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Sedimentary records of recent sea level rise and acceleration in the Yucatan Peninsula

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ABSTRACT

Recent eustatic sea level rise (SLR) is one of the most striking manifestations of recent climate change as it directly impacts coastal activities and ecosystems. Although global SLR is well-known, local values differ due to vertical land motion, and changes in atmospheric pressure, ocean currents and temperatures. Although a reliable estimation of local SLR trends is needed to assess coastal zone vulnerabilities and plan adaptation strategies, instrumental records are usually short or sparse, especially in developing countries. Here we show that ^{210}Pb-dated sedimentary records from mangrove saltmarshes can provide useful decadal records of local SLR trends. We quantified sediment accretion rates in sediment cores from remote mangrove saltmarshes of the Yucatan Peninsula. Best SLR records were observed for cores collected near mean sea level (MSL). During most of the XX century the SLR rate ranged from 1-2 mm yr^{-1}, increased to a maximum of 4.5 ± 0.6 mm yr^{-1} and the acceleration was 0.13 mm yr^{-2}. Assuming either a constant SLR rate or acceleration, by the end of this century MSL level will be 39 cm or 91 cm above the present value. Both coastal infrastructures and ecosystems will be negatively affected by SLR and society will need to adapt relatively fast to the new conditions.

1. Introduction

Recent eustatic sea level rise (SLR) is mainly due to deglaciation of continental ice, thermal expansion of the oceans and changes in continental water storage, and it is increasingly stressing coastal ecosystems (Church et al., 2008). However, local impacts are directly related to the relative sea level (or mean sea level, MSL) referred to a fixed point on earth, which also includes vertical crust movements such as the glacial isostatic adjustment (Wu et al., 2010) and local subsidence (Nicholls and Cazenave, 2010). Although this is usually measured with tide gauges, their geographical density and record-length, notably in developing countries, are often not enough to provide society with the required information to unambiguously reveal SLR, and plan adaptation and mitigation strategies. Therefore, in most world regions, sedimentary records are the only plausible alternative to establish long enough (decadal to centennial) records to estimate local SLR trends.

Sedimentation processes in intertidal areas and their relation with SLR have been the subject of many studies (e.g. Leorri et al., 2010; Barlow et al., 2014; Ruiz-Fernández et al., 2016; Sanders et al., 2016). The main external forcings of saltmarsh sedimentation are sea level and sediment supply, and the latter governs the ability to maintain elevation with SLR (Nolte et al., 2013), thus saltmarsh sedimentary records may contain useful information on SLR. In the decadal to centennial scale, the most useful chronological tool is the ^{210}Pb sediment dating method (Sanchez-Cabeza and Ruiz-Fernández, 2012)

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and changes in accretion rates have been sometimes attributed to sea level rise, as for example in the US Atlantic (Bricker-Urso et al., 1989), the Gulf of Mexico (Lynch et al., 1989), the Mexican Pacific (Ruiz-Fernández et al., 2016) and the Wider Caribbean region (Parkinson et al., 1994).

In this work, we quantified recent sediment accretion in three remote mangrove saltmarshes from the Yucatan Peninsula (Sian Ka'an biosphere reserve), at different orthometric heights, by ^{210}Pb sediment dating. Geochemical (C/N) and isotopic (δ^{13}C) proxies of marine *versus* terrestrial sources were used to relate recent changes to marinization caused by SLR. We expect this results to be useful for the reconstruction of local SLR rates in regions with short or nonexistent instrumental records, and results be used by coastal zone managers for a sound planning of adaptation strategies.

2. Materials and methods

2.1. Study area

The Yucatan Peninsula is a large carbonate platform mainly composed of limestone sedimentary rocks, with low topographic relief and a karstic nature. The peninsula is the Mexican region with more mangroves (55% of the total; CONABIO, 2009), which are at risk because of sea level rise and other anthropogenic pressures. It has ecological and socio-economic importance because of its biodiversity, fishery resources, historical heritage and tourism. The region is tectonically stable (Zúñiga et al., 2000; Marquez-Azua et al., 2004) and is glacio-hydro-isostatic stable in relation to equilibrium (Potter and Lambeck, 2004).

The Sian Ka'an Biosphere Reserve, a large coastal ecosystem on the Caribbean coast, is rich on mangroves and saltmarshes. Samples (Fig. 1 and Table 1) were collected from hypersaline areas behind mangroves, usually with little vegetation (named tropical saltmarshes; Ruiz-Fernández et al., 2016). They are periodically inundated with high tides and therefore in relative equilibrium with MSL (Krauss et al., 2014). Cores were collected i) close to a coastal lagoon in the northern area (Laguna Negra, LANE), ii) from an island in the main bay (Cayo Culebra, ISCUL), and iii) from one of the lagoons in the southern area (near Punta Pájaros, PUPA).

2.2. Analytical methods

Site locations were georeferenced by establishing a local reference point with a GPS (Leica GRX1200 classic receiver and Leica AT504 Choke Ring antenna) with a nominal post-processing vertical precision of 6 mm. Station heights were measured with a Leica GS10 receiver and a Leica AS10 geodesic antenna, with a nominal vertical precision of 3.5 mm. Levelling was achieved with a Leica DNA03 digital level. The overall height uncertainty was estimated to be close to 6 cm.

Sediment cores were collected with a split push corer (inner diameter 10 cm, length 50 cm long). The same day, one tube half was removed, sediment was carefully cut into 1 cm sections and samples stored in plastic containers. In the laboratory, samples were freeze-dried (except a 1g aliquot for grain size analysis). Geochemical analyses included grain size (laser diffraction of samples digested with 30% H_2O_2, with a Malvern Mastersizer 2000) and magnetic susceptibility (Bartington MS2G). Total nitrogen (TN) and organic carbon (OC) were analyzed with a CE Instruments Flash EA 1112 Element Analyzer after careful removal of the dominant carbonate fraction with 1.5 M HCl. The accuracy of the TN and OC methods was determined by the analysis of the Calibration Sample (soil) LECO,

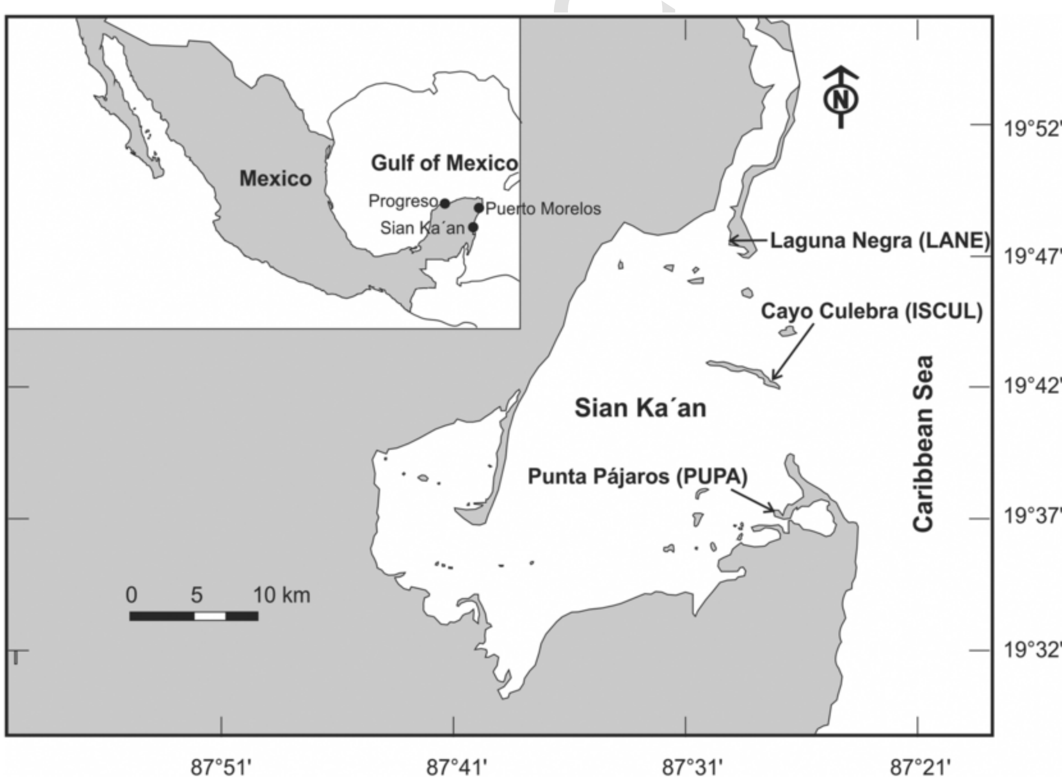


Fig. 1. The Yucatan Peninsula, showing sampling sites and tide gauge stations. The map shows the sampling sites in Sian Ka´an (LANE: Laguna Negra; ISCUL: Cayo Culebra; PUPA: Punta Pájaros). Tide gauges are present in Progreso and Puerto Morelos. Production note: 2 column figure.

Table 1
Sampling information of sediment cores collected in Sian Ka'an, Yucatan peninsula, in April 2013.*

Site	Code	Orthometric height* (cm)	Location
Laguna Negra	LANE	77	19° 47' 25.95" N 87° 28' 49.42" W
Punta Pájaros	PUPA	35	19° 36' 09.27" N 87° 27' 15.58" W
Cayo Culebra	ISCUL	-43	19° 41' 39.61" N 87° 27' 37.53" W

* *Of the core surface*

Part number 502-309, Lot 10002. Recoveries ranged from 97-102% for TN, and from 93-98% for OC.

Sediment chronology was established through ^{210}Pb analysis (Ruiz-Fernández et al., 2009) and common dating models (Sanchez-Cabeza and Ruiz-Fernández, 2012) with Monte Carlo uncertainty estimation (Sanchez-Cabeza et al., 2014). Replicate analyses of the certified reference material IAEA-300 (radionuclides in Baltic Sea sediment) confirmed results within 1σ uncertainty. The Constant Flux (CF) model (also known as the Constant Rate of Supply – CRS - model) was used to calculate the mass accumulation rates (MAR) and the sediment accretion rates (SAR). The age model (section mean ages and layer ages) is included as Supplementary material.

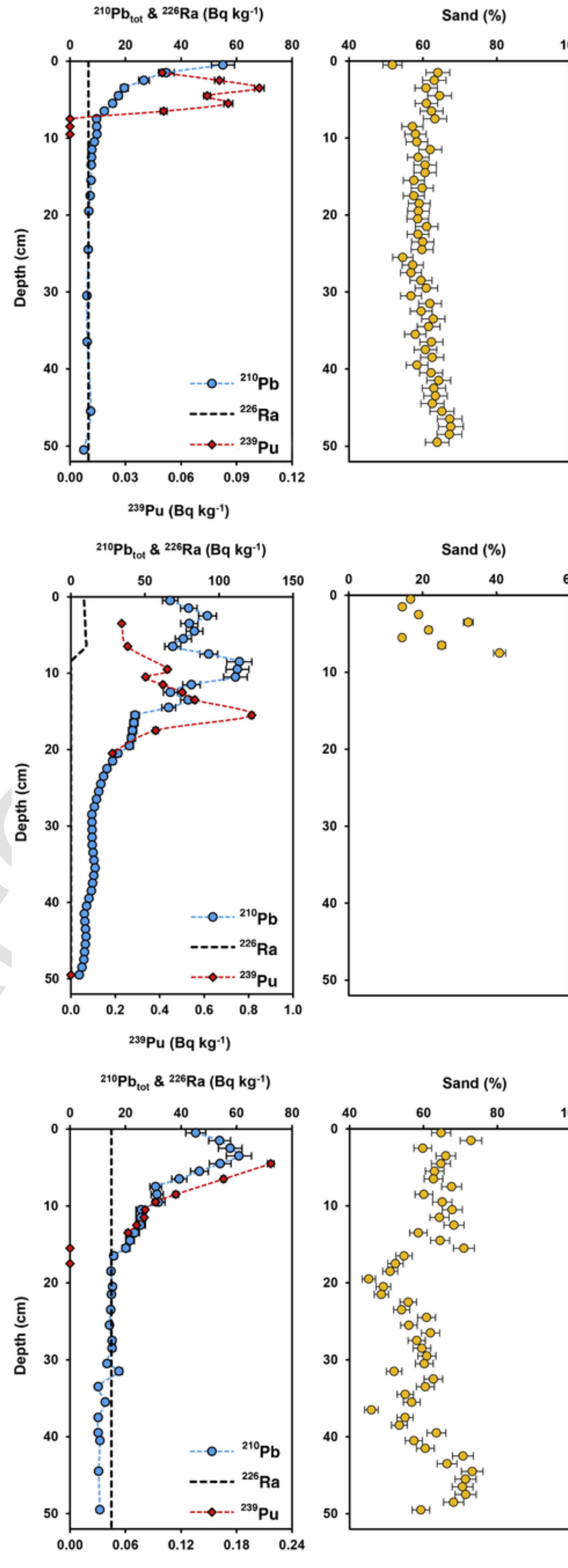
Chronologies were corroborated by the analysis of ^{239}Pu by mass spectrometry. Samples were dissolved by fusion and purification was performed with TEVA (Triskem International) resins. Measurement of Pu isotopes was performed with a Neptune plus high resolution double focusing multicollector ICP-MS (Thermo Scientific Inc.) equipped with ten faraday collectors and five ion counters. Aqueous solutions were introduced into the ICP-MS using a CETAC Arridus II desolvator (Elemental Scientific Inc.).

Samples for δ^{13}C analysis were placed into centrifuge tubes, inorganic carbon was removed by washing with 1N HCl overnight. Samples were rinsed with Milli-Q water and freeze-dried several times until acid was completely removed. δ^{13}C was determined by isotope-ratio mass spectrometry coupled to an elemental analyser (EA-IRMS). Samples were introduced in an elemental analyzer Vario Micro CubeTM coupled to an Isoprime100TM continuous flux mass spectrometer. Values are relative to the international reference standard Vienna Pee Dee Belemnite (± 0.1‰ at 1σ) and replicate analysis of 3 samples showed a variation coefficient of 0.1%.

3. Results

Core data are shown in the Supplementary material. All sediment cores were mostly sandy (Fig. 2), except in the core ISCUL, which showed a remarkable transition from mangrove peat to a sandy sediment at 8 cm depth. Albeit a small fraction, silt and clays were also present. Magnetic susceptibility was not detectable in any sample due to the carbonate nature of the Yucatan Peninsula.

^{210}Pb profiles in cores LANE and PUPA (Fig. 2) showed an asymptotic decrease towards a supported ^{210}Pb (^{226}Ra) value of 6.7 ± 0.9 Bq kg^{-1} and 14.9 ± 0.4 Bq kg^{-1}, respectively. The peat section of the ISCUL core showed undetectable ^{226}Ra concentrations, and the upper sandy segment showed a mean ^{226}Ra activity of 9.5 ± 0.6 Bq kg^{-1} (determined by gamma spectrometry). The LANE profile showed a clear exponential decrease, as expected in the case of constant accretion and sediment composition (almost constant sand contents). The PUPA sand contents is almost constant in the datable segment (above 17 cm) and the uppermost concentration decrease, below



3 cm, can be attributed to increasing accretion rates. In the case of ISCUL, a transition from peat to a sandy sediment is observed above 8 cm. This strong texture changes is reflected on an overall reduction of concentrations, but keeping a similar shape than core PUPA, with a ^{210}Pb maximum concentration in Section 2-3 cm, also suggesting increased accretion in the upper segment.

We derived age models for sections and layers (see the Supplementary material) by using the constant flux (CF) model (Sanchez-Cabeza and Ruiz-Fernández, 2012) and uncertainties were estimated with a Monte-Carlo method (Sanchez-Cabeza et al., 2014). As in other coastal zones of Mexico, ^{137}Cs activities were below the detection limit (*circa* 2 Bq kg^{-1}) in most samples. Therefore, ^{239}Pu maxima (expected to occur in 1963) were used, where possible, to corroborate ^{210}Pb derived ages (Fig. 2): in core LANE the first maximum occurred in the section spanning from 1962-1973; in the core ISCUL, the maximum corresponds to the section spanning from 1963-1966; in core PUPA, a maximum was not observed. In the case of ISCUL, we estimated that the core was incomplete only by *circa* 5% of the ^{210}Pb inventory (see MacKenzie et al., 2011 for a discussion of the limitations of ^{210}Pb dating of incomplete inventories). The ^{210}Pb/^{239}Pu inventory ratios were 303 ± 16, 324 ± 6 and 265 ± 8 for cores LANE, ISCUL and PUPA, respectively. Inventories were very similar for the first two, and slightly lower in core PUPA, what might indicate some degree of perturbation.

Sediment provenance was examined through the analysis of δ^{13}C and the C/N ratio (Fig. 3). In all cases, cores showed a transition from lower (more terrestrial) to higher (more marine) δ^{13}C enrichment in agreement with a lower C/N ratio in the marine section (Fig. 3). Transitions started above i) 2 cm (year 1995) for core LANE, ii) 8 cm (year 1985) for core ISCUL and iii) 15 cm (year 1886) in core PUPA.

4. Discussion

During the last million years, MSL has oscillated mainly following glacial cycles. Interglacial periods, such as now, have occurred nearly every 100 kyr, with higher MSL mainly due to continental deicing and thermal expansion of ocean waters (Stammer et al., 2013). During the last interglacial (*circa* 120 kyr ago) MSL was 5-9 m above present, due to a larger deglaciation of the ice caps (Dutton and Lambeck, 2012). MSL is not globally homogeneous, as it depends on many factors such as the glacial isostatic adjustment, local/regional crust vertical motion and changes in oceanic hydrodynamics (e.g. currents and upwelling; Stammer et al., 2013).

The Yucatan Peninsula has been tectonically stable during the last ~ 140 kyr (Potter and Lambeck, 2004), so MSL should mainly reflect eustatic changes. Due to the instability of ice sheets during the last interglacial stages, such as today, fossil corals revealed that sea level suddenly rose 2-3 m about 121 kyr ago (Blanchon et al., 2009). Since the last glacial maximum (*circa* 20 kyr ago) the SLR rate in the region was about 4.2 mm yr^{-1} during the early Holocene, diminished to *circa* 1.4 mm yr^{-1} during the period 7-4 kyr BP and stabilized at 0.4 – 0.6 mm yr^{-1} until the preindustrial period (Anderson et al., 2014). However, in the Atlantic-Caribbean region sea-level rose abruptly during the main periods of ice sheet collapse (14.2, 11.5 y 7.6 kyr ago), with values as high as 45 mm yr^{-1}, as recorded in fossil corals (Blanchon and Shaw, 1995). Globally, recent SLR has been estimated

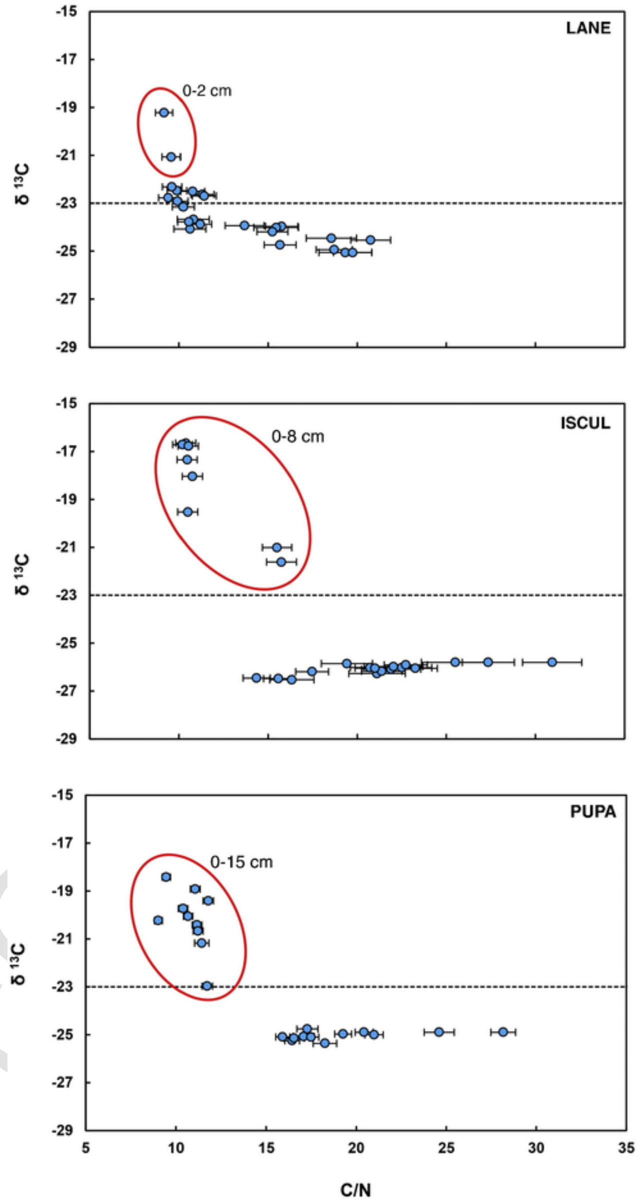


Fig. 3. δ^{13}C vs. C/N plot of sediment cores collected from the Yucatan Peninsula. This is commonly used to identify provenance of organic matter in coastal systems (Lamb et al., 2006). In all cores, surface samples cluster in the typical marine region, characterized by δ^{13}C enrichment (threshold = -23 ‰; Kristensen et al., 2008) and lower C/N. Production note: single column figure.

from tide gauge records to be close to 3 mm yr^{-1} (2.8 ± 0.8 mm yr^{-1} during the period 1993-2009; Church and White, 2011).

Sea level is monitored since the 1940s by the Servicio Mareografico Nacional (Universidad Nacional Autonoma de Mexico). It has been well recognized that the analysis of short tide gauge records (shorter than about 60 years) can lead to erroneous results (Douglas, 1991, 1997). The longest tide gauge record in the Yucatan Peninsula (Progreso city, 52 years) shows a SLR rate of 3.46 ± 0.03 mm yr^{-1} (1947-1999), and is considered to be its most reliable estimation in the region. Closer to Sian Ka'an, the shorter tide gauge record in Puerto Morelos shows a recent SLR rate as high as 10.1 ± 0.2 mm yr^{-1} (2007-2014, 7 years). Although this could be considered to be consistent with a regional acceleration of SLR in North-America,

Fig. 2. ^{210}Pb and ^{239}Pu depth/age (left) and sand (right) in sediment cores collected from the Yucatan peninsula (from top to bottom: LANE, ISCUL and PUPA). Production note: not sure about a recommended width. If needed, the figure could be arranged differently.

mainly due to the weakening of the Atlantic Meridional Overturning Current (Sallenger et al., 2012), the time length is too short to obtain robust conclusions.

All mangrove saltmarshes studied are accreting, though at different rates (Fig. 4). The reasons for this might be several, but we propose that only those sites near MSL are keeping pace with SLR. Excess ^{210}Pb fluxes ($^{210}Pb_{ex}$) were 179 ± 4, 80 ± 3 and 41 ± 2 Bq m^{-2} yr^{-1} in cores ISCUL, PUPA and LANE, respectively, which are strongly and inversely correlated (R^2 = 0.994, Fisher F = 164 >> critical F = 0.05, $p < 0.05$) with core surface orthometric height, indicating sediment erosion in the higher elevation core (LANE), sediment focusing in the lower elevation core (ISCUL) and close to atmospheric fallout in similar environments (Ruiz-Fernández et al., 2016) in the core with surface closer, but above, MSL (PUPA; Table 1).

The mass accumulation rate (MAR, g cm^{-2} yr^{-1}) describes the flux of dry mass to the sediment surface (Fig. 4), and critically depends on the nature of the accumulated particles. MAR of core LANE remains almost constant at 1 g cm^{-2} yr^{-1} for the whole record, with a slight decrease since the 1990s. In the case of core PUPA, values are similar to core LANE, until a clear increase is recorded since the 2000s. Finally, lower MAR is observed in core PUPA until the mid 1980s, corresponding to the peat segment with lower density (see Supplementary table), and then a clear increase is observed until present.

Although sediment accretion is best described by MAR because it is independent of compaction, the appropriate magnitude to be compared with SLR is the sediment accretion rate (SAR; Fig. 4), which was corrected by compaction to a constant density (Lynch et al., 1989). Although all sedimentary records were collected from quite different sedimentary environments, all of them showed similar SARs until the 1990s, ranging from 1-2 mm yr^{-1}, not dissimilar from that reported in Progreso (2.5 ± 1.2 mm yr^{-1} during 1953-1992; Zavala-Hidalgo et al., 2010) and similar to that calculated by linear regression during the period 1947-1960 (1.7 ± 0.2 mm yr^{-1}). Since then, SAR trends showed a different behavior. In the case of the highest elevation core (LANE), SAR remains basically unchanged, with a mean value along the whole core (1900-2013) of 0.9 ± 0.2 mm yr^{-1}, indicating that SAR in this area is not yet being affected by recent SLR due to its higher elevation relative to MSL. The PUPA core records an increase in SLR rate only since 2001, increasing from a value of 1.4 ± 0.3 mm yr^{-1} (1997 - 2001) up to 3.0 ± 0.7 mm yr^{-1}

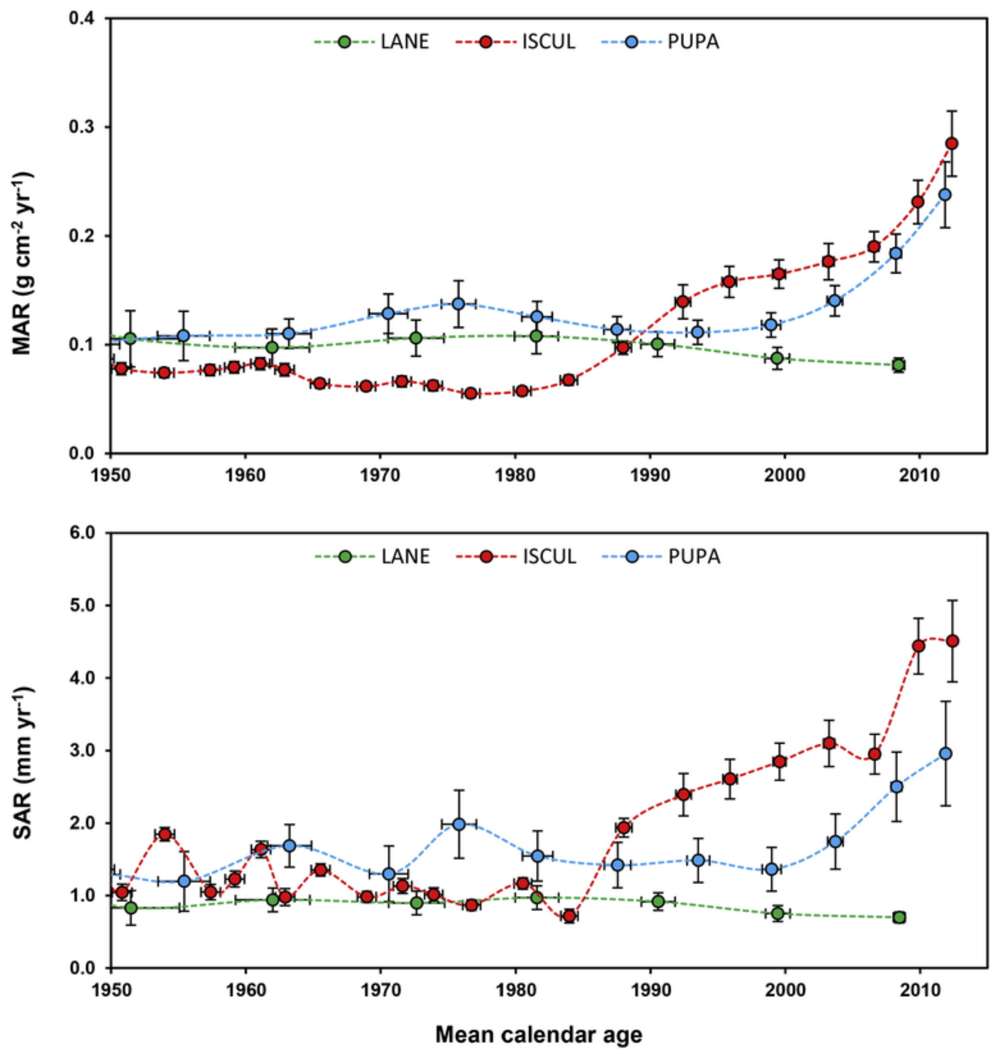


Fig. 4. Mass accumulation rates (MAR) and sediment accumulation rates (SAR, corrected by compaction) in Sian Ka'an, Yucatán peninsula: Laguna Negra (LANE), Cayo Culebra (ISCUL) and Punta Pájaros (PUPA). Maximum dry bulk density was determined from a 20 sections running mean and used to normalize density (Lynch et al., 1989). Production note: 2 column width

(2010-2013), denoting a SLR mean acceleration of 0.12 ± 0.06 mm yr^{-2}. Finally, the lowest core (ISCUL) records an increase in SLR rate since 1985, increasing from a value of 0.72 ± 0.09 mm yr^{-1} (1983-1985) to a maximum surface value of 4.5 ± 0.6 mm yr^{-1} (2011-2013). These accretion rates are within the range of published SARs in mangroves, which range from 1 mm yr^{-1} in Terminos Lagoon, Mexico, to 6.7 mm yr^{-1} in Moreton Bay, Australia (Table 2).

The SAR increase observed in core ISCUL, indicate a SLR mean acceleration of 0.13 ± 0.02 mm yr^{-2}, consistent with that observed in core PUPA. This acceleration is very similar to that reported globally since 1990, namely 0.12 mm yr^{-2} (Merrifield et al., 2009) but larger than global values (0.013 ± 0.006 mm yr^{-2}; Church and White, 2006) likely due to the larger contribution of seawater thermal expansion in the Caribbean Sea. We concluded that, although both PUPA and ISCUL cores are reflecting recent SLR, PUPA might be showing some degree of perturbation of the $^{210}Pb/^{239}Pu$ inventory ratio, and ISCUL is probably the best SLR rate record in the area, due to its location close but below MSL and thus providing a longer record.

5. Conclusions

The Yucatan peninsula has received special attention in the reconstruction of SLR since the last interglacial because it has been tectonically stable during that period. Our work confirms that, at present, all studied ecosystems show geochemical (C/N) and isotopic ($\delta^{13}C$) fingerprints of increasing marinization due to recent sea level rise, and that mangrove saltmarsh sedimentary records may contain useful SLR information when collected near, and likely below, mean sea level. We suggest that a similar approach can be used in saltmarshes worldwide to identify sediments that are actively recording present marine transgression due to sea level rise.

Sediment accumulation rates derived from ^{210}Pb dated mangrove saltmarsh cores are similar to expected mean SLR before instrumental data were available in the region. In two cases, they already record a recent SLR increase. Under the conservative assumption that regional SLR in the Yucatan Peninsula remains constant from now on, and based on the ISCUL record (surface SAR 4.5 ± 0.6 mm yr^{-1}), local MSL will be about 40 cm above the current value (2013) by the end of the XXI century, within the IPCC projections for the Representative Concentration Pathways (RCP) 2.6, 4.5 and 6.0 (Stocker et al., 2013). However, assuming that the almost identical acceleration (~ 0.13 mm yr^{-2}) observed in two sedimentary records (ISCUL and PUPA) remains constant, the expected local MSL will be 91 cm above the present value, on the higher limit of the likely range for the worst case scenario (RCP8.5). These conclusions must be taken with caution, and further research is needed in order to reduce the uncertainties, confirm the observations and expected impacts in this particular ecosystem, by increasing the number of cores collected near or below MSL. Coastal zone managers, and society in general, need to take this into account when maintaining and planning new coastal infrastructures. For example, the Mayan Riviera is characterized by large tourist resources built close to the shoreline, and many urban areas and infrastructures are close to mean sea level. Mangrove ecosystems will also be negatively affected by more marine conditions, and therefore salinity, which added to warmer temperatures will make them even more vulnerable to recent climate change. We speculate that recent massive mangrove deterioration worldwide might be at least partially due to both factors. Coastal communities will therefore need to adapt relatively fast to the new conditions, as both costal infrastructures and ecosystem services, such as those provided by mangroves, will be negatively affected.

Table 2
Sediment accretion rates in mangrove sediments worldwide.

Location	Temporal range	Sediment accretion rate (mm yr^{-1})			Reference
	(collection year)	Minimum	Maximum	Mean	
Rhode Island, USA	~ 60 years (1983)	2.5	6.0	4.3 ± 1.3	Bricker-Urso et al., 1989
Rookery Bay, Florida, USA	~ 100 years (1987)	1.4	1.7	1.6	Lynch et al., 1989
Terminos Lagoon, Mexico	~ 100 years (1987)	1.0	4.4	2.4	Lynch et al., 1989
Wider Caribbean Region	Not reported			3.7	Parkinson et al., 1994
Solent estuarine system, UK	100 years	4	5		Cundy and Croudace, 1996
Sepetiba Bay, Brazil	Not reported (1995)	1.2	1.8		Smoak and Patchineelam, 1999.
Skallingen, Denmark	1963-2003 (2003)	1.5	2.3	1.9	Andersen et al., 2011
Everglades National Park, Florida, USA	1924-2000 (2009)			3.3	Smoak et al., 2013
	1924-2000 (2009)			2.1	Smoak et al., 2013
	2000-2009 (2009)			5.9	Smoak et al., 2013
	2000-2009 (2009)			6.5	Smoak et al., 2013
Everglades National Park, Florida, USA	1960-2010 (2010)			3.7 ± 0.7	Breithaupt et al., 2014
	2000-2010 (2010)			4.8 ± 1.0	Breithaupt et al., 2014
Moreton Bay, Australia	1920-2000 (2013)	4.2	6.7		Sanders et al., 2016
	1920-2013 (2013)			4.2	Breithaupt et al., 2014
Yucatan Peninsula, Mexico (ISCUL)	*1951-1985 (2013)*	*0.7*	*1.9*		*This work*
	1985-2013 (2013)	*1.9*	*4.5*		*This work*

Declaration of interest

The authors state that they have no conflicts of interest.

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Appendix A. Supplementary data

Table containing radiochronology and other geochemical variables reported in this work. Supplementary data to this article can be found online at doi:http://dx.doi.org/10.1016/j.scitotenv.2016.08.142.

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