FINAL REPORT

Modeling land subsidence in coastal Louisiana due to the growth of the Mississippi Delta

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Organization: Tulane University
Funding (not including indirect costs): $25,532

1. Work accomplishments

Most of the world's large deltas are densely populated and heavily reclaimed. These areas are both economically and ecologically important to human livelihood. But, given the low-lying nature, these areas are environmentally fragile. The Mississippi Delta appears to be the best example in this regard. This river-dominated and bird-foot-like delta is extremely vulnerable because of frequent hurricane strikes and human activities. The ongoing accelerated sea-level rise due to global warming is posing an adverse impact on the sustainability of social and economic development. But the most severe problem is land subsidence.

Understanding the driving forces of land subsidence is practically important for municipal engineering, land-use planning, and costal restoration. Yet policymakers and the general public are facing with confusing information about both the mechanism and the magnitude of the subsidence. There are a number of deformational processes driving the subsidence. But some of them only have limited and localized impact. The sedimentary flexural deformation has long been regarded as a major player in driving the subsidence of the Pleistocene basement. Following postglacial sea-level rise, sediment loading on the surface of the Earth known as the infill of the deeply incised lower Mississippi River valley as well as the growth of the Mississippi Delta would deform the underlying lithosphere, thereby leading to a widespread subsidence. Previous modeling work shows that anomalously large rate of subsidence (ca. 6 mm/yr) occurred near the bird-foot delta, and most of the inland deltaic plain experienced a subsidence rate of 3 mm/yr (Ivin et al., 2007; Blum et al., 2008). Nevertheless, so many uncertainties such as earth model parameter choice, the sediment loading chronology and loading geometry need to be addressed to obtain reliable prediction.

In this work, we employed a better constraint sedimentary loading model to predict lithospheric flexural subsidence in coastal Louisiana due to postglacial development of the Mississippi Delta. This model was developed in the University of New Orleans by Prof. Mark Kulp (2000) based on about 600 borehole and seismic profiles. Our results show that the rate of sedimentary flexural subsidence in the inland portion of the deltaic plain is smaller by about an order of magnitude than that revealed by previous work. This is in great consistence with geological data derived from paired relative sea-level records from the Mississippi Delta and the Louisiana Chenier Plain (Yu et al., in review).

Sensitivity analysis to earth model parameter:

We use a spherically symmetrical, radially layered, and gravitationally consistent isostatic earth model to predict lithospheric flexural deformation in response to postglacial growth of the Mississippi Delta. This model has been well tested using geological, instrumental, and satellite geodetic data, and it has been extensively used to predict postglacial sea-level changes and three-dimensional deformation of the crust at a global scale induced by the melting of condimental ice sheets. The three key input parameters to this model are: (1) thickness of the lithosphere; (2) viscosity of the upper mantle; and (3) viscosity of the lower mantle.

This earth model is driven by a sedimentary loading model (i.e. the top-stratum isopach) developed and maintained by Prof. Kulp in the University of New Orleans (Fig. 1). The early-Holocene valley fill is not included in this model so far. The vertical growth rate of this sediment package is assumed to be constant from 7500 years BP on ward. The temporal resolution is 500 year. This means that the entire sediment package is sliced equally into 15 slabs, which are loaded onto the earth surface sequentially. We then calculate the accumulated flexural deformation of the lithosphere to this Heaviside-type loading.

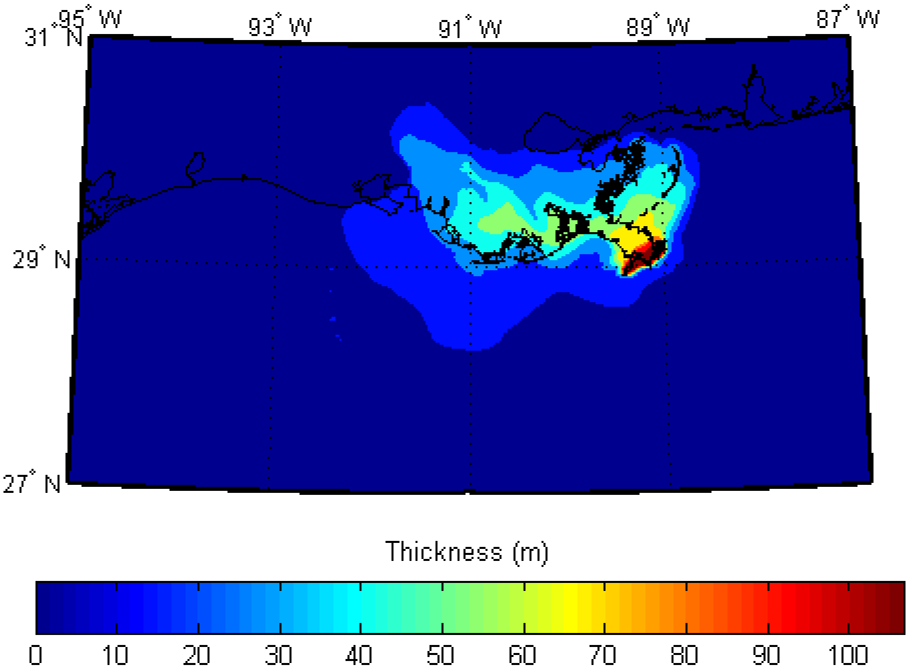

Fig. 1. Holocene sediment isopach showing the geometry of the Mississippi delta plain (Loading model 1, Kulp, 2000).

We performed sensitivity analysis of predictions to a large range of earth model parameters using this sedimentary loading model. A total of six earth models are used in this work (Table 1).

Table 1. Earth models used in this study.

Earth model ID.	Lithospheric thickness (km)	Upper mantle viscosity (10^{21} pa·s)	Lower mantle viscosity (10^{21} pa·s)
46p310	46	0.3	10
71p110	71	0.1	10
71p31	71	0.3	1
71p310	71	0.3	10
71p510	71	0.5	10
96p310	96	0.3	10

Three scenarios were tested:

- *Scenario 1*: lower and upper mantle viscosity is fixed, while lithospheric thickness is changed from 46 to 96 km.
- *Scenario 2*: lower mantle viscosity and lithospheric thickness are fixed, while upper mantle viscosity is changed from 0.1 to 0.5×10^{21} pa·s.
- *Scenario 3*: upper mantle viscosity and lithospheric thickness are fixed, while lower mantle viscosity is changed from 1 to 10×10^{21} pa·s.

Varying these model parameters can lead to significant impact on the results (Fig. 2). The predicted subsidence, as illustrated in Fig. 2, appears to be exceptionally sensitive to lithospheric thickness in this passive continental margin (Fig. 2A) — the thinner the lithosphere, the more the subsidence. Likewise, slightly changing the viscosity of the upper mantle can lead to a substantial variation of the relaxation time of the deformation, but it does not affect the total amount of land subsidence so much (Fig. 2B). In contrast, predicted subsidence seems to be insensitive to the changes in lower mantle viscosity (Fig. 2C).

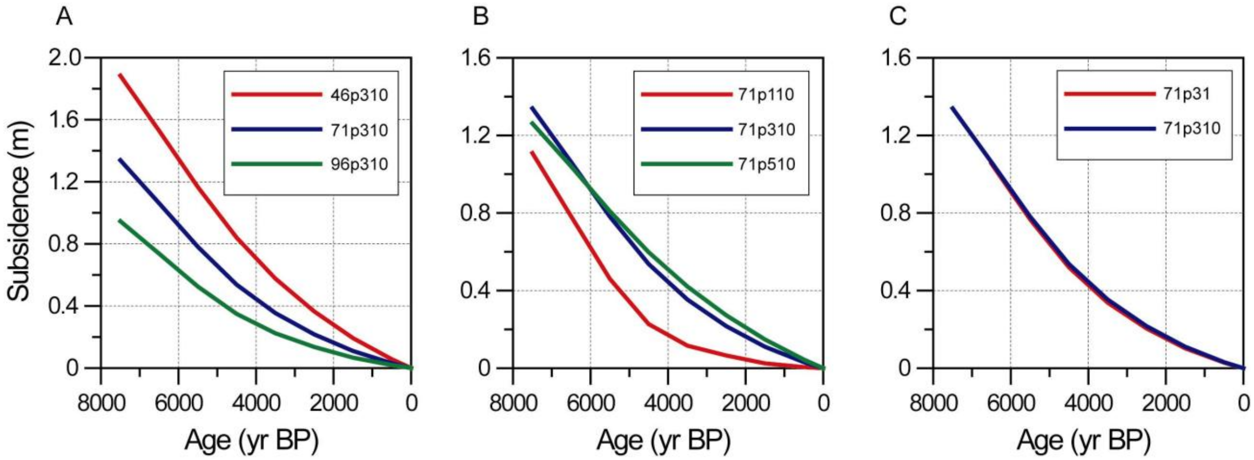

Fig. 2. Predicted lithospheric flexural subsidence in Lutcher-Gramercy area during the last 7500 years using sedimentary loading model 1 and a variety of earth models (see Table 1 for model ID). These results demonstrate the sensitivity of the model predictions to variations in key earth model parameters: (A) lithospheric thickness; (B) upper mantle viscosity; and (C) lower mantle viscosity.

In summary, our sensitivity analyses reveal that lithospheric thickness appears to be a key parameter affecting the magnitude of the deformation in this area, while the upper mantle viscosity governs only the relaxation time but not the total amount of the deformation. The lower mantle viscosity plays a very subtle role in governing the deformation — changing this parameter even by an order of magnitude does not lead to any significant variation in the predicted subsidence.

Sensitivity analysis to loading geometry:

In this experiment, we explored the impact of loading geometry to the predictions using a set of earth model parameters that lie in the middle of their ranges given in Table 1. Specifically, lithospheric thickness is set to 71 km, upper mantle viscosity 0.3×10^{21}Pa·s, and lower mantle viscosity 10×10^{21} Pa·s. Two sedimentary loading models are considered:

- *Model 1*: Stationary deltaic lobe from 7500 BP to the present (Fig.1).
- *Model 2*: Shifting deltaic lobes from 7500 BP to the present (Fig. 3).

For each model, a linear growth rate is assumed.

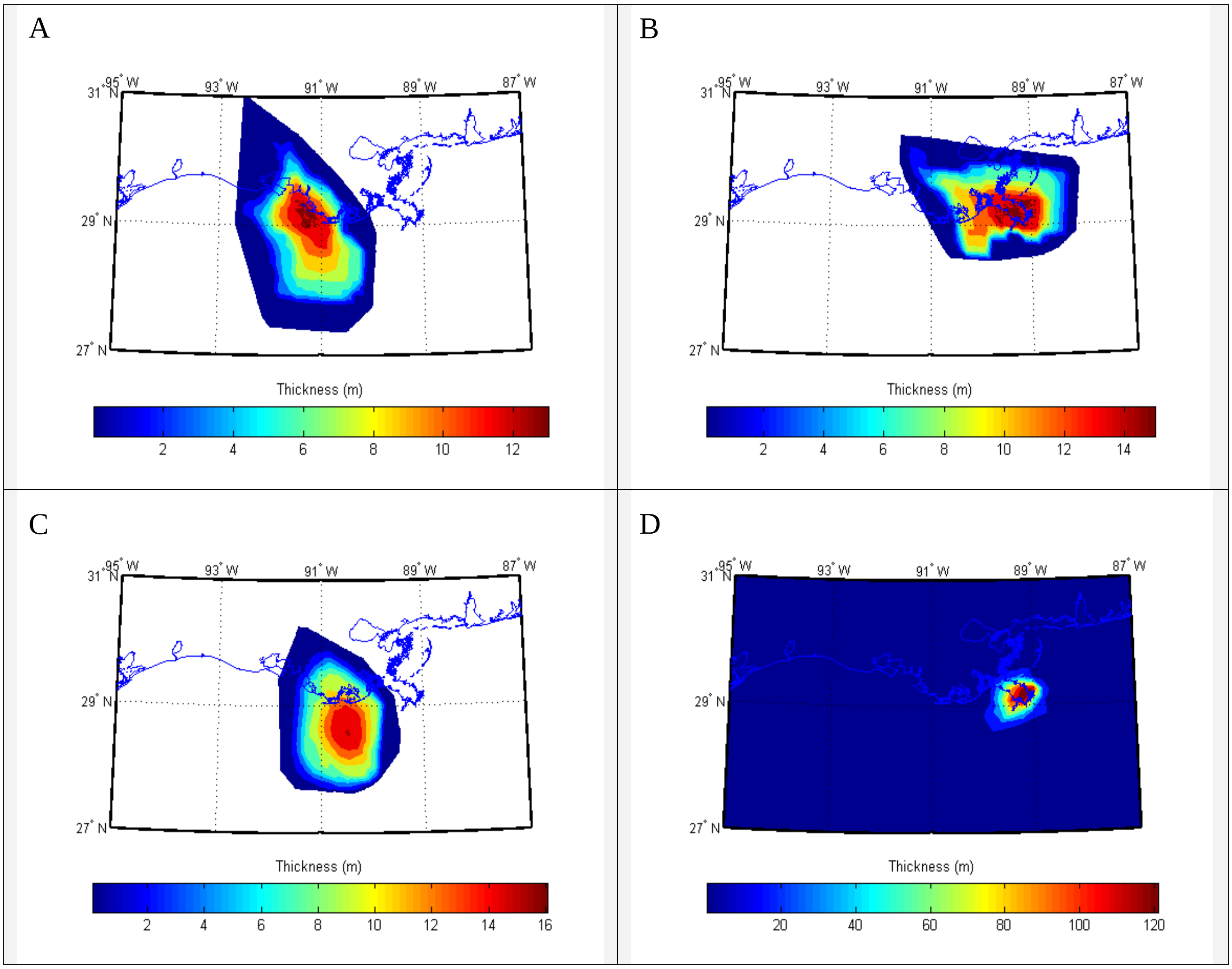

Fig. 3. Shifts of deltaic lobes with time during the last 7500 years (Loading model 2). A. Lobe 1 (7.5-4.1 ka BP); B. Lobe 2 (4.1-2.3 ka BP); C. Lobe 3 (2.3-1.0 ka BP); D. Lobe 4 (1.0 ka BP- the present). The timing of each lobe is from Kulp (2000).

The predicted subsidence using these two contrasting loading models exhibits a similar spatial pattern (Fig. 4). Specifically, both models predict a minor subsidence rate of ca. 0.2 mm/yr in the inland portion of the Mississippi Delta, which is consistent with Holocene sea-level records (Yu et al., in review) and long-term bio-stratigraphical data. This value is about an order of magnitude smaller than previously modeled (Ivin et al., 2007; Blum et al., 2008). Note that a hot-spot-like sinking occurs in the bird-foot delta where the Holocene sediment thickness is about 120 m. But Model 2 predicts a much higher subsidence rate than Model 1 does.

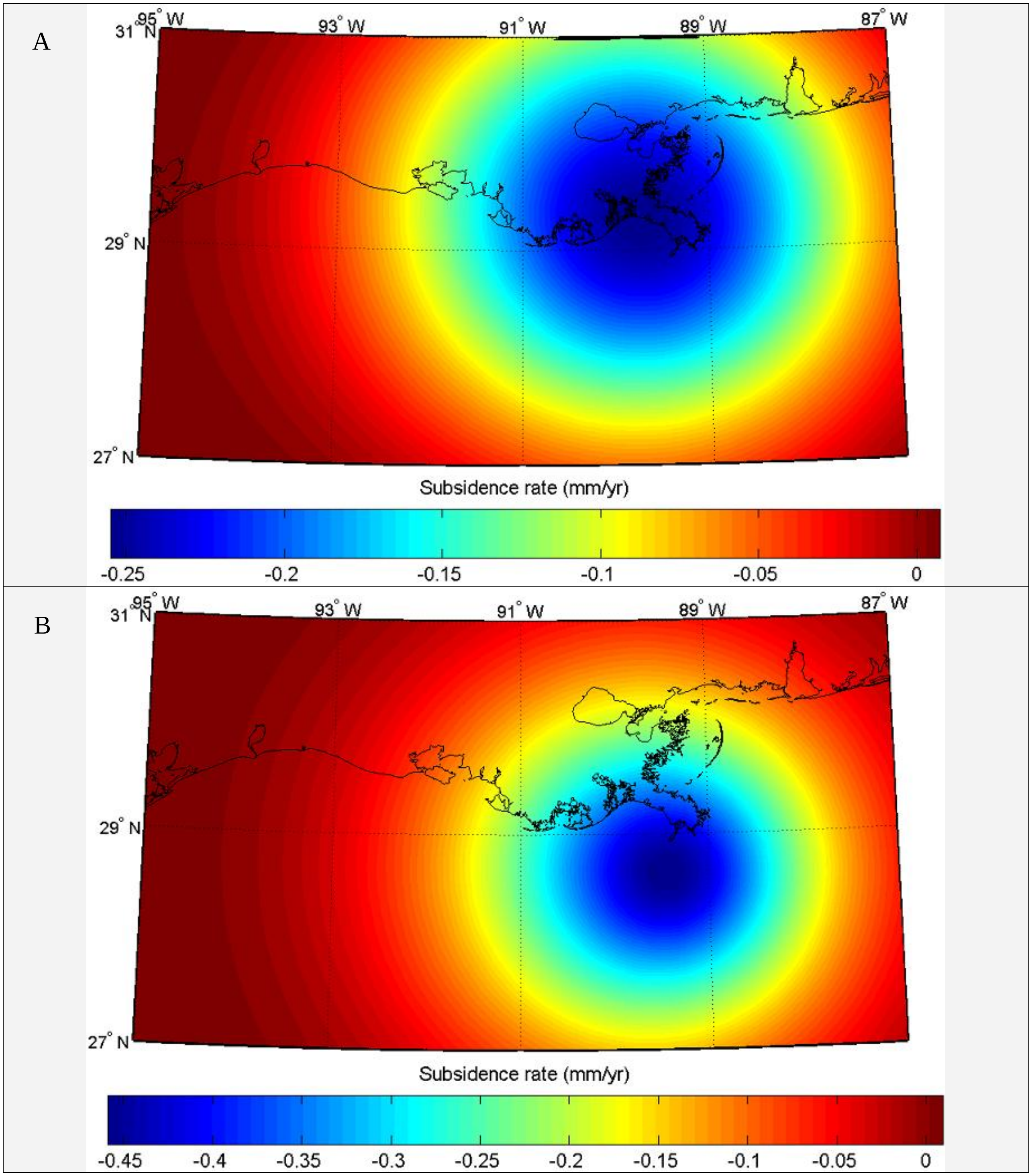

Fig. 4. Predicted spatial pattern of lithospheric flexural subsidence rates in coastal Louisiana using different sedimentary loading models but the same set of earth model parameters. (A) Loading model 1; (B) Loading model 2.

2. Outlook into future work

The ultimate deliverable outcome of this work is to provide a plausible prediction of flexural subsidence in coastal Louisiana with an error envelope defined by the end-member values of the earth model parameters. Towards this end, continued support form CREST is required. In future work, a more robust constraint from geological and instrumental data (e.g. paired RSL records of the Mississippi Delta and the Chenier Plain and GPS data obtained from receivers sitting on a compaction-free basement) will be used to guide the choice of earth model parameters so as to generate more reliable results. In addition, Prof. Kulp's group is developing a sediment model for postglacial valley fill, which will fill the gap between the growth of middle- and late-Holocene delta lobes and the last-glacial submarine fan in the model space. Once this work is done, we will be able to generate prediction of flexural subsidence using a full version of the sedimentary loading model spanning from MIS 2 to the present.

3. Applications

Publication:

Yu, S.-Y., Törnqvist, T.E., and Ping, H.**,** Continuous Holocene relative sea-level rise along the central US Gulf Coast and its geodynamic implications. *Proceedings of the National Academy of Sciences*, in review.

Conference contributions:

Yu, S.-Y., Törnqvist, T.E., Milne, G.A., and Kulp, M.A., Modeling the sediment loading effect on land subsidence in the Mississippi Delta. American Association of Petroleum Geologists Annual Meeting, New Orleans, April 11-14, 2010.

Törnqvist, T.E., Yu, S.-Y., Shen, Z., Milne, G.A., Kulp, M.A., and Gonzalez, J., Coastal subsidence and accelerated sea-level rise: A dual threat for the Mississippi Delta. American Association of Petroleum Geologists Annual Meeting, New Orleans, April 11-14, 2010.

Törnqvist, T.E., Li, Y.-X., and Yu, S.-Y., Early Holocene ice-sheet/sea-level interactions. The 3rd PALSEA workshop. Bristol, September 20-24, 2010.

Törnqvist, T.E., Yu, S.-Y., and Hu, P., Continuous Holocene relative sea-level rise along the Central US Gulf Coast: Implications for Mississippi Delta subsidence rates. GSA 45th Annual Meeting – South-Central Section. New Orleans, March 27-29, 2011.

Management outcome:

Our sea-level research group has get involved in the EcoPartnership between Tulane University and the East China Normal University. This is a 4-year collaborative program striving to better understanding wetland dynamics in both China and coastal Louisiana. Also, we have initiated a long-term collaboration with the sea-level modeling group in the University of Ottawa, Canada. A deliverable outcome of this joint effort will be an integrated model of land subsidence and sea-level changes for large river deltas.