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While sea-level rise will generate major reshaping of coasts in the next decades [1,2], severe or catastrophic coastal erosion is commonly generated by local to regional

factors among which are variations in sediment supply [3], natural or human-induced subsidence, especially in deltaic areas subject to cyclones [4,5], and tsunami [6]. Here, we confirm the hypothesis of [7] and show from satellite imagery that the fluctuations of the 1500 km-long muddy coast of South America between the Amazon and the Orinoco rivers have been governed primarily by the lunar 18.6 year nodal cycle over the last twenty years, with sea-level fluctuations from global warming or Niño Niña events being of secondary importance. From now to 2015, the predictable 18.6 cycle will lead to an approximate mean high water sea-level rise of 6 cm on the Amazon-Orinoco coast, compared to a more than 2 cm rise due to global warming, and will generate sixty percent of a projected 150 m shoreline retreat in French Guiana. Many of the world's coasts will experience a tide constituent-induced rise in sea-level exceeding ten centimetres over the next decade.

The low-frequency tide constituent results from the rotation of the nodal points of the lunar orbit and the ecliptic (the solar orbit) with a periodicity of 18.6134 yr [8,9]. By modifying the tidal amplitude by about 3%, this predictable phenomenon modulates the mean high water level by several centimetres. A full investigation of the hypothesis of [7] requires the periodic update of shoreline positions over significant spatial scales, a task greatly facilitated by the development of the monitoring of Earth from space over the last several decades. It also requires working on pristine coastlines, a rather rare situation worldwide, but one perfectly met by the muddy Amazon-Orinoco coast, referred to as the Guyanas coast. This is especially true of French Guiana, which is completely devoid of shoreline defences and groundwater or petroleum extraction activities that could generate subsidence. Thus, the dramatic changes exhibited by this coast are solely under the influence of natural processes, the most significant of which is the migration of 1.0-1.5 10^8 tons per year of mud that moves as mud banks from the Amazon to the Orinoco [10,11,12] (suppl. Info: Fig. 1). Another important attribute in terms of shoreline change is the flatness of this coast. With mean intertidal slopes ranging from 1:1000 to 1:3000, a mean sea-level elevation of 10 cm can result in flooding of thousands of hectares of mangrove forest and may induce a shoreline retreat of 100 to 300 m. A last important characteristic of this coast is the rapid adaptation to changes. *Avicennia germinans* is the only mangrove species that has developed a strategy of colonization that is sufficiently rapid as to take advantage of the substrate provided by the migrating mud banks. *A. germinans* tree communities can be wiped out extensively during interbank phases, but can reappear in the same proportions within a period of two years. The seaward limit of mangrove swamps makes a reliable ground level marker because mangrove seedlings colonize the leading edge of the mud banks, at a preferential level controlled by tidal characteristics. It is the best estimate for the shoreline position. If the mhwl is fluctuating, the mangrove response should indicate this through large-scale progradation and erosion [13]. Yet, there are clearly other processes than the nodal cycle at work, among which are the sea-level rise due to the expansion of the global ocean volume, the sea-level fluctuations under the influence of the El Niño Southern Oscillation (ENSO) and the Amazon sedimentary discharge fluctuations. These major processes are considered in the present work.

Sixty satellite images covering 39 dates from October 20, 1986 to January 15, 2006 were used to assess shoreline dynamics in French Guiana (suppl. Info: Table). Following [14], the shoreline boundary was conservatively considered to be the limit of mangrove vegetation in order to compensate for the effects of the 2–3 m semi-diurnal tide in the area. Data were interpolated linearly, using the method developed by [15], to provide a data matrix regularly distributed in time and space (Fig. 1a). Cubic and nearest interpolators provide similar results (suppl. Info: Fig. 2). To extrapolate our approach at a regional scale, we generated three mosaics of the Guyanas coast (black box in Fig. 3) for the years 1999, 1995, and 2006. This database is the most comprehensive one ever set up to study the coastal processes of the region.

Figure 1.

The shoreline of French Guiana exhibits five alternating sectors of mangrove colonization and erosion each 30-40 km long (Fig. 1a). These sectors tend to shift north-westward and constitute the fingerprint of mud banks in migration from Brazil to Surinam (at a rate of 1-3 km y^{-1}). The most dynamic spatial variations are observed between 570 km and 650 km from the Amazon. In this region, some areas suffered erosion of more than 2 km while others prograded over more than 3 km in twenty years. Hot spots of shoreline changes also developed at the river mouths (Fig. 1a, triangles on right y axis) as a result of complex geomorphic adaptations to sea-level fluctuations and longshore sediment transport [1,16-18]. As these river-mouth sectors correspond to only 5% of the coastline, we have decided to include them in the calculation of the mean shoreline fluctuations over time (Fig. 1b). In the late 1980s, the mangrove fringe was wider and corresponded to an average distance seaward of 100-130 m relative to its current position. It then suffered severe erosion up to 1999-2000, at a rate of about 30 m y^{-1}. This severe erosional phase was then followed by another spectacular period during which the coast prograded by about 200 m to attain its current position (Fig. 1b). Following the method proposed by [10] and adapted by [14], the quantitative erosion/accretion of mangrove surfaces presented in Fig. 1b can be converted to estimates of sediment volumes. Over the 1988-1999 period, the coastal sediment balance lacked approximately 37 MT y^{-1} so that the shoreline retreated. The trend has reversed since 2000 with an estimated excess in shoreline sediment of 35 MT y^{-1}. This massive progradation event is not unique and a similar event was observed in neighbouring Surinam from 1966 to 1970 [19]. More generally, it appears that periods of erosion and progradation monitored by [20] and [19] and the ones reported in the present work indeed correlate with the 18.6 y nodal cycle and emphasise the plausibility of the hypothesis of [7] (Fig. 1c).

Taking the analysis one step further requires examination of the main sources of forcing, among which is the Amazon River. Alone, it accounts for 10% of the total sediment discharge supplied by the world's rivers to the oceans [21] and almost all of the sediment along the coast of Guyanas [22]. Since 2000, the suspended sediment discharge of the Amazon has increased by about 18% (as compared to the 1996-99 period of reference [23]). This increase will probably reinforce the sediment supply along the coast of French Guiana in the near future but it is very unlikely to be responsible for the phase of colonization under progress since 2000. First, the Amazon sediment inputs are usually reworked on the continental shelf and sequestered along the coastal zones of the north of Brazil for several years before being transported north-westward [24]. Secondly, even if the input to the mud bank system was instantaneous, it would have added only about 10-15 MT y^{-1} if we assume a direct and proportional adjustment of the regional sediment fluxes [11]. This value is five times lower than the 72 MT y^{-1} that sparked the change from erosion to accretion in 2000 (Fig. 1b ; suppl. Info: Fig. 3). Finally, the migration rate of mud banks in French Guiana is in the range of 1-3 km y^{-1}. If the increase in the Amazon discharge was the main factor explaining the shoreline progradation observed in French Guiana over the last seven years, then major areas of pioneer mangroves should have developed to the east closer to the source. This major colonisation is not observed in Fig. 1a. Three forcing mechanisms, namely the nodal cycle, sea-level rise by global warming, and the El Niño Southern Oscillation interact to modulate the mhwl. Considering the mhwl instead of the mwl significantly modifies our apprehension of the shoreline dynamics, as shown in Fig. 2a. The mhwl (Fig. 2a, blue curve) increases almost linearly up to 1996, and then undergoes strong fluctuations from 1997 to 1998. These fluctuations are the local signature of the major ENSO 1997-1998 event. From the end of 1998 to early 2003, the mhwl decreases by about 4 cm. It rises again from that date.

Figure 2.

By making the assumption that the horizontal shoreline fluctuations correspond at such a timescale to a simple adjustment of the ecosystem to the cross-shore vertical fluctuations, and by considering a mean intertidal shoreline slope of 1:2000, we can easily compare the measured shoreline fluctuations with those expected from long-term mhwl fluctuations (Fig. 2b, pink, green curves and the grey curve, respectively). We obtain an overall fit that confirms the predominant role played by the lunar 18.6 year nodal cycle, as hypothesised by [7]. It appears clearly that the mean sea-level rise attributed to global warming (dashed line) contributes to shoreline fluctuations over time (coefficient of determination r^2=0.24 with a confidence level >99%), but to a lesser extent than the nodal cycle (r^2=0.68, with a CL >99%). The two effects combined (sea-level rise of 2.3 mm y^{-1} and nodal cycle) are nicely correlated to the French Guiana shoreline fluctuations (r^2=0.90, with a CL >99%). Results are comparable when considering mean intertidal slopes in the range 1:1500 – 1:2500 (relative difference of 5% and 8%, respectively). At a regional scale, the shoreline dynamics exhibits the same trend, as highlighted by the agreement between the data from French Guiana and the three mosaics covering the Guyanas coast (circles).

El Niño phases have also visible impacts on the shoreline, enhancing erosion just after the 1997-1998 event and even after the 1991-1993 event, although to a much weaker extent (Fig. 2b). The 1997-1998 event caused one of the most severe droughts of the 19th century in the Guyanas, with major consequences on the ecosystem [25-27], while engendering unprecedented erosion of the few sandy pocket beaches in French Guiana [28]. It is interesting to note that after a time of resiliency of about three years, the mean shoreline position resumes the trend defined by the coupled effect of the nodal cycle and sea-level rise by global warming.

Figure 3.

This study confirms the hypothesis of [7] that low tidal constituents are a major controlling factor in the evolution of the very gently sloping muddy coastal plain and shoreface of the Guyanas. While tides have no effect on the long-term sea-level trend, they induce important fluctuations of the mhwl, when considering decadal timescales. As this timescale is particularly important for shoreline management and for policy makers, it is crucial to highlight the shoreline fluctuations associated with the 18.6 year cycle. From now to 2015, the coast of the Guyanas, is expected to retreat by about 150 metres, 60% of this retreat resulting from the effect of the low-frequency tide constituents and 40% from sea-level rise due to global change. The nodal tidal cycle has a predictable effect on the tidal amplitude everywhere. It modulates the tidal amplitude by about 3% so that regions experiencing macro-tidal regimes are particularly concerned. Over the next decade, many coastal areas in Australia, Canada, China, England and France will experience a sea-level rise of several tens of centimetres due to the 18.6 tidal cycle (Fig. 3). This rise will certainly contribute significantly to coastal erosion generated by global sea-level rise.

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Figures

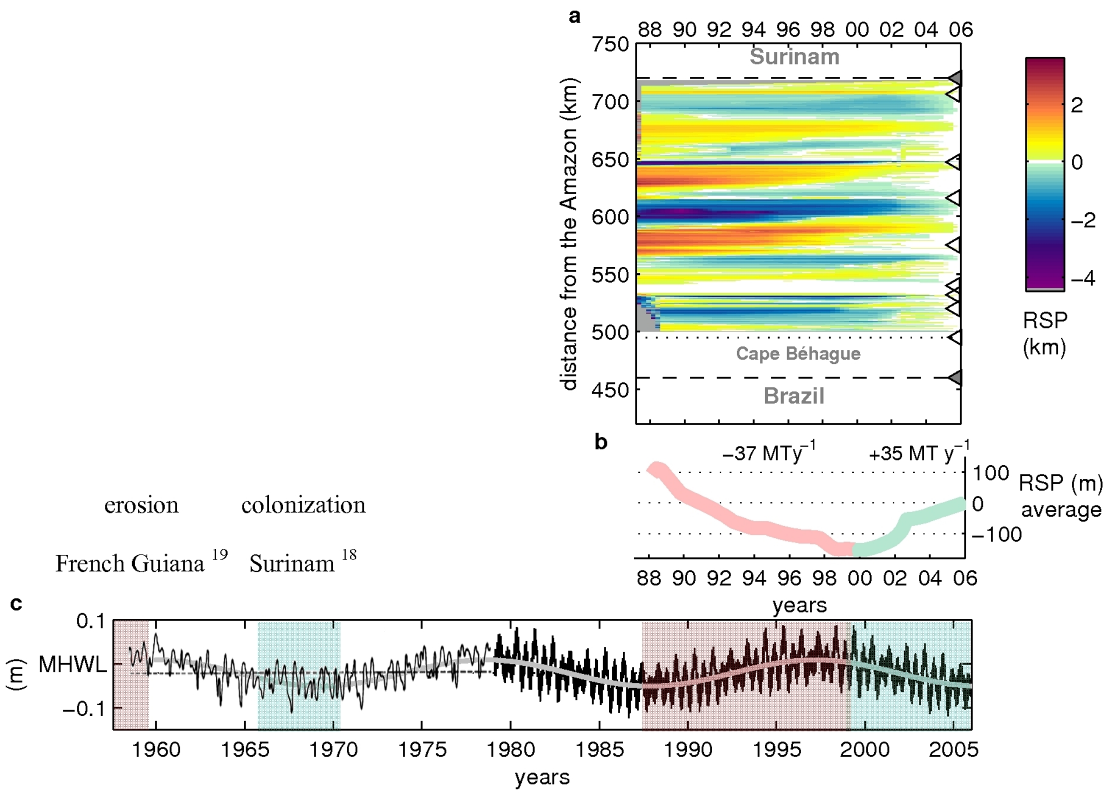

Figure 1. Spatio-temporal fluctuations of the shoreline and of the tide levels in French Guiana. a, Relative shoreline position (RSP, cross-shore) of the coast of French Guiana using the year 2006 as the reference year. Blue and red areas are associated with progradation and erosion, respectively. Triangles indicate the positions of the main river mouths. Black triangles and dashed lines delimit international borders. b, The curve represents the relative shoreline position when averaged over the 220 km long area of survey. The thickness is representative of the accuracy (±20 m). c, Nodal cycles of the mhwl in Surinam and French Guiana. From 1958 to 1978, tidal gauge measurements in the mouth of the Surinam river [7]; from 1979 to the present, data from the tidal

model of the Service Hydrographique et Océanographique de la Marine (SHOM, France www.shom.fr/ann_marees) obtained from tidal gauge measurements on Devil's Islands (French Guiana). The corresponding phases of overall erosion and colonization reported by previous studies [18,19] and in this work are shown as red and green patches.

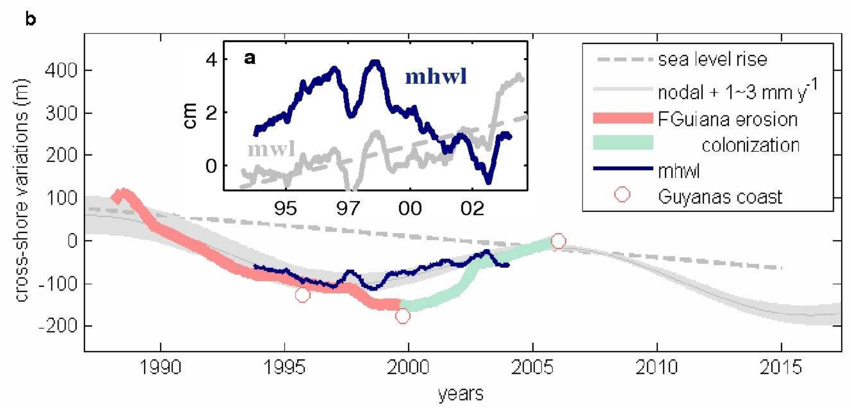

Figure 2. Measured and estimated shoreline fluctuations along the Guyanas coast. a, Temporal fluctuations of the mean water level (mwl) and of the mean high water level as estimated from Ssalto/Duacs © products. b, Measured (pink curve = erosional phase and green curve = accretional phase) and expected (grey and blue curves) shoreline fluctuations along French Guiana, using 2006 as the reference year. The white dots indicate the measured regional trend, when considering the 1500 km long Guyanas coast.

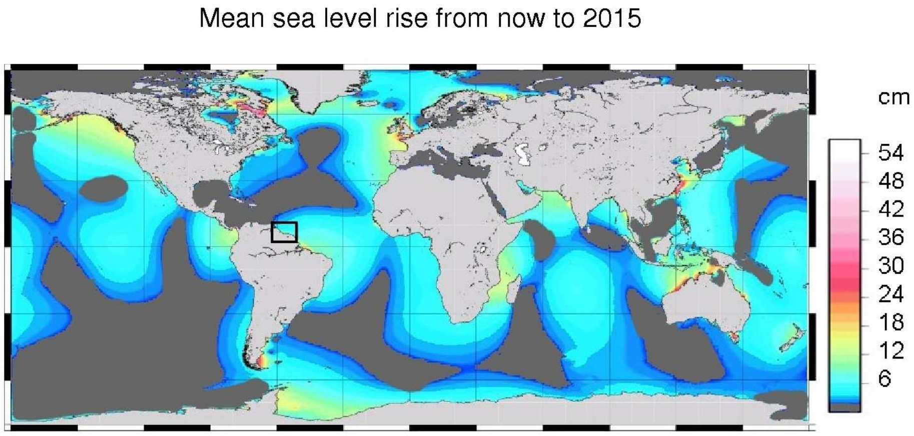

Figure 3. Predicted shifting of the mhwl under the 18.6 year nodal cycle for the next decade (adapted from the global map of tidal amplitude proposed by [29] by considering a modulation of signal of 3%). Grey areas correspond to locations of decrease or negligible rise. The black box (48W-62W-2N-12N) delimits the mud bank system of the Guyanas, South America.