Impact of the Holocene sea-level changes in coastal, eastern and Central Amazonia

by

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Abstract

Pollen records from six sites are summarised and compared to provide insights in Holocene changes in the Amazon coastal and lowland regions of northern Brazil. The hydrology of Amazonian wetlands, especially those in the eastern part of the Basin, is strongly influenced by the Atlantic sea-level. Rapid sea-level rise in the early Holocene stabilized at near modern levels at ca. 7500 14C yr B.P. Mangroves first occur in coastal sequences of northeastern Pará State about 7500 14C yr B.P. The arrival of the mangroves in the pollen sequences is taken as an indication of sea-level. The retreat of mangroves after about 6700 14C yr B.P. reflects a lower relative sea-level. The modern mangroves developed mostly between 4000 and 3500 14C yr B.P. or somewhat later at the present-day coastline.

First impact of early Holocene sea-level rise in the Amazon Basin is found by the change of active to passive river systems between at ca. 8300 and 8000 14C yr B.P. Later, local Mauritia palm swamps developed along river margins in central and eastern Amazonia. The timing and length of this period differs and is probably related to the different location and topography of the rivers. It is suggested that the Mauritia palm swamp stage is a regional phenomenon for the whole low lying Amazon Basin. First várzea and igapó forests (seasonally inundated forests) developed at that time as well, but the area of this seasonally inundated forests was still small. The modern large extension of várzea and igapó forest areas is relatively young in age. In eastern Amazonia, marked increase of várzea/igapó forests is documented since 5120 14C yr B.P., especially since 2470 14C yr B.P., and in central Amazonia since 4070 14C yr B.P. and especially since 2080 14C yr B.P. The development of huge seasonally inundated areas must have had an important influence on the Amazonian water and carbon cycle and the regional climate in Amazonia. Keywords: Northern Brazil, palynology, palaeoecology, mangrove, Amazon rainforest, várzea, igapó, Holocene, sea-level.

Resumo

Registros de polén de seis locais estão resumidos e comparados com as mudanças na Amazônia costeira e regiões de terras baixas do norte do Brasil. A hidrologia das terras alagadas da Amazônia, especialmente aquelas da parte leste do bacia, é fortemente influenciada pelo nível do mar atlântico. Com rápidos níveis do mar durante o Holoceno inferior, o nível atual foi atingido há cerca de 7500 14C anos A.P. Os primeiros manguezais ocorreram na costa nordeste do Estado do Pará por volta de 7500 14C anos.

$^*$Dedicated to Prof. Dr. Harald Sioli on the occasion of his 90th anniversary.

ISSN 0065-6755/2002/041/ © MPI für Limnologie, AG Tropenökologie, Plön; INPA, Manaus

O primeiro impacto do aumento do nível do mar durante o Holoceno na bacia Amazônica é evidenciado pela mudança do sistema fluvial de ativo para passivo entre 8300 e 8000 °C anos a.P. Em seguida, palmeiras de Mauritia desenvolveram-se ao longo da margem dos rios na parte central e leste da Amazônia. O intervalo de tempo entre a formação e extinção destes período diferente e está provavelmente relacionado à topografia dos rios. Isto sugere que o estiágio com pintados de palmeira de Mauritia é um fenômeno regional para todas as zonas baixas da Bacia Amazônica. As primeiras florestas de várzea e de igapó (Florestas inundadas sazonalmente) desenvolveram-se nesse momento, mas a área desta sazonalmente inundada floresta foi ainda pequena. A atual grande extensão das áreas de florestas de várzea e igapó é relativamente jovem. No leste da Amazônia, marcados aumentos das florestas de várzea/igapó é documentado desde 3120 °C anos a.P., especialmente desde 2470 °C anos a.P., e na Amazônia central desde 2080 °C anos a.P. O desenvolvimento de enormes sazonalmente inundadas florestas deve ter tido importante influência nas águas da Amazônia, no ciclo do carbono e no clima regional na Amazônia.

Introduction

The Amazonian region includes areas of mangrove, salt marshes, and secondary Amazon rainforest vegetation. The Amazon Basin is low lying with >1,000,000 km² at <100 m elevation. For much of its course, the Amazon has a grade of 1 in 100,000. The level of Manaus, which lies 1200 km inland is only 14 m a.s.l. (GRABERT 1991). As a consequence, in the eastern half of the basin the development of rivers and lakes is strongly influenced by Atlantic sea-level fluctuations. The amount of annual rainfall as well as the sea-level dynamics influence the occurrence of seasonally inundated forests, which form an area of up to 700,000 km² (PÁVIA 1995). Also Amazonian coastal ecosystems such as mangroves and salt marshes are related to sea-level fluctuations.

In order to understand past environmental changes in Amazonia such as the natural amplitude of Amazonian ecosystem dynamics, including coastal ecosystems such as mangroves, as well as Amazonian river and climate changes, palaeocological and palaeoenvironmental studies are important. Several lacustrine and mangrove sediment deposits have been studied by pollen analysis. The aim of this paper is to compare and summarise recent published pollen records and to give an overview of natural environmental changes in the coastal and Amazon Basin region, related to the impact of the Holocene sea-level changes.

Vegetation and climate

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Vegetational the vicinity of the Rio Negro and the Lago Calado (Fig. 1). The terra firme lake has an outflow to the Rio Solimões that connects the water bodies during times of high water levels. A network of small rainforest streams from the Amazon terra firme forest flow into the lake. Controlled by the Solimões water level, the water depth of the lake fluctuates on an annual cycle between about 1.2 m in November and roughly 12 m in June. During the same period the lake surface area changes from 2 to 8 km². Today várzea/igapó forests cover about 5-10 % of the total forest area of the Lago Calado region.

Holocene environmental changes

Coastal region of Amazonia

Vegetational changes which reflect sea-level fluctuations are evident in pollen records from the coastal region of northern Brazil. In the Lagoa da Curuçá sediment core, Rhizophora pollen grains were already present during the Last Glacial/Holocene transition. These pollen grains were probably transported by wind over some distance into the lake. Mangrove apparently developed along the rivers near the lake between 7250 and 5600 14C yr B.P. The subsequent retreat of mangroves from these rivers reflects lower relative sea-level stands between ca. 5600 and 3100 14C yr B.P. Mangrove was replaced by successional stages of palms, first Mauritia, then Arecaceae II and Mauritia, suggesting a somewhat lower ground water table in the Lago da Curuçá area. Mangrove expanded again along the rivers near the lake after 3130 14C yr B.P., indicating the return of relatively high relative sea-levels.

Based on the Lago do Crispim record, mangroves first developed along the river close to the core site between 7550 and 6620 14C yr B.P. There is evidence that areas, originally covered by dense, tall coastal Amazon rainforest, were partly replaced by mangrove and some restinga vegetation during the early Holocene. Decreasing Rhizophora pollen abundances document a retreat of mangroves, reflecting sea-level regression starting at around 7000 14C yr B.P. The marked reduction of mangroves near the lake indicates a lower relative sea-level between around 6620 and 3630 14C yr B.P. During this period a local Mauritia/Mauritia palm swamp formed. That palm trees are sensitive to the local ground table changes is well known (HENDERSON 1995). Marked coastal environmental changes occurred at around 3630 14C yr B.P. driven by sea-level transgression. Mangroves expanded again close to the site. The local palm swamp was replaced by a Cyperaceae swamp. Rainforest and restinga vegetation adjacent to the swamp were replaced by salt marshes as sea-level rose. The Atlantic Ocean was close to the core site, but the site, which is only 1-2 m above modern sea-level, was apparently never affected by marine incursions during the Holocene. Reduced mangrove vegetation since ca. 1840 14C yr B.P., may be due to a slightly lower relative sea-level or to human impact.

The Lago Aquiri record, far inland from the modern ocean, shows the formation of mangrove between 7450 and 6700 14C yr B.P. Due to a sedimentary gap, only the last century is recorded. For this period pollen data indicate the present-day environment, seasonally inundated swamp savanna and secondary forests on somewhat higher elevated areas. Mangroves were not found.

Sea-level changes also play an important role in the development and dynamic of mangrove ecosystems on the Bragança Peninsula. The radiocarbon dates indicate that the development of mangroves started at the three sites at different times: Campo Salgado at around 5120 14C yr B.P., Bosque de Avicennia at 2170 14C yr B.P. and Furo do Chato at 1440 14C yr B.P. The development of mangrove during the early Holocene, as documented from the other sites, is so far not registered on the peninsula.

The presence of mangrove at Campo Salgado, the highest elevated site on the peninsula which is today a salt marsh, suggests relatively high sea-levels since the mid Holocene. The highest amount of non-mangrove shrub and tree pollen in the basal samples, suggests that mangroves here also replaced an earlier coastal forest ecosystem prior to 5120 14C yr B.P. Compared with other sites from northern Brazil, it is suggested that the relative sea-level during the mid Holocene was only slightly higher than today. Results from the site Lago do Crispim, which is located next to the modern coastline and only 1-2 m a.s.l., indicate that it was never flooded during the Holocene (BEHILING & COSTA 2001). Poor pollen preservation between 750 and 420 14C yr B.P., indicate that mangrove deposits were exposed and the area of the Campo Salgado site was
relatively dry. The frequency of inundation must have been lower in response to lower sea-levels. Pollen assemblages indicate that an open Poaceae-dominated salt marsh with *Avicennia* shrubs developed after 420 14C yr B.P. The change from a Poaceae-dominated to a Cyperaceae-dominated modern salt marsh during the last 200 14C yr B.P., may be related to a lower relative sea-level. The high *Avicennia* pollen concentrations in the sediments from Bosque de Avicennia during the last 180 14C yr B.P., also suggest a regression of sea-level. Studies by COHEN et al. (2003), show that there is a recent relative sea-level rise on the Bragança Peninsula during the last three decades.

**Eastern and central region of Amazon lowland**

Sedimentological data from the Rio Curuá core in the Caxiuana region of eastern Amazonia show that the relatively high-energy river changed to a low energy river at ca. 8000 14C yr B.P. The period prior to 7030 14C yr B.P. was characterised by the transition to a passive fluvial system. A well-drained, highly diverse terra firme Amazon rainforest was found at that time. Later, a *Mauritia* palm-swamp developed along the margins of the river between 7030 and 5970 14C yr B.P. The area of inundated *Várzea* and igapó forest along rivers were at that time relatively small. Subsequently, the river changed to shallow lake-like conditions. Abundant terra firme rainforest still occupied the well-drained areas. At 3120 14C yr B.P., the increase of *Virola* (probably *Virola surinamensis*), *Euterpe/Geonoma*-type (probably the palm *Euterpe oleracea*), and *Macrolobium*, trees which are common in inundated forests (FERREIRA et al. 1997), suggest a first expansion of inundated forest area. After about 2470 14C yr B.P., the pollen data reflect the largest extent of seasonally inundated forests and Rio Curuá reached a water level similar to that of present.

Sedimentological data indicate that the deposits of the core base from Lago Calado in central Amazonia correspond to a fluvialite palaeoenvironment in the Lago Calado valley prior to 8280 14C yr B.P. Pollen analytical results show the formation of a local *Mauritia* palm-swamp along the river margin between 8280 and 7700 14C yr B.P. At that time, highly diverse terra firme Amazon rainforest and poorly developed *Várzea* and igapó forests along the river characterised the vegetation of the study region. The small expansion of *várzea*/igapó forests and a strong presence of aquatic plants started at 7700 14C yr B.P., reflecting the increase of the Amazonian water level and the formation of the Lago Calado. The occurrence of abundant Poaceae and Cyperaceae pollen in the lake sediments since 7700 14C yr B.P., suggest both the local colonisation of unflooded mud banks around the lake margin and the formation of flooding meadows. Open exposed unflooded mud areas, periodically colonised by herbs, are related to cyclic annual Amazonian high and low water stands. In respect to the abundance of Poaceae pollen during the early and mid Holocene, these open areas were large, suggesting short annual high and long annual low Amazonian water stands. After 4070 14C yr B.P. the area of *várzea*/igapó forests increased. Herbs were less frequent, probably due to the smaller area of unflooded mud banks. The Amazonian water levels must have been higher than before and the period of the annual high water stands was probably longer. Since 2080 14C yr B.P., the largest proportion of *várzea*/igapó forests is recorded, reflecting the highest Amazonian water level. Herbs were rare, suggesting that open unflooded mud areas around the lake were relatively small. This may perhaps also indicate that the cyclic annual period of the Amazonian high water level was the longest since 2080 14C yr B.P.

**Discussion and conclusions**

During the Last Glacial Maximum (around 18,000 14C yr B.P.), the Atlantic sea-level was around 120 m lower than today (e.g. SHACKLETON & ODPYKE 1973). During the Lateglacial/early Holocene sea-level rise, huge areas of the exposed coastal shelf were inundated by the Atlantic Ocean. The exposed area along the north Brazilian coast was a belt mostly about 150-200 km wide. Nothing is known about these former ecosystems, but this zone could have been partly covered by Amazon rainforest, savanna, mangrove and other coastal vegetation types.

The compared and summarised pollen record from the Amazon coastal and Basin region document remarkable vegetational and environmental changes, related to the Atlantic sea-level rise during the Holocene (Fig. 2, Table 1). The coastline shifted inland during the Lateglacial/early Holocene sea-level rise. Ancient low elevated coastal ecosystems were destroyed and new ecosystems, such as mangroves developed on intertidal, now higher elevated areas, replacing the former Amazon rain forest. First occurrence of mangrove pollen (*Rhizophora*) in the sediment deposits reflects the early Holocene sea-level rise close to the modern sea-level. Mangrove developed near Lagoa da Curuça between 7250 and 5600 14C yr B.P., at Lago do Aquiri between 7450 and 6700 14C yr B.P. and near Lago Cristipim between 7550 and 6620 14C yr B.P. The occurrence of some *Rhizophora* pollen grains in the Lagoa da Curuça record, already at the beginning of the Holocene at 9430 14C yr B.P. or earlier), is probably related to wind transported pollen over somewhat longer distances. Evidence of a mangrove environment in the Aquiri region, about 120 km inland from the modern coastline, supports a significant early Holocene transgression near the Rio Mearim.

Due to the very low elevational gradient of the central and eastern Amazonian rivers, the levels of the Amazonian water depend also on Atlantic sea-level. During last glacial low sea-level stages, when the sea-level was over 100 m lower than today, the gradient was steeper resulting in erosional processes in the Amazon Basin. The Amazon and its tributaries incised and the riverbeds were several tens of meters deeper than today (SIOLO 1957; IRION 1982, 1984; IRION et al. 1995, 1997). With the post-glacial rise of the Atlantic sea-level, the waters in the Amazon Basin rose as well.

The influence of the early Holocene sea-level rise in the Amazon Basin is found by the change of active to a passive river system of the Rio Curuá record in eastern Amazonia and of the Lago Calado record in central Amazonia at ca. 8000 14C yr B.P. and at 8280 14C yr B.P., respectively. These events occurred about 500-1000 years earlier, than the first mangrove formation near the modern coastline. In both records is found a local *Mauritia* palm swamp stage, in Rio Curuá in eastern Amazonia between 7030 and 5970 14C yr B.P. and in Lago Calado in central Amazonia between 8280 and 7700 14C yr B.P. The timing and length of this successional period differs, which may be relating to the different location and topography of the two rivers. These palm swamp stages occurred before or during the period of the mangrove development in coastal Amazonia. It is supposed that the *Mauritia* palm-swamp stage is a regional phenomenon for low-lying areas in the Amazon Basin, related to the sea-level rise during the early Holocene. First *várzea* and igapó forests developed at that time as well, but the area of seasonally inundated forests was small.

In the coastal region is found a retreat of the mangroves, reflecting a lower relative sea-level: in Aquiri since 6700 14C yr B.P., in Lago Cristipim between 6620 and 3630 14C yr B.P. and in Lagoa da Curuça between about 5600 and 3950 14C yr B.P. The inter-
polated age of 5600 14C yr B.P. for the Lagoa record can be older, due to the poor radiocarbon dating of the core. During this mid Holocene sea-level transgression, in lowland Amazonia are recorded shallower water levels than today, between 5970 and 3120 14C yr B.P. in Rio Curuí and between 7700 and 4070 14C yr B.P. in Lago Calado.

The second major period of mangrove formation at the modern coastline occurred during the late Holocene, at the Lagoa da Curuçã record since around 3950 14C yr B.P. and at the Lago Crispim record since 3620 14C yr B.P., reflecting the highest Holocene sea-level stands. The first development of mangroves on the Bragança Peninsula is found in the Campo Salgado area at around 5120 14C yr B.P. It is suggested that the radiocarbon date form the Campo Salgado core base is too old in comparison with events of the Lago do Crispim, Lagoa da Curuçã and the two Amazon Basin record. The beginning of the mangrove development at the Campo Salgado site is probably not older than 4000 14C yr B.P. The formation of mangroves at the Bosque de Avicennia site started at around 2170 14C yr B.P. and at the Furo do Chato since around 1440 14C yr B.P. In the eastern Amazon Basin a marked increase of várzea/igapô forests is documented in the Rio Curuí record since 3120 14C yr B.P. and especially since 2470 14C yr B.P. In the central Amazonia a marked increase of seasonally inundated forest is found since 4070 14C yr B.P. and especially since 2080 14C yr B.P. The marked increase of inundated areas of várzea/igapô forests is apparently related to the late Holocene sea-level rise and almost the complete low lying Amazon Basin seem to have experienced this change. Huge areas of terra firme Amazon rainforest were replaced by várzea and igapô forests during the late Holocene. The development of large seasonally inundated areas must have an important influence on the Amazonian water and carbon cycle and the regional climate in Amazonia.

The development and the modern extension of mangrove forests in the Amazon coastal region and the large extended areas of modern seasonally inundated várzea/igapô forests in the lower Amazon Basin, consequently are relatively young in age. The Atlantic sea-level rise was probably the major factor in palaeoenvironmental changes, but high water stands might also partly related to climate change, thus means greater annual rainfall rates in Amazonia. There is evidence of Amazon rain forest expansion, both north and south of the equator, reflecting a change to wetter climatic conditions (higher precipitation rates and longer wet periods) since mid and especially during the late Holocene (BEHLING & HOOGHIEMSTRA 2001). In the northwestern Amazon rainforest/savanna transition zone, (Llanos Orientales in Colombia), rainforest expansion is documented since 6000 14C yr B.P. and was further intensified after 3000 14C yr B.P. (BEHLING & HOOGHIEMSTRA 2000). In southwestern Amazonia, there is evidence of Amazon rain forest expansion (Laguna Bella Vista and Chaplin, Bolivia) during the late Holocene at least since 3000 14C yr B.P. (MAYLE et al. 2000). The expansion of the Amazon rain forest after 5460 14C yr B.P. is also reported for the southeastern Amazon region (BEHLING 2002).

In western Amazonia (Colombia) the lower terrace of Rio Caquetá was poorly drained after 4000 14C yr B.P., as a result of higher river levels, probably due to higher precipitation rates (BEHLING et al. 1999). In this context in the Lago Calado record, possibly relatively short annual high water levels during the early Holocene and relatively long annual high water levels since 4070 and especially after 2080 14C yr B.P., can be interpreted as signal of climate change to wetter late Holocene periods (BEHLING et al. 2001a).

However, the Atlantic sea-level rise was probably the major factor in palaeoenvironmental changes, but high water stands might also be due to greater annual rainfall during the late Holocene in western, central and eastern Amazonia.

Acknowledgments

The author thanks Dr. Mercedes Lima da Costa, Dr. Paul Colinaux, Dr. Gerold Keim, Dr. Georg Iriom, Dr. Wolfgang Juck, Dr. Nunes de Melo, Marcello Cohen, and Dr. Ruben Lara for cooperative and interdisciplinary research for previously published and here summarised papers. Thanks are to Dr. Henry Hooghmiestra and one anonymous reviewer for providing constructive reviews. This paper resulted from the cooperation between the Center for Tropical Marine Ecology (ZMT), Bremen, Germany and the Universidad Federal do Pará (UPa), Belém, Brazil, under the Governmental Agreement on Cooperation in the Field of Scientific Research and Technological Development between Germany and Brazil financed by the German Ministry for Education, Science, Research and Technology (BMBF) [Project number: 03F0253A, Mangrove Management and Dynamics - MADAM], and the Conselho Nacional de Pesquisa e Tecnologia (CNPq). This paper has the MADAM - contribution number 54.

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**Table 1:** List of the summarised and compared pollen records, showing the timing of two major events of environmental changes. The table includes also data on the modern elevation (m) above mean modern sea-level of the coring site, and at the time of the environmental changes.

<table>
<thead>
<tr>
<th>First event/ Site</th>
<th>Modern elevation (m)</th>
<th>Past elevation (m a.s.l.)</th>
<th>Period (°C yr B.P.)</th>
<th>Length (°C yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laguna de Curuça</td>
<td>35 m</td>
<td>Mangrove</td>
<td>32 m</td>
<td>7525–5600(?)</td>
</tr>
<tr>
<td>Lago Crispim</td>
<td>1.2 m</td>
<td>Mangrove</td>
<td>-6 m</td>
<td>7550–6620</td>
</tr>
<tr>
<td>Lago do Aquirí</td>
<td>ca. 10 m</td>
<td>Mangrove</td>
<td>ca. 1.5–7 m</td>
<td>7450–6700</td>
</tr>
<tr>
<td>Rio Curiú</td>
<td>&lt;3 m</td>
<td>Mauritia-swamp</td>
<td>-11 m</td>
<td>7038–5970</td>
</tr>
<tr>
<td>Lago Calado</td>
<td>23 m</td>
<td>Mauritia-swamp</td>
<td>ca. 5 m</td>
<td>8280–7700</td>
</tr>
<tr>
<td>Campan de Salgado</td>
<td>2.7 m</td>
<td>Mangrove</td>
<td>1.35 m</td>
<td>5120(?)–750</td>
</tr>
<tr>
<td>Bosque d. Avicennia</td>
<td>2.4 m</td>
<td>Mangrove</td>
<td>-4.0 m</td>
<td>2170–0</td>
</tr>
<tr>
<td>Furo do Chato</td>
<td>1.9 m</td>
<td>Mangrove</td>
<td>0.1 m</td>
<td>1440–0</td>
</tr>
<tr>
<td>Rio Curiú</td>
<td>&lt;3 m</td>
<td>&gt;Várzea/Ipó</td>
<td>(-5 m)–4.5 m</td>
<td>3120/2470–0</td>
</tr>
<tr>
<td>Lago Calado</td>
<td>23 m</td>
<td>&gt;Várzea/Ipó</td>
<td>ca. 10/25.5 m</td>
<td>4070/2080–0</td>
</tr>
</tbody>
</table>
Fig. 1:
Map showing the Amazon river system and the location of the site for the coastal region of Amazonia:
(1) Lagoa da Curuçá; (2) Lago Crispim, three records from the (3) Braganca Peninsula; (4) Lago Aquiri, and for the Amazon Basin region: (5) Rio Curuá and (6) Lago Calado.

Fig. 2:
Graph summarising the vegetational changes in the coastal and Amazon lowland region related to Holocene sea-level changes.