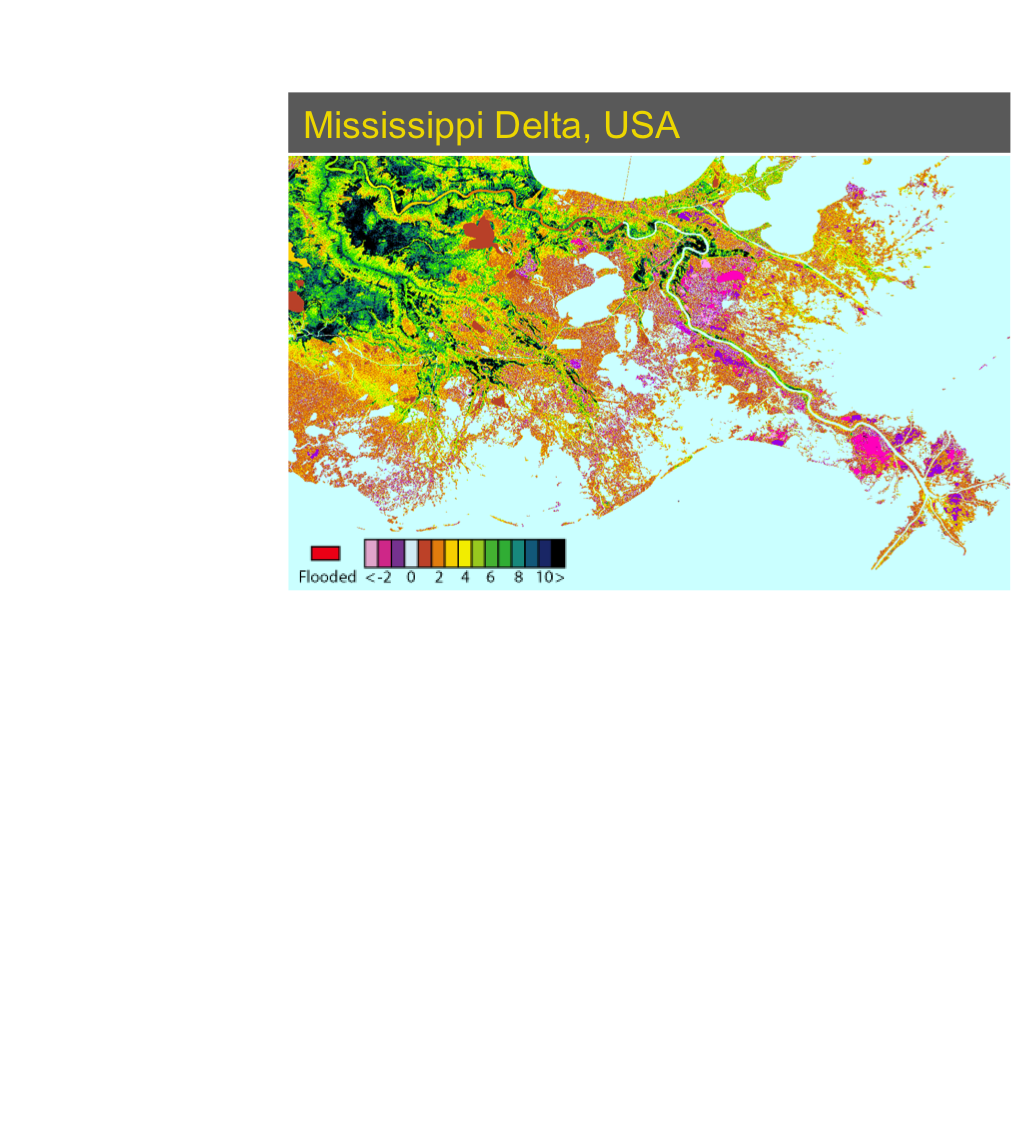
**Sinking Deltas and Global Sea Level Rise**

**(Instructor version)**

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1. **Introduction**

Many of the world’s largest deltas are densely populated and heavily farmed. Worldwide 500 million people live in low-lying deltas. Now many of their inhabitants are becoming increasingly vulnerable to flooding and conversions of their land to open ocean, especially under the background of heavy human activities and global warming. Syvitski et al. (2009) studied 33 deltas all over the world and found that in the past decade, 85% of the deltas experienced severe flooding. The 33 major deltas combined have > 100,000 km2 at elevation < 2 m above sea level, and > 26,000 km2 at elevation < 0 m. The following figure shows the topography of Mississippi Delta, which has a large proportion of land at elevation less than +2 m (in pink, purple and white).



*Figure 1. Topography of Mississippi Delta, USA*

Figure 2 shows the Krishna delta, India, which is classified under the “in great peril” category, because sediment supply to the delta is reduced by ~94 percent. In this photo, sand bags are being places at side of the road to Banki to protect low-lying land from floodwaters of overflowing Mahanadi River.

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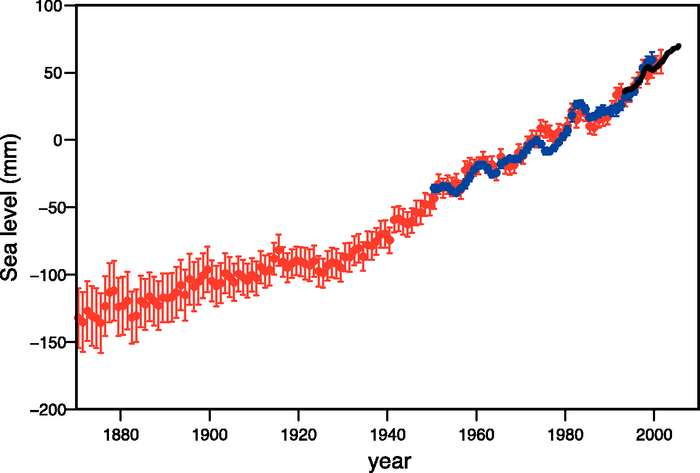
*Figure 2. Enforcing riverbanks in the Krishna Delta, India*

Key paper:

*Syvitski, J.P.M, Kettner, A.J., Overeem, I., et al., 2009. Sinking deltas due to human activities. Nature Geoscience, doi: 10.1038/NGEO0629*

**Practice:**

Question for Students 1



*Figure 3: Annual averages of the global mean sea level (mm). The red curve shows reconstructed sea level fields since 1870 (updated from Church and White, 2006); the blue curve shows coastal tide gauge measurements since 1950 (from Holgate and Woodworth, 2004) and the black curve is based on satellite altimetry (Leuliette et al., 2004). The red and blue curves are deviations from their averages for 1961 to 1990, and the black curve is the deviation from the average of the red curve for the period 1993 to 2001. Error bars show 90% confidence intervals. (Figure modified from IPCC Fourth Assessment Report: Climate Change, 2007)*

*1A*  Figure 3 shows global sea level rise over the last century. Estimate the average annual sea level rise rate from the graph. What has caused sea level rise, please explain?

*Answer for Instructors 1A: Average annual sea-level rise rate is about 1.8mm over the last century. Governing processes: Global sea level rise results from global warming, which heats the ocean water, leading to volume expansion, and then to sea-level rise. In addition, global warming results in the melting of glaciers and ice sheets, and then increases the water volume in the sea, which raises sea level globally.*

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*1B* Use the data in the Excell worksheet to calculate the seawater depth changes caused by thermal expansion. How much will global sea level rise if the temperature increases 2 °C according to the relationship? Look up the ICPP report of 2007 and find out the ‘best estimates’ of how much of the global sea level rise can be be attributed to thermal expansion? <http://www.ipcc.ch/>, look under AR4, 2007.

What is the role of other factors, how much do they contribute?

*Answer for Instructors 1B: The answers have been posted in the worksheet ”Sea water expansion by T”. Global sea level will increase 96mm with 2 °C rise in temperature. For the period 1961~2003, observed sea-level rise due to thermal expansion was 0.42mm/yr and 0.69 mm/yr due to glacier melt (small glaciers, ice caps, ice sheets); between 1993~2003, the contribution to sea level rise increased for both sources to 1.6 mm/yr and 1.19 mm/yr respectively. The following table 1 shows more detailed information (from IPCC, 2007).*

|  |  |  |
| --- | --- | --- |
| **Source of sea level rise** | **Rate of sea level rise (m per century)** | |
|  | *1961~2003* | *1993~2003* |
| *Thermal expansion* | *0.042±0.012* | *0.16±0.05* |
| *Glaciers and ice capes* | *0.050±0.018* | *0.077±0.022* |
| *Greenland ice sheets* | *0.05±0.12* | *0.21±0.07* |
| *Antarctic ice sheets* | *0.14±0.41* | *0.21±0.35* |
| *Sum of individual climate contributions to sea level rise* | *0.11±0.05* | *0.28±0.07* |
| *Observed total sea level rise* | *0.18±0.05* | *0.31±0.07* |
| *Difference (observed minus sum of estimated climate contributions)* | *0.07±0.07* | *0.03±0.10* |

*1C* Why this is important to our society and environment?

*Answer for Instructors 1C: Beach erosion and shoreline retreat affect valuable real estate in developed nations, and affects the livelihood of many coastal communities in developing countries. Shoreline retreat may pinch out coastal wetlands against developed areas, or the wetlands may be harmed irreversibly if the rate of sea-level rise exceeds the rate at which the ecosystem can adapt. Rising sea level can influence the rate of salt-water incursion into coastal aquifers, expansion of the salt-water wedge in estuaries, and the probability of damage from storm surges along coastlines. More than 100 million people live within 1 m of the mean sea level, and the problem is especially urgent and serious for the low-lying small island nations of the world (Meier, M.F., Wahr, J.M., 2002).*

**Question for Students 2**

Relative sea level is defined as sea level related to the level of the continental crust. Relative sea level changes can thus be caused by absolute changes of the sea level and/or by absolute movements of the continental crust (Angremond & Pluim-Van Der Velden, 2001). River deltas are complex systems, because the amount of sediment deposited can load down the continental crust and thus significantly influences its evolution process.

*2A* Annual elevation changes for several deltas are given in the Excell worksheet, as observed from long-term tide gauges (this data is archieved at the PSMSL-the permanent service for mean sea level, http://www.psmsl.org/). Please plot relative sea level rise in the selected deltas, calculate trendlines, and derive the longterm annual relative sea-level rise rate. How do the trends compare to global averaged sea-level rise data?

*Answer for Instructors 2A: The graphs have been plotted in the Excell worksheet ‘Comparison of different deltas’ for the instructors, including the annual rise rate. From the comparison, we could easily acquire that the relative sea level rising rate for the deltas is much larger than the global averaged value.*

*2B* Can you explain why this happened? Which factors do you think may influence this process? (Helpful References: Bohannon, 2010; Tornqvist, et al., 2008; Hyndman, D.W.S, 2009)

*Answer for Instructors 2B: From the definition of relative sea level and the plot in the Excell file (under the worksheet ‘comparison of different deltas’) one can infer that additional processes play a role in the selected deltas, which enhance local relative sea level rise. Several factors potentially lead to accelerated sea-level rise.*

1. *Less aggradation on the delta surface; if the sediment flux input to a certain delta is decreased due to human activities, for example, dam construction. This reduced aggradation destroys the dynamic equilibrium of river and ocean dynamics, leading to erosion of delta and relative sea level rising.*
2. *Natural compaction process in the delta. As the sediment deposited in the delta floodplain it is uncompacted, thus after deposition, it will be compressed by subsequent deposits and the pore space will be reduced over time. Also, peat deposits common in delta and coastal areas will compact easily and can oxidize when groundwater levels are deepening in populated areas.*
3. *Human activities, such as waterextraction, gas or oil drilling in a delta can greatly influence the soil porosity, and accelerate oxidation processes, resulting in compaction of larger magnitude than natural compaction.*
4. *Finally, the redistribution of earth’s mass, such as the growth or shrinkage of nearby ice masses, or the growth of delta deposit loading the crust, will influence a delta’s relative sea level.*

*The instructor can hold a classroom discussion in regard to this question, discussion material for instructors is from the paper Syvitski et al. (2009), which lists a ‘delta balance’ of 5 factors that influence the vertical change in delta surface.*

*The 5 factors are:*

1. *Delta’s aggradation rate: determined from the volume of sediment delivered to and retained on the subaerial delta surface as new sedimentary layers, it could be changed by river flooding, and dam construction.*
2. *Eustatic sea-level rate: determined from changes to the volume of the global ocean over time, as influenced by fluctuations in the storage of terrestrial water and fluctuations in ocean water expansion due to water temperature changes. This factor is mainly determined by global temperature changes.*
3. *Natural compaction: involves natural changes in the void space within sedimentary layers (for example dewatering, grain-packing realignment and organic matter oxidation) and is typically ≤3 mm / yr.*
4. *Accelerated compaction: the anthropogenic contribution to volume change as a consequence of subsurface mining (oil, gas or groundwater), human-influenced soil drainage and accelerated oxidation, and can exceed natural compaction by an order of magnitude.*
5. *Downward vertical movement of the land surface: influenced by the redistribution of Earth’s masses (for example sea-level fluctuations, growth of delta deposits, growth or shrinkage of nearby ice masses, tectonics and deep-seated thermal subsidence).*

**Question for Students 3**

From the plot you generated in question 2, you can see that different deltas have different ‘sinking rates’. There is a lot of debate on the causes of this relative sinking and it is not always resolved what is the dominant factor.

What are potential causes of subsidence for the selected individual delta systems?

3A Potential cause of subsidence in the Mississippi River delta:

*Answer for Instructors 3A: natural compaction of the Holocene strata (Tornqvist et al., 2008); human activities: extraction of hydrocarbons and associated formation water (Morton, et al., 2005).*

3B Potential cause of subsidence of Ganges delta:

*Answer for Instructors 3B: Sediment flux reduction (dam construction)*

*( <http://www.deccanherald.com/content/28520/this-week.html>)*

*Rise of Himalayas and dewatering of the Proto-Bengal Fan sediment (Milliman and Haq, 1996).*

3C Potential cause of subsidence of the Chao Phraya River delta:

*Answer for Instructors 3C: groundwater mining for urbanization. (Corben, R. and Writer, I., 2009); Dam and channels construction (http://news.bbc.co.uk/2/hi/science/nature/8266500.stm)*

3D Potential cause of subsidence of the Magdalena delta:

*Answer for Instructors 3D: reduced aggregation rate (Syvitski, et al., 2009, Table 1); Accelerated compaction of sediment (Where sinking land meets rising water, 2009)*

*Discuss in classroom what values for subsidence students found, and how different these estimates are.*

**Question for Students 4**

As a delta is sinking, how will this process influence the society and environment?

*Answer for Instructors 4: As the delta sinking, its environments and human populations on it are under a growing risk, increasing areas of lowlying land potentially increases coastal flooding, wetland loss, shoreline retreat and loss of infrastructure, and thus can greatly influence local people’s lives, and threaten the ecological system.*

**Question for Students 5**

As the delta sinking is such a big problem, do you have any idea what humans can do to slow down this process?

*Answer for Instructors 5: We learned that delta subsidence is caused by both global sea-level rise and local subsidence processes. So what everyone can do is to interrupt the global warming, which can be realized by reducing the amount of greenhouse gases, especially CO2 to the atmosphere, we should try to look for and widely used new energy, such as solar, wind, tidal energy. This will take effect over the longerterm (century +\_ scale), and policy changes to better mitigate flooding hazards are probably needed in many deltas.*

*Local measures can be taken to reduce subsidence in specific deltas, as an example we know that the sinking of the Chao Phraya River delta is mainly because of groundwater mining, so people there should try to improve their ability to more effectively use the available water and reduce groundwater use. There are some success stories; gas mining in the Po delta, Italy was halted after it was convincingly shown that this mining caused accellerated subsidence and sinking rates are back to more natural levels.*

**3 References**

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