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Locations of U.S. dams.
Sea ice concentration.
Arctic coastline erosion.

Sinking Deltas due to Human Activities*

Irina Overeem[1], J. Syvitski, A. Kettner, E. Hutton, and B. Brakenridge

Search and Discovery Article #70094 (2010)
Posted March 14, 2011

*Adapted from presentation at Tulsa Geological Society, March 1, 2011.

Editor's note: This presentation is an update/sequel to Search and Discovery Article #50339 (2010) ("Human and Natural Controls on a Delta's Surface Elevation Relative to Local Mean Sea Level" by J. Syvitski, A. Kettner, I. Overeem, E. Hutton, M.T. Hannon, and B. Brakenridge).

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Abstract

Deltas are densely populated, intensively farmed landforms, that are being threatened not just by rising sea levels, but more so by sediment compaction from water, oil and gas mining, sequestration of sediment in upstream reservoirs, and from floodplain engineering. Highresolution topographic data obtained from the 2002 Space Shuttle Radar survey (SRTM), are used to assess a representative suite of 33 major world deltas which have elevations near, at, or below mean local sea level, and for morphodynamic insight on how sediment has historically been deposited. Visible and near-infrared satellite imagery (MODIS Terra and Aqua sensors) are used to assess flooding over 2000-2008, to assess: 1) whether modern deltas are prone to flooding, 2) whether the flooding is from land-derived runoff or ocean surges, and 3) whether the flood waters contain enough suspended sediment to contribute to delta plain aggradation. Historical maps provide evidence on how rivers once flowed through deltas.

Many of the deltas have substantive areas below local mean sea level. Of 33 representative world deltas examined, 85% experienced severe flooding in the last decade, temporarily submerging 260,000 km^2, yet only 10% of this flooded area is below sea level. Areas vulnerable to flooding may increase by 50% under projected 21st century eustatic sea level rise, but this is a conservative estimate given the current trends in the reduction in sedimentary deposits that would otherwise buffer deltas. While modern eustatic sea level rise contributes to the problem — and often is discussed in the news — accelerated compaction, and reduced delta plain aggradation of sediment are of *much* larger concern for populated deltas.

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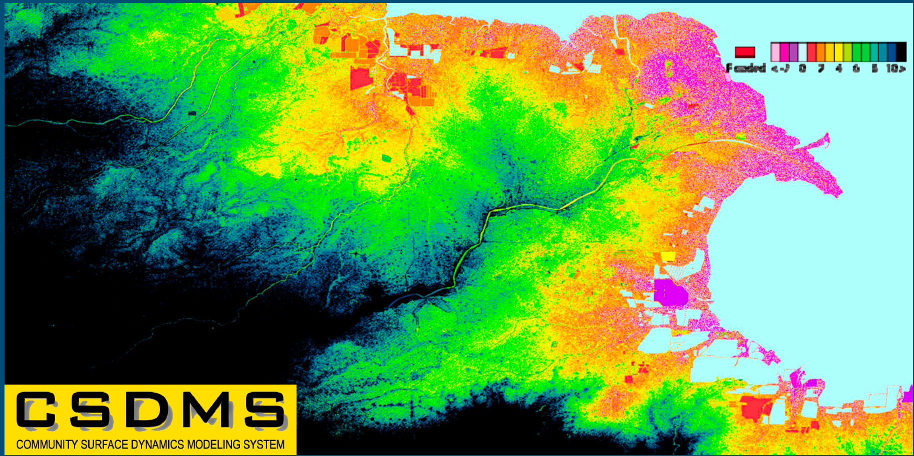
Sinking Deltas due to Human Activities



Dr. Irina Overeem, Syvitski, J., Kettner, A., Hutton, E., Brakenridge, B.
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Ganges Delta and Calcutta flooded under sea level rise, from ”An Inconvenient Truth” (2006)

Critics: “6m is a sledge hammer estimate…”

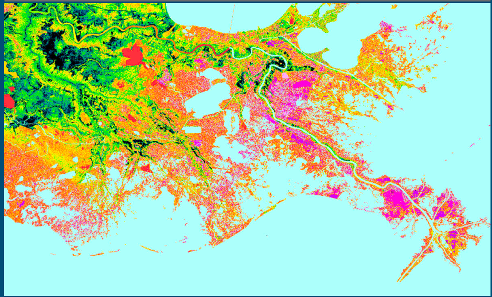
And my own ‘delta bias’ tells me ….it is not just a matter of topography!

NASA SRTM topography data and numerical modeling

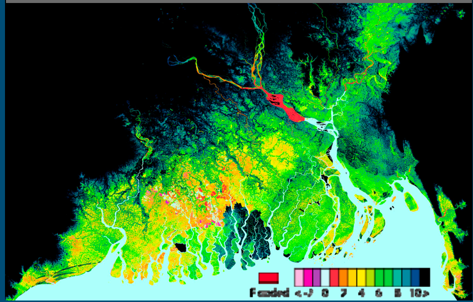
- Remote-sensing data: NASA Shuttle Radar Topography Mission, world topography data (60°N to 59°S), at 30 m horizontal resolution, ~1 m vertical. MODIS visible band images for daily flood mapping.
- Numerical Models: HydroTrend, WBM, CEM, SedFlux, AquaTellus (all in the framework of CSDMS).
- learn more about CSDMS, modeling and free models:
- http://csdms.colorado.edu/wiki/Main_Page

Problem: Deltas are low-lying land

Mississippi Delta, USA



Ganges-Brahmaputra Delta, India & BD



Worldwide ~500 million people live in low-lying deltas

Thirty-three major deltas combined have >100,000 km^2 at elevation < 2m a.s.l.
Thirty-three major deltas combined have >26,000 km^2 at elevation < 0m a.s.l.

Controls on Delta Elevation

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

Δ_{RSL} = Vertical change in delta surface elevation (m/yr)

A = Aggradation Rate (m/yr)

ΔE = Eustatic Sea Level Rise (m/yr)

Cn = Natural Compaction (m/yr)

Ca = Accelerated Compaction (m/yr)

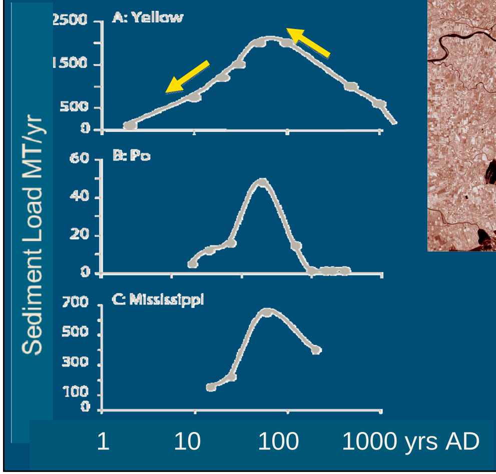
M = Crustal Vertical Movement (m/yr)

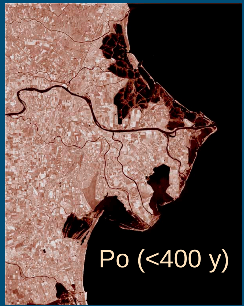
(Cn, Ca, M:) Difficult to isolate terms, derived from tide-gauges

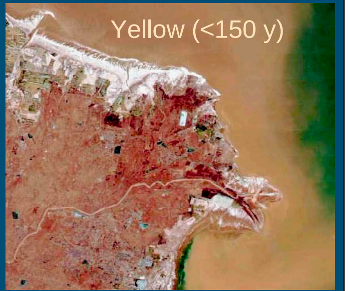
Presenter's Notes: Most terms in the equation have spatial variability; aggradation rate is higher in proximity to major distributaries; natural compaction is more rapid in clay/peat; accelerated compaction shows 'bulls-eyes' in zones where mining is most intense. Vertical movement can be localized due to fault distribution.

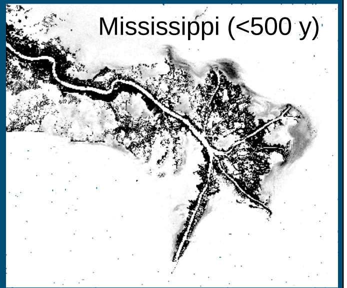
$$\Delta_{RSL} = A - \Delta E - C_n - C_A \pm M$$

Aggradation is the rate sediment is delivered to and retained on a delta as sediment deposits.



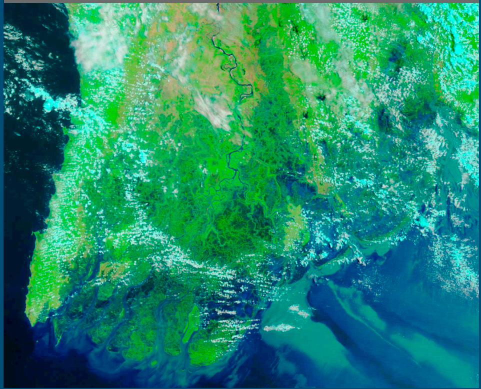




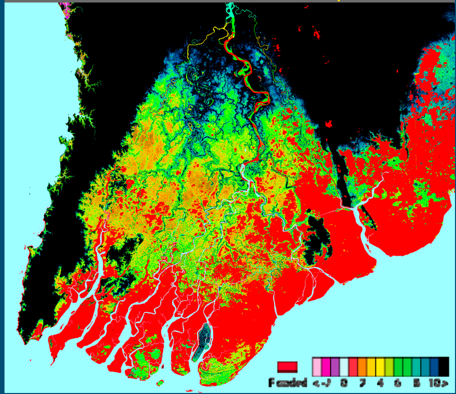


Deltas do flood regularly

Cyclone Nargis, Irrawaddy Delta
MODIS Terra, May 5th, 2008.



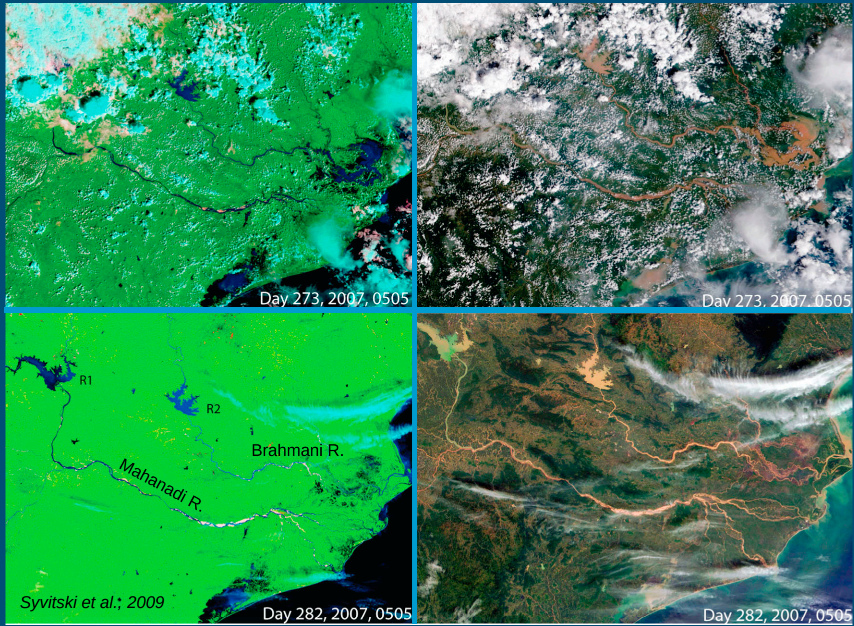
SRTM 90m topographic data overlay
with MODIS flood extend map in red.



Floods are widespread, 85% of the studied deltas experienced flooding.
From 2001-2008, in the 33 deltas ~260,000 km^2 was submerged by floods.

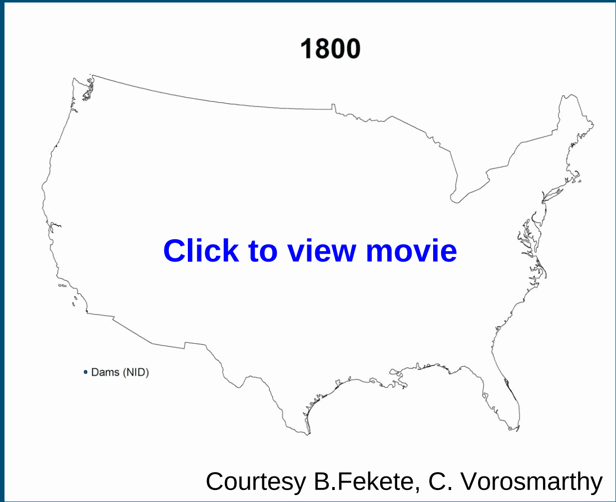
Presenter's Notes: Accuweather.com. Cyclone Nargis made landfall with sustained winds of 130 mph and gusts of 150-160 mph, which is the equivalent of a strong Category 3 or minimal Category 4 hurricane. This is a very large area.

<u>Aggradation</u> includes sedimentation between distributary channels from overbank flooding



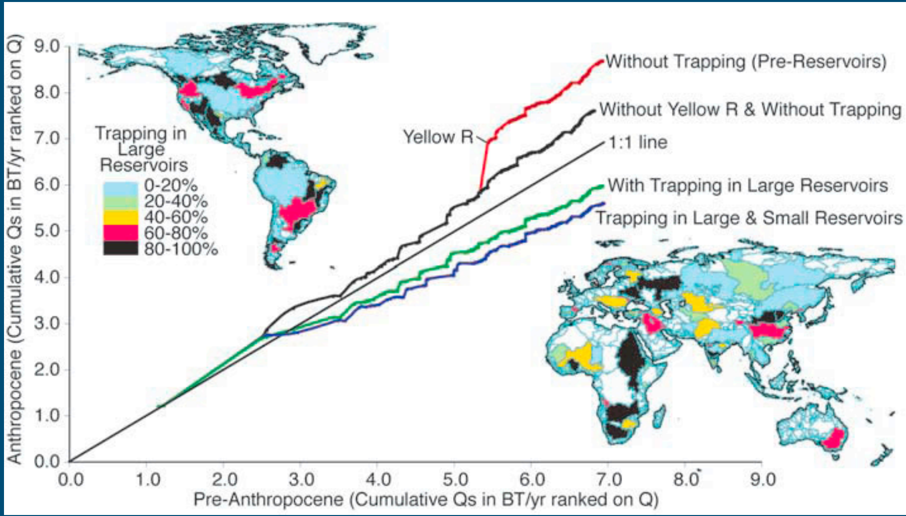
MODIS imagery of the Mahanadi and Brahmani Rivers, East India

Reduced Aggradation due to Damming



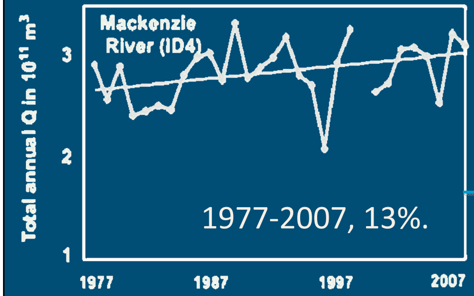
Reduction of sediment delivered to deltas due to damming, modeled with simple retention algorithms (in HydroTrend or WBM)

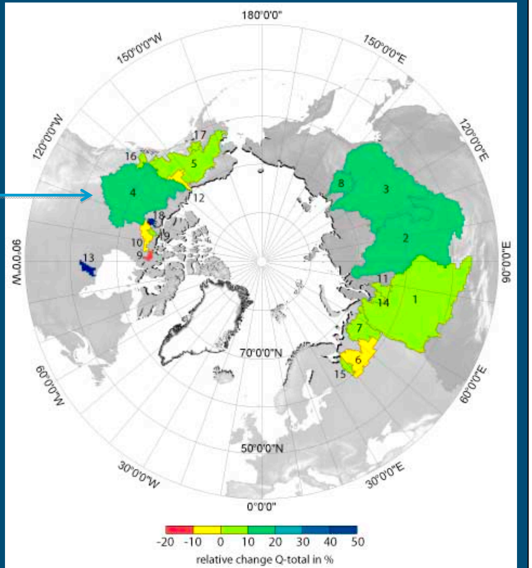
Reduced Aggradation due to Damming



Global simulation of BQRT model/WBM with reservoir trapping algorithms.
1.4 ± 0.3 billion tons per year LESS sediment reaches the coast worldwide.
0.4 billion tons per year LESS sediment reaches 33 studied major deltas.

Arctic Deltas: Increased Aggradation due to Higher Discharge?

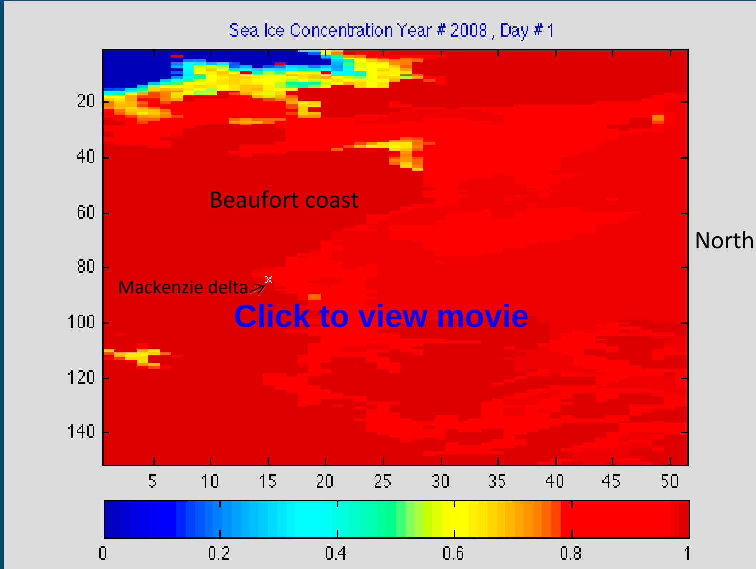




17 major Arctic rivers, on average 10% increasing water discharge over last 30 years (Overeem et al., 2010).

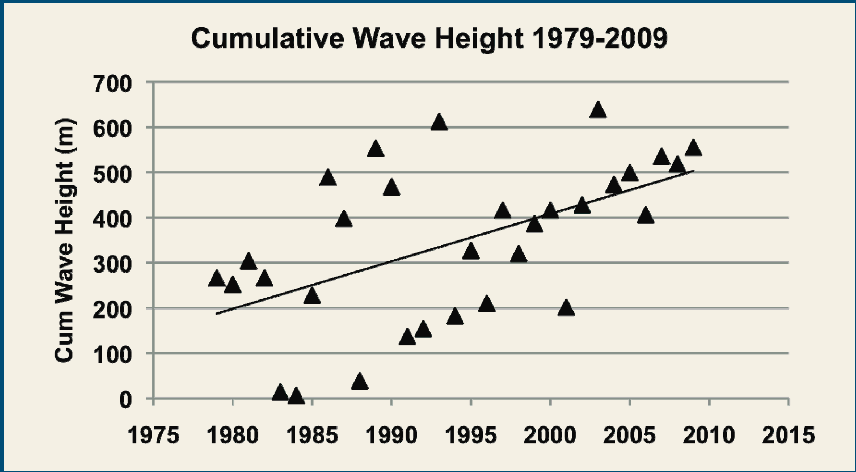
Presenter's Notes: 17 arctic rivers; most have positive trends…

Sea Ice Concentration 2008



Overeem, I et al., in review GRL 2011

Sea-Ice, Fetch and Wave Model; Beaufort Coast



Number of ‘open water days’ along the Beaufort coast increased from ~45-90 in 30 years.
Wave action over the season increased accordingly (Overeem et al., in revision, 2011).

Coastal Erosion

15m/year land-loss on permafrost coast

Controls on Delta Elevation

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Δ_{RSL}	=	Vertical change in delta surface elevation (m/yr)
A	=	Aggradation Rate (m/yr)
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Cn	=	Natural Compaction (m/yr)
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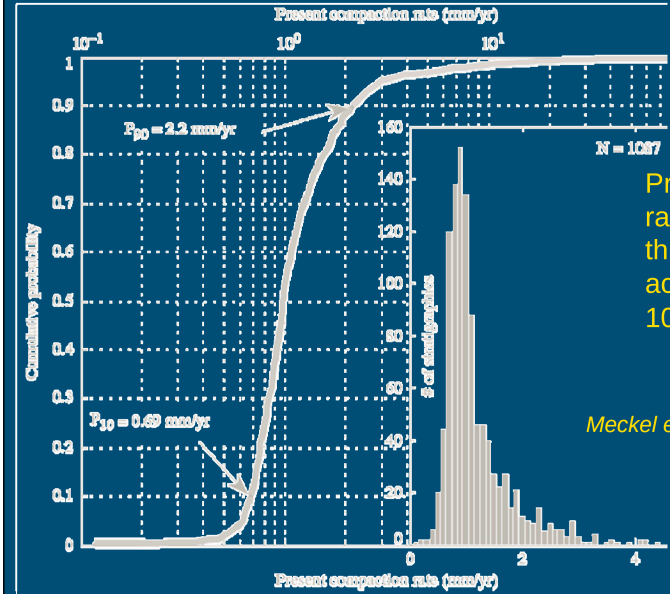
M	=	Crustal Vertical Movement (m/yr)

Difficult to isolate terms (Cn, Ca, M), derived from tide-gauges

Natural Compaction Rates changes in the void space within sedimentary layers (dewatering, grain-packing realignment, organic matter oxidation)

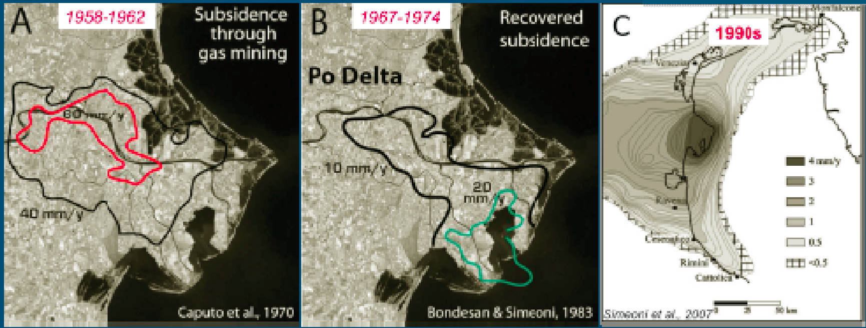
$$\Delta_{RSL} = \pm A - \Delta E - C_n - C_A \pm M$$



Present compaction rates for deposits with thickness of ≈100m and accumulation time of ≈ 10Ky.

Meckel et al., 2007

Accelerated Compaction due to Subsurface Mining



Example: Po delta has greatly been influenced by gas and groundwater mining, Subsidence rates as high as 80mm/yr were observed.
Natural compaction ranges between 1-5mm/yr.

70% of the 33 studied deltas experience at least minor groundwater and/or hydrocarbon mining ,inducing accelerated compaction.

Accelerated Compaction Rates

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

Examples

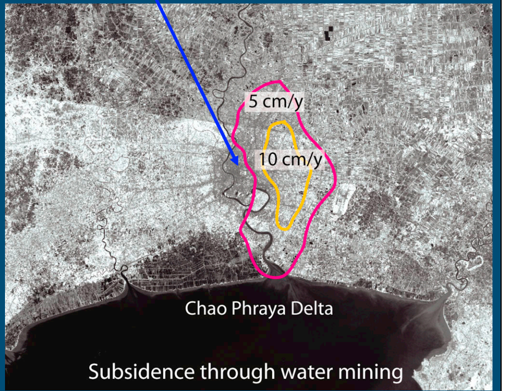
Yangtze: 28 mm/y before controls

Niger: 25 to 125 mm/y

Chao Phraya: 50 to 150 mm/y

Po: 60 mm/y before controls

Bangkok's population went from 1M to 12M in 35 years



Saito et al., 2008

Controls on Delta Elevation

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

Sea Level Rise

Δ_{RSL}	=	Vertical change in delta surface elevation (m/yr)
A	=	Aggradation Rate (m/yr)
ΔE	=	Eustatic Sea Level Rise (m/yr)
Cn	=	Natural Compaction (m/yr)
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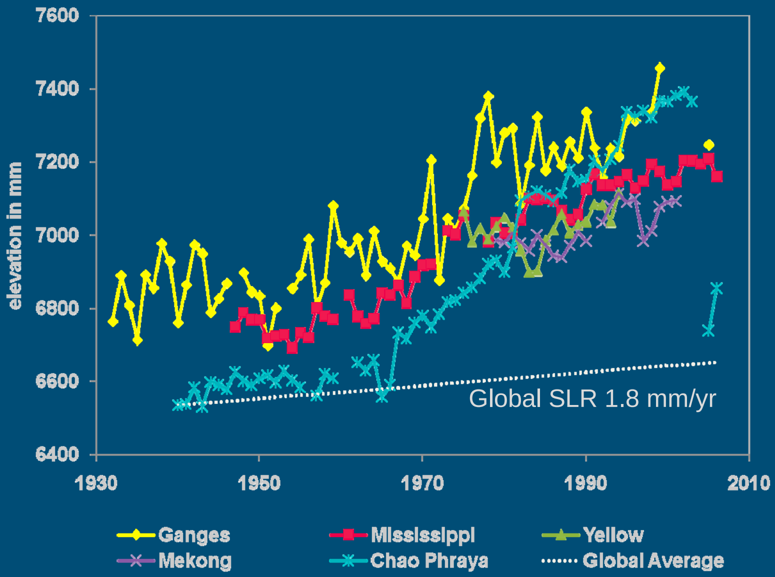
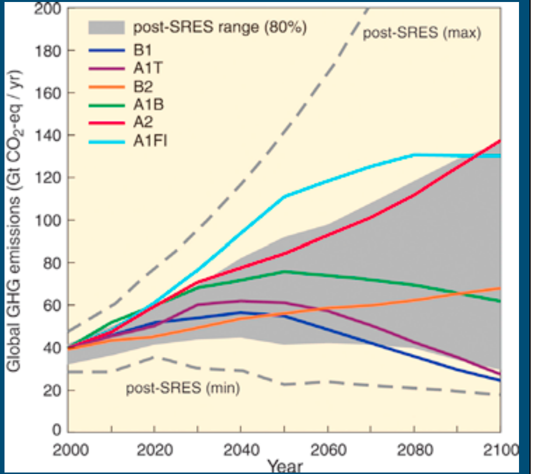
Relative Sea level Rise in Deltas



Relative sea level rose 4 times faster within deltas than globally.

Projected Eustatic Sea Level Rise

Climate Scenario	Temperature	Sea Level Rise in m
B1	1.8	0.18 - 0.38
A1T	2.4	0.20 - 0.45
B2	2.4	0.20 - 0.43
A1B	2.8	0.21 - 0.48
A2	3.4	0.23 - 0.51
A1F1	4.0	0.26 - 0.59



Projections of sea level rise range between 0.18-0.71m for 2090-2099.
Best estimate globally average 0.44m (IPCC, 2007).
This estimate does NOT include 'sinking' through reduced aggradation and compaction.

Presenter's Notes: IPCC list the scenarios of projected emissions and tabelizes the projected associated temperature changes and sea level rise for 2090-2099 as compared to 1980-1999 (IPCC 2007).

Longterm sea level and temperature

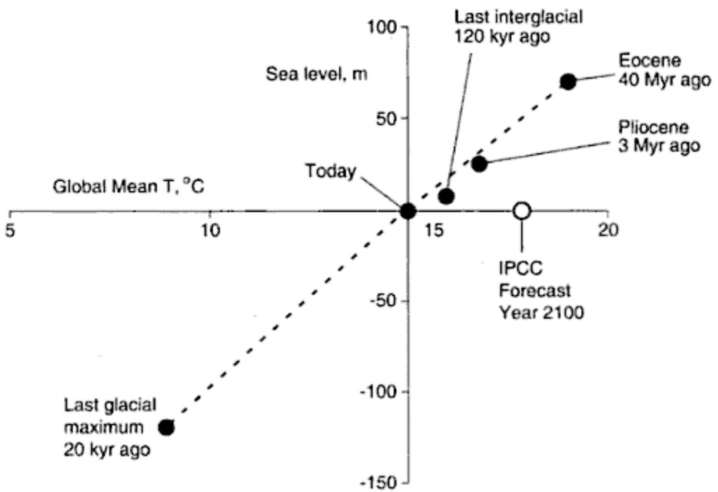
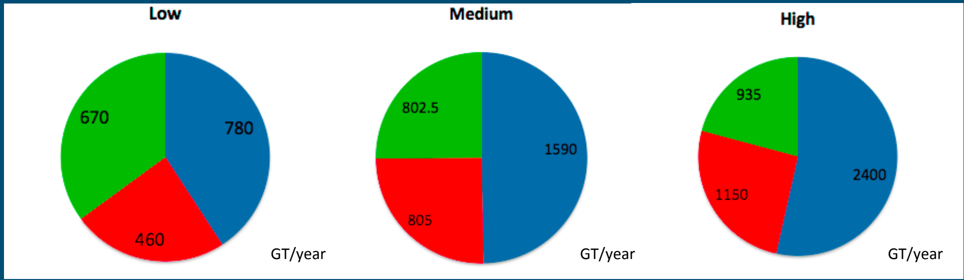


FIGURE 17. Covariation of sea level with global average temperature in the geologic past, compared with the IPCC forecast for sea level rise by the year 2100. (From David Archer, 2009)

Relative Rates of Contribution of Land Ice to Eustatic Sea Level Rise for 2025



Low estimate   Central estimate   High estimate

Greenland

Glacier/Ice Caps

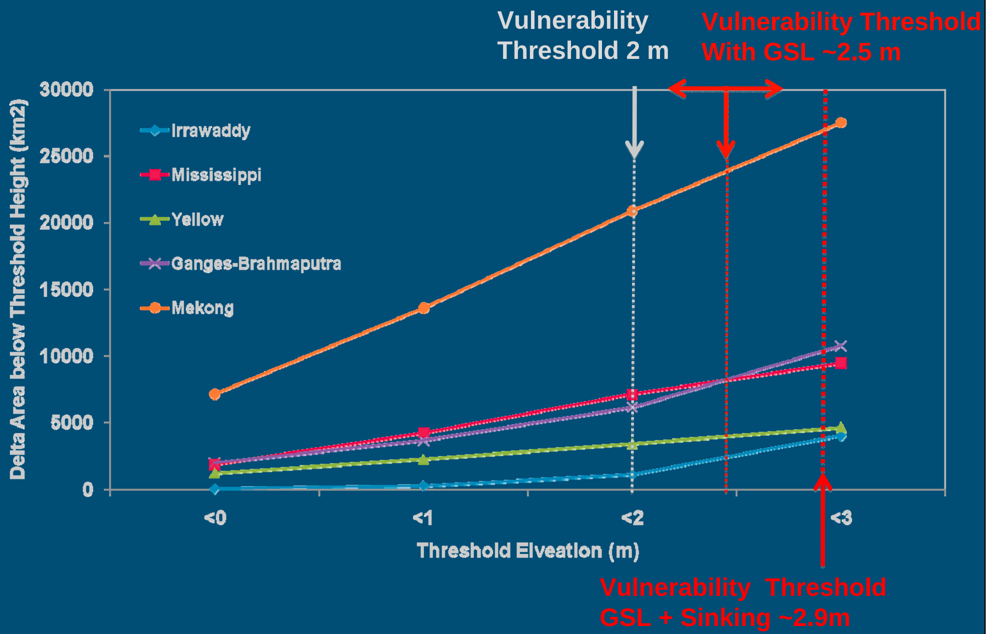
W. Antarctica

Net Eustatic SLR Rate Equivalents at 2025,
based on extrapolation of present-day melt rates:

Low estimate	5.2 mm/yr
Central estimate	8.8 mm/yr
High Estimate	12.4 mm/yr

Courtesy Tad Pfeffer, INSTAAR, University of Colorado, unpublished data.

Vulnerable Land in Deltas?



Coupled HydroTrend-Sedflux Model for Ganges-Brahmaputra delta

INPUT(t)

sea level(t), bathymetry (t-0)
Q, Qs, Qb (HydroTrend)

PROCESSES

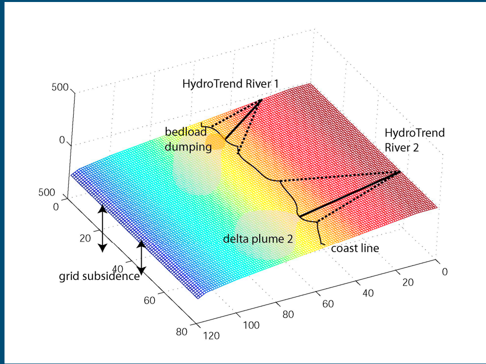
River: avulsion, floodplain SR
Marine: delta plume, storms
Basin: compaction, subsidence

OUTPUT (x,z,t)

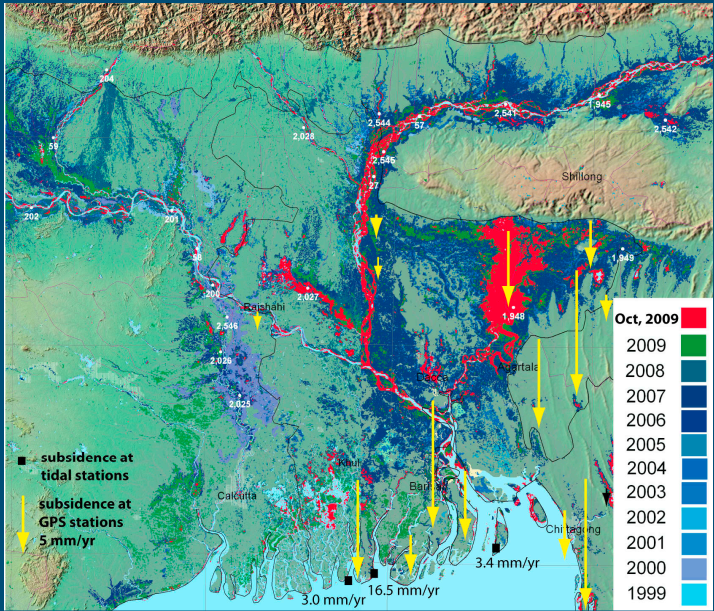
- 3D-geometry
- grain size, age

Details and Equations:
Three-dimensional modeling of deltas
Overeem et al., 2005. SEPM Spec Publ.

Hutton, Syvitski
(2007), Computers and Geosciences.

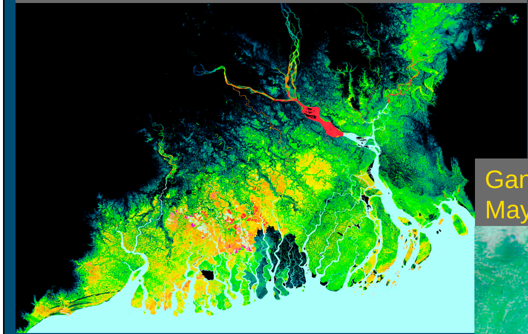


Ganges-Brahmaputra Delta: Subsidence and Sea level

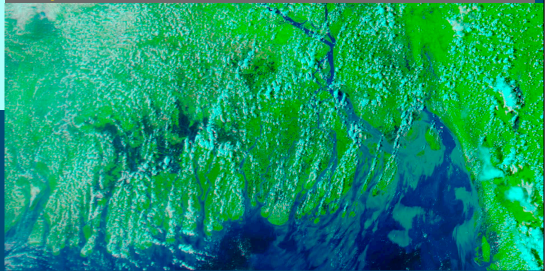


Coastal Flooding in Deltas

Ganges-Brahmaputra Delta, India & BD

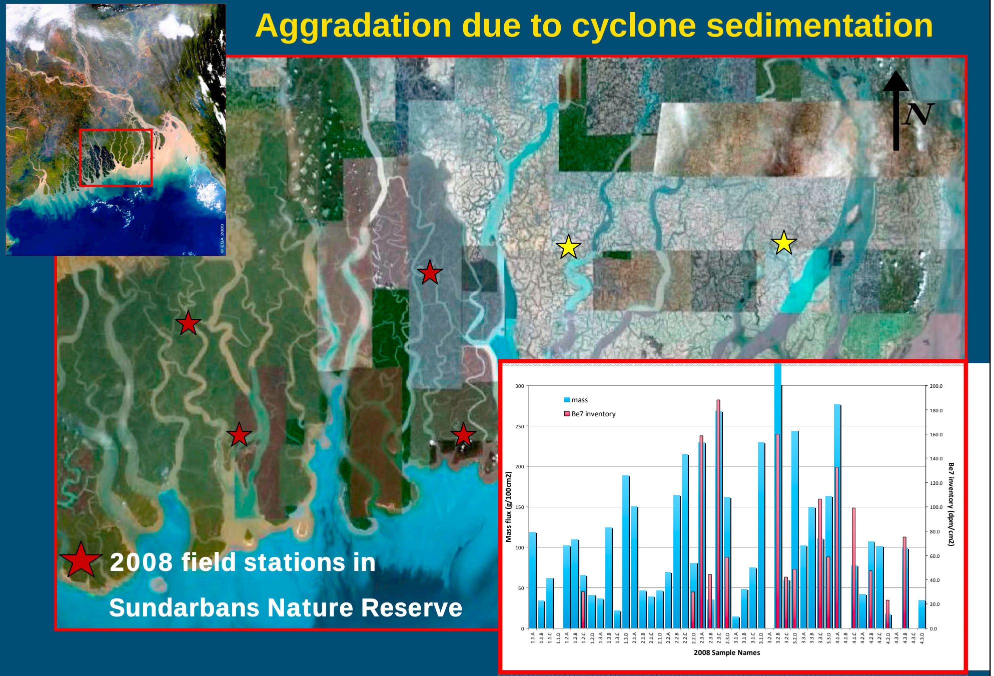


Ganges-Brahmaputra Delta, MODIS 250m, May 2009

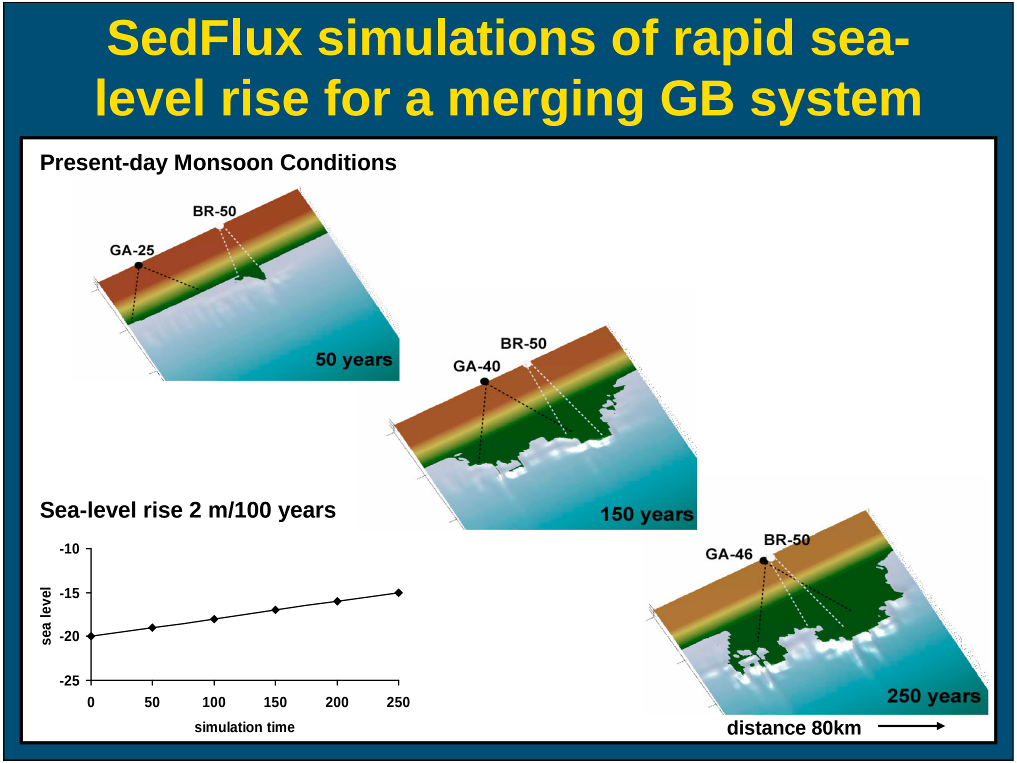


Cyclone Aila, May 2009 Bangladesh. Extensive flooding in Sundabans.
Ocean storm set-up was reported ~6-7 m!

Aggradation due to cyclone sedimentation



Average aggradation from sediment traps ~11mm over monsoonal cycle.
Courtesy K. Rogers,PhD thesis Vanderbilt University



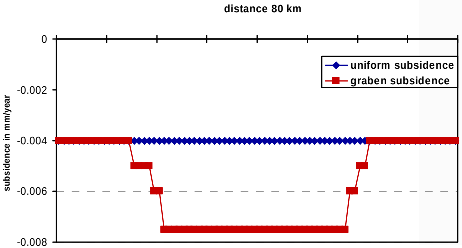
Presenter's Notes: The two river systems are simulated in one grid here. The Ganges migrates gradually eastward over the grid and merges over the last 100 years with the Brahmaputra that is more confined. The little dots indicate the approximate positions of the hinge point, the dotted lines show the zone wherein the respective rivermouths avulse over time. Even under present-day conditions the two river systems combined still show progadation in this coastal stretch of 80 km.

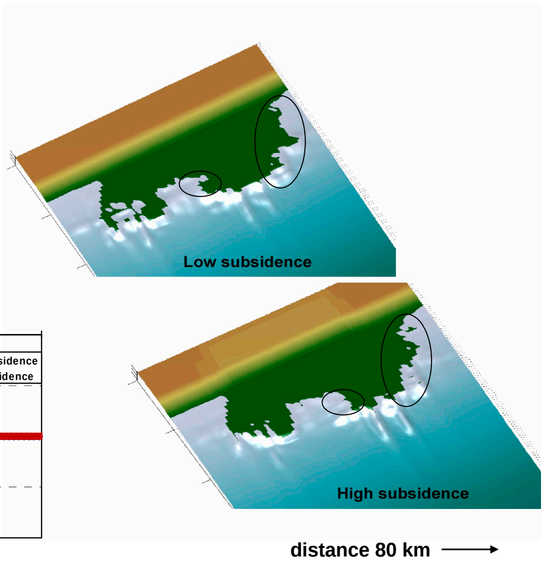
SedFlux simulations of rapid sea-level rise for a merging GB system

Present-day Monsoon Conditions
Different Subsidence Rates

'low subsidence'
4 mm/year uniformly over entire grid

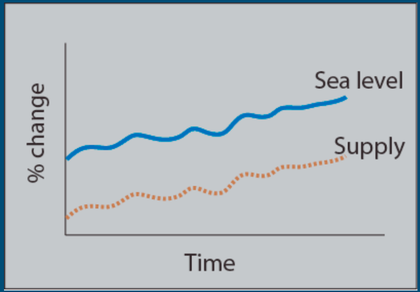
'high subsidence'
7.5 mm/year locally in 'graben'

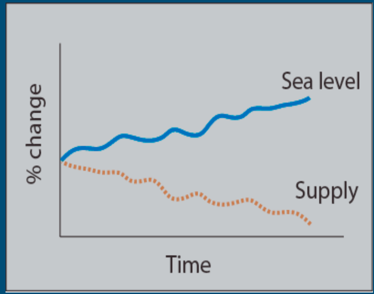




Presenter's Notes: System is definitely still dominated by its large flux of incoming sediment…

Concept: correlated controls





Implication: delta system is more resilient to rising sea-level, because it is able to build rapidly.

Worst-case scenario! Results in Sinking Deltas

Conclusions

- SRTM data reveals extent and location of delta areas near or below mean sea level. Thirty-three delta systems have > 100,000 km^2 below 2m a.s.l.

- MODIS imagery from 2001 onwards helps mapping of flooding (either from ocean storms or river floods). 75% of studied deltas experienced flooding in last decade; 260,000 km^2 was temporarily submerged.

- Deltas are sinking on average 4 times more rapidly than can be explained by eustatic sea level rise alone.

- We attribute rapid sinking to human interference in river basins and their deltas.

1. Sediment delivery to deltas has greatly been reduced. We model that 3500 billion tons less sediment reaches the deltas per year.
2. Engineering of channels inhibits delivery of sediments to delta floodplain.
3. Compaction due to mining is a major factor in 70% of studied systems.

Vulnerable low-lying lands are expanding rapidly. Threshold for ‘vulnerability’ is farther inland in hurricane / tropical storm-influenced deltas.

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Community Surface Dynamics Modeling System (CSDMS)

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