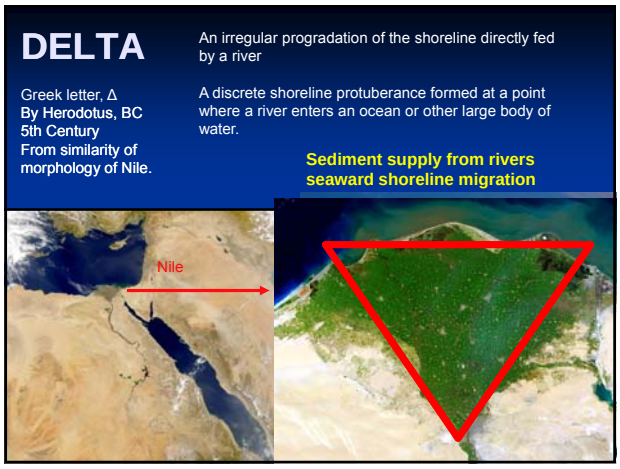
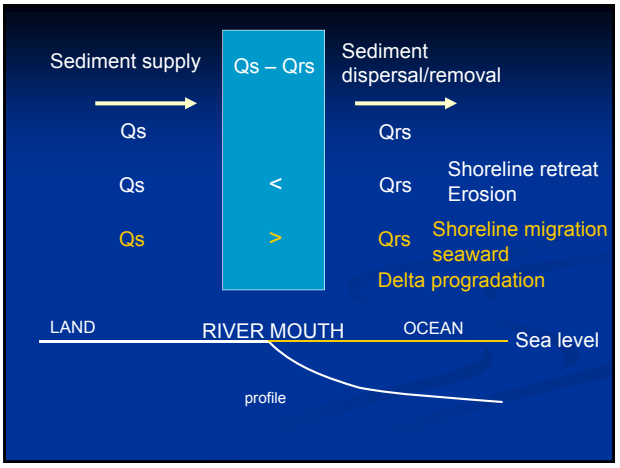
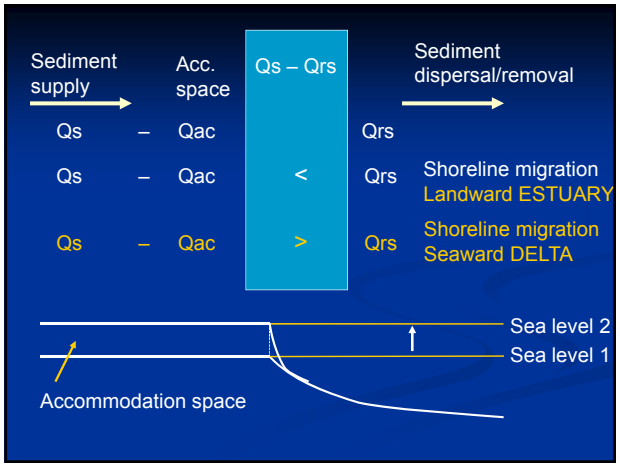
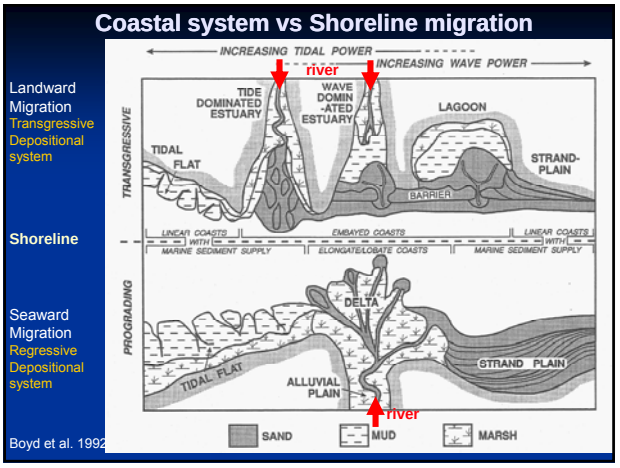
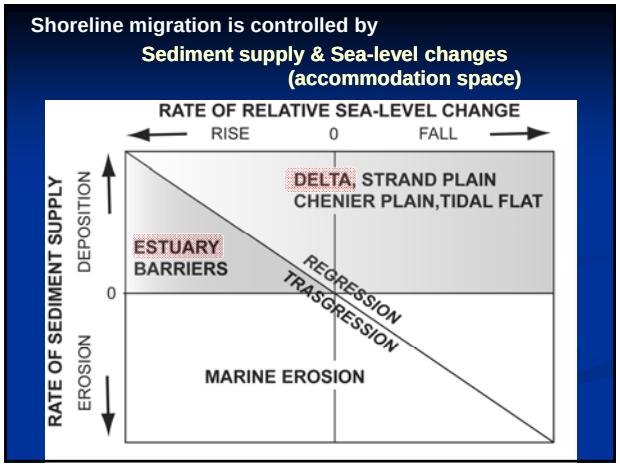

Collège de France, 11 June 2013
Climate change and sea level rise; Coastal vulnerability and societal impacts
Coastal Vulnerability of Asian Mega Deltas:
Natural Delta System versus Human-influenced Recent Changes
Delta initiation and recent changes in relation to sea-level rises
Special thanks to prof. Anny Cazenave, Collège de France, TOTAL
Yoshiki SAITO
Geological Survey of Japan, AIST


DELTA
An irregular progradation of the shoreline directly fed by a river
Greek letter, Δ
By Herodotus, BC 5th Century
From similarity of morphology of Nile.
A discrete shoreline protuberance formed at a point where a river enters an ocean or other large body of water.
Sediment supply from rivers
seaward shoreline migration
Nile


Sediment supply
Qs – Qrs
Sediment dispersal/removal
Qs
Qrs
Qs
<
Qrs
Shoreline retreat
Erosion
Qs
>
Qrs
Shoreline migration
seaward
Delta progradation
LAND
RIVER MOUTH
OCEAN
Sea level
profile

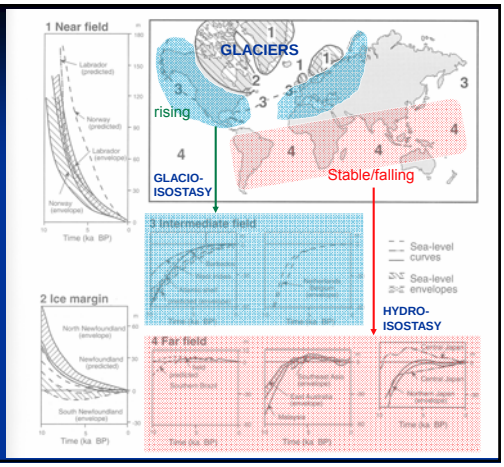

Sediment supply
Acc. space
Qs – Qrs
Sediment dispersal/removal
Qs – Qac
Qrs
Qs – Qac
<
Qrs
Shoreline migration
Landward ESTUARY
Qs – Qac
>
Qrs
Shoreline migration
Seaward DELTA
Sea level 2
Sea level 1
Accommodation space


Coastal system vs Shoreline migration
Landward Migration
Transgressive Depositional system
Shoreline
Seaward Migration
Regressive Depositional system
Boyd et al. 1992
INCREASING TIDAL POWER
INCREASING WAVE POWER
river
TIDE DOMINATED ESTUARY
WAVE DOMIN-ATED ESTUARY
LAGOON
TIDAL FLAT
STRAND-PLAIN
BARRIER
TRANSGRESSIVE
LINEAR COASTS WITH MARINE SEDIMENT SUPPLY
EMBAYED COASTS
ELONGATE/LOBATE COASTS
LINEAR COASTS WITH MARINE SEDIMENT SUPPLY
PROGRADING
DELTA
STRAND PLAIN
TIDAL FLAT
ALLUVIAL PLAIN
river
SAND
MUD
MARSH

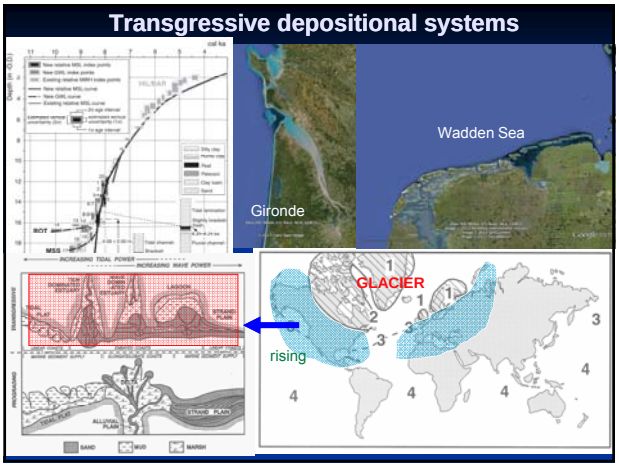

Shoreline migration is controlled by
Sediment supply & Sea-level changes
(accommodation space)
RATE OF RELATIVE SEA-LEVEL CHANGE
RISE
0
FALL
RATE OF SEDIMENT SUPPLY
DEPOSITION
EROSION
0
DELTA, STRAND PLAIN
CHENIER PLAIN,TIDAL FLAT
ESTUARY
BARRIERS
REGRESSION
TRASGRESSION
MARINE EROSION

Holocene Sea-level Changes are controlled by
1) Eustatic SLC
2) Glacio-
3) Hydro-isostasy,

4) Tectonics
Local factors

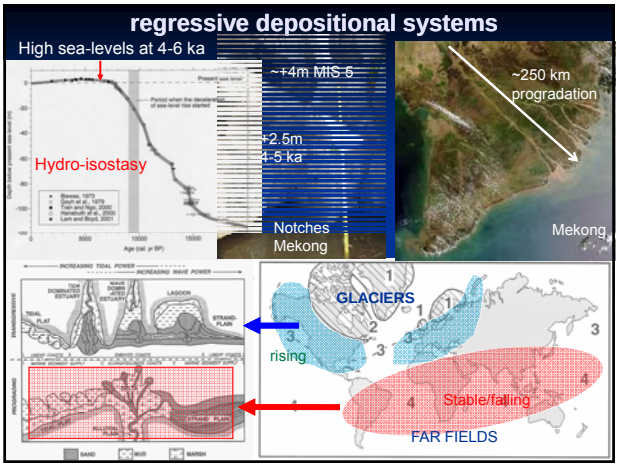


Transgressive depositional systems



regressive depositional systems

High sea-levels at 4-6 ka

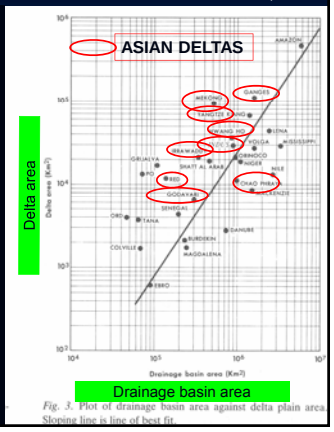


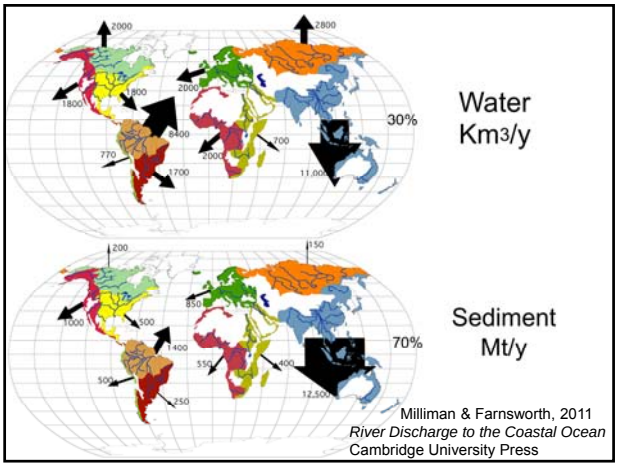
Wide deltaplain

Coleman & Roberts, 1989

Characteristics of deltas in Asia

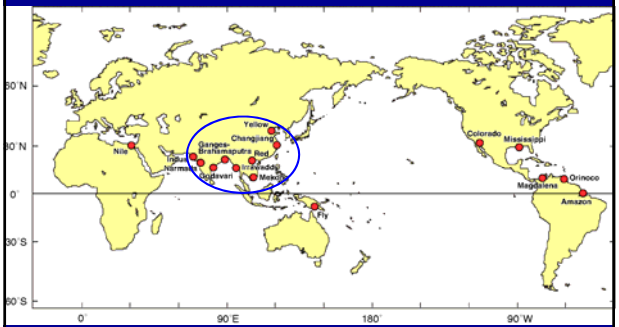
Stable/falling sea level
Sediment supply



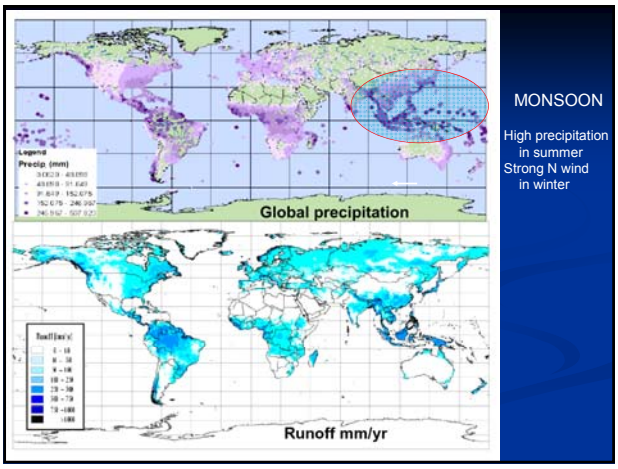


Milliman & Farnsworth, 2011
River Discharge to the Coastal Ocean
Cambridge University Press

LARGE RIVERS & DELTAS



Large rivers & deltas are located mostly in Asia.
Nine of top 16 largest rivers in sediment discharge are in Asia



Wide deltaplain

Coleman & Roberts, 1989

Asian deltas have a wide deltaplain, consisting of marine/deltaic sediments deposited during the last 6-8 ky

Delta progradation
Mekong: > 250 km
Yangtze (Changjiang): ~250 km
Yellow River (Huanghe): 150km
Red River (Song Hong): 100 km

Stable/falling sea level
Sediment supply

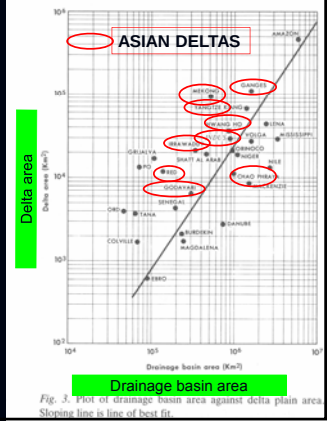


Fig. 3. Plot of drainage basin area against delta plain area. Sloping line is line of best fit.

POPULATION

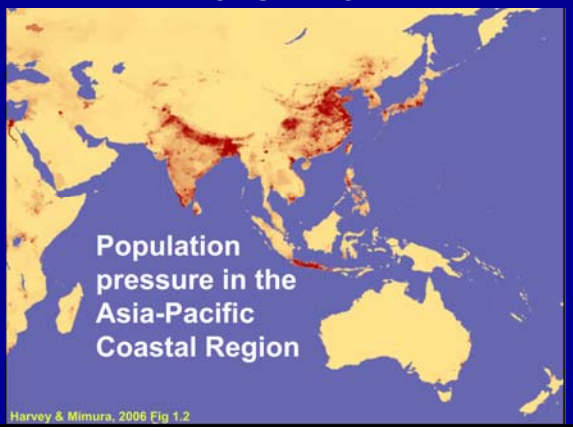


Table 10.3. Estimates of population within the Holocene deltaic plains of megadeltas, based upon GPW-3, 2.5 arc minute gridded population of the world (CIESIN) for 2000 and 2015

9 mega-deltas

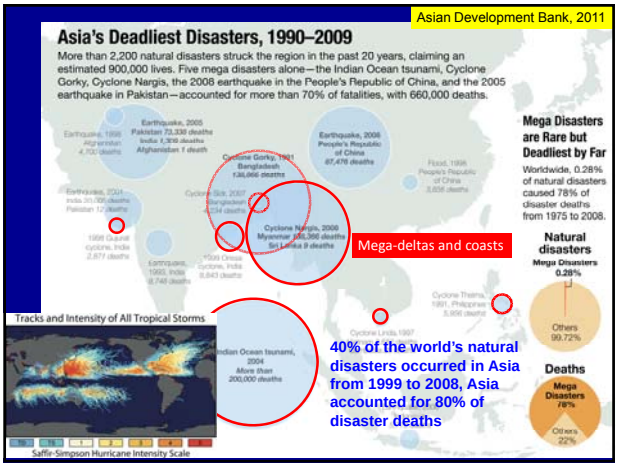
Megadelta	Area km^2	Population 2000	Population 2015	Increase (%)
Indus	19800	3058500	4425100	+45
GBM	115600	129931100	166217000	+28
Irrawaddy	31500	10591700	12163600	+15
Chao Phraya	11600	11485600	16487900	+44
Mekong	37900	15754200	19039800	+21
Song Hong (Red)	9900	13293900	16063400	+21
Pearl	5900	9846400	27166900	+176
Changjiang	15600	25945700	33147500	+28
Huanghe	25100	14060400	16614100	+18
[Jiangsu]	30300	19930700	14978400	−25

Note: Area of delta plain has been determined from gridded population cell count, and is only approximate as it does not take into account areas that are covered by water, including major distributaries.

Total population: 254 M (Delta globally: 500 M) 326 M

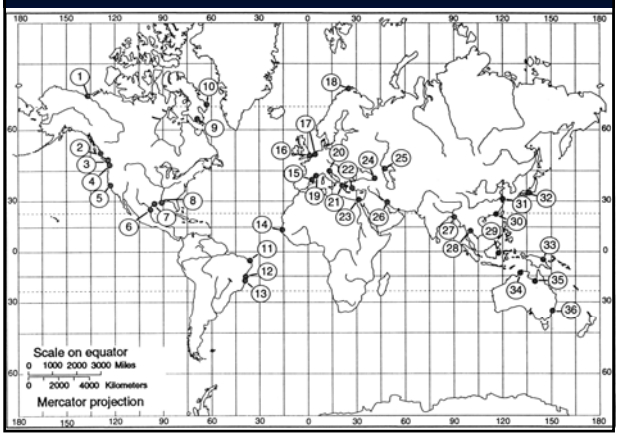
Population density: 834 1076 pop/km2

Delta world-average: 500 pop/km2 in 2002 (Ericson et al., 2006)
Global average: 50 pop/km2 in 2002 (Ericson et al., 2006)



Holocene deltas & their initiation

Stanley & Warne (1994) 36 deltas Science



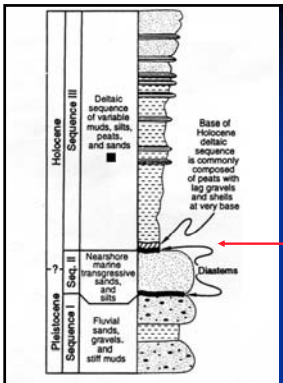


Fig. 1. Simplified lithostratigraphic section showing the threefold late Pleistocene to Holocene succession. We focused on the age of the readily identifiable base of sequence III, usually comprising near mean sea-level facies.

Stanley & Warne (1994)

Deltaic sediment

Basal peat and lags

Transgressive sediment

Pleistocene fluvial sediment

Stanley & Warne (1994)

C-14 age

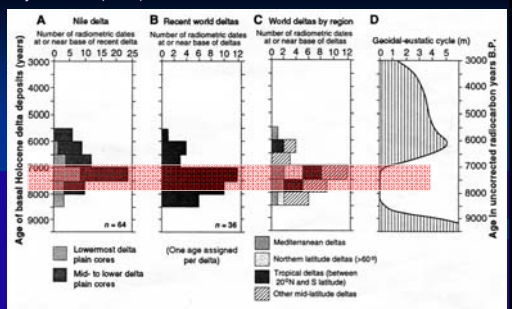
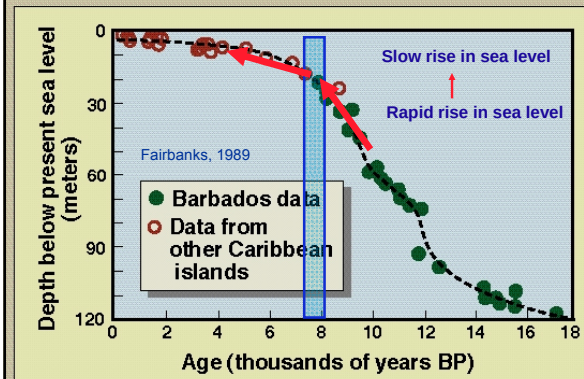


Fig. 3. Summary of age data from the 36 Holocene deltas. (**A**) Age distribution of basal Nile delta deposits, differentiating dates from 19 samples collected in lowermost delta plain cores from 45 samples collected in landward, mid- to lower delta plain cores. (**B**) Age distribution of oldest dated basal Holocene sections from the 36 deltas considered in this study (Table 1); delta positions are shown in Fig. 2. (**C**) Age distribution of basal Holocene sections from the 36 deltas, depicted by geographic position. (**D**) Geoidal-eustatic cycle, as related to core-mantle changes [modified after (*21*)], showing a marked change during the 8000 to 7000 year B.P. period, which closely corresponds with initiation of most world deltas examined in this report. Curve converted from sidereal to radiocarbon years B.P. [compare with (*21*)].

Sea Level Changes During Last Deglaciation



Punctuated eustatic sea-level rise in the early mid-Holocene

Michael I. Bird[1,*], William E.N. Austin[2], Christopher M. Wurster[1], L. Keith Fifield[3], Maryam Mojtahid[1], and Chris Sargeant[3]

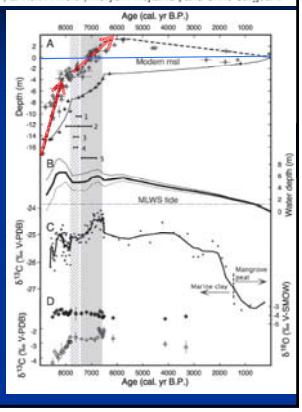
Geology, 2010

Bird et al., 2007, 2010

Singapore Mangrove peat on basement

7.0-7.5 ka: sea-level rise of ~4 m

9–8 ka: rapid sea-level rise of >>10 m



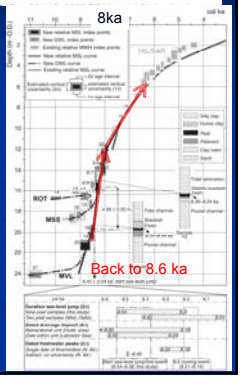
Timing and magnitude of the sea-level jump preluding the 8200 yr event

Geology, 2010

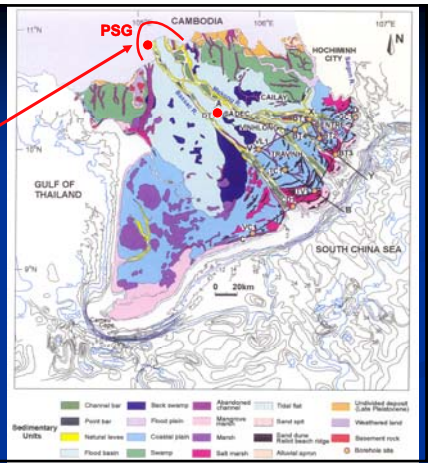
Marc P. Hijma[1,2*] and Kim M. Cohen[1,2]

ABSTRACT

Evidence from terrestrial, glacial, and global climate model reconstructions suggests that a sea-level jump caused by meltwater release was associated with the triggering of the 8.2 ka cooling event. However, there has been no direct measurement of this jump using precise sea-level data. In addition, the chronology of the meltwater pulse is based on marine data with limited dating accuracy. The most plausible mechanism for triggering the cooling event is the sudden, possibly multistaged drainage of the Laurentide proglacial Lakes Agassiz and Ojibway through the Hudson Strait into the North Atlantic ca. 8470 ± 300 yr ago. Here we show with detailed sea-level data from Rotterdam, Netherlands, that the sea-level rise commenced 8450 ± 44 yr ago. Our timing considerably narrows the existing age of this drainage event and provides support for the hypothesis of a double-staged lake drainage. The jump in sea level reached a local magnitude of 2.11 ± 0.89 m within 200 yr, in addition to the ongoing background relative sea-level rise (1.95 ± 0.74 m). This magnitude, observed at considerable distance from the release site, points to a global-averaged eustatic sea-level jump that is double the size of previous estimates (3.0 ± 1.2 m versus 0.4–1.4 m). The discrepancy suggests either a coeval Antarctic contribution or, more likely, a previous underestimate of the total American lake drainage.



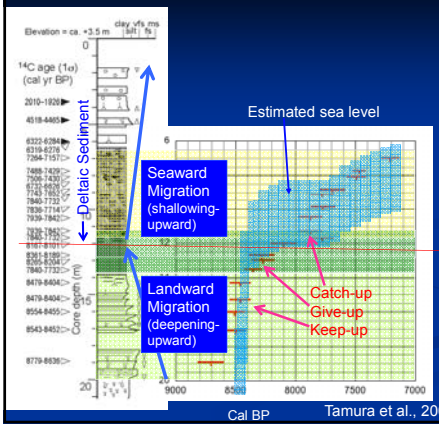
MEKONG DELTA TOPOGRAPHY & BATHYMETRY



The shoreline was in Cambodia during the Mx transgression, early-middle Holocene

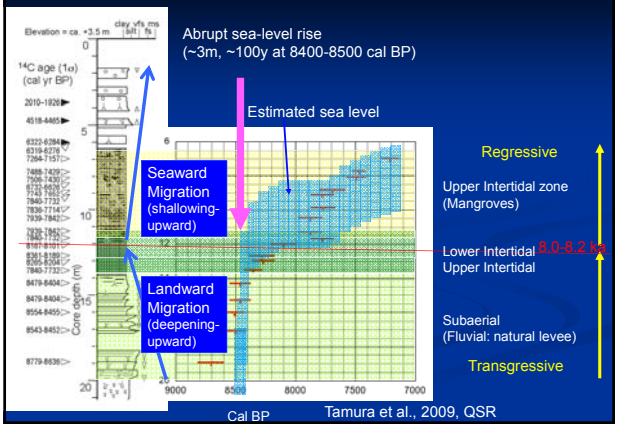
Morphological map
Nguyen et al., 2000
After Ta et al., 2002

Mekong delta core from Cambodia: 3 drilled cores

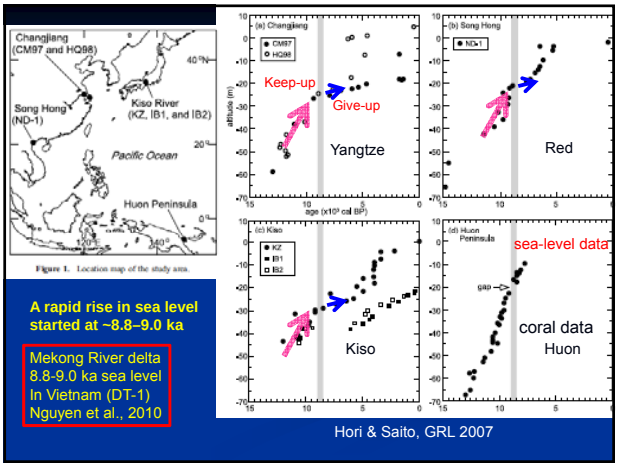


Tamura et al., 2009, QSR

Mekong delta core from Cambodia



Tamura et al., 2009, QSR



A rapid rise in sea level started at ~8.8–9.0 ka

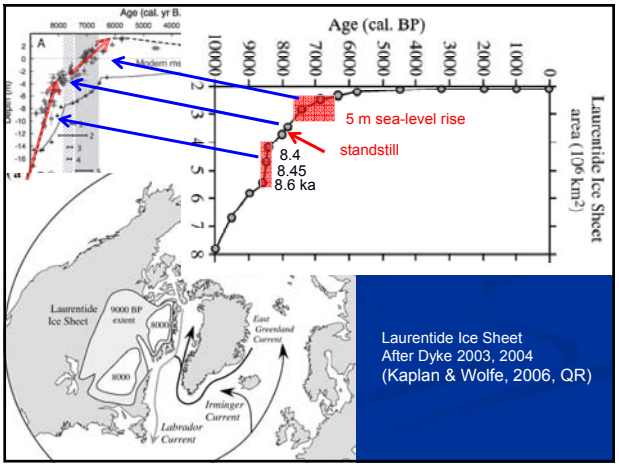
Mekong River delta
8.8-9.0 ka sea level
In Vietnam (DT-1)
Nguyen et al., 2010

Hori & Saito, GRL 2007

9.0(8.8) to 8.2 ka:
a rapid sea-level rise
with a maximum rate of 2–3m/100y at around 8.5 ka
total 12–16 m SL rise (8.8–8.2 ka)

Relative sea level rise from 8.8 ka in Vietnam to 8.2 ka in Cambodia is ~20m.
Tamura et al. (2009) QSR, Nguyen et al. (2010) Sed Geol, Li et al., (2012) QR

Followed by delta progradation
(MFS & Delta initiation: 8.0-8.2 ka)
Makong River, Red River and Yangtze River deltas

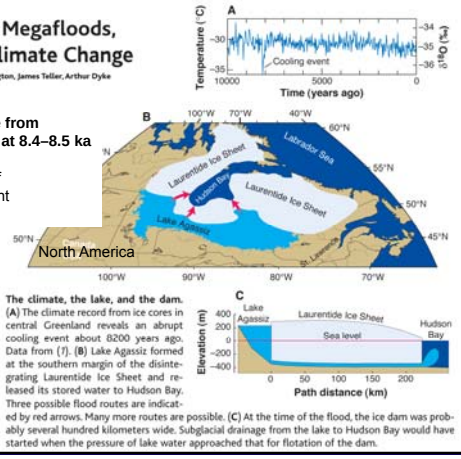


Laurentide Ice Sheet
After Dyke 2003, 2004
(Kaplan & Wolfe, 2006, QR)

Superlakes, Megafloods, and Abrupt Climate Change

Garry Clarke, David Leverington, James Teller, Arthur Dyke

Meltwater release from the Lake Agassiz at 8.4–8.5 ka ~40 cm SLR
As a key trigger of 8.2 ka cooling event



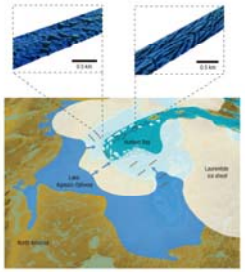
The climate, the lake, and the dam. (A) The climate record from ice cores in central Greenland reveals an abrupt cooling event about 8200 years ago. Data from (7). (B) Lake Agassiz formed at the southern margin of the disintegrating Laurentide Ice Sheet and released its stored water to Hudson Bay. Three possible flood routes are indicated by red arrows. Many more routes are possible. (C) At the time of the flood, the ice dam was probably several hundred kilometers wide. Subglacial drainage from the lake to Hudson Bay would have started when the pressure of lake water approached that for flotation of the dam.

Clark et al., Science, 2003

The last stampede of a glacial lake

Lakes dammed by ice will commonly spill in catastrophic outbursts. Lake Agassiz-Ojibway, at the margin of the Laurentide ice sheet, burst 8,470 years ago in a subglacial flood whose marks have been scratched into the seafloor of Hudson Bay.

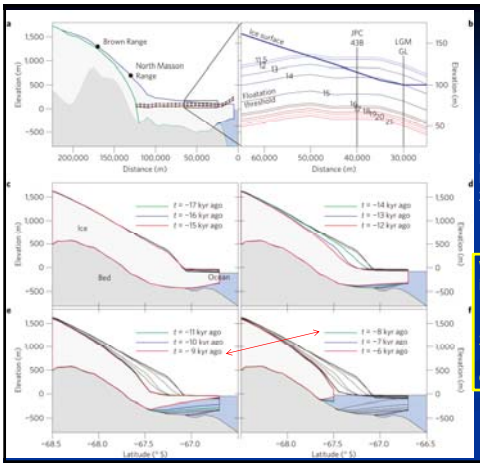
Martin Jakobsson



Meltwater & Iceberg Formation from LIS at ~8.5 ka

Jakobsson, 2008 Nature-geoscience

Iceberg formation is an important process to explain a rapid rise in sea level, in addition to normal melting process.

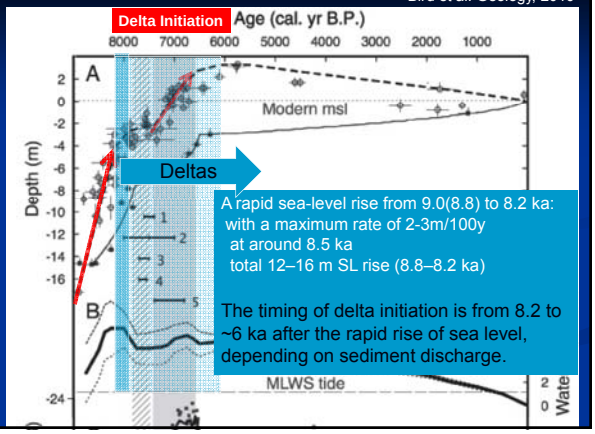


East Antarctic ice sheet

Mackintosh et al. Nature Geoscience 2012

We need more information on
1) the sources of meltwater
2) sea-level changes during 8.8-8.2ka

Bird et al. Geology, 2010



A rapid sea-level rise from 9.0(8.8) to 8.2 ka: with a maximum rate of 2-3m/100y at around 8.5 ka
total 12–16 m SL rise (8.8–8.2 ka)

The timing of delta initiation is from 8.2 to ~6 ka after the rapid rise of sea level, depending on sediment discharge.

Recent changes: delta collapse

Reduction of sediment discharge

Relative sea-level rise

Sediment discharge in Mt/y

	1950–1960	~2000–
Yellow	1300	148
Yangtze	480	146
Pearl	80	38
Red	130	52
Mekong	160	160
ChaoPhraya	25	2
Irrawaddy	260	260
G-B	1100	1100
Godavari	170	57
Indus	250	13
Total	3955	1976

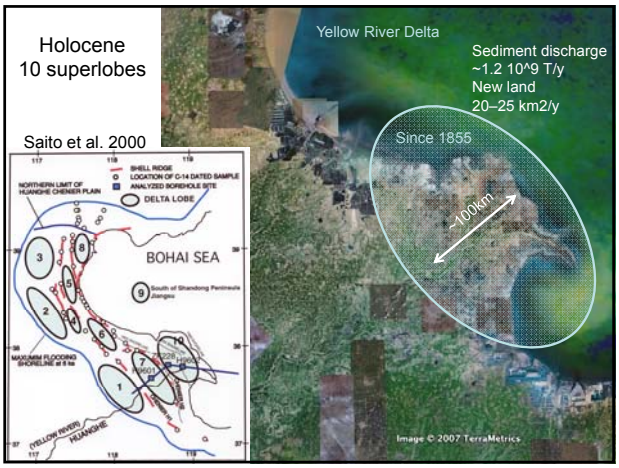
50%

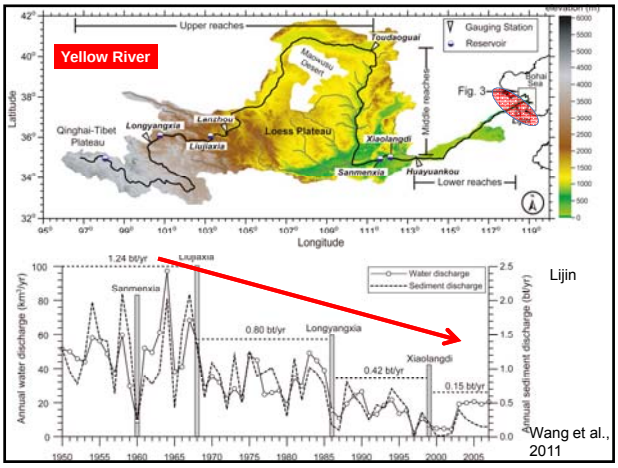
20%

Impacts of sediment reduction on delta

Yellow River (Huanghe) delta

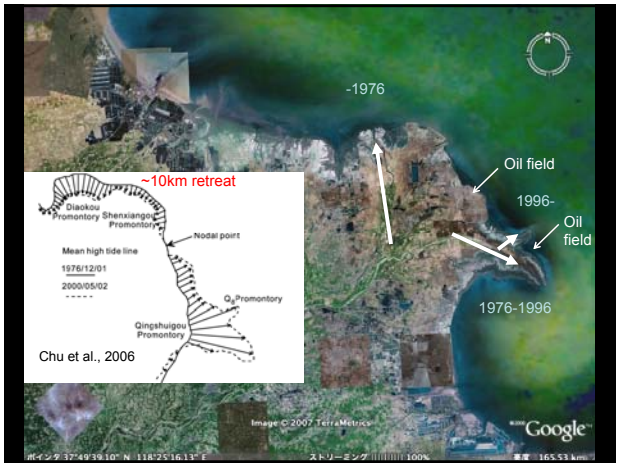
Yangtze River (Changjiang) delta

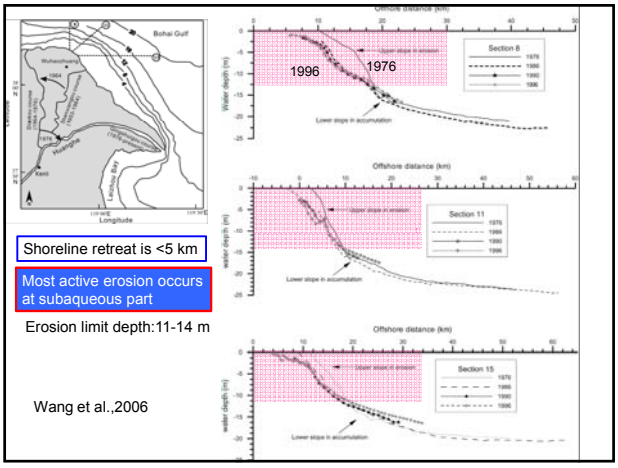




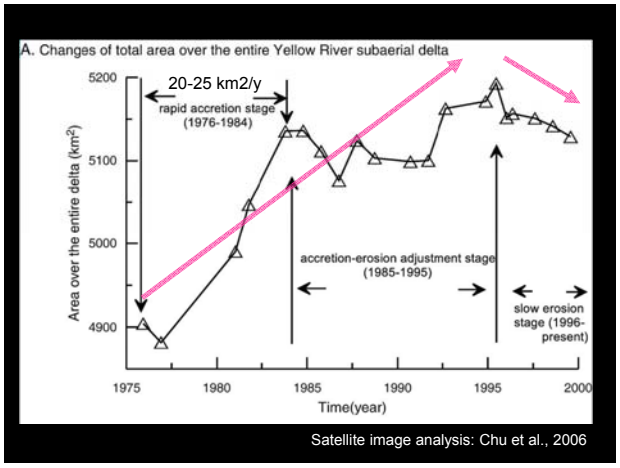
Lijin

Wang et al., 2011

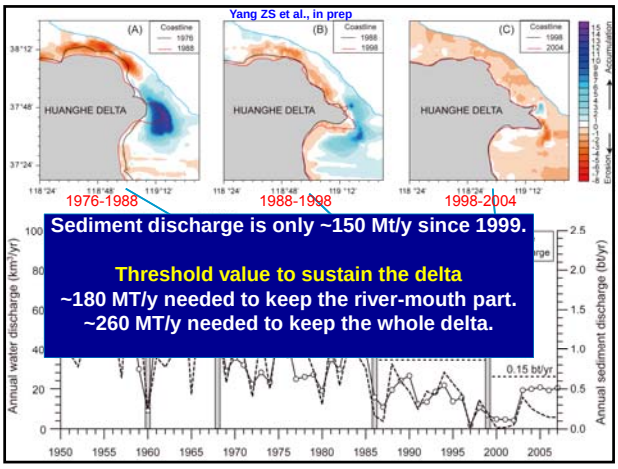


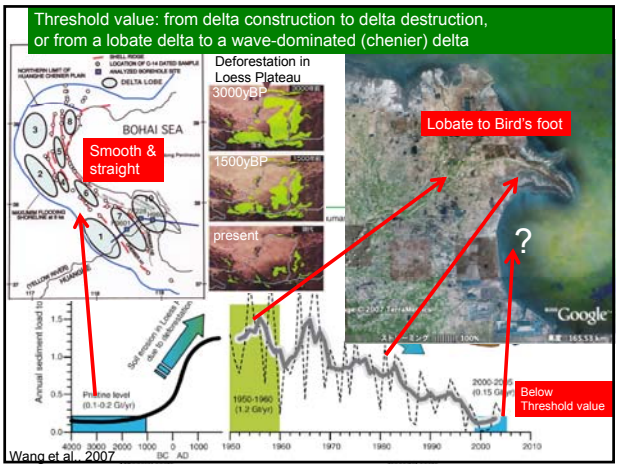


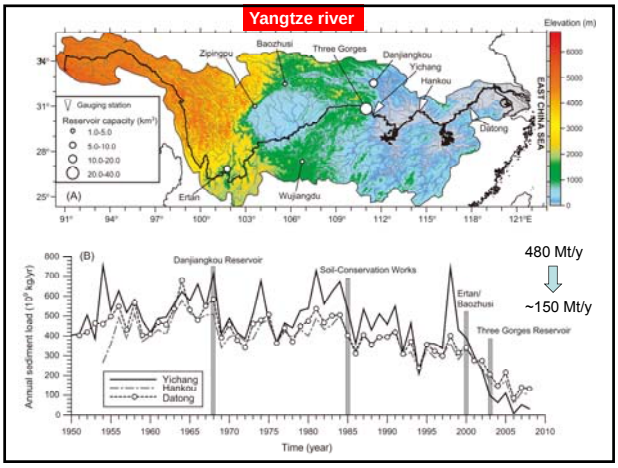
Wang et al.,2006

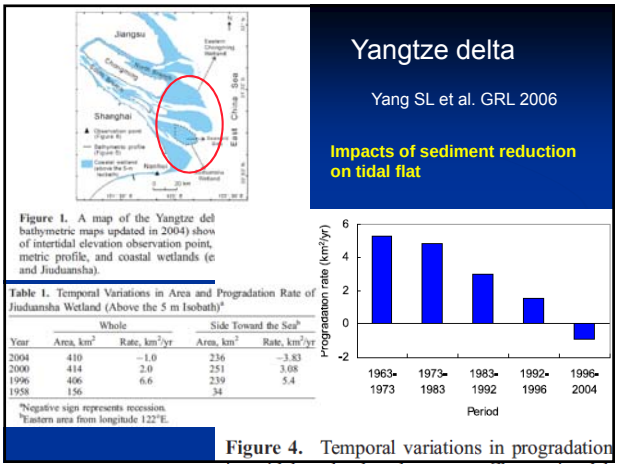


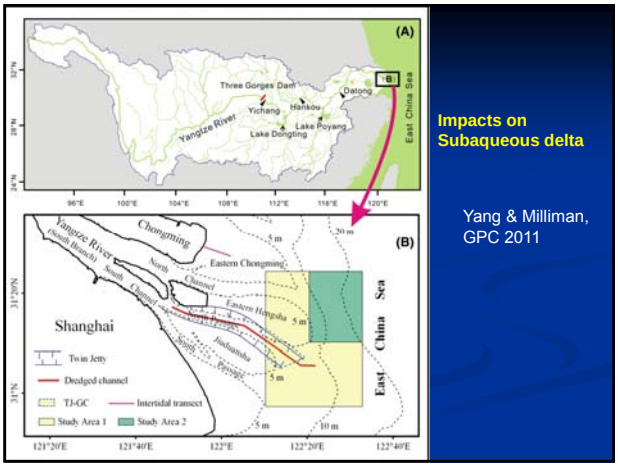
Satellite image analysis: Chu et al., 2006

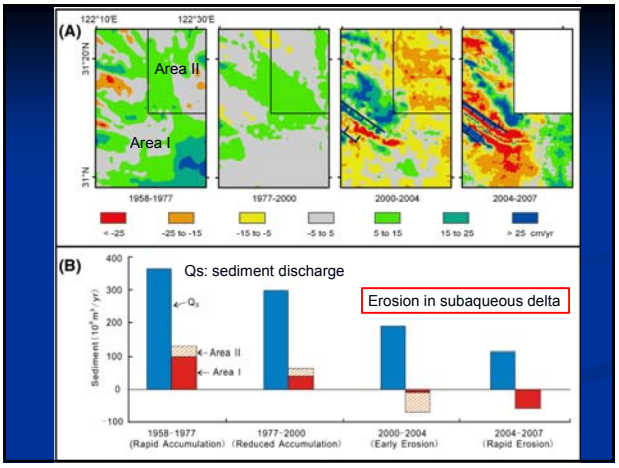

Yang ZS et al., in prep
HUANGHE DELTA
1976-1988
1988-1998
1998-2004
Sediment discharge is only ~150 Mt/y since 1999.
Threshold value to sustain the delta
~180 MT/y needed to keep the river-mouth part.
~260 MT/y needed to keep the whole delta.
Annual water discharge (km³/yr)
Annual sediment discharge (bt/yr)
0.15 bt/yr

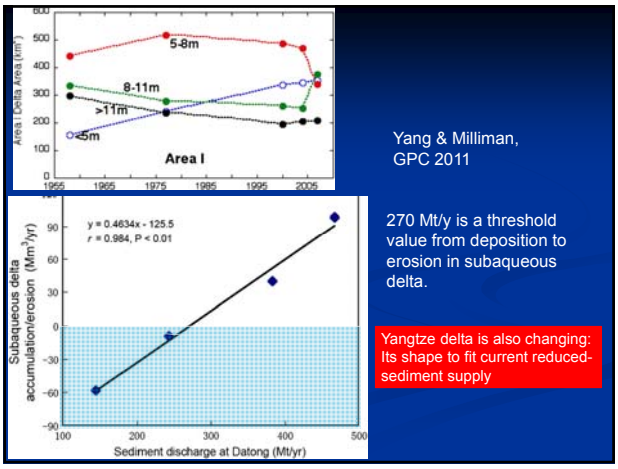

Threshold value: from delta construction to delta destruction,
or from a lobate delta to a wave-dominated (chenier) delta
Deforestation in Loess Plateau
3000yBP
1500yBP
present
BOHAI SEA
Smooth & straight
Lobate to Bird's foot
?
Below Threshold value
Wang et al., 2007


Yangtze river
Elevation (m)
Gauging station
Reservoir capacity (km³)
Danjiangkou Reservoir
Soil-Conservation Works
Three Gorges Reservoir
480 Mt/y
~150 Mt/y
Yichang
Hankou
Datong
Time (year)


Yangtze delta
Yang SL et al. GRL 2006
Impacts of sediment reduction on tidal flat
Figure 1. A map of the Yangtze del bathymetric maps updated in 2004) show of intertidal elevation observation point, metric profile, and coastal wetlands (e and Jiuduansha).
Table 1. Temporal Variations in Area and Progradation Rate of Jiuduansha Wetland (Above the 5 m Isobath)
Progradation rate (km²/yr)
Period
Figure 4. Temporal variations in progradation


Impacts on Subaqueous delta
Yang & Milliman, GPC 2011
Three Gorges Dam
Yangtze River
Lake Dongting
Lake Poyang
East China Sea
Shanghai
Chongming
Eastern Chongming
Twin Jetty
Dredged channel
TJ-GC
Intertidal transect
Study Area 1
Study Area 2

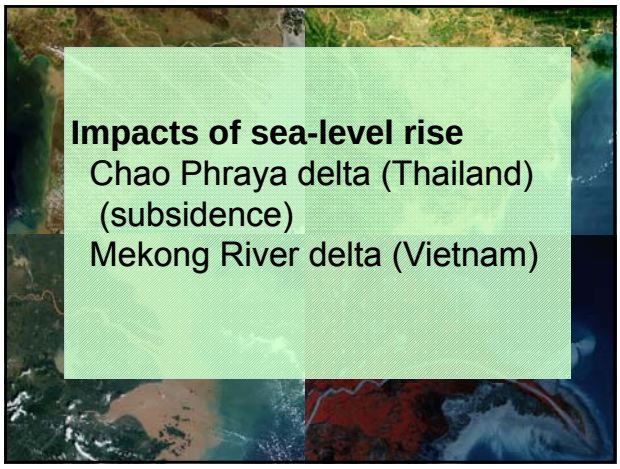

Area II
Area I
1958-1977
1977-2000
2000-2004
2004-2007
Qs: sediment discharge
Erosion in subaqueous delta
Sediment (10⁶ m³/yr)
1958-1977 (Rapid Accumulation)
1977-2000 (Reduced Accumulation)
2000-2004 (Early Erosion)
2004-2007 (Rapid Erosion)



Yang & Milliman, GPC 2011

270 Mt/y is a threshold value from deposition to erosion in subaqueous delta.

Yangtze delta is also changing: Its shape to fit current reduced-sediment supply

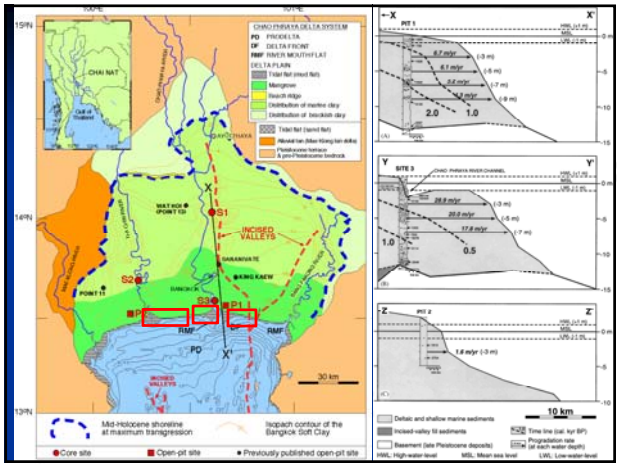


Impacts of sea-level rise

Chao Phraya delta (Thailand) (subsidence)

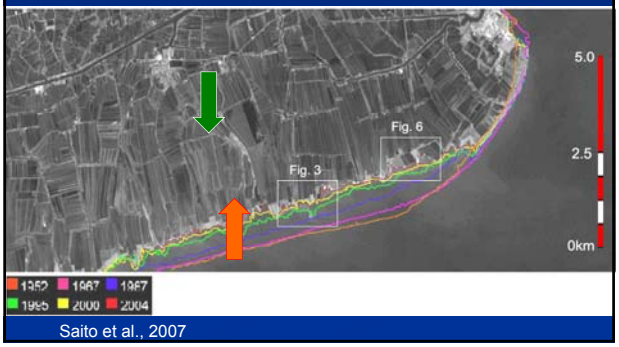
Mekong River delta (Vietnam)

Marine Inundation: Impact of sea level rise Chao Phraya delta



Upper Gulf of Thailand

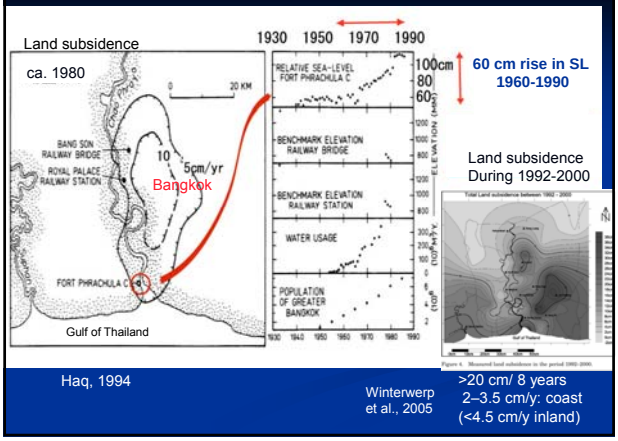
Delta progradation with a rate of 20 m/y for the last 6 ky
1 km shoreline retreat for the last 50 years (20 m/y)



Saito et al., 2007

Zigzag shoreline by coastal erosion

Relative sea-level rise due to subsidence



Haq, 1994

Winterwerp et al., 2005

>20 cm/ 8 years
2–3.5 cm/y: coast
(<4.5 cm/y inland)

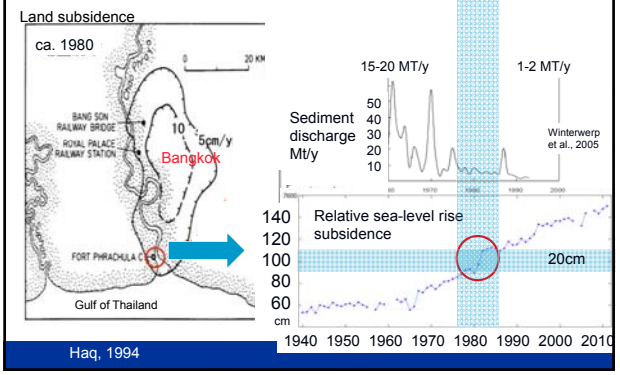
Upper Gulf of Thailand: by Thanawat

During 1969–1976, accretion: 8.9 km^2, erosion: 4.5 km^2 net accretion rate: 0.62 km^2/y;
During 1976–1987, accretion 4.9 km^2, erosion 10.3 km^2, net accretion rate: –0.49 km^2/y
During 1987–1997, accretion 7.4 km^2 , erosion 4.5 km^2, net accretion rate 0.25 km^2/y

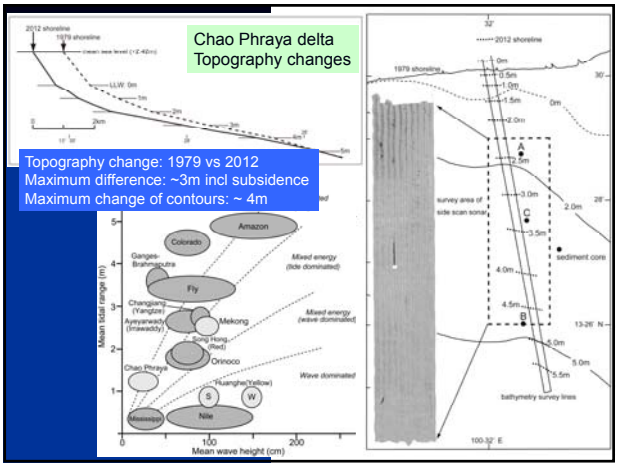
1 km shoreline retreat

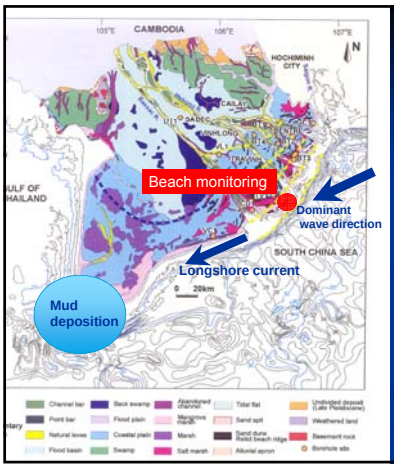
Saito et al., 2007

Coastal erosion and sea-level rise: Chaophraya



Haq, 1994





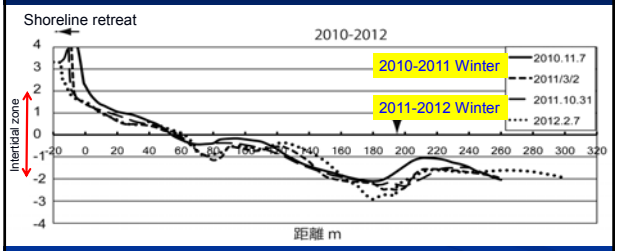
Repeat survey in Tra Vinh
From Nov 2005 to Feb 2012: 9 times

Summer monsoon
Sediment supply & deposition in delta front platform
Sediment transport to NE
Weak wind/waves

Winter monsoon
Sediment resuspension in delta front platform
Sediment transport to SW
Formation of Camau Pen.

Strong wind/waves
High water level

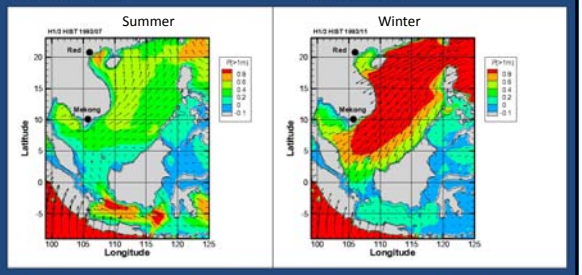
Repeat survey of a tidal beach from 2010 to 2012



>10 m retreat of the shoreline occurred in 2011
Mainly around 18th-20th February and around 24th December in 2011
2010-2011 Winter
2011-2012 Winter

After Uehara, 2010

Occurrence probability of waves higher than 1m

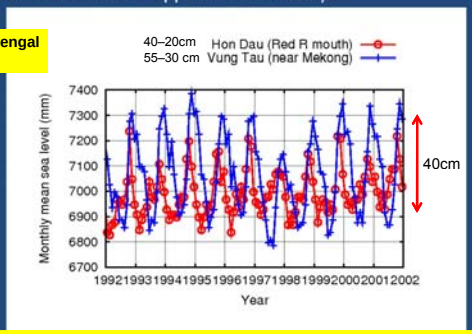


Red River Delta: strong wave occurs more frequently during summer (from south)
waves from north generally do not develop because of limited fetch

Mekong Delta: strong wave occurs more during winter monsoon (from NE)

After Uehara, 2010

Sea-level variation: apparent seasonal cycle

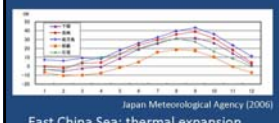


High during autumn to winter, low during spring to summer
-- range of seasonal change exceeds the secular sea level rise

After Uehara, 2010

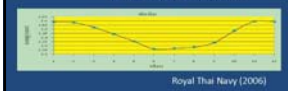
Cause of the seasonal sea-level change

Seasonal change in mean sea level



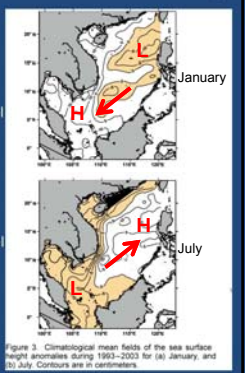
January
Low sea level at NE SCS

East China Sea: thermal expansion
(high during summer)

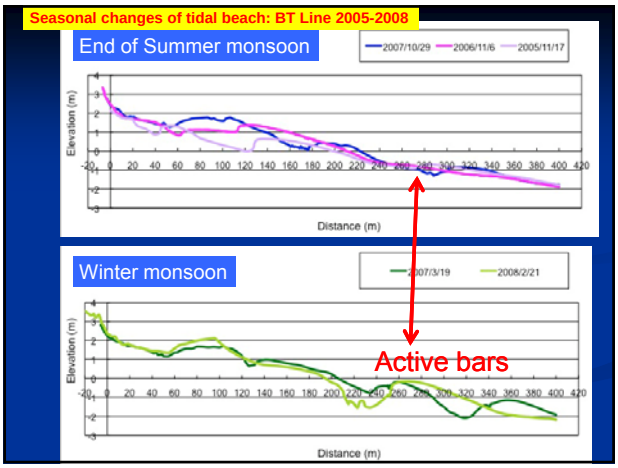


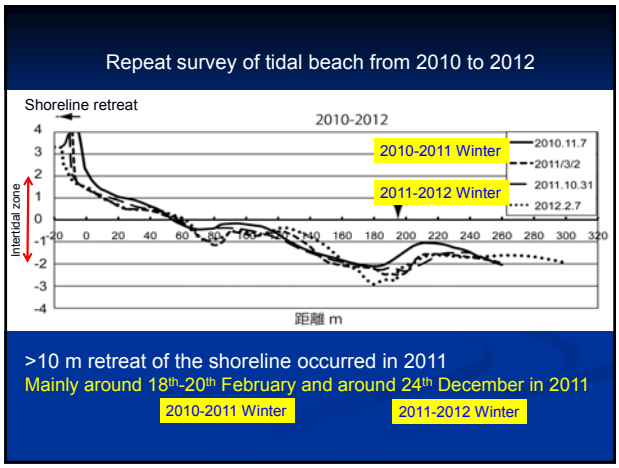
July
Low sea level at W SCS

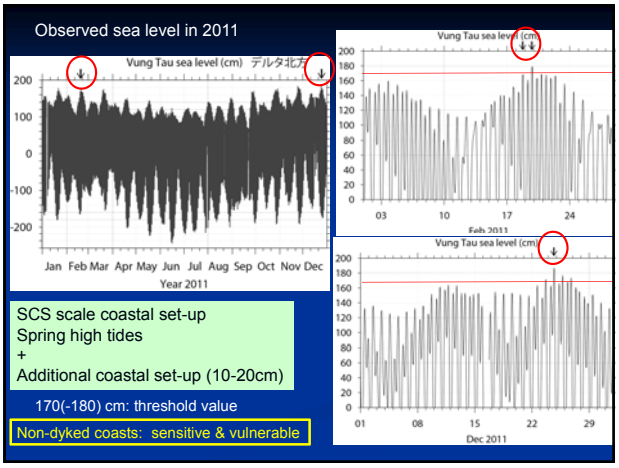
South China Sea: wind effect
(low at summer in Gulf of Thailand)

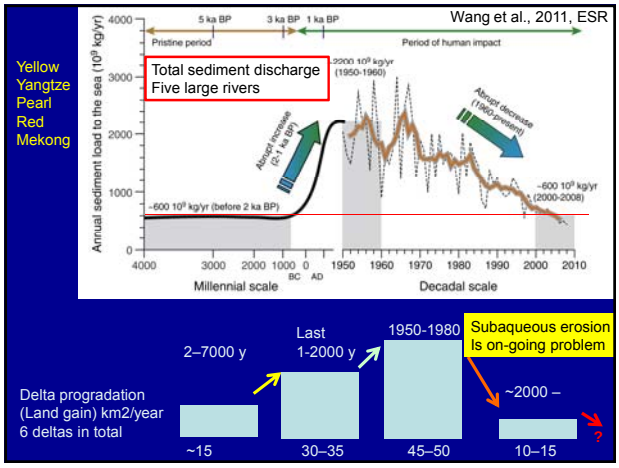


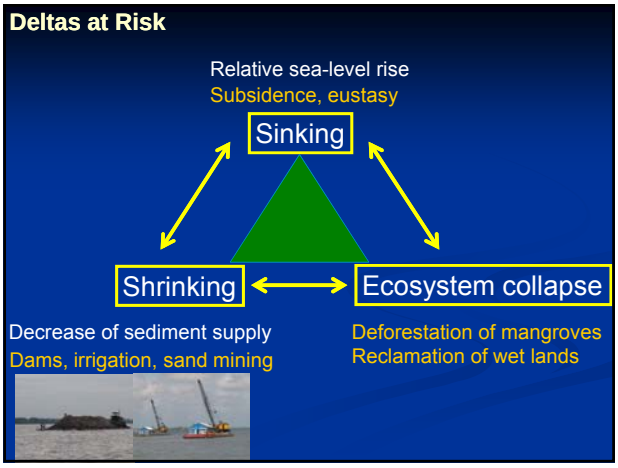
Fang et al.(2006)

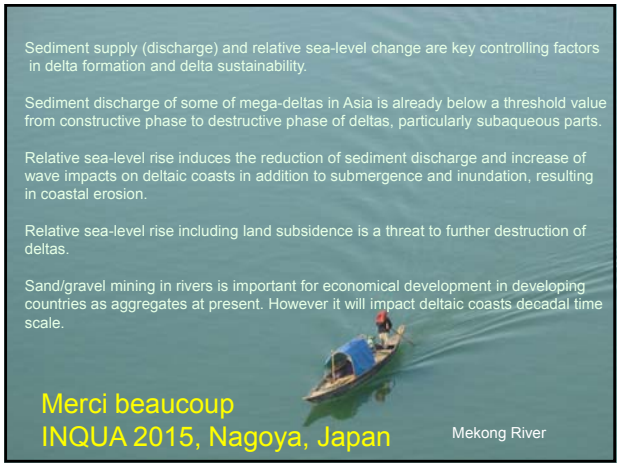

Seasonal changes of tidal beach: BT Line 2005-2008
End of Summer monsoon
2007/10/29
2006/11/6
2005/11/17
Elevation (m)
Distance (m)
Winter monsoon
2007/3/19
2008/2/21
Active bars


Repeat survey of tidal beach from 2010 to 2012
Shoreline retreat
2010-2012
2010-2011 Winter
2011-2012 Winter
2010.11.7
2011/3/2
2011.10.31
2012.2.7
Intertidal zone
距離 m
>10 m retreat of the shoreline occurred in 2011
Mainly around 18th-20th February and around 24th December in 2011
2010-2011 Winter
2011-2012 Winter


Observed sea level in 2011
Vung Tau sea level (cm)
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Year 2011
Feb 2011
Dec 2011
SCS scale coastal set-up
Spring high tides
+
Additional coastal set-up (10-20cm)
170(-180) cm: threshold value
Non-dyked coasts: sensitive & vulnerable


Wang et al., 2011, ESR
Yellow
Yangtze
Pearl
Red
Mekong
Total sediment discharge
Five large rivers
Annual sediment load to the sea (10⁸ kg/yr)
5 ka BP
3 ka BP
1 ka BP
Pristine period
Period of human impact
Millennial scale
Decadal scale
Delta progradation
(Land gain) km2/year
6 deltas in total
2–7000 y
Last
1-2000 y
1950-1980
Subaqueous erosion
Is on-going problem
~2000 –
~15
30–35
45–50
10–15


Deltas at Risk
Relative sea-level rise
Subsidence, eustasy
Sinking
Shrinking
Ecosystem collapse
Decrease of sediment supply
Dams, irrigation, sand mining
Deforestation of mangroves
Reclamation of wet lands


Sediment supply (discharge) and relative sea-level change are key controlling factors in delta formation and delta sustainability.
Sediment discharge of some of mega-deltas in Asia is already below a threshold value from constructive phase to destructive phase of deltas, particularly subaqueous parts.
Relative sea-level rise induces the reduction of sediment discharge and increase of wave impacts on deltaic coasts in addition to submergence and inundation, resulting in coastal erosion.
Relative sea-level rise including land subsidence is a threat to further destruction of deltas.
Sand/gravel mining in rivers is important for economical development in developing countries as aggregates at present. However it will impact deltaic coasts decadal time scale.
Merci beaucoup
INQUA 2015, Nagoya, Japan
Mekong River

Subsiding coastal megacities with the maximum observed subsidence (in m)

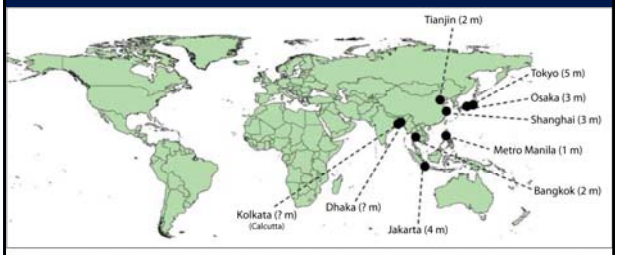
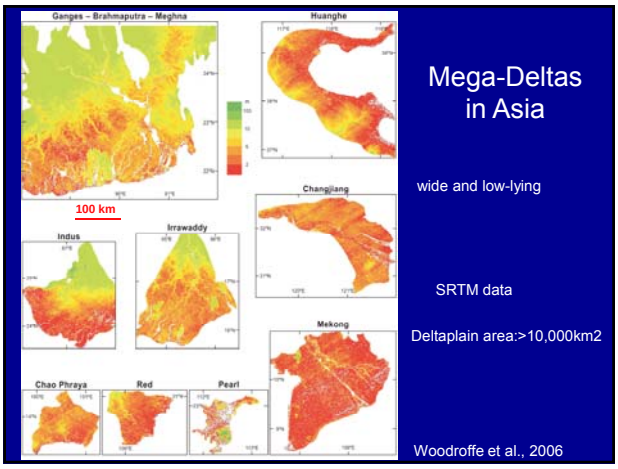


Figure 2. Subsiding coastal megacities with the maximum observed subsidence (in meters). Dhaka and Kolkata are thought to be subsiding, but data are limited. *Adapted and updated from Nicholls (1995).*

Nicholls, R.J. 2011



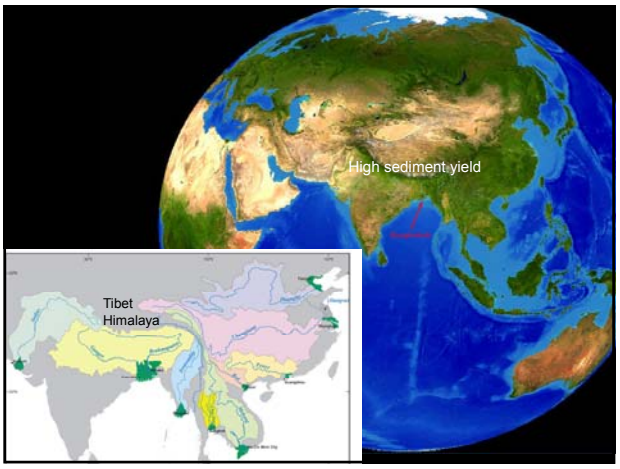
Mega-Deltas in Asia

wide and low-lying

SRTM data

Deltaplain area:>10,000km2

Woodroffe et al., 2006



Special thanks to prof. Anny Cazenave, Collège de France, TOTAL

rice bowl

Deltaic lowlands

sushi

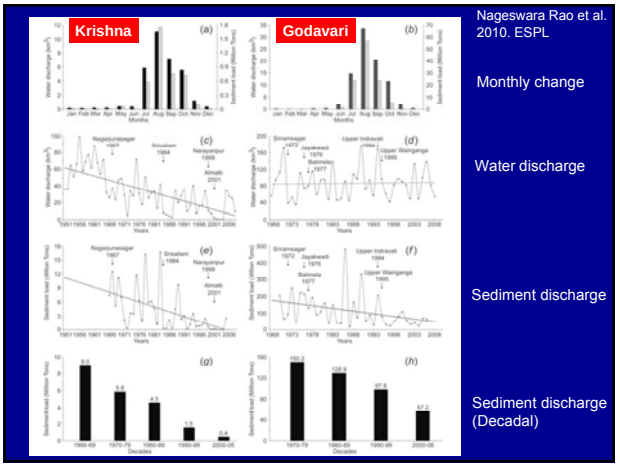
WG-2: IPCC AR4 2007

Some systems and sectors are very vulnerable. Some regions will be more affected than others

- The Arctic
- Sub-Saharan Africa
- Small islands
- Asian megadeltas

IPCC 4AR 2007

WMO UNEP



Nageswara Rao et al. 2010. ESPL

Monthly change

Water discharge

Sediment discharge

Sediment discharge (Decadal)