Societies' adaptation to sea level changes from prehistory to the present day

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Abstract

This paper presents long-term interactions between human societies and sea-level changes since the Last Glacial Maximum. It identifies three main phases: a rapid post-glacial sea-level rise (15,000-7,000 years BP; BP = years before present, conventionally referenced to CE 1950) leading to coastal submergence and contraction of habitable areas; a slower rise during the Holocene and historical periods, favouring coastal progradation in many sedimentary systems while producing contrasting shoreline trajectories along rocky, subsiding, tectonically active, or sediment-starved coasts; and, since the late twentieth century, an accelerated rise linked to anthropogenic climate change, whose impacts are increasingly perceptible within a human lifetime at the global scale. This recent shift marks a major paradigm change in human-coastal relationships. It highlights the necessity of improving our understanding of long-term human/sea-level interactions in order to better assess and anticipate current and future coastal challenges, and calls for strengthened research collaboration between developed and developing countries, particularly in vulnerable intertropical regions.

Keywords: Sea-level rise, Holocene, Anthropocene, Archaeology, Coastal risk and hazards

Cet article présente les interactions à long terme entre les sociétés humaines et les variations du niveau de la mer depuis le dernier maximum glaciaire. Il distingue trois phases principales: une élévation rapide du niveau de la mer entre 15 000 et 7 000 BP ayant entraîné la submersion des côtes et la réduction des zones habitables; une élévation plus lente au cours de l'Holocène et des périodes historiques, favorisant, dans de nombreux systèmes sédimentaires, la progradation côtière, tout en maintenant des trajectoires contrastées dans les secteurs rocheux, subsidents, tectoniquement actifs ou pauvres en sédiments; et, depuis la fin du XX^{e} siècle, une élévation accélérée liée au changement climatique, dont les impacts sont désormais, et pour la première fois, perceptibles au cours d'une vie humaine. Ce changement récent marque un changement de paradigme majeur dans les relations entre l'homme et le littoral. Il met en évidence la nécessité d'améliorer notre compréhension des interactions à long terme entre l'homme et le niveau de la mer afin de mieux évaluer et d'anticiper les défis côtiers actuels et futurs et appelle à un renforcement de la collaboration en matière de recherche entre les pays développés et les pays en développement, en particulier dans les régions les plus vulnérables.

Mots clés: Elévation du niveau de la mer, Holocène, Anthropocène, Archéologie, Risques littoraux

Introduction

Since the end of the Last Glacial Maximum, sea level has undergone very large fluctuations that have shaped coastal environments and human settlement patterns. In the current context of climate warming driven by greenhouse gas emissions, recent projections by the Intergovernmental Panel on Climate Change indicate a rise in mean sea level of approximately 0.28 to 1.01 m by 2100, depending on emission scenarios (IPCC, 2023). These values fall within an order of magnitude comparable to the highest rates observed during the last post-glacial transgression, between 15 000 years before present and today. From 15 000 to

7 000 years BP, sea level rose rapidly, increasing from approximately -120/-130 m to near-present levels (Lambeck et al., 2014). This process affected hunter-gatherer populations and, subsequently, groups undergoing sedentarization in several regions of the world (the Middle East, the eastern Mediterranean, South and East Asia, among others). Archaeological evidence shows that these societies were confronted with shoreline retreat dynamics, as well as transformations in environments and available resources. In contrast, between 7 000 BP and the early twentieth century, sea-level rise proceeded at a much slower rate. Within this context, increased sediment supply linked to the expansion of the agricultural oecumene favored, in some areas, coastal progradation, and delta formation (Anthony et al., 2014). Historical societies thus evolved predominantly within expanding coastal environments, despite regional variations related to isostatic and tectonic factors (Fouache and Pavlopoulos, 2005). Since the mid-twentieth century, however, the situation has changed. The acceleration of sea-level rise, combined with a reduction in sediment supply (notably due to dam construction), has led to increased coastal erosion. This process is occurring at a time when human populations are increasingly concentrated along coastlines (Cosby et al., 2024). Our era is distinguished by being the first capable of precisely documenting both past and present changes, while simultaneously being directly exposed to their impacts due to the high density of coastal infrastructure worldwide. This raises critical questions regarding adaptive capacity in the face of rapid sea-level rise, as well as associated responsibilities, particularly toward the most vulnerable regions. This article proposes to examine these dynamics over the long term, from prehistory to the present, by comparing societal contexts and modes of adaptation.

Pleistocene eustatic variability and its implications for prehistoric settlement dynamics

At the Quaternary scale, variations in global sea level, or eustasy, constitute a fundamental parameter that is increasingly taken into account in understanding prehistoric settlement dynamics. Introduced as early as the late nineteenth century, this concept refers to absolute fluctuations in mean ocean level, independent of local lithospheric movements, and primarily controlled by changes in the volume of ocean water masses. These variations are largely governed by glacial-interglacial cycles, through processes of water storage in the form of continental and oceanic ice (glacio-eustasy) and its return to the oceans during deglaciation phases, to which is added the thermal expansion of seawater under conditions of climate warming (Church and White, 2011; Lambeck et al., 2001, 2005).

Palaeoclimatic reconstructions derived from marine and ice cores, particularly through oxygen isotope ratios ($\delta^{18}O$), make it possible to establish detailed eustatic curves and to subdivide the Pleistocene into Marine Isotope Stages (MIS) (Waelbroeck et al., 2002; Rohling et al., 2009; Spratt & Lisiecki., 2016) **(Figure 1)**. The Late Pleistocene alone (≈ 129 000 - 11 700 BP) provides a particularly clear illustration of this variability, with a succession of glacial and interglacial phases marked by significant sea-level fluctuations. The Eemian interglacial (MIS 5.5) represents a distinctive case, characterized by a sea level slightly higher than present by several metres, within a warmer and more humid climatic context (Kopp et al., 2009) **(Figure 1)**.

However, beyond this variability, long-term analysis highlights a dominant and rather striking trend: sea level remained below present levels for most of the Pleistocene. With the exception of relatively brief interglacial phases, sea levels fluctuated between -20 m and -120 m, reaching their minimum during the Last Glacial Maximum (MIS 2), around 21 000 years BP (Lambeck and Chappell, 2001). Thus, present-day high sea-level conditions appear exceptional at the Pleistocene scale, with intervals at or above present sea level representing only a limited fraction of the Late Pleistocene record illustrated in Figure 1 (Waelbroeck et al., 2002).

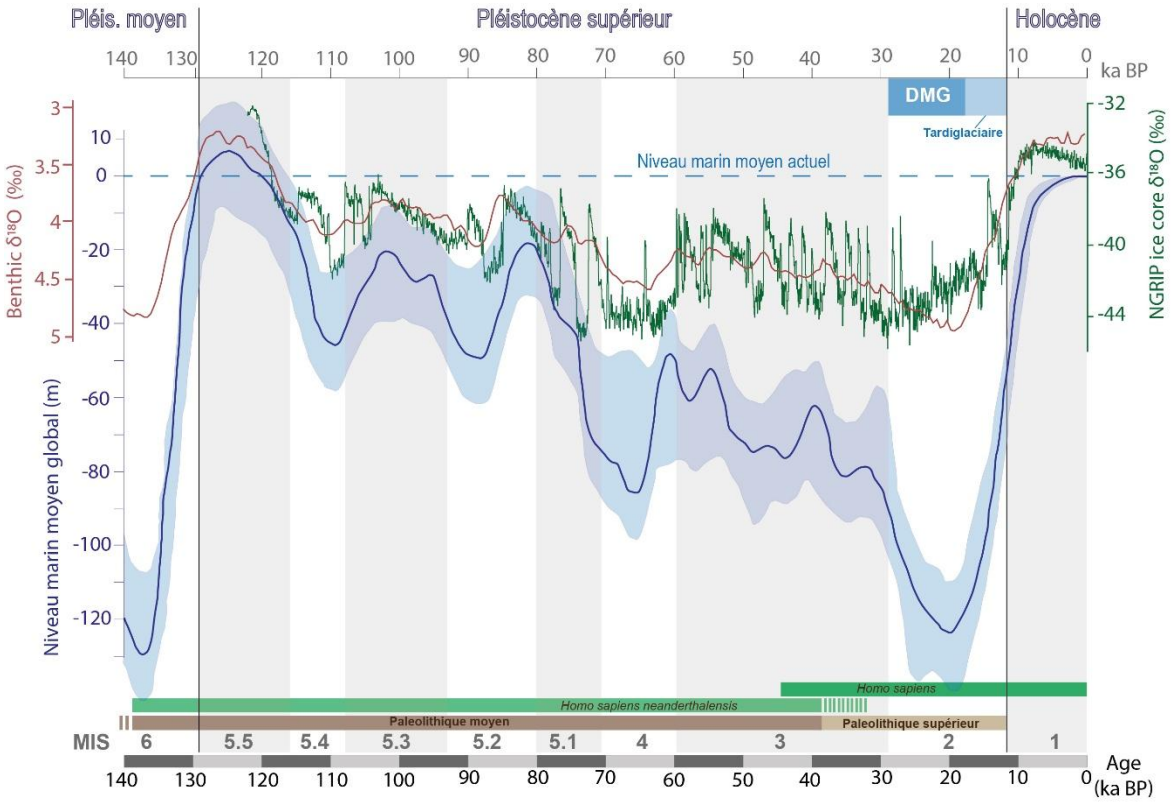


Figure 1: Comparison between the global mean sea-level curve for the Late Pleistocene and the Holocene (with uncertainties shown in light blue) (Waelbroeck et al., 2002) and paleoclimatic records based on the $\delta^{18}O$ proxy from the NGRIP ice core for the Northern Hemisphere (Kindler et al., 2014). Marine Isotope Stages (MIS), as defined from benthic $\delta^{18}O$ LS16 data (Lisiecki et Stern, 2016), are indicated in grey. The archaeological chronology shown is restricted to the Middle and Upper Palaeolithic. (Figure adapted from Benjamin et al., 2017)

This configuration likely had major implications for prehistoric societies. Low sea levels led to the emergence of vast portions of continental shelves, profoundly altering continental configurations and generating land corridors that are now submerged. These areas may have played a decisive role in processes of human population dispersal. Among the most significant examples are the Bering Strait, which enabled the peopling of the Americas from Eurasia (Farmer et al., 2023), the Sunda Shelf in Southeast Asia, also known as Sundaland,

connecting the major Indonesian islands to the mainland (Cheng and Faidi, 2025; Bird et al., 2005; Voris, 2001) **(Figure 2)**, and the Sahul Shelf, which facilitated access to Australia and New Guinea (Hantoro et al., 1995). In Europe, the now-submerged plains of the North Sea, known as Doggerland, also constituted key zones of movement and occupation.

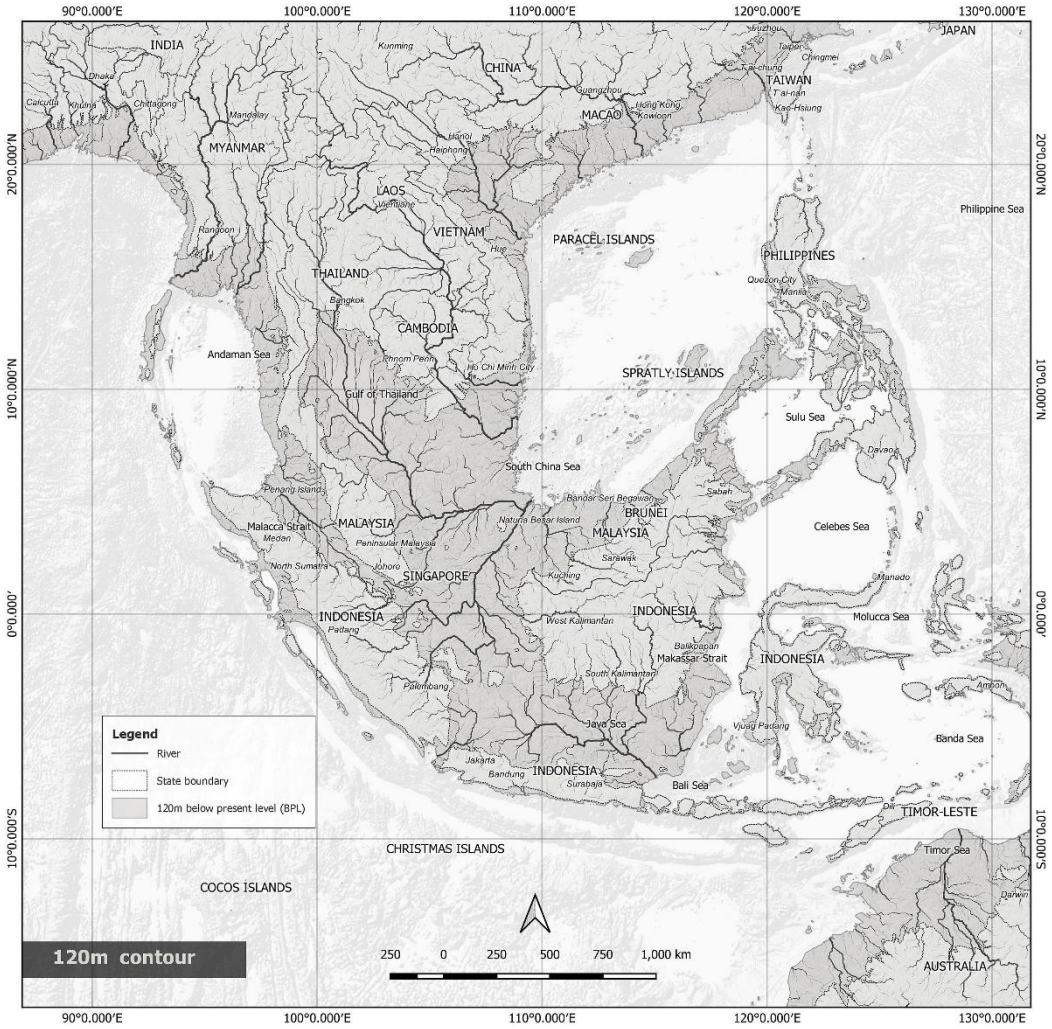


Figure 2: Detailed map of the Sunda Shelf (Southeast Asia) during the Last Glacial Maximum, when sea level was approximately 120 meters lower than at present. Dark grey shading indicates areas that are currently submerged but were exposed at that time, while light grey shading represents areas that are currently above sea level. The map also shows the orientation of palaeodrainage networks. Source: Cheng and Faidi, 2025.

These corridors may have facilitated the progressive dispersal of hominins on a global scale. The earliest expansions out of Africa, attributed to Homo erectus, occurred within this context of increased connectivity between continental landmasses. Later, the migrations of Homo sapiens during the Late Pleistocene benefited from these low sea-level conditions, enabling rapid dispersal into Eurasia, Oceania, and subsequently the Americas: coastal environments likely functioned as preferential dispersal routes at the scale of the Palaeolithic (Bailey et al., 2015). Conversely, interglacial phases of rising sea level contributed to the fragmentation of these landscapes, promoting situations of isolation, particularly in insular contexts. This phenomenon is well illustrated by the case of Homo floresiensis (Morwood et

al., 2005), whose distinct insular evolution in Indonesia reflects the effects of prolonged geographic isolation.

Finally, these eustatic fluctuations raise major challenges for contemporary archaeological research. A significant proportion of the territories frequented by Pleistocene hunter-gatherer societies, particularly resource-rich coastal zones, is now submerged. These areas constitute an archaeological heritage that is difficult to access yet essential for understanding prehistoric lifeways. The example of the Cosquer Cave, occupied between 33 000 and 18 500 BP and whose entrance now lies nearly 35 m below sea level (although it was accessible at the time of occupation) provides an emblematic illustration of this issue (Clottes et al., 1992).

Quaternary eustatic variations in general, and Pleistocene ones in particular, constitute an essential analytical framework for understanding, from a global perspective, the interactions between environmental dynamics and the trajectories of Palaeolithic human societies.

From 15 000 BP to 7 000 BP: consequences of the last post-glacial sea-level rise for Mesolithic and Neolithic populations

Between the Last Glacial Maximum (LGM) and the beginning of the Holocene (the current interglacial, which started 11 700 years ago), post-glacial sea-level rise followed a rapid but non-linear global trajectory, punctuated by phases of acceleration (meltwater pulses) (Brendryen et al., 2020) and periods of relative slowdown, such as during the Younger Dryas cold event. At the millennial scale, rates of sea-level rise reached on average 0.7 to 0.8 cm/year between 15 000 and 7 000 BP (Benjamin et al., 2017), with significantly faster episodes. Between 15 000 BP and 11 700 BP, sea level rose by nearly 40 metres. This marine transgression leds to profound transformations of landscapes: the progressive submergence of continental shelves resulted in the loss of vast terrestrial surfaces, estimated at nearly 2.5 million km² for Europe alone, with particularly marked transgression in the North Sea and the English Channel **(Figure 3)**.



Figure 3: Hypothetical geography of Europe and the Mediterranean basin under a sea level of -120 m, as during the Last Glacial Maximum (LGM): nearly 40 % more continental land was exposed. For clarity, ice sheets and mountain glaciers are not represented. The present-day coastline is retained to emphasize the magnitude of palaeogeographic changes. (Sources: ASTER GDEM DEM for topographic data and EMODnet for bathymetry) (Real. A. Chabrol).

At the global scale, several tens of millions of square kilometres of areas now submerged (including regions of the Persian Gulf, the Adriatic Sea, and the margins of Southeast Asia) were then exposed and potentially habitable. These landscapes, once traversed by river networks and covered with forests, constituted environments favourable to human occupation, as illustrated by the case of Doggerland, a vast territory connecting Great Britain to the European continent, intensively occupied by Mesolithic groups before its progressive submergence and eventual disappearance, possibly accelerated by catastrophic events such as the Storegga Slide tsunami around 7 000 BP (Krüger et al., 2017; Walker et al., 2020). In certain closed or semi-enclosed basin contexts, these changes may have been much more rapid and pronounced. This is notably the case of the Black Sea, formerly a freshwater lake whose connection to the Mediterranean via the Bosphorus, around 8 400 BP, leds to a rapid transformation of coastal environments and lacustrine margins into marine settings (Ryan et al., 2003; Giosan et al., 2009). Between 11 700 and 7 000 BP, sea level rose from approximately -60 m to -10 m, before entering a phase of marked deceleration. This widespread marine transgression during the early Holocene necessarily implied a contraction of accessible territories, particularly for Mesolithic groups settled in low-lying areas, while

also contributing to the formation of new and constantly evolving coastal landscapes. Nevertheless, although these transformations appear considerable in spatial terms and in retrospect, their perception at the scale of human societies was probably more gradual, if not imperceptible. Evidence from submerged Neolithic sites, such as Atlit Yam (Galili & Nir, 1993) and Pavlopetri (Henderson et al., 2011; Poulos et al., 2022), indicates that their submersion occurred after their occupation, suggesting that sea-level rise, although sustained over the long term, was not necessarily experienced as an abrupt phenomenon, but rather as a progressive environmental constraint embedded within a trajectory of continuous change.

In this context, the recurrence of flood narratives across many cultural traditions invites further reflection on how these environmental upheavals were perceived and transmitted. The example of the rapid infilling of the Black Sea around 8 400 BP provides a particularly relevant case. Such an interpretation, however, remains debated in the absence of archaeological evidence for population movements at that time in surrounding regions, and given that the earliest written traditions relating to flood myths originate primarily from the Assyrian and Mesopotamian worlds. Nevertheless, the widespread occurrence of these narratives represents a promising field of investigation, provided that multidisciplinary approaches are employed, combining geoarchaeological, palaeoenvironmental, and anthropological data. In this regard, certain iconographic evidence, such as the rock art of Arnhem Land in Australia depicting the appearance of the Barramundi (an estuarine fish absent from earlier assemblages), suggests that transformations associated with post-glacial transgression may have been incorporated (in symbolic forms) into the representational systems of human societies (Lewis, 2019).

More generally, it can be argued that human societies were only significantly affected in their lifeways and access to resources by the consequences of sea-level rise once, following the processes of Neolithization at the beginning of the Holocene, they became sedentary and agricultural.

Between 7 000 BP and the early twentieth century, societies were instead confronted with the progradation of sedimentary coastlines.

From 7 000 BP onward, the marked deceleration of post-glacial sea-level rise profoundly altered coastal dynamics as well as the constraints affecting human societies. Although marine transgression continued, it became sufficiently moderate that it no longer constituted the dominant driver of coastal evolution, giving way instead to processes of coastal progradation, particularly at river mouths and in sediment-rich coastal plains. This pattern was not universal: rocky coasts, subsiding or tectonically active margins, and sediment-starved systems could experience markedly different shoreline trajectories. This shift marks the onset of deltaic system development through the progressive infilling of estuaries, within a framework controlled by fluvial inputs, subsidence, and marine dynamics (Anthony et al., 2025). In this context (and for the first time), human societies were less

confronted with the risk of marine submergence than with the seaward advance of land, and thus with a relative distancing from the coastline in progradational settings. From the Neolithic onward, and even more so during the Bronze Age and Antiquity, increasing anthropogenic pressure on catchments (deforestation, cultivation, pastoralism) leds to a significant rise in soil erosion and, consequently, in sediment transfer to coastal zones. This intensification of alluviation contributed to the formation of extensive deltaic plains and sandy coastal systems (beaches, spits, barriers), the vast majority of which, at the global scale, developed over the last 7 000 years. Numerous and particularly illustrative examples can be found in Mediterranean contexts. The delta of the Achelous River in Greece provides a striking case, with the ancient port of Oeniadae now located several kilometres inland and its harbour infrastructures currently isolated from the sea (Fouache et al., 2005). The Thessaloniki plain, occupied since the Neolithic (site of Nea Nikomedeia), has experienced a significant seaward shift of the coastline (Ghilardi et al., 2012). Similarly, the hills embedded within the alluvial deposits of the Kalamas River delta, opposite the island of Corfu, were islands during the Neolithic and the early Bronze Age (Chabrol et al., 2025) **(Figure 4)**. At a broader scale, comparable processes are observed in major fluvio-deltaic systems such as those of the Nile, the Yangtze, the Indus, and the Büyük Menderes, where increased sediment supply (driven by both climatic forcing and human activities) has promoted rapid coastal progradation, thereby reshaping shoreline geometries and, in some cases, forcing populations to adapt or abandon their settlements.

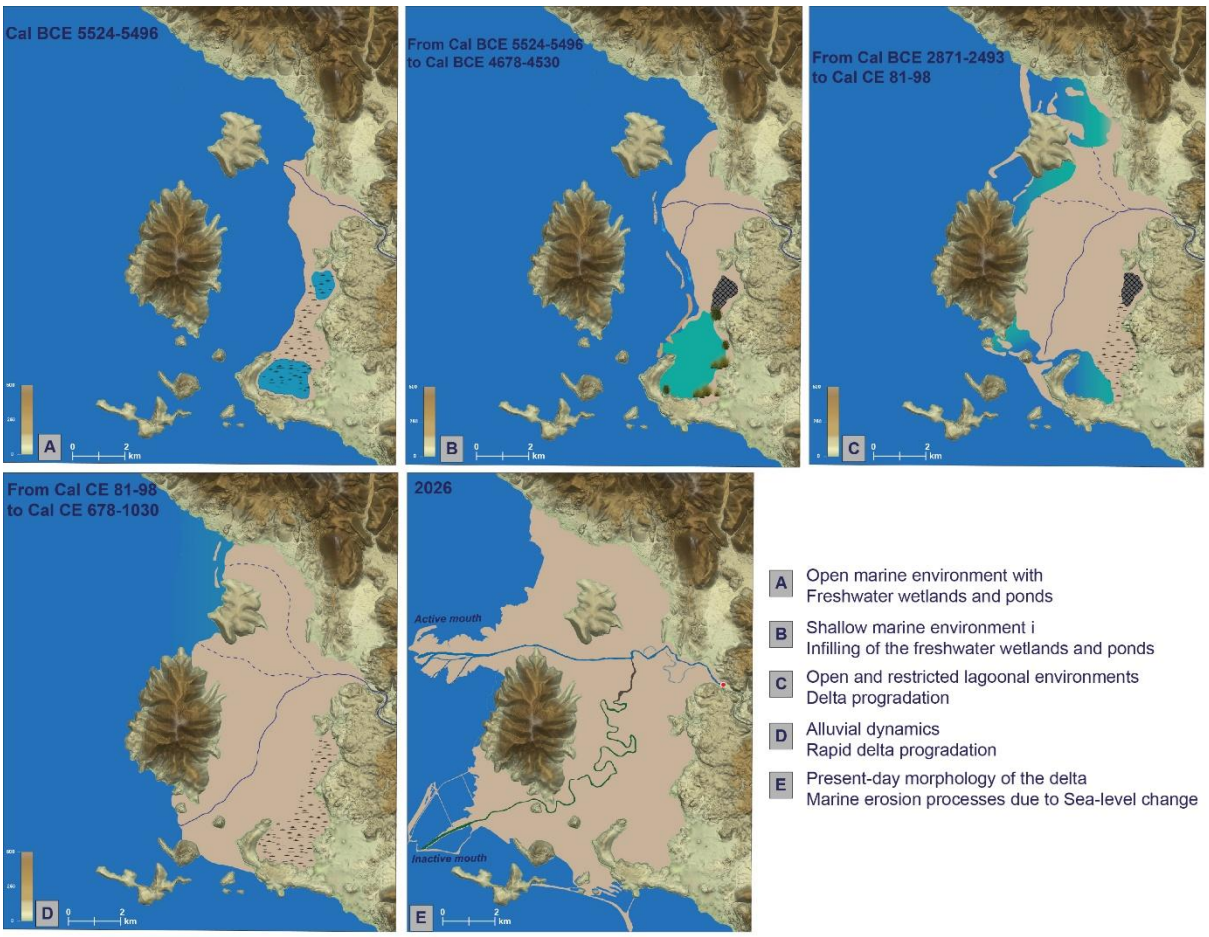


Figure 4: Palaeogeographic reconstructions of the Kalamas delta (Greece) since 7500 BP. (Chabrol et al., 2025)

Within this framework, the concept of the "anthropogenic delta," developed in recent years, highlights the increasing role of human societies in shaping the evolutionary trajectories of these environments (Anthony et al., 2025, 2014; Salomon et al., 2024). While the earliest effects of anthropogenic influence can be traced back to the Neolithic, they became decisive from Antiquity onward, when intensified deforestation, the expansion of cultivated land, and demographic pressure led to a marked increase in sediment fluxes. To these upstream drivers were added direct interventions along coastlines (harbour construction, wetland drainage, among others), which altered sedimentation processes and water circulation patterns. Deltas thus emerge as hybrid systems, in which natural processes and human actions interact closely. This progressive anthropization, rooted in the second half of the Holocene, foreshadows contemporary imbalances: today, the reduction in sediment supply due to dam construction, subsidence induced by groundwater extraction, and the concentration of urban development in delta regions all contribute to increasing their vulnerability to coastal hazards and to ongoing sea-level rise, which has persisted throughout the Holocene.

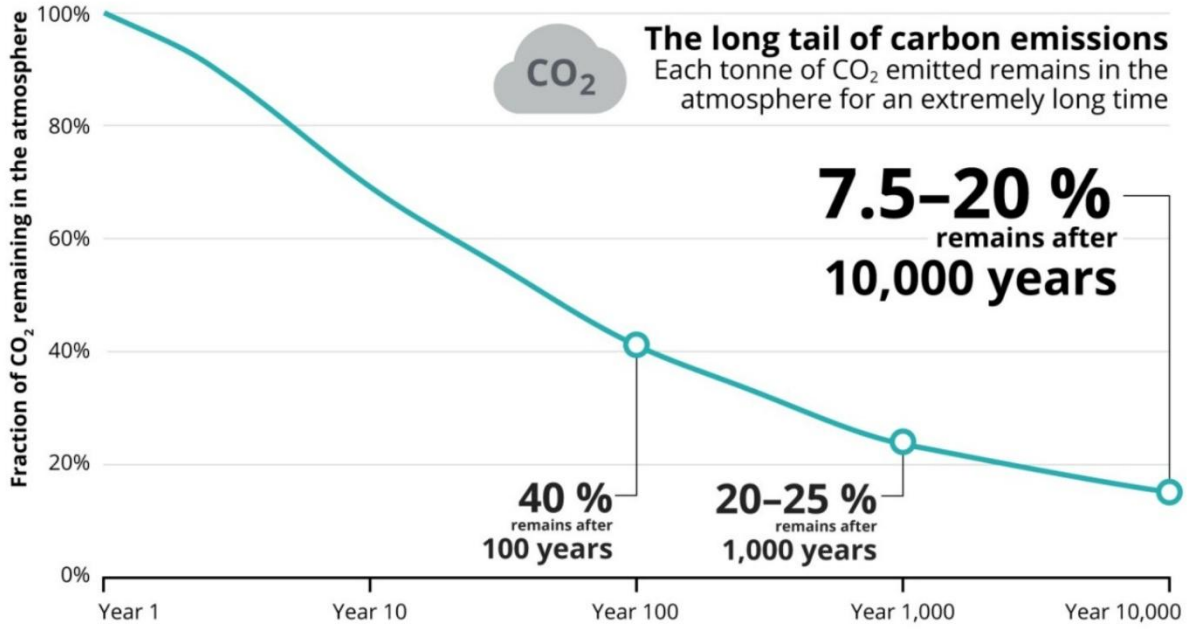
A constraint now perceptible: contemporary societies and the acceleration of sea-level rise

Today, the renewed acceleration of sea-level rise represents a paradigm shift in the long-term history of interactions between human societies and eustatic variations. Unlike prehistoric groups confronted with post-glacial transgression (still relatively sparse, mobile, and only weakly dependent on fixed infrastructure, with the possible exception of caves) contemporary societies are predominantly coastal, highly urbanized, and, in reality, technically vulnerable. Approximately 2 billion people live within 50 km of coastlines, including 1 billion within 10 km (Cosby et al., 2024), in areas where ports, major cities, energy networks, industrial zones, agricultural deltas, and transport infrastructures are concentrated. According to the Intergovernmental Panel on Climate Change, global mean sea level could rise by 0.28 to 0.55 m by 2100 under a very low emissions scenario, and by 0.63 to 1.01 m under a very high emissions scenario (IPCC, AR6, 2023). This rise, now clearly perceptible on the scale of a human lifetime, transforms a phenomenon once primarily understood over centennial or millennial timescales into an immediate social constraint: shoreline retreat, more frequent flooding, salinization of groundwater and soils, habitat loss, and forced displacement. Moreover, these processes are exacerbated by unsustainable anthropogenic management of fluvio-coastal systems: dams trapping sediments, large-scale sand extraction, coastal artificialization, and subsidence induced by groundwater withdrawal. Dams have significantly reduced sediment fluxes to the oceans in many river basins, by up to 49 % compared to pre-dam conditions in major northern river systems (Dethier et al., 2022), while sand extraction continues to increase at a rate considered unsustainable by the United

Nations Environment Programme[1] (Programme, U. N. E. (2022)). The consequences are particularly critical for low-lying coastal plains, deltas, and small island states, often located in countries of the Global South, where financial capacities for adaptation are most limited despite maximum human exposure (Duijndam et al., 2025). The World Bank's Groundswell assessment estimates that climate change could trigger up to 216 million internal migrations by 2050 across six world regions (Rigaud *et* al., 2018), notably due to sea-level rise, water scarcity, and declining agricultural yields.

Initial examples of relocation are no longer hypothetical. In Tuvalu, where sea level has risen by approximately 15 cm over the past thirty years, authorities have implemented the "Tuvalu National Adaptation Plan"[2] within the framework of the "Tuvalu Coastal Adaptation Project"[3], and more than one third of the population has applied for migration opportunities opened by Australia under the Falepili Treaty (Guo and Genauer, 2025). Similarly, villages in Fiji have begun to be relocated inland, while comparable processes of coastal abandonment are also observed in Pakistan (Daraz et al., 2024). Thus, contemporary sea-level rise can no longer be considered a purely natural dynamic: for the first time since the Last Glacial Maximum, it has become a global socio-environmental risk, produced both by climate warming and by development choices that have weakened the natural resilience of coastal systems.

An aggravating factor for contemporary societies lies in the fact that, even if global greenhouse gas emissions were to cease today, it would take more than ten centuries for atmospheric concentrations to return to pre-industrial levels (Zickfeld et al., 2013; Inman, 2008) **(Figure 5)**.



Fraction of emitted CO_2 remaining in the atmosphere in years after emission up to 10,000 years

[1] https://www.unep.org/news-and-stories/story/problem-our-dwindling-sand-reserves
[2] https://unfccc.int/sites/default/files/resource/NAP_Tuvalu_2025.pdf
[3] https://tcap.tv/about-tcap

Figure 5: The persistence of carbon dioxide in the atmosphere. Graph based on data from Inman, 2008. Source: https://anticiper.org/constat/le-co2-emis-aujourd-hui-mettra-plus-de-1000ans-a-etre-absorbe.php

Consequently, contemporary societies will face long-lived consequences of anthropogenic climate change, including continued sea-level rise over centuries to millennia. However, the magnitude and timing of long-term sea-level rise remain scenario-dependent and uncertain; atmospheric CO_2 persistence alone does not imply a specific minimum rise. IPCC AR6 assesses that sea level is committed to remain elevated for thousands of years and that multi-metre rise becomes increasingly plausible on millennial timescales under sustained warming (IPCC, 2021, 2023). The societal priority is therefore to develop scenario-based maps of future coastal inundation that explicitly account for regional relative sea-level change and associated uncertainties. Forecast maps of submersion hazards at 5-, 10-, and 20-year horizons, when combined with maps of human settlements and infrastructure, can subsequently be used to derive risk maps **(Figure 6)**. This approach is well established in the field of "geography of risk and hazards" yet it constitutes an essential prerequisite for the implementation of any spatial planning or managed retreat policies aimed at addressing the impacts of global sea-level rise. However, in this domain, the delay remains considerable.

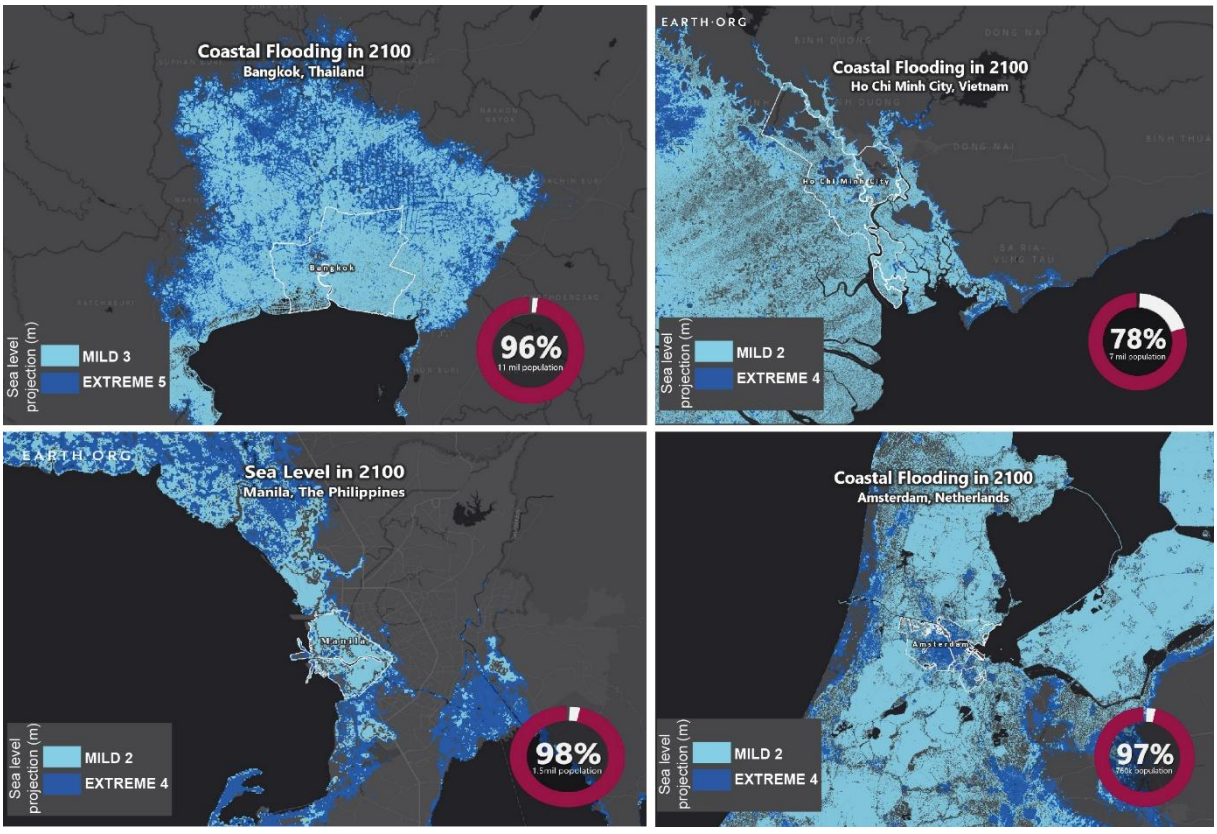


Figure 6: Illustrative coastal-flooding maps for 2100 under hypothetical 3 m and 5 m sea-level-rise scenarios. These values should not be interpreted as the IPCC AR6 likely projections for 2100 (0.28–0.55 m under SSP1-1.9 and 0.63–1.01 m under SSP5-8.5); rather, they represent high-end illustrative inundation scenarios used by the source website. The percentages shown in the lower-right panels

refer to the populations exposed in the mapped areas. Source: https://earth.org/sea-level-rise-projections/

Risk assessments have informed a range of adaptation and territorial-planning responses, but the underlying drivers are often multiple and should not be attributed to sea-level rise alone. In the Netherlands, selected programmes combine flood-risk reduction, river and coastal management, and spatial planning, including the deliberate restoration or re-flooding of some areas where this can reduce risk or provide ecological benefits[4]. In Indonesia, the planned relocation of the national capital from Jakarta to Nusantara likewise reflects a combination of factors, including severe land subsidence, recurrent flooding, congestion, environmental degradation, and broader territorial-development objectives; sea-level rise acts as an additional long-term risk rather than a single causal driver (Van de Vuurst and Escobar, 2020). More generally, the cases discussed above should be distinguished analytically as adaptation to sea-level rise, responses to subsidence and coastal erosion, disaster-risk reduction, managed retreat, or migration shaped by interacting environmental and socioeconomic factors.

Such an analysis of hazard exposure is indispensable. Unfortunately, it reveals that the most affected areas (namely low-lying, subsiding coastal plains with the highest population densities) are predominantly located within the intertropical zone, with the vast majority situated in countries of the Global South (Kulp and Strauss, 2019; Rentschler et al., 2022).

Conclusion

The long-term analysis of interactions between human societies and sea-level variations highlights three major phases since the end of the Last Glacial Maximum. Between 15 000 and 7 000 BP, the rapid rise in sea level led to a contraction of habitable spaces through the submergence of continental margins. From 7 000 BP onward, throughout protohistoric and historical periods, although sea-level rise continued, its deceleration (combined with increased sediment supply) promoted coastal progradation, to which societies adapted over the long term and which they actively transformed. It is only from the late twentieth century that a major shift occurred: the renewed acceleration of sea-level rise, linked to climate warming, combined with the anthropogenic reduction of sediment fluxes and the strong concentration of populations along coastlines, has made its effects perceptible for the first time at the scale of a human lifetime. This transition represents a major paradigm shift since the end of the last glaciation. In this context, societal adaptation becomes not only a scientific issue but also a central societal challenge. While research remains unevenly distributed (largely concentrated in countries of the Global North) these challenges primarily concern intertropical regions of the Global South, where exposure and vulnerability are greatest. Improved understanding of long-term society-environment interactions, along with greater sharing of resources and knowledge between Northern and Southern countries,

[4] https://dutchclimaterisk.nl/hazards-data/water-related/acute/flood-coastal-fluvial-0/policies-regulations/

therefore appears to be an essential condition for better understanding these processes and supporting responses to contemporary coastal challenges.

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