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Research Article

Dynamics of a macrotidal estuary along 400 years based on historical maps and remote sensing: Araguari river, Amazon coast, Brazil

Dinâmica de um estuário macrotidal ao longo de 400 anos baseada em mapas históricos e sensoriamento remoto: rio Araguari, Costa Amazônica, Brasil

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Abstract: Estuaries are environments subject to rapid morphological changes driven by variations in hydromorphological and climatic patterns. On the Amazon coast, these transformations have also been intensified by anthropogenic processes. Remote sensing imagery enables the detection of such changes in much greater detail than historical maps. This study presents the morphological evolution of the Araguari River estuary from the 17th to the 21st century, based on a multitemporal analysis of historical maps and remote sensing imagery, correlated to field data. The results indicate that the morphology of the outer meander of the river's mouth was short-life: it formed during the 18th century and was infilled in 2014. The colmatation of drainages channels within the tidal-influenced floodplain and a point bar formation on the estuarine margin, coincided with the disappearance of Carpori Island - a key element of the Cabo Norte paleo physiography. Morphological changes in the estuarine plain, observed since the mid-20th century, are associated with the formation of mid-channel bars and mouth bars as a result of the interaction between tidal bores, tidal currents, and fluvial processes. Over the past 40 years, multitemporal analyses have revealed a superposition of natural processes and anthropogenic interventions.

Keywords: estuaries; morphological change; historical charts; remote sensing.

Resumo: Os estuários são ambientes sujeitos a rápidas mudanças morfológicas, impulsionadas por variações nos padrões hidromorfológicos e climáticos. Na costa amazônica essas mudanças têm sido intensificadas também por processos antropogênicos. Imagens de sensores remotos podem registrar tais transformações com muito mais detalhes quando comparadas aos mapas históricos. O trabalho apresenta a evolução morfológica do estuário do rio Araguari entre os séculos XVII e XXI, com base na análise multitemporal de mapas históricos e imagens de sensores remotos, correlacionadas a dados de campo. Os resultados indicam que a morfologia do meandro externo da foz do rio Araguari teve existência efêmera: formou-se ao longo do século XVIII e foi preenchida em 2014. A colmatação das drenagens dentro da planície de inundação influenciada por marés, bem como a formação de uma barra em pontal na margem do estuário, ocorreram simultaneamente ao desaparecimento da ilha Carpori - elemento marcante da paleofisiografia do Cabo Norte. As mudanças morfológicas na planície estuarina, registradas desde meados do século XX, estão associadas à formação de barras de meio de canal e barras de desembocadura, resultantes da ação combinada da pororoca, das correntes de maré e dos processos fluviais. Nos últimos 40 anos, as análises multitemporais revelam uma superposição entre processos naturais e intervenções antropogênicas.

Palavras-chave: estuários; mudanças morfológicas; mapas históricos; sensoriamento remoto.

1. Introduction

Coastal landscapes have always been subject to important changes under the influence of astronomical, geological, hydrodynamic and climatic forces (PERILLO, PICCOLO, 2011), and more recently anthropogenic ones (ZHOU et al., 2018). These forcings occur at different temporal scales and they can have different behaviors, e.g., cyclical, progressive or catastrophical (POLIDORI, 2020).

The interactions between these forces and the coastal environment are not yet fully understood, so the evolution is difficult to predict. However, a better understanding of coastal processes is likely to result from the analysis of old and modern cartographic data, such as historical maps and remote sensing images, which may be used for analysis and spatial description of coastal landscape modifications (FROMARD et al., 2004; CHEN et al., 2005; BERTOLO et al., 2012; GARDEL et al., 2022). In Brazil, few studies have made use of these documents to examine changes in the coastline, despite the existence of cartographic archives dating back to the 16th century (FURRIER, MEDEIROS, 2011).

Two approaches can be considered to characterize temporal changes using maps and satellite and/or aerial images:

The first approach consists in recognizing environmental dynamics and geomorphological features produced in the past and recorded in the coastal plain, such as abandoned channels, paleodeltas, former estuaries, and accretionary plains records. All these elements may be visible in the images. However, not all stages of change can be recognized, especially in the humid tropics, where thick vegetation may inhibit the identification of records. Furthermore, the records can be superimposed on several time scales, making it difficult to identify and rebuild events. The anthropogenic processes add a further difficulty, turning hard to understand the environmental evolution during the last decades with the proper chronology of events.

The second approach consists in comparing recent remote sensing images with old ones. Such a comparison can reveal channel migration, cut-off processes, channel avulsion, which can be measured if the images are properly registered and rectified into the same cartographic projection. Satellite imagery archives dating back to the 70s and aerial photography from the 30s allow a multitemporal analysis, which is, of course, limited to a few decades.

In this context, historical maps allow us to go back further in time up to the 17th century, and represent an important source to better understand coastal environment modifications, mainly in areas under rapid evolution, such as the Amazon coast. Historical maps show the hydrographic network and the terrain morphology at different times, despite a limited accuracy as described by Jongepier et al. (2016). Some of the maps are limited to details that are useful for navigation, and don't include all the physiographic features. However, these maps allow the reconstruction of the recent geological evolution, like in the case of the adjacent coastal plain at the mouth of the Amazon River.

The Amapá coastal plain is one of the few areas in the world where natural changes occur as fast as those driven by anthropogenic processes. Highly dynamic erosional and depositional processes can reshape the coastal plain within just a few centuries, due mainly to the Amazon River influence (SILVEIRA, 1998). As a result, historical maps which are traditionally used to track anthropogenic changes, can also be effectively employed to document natural transformations in this coastal environment.

Recovery of recent coastal environment evolution through old maps has been tested in other regions (COOPER et al., 2004; WAL, PYE, 2004; JABALOY-SANCHEZ et al., 2010), showing that historical maps can be additional tools to study the evolution of recent coastal environments, despite some limitations due to location uncertainty, ambiguous graphic choices and poor conservation conditions, even in the case of rapid coastal changes (CAMFIELD, MORANG, 1996; LUKAS, 2014). This confirms the potential of historical maps for coastal geomorphology (GUPTA, RAJANI, 2020).

In Brazil, despite the existence of cartographic collections dating back to colonial times and their potential for detecting changes (FURRIER, MEDEIROS, 2011), it is not common practice to use these data for coastal geomorphology. Coastline transformations occur over a large part of the Atlantic coastline, corresponding to erosion and sedimentation processes due to oceanic forcings like waves, tides and sea-level fluctuations accompanied by important shoreline shifts in mangrove areas and beaches (MUEHE, 2006; ROSSETTI 2008). Other transformations are of anthropogenic origin, but the impact of human activities studied by anthropogeomorphology focuses more on mining (SOUZA, PEREIRA, 2015) and agricultural activities (ZANATTA et al. 2017) than on urbanisation and exploitation of the coastline. Whether considering natural or anthropogenic processes, satellite remote sensing can be used to highlight coastal changes over several decades, as has been done by several authors on the coastlines of Pará (SÁ GUERREIRO et al. 2013), Ceará (SILVA et al. 2020), Espirito Santo (MIRANDA et al. 2024), among others. Historical maps can also be used to study transformations over several centuries (FARRAPEIRA NETO et al., 2023), but this approach remains limited, possibly because the geometric accuracy of these maps is insufficient to measure shoreline shifts of limited amplitude.

In contrast, the northern coastline around the mouth of the Amazon has undergone spectacular transformations over the last few centuries, and the fact that this region has been disputed by various colonial powers has led to a significant cartographic production. Silveira (1998) used maps of Alexandrino (1749), Cavalcante (1896) and Braz de Aguiar (1923) of the Amazonian coastal plain, and compared them with vertical aerial photos (1970) and aerial radar images (1972) to reveal ancient morphological features of deltas, bays and channels within the Amapá coastal plain. Some of them are records of geomorphological and hydrographical conditions registered in the old maps, demonstrating fast changes in the coastal plain. Plaziat and Augustinus (2004) used maps of the 18th and 19th centuries to understand the processes of the progradation and retrogradation of mud flats in the coastline of French Guiana. The existence of these mudflats has been reported in historical maps since the 18th century. On the other hand, the availability of satellite images for the last four decades has allowed analyses of the variations of the coastline (SILVEIRA et al., 2002; BATISTA et al., 2009; SILVA et al., 2011; BAIA, SILVA Jr., 2025) that demonstrate the dynamism of the coastal features.

Following on from those studies, this article draws on a wider range of sources and focuses on the Araguari plain, which has undergone rapid changes over the last decades. The objectives of this article are (1) to present the historical changes registered over the last 400 years in the Araguari River estuary using historical maps and remote sensing images and (2) to illustrate the potential and limitations of historical maps and remote sensing imagery to better understand the evolution of coastal environments subject to fast changes.

2. Study Area

The Amapá coastal plain is located on the left bank of the Amazon, at equatorial latitude in northern Brazil. It is under the influence of the Intertropical Convergence Zone (ITCZ), which interacts with the North Atlantic Oscillation (NAO) (JAHFER et al., 2020; SANTOS et al., 2010) and with a great source of fresh water from the Amazon River, which discharges nearly 17% of all freshwater into the oceans (CALLÈDE et al., 2010). This coastal plain is subject to instabilities due to recent geological factors – neotectonic and regional coastal processes (ALLISON et al., 1995; SILVEIRA, 1998). In the last centuries this region has registered rapid changes, mainly in its drainage network (SILVEIRA, 1998), and these processes have been accelerated in the last decades due to buffalo breeding (SANTOS et al., 2003; SANTOS et al., 2009).

The macrotidal estuary of the Araguari River (mean tide 5.2 m – COSTA, SILVEIRA, 1998) was the main estuary on the Northern coast of Amapá State, until its closing in 2014, with deviation of its flow towards the Amazon River (SANTOS et al., 2016; ROSÁRIO et al., 2017). The estuary was located in the vicinity of the Amazon River mouth, South of the Cabo Norte (Northern Cape) region, with direct influence of water and sediments transported by the Amazon River. It was a relatively young estuary (COSTA, SILVEIRA, 1998) formed on a coast subject to rapid changes, and therefore, it was an ideal laboratory for testing of various types of cartographic and remotely sensed data for the analysis of coastal changes. The Araguari River is about 500 km long, with its source in crystalline rocks, 200 m above sea level. The Southern coastal plain of the Araguari River is integrated with the coastal plain of the Amazon River. The Northern coastal plain is part of a region of lakes interconnected with other rivers and channels that drain the Eastern portion of the Atlantic coastal plain of the Amapá State (Figure 1) (SANTOS, 2006).

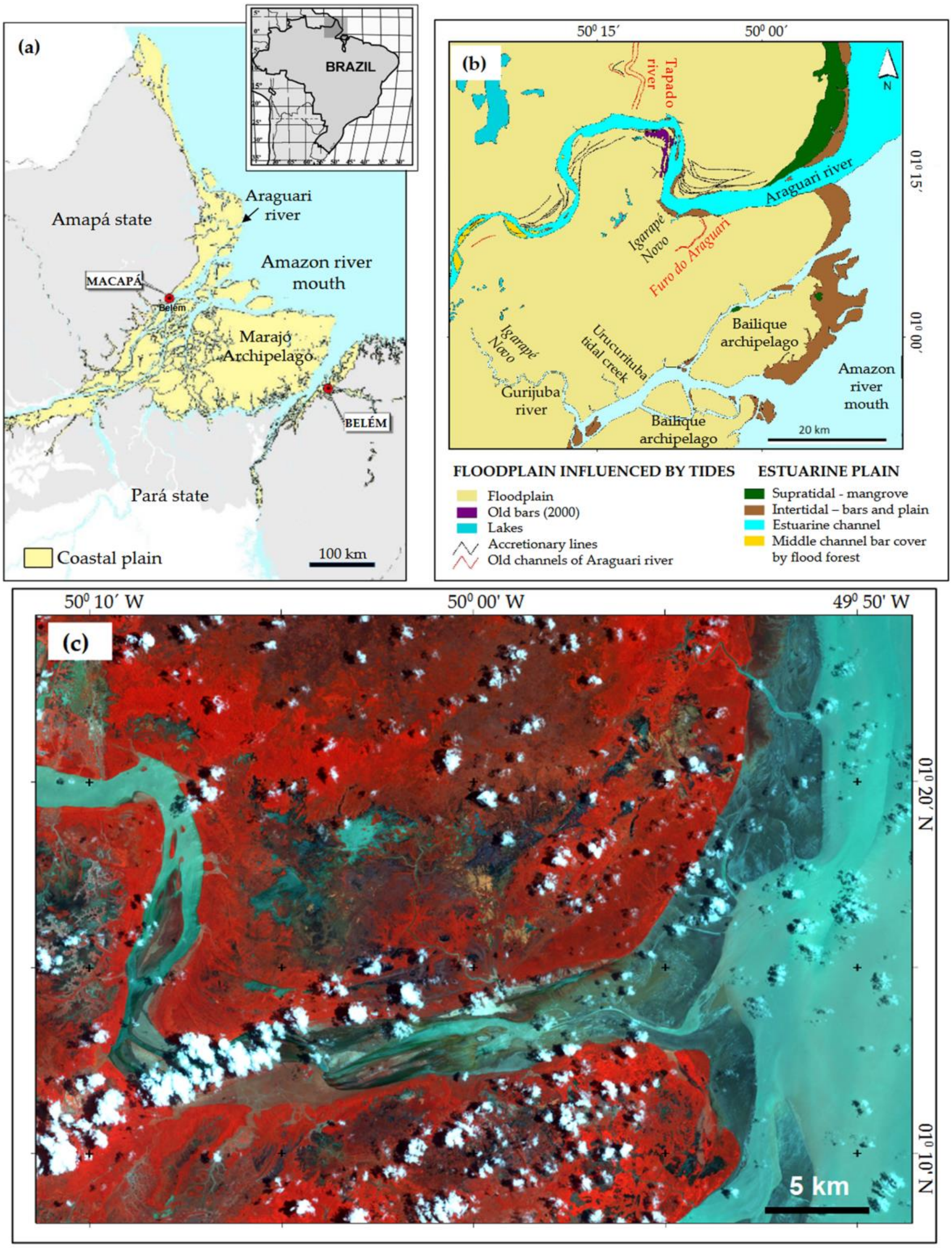

Figure 1. Study area: (a) Location of Araguari River estuary in the Amazon river mouth; (b) map of two morphological units and paleofeatures described in this work (modified from Santos, 2006, based on Landsat image 2000), note the location of Uricurituba tidal creek; (c) Landsat image of September 14, 2014, composição RGB532, (courtesy of the U.S. Geological Survey).

The inner limit of the Araguari estuary is located in the medium course of the river, and it presents a slight slope, slow speed, and reduced outflow capacity. Faster outflow conditions only occur when the water level reaches up to 1.50 m over the floodplain. In normal conditions, the water level on the floodplain varies from 0.5 to 1.0 m and, in exceptional cases, up to 2.50 m, like during the flood of 1984 (PROVAM, 1990). The flood condition is the result of a low topography and a high precipitation rate (3000 mm/yr) with 70% rainfall concentrated from December to May (QUADRO et al., 1996).

The Araguari River was the main contributor of water (~2,3 x 10^9 m3/yr) and sediments (7 x 10^5 tons/yr) of the northern Amapá coast to the ocean (ALLISON et al., 1995) – maximum discharge, in May, and minimum, in December. During the flood period, a great part of the drainage is interconnected, which allows navigation in small boats (SANTOS, 2006).

Tide reaches approximately 225 km from the coastline; however, the enormous discharge of freshwater in the ocean provided by the Amazon River does not allow an expressive salinity gradient in the Araguari estuarine waters (LAUT et al., 2010; SANTOS et al., 2016). Tidal bore, until 2014, was a common phenomenon with occurrence up to 50 km inland, and played a major role in the continuous process of deposition and erosion of sediment at the mouth of the estuary (SANTOS et al., 2005).

The estuary was built in semi-consolidated sediments of the Pre-Araguari Unit (COSTA, SILVEIRA, 1998), with its depositional history linked to ancient river systems (JARDIM et al., 2018) and relative sea level changes in the Holocene.

The estuarine channel is characterized by fill deposits typical of young systems with the establishment of its last meander five hundred years ago (COSTA, 1997; COSTA, SILVEIRA, 1998). Sediments in the estuarine channel were predominantly muddy and silty, slowly shifting to very fine sand near the river mouth (SANTOS, 1994).

The Araguari River presents two morphological units: the alluvial and estuarine plains. The alluvial plain is in a narrow valley with the drainages strongly embedded in the crystalline and metamorphic rocks (CORDANI et al., 2016). The estuarine plain is built over the sediments of the Holocene (COSTA, SILVEIRA, 1998) in the floodplain influenced by tides (SANTOS, 2006; JARDIM et al., 2015). Over this plain, there are numerous paleochannels, abandoned meanders, and paleodeltas described as traces of old drainages, including paleotraces of Araguari River (BOAVENTURA, NARITA, 1974; SILVEIRA, 1998; SANTOS et al., 2007; JARDIM et al., 2015; JARDIM et al., 2018).

3. Materials and Methods

The material used in this work consists of historical maps from the 17th to 20th centuries, as well as airborne and orbital remote sensing images. The frequency of remote sensing data has increased in the last thirty years of the 20th century.

3.1. Historical Maps

Historical maps of these coastal areas have existed since the 16th century, and modifications can be followed since the beginning of the 17th century. Adonias (1963) provided a compendium of information about historical maps of the Amazon region. These maps offer a very rough description of the interior of the continent; sometimes even with legendary elements, while they are much more detailed near the coast, with precise hydrographic surveys intended to help navigation and indications of the presence of native groups for commercial relations. During the 18th and 19th centuries, the governments of France and Portugal (and later Brazil) argued over the position of Guyana's border, resulting in the creation of several military maps of the disputed area between the Oiapoque and Araguari rivers (MATTOS, AGUILAR, 2011).

A preliminary observation shows that Cabo Norte and the lower course of the Araguari appear in all the maps shown, but the changes in the general shape of the coast and the estuary are difficult to attribute to an actual transformation or to approximations in the survey. All the maps show the island of Maracá to the north of the estuary, and, with more uncertainty, the Carpori Island appears in some of them. The maps provide varying degrees of information on the hydrology of the continent, with an alluvial plain covered by large marshy areas and connecting rivers.

The degree of detail varies greatly between maps, both in terms of hydrography and toponymy, no doubt due to the different contexts and objectives of each map. For example, Fritz (1691), a Jesuit missionary, and La Condamine (1745), a French academician returning from a geodetic mission in Peru, mapped the entire course of the Amazon River without the conditions for detailed local surveys, while Mager (1893) had to demonstrate that the French government had detailed knowledge of the territory it was claiming in preparation for the 1900 arbitration against Brazil (MATTOS, AGUILAR, 2011).

Despite their potential to describe the coast, the interpretation of historical maps is limited by several difficulties. Poor storage conditions and improper handling resulted in distortions, wrinkles, holes, and rips. The cartographic projections are not explicitly defined, the longitudes are very inaccurate until the 18th century (while the latitudes have long been more accurate), and some maps are copies made by different authors with displacement of toponyms and with varying degrees of accuracy depending on the purpose of the work. Some maps do not indicate the date or indicate a wrong date, since published maps often contain outdated information collected 10 to 20 years before the date of issue.

For this work, historical maps were scanned and used for visual interpretation (Table 1). The features were compared with those registered in satellite images and aerial photographs. Comments registered on the maps and notes about these maps also contribute to understanding the changes (see item 4.1).

Table 1. Summary of the historical maps used for this study.

Year	Author	Observations
1618	Walter Raleigh[1]	navigation map
1691	Samuel Fritz[2]	copy 18th century
1745	La Condamine[1]	correction from Samuel Fritz´s map (issue of 1691)
1802	P.-V. Maloeut[1]	copy the map of S. Mentelle from the 18th century
1798	Alexandrino[2]	copy with later notes between 1798 and 1858
1858	Saint-Quantin[3]	description of the Tapado River
1860	José da Costa Azevedo[1]	description of hydrography between Araguary and Calçoene rivers
1893	Henri Mager[3]	Cabo Norte consolidated

Sources: [1] Library of Brazilian Navy, [2]AHEx, [3]Archives Départementales de la Guyane.

3.2. Remote sensing imagery

Remote sensing imagery was used for the observation of the changes at regional and local scale, providing evidence of present features over the last decades (since the 1950s) and records of some morphological features of the past.

3.2.1. Aerial photography

Aerial photographs of the Araguari estuary were taken during the 1950s by the Brazilian Navy to better recognize the coastline to support the bathymetric surveys and the installation of tide gauges.

These aerial photographs were used only for visual observation because they did not possess original data such as flight and camera parameters for their orthorectification. Those images were acquired in 1952, 1966 and 1970 with scales ranging from 1:50,000 to 1:30,000.

The analogical aerial photographs were digitized with a resolution of 300 dpi (i.e. 2,5 to 4 m ground sampling distance depending on scale) and the distorted overlap borders were removed. Two mosaics were completed and used for visual comparison with the maps and satellite images. Digital processing was made using the Panavue Image Assembler software and the Regeemy Image Registration and Mosaicking software.

3.2.2. Aerial radar imagery

In the 1970s, the Brazilian government ordered an airborne radar campaign of an unprecedented extent (over 4.3 million km^2): the Radar da Amazonia (RADAM) project. The Goodyear Electronic Mapping System (GEMS) X-band radar embedded on a Caravelle is a Side Looking Airborne Radar (SLAR), synthetic aperture radar not having reached maturity at this time. In 1971, it flew over and mapped in 1971 the legal Amazon, i.e., all Brazilian states covering the Amazon, including Amapá. After 1975, the project was then expanded to the whole of Brazil (RADAM Brazil). The product obtained is an analog image mosaic with a 1:400,000 scale (AZEVEDO, 1971). At the beginning of the 2000s, since the interest in these data did not weaken, they were digitized and radiometrically processed (ESCOBAR et al., 2005). The data are available free of charge from the Brazilian Geological Service (SBG) website.

3.2.3. Satellite imagery

The first satellite images of the region were taken in the 1970s by the Landsat Multispectral Scanner (MSS). Additional optical imagery has been acquired until 2019 from the sensors of the subsequent Landsat missions, i.e., Thematic Mapper (TM); Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) (Table 2).

Table 2. Remote sensing images were used in this work.

Date	Sensor	Pixel size (m)
July 15, 1986	L5 MSS	57 x 57
August 08, 1992	L4 TM	28.5 x 28.5
November 18, 2000	L7 ETM+	28.5 x 28.5
October 26, 2006	L5 TM	30 x 30
September 14, 2014	L8 OLI	30 x 30
September 12, 2019	L8 OLI	30 x 30

The Landsat images were obtained with geometric correction (L1T) and accessed from the United States Geological Service (USGS) at the website: https://glovis.usgs.gov/appm.

The advantage of Landsat regarding higher resolution systems is that its characteristics have remained constant for almost four decades, so that they are very suitable for long-term change monitoring. Indeed, multitemporal image comparison is not biased by sensor changes like resolution improvement.

The processing of the satellite images was done using the ENVI software. The co-registration was achieved with a Root Mean Square Error (RMSE) of 1 pixel (30 m) for the relative location. The images were digitally processed to highlight morphological features for analysis and comparison with the historical maps and the images of the other remote sensors. The Landsat image from 2000 was processed using Selective Principal Component Analysis (SILJESTRÖM et al., 1997).

3.3. Auxiliary data

Aerial photographs taken in 2005 and 2013 at low altitude with a 35 mm focal camera were used for visual recognition of the morphological features.

Eighteen field interviews were conducted in 2003, with residents who live along the Araguari River, to recover the recent history of changes in the drainages. The results were used to confirm the interpretation of remote sensing images and historical maps. These interviews were used to recognize other indicators of change, such as toponymy (SANTOS et al., 2003). Other interviews were carried out between 2015 and 2017 after the closing of the Araguari River mouth.

Toponymy reveals information about the genesis of the drainage, for example the use of the term novo (new) identifies a recent drainage. Two local examples illustrating that toponymy is a meaningful indicator of recent evolution are Igarapé Novo and Lago Novo. Indeed, several small drainages are called *igarapé* or *vala* by the residents along the coastal plain. The term *vala* indicates channels made by water buffalo, or by man, while *igarapé* indicates the action of natural processes (SANTOS et al., 2003).

The words *vala*, *novo*, and *igarapé* were detected through observations in maps and field interviews with local people.

3.4. Change detection methods

The changes in landscape were identified through the multitemporal analysis of historical maps, remote sensing images with correlation to auxiliary data and terrain change indicators.

3.4.1. Multitemporal analysis

The multitemporal analysis was carried out through visual comparison between historical maps, aerial photographs, RADAM aerial images, and Landsat images. Image co-registration was performed only for the Landsat data to detect and locate accurately the changes in the floodplain. The comparisons were done using the ArcGIS package (License ESU317956153).

It should be noticed that geometric registration is particularly difficult in such a dynamic environment. Indeed, the tie points could only be chosen in stable areas of the floodplain. Moreover, since the satellites have a sun-synchronous orbit, the images are always acquired at the same local time, and therefore not at the same water level due to the tides. This can result in considerable apparent changes between images (Figure 2).

Similarly, natural hydrological cycles change the appearance of observed landscapes according to water level variations. Thus, despite the rarity of cloudless skies, optical images can be acquired during the rainy season, but they show a coastal plain where certain hydrographic features are covered by water.

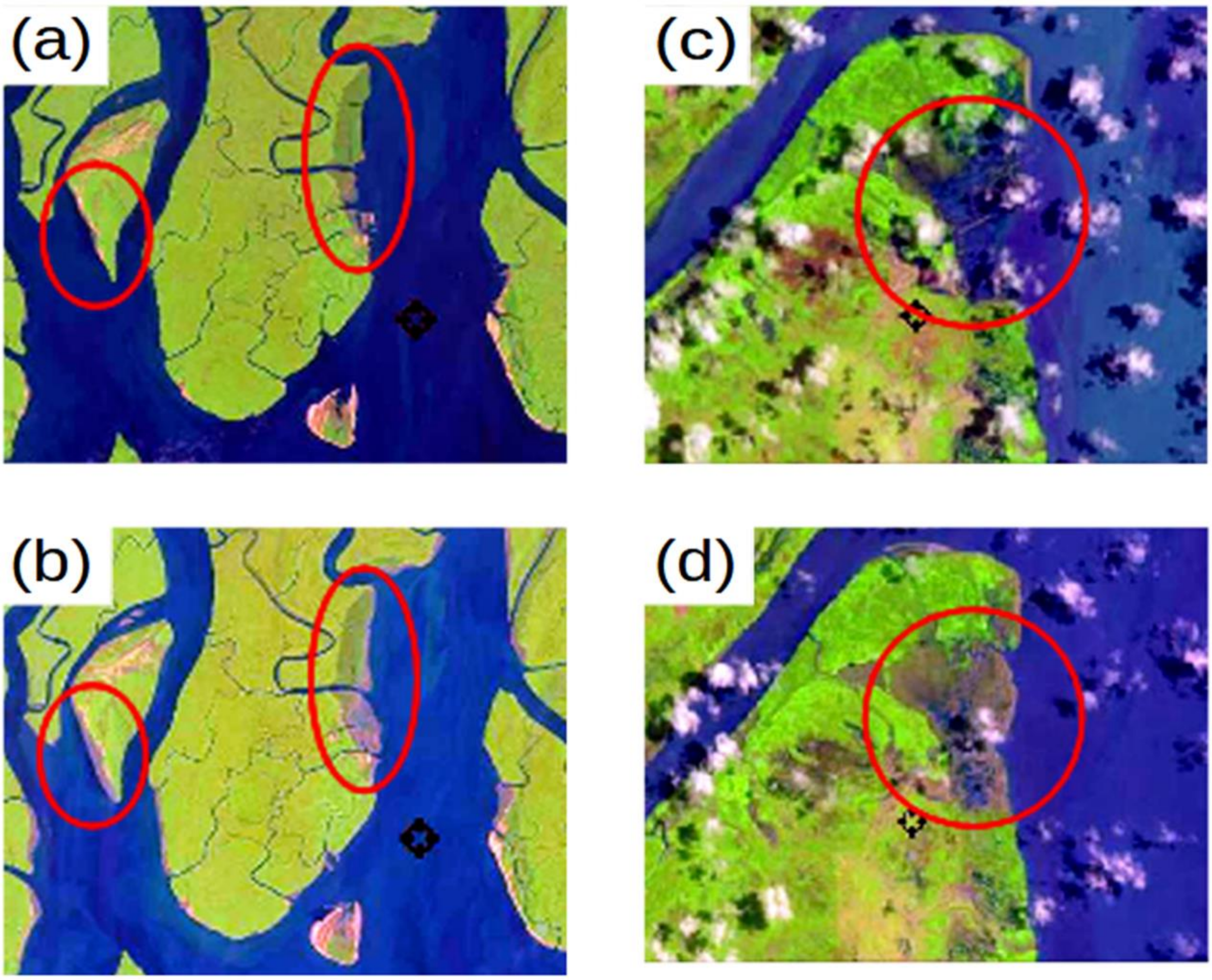

Figure 2. Variation in the water level due to tides (red circle) in two tropical areas throughout the Landsat image sensor OLI in the same season. Asia: (a) February 08, 2019, and (b) February 24, 2019, low tide. Brazil, East of Amazon River mouth: (c) September 09, 2018, high tide; and (d) August 24, 2018, low tide. Source: Landsat images courtesy of the U.S. Geological Survey.

3.4.2. Change indicators

Indicators of terrain change patterns were identified through the interpretation of multi-temporal remote sensing images to highlight morphological evolution. These preliminary findings were subsequently validated through systematic fieldwork, which consisted of on-site observations, GPS positioning and photographic documentation at selected control points within the study area.

The morphological evolution is mainly highlighted by indicators of change in the land cover pattern as described by Santos et al. (2009). The indicators were used to identify accretionary events, channel avulsion and the presence of ancient islands.

Accretion and avulsion events are geomorphologically expressed through land cover variations with the zonation and linear arrangement of forest vegetation in contact with open grassland areas, reflecting the migration and reworking of channel margins over time. The presence of paleo islands is evidenced by discrete, homogeneous forest patches that stand out amidst herbaceous vegetation, representing relict landforms (old terraces) inside the coastal plain (see item 4.1.2).

4. Results

During the past 400 years, the evidence of morphologic changes was revealed by historical maps and remote sensing images. These changes resulted in the environmental transformation of the Araguari River estuary until it was closed in 2014.

4.1. Changes on the floodplain influenced by tides

4.1.1. Cabo Norte stability and disappearance of the Carpori Island

The Cabo Norte is one of the most important features of the Amapá coastal plain, south of the Araguari River estuary. The existence of this cape can be seen in maps since the 18th century (Figure 3). In the very old maps this cape is associated with the Carpori Island (Figure 3a to e), which disappeared at the end of the 18th century, when this island was incorporated to the continent forming the Região dos Lagos (Figure 3f).

The Carpori Island was located in the mouth of the old Araguari River, between two channels, one to the west of the island and the other one to the south (Figure 3c and d). These channels formed two arms in the mouth of the Araguari River. In the maps, they seem to have similar dimensions and appear navigable.

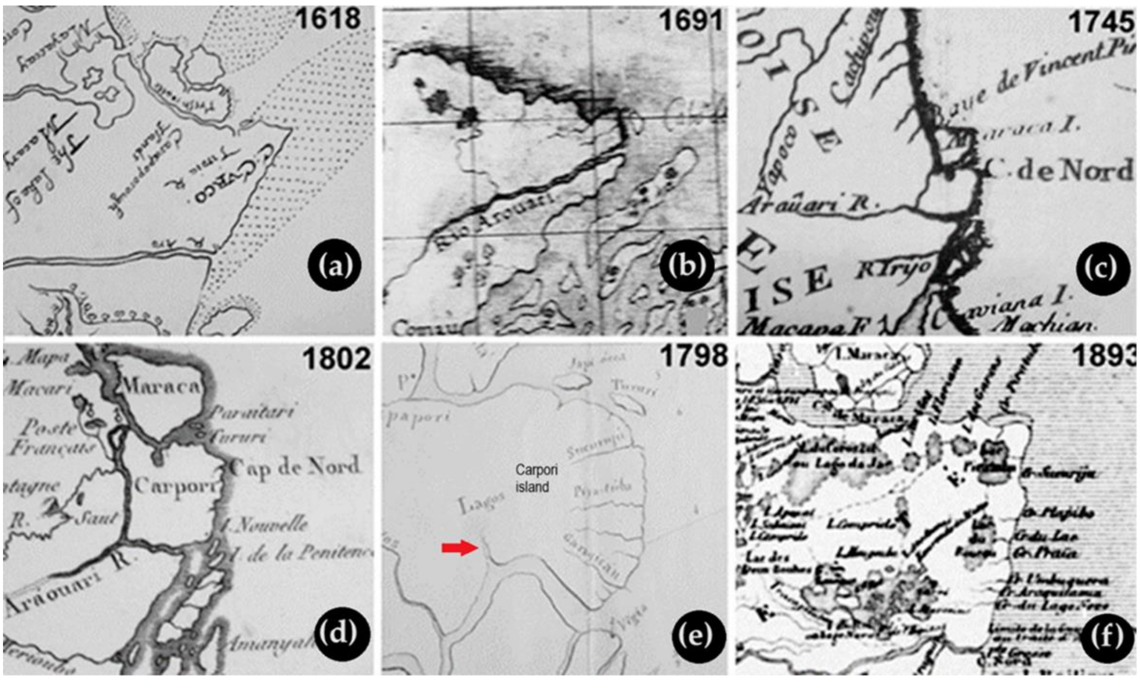

Figure 3. The Cabo Norte floodplain throughout the centuries until the disappearance of Carpori Island. Maps Walter Raleigh (a), Samuel Fritz (b), La Condamine (c), P. Maloeut (d), Alexandrino (e) and Henri Mager (f).

Sources: maps (a), (c), and (d) - from the Library of the Brazilian Navy; (b) and (e) – from the archive AHEx; (f) – from the "Archives Départementales de la Guyane".

The west arm of the Araguari River was filled, confirmed on the map of Saint-Quantin´s map in 1850 (Figure 4a – yellow star, 4b – red arrow): "...*on remarquera combien est significatif le nom de Rio-Tapado… que porte la plus grande des criques de l'Araouari qui va se perdre dans les lacs et marais qui ont remplacé la seconde branche de fleuve, depuis l'obstruction de son embouchure*" (Saint-Quantin, 1858). In 1798 (Figure 3e – red arrow) a part of this drainage appears active.

4.1.2. Disappearance of the Furo do Araguari in the south portion of the estuary

The Furo do Araguari was a channel linking the Amazon River mouth to the Araguari River, as observed on maps from the 18th century up to the 20th century.

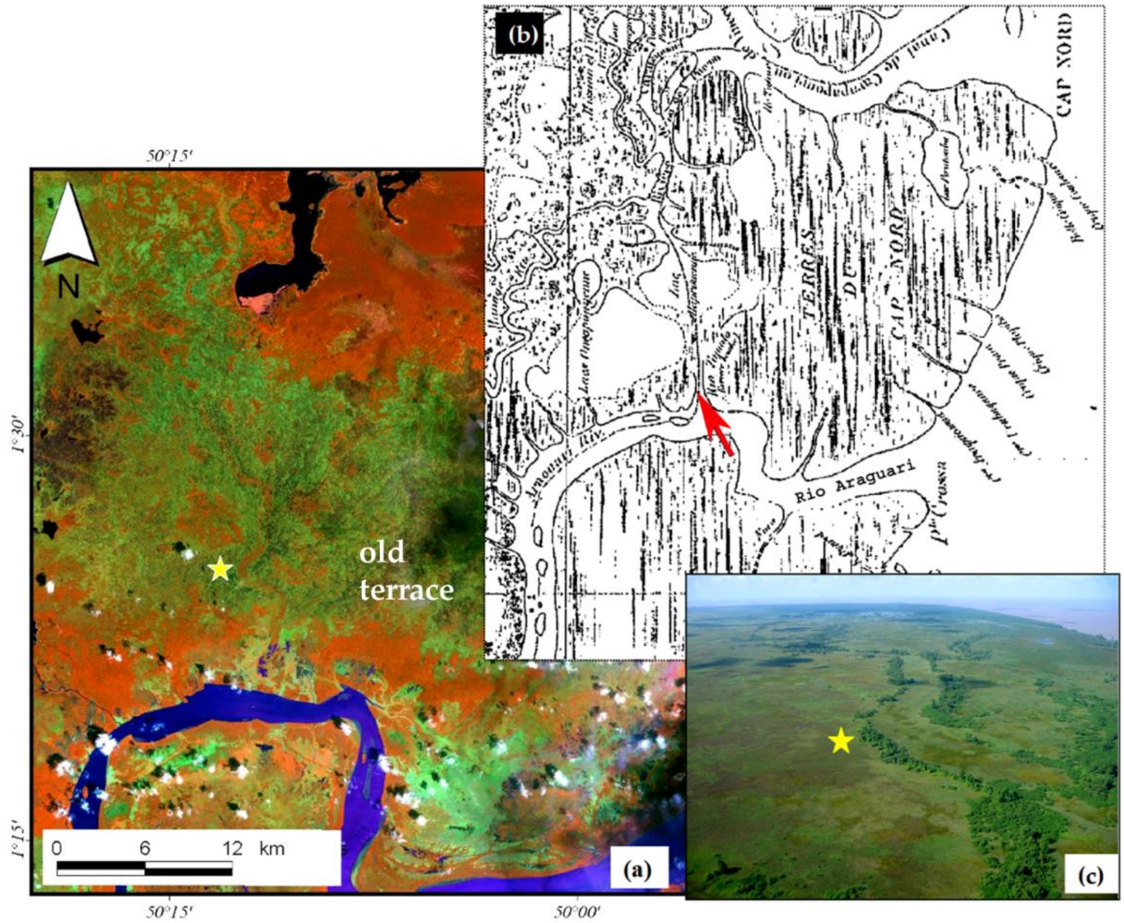

Figure 4. Colmated channel in the current floodplain characterizing the West side of Carpori Island. This channel indicates the N-S ancient arm of the Araguari River: (a) Landsat ETM+7 image, November 2000 (courtesy of the U.S. Geological Survey) showing the drainage in the West side (yellow star) of the Carpori Island; (b) Map of Saint-Quantin 1850 showing the Tapado River (red arrow), ancient channel West of the Carpori Island (from Saint Quantin, 1858); (c) Aerial photography showing the same channel (yellow star), January 2005. The alignment of vegetation defines the old channel (Photo: Odete Silveira, source: IBAMA).

In 1798, a copy of a map contained undated notes, referring to the obstruction of the Furo do Araguari (Figure 5a), suggesting that it was closed after 1798, according to information recorded by Adonias (1963). Although this drainage does not exist any longer, it appears as a paleodrainage in remote sensing images (Figure 5b) and it is still present in the memory of some residents living near the Amazon River mouth, as confirmed by field interviews.

The Furo do Araguari separated an island to the east along the Amazon River mouth, which may explain the presence of dense vegetation, currently located south of the Araguari River plain. This area is formed by a prominent terrace with a network of large drainage streams called Igarapé Grande (Figure 5b). This is one of the few well-structured drainage networks, which is currently unusual in the coastal plain. In the eastern portion of the island, an accretion process was initiated, and it formed what is today called Ponta Grossa (Figure 5b). At the same time, a point bar was formed on the north side of the Araguari River.

Both the Furo do Araguari (Figure 5) and Tapado River (Figure 4) are still shown as active drainages on maps in the 20th century.

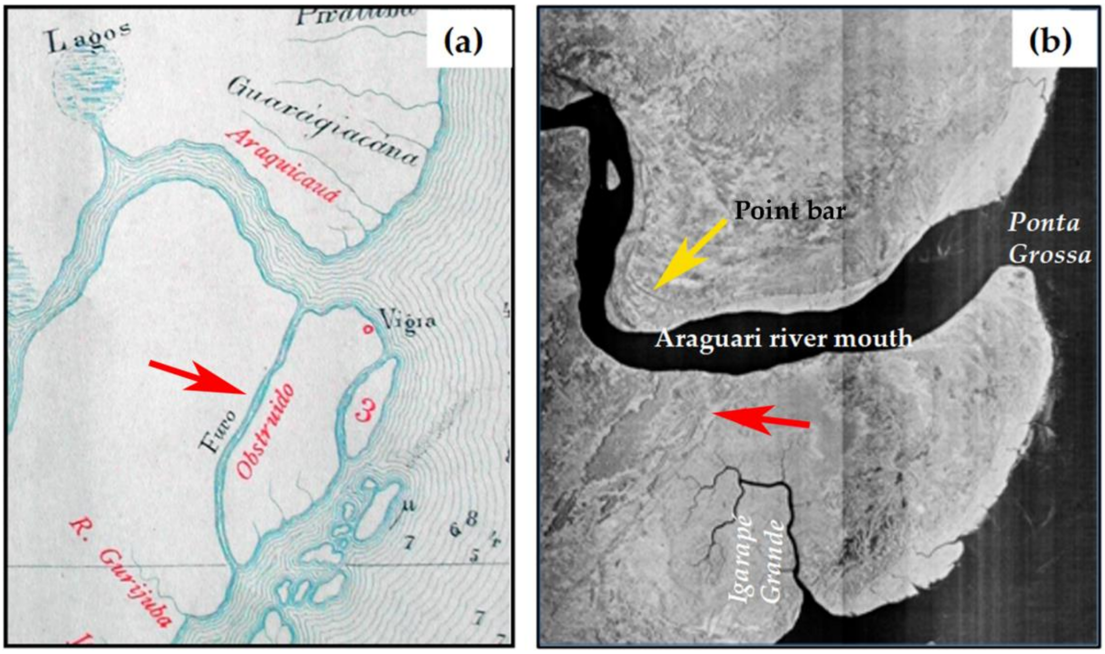

Figure 5. Closing of the Furo do Araguari: (a) Map of Alexandrino (1798) with later annotation (in red) about obstruction of Furo do Araguari (map from AHEx); (b) paleodrainage of Furo do Araguari (red arrow) in RADAM image (1971).

4.1.3. Evolution of secondary channels

Aerial photographs from 1952 (Figure 6a) and 1970 (Figure 6b) show a small channel developing. The multitemporal analysis of the Landsat MSS (1986), TM (1992), and ETM+ (2000) images reveals that the size and spatial organization of the Igarapé Novo drainage network would have started during the 1980s (Figure 6c and d). This is confirmed by field interviews, indicating that the Igarapé Novo drainage network began to form in the 1980s.

However, these secondary channels were clogged in 2013, before the complete colmatation of the Araguari River mouth in 2014 (Figure 6e).

4.2. Changes in the Araguari estuarine plain

4.2.1. Morphology development of the outer meander

Historical maps reveal modifications of the outer meander around the 18th century, probably leading to the disappearance of Carpori Island, which was part of the old Cabo Norte. In Saint-Quantin's map of 1850 (Figure 4b), the mouth of the estuary is similar to the last configuration of the outer meander.

The floodplain in the left portion of the Araguari River is connected with the Carpori Island. In Alexandrino's map (Figure 3e – red arrow) the former place of the old channel was labeled as Sequitos de Lagos (Suite of Lakes).

Comparing the maps of Figure 3 with the satellite images (Figures 3e, 4a), the southern channel of the Carpori Island disappeared and was substituted by the recent Araguari River estuary.

In the maps before the 19th century, the Araguari River mouth had a straight channel flowing west to east, and not in a sinuous pattern (Figure 3e) flowing in a northeast direction (Figure 5b) until 2014.

Boaventura and Narita (1974) observed terrace features in RADAM images. They are most likely a result of the migration of the Araguari River to the South. However, terraces could be evidenced at the point bar in the outer meander of the Araguari River (Figure 5b – yellow arrow). This point bar may have developed between the 19th and 20th centuries after the closing of the N-S channel of the Araguari River.

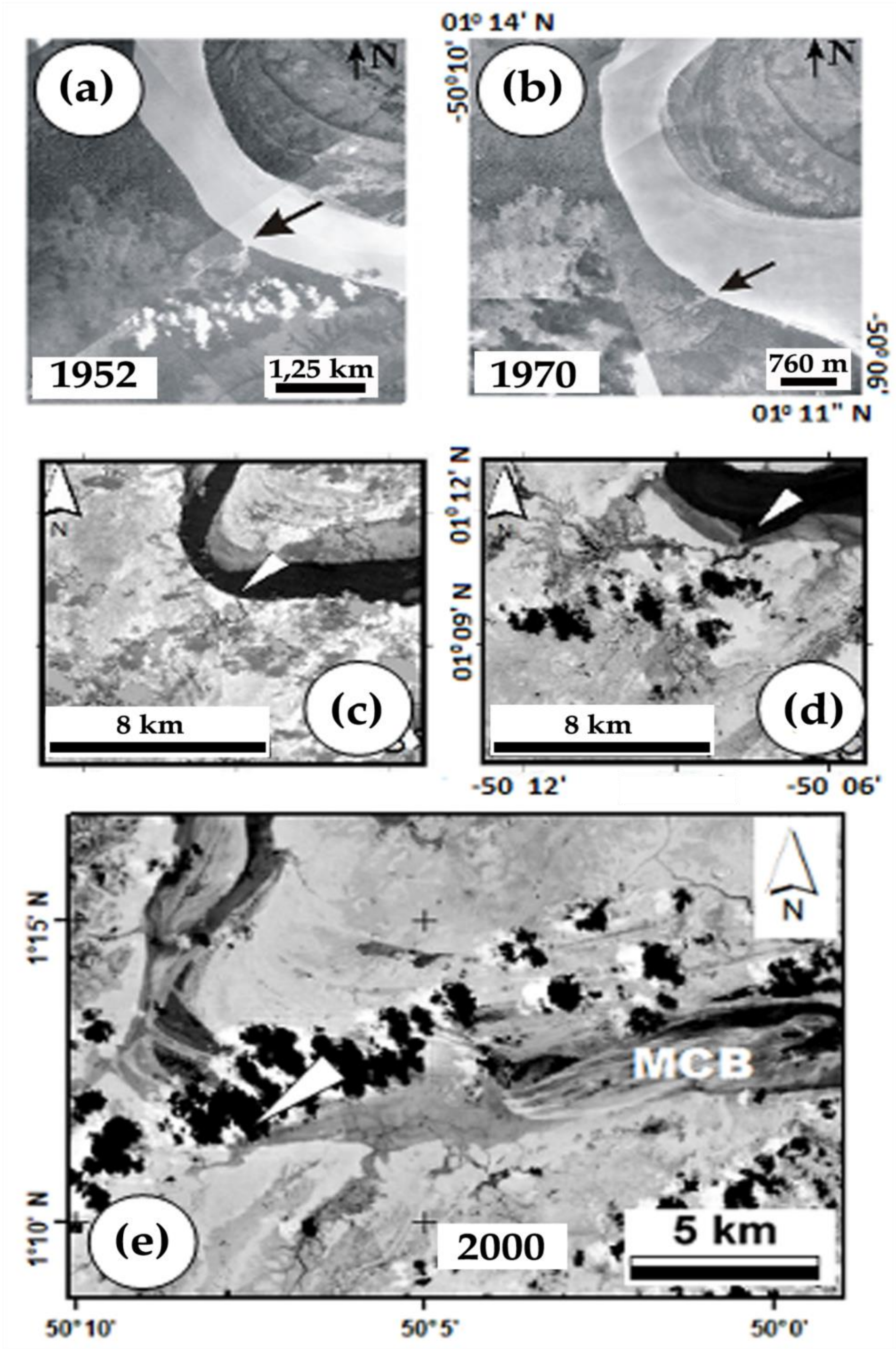

Figure 6. Organization of the drainage basin of Igarapé Novo between 1952 and 2000 in aerial photographs from 1952 (a) and 1970 (b) showing an incipient channel. Development of the drainage basin between 1992 (c) and 2000 (d) with the building up of mouth bars in the Igarapé Novo channel. (e) Channel closed and coalescence of mouth bars with mid-channel bar (MCB), September 2014. Source: aerial photography from DHN (Brazil Navy) and Landsat images courtesy of the U.S. Geological Survey.

4.2.2. Changes in the internal areas of the outer meander

Three major changes have been observed over the past three decades in the internal area of the outer meander of Araguari River estuary.

Multitemporal analysis of satellite images from 1992 and 2000 shows a coastline retreating of approximately 750 m (Figure 7a and b). In 2000, the previous border of the estuary was marked by an island with dense vegetation, which in the image of 1992 still belonged to the continent (Figure 7a). In the current floodplain, areas with forests between areas of herbaceous vegetation mark the location of the colmated channels and retreated border.

Between 1986 and 2000, while the estuary border continued to retreat (Figure 7), new mid-channel bars were formed (Figure 7c). They were in process of consolidation, with the presence of herbaceous vegetation observed in the fieldwork of 2005 in front of the Princesa Farm.

The analysis of Landsat images from 1992 and 2000 also revealed the formation of new mouth bars in Igarapé Novo (see map of Figure 1b) around the concavity of the outer meander of the Araguari River estuary (Figure 6e). However, before 1992, this area was in an erosive process, and there were no mouth bars in Igarapé Novo (Figure 6b).

The image of 2014 (Figure 1c) – same year as the Araguari River closing – shows that after the closure of the Igarapé Novo, a new series of middle channel bars formed in this part of the neck of the Araguari River. Mid-channel bars joined with the point bar (Figure 7b) and the mouth bars (Figure 6d, 6e), leading to the closure of the outer meander of the Araguari River channel, first in the direction of the estuarine mouth and later upstream towards Princesa Farm, near the Tapado River (Figure 4).

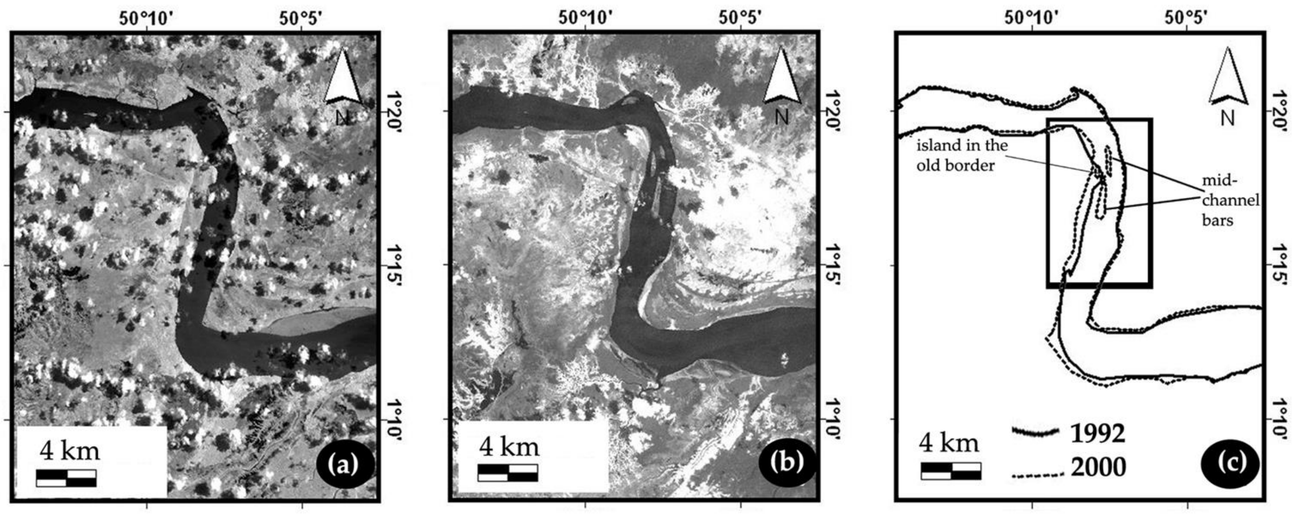

Figure 7. Morphological variation of the meander where the tidal bore was active until 2012. Coastline changes between 1992 (a) and 2000 (b) and the presence of an island in 2000 (c) mark the record of the ancient border of the Araguari River estuary. Source Landsat images (courtesy of the U.S. Geological Survey) and map by the author.

5. Discussion

5.1. Modifications and associated processes

The multi-temporal analysis of cartographic and remote sensing data allowed us to reconstitute the history of the Araguari River estuary during the last centuries, and more precisely during the last half century, based on the observation of changes in the floodplain influenced by tides and in the estuarine plain. These changes mainly consist of the colmatation of the drainage network and deposition and erosion processes due to fluvial and tidal currents, as well as the tidal bore.

Colmatation processes over the centuries in the floodplain of the Araguari River estuary are evidenced by the presence of numerous paleochannels across the coastal plain. Most of these paleochannels had already been registered by Boaventura and Narita (1974) and Silveira (1998). This process may have been caused by readjustment of hydrological networks, maybe by tectonic factors combined with a continuous supply of sediment by Amazon river into the coastal plain (SILVEIRA, 1998; ANTHONY et al., 2021).

The processes related to margin erosion in the Araguari River estuary and the development of mid-channel bars (Figure 8) are caused by fluvial currents and reworking of sediments by tidal currents and tidal bore action. The tidal bore causes rapid erosion and deposition with high vertical and lateral ratios (SANTOS et al., 2005; SANTOS et al., 2016). This may explain the rapid changes observed in the morphology of this estuary. However, the formation of so many *vala* in the region (SANTOS et al., 2003) can have accelerated the changes in the drainage network.

Fieldwork and multitemporal analysis of satellite images confirm an increase of the number of mid-channel bars in the mouth of the estuary (Figure 8). In 2014, mid-channel bars were building up in the area where the tidal bore lost its energy, quickly forming sedimentary deposits of silty sand and fine sand.

In the southern region of these areas, depositional processes are evidenced by the formation of mouth bars in Igarapé Novo (Figure 6d). In this area, erosional processes should have taken place in the concavity of the meanders. Instead, mouth bars appeared due to the presence of Igarapé Novo and another channel formed close to it. These channels create hydraulic barriers that block the sediments in this region, allowing the development of bars on both sides of the channels (see SANTOS et al., 2009).

The continuous supply and deposition of sediments fills the channels which separates the bars and contributes to elevating the ground surface level. Because of the sedimentation, the surface is gradually more exposed, leading to formation of herbaceous vegetation, which later will be replaced by forest. In 2012, fieldwork revealed that the bars were in process of reconfiguration and covered by mangrove forest.

When these processes occur in the mid-channel bars, islands are formed within the estuary. These islands can be incorporated into the margins of the estuary and become part of the continent. This incorporation process seems to have occurred with an island that marked the previous border of the estuary described between 1992 and 2000 (Figure 7). As a result, forests stand out among the grassland inside the floodplain of the estuary, indicating processes of island formation and channel colmatation. In regional literature, these features are sometimes misunderstood and confused with point bars, when in fact they were islands that eventually became part of the continent.

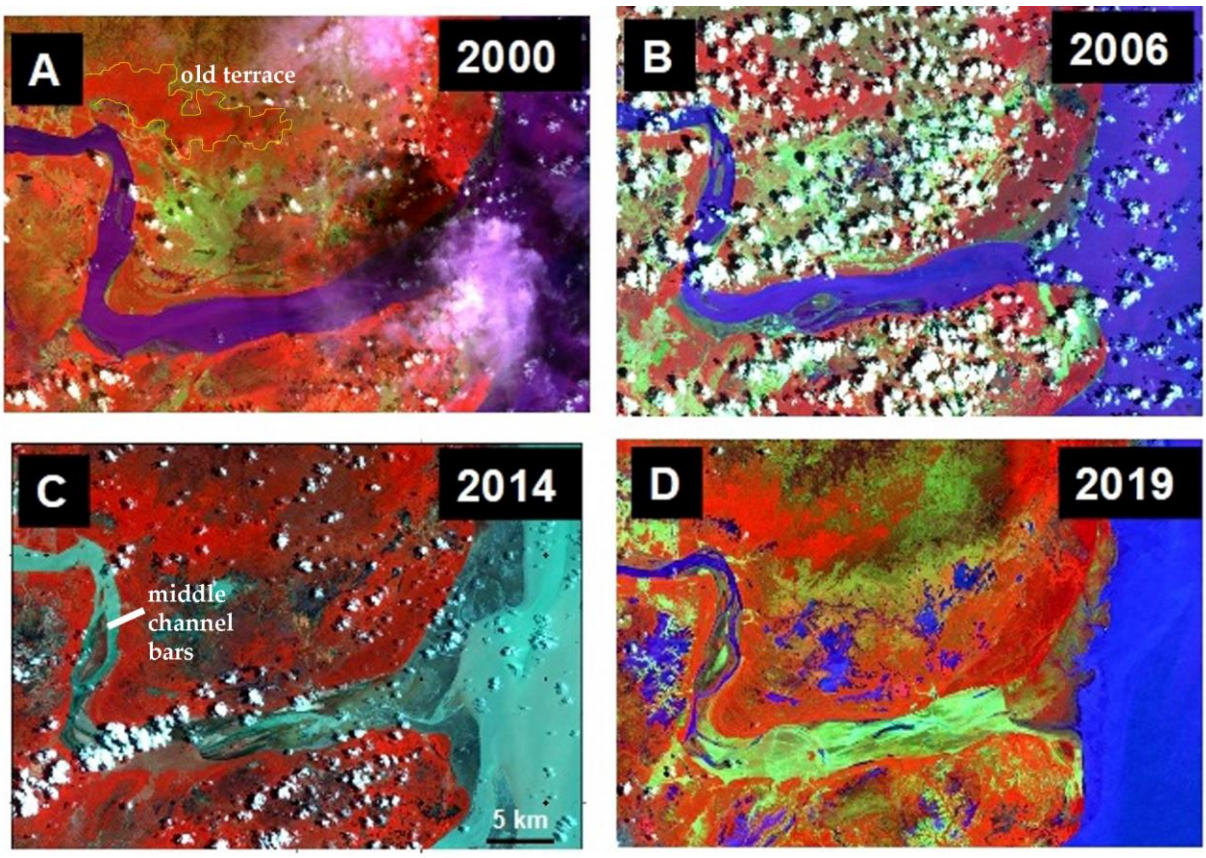

Figure 8. Two decades of changes of the Araguari mouth through Landsat images with composite bands to highlight the intertidal zones. All the images were acquired near low tide situations: (a) November 2000 (Landsat ETM+, composição RGB472), it is possible to see several the mouth bars in front of the point bar near Igarapé Novo; (b) October 2006 (TM5, composição RGB472), increasing of channel bars and sedimentation in the Southern border of the Araguari estuary even before the opened of Uricurituba channel to the Araguari and narrow passage at the end of estuary due the accretionary process; (c) September 2014 (Landsat OLI, composição RGB572), year of closing of Araguari estuary, note the coalescence process of the bars and increase of middle channel bar (see Figure 7); (d) September 2019 (Landsat OLI, composição RGB572) Araguari River mouth completely closed and with the pattern of land use by cattle ranching. Source: Landsat images courtesy of the U.S. Geological Survey.

5.2. Changes caused by human intervention

In addition to the fast changes caused by natural processes, some changes also originated from anthropogenic processes at the same time scale.

At the end of the 18th century, the Arbitration Commission investigating the contested area, noted in the map of 1808, that the Furo do Araguari was obstructed by human action (ADONIAS, 1963).

Concerning the recent change and colmatation of the Araguari River (SANTOS et al., 2016) with deviation of the Araguari River flow toward the Amazon River through the Uricurituba channel, satellite images and fieldwork (SANTOS, COSTA-NETO, 2015) indicate that at least five anthropogenic drainages (*valas*) had already captured part of the flux of the Araguari River towards the Amazon River floodplain.

In 2011 (year of La Niña), a new *vala* formed near Boa Sorte Farm, and the estuarine channel of Araguari diverted most of its flux between the mouth and this *vala*. This *vala* was connected with several ditches of the floodplain south of the Araguari River and with an original tidal channel (Uricurituba – see map of Figure 1b) pre-existing in the eastern part of the border of this floodplain, near the Bailique Archipelago. These modifications were documented during the expeditions of PROECOTUR project (2001) and the cooperative projects of the PETROMAR network (2001-2014), and by fieldwork in 2015 (SANTOS, COSTA-NETO, 2015) and 2017. Santos et al. (2018) calculated that 97% of Araguari River´s discharge flowed through this drainage route toward the Amazon River in March 2015.

5.3. Potential of historical maps and remote sensing imagery to detect morphological changes

The combined analysis of historical maps and remote sensing images has allowed the detection of landscape changes in the Araguari River estuary over a long period.

In general, the potential of historical maps and remote sensing images to recognize records of morphological change depends on the size of the features in relation to the geometric accuracy of the maps and their level of detail (resolution in the case of remotely sensed images). Aerial photographs made it possible to clearly identify changes in smaller paleochannels and bars that do not appear on maps. In the RADAM images, it was possible to see all features indicating changes regardless of their dimensions, since radar images are very sensitive to morphological features due to their side-looking acquisition (JARDIM et al., 2018). Landsat satellite images are very reliable for identifying the large features based on the radiometric and geometric changes in the land cover patterns, but the cloud cover limits them. In addition to the limitations of each sensor, remote sensing imagery cannot show the entire information related to scars of the geomorphological history of the Araguari River estuary, due to overlapping events resulting in the masking of records, which may make it hard to observe the changes in recent satellite images.

Historical maps allowed for comparing large features also visible in the remote sensing images, like the paleochannels and paleo islands, to determine part of the geological history of the Araguari River estuary since the 17th century; which demonstrates the importance of these maps as a powerful tool for dating geomorphological processes over the past centuries (TRIMBLE, 2008; GUPTA, RAJANI, 2020).

However, the information extracted from these data is not necessarily complete or reliable. In most cases, the maps do not indicate small features such as bars due to the scale limitation and to the fact that these features were not necessarily relevant for the cartographers. For instance, the presence of muddy or sandy banks was plotted on the maps only if they were important for navigation.

Some divergences were also found in the evolution of morphological features when comparing historical maps. These disagreements are mainly related to the evolution of the old N-S Araguari River channel. For example, 19th century maps still preserve Carpori Island. This is due to the fact that some maps were copied from previous ones by cartographers who were unaware of landscape transformations and could rely more on an old map than on recent surveys taken under unfavorable conditions. Furthermore, deliberate errors associated with the delimitation in the contested area may have occurred, like the location of the Baia de Vincent Pinzon and the positioning of the name of the Cabo Norte.

To go further and make the greatest possible use of these ancient documents, without their defects leading to misinterpretation, it would be necessary to recover the history of each map in order to make more precise geometric corrections. This would make it possible to go beyond the visual analysis carried out in our study and propose a quantitative comparison between maps and remote sensing images. Moreover, we need to consider the historical context in which they were produced, which requires more in-depth studies, in this region as elsewhere, taking account of technical resources and geopolitical circumstances, to understand better the extent to which the ancient maps describe the topographical situation at the time, as well as a greater effort for preservation in dedicated archives.

6. Conclusion

Changes in and around the Araguari River estuary during the last four centuries present a complexity that must be considered in light of the evolution of the environments in the coastal plain of Amapá.

Although the coastline is mostly in retreat due to relative sea-level rise, centuries of records show that the Araguari River estuary has been undergoing a continuous aggradational process, which has accelerated over the last 40 years, possibly due to the superposition with anthropogenic processes. Change indicators attest that natural and anthropogenic processes have coexisted in the environment for several decades.

The natural morphological paleofeatures recorded in satellite and aerial imagery can be considered relevant indicators of historical changes and corroborated by the records of historical maps. Recognizing this evidence is important in areas where the morphology is affected by anthropogenic impacts, allowing appropriate interpretation of changes in the dynamic environment of the coastal plain of Amapá. However, due to the existence of semidiurnal macrotides and other seasonal water level variations, the image series that are available in this region are not well suited for multi-temporal comparisons.

Two difficulties related to the data themselves have also been pointed out, namely, the size heterogeneity of the features and the lack of positioning accuracy in the historical maps. Despite these limitations, the analysis of remote sensing imagery and historical maps, in addition to popular memory and regional toponymy, was used to identify changes, which confirms the potential of this method.

Finally, historical maps provide valuable information to understand recent coastal evolution and help coastal management programs. They can be used by geoscientists in areas under rapid change. For these reasons, they should be carefully preserved and studied more thoroughly.

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