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A better understanding of mud cracking processes gained from in situ measurements on an intertidal mudflat in French Guiana

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Recent work on Amazon-derived mud banks has revealed that desiccation processes can occur over elongated off-shore mud bars that form on these banks. Once mud cracks appear there, opportunistic mangroves, i.e. *Avicennia germinans*, commence the colonization process. Through the advantage of buoyancy of the mangrove propagules which can be trapped by the mud cracks, propagules can establish sometimes 1-2 kilometres offshore of the adult colonies. In a few months, these pioneer colonies become new sources of propagules, promoting rapid ecosystem expansion. Thus, mud cracking may be seen as an important factor in mangrove resilience. A field experiment was conducted during the 2008 equinoctial spring tide in French Guiana. The study area is located on the landward face of an elongated mud bar. A digital elevation model (DEM) was computed from DGPS and high-resolution laser station data. Meteorological data including air temperature and humidity, wind speed and orientation, rainfall, solar radiation, temperatures of the mud surface and at a depth of 30-cm, were recorded. Additionally, the water content of the upper mud layer was monitored along a topographic transect. An installed camera took instant photographs every half hour. Preliminary results show that climatic conditions are not the main parameter controlling the desiccation process. Strengthening and consolidation of mud are mainly controlled by mud elevation (water loss by draining) and by the local tidal signal (determinant in spatial behaviour). The DEM enabled computation of the tidal frequency emersion signal, an important tool in analyzing the spatio-temporal patterns of mud cracking and mangrove colonization.

KEYWORDS: *mud bank, desiccation, neap tide, spring tide, mangrove colonization*

INTRODUCTION

The 1500 km-long coast of South America between the mouths of the Amazon and the Orinoco is one of the world's muddiest. Due to the action of waves (GRATIOT et al., 2007) and of the North Brazil Current (NBC; NIKIEMA et al., 2007), the French Guiana coast undergoes a north-westward alongshore migration of 40-km long mud banks and the alluvial shoreline is permanently fluctuating (e.g. AUGUSTINUS, 1978; FROIDEFOND et al., 1988; EISMA et al., 1991). The mud banks are spaced 15 to 25 km (separated by temporally changing 'inter-bank areas' as the banks migrate), are up to 5 m thick, 10 to 60 km long, 20 to 30 km wide, and migrate at velocities ranging from 1 to more than 5 km a⁻¹, driven essentially by waves, aided by tidal and wind-forced currents (e.g. WELLS and COLEMAN, 1981; RODRIGUEZ and MEHTA, 1998;

GARDEL and GRATIOT, 2005; GRATIOT et al., 2007). Wave–mud interaction involves mud liquefaction by waves as they are dissipated in the highly viscous muddy layer, and mud bank migration generated by the longshore component of waves obliquely incident to the shore (GRATIOT et al., 2007). Apart from variations in sediment supply from the Amazon, changes in the intensity and direction of the trade winds and their effects on waves have also been held responsible for temporal variability in mud bank migration rates (EISMA et al., 1991; ALLISON et al., 1995; 2000).

Once established along the coast, the central parts of mud banks sheltered from waves are rapidly colonized by *Avicennia germinans* mangrove forests (FROMARD et al., 2004). However, at the trailing edges of mud banks exposed to wave breaking, the mangrove-colonised shoreline can undergo erosion of up to 200 m per year (GARDEL and GRATIOT, 2006). GRATIOT et al. (2008) have highlighted the significant role of the 18.6 year tidal cycle on the fluctuations of the mangrove-colonised shoreline.

Recent work has shown that mangrove colonization is conditioned by mud dewatering and consolidation (FIOT and GRATIOT, 2006) which are dependent on local topography (ANTHONY et al, 2008), i.e. tide submersion frequency, and sheltering from wave forcing (PROISY et al, 2009).

Elongated mud bar-shaped areas of wave damping (ALLISON and LEE, 1995; GRATIOT et al, 2007) constitute new off-shore points of mangrove colonisation. As these are 'elevated' features relative to the surrounding topography (20-30cm higher than the rest of the mud bank, FIOT and GRATIOT, 2006), mud bars are no longer submerged at each tide. They become exposed to drying and evaporative processes, which are strongly hinged on the semi-lunar tidal cycle. FIOT and GRATIOT (2006) demonstrated in the laboratory that mud cracking appears when drying and evaporative processes last sufficiently. Above an elevation of 2.6 m above the hydrographic zero, five consecutive days of emersion (CDOE) are sufficient to allow for mud cracking, which, in return, seems to play a determinant role in the rapid and extensive colonisation of the whole mud bank under consolidation. Indeed, we observed *in situ* that mud cracks over elongated mud bars act as mechanical traps for mangroves propagules during spring tides (FIOT and GRATIOT, 2006; PROISY et al, 2009). This mechanism is probably at the origin of a unique ecological process which starts at the highest and seaward edge and has been referred to by the latter authors as a top-down 'opportunistic' colonization which strongly differs from the 'classical' regular step-by-step colonization from adult mangrove landward positions.

However, to fully explain the spatial synchronization of desiccation and propagule trapping, there is a need for additional insight into the temporal synchronization of mud crack formation and propagule availability. Although some laboratory experiments have explained the formation and the evolution of desiccation on the basis of drying and wetting cycles (YESILLER et al, 2000; FIOT and GRATIOT, 2006), to our knowledge, ground measurements of this important mud process still need to be implemented.

The work reported here aims at understanding the *in situ* formation of mud cracks during the equinoctial spring tide on the landward face of an elongated mud bar in French Guiana. It presents a preliminary analysis of the evolution of the main climatic parameters and sediment characteristics (concentrations, grain sizes, and mineralogy) recorded between March and April 2008.

METHODS AND DATA COLLECTION

Study site

A preliminary field reconnaissance campaign with DGPS was necessary in order to choose the site to be instrumented and obtain the XYZ coordinates of a point. This was a very important step because this point is central to the analysis. The experimental site selected is located in the middle part of the Macouria mud bank 25 km northwest of Cayenne city and 10 km southeast of Kourou city in French Guiana, on the landward face of a mud bar (Figure 1).

The datum used for the DGPS point is WGS84 and the projection North UTM zone 22. The coordinates of this point are: x: 314809.4, y: 569614.6 and the elevation 2.67 m above the hydrographic zero (Figure 2-A/ n°A).

The difficult access to the site was a guarantee against disturbance by humans, excepting that induced in a minimal way by our small field team. However, as a result of this, the frequency of sediment sampling was quite low (three for the present study). At the start of the experiment, the site still exhibited healed cracks that are a sign of former drying and wetting cycles. Wetting cycles due to the tide do not shift cracks but heal them, thus leaving scars on the mud surface.

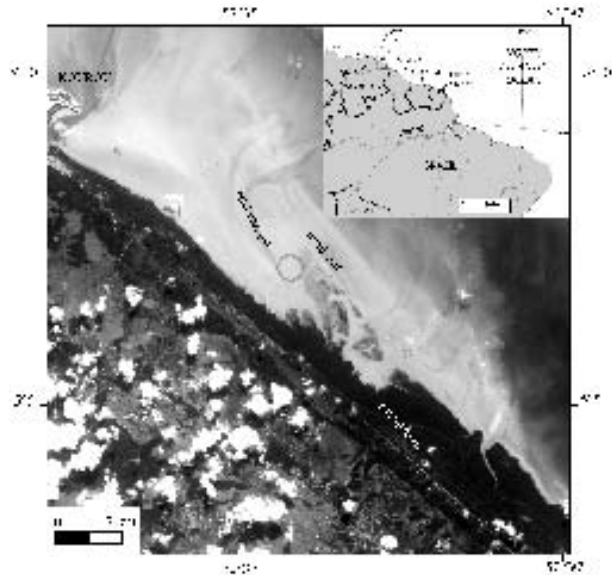


Figure 1. Location of the instrumented field site in French Guiana.

Period of study

In French Guiana, as the peak of fructification for *Avicennia germinans* occurs during the spring season (PROISY et al., 2009), the amount of propagules ready to be dispersed or trapped is maximum from April to July (the propagules can survive 100 days). For these reasons, we scheduled our first field campaign from March to mid-April 2008, which corresponds to the equinoctial period of spring. This period also corresponds to the "little dry season", a relatively dry month during the rainy season (which lasts from the end of December to June). Therefore, we believe that neap tides preceding the equinoctial spring tide period are favourable to mud crack formation as duration to air exposure is sufficient for drying and evaporative processes.

We computed the probability of mud crack occurrence at an elevation of 2.67m above the hydrographic zero using the 2008 tidal harmonic components provided by the Service Hydrographique et Océanographique de la Marine (SHOM; www.shom.fr) as described in PROISY et al., (2009). As shown in Figure 2-B/, the period between March 28 and April 2 was favourable for continuous desiccation.

Sensor installation and parameter monitoring

A set of sensors was installed in March 2008 before the emersion period. It consists of a digital camera and a weather station. Measurements were conducted from March 28 to April 2 2008.

The weather station (WMR200, © Oregon Scientific) records the wind at a 1 minute frequency 2 m above the substrate (direction in degrees and speed in $m.s^{-1}$), air temperature (degrees Celsius), air humidity (%), and rainfall at a height of 1 m from the ground ($mm.h^{-1}$) (Figure 2-A/ n°D).

The digital camera was placed 2.5m above the ground to take one oblique photograph of the experimental site every hour (Figure 2-A/ n°B.). Because of the obliquity of the camera, only the surface of the mudflat nearest to the instrument is sufficiently visible on the photographs. As a result, a small area between Station 1 and Station 2 is extracted from the photographs (Figure 2-A/). Because of technical limitations, only pictures taken between 7 a.m. and 6 p.m. were considered. All of them were geometrically corrected (using ErMapper 7.1 software © Earth Resource Mapping) for superimposition and quantitative analysis of mud cracks dynamics. A manual digitalization of the mud



Figure 2: A/ Instrumentation in the study site. The white rectangle covers the surface extracted from photographs between station 1 (ST1) and station 2 (ST2). A: DGPS point, B: camera, C: scales along a transect, D: weather station. B/ presents the tide levels from 1/10/2008 to 4/09/2008. Black stars denote $CDOE \geq 5$ at a 2.67 m. elevation.

cracks has been preferred to automatic extraction using image spatial filters.

In the southward axis of the camera mast, along a transect marked, 3 stakes spaced 10 m apart served as a graduated scale (figure n°4), and farther towards the tidal channel (Figure 2-A/n°C), a field topographic survey was carried out using a very high-resolution laser electronic total station. Instrumental errors are ± 3 mm for distance and height and $\pm 0.0015^\circ$ for direction, while additional errors of up to few cm can be caused by operational instability on the muddy substrate.

Surface sediment samplings along the transect were carried out on March 28 and 31 and on April 2 in order to evaluate trends in sediment concentration ($g.l^{-1}$) and thus sediment consolidation during emersion. Sediment concentrations were obtained by weighing first the fresh samples, then the samples after drying at 50° Celsius in an oven for several days.

RESULTS

Mud cracking and sediment surface concentration

The first result concerns quantification of mud cracks from the set of mud crack images (Figure 3). Results are expressed in

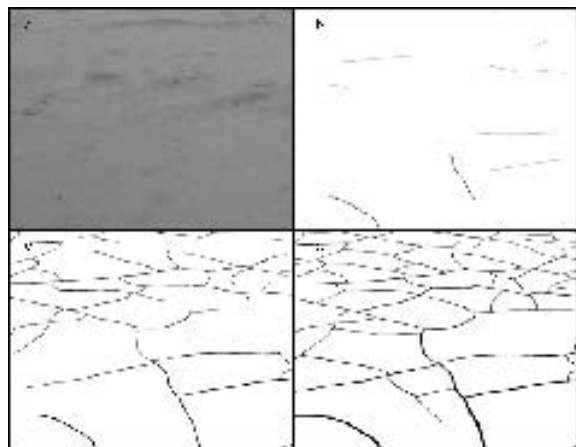


Figure 3: Evolution of mud cracks during the field campaign. a/ presents the first photographs considered for the monitoring. Scars of former mud cracks are visible. b/ presents mud cracks at the end of day 1, c/ at the end of day 2, and d/ at the end of the campaign.

number of new mud crack pixels appearing between two successive images. This method only considers mud crack length and width and does not take into account their depth because this parameter cannot be estimated from photographs.

Figure 4a presents this result as well as the evolution of sediment surface concentration. Mud cracks seem to appear during daytime because no new or few pixels appear between the last images of the previous days (6 p.m.) and the first images (7 a.m.). For each day, peaks of desiccation occur at the warmest hours of the day, i.e. between 11 a.m. and 4 p.m.. 5 % of the all mud cracks occurring on day 1 of emersion. The most effective day is day 2 since it represents 51% of all mud cracks. A decrease in mud crack formation occurred from day 3, (23% of the all mud cracks) and continued on days 4 and 5 (respectively 18% and 3%). No new mud cracks appeared on the last day. Using the CIF (Crack Intensity Factor, which is the ratio of area of cracks to the total surface area) to quantify mud crack progression (YESILLER et al., 2000) yielded a value of 0.24% for day 1, 2.5% for day 2, 3.5% for day 3, 4.3% for day 4, and 4.4% for day 5.

Between March 28 and 31, rates of consolidation (see Figure 4a) were higher at station 1 (increase from $716 g.l^{-1}$ to $995 g.l^{-1}$) than at station 2 ($624 g.l^{-1}$ to $713 g.l^{-1}$). From March 31 to April 2, they were much lower ($995 g.l^{-1}$ to $1009 g.l^{-1}$ at station 1 and $713 g.l^{-1}$ to $756 g.l^{-1}$ at station 2).

The topography along the transect was extremely flat. The height difference, for instance, between stations 1 and 2 was less than 1 cm, which is within the uncertainty band.

Influence of meteorology

Meteorological measurements do not highlight any particular conditions during the survey. Only some records are presented here revealing normal trends for equatorial meteorological conditions. During the period, rainfall is considered to be insignificant as only two short events occurred, one in the night of April 1-2 and the other in the morning of April 2. Figure 4b presents curves of air temperature, ground temperature (-0.3 metres) and the heat index. The heat index is the felt temperature depending on air temperature and air humidity. This figure shows the difference between daytime and night temperatures and also the gap between air temperature and ground temperature. Air temperature and heat index are higher between 11 a.m. and 16 p.m. with a maximum around 13 p.m. whereas ground temperature, as expected, presents smoother ranges with a temporal shift of 3-5 hours.

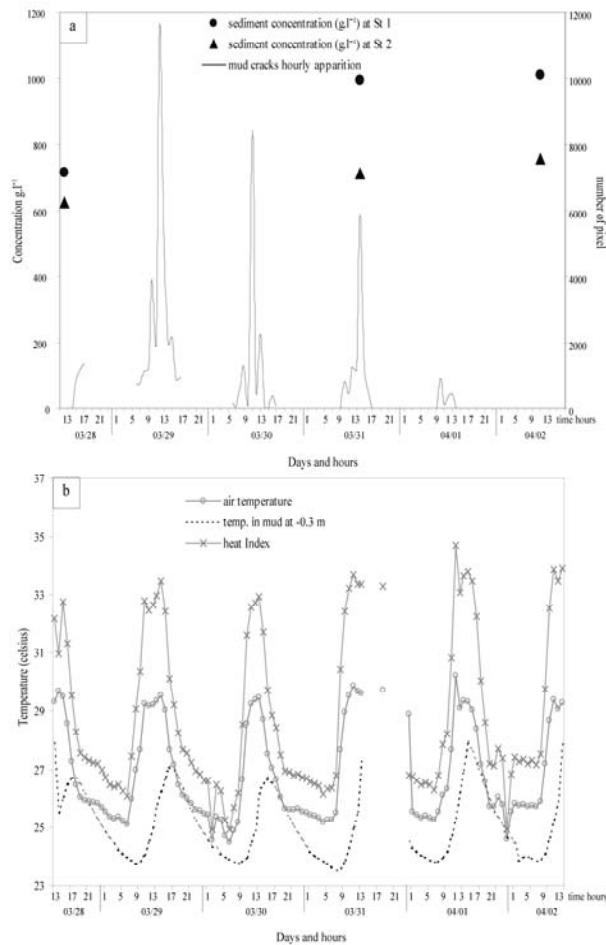


Figure 4: a/ appearance of mud cracks during the survey and evolution of sediment concentration. b/ Air and ground temperatures.

DISCUSSION AND CONCLUSION

During this field experiment, meteorological parameters (especially temperature) turned out to be of little significance in explaining alone the formation of mud cracks. This experiment constitutes a snapshot of just one situation within the year. During the rainy season (more than 3000 mm.y^{-1}) mud cracking must be slowed down by rain through re-humidification and fine-grained particle mobilization by soil washing.

On mud crack formation/re-activation

This experiment has shown that much of the mud crack formation occurred within the first 1.5 days (nearly 50 % of the mud cracks during the campaign). This is in agreement with laboratory experiments on different soils showing a short and intense mud crack formation episode during drying after a wetting event (YESILLER et al., 2000). Furthermore, this snapshot campaign records the re-activation of cracking after a tidal wetting cycle. This implies that the initial mud cracking process at this site started during previous tidal flooding and drying cycles. YONG and WARKENTIN (1975) have shown that the cracking process in a clay soil started during a first drying then wetting

cycle. The first drying episode causes, in some locations, shrinkage and the breaking of particle bonds, thus weakening the

soil. The next wetting cycle is considered to further weaken the soil, causing lower cohesion through the new supply of water. Therefore, a new drying cycle would significantly activate the cracking process at the weakest part of the soil where cohesion is low. In fact, the initial phase in the mud cracking process has not been observed during this campaign. Considering the necessary conditions for initial mud crack formation on French Guiana coasts, i.e. five consecutive days of emersion (CDOE) and a 2.6 m threshold elevation (FIOT and GRATIOT, 2006), it is possible to compute, using a tide model (from SHOM) the hypothetical previous events responsible for its occurrence (cf Figure 2-B/). The initial mud cracking may have took place during 2 previous neap tides, ie, at the beginning of February or at the beginning of March.

In laboratory experiments on a clay-rich soil, YESILLER et al. (2000) have shown that, once formed during a first drying cycle, mud cracking progression slows down during the next drying cycles until a threshold value where no more mud cracks appear. They also showed that mud cracks can be reactivated very rapidly (within 0.5 day) after a wetting cycle.

In the present case, under natural conditions and with a material richer in clay, mud cracking seems to follow the same trends. It is therefore possible to propose the following: (1) once formed during a first 5 consecutive days of emersion (CDOE), or more, mud crack formation will not progress significantly during next tidal drying cycles; (2) reactivation of mud cracks can be very rapid (with 50% of them present during the first 1.5 days after emersion).

On parameters influencing mud cracking in natural conditions

Cracks outline roughly polygonal areas that define a honeycombed surface. The cracks can reach significant sizes of up to 1-2 m, compared to mud cracks of temperate latitudes (10-20 cm). This aspect is related to very slow drainage activity, due to (1) a high proportion (60 %) of grain sizes under $20 \mu\text{m}$, (2) a high proportion of clay minerals (more than 50 %) dominated by smectite, and (3) a very flat slope.

The network of mud cracks influence the circulation of tide water on and inside the mudflat, as the developing cracks are first filled at the beginning of the flood, and drained at the end of the ebb. Humidity is also maintained a longer time and water loss is also restricted.

Mud cracks can be up to 20-30 cm deep. However, the depth of mud cracks is generally the thickness of the mud layer, as has been reported for temperate mudflats. In this particular location of the mud bank, the local topography versus water level suggests that the mud deposit is very thin, 2-3 cm (the altimeter data not commented in this paper). This implies that each time mud cracks are generated on a new mud layer, the cracking process starts using the former mud cracks, with a bottom-up process (WEINBERGER, 1998) comprising developing splits that pass through different mud layers, and not one set of mud cracks on each mud layer.

Mud cracks are locally smaller (20-30 cm polygons) near the banks of small drainage channels (runnels 50 cm deep). These specific mud cracks appear early and quickly dry out. This is linked to a better drainage activity. In these locations, which correspond to runnel levees, the higher topography favours colonization by *Avicennia germinans*. These areas are also preferred by crabs for their burrows. Biological activity (root activity and bioturbation by burrowing) increase the drainage capacity, and therefore, mud desiccation.

On mangrove colonization and seed availability

The field campaign was scheduled at this period for at least two reasons. The first was to study mud crack formation/re-activation during a neap tide with 6 consecutive days of emersion. This phenomenon has been observed and quantified. The second reason, which has not yet been discussed in this paper, was to observe seed arrival with the spring tide (from April 3 to April 9) and their trapping by mud cracks. In fact, in spite of the peak of fructification for *Avicennia germinans* only few seeds were available at this site. Reasons for this situation are probably due to the site exposition to flood tide currents. Flood tides gain ingress to the tidal channel to penetrate this part of the mud bank so that the site seems to be long way from hypothetical seed sources. However it is reasonable to imagine a very rapid colonization of this site as soon as seeds will be available.

Conclusion

Mud cracking is the first step of mudflat colonization by mangroves. The specificity of the mud cracking process during this field campaign is linked to: (1) topography of the mudflat, requiring a minimum elevation of 2,60 m, (2) sufficient consecutive days of emersion (5 days of consecutive emersion minimum), and (3) favourable climatic conditions (dry season).. Once the mud crack network formed on the mudflat, it is somehow "recorded", even if subsequent mud deposition during later event can cover the whole mudflat. Mud cracks can also be easily reactivated, via the initial network, as soon as the parameters previously cited occur in conjunction. The specificity of mud grain size (fine grain size, high clay content) and mudflat topography (very low slope) explain the morphology of mud cracks (very long, large and deep) and their capacity to trap propagules but also their germination by preventing their desiccation within the splits.

Future research should focus on a better understanding of: 1/ the role of neap tides and the equinoctial spring tide in consolidation processes, 2/ initial mud crack formation, 3/ impact of seasonality on mud crack activity, i.e., what happens, for instance, during the rainy season? 4/ the arrival of seeds with spring tides on the desiccated surfaces.

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