

Climatic Influences on Stratigraphy - Applications of Coupled Models*

Irina Overeem¹

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¹CSDMS (Community Surface Dynamics Modeling System), University of Colorado, Boulder, CO (irina.overeem@colorado.edu)

Abstract

Numerical models can serve to explore the effects of key boundary conditions, like tectonics, sea level change, and climate changes, on stratigraphic architecture.

Climate changes are explored most often through the effects of changes in sediment supply to the depositional basin. Recent model experiments show complexities of sediment supply in response to climate change and take this into account to provide stratigraphic responses. A first complexity is that drainage basins in a similar climate zone can have a large variation in responses due to differences in basin geometry or the relative influence of glaciation. Sediment supply, a second complexity we recognize, can vary 'in-phase' or 'out-of-phase' with sea-level change depending on the coherency between climate change in the drainage basin and eustatic change. Such factors impact stacking patterns in both onshore and offshore environments.

However, geomorphological and process studies show that the influence of climate on stratigraphy goes beyond sediment supply. Climate can have an impact on much smaller-scale architectural characteristics, as well; for example, in fluvial systems climate influences the delivered grain size; it may affect sinuosity, flooding profile, channel pattern and depth. Similarly, wave climate impacts frequency and thickness of storm layers in shallow marine depositional architecture, and deepwater systems may be partly forced by climate-driven events.

This level of process-control detail is still a state-of-the-art research topic, which is being addressed within the modeling framework of the Community Surface Dynamics Modeling System (CSDMS). We show examples of sophisticated climate model realizations and process-based terrestrial models which are presently being coupled to stratigraphic models to investigate predictability of the relation between climate controls and stratigraphic architecture.

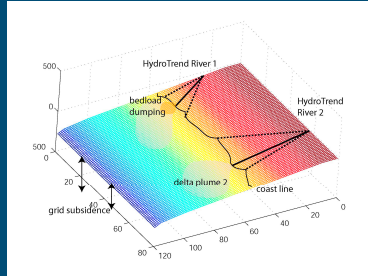
Selected References

- Alekseevskiy, N.I., D.N. Aibulatov, and S.V. Chistov, 2000, Shoreline dynamics and the hydrographic system of the Volga Delta, *in* Dynamic Earth Environments: Remote Sensing Observations from Shuttle-*Mir* Missions, K.P. Lulla and L.V. Dessinov, eds.: John Wiley & Sons, New York, p. 159-169.
- Anderson, D.M., J.T. Overpeck, and A.K. Gupta, 2002, Increase in the Asian southwest monsoon during the past four centuries: *Science*, v. 297, no. 5581, p. 596-599.
- Arpe, K., L. Bengtsson, G.S. Golitsyn, I.I. Mokhov, V.A. Semenov, and P.V. Sporyshev, 2000, Connection between Caspian Sea level variability and ENSO: *Geophysical Research Letters*, v. 27, p. 2693-2696.
- Goodbred, Jr., S.L. and S.A. Kuehl, 1999, Holocene and modern sediment budgets for the Ganges-Brahmaputra River: Evidence for highstand dispersal to floodplain, shelf, and deep-sea depocenters: *Geology*, v. 27, p. 559-562.
- Goodbred, Jr., S.L. and S.A. Kuehl, 2000, Enormous Ganges-Brahmaputra sediment load during strengthened early Holocene monsoon. *Geology*, v. 28, p.1083-1086.
- Goodbred, Jr., S.L. and S.A. Kuehl, 2000, The significance of large sediment supply, active tectonism, and eustasy on margin sequence development: Late Quaternary stratigraphy and evolution of the Ganges-Brahmaputra delta: *Sedimentary Geology*, v. 133, p. 227-248.
- Kudrass, H.R., A. Hofmann, H. Doose, K. Emeis, and H. Erlenkeuser, 2001, Modulation and amplification of climatic changes in the Northern Hemisphere by the Indian summer monsoon during the past 80 k.y.: *Geology*, v. 29, p. 63–66.
- Overeem, I., S.B. Kroonenberg, A. Veldkamp, K. Groenesteijn, G.V. Rusakov, and A.A. Svitoch, 2003, Small-scale stratigraphy in a large ramp delta: recent and Holocene sedimentation in the Volga delta, Caspian Sea: *Sedimentary Geology*, v. 159, p. 133-157.
- Overeem, I., A. Veldkamp, L. Tebbens, and S.B. Kroonenberg, 2003, Modelling Holocene stratigraphy and depocentre migration of the Volga delta due to Caspian Sea-level change: *Sedimentary Geology*, v. 159, p. 159-175.
- Overeem, I. and J.P.M. Syvitski, 2010, Experimental exploration of the stratigraphy of fjords fed by glaciofluvial systems, *in* Sediments and Depositional Architecture: Geological Society, London, Special Publications, v. 344; p. 125-142.

Overeem, I. and J.P.M. Syvitski, 2010, Shifting discharge peaks in arctic rivers, 1977-2007, *in* Sedimentary Fluxes and Budgets in Changing Cold Environments: Quantitative Analysis and Scaling Issues: Geografiska Annaler, Series A. Physical Geography, v. 92, no. 2, p. 285-296.

Peltier, W.R., 2004, Global glacial isostasy and the surface of the ice age earth: the ICE-5G (VM2) Model and GRACE: Annual Review of Earth and Planetary Science, v. 32, p. 111–149.

Climatic Influences on Stratigraphy- Applications of Coupled Models



Irina Overeem
CSDMS-Community Surface Dynamics Modeling System
University of Colorado, Boulder, CO

CSDMS

COMMUNITY SURFACE DYNAMICS MODELING SYSTEM

Promotes development and use of numerical modeling in earth surface dynamics research.

> 300 members, (int.) nationally, academic, industry, government

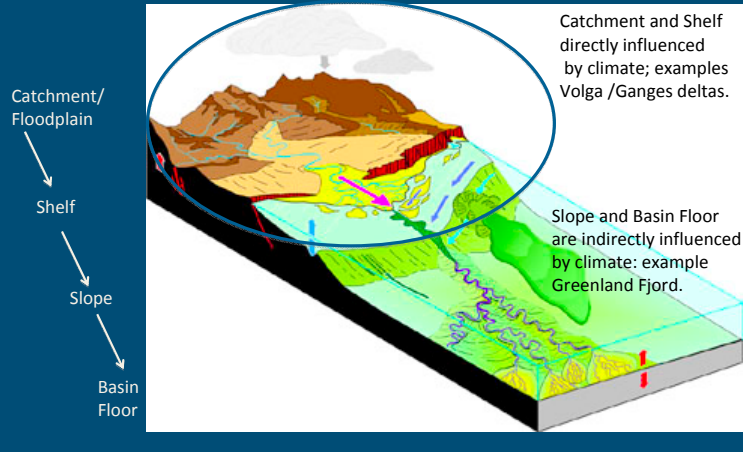
- Model, Data and Educational Repositories
- Access to supercomputer system

Development of an easy-to-use Coupling Tool



Presenter's notes: CSDMS integrates modeling into its research; I follow this philosophy during this talk

Climatic Influence on Stratigraphy?



Presenter's notes: Traditionally the domains between climate–hydrological models and stratigraphic models are not intimately linked....coupled models are needed to connect the domains...

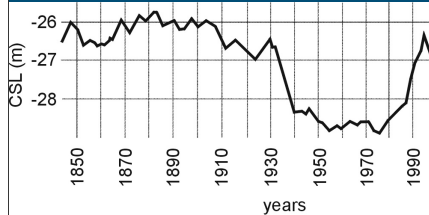
Talk Theme

- Climate-driven Sediment Supply– Sea Level Correlation Complexities.

Coupled Modeling with AquaTellUS, HydroTrend, Ice-5G and SedFlux :

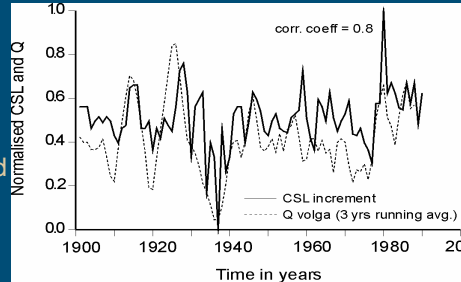
- 1) Volga delta: high supply, sea level rise.
- 2) Ganges delta: high supply, sea level rise.
- 3) Greenland Fjords: high supply, sea level fall.

Volga river and Caspian Sea



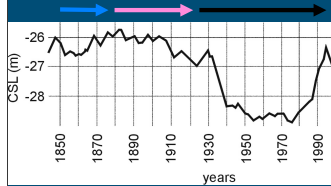
Caspian Sea went through a 3-m sea-level cycle over the last century.

Caspian Sea level is controlled by Volga discharge, which in turn depends on precipitation. Arpe et al., (2000) showed correlation with ENSO.

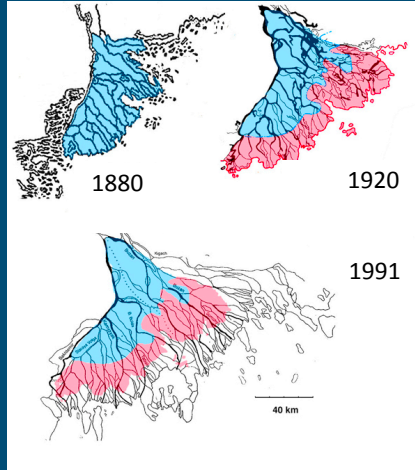


Presenter's notes: 80% of inflow originates from Volga River. Caspian sea-level changes show a statistically significant correlation with changes in the discharge of the Volga River. These, in turn, have been shown to record variations in precipitation over the Volga drainage basin, related to variations in the amount of Atlantic depressions that reach the Russian mainland. Arpe et al., (2000) showed the correlation with ENSO.

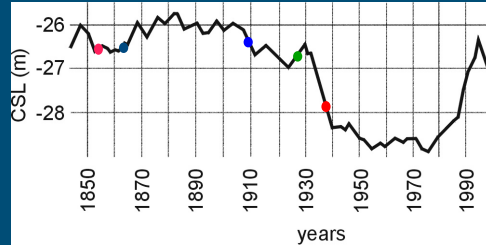
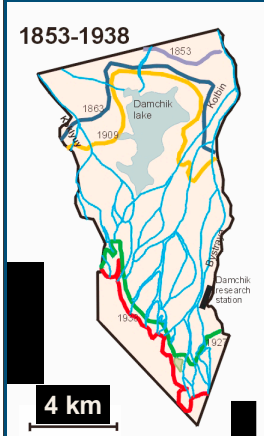
Delta progradation over last century



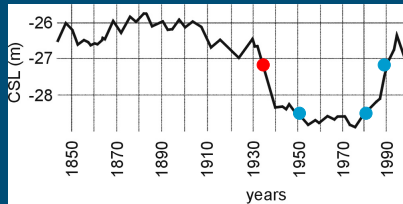
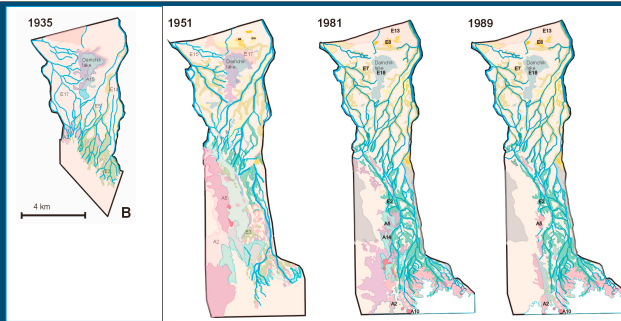
(After Alekseevskiy, Aibulatov, Chistov, 1999), based on combination of old maps and surface topography.



Sea-level fall - low sediment supply

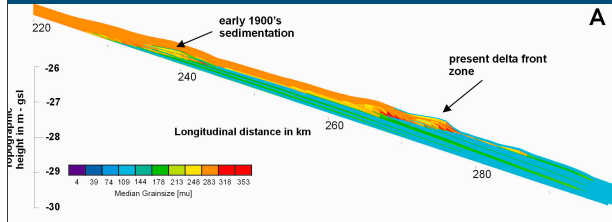


- Relative stable coast 1850–1909 ‘highstand’
- Rapid progradation 1909-1927 due to emergence, s.l. fall 0.6 m
- Slow progradation 1927-1938, despite additional 1.2m s.l. fall because of reduced sediment supply.

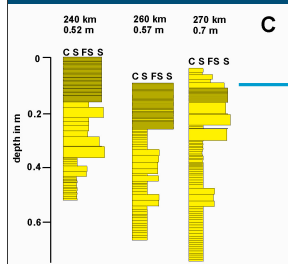


- Rapid progradation 1935-1951, emergence and skeleton of channels
- 1951-1981 lowstand, channel network fills.
- 1981- 1990 coastline is stable despite 1,5 m sea level rise.

AquaTellus Model Simulations



Discontinuous sedimentation, large depocenter shifts



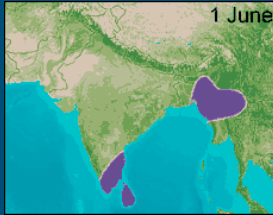
Drowning of delta brings muds on top of sands

(Overeem et al., 2003)

Presenter's notes: Message: Volga delta during sea level drop does carry much less sediment to build. The progradation is through emergence and a skeleton of a channel network. During sea level rise there is a lot more sediment coming into the system, and thus the retreat is slow. Delta stands its ground..

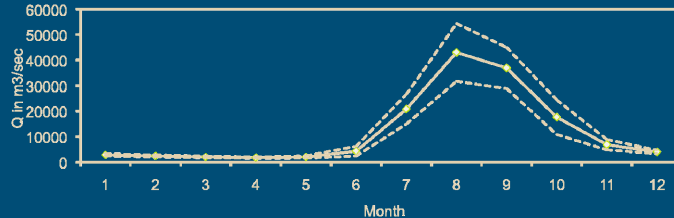
Is this a unique situation? Maybe not ...Ganges delta.....

Indian monsoon dominates Ganges River



(Source: BBC weather, 2005)

Ganges River (Farakka station 1949-1973)

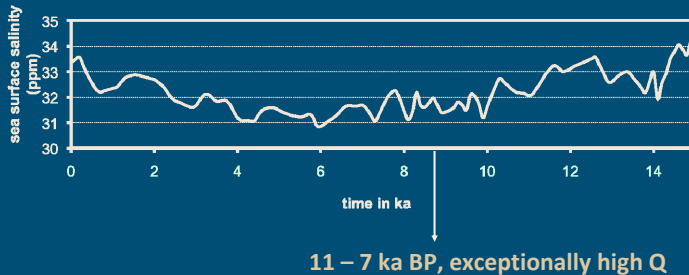


Presenter's notes: Again a strong climatic influence on river discharge and sediment load. The observed monthly discharge tracks monsoonal precipitation.

95% of the annual sediment load is discharged during the summer SW monsoon.

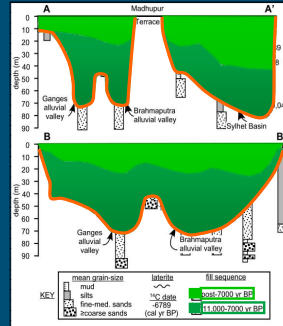
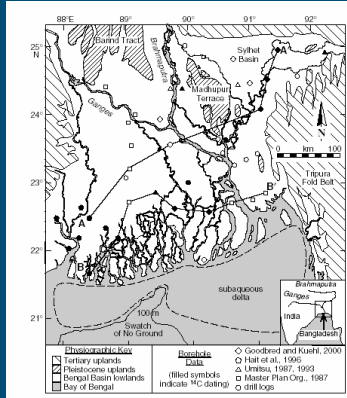
Long-term Indian Monsoon

Indian monsoon proxy: salinity in the Bengal basin (e.g. Kudrass et al., 2001). Indicates that paleo-river discharges were higher.



Presenter's notes: A lot of what is known about the long-term variability comes from proxy data, most notably foraminifera records from the Arabian Sea. Dave Anderson has been intimately involved. *Globigerina bulloides*. Most important trend is an INTENSE MONSOON early Holocene versus weaker conditions LGM and late Holocene. Monsoon intensity tracks solar insolation, but also Northern Hemisphere glacial coverage (albedo effect?). Northern hemisphere summer radiation was 8% greater at 9ka (Anderson et al., 2002). EXAMPLE of another proxy record is the reconstruction of the salinity depicted here. Main point LGM up to approximately 13ka is relatively dry (low freshwater and thus high salinity). Early Holocene--lots of fresh water; high river Q → Bay of Bengal, relatively fresh.

Sediment supply high at early Holocene



Goodbred & Kuehl (1999, 2000)

Borehole reconstruction-

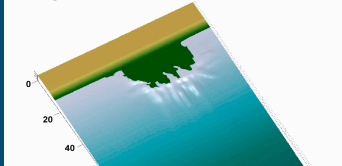
Sediment volume is $8.5 \times 10^{12} \text{ m}^3$, nearly 60% of which was stored from 11- 7kBP.

Implies 2.2 times higher flux at early Holocene!

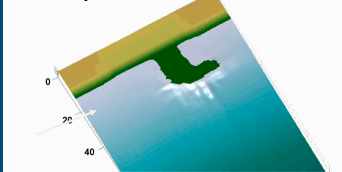
SedFlux simulation results

Present-day Monsoon Conditions

Ganges

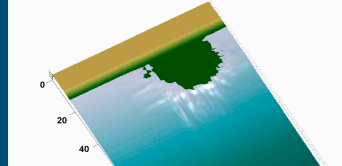


Brahmaputra

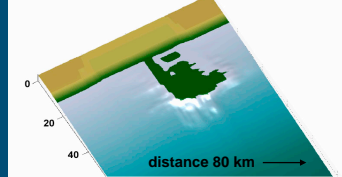


Increased Monsoon Conditions

Ganges



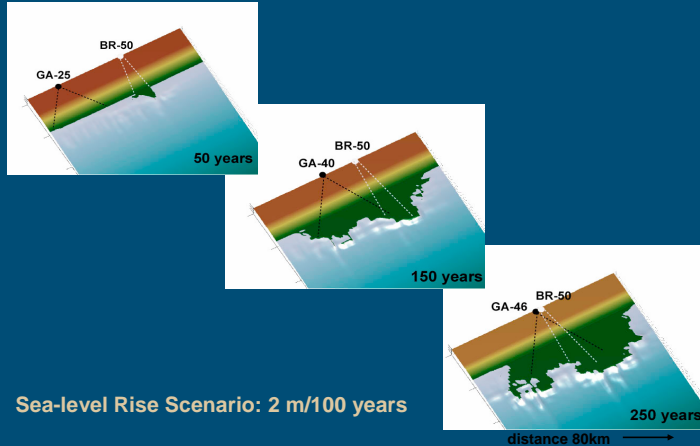
Brahmaputra



500 year experiments (SLR = 2 m per 100yrs)

Presenter's notes: (1) There is distinctly less progradation under present-day monsoon conditions for both river systems as compared to the increased monsoon conditions. (2) The Brahmaputra system switches around less due to the confining nature of its graben with rapid subsidence (Ganges subsides 4 mm/yr over the entire grid; the Brahmaputra grid subsides locally 7.5 mm/yr). This makes the system more vulnerable for sea level rise.

SedFlux simulations of sea-level rise



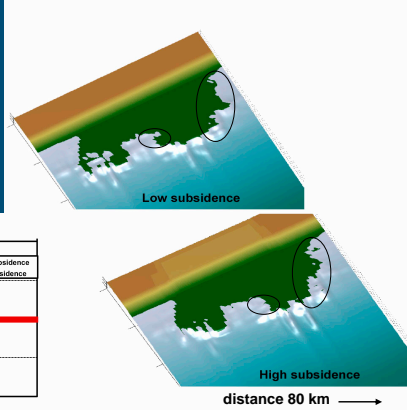
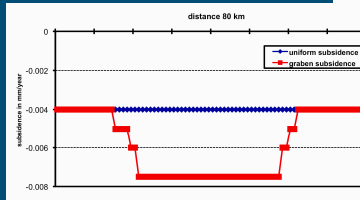
Presenter's notes: The two river systems are simulated in one grid here. The Ganges migrates gradually eastward over the grid and merged over the last 100 years with the Brahmaputra that is more confined. The little dots indicate the approximate positions of the hinge point; the dotted lines show the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

Supply and Subsidence?

Present-day Monsoon Conditions
Different Subsidence Rates

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

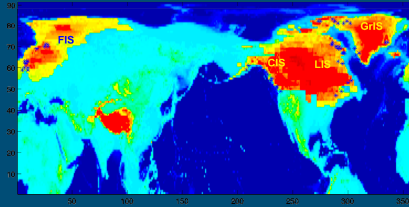
'high subsidence'
7.5 mm/year locally in 'graben'



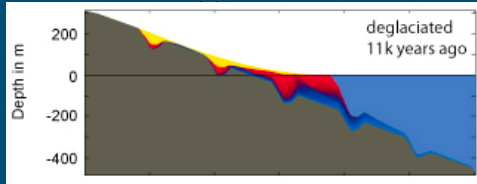
Presenter's notes: System is definitely still dominated by its large flux of incoming sediment...

FIGURE 2

Coupled Glacial-Isostasy – Sea level

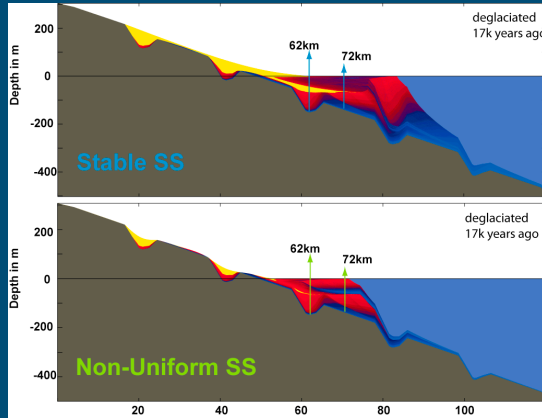


Ice-5G model (Peltier et al, 2004) defines deglaciation timing, rapid isostatic rebound outpaces global sea level rise → forced regression.



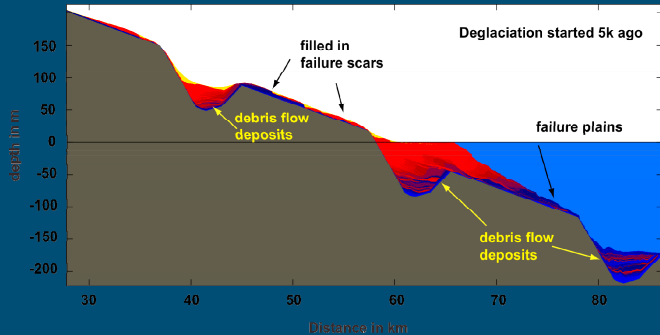
Stratigraphic X-section shows emerged forced regression deposits, more recent onlap of fluvio-marine progradation. Overeem & Syvitski, (in press 2010).

Non-Stable Sediment Supply

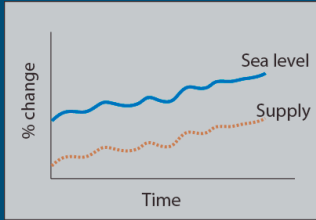


Assume a decrease of sediment supply as deglaciation progresses;
stacking pattern are quite different!

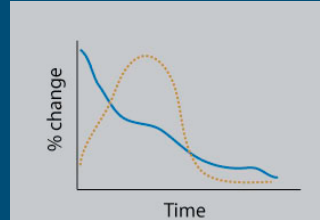
Fjord Stratigraphy influenced by High Energy events



Concept: correlated controls



Sedimentary system is resilient to rising sea level because it is able to build rapidly.



Sedimentary change is amplified; i.e., system is rapidly prograding due to forced regression. Timing matters!!

Presenter's notes: Add a third graphic for fjord.....which has high supply during lowering sea level.

Conclusions

- Stratigraphy is strongly a function of climate. It is not a linear system; relationships between controls have vastly different patterns.
- Three examples coupled Glacio-Tectonic models, Drainage basin Models with Stratigraphic Models...Models need to couple Terrestrial-Marine-Basin Floor domains to explore propagation of climatic effects.
- Ease-of-use of the CSDMS Modeling Tool – every geoscientist and student can set up model experiments and use the GUI. Release expected by this summer!