Regional sea level change and variability in the Caribbean sea since 1950

Research Article

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Abstract:
We investigate the regional variability in sea level in the Caribbean Sea region over the past 60 years (1950-2009) using an Empirical Orthogonal Function (EOF)-based 2-dimensional past sea level reconstruction (a mean of 3 reconstructions based on few long tide gauge records and different sea level grids from satellite altimetry and ocean circulation models) and satellite altimetry data for the last two decades. We find that over the past 60 years, the mean rate of sea level rise in the region was similar to the global mean rise (∼1.8 mm/yr). The interannual mean sea level of the place Caribbean region appears highly correlated with El Nino-Southern Oscillation (ENSO) indices. Interpolation of the sea level reconstruction grid at different sites, in particular at the Caribbean Islands where tide gauge records are either very short or inexistent, shows that locally, the sea level trend is on the order of 2 mm/yr, i.e. only slightly larger than the mean trend over the region. Besides, correlation with ENSO is in general good, especially since the mid-1980s. We also find a significant correlation between the interannual variability in sea level and hurricane activity, especially over the past decade during which hurricane intensity and sea level interannual variability have both increased.

Keywords:
Caribbean Sea • sea level variability • 2-D past sea level reconstruction • satellite altimetry • tide gauge • ENSO • hurricane

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1. Introduction

Sea level is a very sensitive indicator of climate change and variability as it integrates the responses of all components of the climate system to natural and human-induced forcing. Sea level also reflects the natural variability of the climate system. During the 20th century, the global mean sea level (GMSL) has risen at an average rate of ∼1.8 mm/yr (e.g., Church and White, 2011). Since the early 1990s, sea level is routinely measured by high-precision satellite altimetry which indicates a GMSL rise of 3.2 mm/yr since over 1993-2011. Sea level budget studies conducted over the altimetry era (since 1993) have shown the GMSL rise results from ocean thermal expansion (contributing by ∼30%) and land ice loss from glaciers and the Greenland and Antarctica ice sheets (contributing in total to ∼55%-60%) (e.g., Church et al., 2011, Cazenave and Llovel, 2010, Cazenave and Remy, 2011).

Satellite altimetry has revealed high regional variability in the rates of sea level rise, with faster rates (up to 3 times than the global mean) in the western Pacific, North Atlantic and southern oceans. The main cause of regional variability over the altimetry era is non uniform ocean heat content as well as salinity variations (e.g., Lombard et al., 2005, 2009). 2-dimensional past sea level reconstructions developed to study the regional variability in sea level prior to the altimetry era (e.g., Church et al., 2004, Llovel et al., 2009, Ray and Douglas, 2011, Meyssignac et al., 2012a) have shown that the spatial trend patterns are not stationary but fluctuate in time and space in responses to the natural modes of the ocean-atmosphere coupled system like El Nino-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO) (e.g., Meyssignac et al., 2012a, b). This indicates that, at regional scale,
there is a low-frequency (multidecadal) component of the regional variability that superimposes to the GMSL rise. This component may either amplify or reduce the GMSL rise. When investigating the effective rate of sea level change in selected regions, it is of primary importance to account for this regional component in addition to the global mean rise. In a previous study focusing on the western tropical Pacific islands, (Becker et al., 2012) found that at Funafuti, an island in the Tropical Pacific belonging to the nation of Tuvalu, because of the low-frequency regional variability component, the total (absolute) sea level rise is almost three times the global mean rate of sea level rise over the past half century (i.e., \( \sim 5 \) mm/yr versus 1.8 mm/yr over 1950-2010). This shows the importance of estimating the rate of sea level rise not only globally but also in terms of regional variability in order to understand the level of impacts that the sea level rise can have on the local population.

In the present study, we focus on the Caribbean Sea, a region surrounded by highly populated countries and islands, and develop an approach similar to that of (Becker et al., 2012) to determine the total sea level change (i.e., GMSL plus regional variability) in this area since 1950.

The Caribbean Sea, located between 9°N and 22°N latitude and between 60°W and 89°W longitude is bound by South America to the South, Central America to the West. The Antilles, a chain of islands, separate the Caribbean Sea from the Atlantic Ocean to the North and East and from the Gulf of Mexico to the South West. The Caribbean region, situated largely on the Caribbean plate comprises more than 7000 islands, islets, reefs and cays. Most of the Caribbean islands lie close to the boundaries of the Caribbean plate and hence are geologically active with earthquakes from time to time and a number of volcanic activities. The Caribbean islands are considered to be one of the vulnerable islands under future sea level rise (Nicholls and Cazenave, 2010) with more than 50% of the population living within 1.5 km of the shore (Mimura et al., 2007).

To estimate the low-frequency regional sea level variability in the Caribbean, we make use of an Empirical Orthogonal Function (EOF)-based (Preisendorfer, 1988) 2-dimensional past sea level reconstruction (Meyssignac et al., 2012a). This is a mean of 3 reconstructions that combines nearly one hundred long tide gauge records (1950-2009) with different sea level grids of shorter duration. The Caribbean does not possess many good quality tide gauge records and even the few available (about 10) do not cover the whole 60 years period. Of the available records, only Magueyes has been used in the global sea level reconstruction. Thus the reconstruction is an important tool to study the regional sea level variability. To understand what drives the Caribbean Sea regional variability, we estimate the effects of ocean temperature and salinity on the observed sea level variations and also compare the sea level with different climatic indices, in particular ENSO indices. We also investigate a potential link between sea level variability and hurricane activity in the Caribbean region.

2. Data

2.1. Satellite Altimetry

We use the DT-MSLA “Ref” series of satellite altimetry data provided by Collecte Localisation Satellite (http://www.aviso.oceanobs.com/en/data/products/surface-height-products/global/msla/index.html). The data set is based on the combination of several altimetry missions namely Topex/Poseidon (T/P), Jason-1 and 2, Envisat and ERS 1 and 2. It is a global homogenous inter-calibrated dataset based on a global crossover adjustment that considers T/P and then Jason-1/2 as reference missions. Usual geophysical corrections are applied: solid Earth, ocean and pole tides, wet and dry troposphere, ionosphere (see Ablain et al., 2009 for details) and inverted barometric correction (Carrere and Lyard, 2003). The altimetry data set is used over the time span from January 1993 until December 2009. It is available as 0.25° x 0.25° Mercator projection grids at weekly intervals.

2.2. Tide gauges

Revised Local Reference monthly mean sea level data of the Permanent Service for the Mean Sea Level (PSMSL; Woodworth and Player, 2003; http://www.psmsl.org/) are used in this study. As mentioned above, the tide gauge coverage in the Caribbean Sea region is rather poor. Only 7 tide gauges have \( > 30 \) years of data between 1950 and 2009. In this study, we have made use of 10 tide gauge records: 7 having \( > 30 \) years of data and 3 having data only between 15 to 20 years but of good quality. Linear interpolation was performed to introduce missing data in the gaps whenever the gaps are \( \leq 4 \) consecutive years (otherwise the record is not considered). Gaps and discontinuities occur in the tide gauge records due to natural factors like earthquakes or changes in instrumentation or even due to anthropogenic factors. Fig. 1 (as star symbols) shows the location of the tide gauges and their characteristics are given in Table 1 (in Fig. 1 -as blue dots- and Table 1 are also listed a few additional tide gauges with shorter records, records with time gaps exceeding 4 consecutive years or incorrect tide gauge data. In view of the poor quality of the tide gauge records, only the past sea level reconstruction (see Section 2.3), and observed altimetry data have been considered in these locations in order to study the past and recent sea level variability.

The tide gauge time series have been corrected for the inverted barometric response of sea level to atmospheric pressure forcing using the surface pressure grids from the National Centre for Environmental Prediction (NCEP Kalnay et al., 1996). Glacial Isostatic Adjustment (GIA) is very small in the Caribbean region and henceforth the tide gauge records have not been corrected for GIA. In order to concentrate only on the interannual variability, the seasonal cycles have been filtered through a least-squares fit of 12-month and 6-month period sinusoids.
2.3. Sea level reconstruction

Satellite altimetry since 1993 shows that sea level rise is not uniform and that it follows a characteristic spatial pattern. However this mostly reflects the interannual-decadal variability and the low frequency trends cannot be captured because the altimetry record is still short. Numerical ocean models and ocean reanalyses tools can produce the regional sea level trends on a longer time span (e.g., Carton and Giese., 2008; Kohl and Stammer, 2008; Penduff et al., 2010). To retrieve past regional variability in sea level prior to the altimetry era, other approaches can be made use. These approaches called reconstruction techniques combine long tide gauge records of limited spatial coverage with shorter, global gridded sea level data, either from satellite altimetry or from numerical ocean models (Church et al., 2004, Hamlington et al., 2011; Llovel et al., 2009; Meyssignac et al., 2012a; Ray and Douglas, 2011). Most of these studies interpolate in an optimal way (see Kaplan et al., 2000 for more details) the long tide gauge records with the principal EOF modes of ocean variability deduced from the altimetry-based gridded sea level data or ocean model outputs. Results do depend on underlying assumptions, i.e., that the principal modes of variability of the ocean are well captured by the relatively short altimetry record or from imperfect ocean models, and thus are representative over the longer time span of the reconstructed period (generally since the early 1950s). Here we use a mean of 3 different global reconstructions developed by Meyssignac et al. (2012a) over 1950-2009. These reconstructions are derived from 2-D sea level grids from the ocean circulation model DRAKKAR (Penduff et al., 2010), the SODA reanalysis (Carton et al., 2008) and from satellite altimetry (data from AVISO). For more details, (refer to Meyssignac et al., 2012a).

In the following, we call the mean reconstruction as MRESL.

2.4. Steric sea level (effects of ocean temperature and salinity changes)

Changes in the climate system’s energy budget are predominantly revealed in ocean temperatures (Levitus et al., 2005, Bindoff et al., 2007) and the associated thermal expansion contribution to sea-level rise (Bindoff et al., 2007). Anomalies in temperature and salinity in the ocean water column change density, which further gives rise to sea level variations. In this study, we have used the annual-mean steric sea level anomalies for the period 1950-2009 computed from the global gridded temperature (T) and salinity (S) data set of Ishii and Kimoto, 2009 (version 6.12). Steric sea level anomalies were computed over the range of 0-700 m depth. The annual and semi-annual signals were removed and the annual average was performed.

3. Spatial Trend Patterns in the placeCaribbean Sea

3.1. Trend patterns from satellite altimetry and the mean sea level re-construction over 1993-2009

Over the period from 1993 to 2009, the altimetry-based mean sea level trend averaged over the Caribbean Sea region – see Fig. 1a for the area contours– amounts to 1.7 ± 0.6 mm/yr. The spatial trend patterns over 1993-2009 in the region are shown in Fig. 1a. Strong positive trends are observed along the coast of the South American continent with trend maxima in the range of 4-5 mm/yr around 10°N and 60°W to 70°W, an area containing the Lesser Antilles islands of La Tortuga, Curaçao and Aruba. High trends are also observed around 10°N and 80°W to 83°W. Smaller trends of about 2 mm/yr are observed around the Greater Antilles islands of Jamaica, Cayman and around the islands of the Lesser Antilles in the eastern Caribbean.

For comparison, Fig. 1b shows the spatial trend patterns in the Caribbean Sea during 1993 to 2009 as derived from the mean re-
construction sea level (MRESL). We can observe that the spatial trend patterns between the satellite altimetry and MRESL are well correlated spatially but the altimetry-based trend amplitudes are larger, especially along the coasts of South America.

Fig. 2 shows the spatial sea level trend pattern from 1950 to 2009 over the Caribbean Sea based on the MRESL. As expected the spatial patterns are different from those on the shorter period (altimetry era) (see the difference in colour scale). Over 1950-2009, the mean sea level trend over the region amounts to 1.8 ± 0.1 mm/yr, a value very similar to the global mean sea level rate (≈ 1.8 ± 0.5 mm/yr) for the past 60 years as obtained from Church and White (2011) and Meyssignac et al. (2012a). In Fig. 2, we also note a local maximum reaching 3 mm/yr in the central Caribbean Sea.

3.2. Steric effects on the placeCaribbean sea level

Fig 3a and Fig 3b show the spatial trend pattern of the MRESL and steric sea level (sum of thermal expansion and salinity effects) over the Caribbean Sea between 1950 and 2009 after having removed the global mean trend of each data set (i.e., 1.8 mm/yr and 0.3 mm/yr for MRESL and steric sea level respectively). Both figures show similar positive trend above 1 mm/yr in the centre of the Caribbean Sea with the trend more concentrated below the Jamaican island in the case of MRESL, whereas the concentration is more towards the Lesser Antilles in the case of the steric sea level. Positive trend patterns to the south of the Cuban island are also clearly visible in both the MRESL and steric sea level. We observe a strong dipole-like positive-negative trend pattern in the steric sea level at the mouth of the Caribbean Sea opening to the placeGulf of Mexico. Similar pattern, however not inside the placeCaribbean region is also observed in the MRESL above the island of Cuba. Fig. 4 shows the interannual sea level variability over the Caribbean Sea obtained by geographically averaging the MRESL over the Caribbean from 1950 to 2009. The mean trend of 1.8 mm/yr has
been removed. The detrended steric sea level has been superimposed to the detrended MRESL curve. We observe that the maxima and minima of the steric sea level and MRESL curves are well correlated, suggesting that the same processes drive the interannual variability of the sea level and its steric component.

3.3. Interannual sea level variability and climate indices

In this section, we investigate what are the main climate modes that drive the interannual to multidecadal variability in sea level in the Caribbean region. Fig. 5 shows the comparison between detrended MRESL and climate index NINO3.4. NINO3.4 index is one of the several ENSO proxies. It is based on sea surface temperature (SST) anomalies averaged in the region bound by 5°N to 5°S and from 170°W to 120°W. It is to be noted that there is a time lag of 6 months between NINO3.4 and MRESL (NINO3.4 leads MRESL) and this lag has been corrected. Though there is no significant correlation between NINO3.4 and MRESL over the entire time period, the correlation is equal to 0.6 between 1985 and 2009. Fig. 5 also shows the climate index CAR superimposed to the detrended MRESL. CAR-Caribbean SST index is the time series of SST anomalies averaged over the Caribbean (Penland and Matrosova, 1998). Overall we note a correlation of 0.5 between CAR and MRESL over the whole time span. Neglecting the temporary anti-correlation in the early 1990s, the correlation increases to 0.7 between 1985 and 2009. The reasonably good correlations existing between MRESL, NINO3.4 and CAR indices indicate that the interannual sea level variability in the Caribbean is influenced by and responds to ENSO events. In order to capture the characteristics of the Caribbean Sea level variability, an EOF decomposition of the MRESL was performed over the Caribbean for the 1950-2009 time span. Fig. 6a, b show the 1st and 2nd modes of MRESL EOF decomposition respectively. The EOF mode 1 with 88% of the total variance captures the trend over the Caribbean. Indeed, the spatial map on Fig. 6a corresponds well to the trend map on Fig. 1b. Fig. 6a also shows the geographically averaged trend over the Caribbean superimposed to the temporal curve corresponding to the EOF mode 1. Both the temporal curves are highly correlated (correlation equal to 1). The temporal curve corresponding to the 2nd EOF mode with 4% of total variance has a correlation of 0.6 with NINO3.4 climate index as shown in Fig. 6b.

4. Sea level variability from tide gauge, MRESL and observed altimetry at various locations in the Caribbean region.

Sea level variability at different locations in the Caribbean was analysed by making use of tide gauge data, MRESL and observed altimetry at the tide gauge sites. Though there are many tide gauges available in the Caribbean, only ten sites could be used in the
study. In effect, the selection of the tide gauges from the available records was performed based on the time period of availability of the data, time gap between the discontinuities and the quality of their data. The chosen records were then compared with the MRESL and in certain cases, with observed altimetry data depending on the availability of the tide gauge data during the altimetry era. Table 1 summarizes tide gauge as well as reconstructed and altimetry trends, correlation coefficients between detrended tide gauge, reconstructed and altimetry time series.

In Fig. 7 is shown the comparison of the detrended tide gauge series (in red) with the detrended MRESL (in black) and altimetry series (in blue) interpolated at the corresponding tide gauge locations. Except for two tide gauges (Cartagena and Cristobal), the rest of the (detrended) tide gauges records have correlations (≥ 0.5) with detrended MRESL. Magueyes, located in Puerto Rico is the only tide gauge site that has been used in the 2-D global sea level reconstruction of Meyssignac et al. (2012a). So, when possible, comparison between other tide gauges and the reconstruction is a validation of the reconstruction, allowing us to assess its quality (at least in terms of interannual variability).

Between 1950 and 2009, the individual mean sea level trend from MRESL at several tide gauge sites is in the range of 1.9 to 2.3 mm/yr. In few cases (Magueyes, San Juan, Lime Tree Bay, Marigot, Gustavia and Pointe-a-Pitre), it is even lesser than the global mean trend (1.8 mm/yr).

4.1. North, South and the Eastern Caribbean

As we have seen in Fig. 7 and Table 1, there is overall good correlation between available tide gauge records and reconstructed sea level on interannual time scale. Thus, the tide gauge records could be replaced by the MRESL in the Caribbean in order to provide information on the sea level variability at islands and coastal zones that do not have long term tide gauge records. Fig. 8 shows the detrended mean reconstructed sea level (in black) over the last 60 years in three different zones: 1) the Southern Caribbean comprising the Central and South American countries of Costa Rica, Guatemala, Honduras, Panama, Colombia and Venezuela; 2) the Northern Caribbean containing the island nations of Cayman Islands, Cuba, Dominican Republic, Haiti, Jamaica, Puerto Rico, U.S Virgin islands and 3) Eastern Caribbean with islands of Guadeloupe, Martinique, Saint Barthélemy and St. Martin. The altimetry based detrended sea level (in blue) between 1993 and 2009 is also superimposed to the detrended MRESL. The difference between Fig. 7 and Fig. 8 is that in Fig. 7, only locations with the availability of tide gauges (star symbols in trend maps) are considered whereas in Fig. 8 few other stations (blue dots in trend maps) where only the MRESL and altimetry are available are also included in order to study the 3 above mentioned zones. In Fig. 8, we can observe that on a longer time scale, the interannual sea level variability in the North Caribbean is higher than in the Southern Caribbean while the Eastern Caribbean shows greater interannual variability during the recent decades. Both the Northern and Eastern Caribbean show prominent peak during 1982, roughly coinciding with the El Niño event in 1982.

4.2. Sea level variability and hurricanes

Klotzbach (2011) showed that the interannual variability of hurricanes in the Caribbean region is driven by ENSO and that more activity occurs with La Nina conditions than with El Nino conditions. The last two decades (in particular since 1999) have recorded more La Nina events (in particular in 1999/2000, 2007/2008 and
2010/2011) than before. Furthermore, Goldenberg et al. (2001) showed that the years 1995 to 2000 have seen a 2.5 fold increase in major hurricane activity and a fivefold increase in hurricane activity affecting the Caribbean due to simultaneous increases in North Atlantic sea surface temperatures and decreases in vertical wind shear. These authors also showed that this phenomenon is likely to persist for an additional 10 to 40 years. In section 3.2 we have seen that the NINO3.4, a proxy of El Niño and La Niña events, and CAR, an index based on the Caribbean SST correlate well with MRESL over the Caribbean since 1985. This period also corresponds to the increased frequency of La Niña events and hurricane activity.

Pielke et al. (2003) showed that between 1944 and 1999, the Northern Caribbean hurricanes (hurricanes hitting Bahamas, British Virgin Islands, Cayman Islands, Cuba, Dominican Republic, Haiti, Jamaica, Puerto Rico etc.) show high interannual variability as well as large multi decadal changes with a long term average of 1.0 hurricane strike per year. The Eastern Caribbean experiences hurricanes at a lower rate than the Northern Caribbean with 0.4 hurricane strike per year, whereas the hurricanes hitting the Central and South American part of the Caribbean show small decadal changes with only 0.2 strike per year. The pattern is very similar to the interannual variability in sea level observed in the Northern and Southern Caribbean as discussed in section 4.1, i.e. Northern Caribbean showing higher interannual sea level variability than the Southern. This seems to suggest that both the sea level interannual variability and hurricane activity in the place Caribbean are related. Further investigation is needed to understand the link between the sea level variability and hurricane activity in that region.

5. Conclusion

In this study, we have analysed the sea level variability in the Caribbean since 1950 by making use of the mean of a mean 2-D past sea level reconstruction, observed satellite altimetry and tide gauge records wherever available. We observe that the spatial trend pattern in sea level during 1950-2009 is quite different from that during the altimetry era (since 1993). Moreover the mean sea level trend in the Caribbean is very similar to the global mean sea level rise rate thereby indicating that the Caribbean is not facing a sea level rise larger than the global mean rise (unlike at some islands of the western tropical Pacific, as shown by Becker et al., 2012). Our results also show that the increase in the number of hurricanes during the recent decades have caused so far more damages to the coastal areas than the sea level rise itself. However, projected sea level rise in the future decades in response to global warming will represent an additional threat in this region.

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