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RESEARCH ARTICLE

Global climate change and local watershed management as potential drivers of salinity variation in a tropical coastal lagoon (Laguna de Terminos, Mexico)

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Abstract The wide range of ecological goods and services provided by tropical coastal lagoons and wetlands are under considerable pressure due to the synergistic effects of local anthropogenic impact and global climate change. In transitional waters, salinity is a key driver of ecological processes mostly depending on the balance between marine and river inputs, a balance that can be significantly modified by climate change and by anthropogenic alteration of the watershed. Mesoamerica being considered as a climate change hot-spot and as an ecoregion strongly vulnerable to global change, our study aimed at analyzing the relationship between salinity, river runoff, and rainfall variability in a tropical coastal lagoon and to assess the respective influence of climate change and watershed management. The study focusing on the large and shallow coastal lagoon of Laguna de Terminos in south eastern Mexico established: (1) the variability in salinity distribution along the yearly cycle and the occurrence of a high salinity anomaly period during the wet season of 2009; (2) the relationship between lagoon waters salinity and river inputs further underlying the anomalous situation encountered in 2009; (3) a long term increase in river discharge during the past 60 years, indicating potential salinity decrease in the lagoon during that same period; (4) an absence of any change in rainfall linking the increase in runoff to watershed management rather than long term trend in climate change. Additionally, the specific context of the 2009–2010 Central-Equatorial Pacific El Niño is underlined and the potential relationship between river discharge and ENSO is discussed. Those results should be of significant practical value to decision-makers who are often keen to point the finger at global climate change when local environmental management is also and sometime most significantly responsible.

Keywords Tropical · Coastal · Lagoon · Watershed · Salinity · Climate change · ENSO · River discharge · Land use · Environmental management · Sustainable development · Mexico · Mesoamerica · Terminos

Introduction

Coastal lagoons and their transitional waters (McLusky and Elliott 2007) are highly sensitive to the alteration of hydrological cycle resulting from the combined effect of climate change and watershed anthropization, climate change generally having a direct impact on the global distribution of water resources while watershed alterations mainly controlling local, surface hydrological processes (Kundzewicz et al. 2007). On the global scale, Central America has been singled out as the most prominent tropical climate change hot-spot (Giorgi 2006) and, despite large modeling uncertainties about climate change impact,

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most studies converged to anticipate a general decrease in mean precipitation and an increase in drought and severe drought periods in southern Mexico and Central America (Imbach et al. 2012; Chiabai 2015). Local change in land use and watershed management are other significant sources of hydrological cycle alteration as a doubling of overall freshwater runoff has been reported between humanly impacted and non-impacted watersheds in the Mesoamerican region (Burke and Sugg 2006). Alteration of hydrological cycle will be the source of significant environmental, economic and social impacts in a region where vulnerability to extreme climatic events is considered on the rise (Hidalgo et al. 2013; Vázquez-González et al. 2014) and discriminating between those two main sources of alteration is essential to the understanding of the processes at stake and to the definition of sustainable development strategies.

In transitional waters, salinity is the main conservative tracer of mixing processes between marine and freshwater sources, and an essential driver of structural and functional characteristics of aquatic biota (Telesh and Khlebovich 2010). By defining osmosis conditions it rules the distribution and metabolism of species but it also interacts with a wide range of chemical processes and correlates with continental and anthropogenic inputs. In microtidal semi enclosed lagoons, salinity variations at and over the monthly time scale are largely controlled by variations in freshwater inputs. As a consequence, changes in freshwater regime have been extensively reported to affect environmental status, ecosystem functioning, biodiversity and living resources in tropical and subtropical coastal systems (Putland et al. 2014; Sale et al. 2014; Andrade et al. 2015; Palmer and Montagna 2015). In the Gulf of Mexico, large scale decline in offshore or lagoon fisheries has been related to external factors such as climate change including changes in precipitation patterns and river flow (Martínez Arroyo et al. 2011), and land use intensity (Vázquez-González et al. 2015). In the shallow Mexican coastal lagoon of Terminos, recent concern has been issued that an increase in salinity related to climate change might be occurring, detrimentally impacting juvenile developmental stages of exploited species (Ramos Miranda et al. 2005a, b; Sosa López et al. 2005; Villéger et al. 2010). Those authors observed a loss in functional diversity and a biotic homogenization in the fish community of Terminos Lagoon which they linked to a salinity increase between 1980–1981 and 1998–1999. This was interpreted as a climate change related shift from hypohaline to euhaline/hyperhaline status due to a decrease in river runoff (Ramos Miranda et al. 2005a). Concurrently, recent catastrophic flooding events attributed to climate change occurred in the Tabasco and Chiapas Mexican states adjacent to Terminos Lagoon, resulting in economic and, more dramatically, human losses. However, a detailed study of those flooding events also pointed at local watershed management as an important source of hydrological regime alteration (Aparicio et al. 2009). If most climate change modeling approaches expect an increase in hydrological variability and the subsequent reinforcement of extreme events of flooding and drought, they also converge to anticipate a future general decrease in precipitation in Mesoamerica (Met Office 2011). Those climate change hypotheses generated the following scientific questions: (1) what are the ongoing trends regarding salinity variation in Terminos Lagoon, (2) do those variations relate to hydrological cycle alterations, and (3) what are the respective contributions of global climate change and local watershed management to those ongoing processes?

Materials and methods

Study site

Terminos Lagoon is located on the southern coast of the Gulf of Mexico in the Mexican state of Campeche (Fig. 1a). It stretches over a surface of 1,936 km^2 (Fig. 1b) with an average depth of only 2.4 m, corresponding to a total water volume of 4.65 km^3 (Contreras Ruiz Esparza et al. 2014). It is fringed by Carmen Island on its seaward side and connected to the Gulf of Mexico through Carmen Inlet and Puerto Real Inlet on its westward and eastward sides, respectively. To the east stretches the Yucatan Peninsula, characterized by low rainfall and a porous calcareous basement resulting in the absence of proper river catchment, with rainfall penetrating directly through the carbonate basement, thus supplying the groundwater cap which discharges as diffusive non-point sources all along the Gulf of Mexico and Caribbean Sea coasts. To the west and south lie the lowlands of Tabasco and the highlands of Chiapas and Guatemala, the latter of which receives heavy tropical rainfall. Four rivers, of which two combine to form a single estuary, reach Terminos Lagoon (Medina-Gómez et al. 2015) delivering an average yearly volume of 11.96×10^9 m^3 $year^{-1}$ of freshwater, corresponding to roughly 2.6 times the lagoon volume. Yearly net rainfall of 293 mm $year^{-1}$ (1805 mm $year^{-1}$ precipitation minus 1512 mm $year^{-1}$ evaporation) (David and Kjerfve 1998; Espinal et al. 2007) accounted for a net fresh water input of 0.57×10^9 m^3 $year^{-1}$, whereas groundwater contribution accounted for 4×10^6 m^3 $year^{-1}$ (David 1999). Total annual net freshwater input to Terminos Lagoon was thus estimated at 12.53×10^9 m^3 $year^{-1}$, of which river discharge, net precipitation, and groundwater seepage, respectively, accounted for 95.42, 4.55 and 0.03 %.

The rivers Chumpán, Candelaria–Mamantel and Palizada, respectively, deliver an average of 0.6, 2.26, and

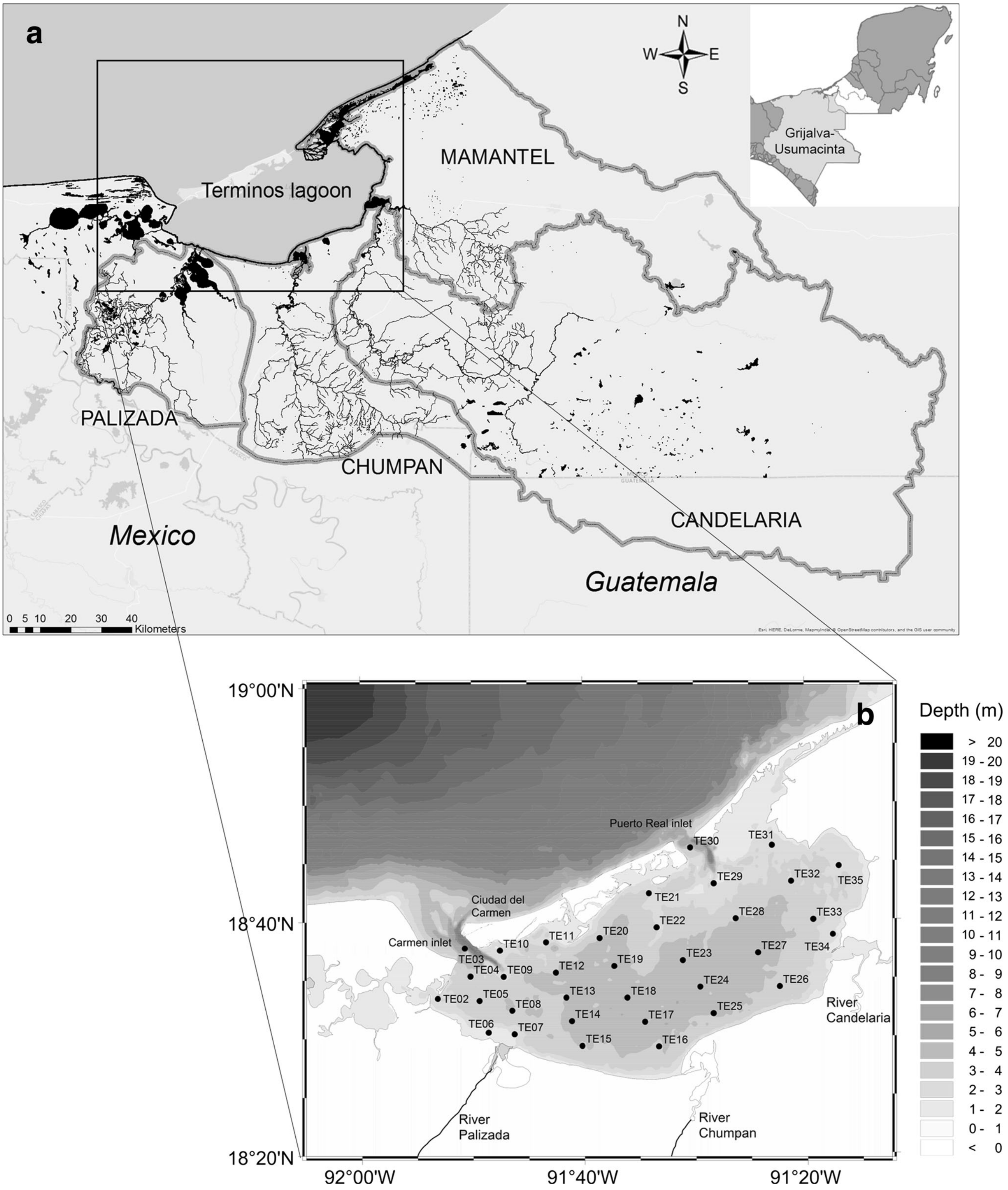

Fig. 1 **a** Main and detailed watersheds contributing to freshwater inputs to the Terminos Lagoon and **b** bathymetry of Terminos Lagoon with location of sampling stations

9.1×10^9 m^3 $year^{-1}$ of freshwater to Terminos Lagoon. Beyond its own small river catchment, the Palizada is a tributary of the Usumacinta River, which in turn relates to the intertwined Grijalva–Usumacinta basins that stretch over a total area of 112,550 km^2 (Hudson et al. 2005). Receiving an average annual rainfall of 1709 mm $year^{-1}$, the Usumacinta River discharges an average annual freshwater volume of 69×10^9 m^3 $year^{-1}$, approximately one-tenth being diverted through the Palizada River into Terminos Lagoon, the remaining nine-tenths merging with the Grijalva River catchment and directly reaching the Gulf of Mexico open waters.

Climate varies between the tropical wet and dry category in the lowlands and the tropical rainforest category in the highlands. There are three distinct seasonal periods throughout the year: the relatively dry period from February to May and the rainy period from June to September are separated by a period of northern gales called "Nortes".

Data collection and analysis

Daily river flow rates were obtained from the Mexican Comisión Nacional del Agua (CONAGUA) hydrological surveys online database Banco Nacional de Datos de Aguas Superficiales (BANDAS) (ftp://ftp.conagua.gob.mx/Bandas/, accessed 5–6 September 2014). Long-term records of daily river flow rates were available for the 1995–2011 period for the Mamantel River, for the 1992–2011 period for the Palizada River, for the 1953–2011 period for the Candelaria River, and for the 1948–2011 period for the Usumacinta River (Bocca del Cerro hydrological station, upstream Terminos Lagoon). Given the quality of each data series and the dominance of Palizada River inputs to Terminos Lagoon, the present paper focused on the data series from the Palizada and Bocca del Cerro stations from the Grijalva–Usumacinta watershed.

Daily rainfall concurrent to river flow rate time series at Bocca del Cerro station and precipitation and evaporation records at the Sabancuy meteorological station on the north-western shore of Terminos Lagoon allowing for the calculation of precipitation minus evaporation ($P - E$) were obtained from the Servicio Meteorológico Nacional database, also managed by CONAGUA and accessible through the Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE) website "Base de Datos Climatologica Nacional—Sistema CLICOM" (http://clicom-mex.cicese.mx/, accessed 5–6 September 2014).

Salinity data with a precision of 0.001 were obtained from vertical profiles conducted with a SeaBird® SBE 19 CTD over a network of 34 stations (Fig. 1b) and a total of 13 sampling trips covering the 2-year period from October 2008 to November 2010, with a more intensive sampling effort during 2010 (7 sampling trips). Data acquisition frequency was 0.25 s and only downward profiles at a velocity of circa 0.5 m s^{-1} were retained for data analysis. The SBE 19 CTD was calibrated by the manufacturer on a yearly basis. Additionally, the data from a similar survey on salinity distribution conducted in 1980 on a network of 18 sampling stations covering the whole lagoon (Yáñez-Arancibia et al. 1983) was joined to our 2008–2010 survey for comparison.

Average salinity between 0 and 75 cm depth was spatially interpolated using UNIRAS A/S® software to generate 2D distribution maps. However, the lagoon size imposed sampling over several days (4–6), potentially rendering such asynchronous sampling strategy sensitive to short term variability. Salinity variations in the lagoon are driven by variations in (1) tidal exchanges with the Gulf of Mexico, (2) internal lagoon hydrodynamics (tide accounting for 65 % of current variability (David and Kjerfve 1998), (3) precipitation versus evaporation budgets, and (4) river inputs. With limited exchange taking place through two shallow and narrow inlets and with average tidal amplitude of only 0.3 m, tidally driven salinity variations between two sampling points can be considered negligible at the scale of a tidal cycle or even at the scale of a few days (Contreras Ruiz Esparza et al. 2014). River discharge, precipitation, wind regime and daily temperature cycles were constant over each sampling period as well as during the previous 5 days, so the results can be considered as being representative of a stable situation. Finally, it must be acknowledged that, all driving factors combined, water residence time in this 1,936 km^2 system ranges from 1 to 5 months (Robadue et al. 2004), which significantly limits daily variability in salinity at the sampling grid scale.

Linear regression and parametric Pearson (normal data, no outliers) or otherwise nonparametric Spearman correlation tests were computed using Statistica® to assess relationships between data as well as trends in time series. In addition, the seasonal Mann–Kendall test (Hirsch and Slack 1984) was used as it constitutes a well-fitted non-parametric method to statistically assess the presence of monotonic trends in hydrological long-term time series that are generally asymmetrically distributed (Machiwal and Jha 2008).

Results

Salinity

Salinity in Terminos Lagoon was strongly variable at the spatial as well as the temporal scale (Fig. 2) and the seven samplings conducted during year 2010 provided an overview of yearly cycle variations. Salinity in the whole lagoon progressively increased during the dry season, from January to May 2010, and the brackish zone downstream the Candelaria and Palizada estuaries progressively receded and almost totally disappeared in May 2010 when maximum salinity values in the narrow range of 33–37 were reached. Salinity decreased progressively during and

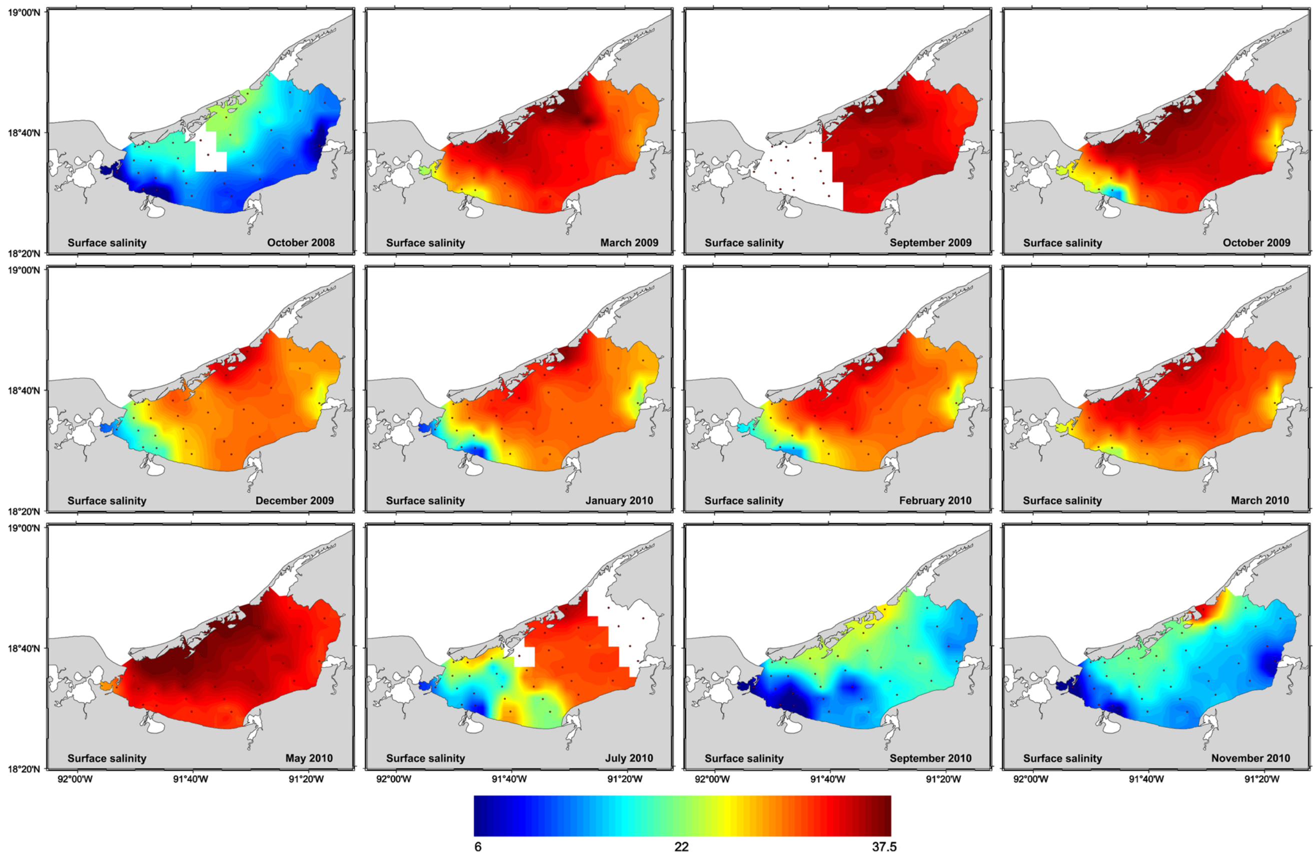

Fig. 2 Distribution of salinity (0–75 cm surface layer average) in Terminos Lagoon from October 2008 to November 2010

after the June–September rainy period down to one-digit values in the most inshore areas and values no higher than 20 leeward of Carmen Island in November 2010. Salinity distribution in March 2009, at the end of the dry period, was strongly similar to the one observed in March 2010. On the contrary, salinity distribution in September–October 2009 strongly departed from the distribution observed in October 2008, and in September–November 2010, salinity remaining high over the whole lagoon. The yearly distribution of salinity averaged over the 34 stations during the 2008–2010 survey, plotted together with previous results from a salinity survey conducted in 1980 (Yáñez-Arancibia et al. 1983) (Fig. 3), confirmed a general yearly pattern characterized by a salinity maximum circa 30 in May–June and a salinity minimum circa 10 in October–November. However, as observed in Fig. 2 and despite the variability inevitably generated by the strong spatial heterogeneity, salinity in October and December 2009 significantly departed from that pattern with high salinity anomalies of 32.41 ± 3.35 and 31.29 ± 3.36, respectively, in comparison to values of 11.18 ± 3.60, 12.77 ± 5.74 and 17.00 ± 5.40 in November 1980, 2008 and 2010, respectively.

River flow rate

Variations in Palizada River monthly averaged flow rates during the 1992–2011 period (Fig. 4) revealed an exceptionally low river discharge during the wet season of 2009 reaching a maximum of 224 $m^3\ s^{-1}$ in September 2009 as compared to 530 and 700 $m^3\ s^{-1}$ in October 2008 and September 2010, respectively. The cumulative discharge of 4.83 ± 1.71 $10^9\ m^3$ in 2009 was the lowest of the whole 1992–2011 time series, below the mean value of 7.19 ± 4.22 $10^9\ m^3\ s^{-1}$ calculated for that same period.

The bivariate analysis of salinity averaged over the 34 stations versus Palizada River mean flow rate for the 30 days preceding the sampling (Fig. 5) revealed a significant relationship ($R^2 = 0.84$) with a negative exponential distribution ($S = 40.033e^{-0.002\text{flow}}$). Once again, the September, October, and to a lesser extent December 2009 sampling periods significantly departed from that general distribution pattern with salinity values higher than those derived from the negative exponential model.

The 20 years Palizada river flow time series did not meet the criteria of data records in excess of 30 years recommended to conduct long term trend analysis of

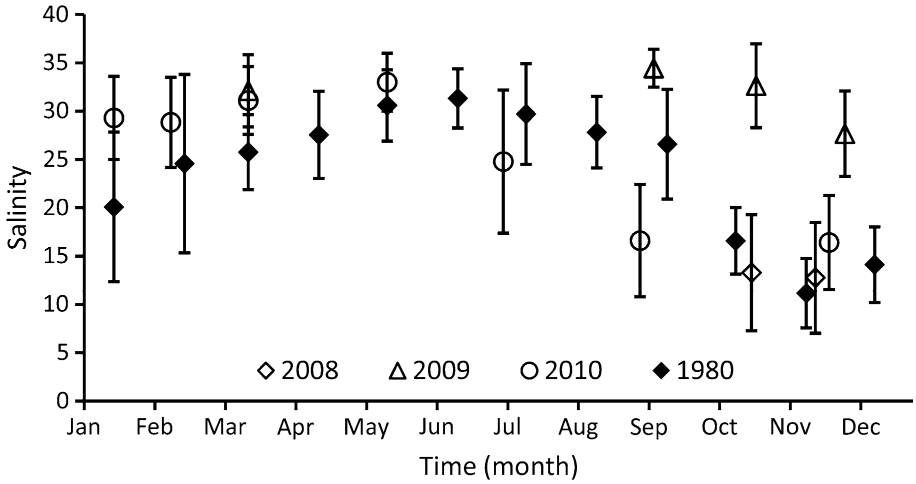

Fig. 3 Monthly evolution of salinity averaged over the whole Terminos Lagoon during the October 2008–November 2010 survey (*open symbols* ± SD as *vertical bars*) and comparison with 1980 data (*full symbols* ± SD as *vertical bars*) from Yáñez-Arancibia et al. (1983)

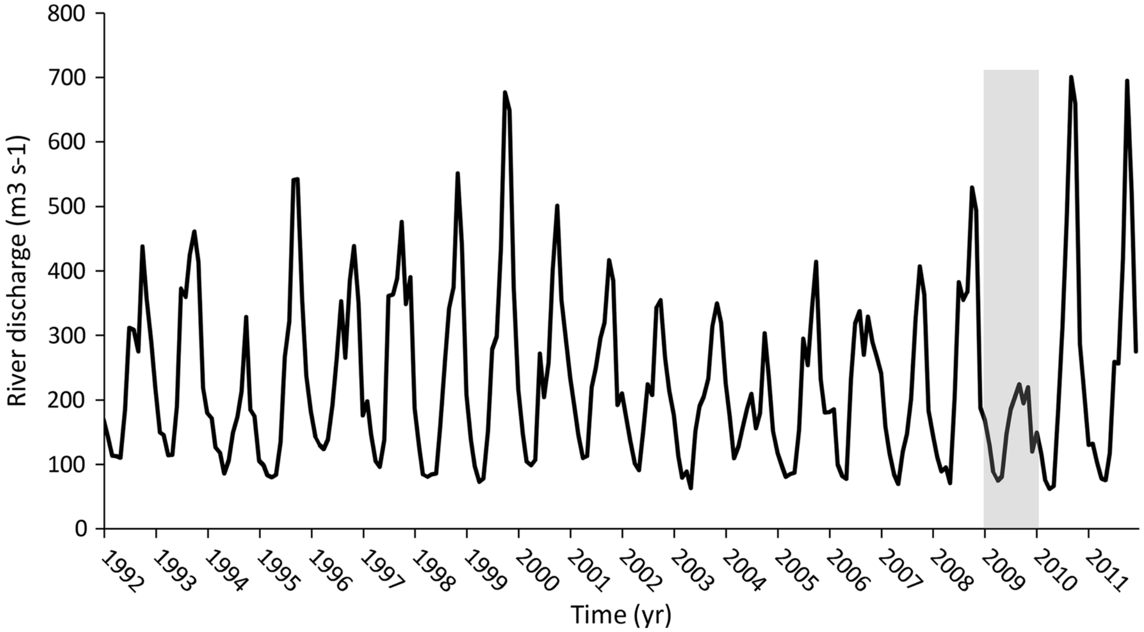

Fig. 4 Palizada River monthly averaged discharge in $m^3\ s^{-1}$ during the 1991–2011 period, year 2009 minimum discharge *underlined in gray shade*

climatic effects (Hanson et al. 2004). However, long term time series available from upstream Usumacinta watershed could be used as an alternative as monthly averaged Palizada River discharge strongly correlated (Spearman $R = 0.93$, $p \ll 0.05$) with Usumacinta River discharge at Boca del Cerro hydrological station, roughly amounting to 10 % of the latter. The available 1948–2011 time series of Usumacinta River flow rate (Fig. 6a) followed a yearly pattern identical to that of Palizada River with low discharge during the April–June dry season and high discharge during the September–November wet season. The seasonal Mann–Kendall nonparametric test (score 4.24, $p < 0.001$) showed a statistically significant positive long term trend and from the linear regression equation it was possible to establish that the annual river discharge increased by 25 % between 1948 (1768 $m^3\ s^{-1}$) and 2011 (2214 $m^3\ s^{-1}$).

The synchronous long-term precipitation time series at Boca del Cerro station (Fig. 6b) yielded an average monthly precipitation rate of 190 mm with a wide range of variation, from no rainfall at all to a maximum monthly precipitation of 661 mm in September 1966. The Mann–Kendall test did not allowed for the rejection of the “no trend” null hypothesis, demonstrating together with the slope-less linear regression the absence of a long-term change in precipitation rates.

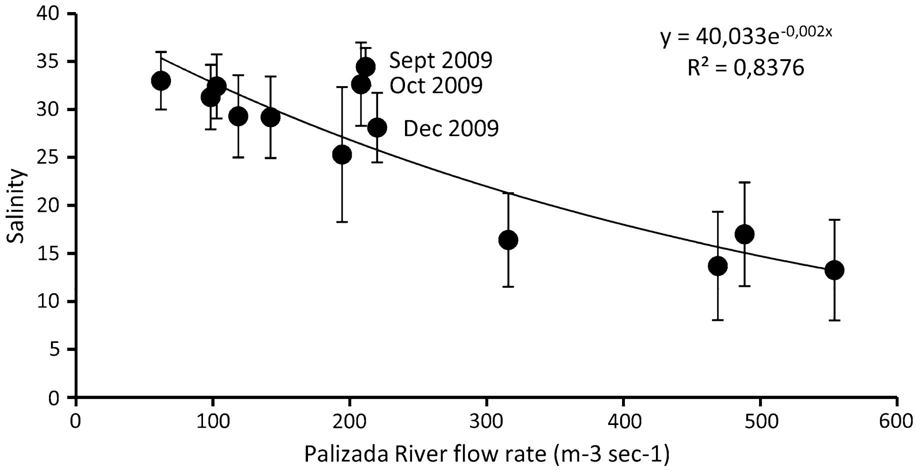

Fig. 5 Relationship between average salinity in Terminos Lagoon (*black dots* ± SD) and monthly averaged Palizada River discharge from October 2008 to November 2010. Negative exponential regression best fit line appears as *black straight line* together with its equation and determination coefficient (R^2)

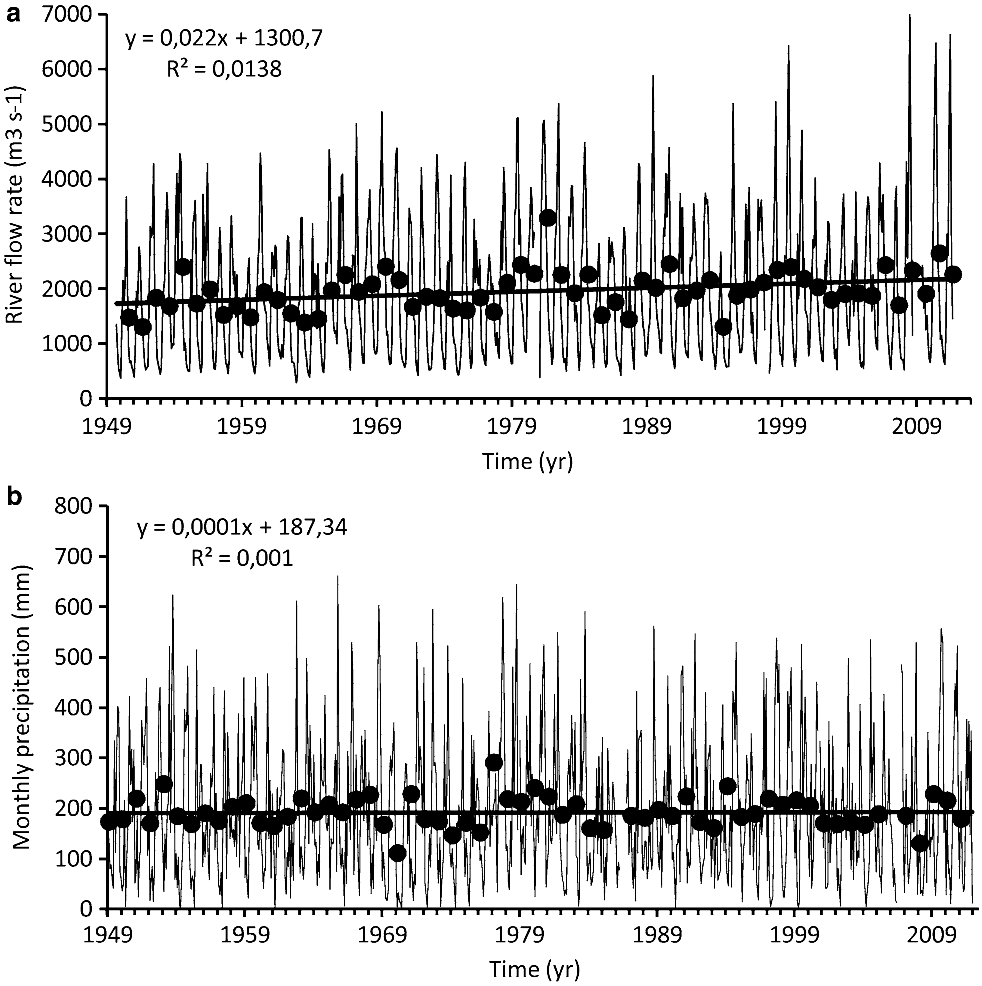

Fig. 6 **a** Monthly averaged (*gray line*) and yearly averaged (*black dots*) Usumacinta River discharge in m^3 s^{-1}, and **b** monthly (*gray line*) and yearly averaged (*black dots*) precipitation rates in mm, at Boca del Cerro station during the 1948–2011 period. Added linear regression lines (*black line*) are from yearly averaged values (*black dots*)

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The 2009 anomalies in salinity and river discharge were concurrent to an El Niño period, the NOAA Oceanic Niño Index (ONI) reaching the 0.5 threshold value in the June–August period of 2009 and rising up to 1.6 in the November–January and December–February 2009–2010 periods (Table 1). The ONI decreased below the 0.5 threshold value during the April–June 2010 period and entered a 10-month La Niña period beginning in the June–August 2010 period. Bivariate analysis of ONI versus averaged river flow rates at Boca del Cerro station using

Table 1 Oceanic Niño Index (ONI) from January 2008 to December 2010

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
2008	*−1.5*	*−1.5*	*−1.2*	*−0.9*	*−0.7*	*−0.5*	−0.3	−0.2	−0.1	−0.2	*−0.5*	*−0.7*
2009	*−0.8*	*−0.7*	*−0.5*	−0.2	0.2	0.4	**0.5**	**0.6**	**0.8**	**1.1**	**1.4**	**1.6**
2010	**1.6**	**1.3**	**1.0**	**0.6**	0.1	−0.4	*−0.9*	*−1.2*	*−1.4*	*−1.5*	*−1.5*	*−1.5*
2011	*−1.4*	*−1.2*	*−0.9*	*−0.6*	−0.3	−0.2	−0.2	−0.4	*−0.6*	*−0.8*	*−1.0*	*−1.0*

ONI values below −0.5 (La Niña) are italicized and ONI values over +0.5 (El Niño) are bold

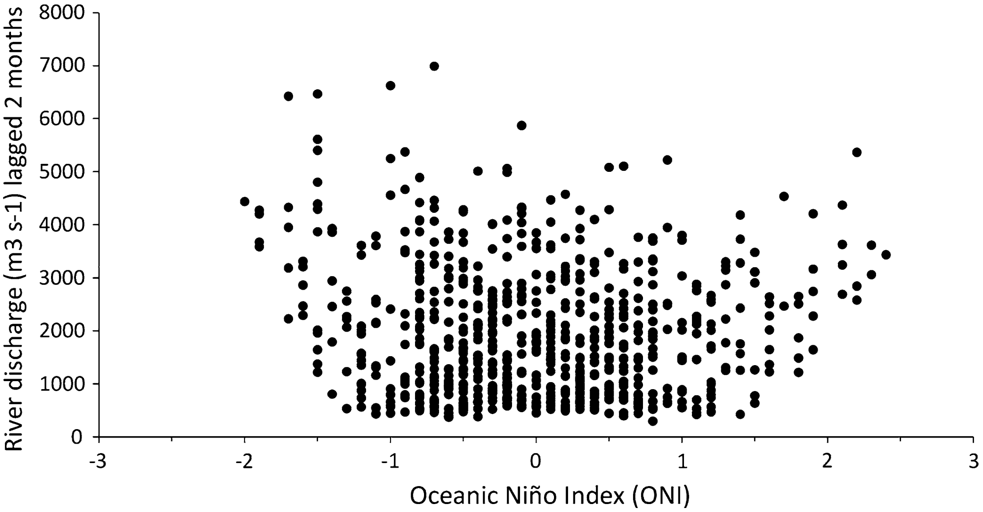

Fig. 7 Bivariate plot of NOAA Oceanic Niño Index (ONI) versus monthly averaged Usumacinta River discharge at Bocca del Cerro station lagged by 2 months

various time shifts showed a very dispersed distribution with no direct relationship as exemplified by the bivariate representation of ONI versus monthly averaged River flow rates lagged by 2 months (Fig. 7).

Discussion

Salinity distribution

Salinity variability in time and space ranged from one digit values (estuarine) to 36 (marine), with spatial gradients strongly shifting as a function of the balance between marine and freshwater inputs. Salinities close to those of marine waters from the Gulf of Mexico (Thacker 2007) were measured in the two inlets and leeward of Carmen Island showing that tidal flooding intrusions of marine waters were rapidly mixed with freshwaters from the Palizada River when entering through El Carmen Inlet whereas they were transported westward along the coast of Carmen Island when entering through Puerto Real Inlet, in agreement with previously reported hydrodynamic patterns (Graham et al. 1981; Kjerfve et al. 1988; David and Kjerfve 1998; Contreras Ruiz Esparza et al. 2014). The seasonal cycle was marked by the progressive extension of saline waters during the dry season (February–May) and inversely, by the progressive extension of the Palizada and Candelaria estuarine plumes during the wet season and the beginning of the dry season (July–December). The low salinity plume from the Palizada Estuary generally spread along the southern shore of the lagoon during the dry season and extended northward toward Carmen Island during the wet season. The low salinity plume from the Candelaria Estuary spread to the north-east part of the lagoon with an extension much more limited than the Palizada estuarine plume due to strong proportional difference in river discharge.

2009 Salinity anomaly

The salinity distribution in September, October, and December 2009, at the end of the wet season and beginning of the dry season, strongly differed from similar periods in 2008 and 2010 as salinity remained very high over the whole lagoon due to a very limited extension of Palizada and Candelaria estuarine plumes. The yearly comparison of lagoon wide averaged salinity identified a general yearly cycle characterized by a salinity maximum around 30 in May–June and a salinity minimum around 10 in October–November and pointed at an anomalous situation developing during the wet season of 2009 when salinity remained high instead of reaching the usually low values observed during the above mentioned yearly cycle. Such anomalous salinity conditions resulted from exceptional climatic conditions encountered in 2009 as Mexico endured its worst drought in seven decades, precipitation statistics ranking July 2009 as the driest since 1941 at the national scale (Davidova-Belitskaya and Romero-Cruz 2010). As a direct consequence, the positive salinity anomaly in Terminos Lagoon at the end of the wet season of 2009 was logically linked to an exceptional deficit in fresh water inputs from the Palizada River in 2009 when compared with the 20 years prior to 2012.

The statistically significant negative exponential relationship between Terminos Lagoon salinity and Palizada River flow rate averaged over the preceding month established a strong direct link between salinity and river discharge, in agreement with the previously mentioned predominance of river inputs of fresh water to the lagoon. However, the values recorded in September, October and to a lesser extent December 2009 significantly departed from that negative exponential distribution pattern, demonstrating that the general decrease in river discharge previously evidenced went along with a shift in hydrological conditions. Annual precipitation minus evaporation ($P - E$) in the Terminos Lagoon area reached −506 mm during the drought affected year of 2009, evidencing a strong imbalance in favor of evaporation. The significance of that imbalance was further underlined when comparing years 2008 and 2010 that yielded $P - E$ values of −29 and +427 mm, respectively. That strong imbalance in favor of evaporation in 2009 explained why salinity values progressively increased away from the general relationship established with Palizada River discharge during the anomalous wet season. The observed positive salinity anomaly recorded in 2009 therefore resulted from a combined deficit in river inputs and excess in evaporation.

Long term river discharge trend

The analysis of the Usumacinta River discharge historical record revealed a long-term increase instead of a climate change-related decrease anticipated from previous studies (Ramos Miranda et al. 2005a; Sosa López et al. 2005). Understanding the reasons for such a long-term change and, in particular, assessing whether it was related to changes in climatic conditions and/or to local watershed management therefore appeared as a key issue, both in terms of scientific inquiry and of environmental management. The observed long term increase in Usumacinta River discharge at Boca del Cerro proved unrelated to onsite precipitation rates as the concurrent rainfall time series revealed a stable long term trend. Considering the vastness and diversity in Usumacinta River catchment hydrogeomorphology, that local comparison is of limited value but exemplify a much more global trend based on surveys at the national scale reporting no statistical evidence of a change in precipitation in Mexico and even cautiously mentioning a possible decrease in the far southeast of Mexico (Met Office 2011). Furthermore, that observed consistency in recent rainfall trend was fully consistent with climate change modeling approaches generally anticipating no significant change in precipitation during the first half of the twenty-first century followed by a precipitation decline ranging from 5 to 30 % by the end of the twenty-first century, depending on the considered IPCC emission scenario (Barcena et al. 2010; Sáenz-Romero et al. 2010; Met Office 2011; Biasutti et al. 2012; Hidalgo et al. 2013).

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The 2009 nationwide drought period responsible for the positive salinity anomaly in Terminos Lagoon was concurrent to a moderately severe El Niño event lasting from July 2009 to April 2010 which was rapidly followed by a La Niña event lasting from July 2010 to April 2011. However, on a long term basis, no direct relationship could be established between Usumacinta River flow rates and ENSO ONI index during the past 60 years. Other studies relating ENSO with rainfall in Mexico reported noticeable but very weak correlation (Pavia et al. 2006; Bravo Cabrera et al. 2010), with precipitation decreasing southward and increasing northward under "El Niño" conditions and increasing under "La Niña" conditions. The same studies also predicted future stronger precipitation deficit during the wet season, leading to severe drought events such as the one observed in 2009. However, a recent study also showed river discharge in the Usumacinta–Grijalva basin to be higher during both El Niño and La Niña than during normal periods of ENSO (Muñoz-Salinas and Castillo 2015), a conclusion in reasonable agreement with the distribution pattern of river discharge versus ONI index observed herein. Even though 2009 stood as the most drastic year in terms of low river discharge, it was far from the most severe El Niño event of the past 60 years but it is noteworthy that the 2009–2010 El Niño was categorized as a Modoki or Central-Equatorial Pacific (CP) El Niño (Ashok et al. 2007), the effects of such a recently identified meteorological situation on the Mesoamerican hydrological cycle still being under scrutiny.

Watershed management

The absence of a relationship between rainfall and the regular increase in Usumacinta River discharge during the past 60 years excluded climate change as a driver of that long-term historical change in hydrological regime, alternatively supporting the hypothesis of a local driver most likely related to watershed management. Deforestation to expand agricultural and ranching lands has been consistently linked to increased rainwater runoff resulting in higher river discharges and such a relationship was suggested by previous work on satellite image analysis. Soto Galera et al. (2010) showed changes from original land cover in more than half of the Terminos Lagoon area during the period from 1974 to 2001, and revealed that 31 % of the area occupied by mature vegetation in 1974 had been degraded by 2001. Tropical forest and mangroves presented the most extensive coverage losses, while urban areas and grassland for livestock farming increased considerably. Net mangrove surface loss was 17,426 ha in Campeche between 1970 and 2005, corresponding to an 8 % loss from the initial mangrove surface area (Valderrama et al. 2014). At a larger scale, during the 1976–2009 period, the watersheds surrounding Terminos Lagoon were the most affected by deforestation of all the watersheds of Mexico: the Grijalva–Usumacinta, Mamantel and Candelaria basins lost 20–30, 30–50 and <10 % of their primary vegetation, respectively. Furthermore, all three basins lost 30–50 % of their secondary vegetation (Cotler Ávalos 2010). Additionally, a comparable increase in river discharge unrelated to precipitation and linked to deforestation and expansion of the agricultural and ranching land was reported from the Candelaria watershed (Benítez et al. 2005). As a consequence, and considering the tight relationship between the Usumacinta River and the Palizada River, the presently ongoing long-term trend in Terminos Lagoon salinity is more likely to be one of decrease rather than increase.

That later conclusion disagreed with the hypothesis of a climate driven long term increase in salinity in Terminos Lagoon that resulted in a shift in fish population (Ramos Miranda et al. 2005a). Considering the two dataset used in that later study, it must be stressed that the February 1980–April 1981 period (data from Yáñez-Arancibia et al. 1983) corresponded to normal ENSO conditions and a 2 years period of above average river discharge (+26 % in 1979, +18 % in 1980) from the Usumacinta watershed, whereas the October 1997–September 1998 period (data from Ramos Miranda et al. 2005a) corresponded to strong El Niño conditions lasting from May 1997 to April 1998 (maximum ONI value of 2.4 in November 1997), and a period of slight excess in river discharge (+9 % in 1997, +8 % in 1998) following a 3-year deficit period (−32 % in 1994, −2 % in 1995, −3 % in 1996). The difference in salinity observed by Ramos Miranda et al. (2005a) between 1980–1981 and 1997–1998 in Terminos Lagoon hence could be related to the inherent variability of that transitional system rather than to a long-term decrease in river discharge driven by climate change, the shift in fish population they evidenced between those two periods most likely corresponding to a short term adaptive response to environmental variability rather than a long term change in ecological conditions.

Conclusion

The present study established that salinity in Terminos Lagoon depended on river inputs and that the occurrence of exceptionally low river discharge and elevated evaporation during the wet season of 2009 were responsible for a positive salinity anomaly affecting the entire lagoon. Over the long term we observed a sustained increase in river flow rates in the Usumacinta River watershed during the past 60 years, implying that salinity in Terminos Lagoon decreased rather than increased during this same period. Stable precipitation rates during that 60 years period suggested that the recorded increase in river discharge resulted from unsustainable land use rather than climate change. Finally, despite the coincidence between the 2009 ENSO event, the observed decrease in river flow rate, and the positive salinity anomaly in Terminos Lagoon, no clear general relationship could be established between river flow rates and the ONI ENSO index. These results should be of significant value to decision-makers who are often keen to hastily point the finger at global climate change when, in fact, local environmental management is also strongly involved.

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References

Andrade H, Santos J, Ixquiac MJ (2015) Ecological linkages in a Caribbean estuary bay. Mar Ecol Prog Ser 533:29–46. doi:10.3354/meps11342

Aparicio J, Martínez-Austria PF, Güitrón A, Ramírez AI (2009) Floods in Tabasco, Mexico: a diagnosis and proposal for courses of action. J Flood Risk Manag 2:132–138

Ashok K, Behera SK, Rao SA, Weng H, Yamagata T (2007) El Nino Modoki and its possible teleconnection. J Geophys Res Oceans 112:C11007

Barcena A, Prado A, Beteta H, Samaniego JL, Lennox J (2010) The economics of climate change in Central America. UN-CEPAL report

Benítez JA, Sanvicente Sánchez H, Lafragua Contreras J, Zamora Crescencio P, Morales Manilla LM, Mas Caussel JF, García Gil G, Couturier SA, Zetina Tapia R, Calan Yam RA, Amabilis Sánchez L, Acuña CI, Mejenes MC (2005) Sistema de información geográfica de la Cuenca del Río Candelaria: Reconstrucción histórica de los cambios en la cobertura forestall y su efecto sobre la hidrología y calidad del agua. In: Kauffer Michel EF (ed) El agua en la frontera México-Guatemala-Belice. Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, pp 19–32

Biasutti M, Sobel AH, Camargo SJ, Creyts TT (2012) Projected changes in the physical climate of the Gulf Coast and Caribbean. Clim Change 112:819–845

Bravo Cabrera JL, Azpra Romero E, Zarraluqui Such V, Gay García C, Estrada Porrúa F (2010) Significance tests for the relationship between “El Niño” phenomenon and precipitation in Mexico. Geofísica Internacional 49:245–261

Burke L, Sugg Z (2006) Hydrologic modeling of watersheds discharging adjacent to the Mesoamerican reef analysis summary. World Resources Institute, p 35. http://www.wri.org/sites/default/files/pdf/mar_hydrologic_model_results_english.pdf

Chiabai A (2015) Climate change impacts on tropical forests in Central America: an ecosystem service perspective. The Earthscan Forest Library, Routledge, London, p 236

Contreras Ruiz Esparza A, Douillet P, Zavala-Hidalgo J (2014) Tidal dynamics of the Terminos lagoon, Mexico: observations and 3D numerical modeling. Ocean Dyn 64:1349–1371

Cotler Ávalos H (2010) Las cuencas hidrograficas de México Diagnostico y Priorizacion. http://www2.inecc.gob.mx/publicaciones/consultaPublicacion.html?id_pub=639

David LT (1999) Laguna de Términos, Campeche. In: Smith SV, Marshall Crossland JI, Crossland CJ (eds) Mexican and Central American coastal lagoon systems: carbon, nitrogen and phosphorus fluxes, LOICZ reports and studies N°13. LOICZ International Project Office, Texel, pp 9–15

David L, Kjerfve B (1998) Tides and currents in a two-inlet coastal lagoon: Laguna de Terminos, Mexico. Cont Shelf Res 18:1057–1079

Davidova-Belitskaya V, Romero-Cruz F (2010) Mexico [in “State of the climate in 2009”]. Bull Am Meteorol Soc 91(7):S142–S143

Espinal JC, Salles PAA, Morán DK (2007) Storm surge and sediment process owing to Hurricane Isidore in Terminos Lagoon, Campeche. In: Kraus NC, Dean Rosati J (eds) Coastal sediments ’07: proceedings of the sixth international symposium on coastal engineering and science of coastal sediment process. American Society of Civil Engineers, Reston, pp 996–1007

Giorgi F (2006) Climate change hot-spots. Geophys Res Lett 33:L08707. doi:10.1029/2006GL025734

Graham DS, Daniels JP, Hill JM, Day JW (1981) A preliminary model of the circulation of Laguna de Términos, Campeche, Mexico. Anales del Instituto de Ciencias del Mar y Limnologia, Universidad Nacional Autonoma de México 8:51–62

Hanson RT, Newhouse MW, Dettinger MD (2004) A methodology to assess relations between climatic variability and variations in hydrologic time series in the southwestern United States. J Hydrol 287:253–270

Hidalgo HG, Amador JA, Alfaro EJ, Quesada B (2013) Hydrological climate change projections for Central America. J Hydrol 495:94–112

Hirsch RM, Slack JR (1984) A nonparametric trend test for seasonal data with serial dependence. Water Resour Res 20:727–732

Hudson PF, Hendrickson DA, Benke AC, Varela-Romero A, Rodiles-Hernández R, Minckley WL (2005) Rivers of Mexico. In: Benke AC, Cushing CE (eds) Rivers of North America. Elsevier Academic Press, Cambridge, MA, USA, pp 1030–1084

Imbach P, Molina L, Locatelli B, Roupsard O, Mahé G, Neilson R, Corrales L, Scholze M, Ciais P (2012) Modeling potential equilibrium states of vegetation and terrestrial water cycle of Mesoamerica under climate change scenarios. J Hydrometeorol 13:665–680

Kjerfve B, Magill KE, Sneed JE (1988) Modeling of circulation and dispersion in Laguna de Terminos, Campeche, Mexico. In: Yañez Arancibia A, Day JW Jr (eds) Ecology of coastal ecosystems in the Southern Gulf of Mexico: The Terminos Lagoon region. Universidad Nacional Autonoma de Mexico, Mexico, pp 111–129

Kundzewicz ZW, Mata LJ, Arnell NW, Döll P, Kabat P, Jiménez B, Miller KA, Oki T, Sen Z, Shiklomanov IA (2007) Freshwater resources and their management. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (Eds.), Climate Change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 173–210

Machiwal D, Jha MK (2008) Comparative evaluation of statistical tests for time series analysis: application to hydrological time series. Hydrol Sci 53:352–366

Martínez Arroyo A, Manzanilla Naim S, Zaval Hidalgo J (2011) Vulnerability to climate change of marine and coastal fisheries in México. Atmósfera 24:103–123

McLusky DS, Elliott M (2007) Transitional waters: a new approach, semantics or just muddying the waters? Estuar Coast Shelf Sci 71:359–363

Medina-Gómez I, Villalobos-Zapata GJ, Herrera-Silveira JA (2015) Spatial and temporal hydrological variations in the inner estuaries of a large coastal lagoon of the Southern Gulf of Mexico. J Coast Res 31:1429–1438

Met Office (2011) Climate: observations, projections and impacts. Met Office, Exeter. http://www.metoffice.gov.uk/media/pdf/t/r/UK.pdf. Accessed 25 Sept 2015

Muñoz-Salinas E, Castillo M (2015) Streamflow and sediment load assessment from 1950 to 2006 in the Usumacinta and Grijalva Rivers (Southern Mexico) and the influence of ENSO. Catena 127:270–278

Palmer TA, Montagna PA (2015) Impacts of droughts and low flows on estuarine water quality and benthic fauna. Hydrobiologia 753:111–129

Pavia EG, Graef F, Reyes J (2006) PDO–ENSO effects in the climate of Mexico. J Clim 19:6433–6643

Putland JN, Mortazavi B, Iverson RL, Wise SW (2014) Phytoplankton biomass and composition in a river-dominated estuary during two summers of contrasting river discharge. Estuar Coasts 37:664–679

Ramos Miranda J, Mouillot D, Flores Hernandez D (2005a) Changes in four complementary facets of fish diversity in a tropical coastal lagoon after 18 years: a functional interpretation. Mar Ecol Prog Ser 304:1–13

Ramos Miranda J, Quiniou L, Flores-Hernandez D, Do Chi T, Ayala Perez L, Sosa Lopez A (2005b) Spatial and temporal changes in the nekton of the Terminos Lagoon, Campeche, Mexico. J Fish Biol 66:513–530

Robadue D Jr, Oczkowski A, Calderon R, Bach L, Cepeda MF (2004) Characterization of the region of the Terminos Lagoon: Campeche, Mexico. PlusDraft 1 Site Profile. Draft for discussion. The Nature Conservancy, Corpus Christi. http://www.crc.uri.edu/download/23s_L1Profile_Draft_Terminos_2004.pdf

Sáenz-Romero C, Rehfeldt GE, Crookston NL, Duval P, St-Amand R, Beaulieu J, Richardson BA (2010) Spline models of contemporary, 2030, 2060 and 2090 climates for Mexico and their use in understanding climate-change impacts on the vegetation. Clim Change 102:595–623

Sale PF, Agardy T, Ainsworth CH et al (2014) Transforming management of tropical coastal seas to cope with challenges of the 21st century. Mar Pollut Bull 85:8–23

Sosa López A, Mouillot D, Do Chi T, Ramos Miranda J (2005) Ecological indicators based on fish biomass distribution along trophic levels: an application to the Terminos coastal lagoon, Mexico. ICES J Mar Sci 62:453–458

Soto Galera E, Piera J, Lopez P (2010) Spatial and temporal land cover changes in Terminos Lagoon Reserve, Mexico. Rev Biol Trop 58:565–575

Telesh IV, Khlebovich VV (2010) Principal processes within the estuarine salinity gradient: a review. Mar Pollut Bull 61:149–155

Thacker WC (2007) Estimating salinity to complement observed temperature: 1. Gulf of Mexico. J Mar Syst 65:224–248

Valderrama L, Troche C, Rodriguez MT et al (2014) Evaluation of mangrove cover changes in Mexico during the 1970–2005 period. Wetlands 34:747–758

Vázquez-González C, Fermán-Almada J-L, Moreno-Casasola P, Espejel I (2014) Scenarios of vulnerability in coastal municipalities of tropical Mexico: an analysis of wetland land use. Ocean Coast Manag 89:11–19

Vázquez-González C, Moreno-Casasola P, Juárez A, Rivera-Guzmán N, Monroy R, Espejel I (2015) Trade-offs in fishery yield between wetland conservation and land conversion in the Gulf of Mexico. Ocean Coast Manag 114:194–203

Villéger S, Ramos Miranda J, Flores Hernandez D, Mouillot D (2010) Contrasting changes in taxonomic vs functional diversity of tropical fish assemblages after habitat degradation. Ecol Appl 20:1512–1522

Yáñez-Arancibia A, Lara-Domíguez AL, Chavance P, Hernández DF (1983) Environmental Behavior of Terminos Lagoon Ecological System, Campeche, Mexico. Anales del Instituto de Ciencias del Mar y Limnologia, Universidad Nacional Autonoma de Mexico 10:137–176