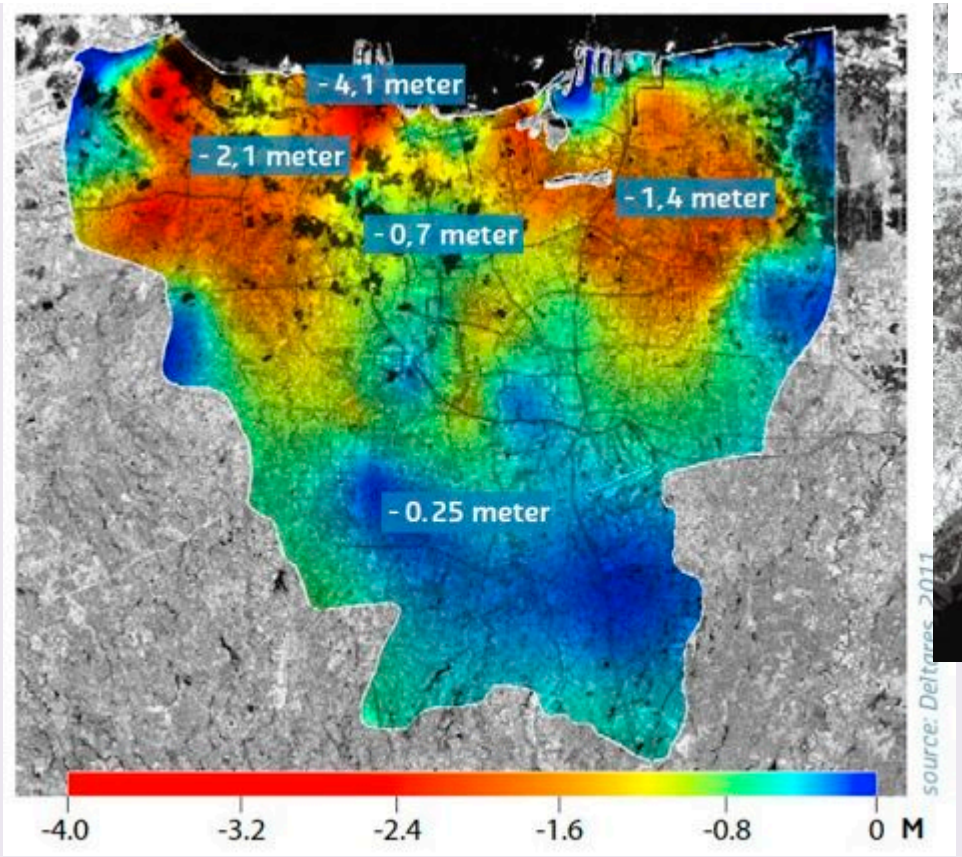
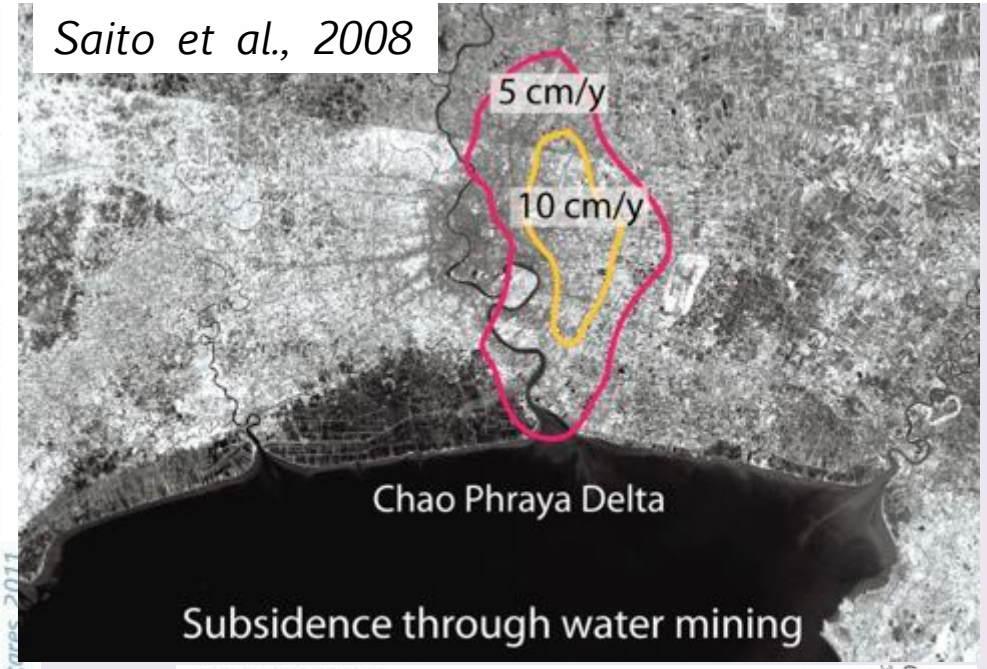
Rates of subsidence can be reduced within years

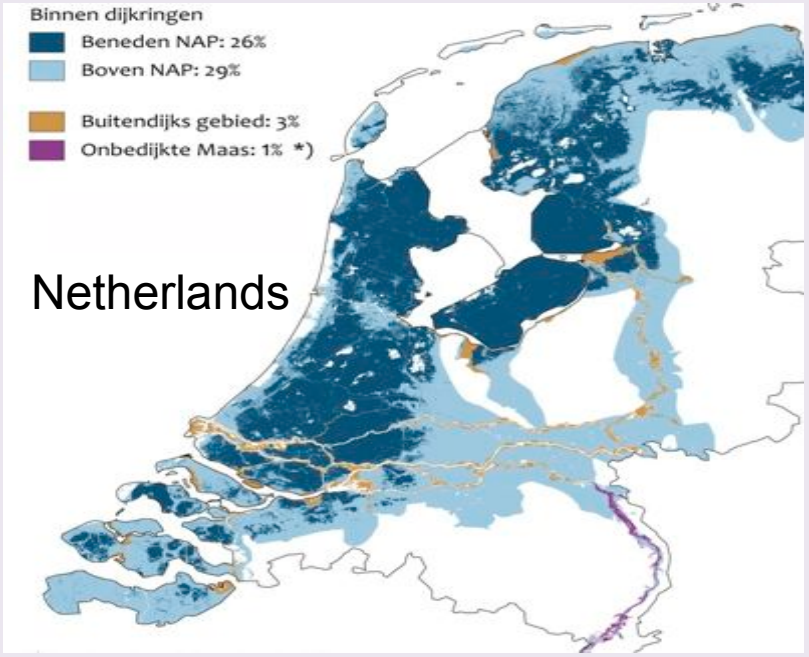


Subsidence of the Po Delta, Italy



Land subsidence in Jakarta
1974-2010 *-Deltares 2011*





Other Examples

Yangtze: 28 mm/y before controls
Niger: 25 to 125 mm/y
Po: 60 mm/y before controls

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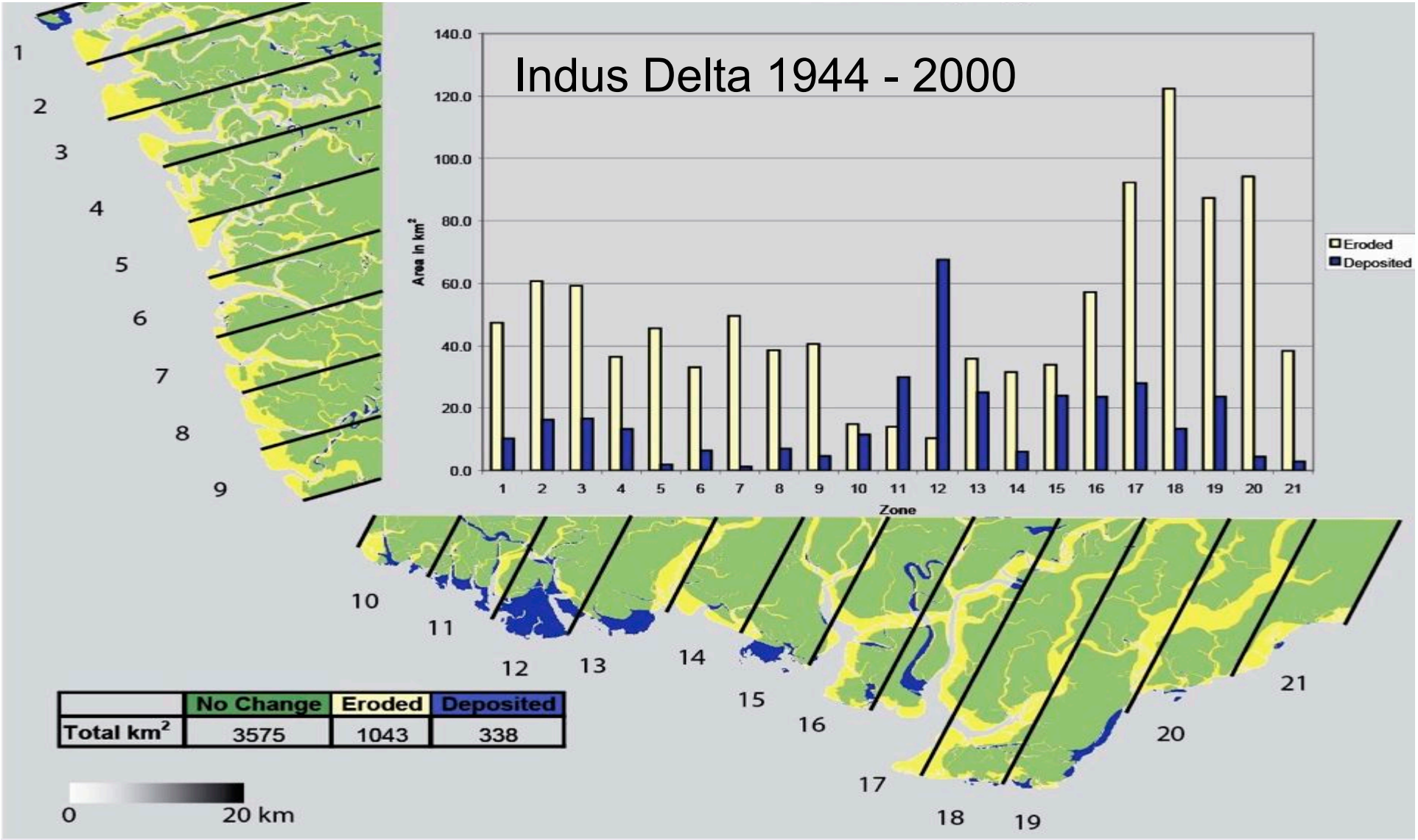
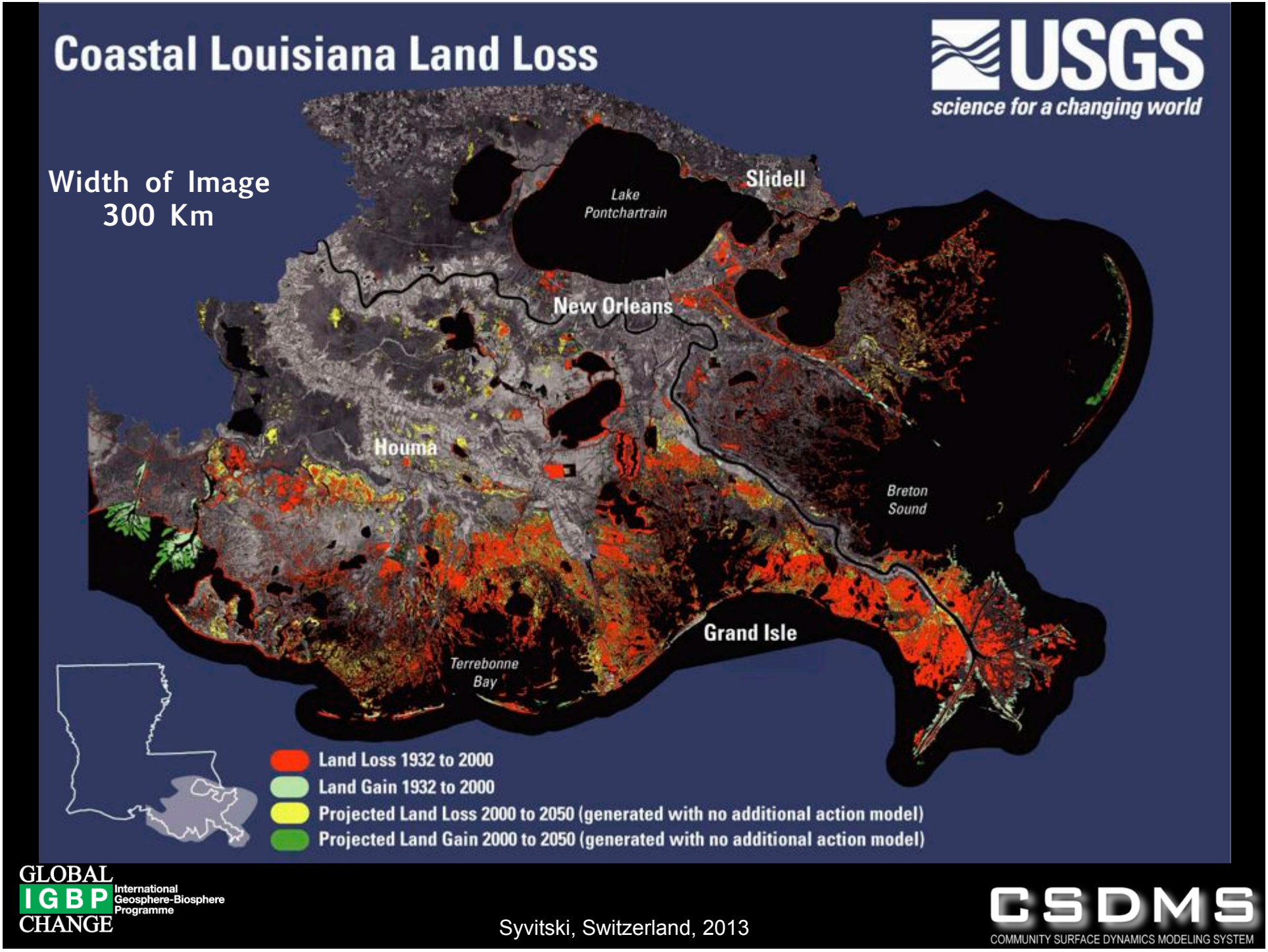


From 1944 - 2000 erosion & widening of the tidal channels dominants. Deposition is restricted to river-mouth areas & infill of abandon channels.



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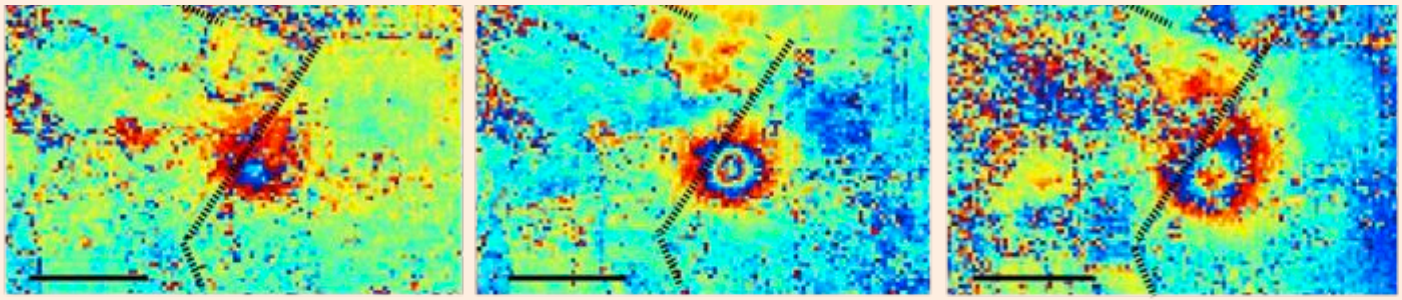
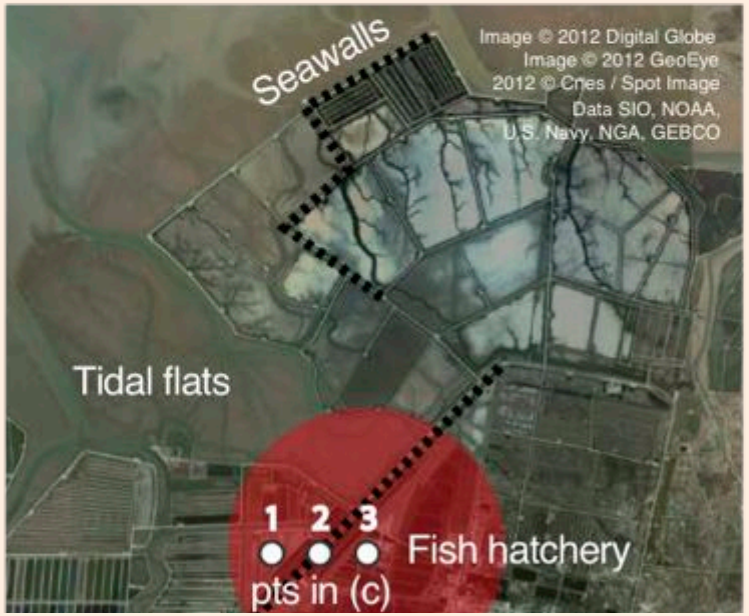


1 m subsidence in 4 yr



17m spatial pixel
~1 to 2mm vertical resolution

Advanced methods like D-InSAR or PS-InSAR isolate the varied ways humans impact the earth's surface
- Higgins et al., 2013

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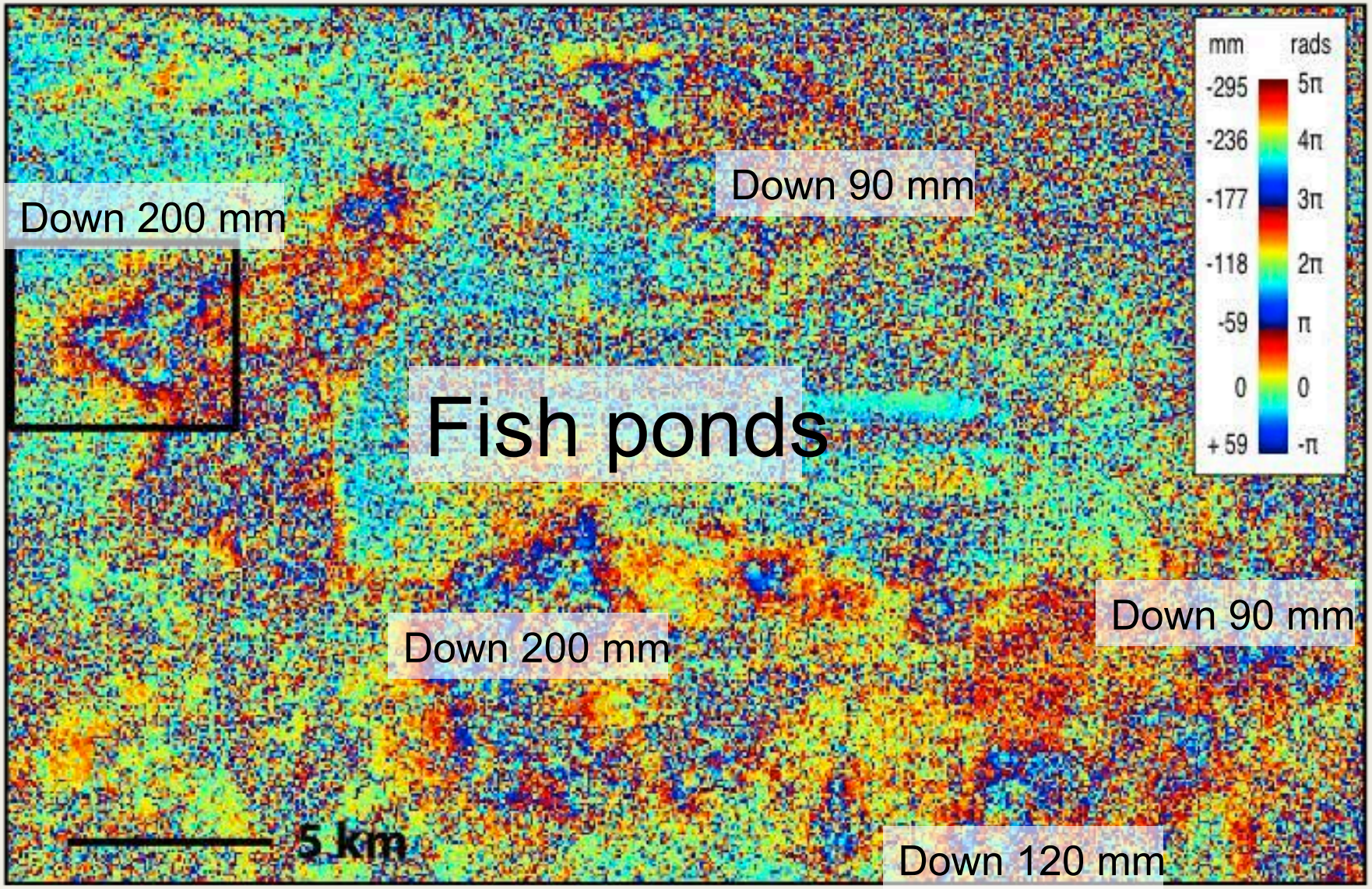
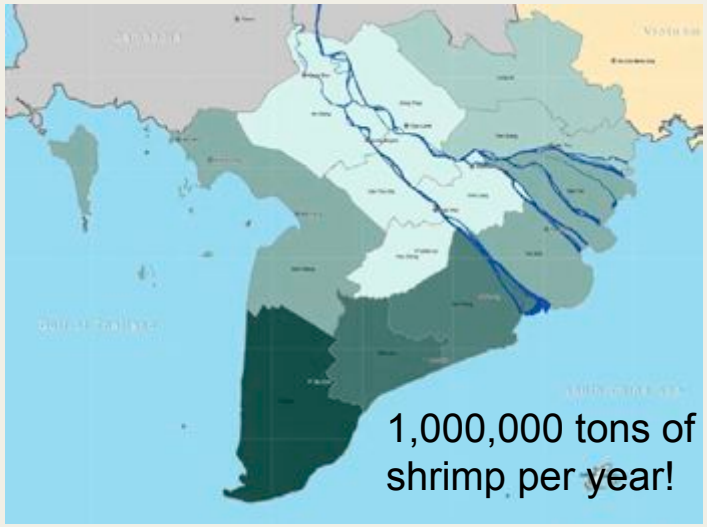


From Higgins et al. (2013)

Mekong delta, Vietnam
Wisdom Project/DLR (2009)



Chao Phraya Delta, Thailand (aerial photo)

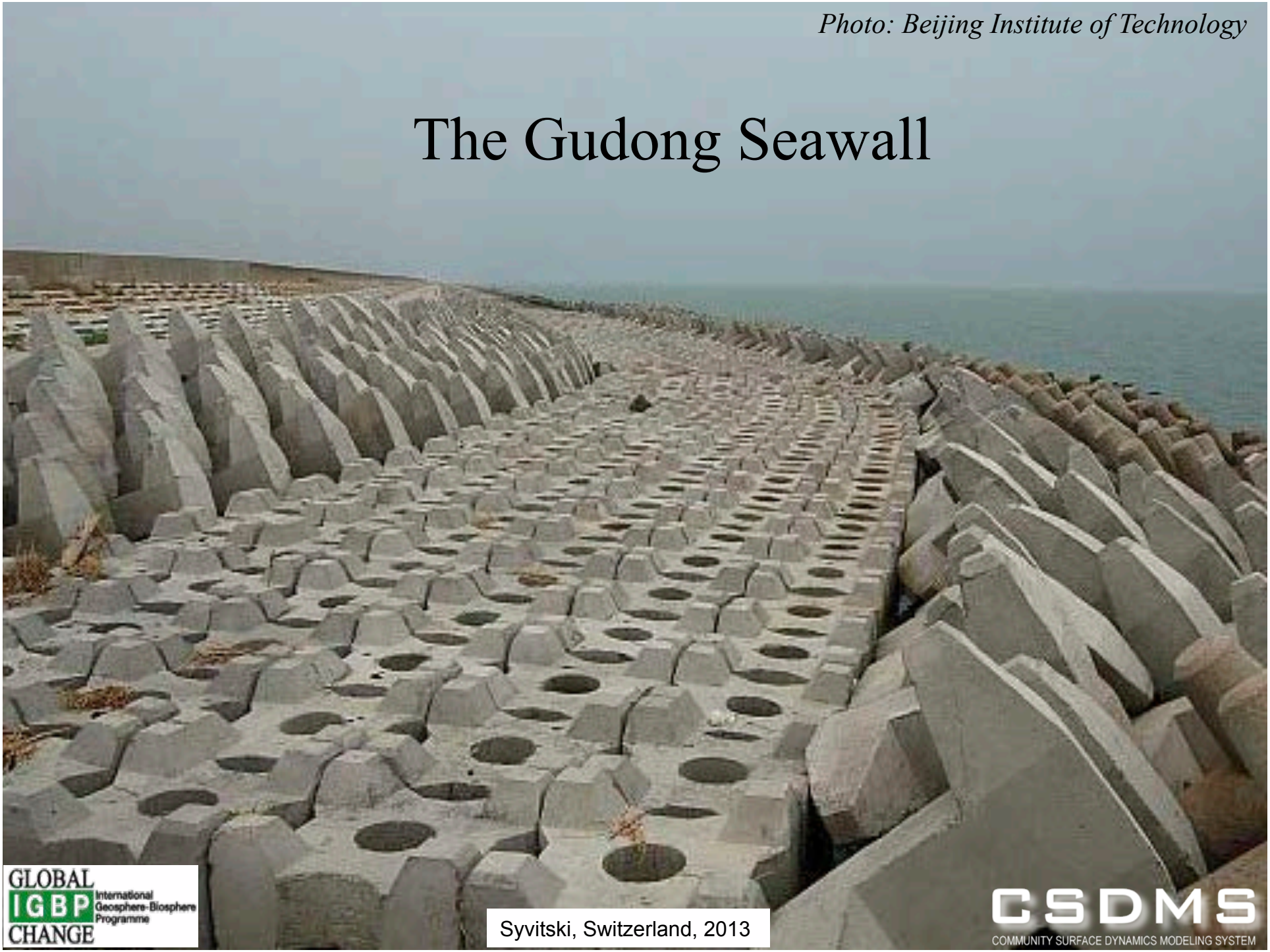
Pearl River delta, China
Courtesy of Mark Bender

Number of fish farmers quadrupled in 20 years
Farmed fish was 60 Mt in 2010
89% of production is in Asia, largely on deltas

Ganges delta, Bangladesh

Photo: Beijing Institute of Technology

The Gudong Seawall



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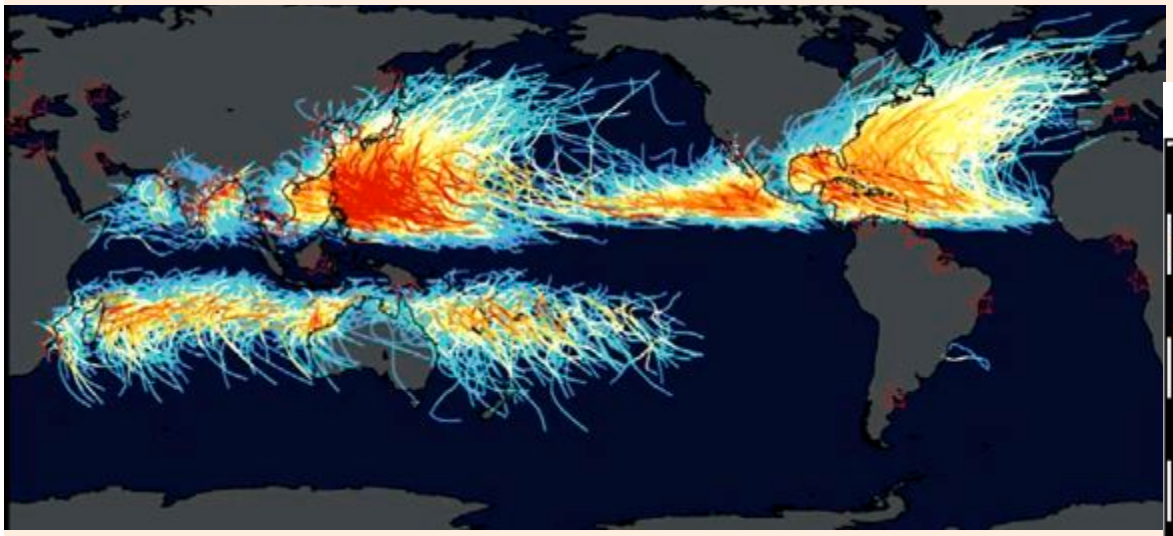
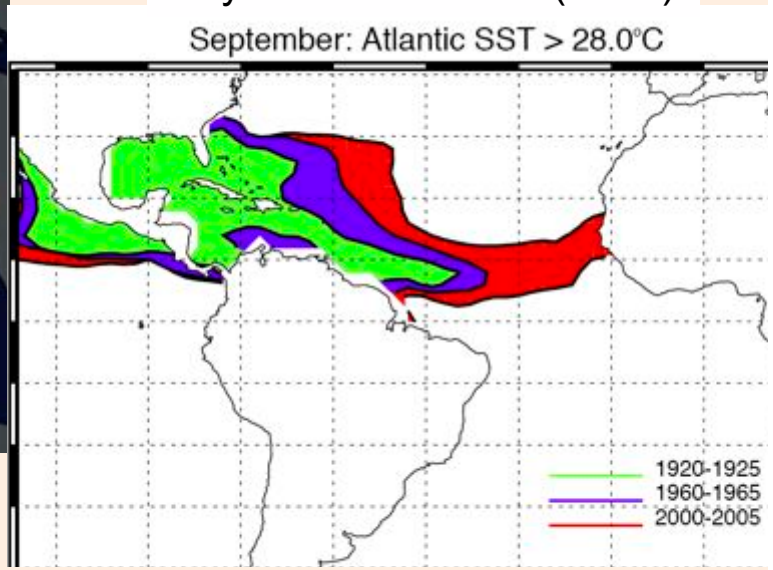
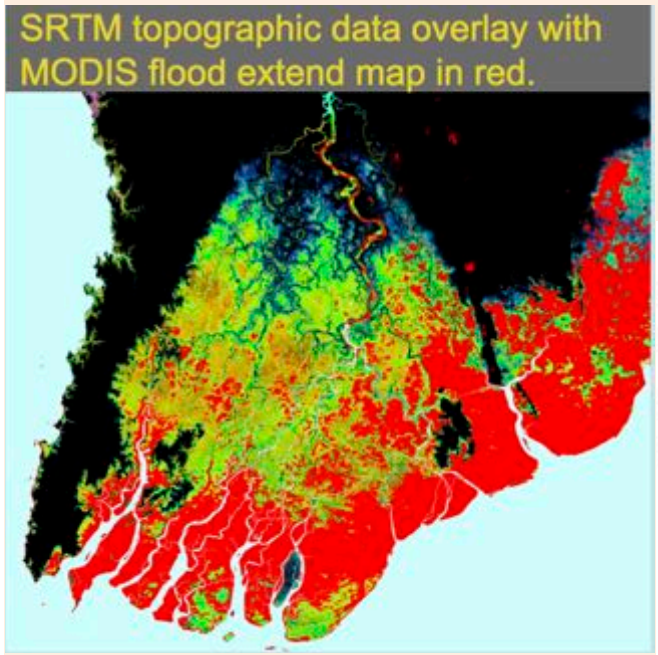
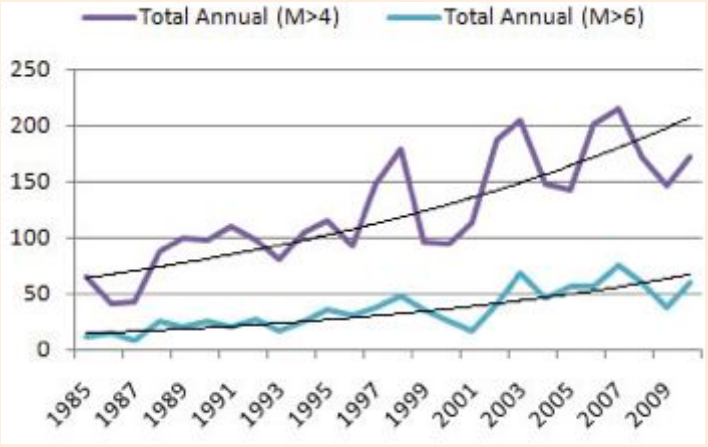
Storm Surges, River Floods — are they on the rise?



Hoyos and Webster (2007)







Hurricane intensity and river floods may be increasing.

Storm surges can lift coastal waters meters above mean sea level.

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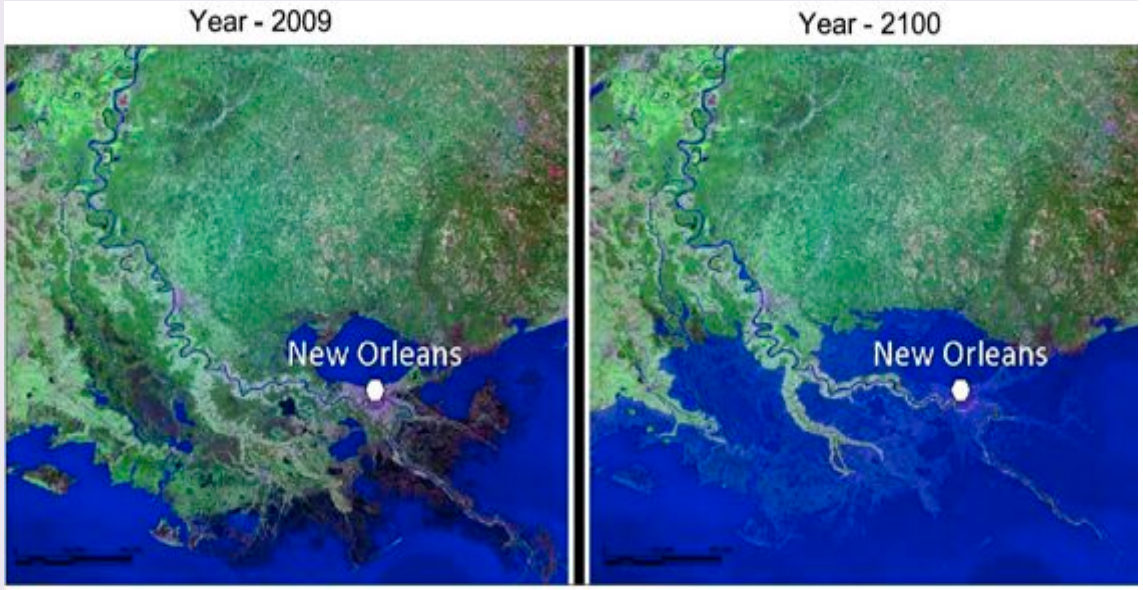
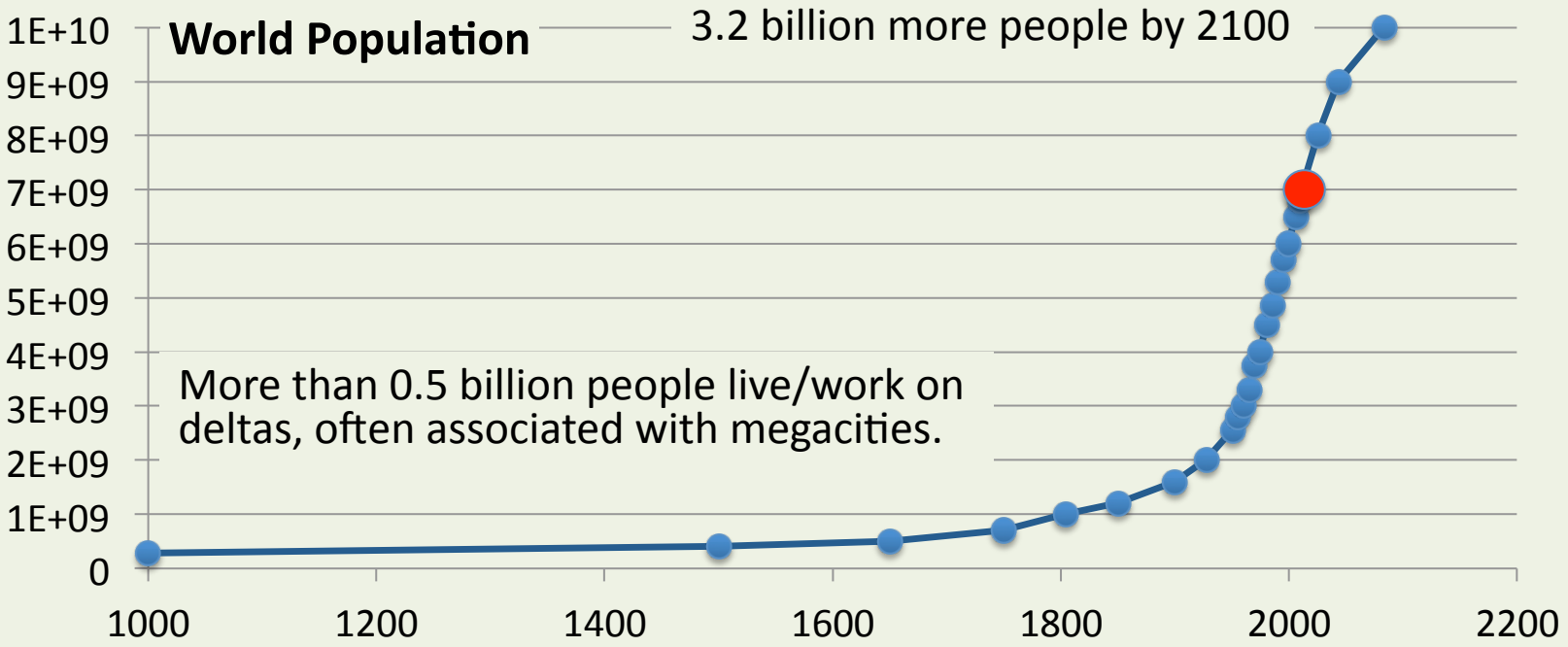
	Delta area (km^2)		
Delta	**<0**	**<1**	**<2**
Brahmani	40	207	640
Chao Phraya	263	734	1775
Ganges B	1988	3682	6173
Indus	1213	2558	4753
Irrawaddy	40	265	1104
Mekong	7156	13621	20908
Mississippi	1876	4258	7142
Nile	5051	7212	9435
Orinoco	197	629	1801
Parana	245	1262	3597
Pearl	2499	3163	3719
Po	602	622	633
Rhone	752	1007	1144
Tigris	2297	5130	9711
Vistula	1221	1376	1488
Yangtze	2206	3896	7084
Yellow	1235	2253	3424
Total area	**29387**	**53032**	**87534**

Globally in the past decade, deltas experienced severe flooding (260,000 km^2) and flooded areas could conservatively increase by 50% under projected 21st century sea-level rise.

Syvitski et al Nature Geoscience 2009



Map: Blum, M.D., and H.H. Roberts (2009), Drowning of the Mississippi delta due insufficient sediment supply and global sea-level rise, *Nat. Geosci.*, 2, 488-491.



City	Delta	1975	2000	2010
Karachi	Indus	4.0	10.0	12.0
Calcutta	GBM	7.9	13.1	15.1
Dhaka	GBM	2.2	9.5	13.0
Rangoon	Irrawaddy	1.8	4.4	6.3
Bangkok	Chao Phraya	3.8	7.4	11.9
Ho Chi Minh	Mekong	2.8	6.6	10.0
Hanoi	Red	1.9	7.8	14.5
Guanzhou	Pearl	3.1	8.9	12.8
Shanghai	Changjiang	11.4	12.9	20.0
Tianjin	Huanghe	6.2	9.2	10.3
Cairo	Nile	6.0	10.5	14.5
Buenos Aires	Parana	10.9	11.8	12.8

12 delta cities have gone from
62 M people in 1975
to
153 M people in 2010

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Sea level rise: *How important is the climate signal compared to human-induced coastal subsidence?*

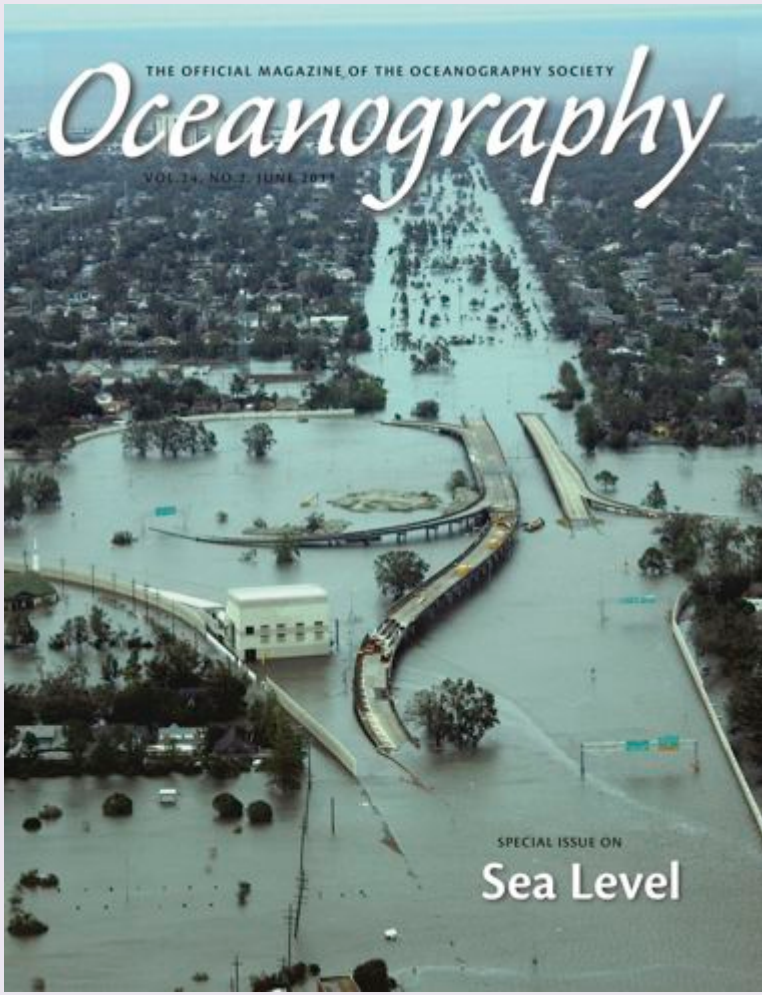
Facts:

20th century — global SLR rose 18 cm
Last 35 years — global SLR rate doubled
21st century — global SLR rate may double again

20th century coastal subsidence — 80–400 cm
Local rates can be greater than 25 cm/y!!!

Answer:

The climate signal has contributed ~10% of the coastal subsidence signal but this might increase to ~30% if there are any deltas left to subside.
Climate change impacts might significantly increase this contribution if storm surge frequency or river flooding were to increase.



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