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Inter-annual sea level variability in the southern Gulf of Mexico (1966–1976)

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[1] Hourly time series at seven locations throughout the southern Gulf of Mexico were used to calculate the trend and the inter-annual sea level. The sea level series from January 1966 to December 1976 were filtered using a Lanczos low pass filter to remove oscillations with periods smaller than one year. The results revealed a sea level increment of about 1.4 mm yr^{-1} from 1966 to 1976 in the southern Gulf of Mexico. The monthly sea level variability obtained after the trends were removed, presented a sea level setup during winter and a sea level depression in summer attributed to seasonal wind conditions. The horizontal representation of averaged sea level in the southern Gulf of Mexico presented a saddle critical point. The associated sea level slope indicated water accumulation at Ciudad Madero in the western side of the gulf and Coatzacoalcos in the southernmost station, and sea level depressions at Tuxpan and Progreso in the southwestern and southeastern side of the gulf, respectively. Nevertheless, one of the most intriguing result is the presence of a Kelvin wave with a two mode oscillation axis that goes from Progreso to Tuxpan. **Citation:** Salas-de-León, D. A., M. A. Monreal-Gómez, D. Salas-Monreal, M. L. Riveron-Enzastiga, and N. L. Sánchez-Santillan (2006), Inter-annual sea level variability in the southern Gulf of Mexico (1966–1976), *Geophys. Res. Lett.*, *33*, L08610, doi:10.1029/2006GL025832.

1. Introduction

[2] The knowledge of sea level trends using long-term sea level series is essential to understand the shoreline changes, and changes in topography/bathymetry. An important indicator of global change is the rise in global mean sea level. Therefore, if a long-term rise in global mean sea level was detected, it would provide further evidence to support the global warming predicted by some climate models due to an increase in "greenhouse" gases [e.g., *Wild et al.*, 2003]. The sea level data collected from tidal gauges over the last century, and the most resent Topex/Poseidon sea level satellite data suggest an increase of the average sea level at a rate of 1 to 2 mm yr^{-1} [*Cross et al.*, 2001]. Regional sea level could be modified by long term wind stress [*Ko et al.*, 2005], which under certain conditions may create long waves with seasonal frequencies [*Blaha and Sturges*, 1981]. Tidal gauge measurements can be affected by land mass movement [*Tronvig et al.*, 2005]. For instance, the sea level rise in the northern Gulf of Mexico [*Tronvig et al.*, 2005] is attributed to subsidence effects, geological compaction, and terrigenous reduction from rivers [*Kjerfve et al.*, 2002; *Turner*, 1990]. The reduction of deltaic wetland in the northern gulf reduces sediment transport [*Day et al.*, 1995] affecting tidal gauge measurements. Whichever the origin of the change in the mean sea level, one of the most evident results is the reconfiguration of the coastline [*Penland and Ramsey*, 1990].

[3] The coastal region in the southern Gulf of Mexico undergoes strong changes, attributed to decreasing river discharges that modify the balance between the density currents and the buoyant forces associated to river discharges. The reduction of river discharges is one of the consequences of the construction of big dams [*Kjerfve et al.*, 2002].

[4] The main producer of subtidal sea level variations in several coastal basins is the wind stress [*Salas-Monreal*, 2002]. In the southern Gulf of Mexico, northwesterly winds produce water level setup [*Fuentes-Yaco et al.*, 2001], whereas southeasterly winds that dominate during summer produce the opposite scenario. During winter, the wind speed decreases considerably from the center gulf toward the coast, owing to land friction. In summer the wind direction is reversed reducing the upwelling and the wind jet, located in the southern-central gulf, where the Coatzacoalcos region is located (Figure 1) [*Salas-de-León et al.*, 1992]. The sea level depression in the northern gulf during winter and the setup in summer are inversed with respect to sea level conditions observed in some estuaries in the southern gulf [*Fuentes-Yaco et al.*, 2001]. Still, sea level conditions in the southern Gulf of Mexico seem coherent with the observations in the Cuban coast, where the maximum sea level is reached one month earlier than the one observed in the southern gulf (October). These effects produce oscillation with periodicities of 3, 4, and 6 months that mask the long annual solar and semi-annual solar tides [*Hernández and Díaz*, 2005].

[5] Although the sea level variability and the increasing trend in the northern Gulf of Mexico has been largely studied [*Zervas*, 2001], little attention has been paid to the southern gulf, where long-term sea level observations remain mostly unexplored. The long-term sea level change has strongly modified the shoreline configuration in the southern Gulf of Mexico. This paper, thus, contributes to advance the knowledge on sea level trend and

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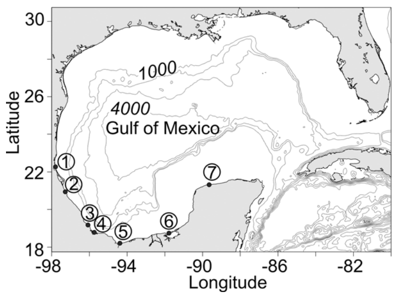

Figure 1. Location of the tidal gauge and the bathymetry (m) stations in the southern Gulf of Mexico.

inter-annual sea level variations in the southern Gulf of Mexico.

2. Data and Procedures

[6] Hourly sea level series at seven tidal gauge stations in the southern Gulf of Mexico (Figure 1 and Table 1) were used to calculate the sea level trend in this region. The series were monthly averaged in order to observe the monthly and annual sea level variations throughout the southern gulf. Frequencies smaller than one year were removed from the monthly averaged series with a Lanczos low pass filter [*Salas-Monreal*, 2002] to emphasize the long sea level periodicities in the southern Gulf of Mexico. The sea level trend and the monthly mean were subtracted from each series to compare the monthly sea level anomaly among stations. The sea level series, published by the National Tidal Bureau from the Institute of Geophysics, at the National Autonomous University of Mexico [*Grivel-Piña and Grivel-Villegas*, 1991] were collected at different time periods, ranging from 17 years (Cd. Madero) to 37 years (Veracruz) (Table 1). These time series coincide from January 1966 to December 1976. A fast Fourier analysis (FFT) was performed to each corrected sea level series to analyze and compare the dominant frequencies of the sea level in the southern Gulf of Mexico. Unfortunately, no subsidence information was available during the development of this study.

3. Results and Discussion

[7] The monthly sea level variations in the southern Gulf of Mexico reflected the large-scale wind-induced sea level setup and depression during the winter and summer months, respectively (Figure 2). The sea level trend in the southern Gulf of Mexico presented a growth rate of 1.4 mm yr^{-1}. The maximum monthly average sea level was observed at

Table 1. Location of the Tide Gauge and Time Series Period of Monthly Averaged Sea Level

Tide Gauge	Name	Latitude, N	Longitude, W	From	To
1	Cd. Madero	22° 13′	97° 51′	1962	1979
2	Tuxpan	21° 00′	97° 20′	1958	1976
3	Veracruz	19° 12′	96° 08′	1953	1990
4	Alvarado	18° 47′	90° 46′	1955	1981
5	Coatzacoalcos	18° 09′	94° 25′	1966	1990
6	Cd. del Carmen	18° 38′	91° 50′	1956	1990
7	Progreso	21° 18′	89° 40′	1952	1985

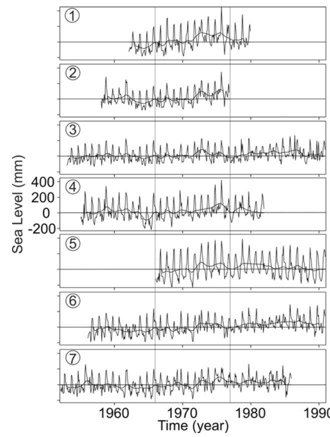

Figure 2. Monthly sea level anomaly (mm) at each station. The black solid line represents the trend after the higher frequencies (<1 year) were removed.

Coatzacoalcos and Cd. Madero, whereas the minimum was observed at Tuxpan and Progreso (Figure 3). The lowest sea level values at all stations were observed during the first six months of the year (Figure 4), the sea level started to increase almost simultaneously from October. In 1972, the sea level increased continuously during most of the months. This irregular sea level increase was appreciated during the subsequent years in every station (Figure 4). The sea level monthly means at all stations from January 1966 to December 1976, presented the lowest sea level values from December to July, with an increasing tendency along the years (Figure 5). The lowest sea level was usually observed during February, and started to increase sharply after August, reaching its maximum on October (Figure 6). Although, February is a month with strong northerly winds, which would suggest sea level setup in the southern gulf, this study shows that when the sea level variation, that is, the induced barotropic gradient caused by wind transport is in geostrophic balance, the resulting balance moved the water toward the west inducing a sea level depression in the southern part of the gulf. After the strong wind relaxes, the minimum sea level in the southern gulf was produced, and the oscillation of the sea level due to the geometry of the gulf produced a small second minimum in June (Figure 6).

[8] One of the most intriguing finding was the symmetry of the horizontal representation of the averaged sea level in

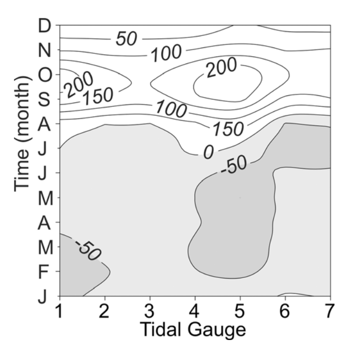

Figure 3. Monthly sea level (cm) averaged contours throughout the entire time series at each of the seven stations.

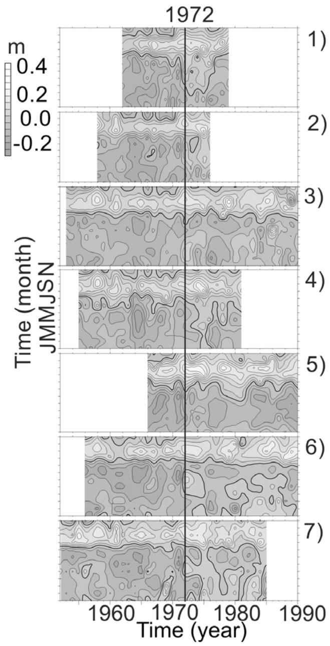

Figure 4. Contours of the sea level anomaly (m), against time in year (x) and month (y) from each of the series.

the Campeche Bay, in the southern Gulf of Mexico, between Cd. Madero and Coatzacoalcos, and between Tuxpan and Progreso, as denoted with the sea level isolines in Figure 7. The highest sea level values were found at Cd. Madero and Coatzacoalcos, while the lowest values were reported at Tuxpan and Progreso. This pattern suggested a Kelvin wave oscillation axis between those stations. Figure 7 reproduces the typical representation of a phase space and the mathematical setup of this representation is a nonlinear ordinary differential equation (ODE) corresponding to a nonlinear autonomous system. The solution of the equation is given by functions of pair order that simultaneously satisfy the system. This is a very well known ODE problem [e.g., *Roos*, 1964]. An increasing direction is associated at any point of the phase space. The increasing direction, in all possible parametric representations, corresponds to solutions of the system. The critical point of the nonlinear system is the saddle point, which is clearly unstable. In terms of the solution of the two-dimensional wave equation, the observed structure corresponds to a two mode oscillation system [e.g., *Weisstein*, 2005]. Therefore, the water

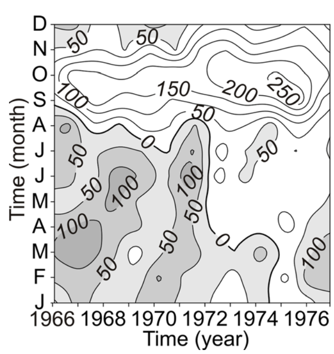

Figure 5. Contours of averaged sea level (cm), from the seven stations, versus time in year (x) and month (y).

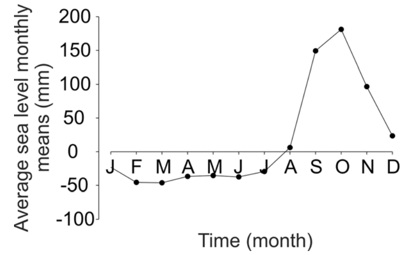

Figure 6. Annual cycle of averaged monthly sea levels (mm) from all the series.

mass should flow toward the lower level regions. The Coriolis effect modified the flow by deflecting the currents, resulting in water accumulation at Cd. Madero and Coatzacoalcos, and sea level depressions at the Tuxpan and Progreso stations. The sea level asymmetry induced coastal currents and a convergence zone with strong vertical currents in the southern Gulf of Mexico, near the Coatzacoalcos station [*Monreal-Gómez et al.*, 2004]. In fact, this process is reflected by the zooplankton distribution [*Espinosa-Fuentes and Flores-Coto*, 2004]. The zooplankton is dragged southward and driven by the convergence near the coast, which creates a zooplankton cell with oceanic characteristics at the surface, estuarine in the middle, and oceanic at the bottom.

[9] The spectral analysis of the non-filtered series presented important oscillations at 3, 4, 6, and 7 months at high frequencies, and at 1, 1.2, 1.5, 2.2, 3.6, and 6 years at low frequencies (Figure 8). In addition, periodicities of 7, 8.5, and 12.6 years were reported at the Veracruz, Alvarado, Cd. del Carmen, and Progreso stations, the longest available time series. The latter is coherent with the decadal variation reported by *Watanabe et al.* [1999] in the northern Gulf of Mexico.

4. Conclusions

[10] The sea level trend analysis over seven stations in the southern Gulf of Mexico revealed a sea level increment at a rate of about 1.4 mm yr^{-1}, during January 1966 to December 1976. The variations of sea level monthly mean reflect the large-scale wind-induced sea level setup and depression during the winter and summer months, respectively. The sea level oscillations are a consequence of seasonal wind stress conditions. The sea level setup during winter and set down in summer depicts an opposite behavior to that reported for the northern Gulf of Mexico, and a one month phase lag with the one observed in the Cuban

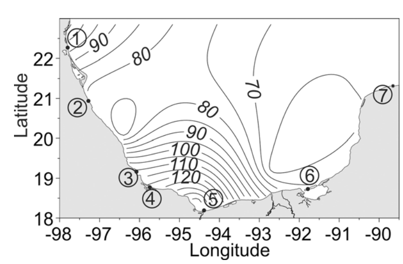

Figure 7. Contour of the monthly averaged sea level (cm) throughout the entire series from each station.

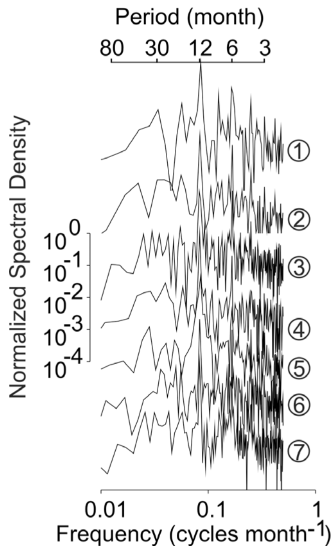

Figure 8. Power spectrum for each of the sea level series.

Coast. The lowest harmonics were associated with seasonal changes such as: dry, rain, and winter storms (or cold-fronts locally named ''norths'') seasons. The sea level setup induced by norths does not last the whole winter, but induces an oscillation with a 6 months period. Others periods (3, 4, and 7 months) are associated to combinations of dry and wet seasons. The sea level symmetry shows a phase space between Cd. Madero and Coatzacoalcos, and between the Tuxpan and Progreso stations, the direction of the phase space indicates water movements, accumulations at the Cd. Madero and Coatzacoalcos stations, and sea level depressions at the Tuxpan and Progreso stations. The water accumulations in the southernmost part of the Gulf of Mexico must induce a convergence zone associated with strong vertical velocity and coastal currents.

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