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# Estimation of vertical land movement rates along the coasts of the Gulf of Mexico over the past decades

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ABSTRACT

We estimated the vertical land movement rates at tide gauge stations along the Gulf of Mexico (GOM) coasts. A novel approach suggested by Kuo et al. (2004, 2008) for combining satellite altimetry and tide gauge data was applied. The obtained vertical land motion rates were compared with the GPS vertical velocities measured at Galveston, Grand Isle, Dauphin Island, Pensacola and Key West stations. The estimated vertical rates range from slow subsidence in the South of Florida and Veracruz to high subsidence rates in Texas and Louisiana where some of the tide gauges subside at the rate of up to 7 mm/yr. A small but noticeable uplift in the NE of the Gulf was detected at Cedar Key and Apalachicola and a very low subsidence at Pensacola tide gauge. We suppose there are some local tectonic processes which contribute significantly to the land movement at these stations. Comparison with the post-glacial rebound model ICE5G-VM2 predictions shows that the drivers of the subsidence on the GOM shelf are of local nature. The resulted absolute sea level rise along the GOM coast was estimated to be about $2.0 \pm 0.4$ mm/yr.



## 1. Introduction

The low-lying coasts of the Gulf of Mexico (GOM) are a site of a large variety of ecosystems and human communities that are highly vulnerable to sea level changes. Sea level rise in these areas is a major problem for coastal strategy planning as the population of the five states of the U.S for example. Gulf coast has been projected by the Census Bureau to increase nearly 40% from 1995 to 2025 (Crosset et al., 2004). An accurate estimate of the long term trends in relative sea-level rise (SLR) along the Gulf coasts is thus of primary importance for appraising the risks associated with the vulnerability of low-lying areas.

The relative sea level fluctuations include both absolute sea level changes and vertical land motion that can be due to glacial isostatic adjustment (GIA), tectonic processes or coastal subsidence or uplift provoked by anthropogenic factors. The rates of the relative SLR in the GOM range from about 1 mm/yr at Veracruz, Mexico, to nearly 10 mm/yr at Grand Isle, in the Mississippi delta (Douglas, 2005). This large variability is mostly due to the subsidence of the northern GOM induced by extraction of hydrocarbons, groundwater withdrawal, land reclamation and sedimentation (Emery and Aubrey, 1991; Douglas, 2005). As to the vertical land movements due to GIA, they are spatially uniform along the GOM coasts and have amplitude less than 1 mm/yr of subsidence (Peltier, 2004). No significant tectonic activity was reported along the northern Gulf coast, the Gulf seismicity being relatively low (Nicholson and Wesson, 1990; Gonzalez and Törnqvist, 2006; Törnqvist et al., 2006) although the coast is not seismically quiescent (Lopez, 1991).

In general, the coast of the Gulf of Mexico is exposed to problematic situations that can be categorized into two different processes: (1) coastal erosion; and (2) loss of wetlands (Boesch et al., 1994; Davis, 2011). Both of these processes are at least partly due to absolute sea level rise exacerbated by vertical land movements (Davis, 2011). This issue particularly concerns the most vulnerable parts of Louisiana and eastern Texas coasts.

Several techniques can be used to monitor the vertical land motion. Tide gauges measure sea level relative to a local reference point attached to the land upon which the gauges are grounded at the coast. Differences between tide gauge sea level records have

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been used in the past to provide a map of relative land movement consistent with previous geological knowledge of the area (Emery and Aubrey, 1991). However, in the context of sea level rise, this approach does not attain accuracy in estimating vertical land movement rates that is required by the coastal community planning. In contrast to the tide gauge data which are measurements of sea level relative to land datum, space geodetic techniques have been used to estimate the geocentric vertical motion relative to the Terrestrial Frame. In the recent years, Global Positioning System (GPS) has become a commonly used geodetic technique due to its high precision, ease of use and affordable equipment. The use of GPS vertical velocities in combination with tide gauge records has provided worthwhile results on the global scale (Wöppelmann et al., 2007). However, the GPS network is heterogeneous and the recording period is sometimes too short to estimate a stable trend in land movement. Many problems remain to be solved. For instance, the importance of a stable and accurate reference frame over decades has repeatedly been underscored (e.g., Beckley et al., 2007; Blewitt et al., 2010), and has become the dominant limiting factor for reducing uncertainties in the recent global sea-level trend estimates (Collilieux and Wöppelmann, 2011). Since the early 1990's, satellite altimetry provides an accurate absolute measurement of sea surface height. Mitchum (1994) proposed to calibrate the time-dependent drift in satellite data by comparing the altimetry and tide gauge measurements. As the length and quality of satellite measurements improve constantly, Mitchum (1998) turned the calibration problem into a method for estimating vertical land motion by differencing absolute sea level heights derived from the satellite altimetry and the tide gauge records. To the extent the sea level signals are coherent; the difference "altimetry minus tide gauge" is a measure of vertical land motion at the gauge. The approach has also been explored by Cazenave et al. (1999); Nerem and Mitchum (2002) and Garcia et al. (2007) among others.

Buble et al. (2010) developed the method proposed earlier by Davis et al. (1999) to separate common-mode relative sea level from spatially variable signals. They used the observations from tide gauges colocated with continuous GPS (CGPS) stations to investigate crustal deformation and absolute sea level changes along the eastern margin of the Adriatic Sea.

To overcome the space coverage limitation of GPS stations and restrictions due to the short length of the altimetry time series, Kuo et al. (2004, 2008) have significantly improved the basic method used by Cazenave et al. (1999) and Nerem and Mitchum (2002), hereafter referred to as the direct approach. As in the direct method, the general idea of the Kuo's approach consists in subtracting the tide gauge data relative to the coast from the geocentric satellite altimetry data. The novelty of this method is in setting some complementary constraints on the estimated "altimetry – minus tide gauge" differences. Kuo et al. (2004) assumed that the trend of absolute or geocentric sea level variations is the same at the neighboring tide gauges Kuo et al. (2004). The method was successfully applied for determining land motion and absolute sea level trend in lakes (Kuo, 2005), the closed seas as the Baltic Sea (Kuo et al., 2004) and the Mediterranean Sea (Wöppelmann and Marcos, 2012) and along the Alaska shelf (Kuo, 2005). In this paper, we applied the Kuo et al. (2004) approach in the estimation of vertical land movement along the coasts of the GOM. At the low enough frequency, the flow on the GOM shelf is quasi-geostrophic (Li and Clarke, 2005) and the absolute sea level signal should be nearly constant along the shelf. Although the wind forcing introduces spatial variability in the absolute sea level signal at the interannual frequencies (Li and Clarke, 2005), its effect seems to be negligible over the periods longer than 5 yr (Douglas, 2005). Thus, the interdecadal absolute sea level fluctuations and especially the trend over the last 50 years are expected to be coherent and in phase over the entire GOM shelf.

The Kuo et al. approach was proved to be superior in terms of precision and accuracy than the direct approach that is still in use (e.g., Garcia et al., 2007; Ray et al., 2010; Braitenberg et al., 2011; Trisirisatayawong et al., 2011). Applying this technique to the Gulf of Mexico shelf is interesting for several reasons: first, the Gulf coast is affected by land motion of large variability (Davis, 2011). Secondly, the tide gauge records along the North coast are of high quality that allows getting accurate estimates of relative sea level trends. Third, the robustness of the method can be checked against the independent GPS vertical velocities in the GOM from the latest ULR solution (Santamaría-Gómez et al., 2012). And finally, the results will provide estimates of absolute vertical motion responsible for relative sea level rise in a vulnerable area affected by: (1) the compaction of sediments carried out by the Mississippi river, (2) local tectonic processes as salt migration or crustal faulting or (3) human activity mostly associated with withdrawals of fluids and the petroleum engineering.

Our investigation begins in Section 2 by reviewing available tide gauge records, the satellite altimetry data and continuous GPS stations co-located at tide gauge stations in the Gulf of Mexico. Section 3 describes the direct method employed by Mitchum (1998), Cazenave et al. (1999) and presents the approach of Kuo et al. (2004, 2008). Section 4 discusses the estimated vertical land motion rates and compares them to the prediction of the last version v1.3of ICE-5G-VM2 model (Peltier, 2004) and to the GPS vertical rates. Section 5 concludes the study.

## 2. Data sets

### 2.1. Tide gauges

The tide gauge records used in this study are monthly averaged time series from the 'Revised Local Reference (RLR)' dataset of the Permanent Service for Mean Sea Level (PSMSL, available at http://www.pol.ac.uk/psmsl). The RLR is the most appropriate dataset for the long term trend studies as its records were previously checked and corrected for local datum stability relative to benchmarks in their nearest vicinity (Holgate et al., 2013). We focused on RLR records from the Gulf of Mexico with a sufficient number of observations to determine long-term relative sea level rates that are believed to represent the long-term climate contributions plus the movement of the land on which the tide gauges are grounded. For 40-year long tide gauge records, the standard errors of the linear trends are typically of 0.5 mm/yr (Douglas 1991, 2001). Tide gauge records were rejected if they did not contain more than 85% of valid data within a time span of at least 40 years. The tide gauge records were truncated at December 2011 (Section 2.3). The names of tidal stations used, along with their location, period of operation and percentage of data gaps are listed clockwise around the Gulf of Mexico from Veracruz, Mexico, to Key West, Florida in Table 1. Fig. 1 shows the location of the 15 selected tide gauge records. Most are located along the northern coast of the Gulf of Mexico. The Galveston II record is the longest: it extends back to 1908. Note that Galveston II is located 2.8 km apart from Galveston I. Both Galveston stations have been operating simultaneously since 1957.

### 2.2. Satellite altimetry

The satellite altimetry data used in this study were weekly gridded sea level anomaly (SLA) fields computed from a merged multi-mission solution of AVISO (http://www.aviso.oceanobs.com/duacs/). The SLA were produced by combining data from several satellite altimetry missions, namely: Topex/Poseidon (T/P) over the