A three-dimensional surface velocity field for the Mississippi Delta: Implications for coastal restoration and flood potential

Makan A. Karegar, Timothy H. Dixon, and Rocco Malservisi
School of Geosciences, University of South Florida, 4202 E. Fowler Avenue, NES 107, Tampa, Florida 33620, USA

ABSTRACT

Accurate estimates of the current rate of subsidence in the Mississippi Delta (southern United States) provide a context for planning of wetland restoration and predictions of storm surge flooding. We present a comprehensive three-dimensional surface velocity field for the Mississippi Delta based on a network of 36 high-precision continuous GPS stations. We show that while the majority of the delta is relatively stable, the southern portion continues to experience high rates of subsidence (5–6 mm yr^{-1}). Our data are consistent with long-term tide gauge records at Grand Isle, Louisiana, and several stations in Florida. The current rate of relative sea-level rise (combined effect of land subsidence and sea-level rise) along parts of the coastal delta is ~8–9 mm yr^{-1}. Most tide gauge stations have recorded sea-level-rise acceleration after A.D. 1970. These data have implications for land reclamation and wetland restoration in the region; parts of the delta may not be viable in the long term.

INTRODUCTION

Parts of coastal Louisiana (southern United States) are undergoing accelerated land loss due to the combined effects of sea-level rise and land subsidence (Morton et al., 2009). In the Mississippi Delta, where rates of land loss are especially severe, subsidence of the land surface reflects natural processes such as sediment compaction and crustal loading, exacerbated by anthropogenic withdrawal of fluids (water, oil, natural gas). Given stable sea level and sediment deposition, a delta will tend toward an equilibrium state where subsidence is more or less balanced by sediment deposition. In the Mississippi River system, however, a series of dams on various upstream tributaries have reduced sediment supply to the delta (Blum and Roberts, 2012), while levees on the lower part of the river have artificially channelized the flow, forcing sediments to be deposited beyond the delta in the deeper Gulf of Mexico. Mitigation efforts can include river diversion to encourage resedimentation, and pumping of offshore sands to restore barrier islands (e.g., CPRA, 2012).

Knowledge of current subsidence rates should be an important component of long-term planning of mitigation, for example allowing efforts to be focused where current subsidence rates are low. Unfortunately, despite its obvious importance, the rate of current subsidence in the delta remains unclear. Dokka (2011) emphasized high rates of subsidence due to fluid extraction, based on geodetic leveling data. Yu et al. (2012) emphasized low rates of subsidence based on studies of Holocene peat. Both of these studies addressed deeper processes in the Earth's lithosphere and did not focus on subsidence caused by shallow processes. Morton and Bernier (2010) and Kolker et al. (2011) suggested that high rates of subsidence correlated with periods of onshore oil production, and that subsidence has declined significantly since the 1990s as oil and gas production moved offshore. State and federal governments are investing significant funds for coastal restoration in the region. Improved knowledge of subsidence could help to better target such efforts.

Part of the problem in quantifying subsidence is that the process may be both temporally (Morton and Bernier, 2010; Kolker et al., 2011) and spatially variable. Some of the variability could relate to the technique used (Meckel, 2008). Spot measurements (e.g., tide gauges or sparse GPS measurements) could therefore alias a spatially complex signal. Moreover, some analyses of subsidence rely on tide gauge data, which record temporal variations due to decadal and multidecadal oceanographic oscillations. Extracting a meaningful subsidence signal in the presence of significant oceanographic and non-oceanographic variations can be challenging.

Dokka et al. (2006) estimated geodetic deformation rates of southeast Louisiana using continuous and episodic GPS data collected between 1995 and 2006 with an average record length of 5 yr; the uncertainties of vertical rates were rather large in that study (0.8–4.8 mm yr^{-1}, with an average of ~2 mm yr^{-1}). New GPS data based on longer time series (average record length of 9 yr) and additional stations (18 new sites) are now available, and allow a substantial refinement (See Table DR1 in Appendix DR1 in the GSA Data Repository[1]) (Fig. 1A). We present a three-dimensional velocity field based on 36 permanent GPS sites in the lower Mississippi basin using data to June 2014. Moreover, new analytical techniques (see the tide gauge discussion herein, and Appendix DR2) allow better extraction of trends from tide gauge time series with multiple oscillatory modes, allowing a more rigorous comparison of GPS and tide gauge data.

GPS DATA AND ANALYSIS

The raw GPS data were processed using the software package GIPSY/OASIS II (v. 6.2); of the Jet Propulsion Laboratory (gipsy-oasis.jpl.nasa.gov) and the precise point positioning technique (Appendix DR1). The stations have nearly continuous observations ranging from 4 to 18 yr. Half of the stations record data for longer than 10 yr. The nonfiducial daily position time series are transformed into the IGS (International GNSS Service) 2008 reference frame. The horizontal components of the nonfiducial daily solutions are also transformed into a North American plate-fixed frame (NA12; Blewitt et al., 2013).

It has long been recognized that the formal errors of displacement time series based on a white noise approximation underestimate the uncertainty of site velocity (e.g., Hackl et al., 2011). Time-correlated (colored) noise can be estimated using spectral analysis and maximum likelihood estimation. Here we use the Allan variance of rates (AVR) method (Hackl et al., 2011) which deals with time-correlated noise in a robust manner (Appendix DR1).

TIDE GAUGE DATA AND ANALYSIS

Tide gauge data have long been used to estimate subsidence of the Mississippi Delta (e.g., Penland and Ramsey, 1990). One challenge is that tide gauges record a combination of land subsidence and sea-level rise, both of which can exhibit variability on a multitude of time and spatial scales, from both natural causes, e.g., decadal and multidecadal oceanographic oscillations (Chambers et al., 2012), and anthropogenic causes such as global warming and hydrocarbon and groundwater extraction (Morton and Bernier, 2010). Nevertheless, with appropriate analytical techniques, the relative sea-level record from tide gauges can be compared to GPS-derived vertical land motion from nearby stations to provide independent data.

We used tide gauge records from the Permanent Service for Mean Sea Level (PSMSL; www.psmsl.org) database for a station at Grand Isle, Louisiana, and several Florida stations, for comparison to nearby GPS stations (Fig. DR2.1 in Appendix DR2). The tide gauge in Pensacola is located on stable upper Pleistocene sediment. The corresponding GPS station (PCLA) is located 7.5 km away. The PCLA GPS station

[1]GSA Data Repository item 2015185, Appendix DR1 (GPS time series analysis) and Appendix DR2 (tide gauge time series analysis), is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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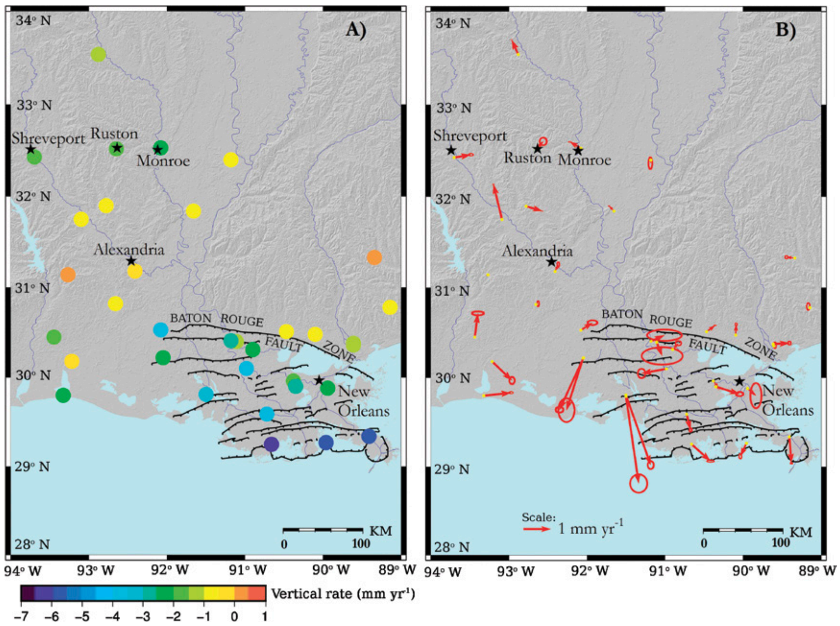

Figure 1. Map showing the locations of GPS sites used in this study and growth fault system in southern Louisiana (USA) from Murray (1961). Black stars show locations of major cities. A: Vertical velocities (circles) in IGS 08 reference frame (see text). Circle colors indicate value of subsidence. B: Horizontal velocities in North America 2012 frame plotted with 95% error ellipses. Yellow circles show locations of GPS stations.

records vertical land motion of −1.0 ± 0.2 mm yr^{-1}, similar to −1.1 mm yr^{-1} estimated at that location from the ICE-5G v1.3 model for glacial isostatic adjustment (GIA) (Peltier, 2004) but ~0.5 mm yr^{-1} faster subsidence than an estimate of GIA-related subsidence at the Mississippi Delta based on the reconstructed Holocene sea-level record (Yu et al., 2012). The average relative sea-level rise rate from 1924 to 2014 at the corresponding tide gauge at Pensacola, Florida, is 3.1 ± 0.9 mm yr^{-1} (Fig. DR2.3), suggesting a local sea-level rise (corrected for vertical land motion as measured by GPS) of 2.1 mm yr^{-1}, higher than average global sea-level rise for the past century (1.7 mm yr^{-1}, Church and White, 2011; 1.2 mm yr^{-1}, Hay et al., 2015). We also use two other tide gauges in Florida to compare results with the tide gauge record at Pensacola, obtaining similar results (Table 1).

Differencing of tide gauge data (e.g., Grand Isle relative to Pensacola) has been used to reduce the influence of decadal scale oceanographic effects (e.g., Kolker et al., 2011). When this is done to estimate subsidence rate, it is important to add back the effects of GIA because it is a real physical effect on the land surface that is lost in the differencing approach.

Our analysis of tide gauge data is based on the Hilbert-Huang transform (HHT) (Huang and Wu, 2008). This method accounts for decadal or multidecadal effects, extracts long-term trends, and distinguishes uniform velocity from records indicating acceleration. The method uses empirical mode decomposition (EMD) and Hilbert spectral analysis to decompose a time series to intrinsic mode functions and a residual with time-dependent amplitudes and frequencies. Numerous studies have documented its efficacy for extracting longer term trends in the presence of significant shorter term oscillations (see Appendix DR2).

RESULTS

GPS results are summarized in Table DR1. With the exception of stations MSHT and LESV, all stations indicate subsidence. The highest subsidence rates are observed at sites near the deltaic shoreline (Fig. 1A). Subsidence rates of <2 mm yr^{-1} occur in northern Louisiana, decrease to ~0 in the mid-Louisiana upland, and then increase to 6.5 mm yr^{-1} in southern Louisiana. Figure 2A shows the vertical velocity component as a function of latitude. In southern Louisiana (south of 30.5°N) subsidence rates increase from <2 mm yr^{-1} north of the Baton Rouge fault zone to 6.5 mm yr^{-1} in the southern Mississippi Delta, with a north-south gradient of 3.4 mm yr^{-1} per 100 km.

Table 1 also lists the subsidence rates inferred from differencing the tide gauge record at Grand Isle from three different reference tide gauge records along the eastern Gulf of Mexico. The HHT estimates for the 3 reference tide gauges, correcting for GIA (adding 1 mm yr^{-1}) have a very limited range, 6.7–6.8 mm yr^{-1}. In contrast, if we use linear regression, the long-term subsidence rate over the same period (1947–2014) for the 3 reference tide gauges varies between 7.7 and 8.2 mm yr^{-1}. Linear regression for the various subperiods, also correcting for GIA, yields a subsidence rate for 1947–1959 of <4 mm yr^{-1}, increasing to ~9–10 mm yr^{-1} for 1959–1994, and decreasing to <5 mm yr^{-1} from 1994 to 2014.

North of lat 30.5°N, the horizontal GPS velocities in the NA12 reference frame are <1 mm yr^{-1}, as expected for stable North America (Fig. 2B). Within the Mississippi Delta, stations show increasing southward motion. This motion may reflect slow downslope movement on a series of listric normal faults due to gravitational sliding (Murray, 1961; Dokka et al., 2006), but could also represent the horizontal component of differential compaction. The boundary between stable sites and southward-moving sites corresponds to the Pleistocene-Holocene contact along the southern lower Mississippi valley margins. The new data suggest a rate of southward displacement lower than suggested by Dokka et al. (2006). Consequently, active faulting, if it occurs, is probably a minor component of subsidence. With the exception of 3 sites

TABLE 1. COMPARISON OF SUBSIDENCE RATE AT GRAND ISLE RELATIVE TO THREE DIFFERENT REFERENCE STATIONS FROM LINEAR REGRESSION AND HILBERT-HUANG TRANSFORM

Tide gauge	Rate from linear regression (mm yr^{-1})				Rate from HHT (mm yr^{-1})	Rate from GIA (mm yr^{-1})
	A.D. 1947–1959	1959–1994	1994–2014	1947–2014	1947–2014	
Grand Isle-Pensacola	3.0 ± 1.1	9.7 ± 0.2	3.7 ± 1.1	7.2 ± 0.2	5.7 ± 0.2	1.1
Grand Isle-St. Petersburg	1.2 ± 2.9	8.5 ± 0.9	3.5 ± 1.4	6.7 ± 0.3	5.7 ± 0.3	0.9
Grand Isle-Key West	1.7 ± 6.7	8.6 ± 0.4	3.9 ± 1.0	6.9 ± 0.2	5.8 ± 0.2	0.7

Note: The subsidence rate (here positive) is calculated by subtracting listed monthly tide gauge record from Grand Isle tide gauge record. The average subsidence rate is computed using linear regression analysis and residual of Hilbert-Huang transform (HHT) analysis. Uncertainties are 1σ and accounts for colored noise using the Allan variance of rates method (Hackl et al., 2011). The glacial isostatic adjustment (GIA) related subsidence rate is from the model ICE-5G v1.3 (Peltier, 2004).

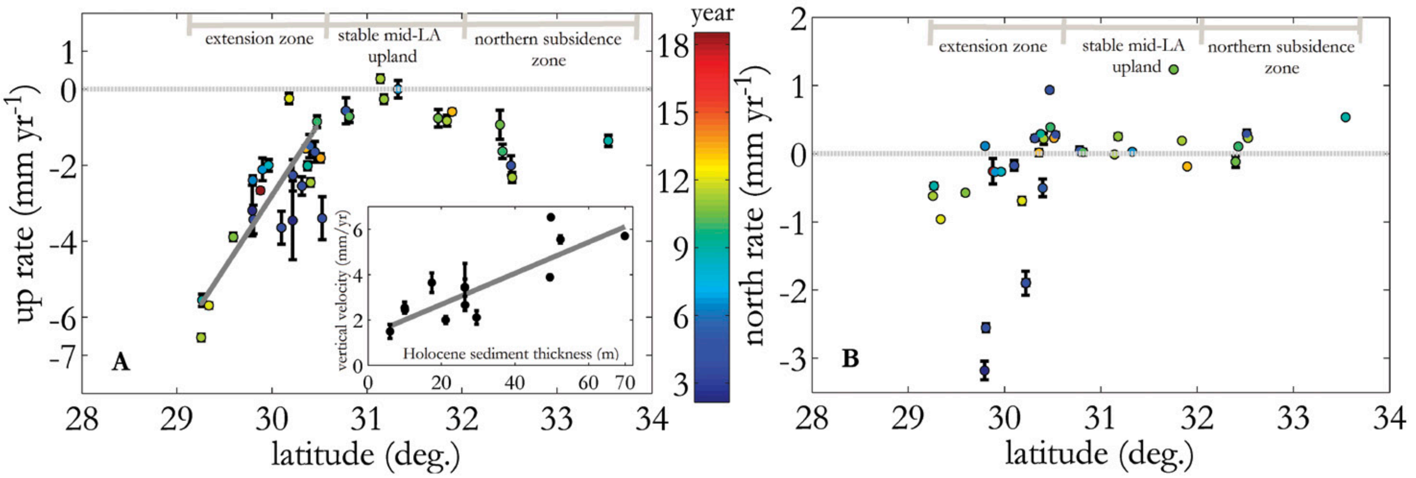

Figure 2. A: Vertical velocities and their standard errors versus latitude. Three geomorphic zones are indicated: extension zone (φ ≤ 30.5°), stable mid-Louisiana (LA) upland (30.5° ≤ φ ≤ 32°), and northern subsidence zone (32° < φ ≤ 34°). Inset shows vertical velocities (mm yr^{-1}) versus Holocene sediment thickness (from Kulp et al., 2002) with linear regression. The correlation between subsidence rate and sediment thickness is 0.85. B: North-south velocities and their standard errors versus latitude. Color bar shows the length of time series for each station.

with shorter time series and higher error bars, the new data suggest that southward motion reaches a maximum rate of ~1.0 mm yr^{-1} at the southern end of the delta.

DISCUSSION

Slow regional subsidence (~1–2 mm yr^{-1}) is indicated in northern Louisiana near the cities of Monroe, Shreveport, and Ruston (Fig. 1A). Total continental water storage estimated from the Gravity Recovery and Climate Change (GRACE; www.nasa.gov/mission_pages/Grace/) satellite in this region shows decreases of 1–3 cm yr^{-1} in equivalent water thickness for these areas from 2003 to 2012 (Famiglietti and Rodell, 2013). Decline in water storage together with glacial forebulge collapse caused by GIA (Peltier, 2004) likely explains the slow subsidence of these upland areas.

Slow vertical rates of motion (0 ± 0.5 mm yr^{-1}) in mid-Louisiana between 30.5°N and 32°N are typical of stable continental interiors. In contrast, areas south of 30.5°N show increasing subsidence, to 6.5 mm yr^{-1}. Two explanations are likely. First, the lower Mississippi Delta is composed of Holocene-age sediments (younger than 12 ka) underlain by Pleistocene-age sediments. Kulp et al. (2002) showed that the thickness of Holocene strata increases southward. The inset plot in Figure 2A shows that subsidence rates in the Mississippi Delta correlate with the thickness of Holocene sediments. This can be explained in terms of faster compaction and expulsion of pore water from younger and thicker saturated sediments (Penland and Ramsey, 1990; Meckel et al., 2006; Törnqvist et al., 2008). Most of the GPS stations in this study are installed on the top of buildings, and so their monuments are actually building foundations that include pilings, vertical structural columns driven to refusal, typically 5–15 m depth. Table DR1 lists the actual foundation depth, where known. Our data therefore do not include the effect of compaction of the uppermost Holocene section, and therefore our subsidence rate estimates for the Mississippi Delta should be considered minimum estimates.

A second possible explanation for subsidence is crustal loading (sedimentary isostatic adjustment, or SIA), where the weight of Holocene sediment causes downward flexure of the crust, with a delayed response due to the viscoelastic nature of Earth's mantle. Ivins et al. (2007) assumed that SIA is the main process that contributes to delta subsidence. Blum et al. (2008) and Wolstencroft et al. (2014) suggested that SIA-related subsidence is not a dominant process in the Mississippi Delta, contributing <1 mm yr^{-1}. A combination of sediment compaction and SIA is also possible. Meckel et al. (2006) suggested that subsidence rates >5 mm yr^{-1} likely reflected processes in addition to compaction.

As summarized in Table 1 and discussed by Kolker et al. (2011) and Morton and Bernier (2010), the high subsidence rates for the period 1959–1994 may correspond to periods of high onshore hydrocarbon production. To investigate this further, and minimize possible effects of sea-level fluctuations, we use three long tide-gauge records along the eastern Gulf of Mexico in stable Florida as reference stations (Table 1). The resulting long-term trend from linear regression represents an average rate influenced mainly by episodic high subsidence rates in 1959–1994. This estimate is 2.1–2.6 mm yr^{-1} higher than the 5.6 ± 0.2 mm yr^{-1} decadal average subsidence rate obtained from GPS measurement at Grand Isle.

To examine if subsidence rates inferred in the past century from tide gauge data were influenced by multidecadal oscillations, the trend was also calculated using the HHT method, which filters the effects of oscillatory modes. Our analysis shows that combining the 1947–2014 subsidence rate calculated from tide gauge data using the HHT method with GIA-related subsidence rate (1.0 mm yr^{-1} at Pensacola; somewhat smaller values for more southern Florida stations) produces results closely comparable to the GPS subsidence rate at Grand Isle (Table 1). The residual component in HHT analysis represents a trend after all oscillation modes (such as decadal and multidecadal variations) are removed (see Fig. DR2.2c). In contrast, the trend obtained from simple linear regression may be influenced by decadal or multidecadal variations and therefore may not accurately reflect long-term subsidence associated with sediment compaction, SIA, or other nonanthropogenic processes (Fig. 3).

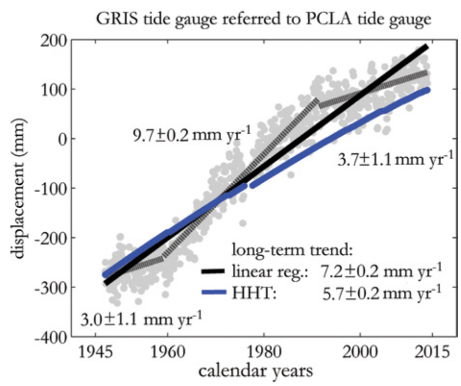

Figure 3. Plot of tide gauge data at Grand Isle, Louisiana (GRIS) referenced to Pensacola, Florida (PCLA) (gray dots) and comparison between average long-term subsidence rate (black line) and change of rate (dash line) obtained from linear regression (reg.) analysis, compared to Hilbert-Huang transform (HHT) analysis (blue line).

The agreement between the subsidence rate obtained from a decade of GPS measurements and those estimated from multidecadal tide gauge records using the HHT method indicates that continuous GPS measurements adequately measure subsidence of the delta, and also suggests that some prior analyses of subsidence based on tide gauge data may have been overly influenced by multidecadal oscillations in either oceanographic effects, subsidence effects, or both (see Fig. DR2.2 and the discussion in Appendix DR2).

IMPLICATIONS FOR COASTAL RESTORATION

The current subsidence rate of the southern Mississippi Delta varies from 5.6 mm yr^{-1} to 6.5 mm yr^{-1} based on three southern delta GPS stations. Tide gauge data for the post-1990s suggest subsidence here of at least 4.5 mm yr^{-1} (adding 3.5 mm yr^{-1}, the minimum rate using the St. Petersburg, Florida, tide gauge as a reference and 1.0 mm yr^{-1} for the GIA signal). These results do not reconcile with the results of Morton and Bernier (2010) and Kolker et al. (2011), who estimated a current subsidence rate of <2 mm yr^{-1} since 1990. Assuming 2.1 mm yr^{-1} for the rate of sea-level rise (the long-term average value at Pensacola), the current rate of relative sea-level rise for the coastal delta is therefore at least 6.6 mm yr^{-1} using tide gauge data and 7.7 mm yr^{-1} using the GPS data. Using the higher average rates of sea-level rise since 1990 (e.g., 2.6 mm yr^{-1} at Pensacola after correcting for GIA; Table DR2.1 in Appendix DR2) implies that total rates of relative sea-level rise for the southern delta are at least 7.1 mm yr^{-1} (tide gauge) and 8.2 mm yr^{-1} (GPS). Using the average subsidence rate for the southern delta measured by GPS (5.9 mm yr^{-1}) and the post-1990 sea-level rate (2.6 mm yr^{-1}) gives a relative sea-level rise rate of 8.5 mm yr^{-1}. As a check on internal consistency, note that this latter value is similar to the total rate recorded at the GRIS tide gauge since 1990, 9.1 mm yr^{-1} (Table DR2.1), which presumably records the combined effects of sea-level rise and land subsidence over the same period. We do not know if such elevated rates of sea-level rise will continue in the future, but this seems likely, and prudent planning would dictate that the higher values be used.

Our subsidence rates do not translate directly into rates of surface lowering, as they do not account for loss of organic material by oxidation or compaction in the upper ~5–35 m of Holocene sediment (which would make our rates minimum estimates of the rate of land lowering), or resedimentation (which would reduce the effects of subsidence). Kirwan et al. (2010) noted the adaptability of coastal marshes to relative sea-level rise in the presence of high suspended sediment concentration due to resedimentation. However, Blum and Roberts (2012) noted that dams on the upper Mississippi have greatly reduced the supply of sediment to the delta. In this context, our new data have important implications for predictions of future land loss and storm surge inundation, as well as land reclamation and wetland restoration efforts. For example, it may be useful to focus such efforts where subsidence rates are lower.

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