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► **To cite this version:**

Denis Lacroix, Olivier Mora, Nicolas de Menthière, Audrey Bethinger, Gaël Durand, et al.. Eight scenarios for anticipating sea-level rise through 2100. 2019. hal-03699574

HAL Id: hal-03699574

<https://hal.science/hal-03699574v1>

Preprint submitted on 20 Jun 2022

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Eight scenarios for anticipating sea-level rise through 2100

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Abstract

An important physical response to anthropogenic climate change is the long term rise in global mean sea-level (GMSL). Given this context the French National Alliance for Environmental Research, which brings together the main French research institutions concerned with environment, tasked its foresight group with shedding light on sea-level rise by 2100, estimating the possible impacts and consequences for the environment and societies, and recommending future research priorities.

We employ a foresight approach based on the scenario method with 23 driving variables for the coastal system and four physical contexts for the sea-level rise (moderate, serious, severe and extreme) leading to the development of eight contrasted and unconnected scenarios starting in 2020 and extending to 2100. Each scenario is defined by a storyline. Storylines are determined mainly by coastal adaptation efforts and the political will to mitigate climate change. These are structured in three families: (1) Priority given to adaptation (four scenarios: Climate control, Frugality and anticipation, Resilient cities, Early adaptation and late mitigation), (2) Denial of the phenomenon (three scenarios: Passivity, Gradual coastal abandonment, From denial to reaction) and (3) Fragmented world (one scenario: Persistent fragmentation).

Scenario trajectories without vigorous and widespread mitigation policies before 2040 show that coastal States will have to deal with 'severe' or 'extreme' sea level rise by the end of the century. 'Severe' or 'Extreme' sea level rise outcomes are envisaged in five of the eight scenarios in the range of possible futures. Two scenarios lead to 'serious' sea level rise and one ideal scenario leads to a 'moderate' state. Adaptation efforts will be less cumbersome and costly when mitigation efforts have been early, widespread and sustained. The optimal scenario considers raising awareness of all actors in societies, leading to the introduction of fast and radical mitigation and adaptation efforts. All other scenarios mean that future generations may have to face major or even irreversible upheavals, at increasing costs.

Keywords: Climate change, sea-level rise, scenarios, submersion, impacts, coastal risks, mitigation, adaptation

1 Introduction

Sea level rise during the 20th century had been clearly described (Church and White, 2011) and it still will be a steady phenomenon during the 21st century (Oppenheimer *et al.*, 2019). Its rate and magnitude will depend on global warming, itself mainly determined by cumulative anthropogenic greenhouse gas emissions. While 21st century projections have long been considered moderate (30-70 cm), recent observations and modelling indicate a current sea level acceleration and possible

higher future sea levels. Indeed, it has accelerated over the twentieth century and will increasingly affect the coastline and coastal areas where large populations and economic activity are concentrated.

The coastal zone with an altitude of less than 10 m (or low elevation coastal zone, LECZ) will accommodate 929 million inhabitants in 2030, an increase of 50% compared to the year 2000 (625 million). It will reach one billion people in 2060 (Neumann *et al.*, 2015). 315 to 411 million people will be potentially exposed to floods in 2060, particularly in China, India, Bangladesh, Indonesia and Vietnam, five countries totalling 50% of the most vulnerable populations, where, on top of rising sea-level, ground water extractions commonly cause local land subsidence in the order of 1cm/year or more (*ibid*). In addition, 12 of the 20 largest ports in the world would be vulnerable to a sea level rise above 1 m in 2100, especially in Asia but also in Europe, including the ports of London and Rotterdam (*ibid*).

Given the considerable investments needed to adapt coastal areas in the medium and longer term, anticipating coastal flooding and erosion risks is a major public policy issue (Church *et al.*; 2013, Wong *et al.*, 2014). Research in environmental sciences helps inform choices in these public policies, particularly in terms of anticipating changes and assessing risks. The projections in the latest Intergovernmental Panel on Climate Change (IPCC) SROCC report consider a likely increase in the average sea level by 2100 of 29 cm for RCP 2.6 through to 110 cm for RCP 8.5 (Oppenheimer *et al.*, 2019), but these likely projections could be exceeded (Stammer *et al.*, 2019).

At local scales, there are significant differences in terms of the exposure of coastal areas and effects (related to specific vulnerabilities), as well as unequal adaptive capacities across territories and states (Haasnoot *et al.*, 2019). The environmental, social and economic consequences will therefore depend on the scale of the phenomenon, current and future characteristics and uses of the considered coastal areas and, above all, the ability to anticipate, react and coordinate governance. These insights support assessments of possible future sea levels exceeding 100 cm by 2100, and their possible impacts. It is insightful to envisage a wide range of environmental/socio-economic futures and to explore possible scenarios based on available knowledge, in order to take stock of the challenges and consequences of rising sea levels. Using a foresight approach allows one to structure and delimit the space for possible evolutions in the decades to come and through until the year 2100. Moreover, relevant information including foresight is essential to inform short-term decision-making, not only to limit risks and impacts until 2100, but also to limit the rate of sea-level rise typically in the 22nd century and beyond (e.g. Mengel *et al.*, 2018).

The objectives of this paper are (a) to present new scenarios accounting the consequences of possible evolutions in sea-level rise on natural environments, economic activities, societies and governance in the broadest sense; (b) to identify research priorities to address in order to meet the challenges of the described scenarios. The approach is necessarily reflective because political, economic and societal choices during this decade will determine the sea level trajectory in the second half of this century (Georghiou and Casingena Harper, 2011). Our scenarios differ from the broader Shared Socio-economic Pathways (SSP) (Riahi *et al.*, 2017), which target adaptation and mitigation in a broader sense and serve as a reference for the IPCC. They also offer an alternative to downscaling SSPs (Reimann *et al.*, 2018), which may not cover all the contrasting potential adaptation and mitigation pathways relevant to coastal zones.

2 Materials and methods

2.1. Motivation for the foresight approach

Research on issues that will arise in the near future in order to allow more timely resources allocation, given the time frame for obtaining results (Funtowicz and Ravetz, 1993). As a result, many research programmes integrate various future time scales, with the time horizon generally ranging from 10 years through to the end of the century. The natural tendency of researchers is to consider only what could be described as ‘clear and credible’ such as ‘median’ projected situations, in other words avoiding pessimistic scenarios or clear ruptures (Hinkel *et al.*, 2015). However, clear

ruptures have taken place before, as a technique can mature over 30 years or more (for example, computer science) before being deployed operationally in a highly modified economic and technological environment (Dupuy, 2002). These visions of scenarios should help researchers to extend the horizon over time in order to better perceive the dynamics at work over the long term, as well as for deeply uncertain future evolutions (Walker et al., 2003).

The storylines describing these scenarios are relevant and useful to embed a wider range of factors than conventional scenarios allow, including weak signals, tipping points and shift-changes in order to better understand the complex dynamics at work over the long term (Clark et al. 2016).

The methods which combine uncertainties and complexity to explore possible qualitative scenarios of the future are globally termed ‘foresight approaches’ in the literature (Zurek and Henrichs, 2007; Ramirez and Wilkinson, 2014).

Here, our motivation to apply a foresight approach to define broad contextual scenarios exploring future situations in the context of sea-level rise is twofold: (1) the long timescale of change involved in sea-level rise (Clark *et al.*, 2016); (2) the deep uncertainties related to sea-level projections, even by the end of the century (Oppenheimer *et al.*, 2019).

The aim of this study is to elaborate the main scenarios for possible evolutions in sea-level rise and their consequences on natural environments, economic activities, societies and governance in the broadest sense. This analysis allows us to outline the type of priority research that is necessary in order to best meet the challenges of the described scenarios. The approach is necessarily reflective because political, economic and societal choices will themselves determine the trajectories of changes in sea level (Georghiou and Casingena Harper, 2011).

2.2. Method and morphological table

One of the most robust and versatile methods for solving complex problems is that of scenarios (Mietzner and Reger 2005; Bishop *et al.*, 2007; Zurek and Henrichs, 2007). It consists of selecting a set of hypotheses formulated for the main variables influencing the issue being addressed in the aim of constructing future scenarios. The number of driving variables and the degree of variability in the assumptions play an important role in obtaining contrasting scenarios, avoiding common biases such as overweighting of the coming 10 years and the reluctance to introduce ruptures (Grienitz *et al.*, 2013; Meissner and Wulf, 2013). The term scenario is used here in its most common sense: “a representation of the future, based on assumptions and consequences (if, then), resulting from an initial situation” and a description of forces and changes (Alcamo, 2009). The method used in this study is based on morphological analysis “which aim at covering the entire set of possibilities in a multidimensional problem (economy, governance, environment and natural resources, demography, geopolitics...), and therefore allows for the construction of exploratory scenarios in contexts of high uncertainty” (Godet, 2000). The morphological table (see Table 3) sets together these alternative assumptions per driver of the system and thus helps visualize and explore combinations of drivers’ assumptions. This systematic method makes it possible to investigate multiple plausible configurations, causal links and interactions between different drivers of a system. It ensures the consistency and plausibility of scenarios (e.g., Zurek and Henrichs, 2007).

In this study, the system, the variables, the hypotheses and the scenarios have been designed by a collective work, based on nine workshops of a multidisciplinary expert group. This expert group gathers about 20 researchers from several institutes. It benefits of a variety of expertise solicited during the workshops: researchers, engineers, stakeholders, decision makers, etc. The variables are the result of a two-step process. First, through a brainstorming session with the expert group, we identified possible issues raised by future sea-level rise, and organized them into seven domains (the “components” of our system). Second, during another workshop we identified the variables corresponding to the issues detected in the first step, and determined which variables should be studied.

Having a system defined by its variables, we conducted a retrospective analysis on each variable through literature reviews. Based on these enquiries, we elaborated alternative assumptions of changes by 2100 for each variable. The expert group discussed assumptions of change of drivers,

combinations of assumptions and their internal consistency, and scenarios as retained plausible combinations of assumptions (Mermet, 2005).

In a final step, each scenario was defined by a combination of assumptions for the evolution of the variables - this combination describing the state of the system in 2100. For this, we selected for each variable an assumption of evolution (two at most if necessary), favouring the general meaning of the combination, its plausibility and robustness, and looking for consistency across hypotheses.

Special attention is paid to the compatibility or incompatibility of hypotheses along the construction process of scenarios. For example, a rapid mitigation, which implies a high level of international cooperation is not possible in a fragmented world. For this reason, a number of caveats have to be considered during the scenario elaboration process.

2.3. Physical states related to sea-level rise

Three factors play a major role in driving sea-level rise: the melting of the Greenland (whose contribution has tripled in 20 years) and Antarctic (where at least two outlet glaciers are suspected to be affected by marine ice sheet instabilities) ice sheets, ocean thermal expansion (steric effect) and the melting of glaciers and ice-caps (Church *et al.*, 2013). The future contribution of the first factor is the most uncertain and is subject of an increasing number of studies showing that the melting of the Antarctic ice sheet may contribute to the cumulative rise in the ocean level beyond the likely range projected by IPCC (Kopp *et al.*, 2017; Le Bars *et al.*, 2017; Bamber *et al.*, 2019). Actually, recent observations have shown an increase in the contribution from the Greenland and Antarctic ice-sheets to rising sea levels (Pritchard *et al.*, 2012; Mouginit *et al.*, 2014; IMBIE team, 2018). Importantly, observations already display an acceleration of the phenomenon, with global mean sea level rise (GMSL) rates increasing from 2.7 mm/year between 1993 and 2004 (+29.7 mm in total) to 3.5 mm/year between 2004 and 2015 (+38.5 mm in total) (Dieng *et al.*, 2017).

Estimates of GMSL rise for 2100 relative to 1986-2005 vary between median values of 0.43 m (likely range 0.29–0.59 m) and 0.84 m (likely range 0.61–1.10 m) for RCP 2.6 and RCP 8.5 respectively (Oppenheimer *et al.*, 2019).

But, considering serious uncertainties about major climate change factors, it is legitimate to consider scenarios beyond the ‘likely’ values provided by the IPCC (Parris *et al.*, 2012; Kopp *et al.*, 2014; Nicholls *et al.*, 2014; Jackson and Jevrejeva, 2016; De Conto and Pollard, 2016; Bamber *et al.*, 2019, Jevrejeva *et al.*, 2019; Stammer *et al.*, 2019; Oppenheimer *et al.*, 2019). In fact, according to the IPCC vocabulary, an outcome which is presented as “likely” means that the probability of this outcome can range from $\geq 66\%$ to 100% probability. This implies that all alternative outcomes are “unlikely” (0-33% probability).

Another important element that we consider is the frequency and intensity of extreme events such as marine submersion, temporary flooding and cyclones (Wong *et al.*, 2014; Leal Filho, 2015). Combined with rising sea level, these extreme events (‘ExE’) can increase the magnitude of the coastal impacts. Actually, coastal impacts will vary by coastline due to both the type of coast and type/magnitude of hazard. Thus, a coast exposed to cyclones is more vulnerable than a coast of the same altitude in a sheltered or non-cyclonic area. Another driver of the risk is the profile of the bathymetry. Coastal sedimentary regions with shallow waters (i.e. Gulf of Mexico) are also more risky areas for human development and activities than steep marine slopes like in Norway or Chile.

To evaluate the situation in 2100, four plausible physical states of the marine system were selected based on 3 parameters (see Table 1): the GMSL rise relative to 2020, the rate of such rise in 2100 (“fast”, which means 10 mm/year or more or “slow”, which means 5 mm /year or less) and finally the change in intensity and frequency of the extreme weather events that have an impact on sea level such as wind, tempest, hurricane, low pressure, etc. A “medium” rate of GMSL (i.e. between 5 to 10 mm/year in 2100) was not selected in order to keep contrasted values for this parameter and to avoid to multiply physical states. Actually, if selected, such “medium” values should logically entail in intermediate states between the four potential physical states in 2100. These scenarios assume that only strong climate change mitigation policies can achieve low rates of sea-level rise in 2100, whereas high sea-level rise rates and absolute values are only associated with large greenhouse gas

emissions. This is broadly consistent with the current state of knowledge in the area of sea-level rise (Oppenheimer et al., 2019).

Table 1: Characteristics of the four potential physical states of the marine system in 2100. (Note that serious, severe or extreme scenario imply a substantial contribution from ice sheets ExE means Extreme Events).

Rise in sea level (<i>order of magnitude; in mm</i>)	Slow increase in 2100 (5 mm/year or less)	Fast increase in 2100 (10 mm/year or more)
500 mm	MODERATE (ExE +) (RCP 2.6 - 4.5)	SERIOUS (ExE +) (RCP 4.5 - 6.0)
1000 mm		SEVERE (ExE ++) (RCP 8.5)
2000 mm		EXTREME (ExE ++) (RCP 8.5)

3 Results: Morphological table, scenario stories and graphical representation

Each scenario is associated with a physical state consistent with the set of assumptions used. For example, within a scenario, the combination of a persistent lack of ambitious targets for greenhouse gas reduction and disparate national policies without a long-term global strategy can plausibly be linked to, at least, a “severe” physical state in 2100.

The morphological table (Table 3) (or scenario construction matrix) is the first result of this work. This table comprises twenty-three variables or “drivers” (grouped into seven components). We describe between two and five assumptions for each variable that were developed by the expert group for different horizons to 2100. This table made it possible to construct the eight global scenarios described below. Table 4 shows the assumptions selected for every variable to build the 8 scenarios.

Based on this morphological table and the schematic physical states (Table 1), we have grouped the eight global scenarios into three families: coastal adaptation, denial and fragmented world. No scenario can be described only as « Business as usual », because many drivers are changing over the century. Most of the scenarios account for the timing of the transition from an initial trend to other development pathways including those ensuring sustainability. This temporal aspect of future changes is not prominent in current approaches, often based on the Shared Socio-economic Pathways (Reimann et al., 2018). The timing of these transitions is very relevant to this foresight work because future sea-level rise is sensitive to the timing of decarbonisation (Bitterman et al., 2017). The description of the scenarios is based on five main items: the degree of climate change mitigation, the level of coastal adaptation effort, the coastal urban development (as the move of population to cities is considered as a mega-trend for the century), the quality of coastal ecosystems and the global movement of population. Table 2 summarizes the features of the eight scenarios according to these 5 main items and the figure 1 presents the various evolutions of the 8 scenarios.

‘Coastal adaptation’ family

This family first gives priority to the adaptation of the coastline in order to preserve as long as possible the viability of coastal habitats, infrastructure and activities. However, its variants relate to the degree of coupling with global mitigation policies, which are implemented more or less early and are more or less proactive.

The family comprises two pairs of trajectories. The first (A1 and A3) correspond to proactive scenarios, where climate change mitigation, achieved through the implementation of political, economic and societal decisions, lead to greenhouse gas concentrations consistent with a 1.5-2°C

global warming above preindustrial levels, consistent with the Paris Agreement. These two proactive scenarios are similar to the mitigation scenario described by Rockström *et al.* (2017) and to SSP-1 (Riahi *et al.*, 2017), leading to limited sea-level rise (moderate to serious context). The second pair (A2 and A4) corresponds to progressive awareness and later action over the course of the century, generating more worrying consequences (serious to severe context) that require greater efforts to adapt coastal areas. These two A2 and A4 scenarios are consistent with elements from the storylines of SSP-1 (“sustainability – taking the green road”) and SSP-2 (“Middle of the road – medium challenge to mitigation and adaptation”) (Riahi *et al.*, 2017).

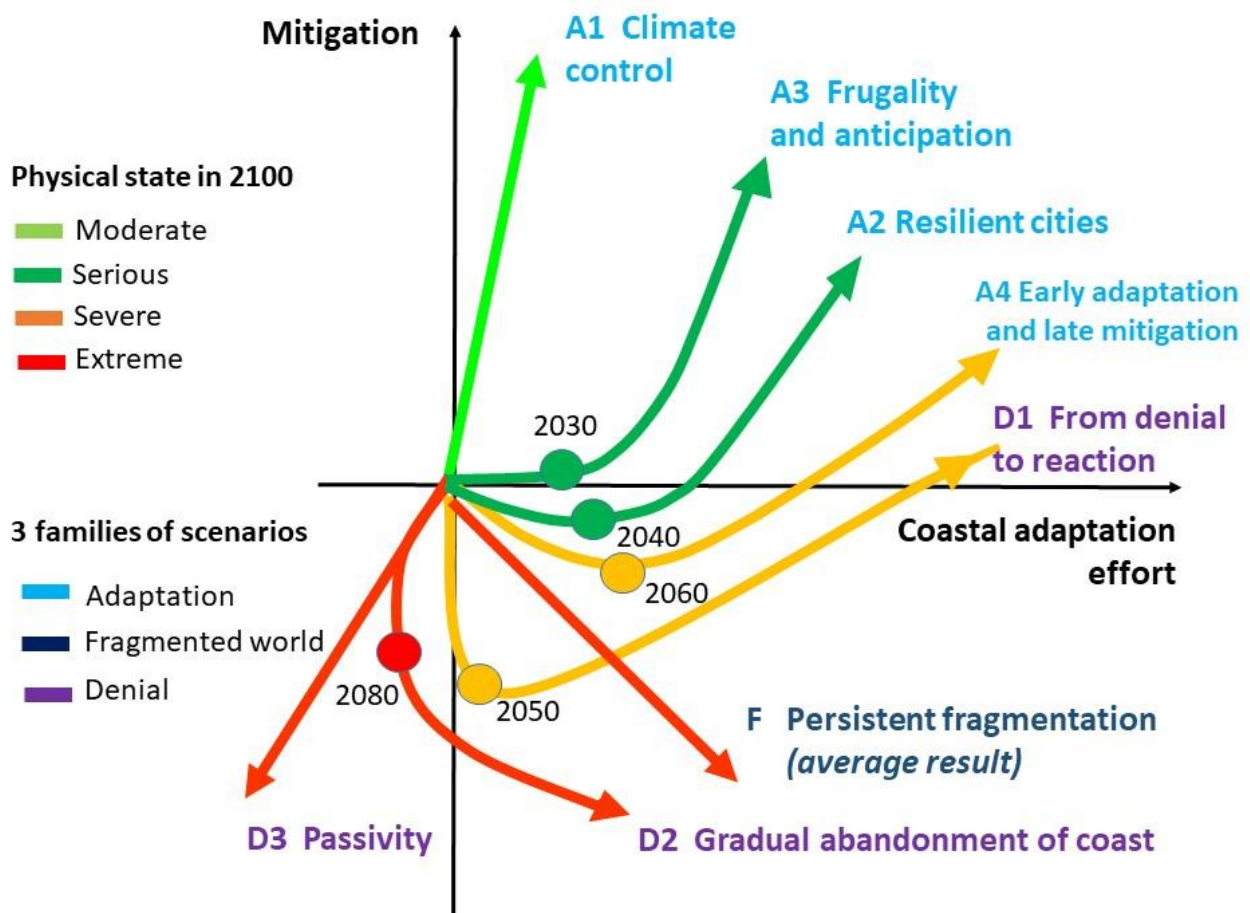


Figure 1 Eight scenarios clustered into three families

(Colours of the titles correspond to the 3 families of scenarios)

Colours of the arrows correspond to the different physical states in 2100.

The intersection of the two axis marks the level of efforts in mitigation and adaptation in 2020

Years indicate the beginning of a change in the climate policy at a world scale)

Scenario A1 - Climate control: as climate change is mitigated, the world coasts need to adapt to “moderate” sea-level rise (Table 1). Coastal adaptation strategies are limited to incremental measures based on the gradual transformation of coastal cities without calling into question the conventional urban development model. This scenario globally matches the goals of the Paris Agreement and the related efforts of the countries (strong mitigation). While extreme weather events occasionally have significant impacts on coastal areas that are more exposed to hazards (Nichols *et al.*, 2018), these hazards do not entail in significant population movements except in the most exposed areas. This scenario is the only one allowing to envisage a “moderate” physical state in 2100.

Scenario A2 - Resilient cities: Sea-level rise remains relatively limited due to international cooperation between metropolitan and state governments for the decarbonisation of economic

activities. But the reaction is a little late (2040) which implies likely a “serious” physical state in 2100. Coastal cities introduce protection through classical civil engineering or ecological engineering, improve modelling to anticipate risks of submersion, regulate groundwater extractions and therefore subsidence mechanisms, reinforce health and food security and strengthen the resilience of energy, communication and transport infrastructures in the face of extreme weather events. While areas with low population density, neglected by adaptation measures, are thus highly exposed to the risk of submersion (Nichols *et al.*, 2018).

Scenario A3 - Frugality and anticipation: The adoption of a culture of frugality in all areas of economic activity by 2030 leads to a reduction in greenhouse gas emissions and a limitation of global warming to 1.5-2°C, consistent with the Paris Agreement. The gradual implementation of coastal governance by adaptation to sea-level rise leads to the generalisation of withdrawal strategies when justified. Consequently, the urban development is restricted to long term safe areas and the quality of ecosystems remain globally stable with a shift of brackish water zones inland. Impacted populations accept relocation inland or to safe zones as the withdrawal had been prepared well in advance. This scenario has to consider a likely “serious” physical state in 2100.

Scenario A4 – Early adaptation and late mitigation: For the first 3 or 4 decades, little is done for climate mitigation while strong efforts are devoted to coastal adaptation. But faced with the intensity of the consequences of climate change after 2060, states implement vigorous coordinated mitigation policies in order to limit the global warming. However, the delayed response implies at least a “severe” GMSL rise so that while adaptation must remain up-to-date and embedded into the 22nd century. Each coastal region focuses on the specific adaptation of its coastline. This is achieved by controlling coastal urbanisation and population growth and anticipating the foreseeable retreat of the coastline through appropriate withdrawals. The quality of ecosystems is changing in several areas as priority is given to cities and urban activities.

‘Denial’ family

This family includes three scenarios in which there is a rejection of climate and environmental change policies at least until 2050. Their storylines are therefore broadly consistent to those of SSP-3 (“regional rivalry”) and SSP-5 (“fossil fuelled development”) in Riahi *et al.* (2017), with D1 moving to SSP-2 (“middle of the road”) after 2050. Gradually, however, under the higher frequency of catastrophic climatic events and a growing awareness among new generations and their taking of responsibilities, a will to act eventually emerges and influences policy. In this configuration, the physical state leads to GMSL rise ranging from “serious” to “extreme”.

Scenario D1 - From denial to reaction: Half a century of denial and lack of adaptation policies lead to increased vulnerability in the coastal zone. Due to the global denial of climate change and no significant measure to mitigate greenhouse gases emissions, the reality of climate change (including sea-level rise) and its consequences (including more frequent extreme events) eventually leads to a coherent global response. Awareness is then collective (decision makers, civil society and citizens) and the fight against the consequences of climate change becomes an absolute priority and is shared at all scales of action. Although late, climate change mitigation actions are ongoing and ambitious coastal adaptation policies develop around the globe. Only the most important cities and industrial areas are protected. Most of the ecosystems are degraded which accelerates the retreat of populations from the coastal areas to upper elevation zones. Thanks to the reaction, the physical state is only severe but not extreme.

Scenario D2 – Gradual abandonment of coast: The global denial of climate change remains the major position of numerous states and no significant measure against greenhouse gases emissions are taken before 2080. Then, the evidence of the excessive cost of the impacts of climate change, especially due to more frequent and devastating extreme events, become so obvious that elites

decide to change their policies. For financial reasons, decision-makers organise a systematic retreat of their goods towards the hinterland except for strategic cities or infrastructures such as ports. They leave the most vulnerable coastal fringes, where the poorest people continue to live because they remain overly dependent on local resources and access to land. At the end of the century, following the repetition of humanitarian disasters, minimum coastal adaptation efforts are made to prevent or limit mass migration inland. The physical state in 2100 cannot avoid to be extreme.

Scenario D3 - Passivity: Due to the lack of coordinated adaptation and mitigation policies, extreme climate events multiply, ecosystems are generally irreversibly degraded, the retreat of the coastline accelerates and migratory flows increase to mass levels as sea level and temperature rise (Missirian and Schlenker, 2017). The overall picture is catastrophic in every respect, with the ‘brutalisation’ of social relations and repeated environmental, economic and humanitarian crises. The physical state in 2100 is the worst of all: extreme.

‘Fragmented world’ family

This third family consists of a unique scenario that brings together a wide variety of configurations. This hybrid trajectory brings together different local, national and regional situations, even opposing ones in terms of adaptation and mitigation strategies. This scenario can be related to SSP-4 “inequality” (Riahi et al., 2017). This juxtaposition can be explained by dynamics that run at different velocities, according to the logic of ‘everyone for himself’. The result in terms of physical state is inevitably extreme.

Scenario F - Persistent fragmentation: This ongoing disconnection of national policies does not effectively mitigate climate change or slow the sea-level rise. On the long term, this results in “serious” to “extreme” sea-level rise scenarios. Obviously, the divergence of mitigation policies among the continents and countries on the same continent cannot be efficient as the relevant response to climate change is a highly coordinated world scale policy as described in the Paris Agreement (2015). It has to be said that this scenario is close to what had been observed for the recent years. The richest coastal regions are pursuing a policy of combatting sea-level rise and a gradual strategic withdrawal from the most vulnerable coastal areas. Conversely, in the absence of the anticipation of coastal changes, the poorest States, where coastal megacities are still developing, are becoming more vulnerable to rising sea levels. This dual logic continues and becomes accentuated during the century with many intermediate variants. At one end, developed countries give priority to adaptation. At the other, poorest countries react, as best they can and according to their available resources (financial, engineering etc.), but the effort is too late to be effective. This results in local mass migrations from the most vulnerable areas.

Table 2: Main components in the 8 scenarios on the coastal are evolution at the 2100 horizon

Component Scenario	Mitigation of climate change	Coastal adaptation effort	Coastal urban development	Quality of ecosystems	Population movement
A1 Climate control	Strong early world scale efforts	Incremental	Conventional model	Stable with some hazards	Without change
A2 Resilient cities	Efficient décarbonation limiting to +2°C	Multiple engineering technologies	Efforts of protection on cities	Protected by ecological engineering	Shift of only most exposed populations
A3 Frugality and anticipation	Efficient décarbonation limiting to +1,5°C	Withdrawal more used than protection	Only in long term safe areas	Good; a shift of brackish water zones	Shift of only most exposed populations
A4 Early adaptation & late mitigation	Efforts start after 2060	Strong efforts to coastal adaptation	Increasing efforts of control	Degradating as priority is given to cities	Shift with increasing anticipation
D1 From denial to reaction	Denial and no measure until 2050	Ambitious but late policies	Protection of main areas only	Decreasing	Shift of a number of cities
D2 Gradual abandonment of coast	Denial and no measure until 2080	Only for vital sites (harbours, main cities...)	Partial relocation of activities in the hinterland	Decreasing irreversibly	Important migrations to the hinterland
D3 Passivity	No effort justified by systematic denial	Important until inefficient	Global relocation of activities in the hinterland	Decreasing irreversibly	Mass and uncontrolled migrations
F Persistent fragmentation	A mosaic of policies remains inefficient	Diverse; no coordination	Mix of mega-cities & flood-prone slums	Decreasing irreversibly	Mass and uncontrolled migrations

Graphical representation of the scenarios

The trajectories of the 8 global scenarios are summarised in Figure 1, which combines climate change mitigation and coordinated efforts on a global scale on the vertical axis and the efforts made in coastal adaptation to sea-level rise on the horizontal axis. The centre of the graph represents the starting point in 2020 and the end of the arrow of each scenario marks the situation in 2100. Each trajectory (each arrow) therefore describes the level of mitigation and adaptation efforts implemented between 2020 and 2100. Inflection points in the trajectories represent changes in policies, when priority changes from adaptation to mitigation. On the vertical axis, the higher you go, the greater the overall mitigation efforts in the scenario under consideration. On the horizontal axis, the more one moves to the right, the greater the coastal adaptation efforts made. ‘Negative’ efforts have been considered: these correspond to adaptation actions that are weaker than those currently implemented, or even to a growing misadaptation of coastlines (Magnan *et al.*, 2016). Similarly, ‘negative’ mitigation has been considered. This corresponds to global policies with an absence or refusal of measures to reduce global warming and is therefore linked to increasing greenhouse gas emissions.

4 Discussion and research needs

Both state and local decision-makers want to have fairly precise sea-level rise projections and timeframes before taking adaptation measures, which could be radical and unpopular (Stammer *et al.*, 2019). Indeed, the major challenge is managing populations, goods and services in vulnerable coastal regions in the medium or even short term (Nicholls *et al.*, 2014; Neumann *et al.*, 2015; Hinkel *et al.*, 2019). It should also be noted that some coastal areas, such as large deltas like the Mekong, Yellow River and Nile, show much faster apparent increases due to continental subsidence, a phenomenon most often of anthropogenic origin (Syvitski *et al.*, 2009; Anthony *et al.*, 2015; Liu *et al.*, 2016). This subsidence rate is very often underestimated, as in the Mississippi (Keogh and Törnqvist, 2019) and the Mekong (Minderhoud *et al.*, 2019) deltas. The ratio between the subsidence rate and the sea level rise rate locally can be of the order of 10 (Minderhoud *et al.*, 2017), or even 100 (Higgins *et al.*, 2013). These phenomena are site-specific and complex as, in many cases, the subsidence is related to the main river flow and its watershed. But this watershed is shared by numerous countries, each of which have unique water demands. Accelerating subsidence in the deltaic zone can thus be caused by an increase in upstream water demand. For example, the subsidence in the Mekong delta in Vietnam depends greatly on the water policies in Laos, Cambodia, Thailand and China (Syvitski *et al.*, 2009; Minderhoud *et al.*, 2017). In the Nile delta, the supply of water depends on energy and agriculture (irrigation) policy of Ethiopia and Sudan exemplified by the current dispute over dam construction in Ethiopia (Yahia, 2013). These highly vulnerable regions may be considered ‘forerunner’ to other less vulnerable regions. Their study makes it possible to better anticipate what could be probable scenarios for other regions that will experience temporary and permanent inundation later on.

The utility of this study lies above all on the credibility and the plausibility of the scenarios suggested as well as on their ability to describe the range of possible futures. Can we objectively take one or more scenarios to help develop strategic plans for shoreline development or low-lying coastal areas? Are these scenarios robust enough to justify choices to protect or, conversely, abandon certain areas? How can we calculate the investments to be committed, and according to which schedule, to conserve a value under various forms of heritage (land, agricultural, real estate, industrial, cultural etc.)?

These questions are all the more difficult to address because the types of risk being considered correspond to the definition of ‘transcendent’ risks according to Beck *et al.* (1992). These are characterised by three elements: (1) poorly controlled spatialisation which leads to an unpredictable impact of phenomena on a global or large regional scale; (2) the difficulty of calculating economic, social and environmental costs; and (3) complete non-compensability, since the damage is partly irreversible.

Moreover, these developments require great political, economic and social efforts if we are to avoid increasing inequalities when faced with risk. The OECD report on the risks associated with marine submersion (OECD, 2019) shows that, if SLR remains in the order of 1 m, the economic consequences could be more or less managed at the same time, whether at the scale of the majority of the countries concerned, or even at a local level. However, in the case of more serious scenarios (from 1.3 to 2 m), the relevant response changes in spatial and temporal scales, notably in terms of anticipating phenomena, adapting infrastructure and coastal towns and organising the transition of the coastal economy.

Two scenarios can be considered as being at the limit of possible futures for coastal areas and very unlikely since they are so extreme. The most reassuring scenario, A1 (‘Climate control’), would require such a rapid and widespread reversal of strong current trends in global emissions of GHG that it seems almost utopic (Rockström *et al.*, 2017). However, such scenarios are useful to remind that there exist pathways to ensure the Earth’s climate stability and the sustainability of human societies. Similar to A1, scenario A3 (‘Frugality and anticipation’) leaves only 10 years before a paradigm shift is required on a global scale. This short timing constitutes a significant challenge for

the implementation of global climate policies: for example, while public concern on climate change is growing in democratic countries, the perception that climate is changing remains closely linked with people's own experience (Kaufmann *et al.*, 2016), with slow onset events such as sea-level rise being hardly perceivable yet in many locations. This diverse perception of the urgency of climate change ultimately questions the feasibility of public support to large social changes within such a short time window.

In contrast, scenario D3 ('Passivity') involves a persistent lack of reaction among most decision makers, despite the accumulation of disasters of all kinds, with the inertia of the system doing the rest. Again, the plausibility of such a 'dark' scenario is low as it is very unlikely that states and societies will remain unresponsive for 80 years despite the rapidly growing economic, social and human costs of climate change, reaching unprecedented levels through a lack of sufficient global action. But this scenario, close to that of persistent fragmentation, has the advantage of emphasising that state selfishness ('everyone for himself') would lead them to an almost guaranteed generalised catastrophe ('disaster for all').

In our view, the most plausible case is that of a political will to prioritise adaptation efforts in relation to mitigation efforts because the latter are more politically and financially demanding. Furthermore, adaptation is first at the local/national/regional levels, whereas mitigation requires a global effort. Indeed, this sequence is that of most scenarios: A2, A3, A4 and even D1. It is also the case in vulnerable countries such as the Netherlands (Haasnoot *et al.*, 2015) and Vietnam (Thao *et al.*, 2014; Bangalore *et al.*, 2017), and regions such as France's Nouvelle Aquitaine (Rocle and Salles, 2018; Le Treut, 2018). In this case, the awareness that 'technology cannot do everything' in face of sea level rise is the turning point in governance. It is then a question of working on two fronts: first, safeguarding what can be preserved in the long term, especially the cities that concentrate wealth and people (our scenario A2 'Resilient cities') and then the mitigation of climate change by tackling its causes. The earlier and more sustained this tipping point in governance is, the less likely the risk of deterioration in the overall situation in the future. But the critical determinant remains the degree of solidarity and concertation of State policies. Neither Vietnam, despite its ability to mobilise a large population, nor the Netherlands, despite the excellence of its technology, can save most of their deltas without mitigation efforts on a global scale.

Even though awareness of climate change and human responsibility has progressed over the past two decades in the minds of both decision-makers and populations, notably in OECD countries (Lee *et al.*, 2015), political and economic choices remain in a general trend of denial, in other words in the trajectories of scenarios D1 'From denial to reaction' and D2 'Gradual abandonment of coast'. Indeed, there is a considerable gap between awareness (knowledge) and action (active response to knowledge gained). However, there is a wealth of studies, information and strong signals such as successive IPCC reports, specialised scientific publications (Crutzen and Stoermer, 2000; Jamieson, 2005; Jouzel *et al.*, 2007), stakeholder conferences (COP) on climate and climatic hazards and also the experience of people (2003 heat wave, hurricane Katrina, etc.). The transition from fossil fuels to renewable energies is certainly under way, but not at a pace nor a global scale sufficient to avoid 'severe' or 'extreme' situations in 2100 (OECD, 2019). Again, in the trajectory until 2100, the later the policy change, the greater the risk of irreversible damage. Indeed, for the 'severe' and 'extreme' scenarios to become true, it has to be recalled that these scenarios require not only a RCP 8.5-like emission pathway, but also a high sensitivity of the Antarctic ice sheet to global warming.

It should be emphasised that, beyond any consideration of the plausibility of the scenarios, 5 out of the 8 lead to 'severe' or 'extreme' situations with a SLR of more than 1 m. Moreover, whatever the trend, it seems advantageous to prepare for a shift in paradigm as soon as possible and among the largest number of countries. This rationale is also valid for countries and regions sheltered from marine submersion. The environmental, economic and societal upheavals linked to global development and planning policies that are not very sensitive to their effects on climate will have a significant impact on them, albeit indirectly. This will take the forms of heat waves, reductions in agricultural productivity, the disappearance of terrestrial ecosystems, massive migrations of animal

and plant populations and species, both useful and harmful, and the migration of endangered human populations etc. (Stern, 2006; Leadley *et al.*, 2010; OECD, 2012).

Given this overview, can we identify the choices necessary to guide trajectories towards desirable situations in 2100 and the levers for change that can be used?

Although it is difficult to argue on an ‘average’ trajectory that is representative of all the world’s countries, the current global trajectory lies within the families of denial and/or fragmentation (GSDR, 2019). It is therefore essential to change the trajectory if we want to avoid ‘severe’ or ‘extreme’ situations. The inertia in the system, both physical and socio-economic, makes the speed of change and the radicality of mitigation policies keys to the transition to ‘moderate’ or ‘serious’ situations in 2100. In fact, Figure 1 shows that 2050 or 2060 are periods of change in which it would be too late to avoid ‘severe’ or ‘extreme’ situations.

This ‘shift’ in trajectory, in other words moving from the denial or fragmentation families to the adaptation would require major and rapid technological leaps (for example, the decarbonisation of the economy in favour of renewable energies, and carbon sequestration) accompanied by a high level of policy coordination and broad societal support. We are a long way from this. Public opinion, and the majority of decision-makers in the economic and political spheres, still think in terms of risks that can be managed over the medium term (OECD, 2012). We should rather be focusing on a systemic threat that requires short-term decisions to maintain a manageable long-term situation. The first key, therefore, is raising awareness of this threat as broadly as possible, calling for a collective and urgent response.

In this context, can research help accelerate this awareness, stimulate and mobilise actors for the necessary changes in policies and behaviour? In order to select the potential priorities for research, the expert group listed the research issues related to each scenario. These issues address various topics in the fields encompassed by the 23 drivers. For each research issue are specified the relevant spatial scale (e.g.: cities, coastal zones, world...), the expected impact of this research and the relevant partnerships such as with UN Commissions, NGOs, specialized agencies like IUCN, research bodies networks...). We identified four major research themes to prioritize moving forwards.

(1) Improve understanding, measurement and projections of the current phenomenon and its consequences. These are essential tools to objectify and to progress in the understanding of global phenomena, to predict and anticipate uncertain and non-linear phenomena and to warn about their potential impacts.

(2) Perceptions and social representations of the phenomenon by human societies (general public, companies, local, regional, national and international structures). This huge and dynamic mass of information of a diverse nature participates in the process of individual and collective reflexivity, awareness and ‘social construction’ of problems as solutions.

(3) Governance of local, regional and global situations in the short, medium and long term in both rural and urban areas. These political sciences influence the economy, urbanism, sociology, anthropology, geography etc. Here, the comparison of the costs of inaction and action could be useful and demonstrated (Stern, 2006). It requires further studies because it is vulnerable to many biases, both explicit and implicit, and also to the steady desire of countries to grow economically, whatever the price to be paid by the environment on the long term. Another field of research could be the identification of opportunities for co-benefits among climate, environmental and social policies, such as the development of a blue economy for nature-based solutions.

(4) Levers for action to support the necessary transitions, such as how to mobilize actors and raise awareness, abandonment of coastal zones, via the engineering sciences, economics, territorial management sciences and incentive tools in connection with political decisions (rules, standards,

subsidies, monitoring etc.), and application technologies (agronomy, hydrology, genetics etc.) to facilitate the adaptation of living organisms to environmental changes in the coastal region.

The linking of these four areas is necessary to build a systemic response to issues of such a magnitude, hence the importance of developing major lines of interdisciplinary research common to the majority of scenarios. Since there is no meta-discipline capable of integrating the mass of knowledge produced to solve such a problem at such scales of time and space, it seems necessary to maintain the principle of subsidiarity of issues by reasoning with the right tools at the right space scale. So, working at the scale of a complete watershed of a river is more relevant, and effective in the longer term, than adding up the national policies of the countries crossed by the river. This is even more justified when the river's delta has already been affected by subsidence. This implies to give research priority to assess water usages along the full length of a complete watershed and recommend cross-national policy to optimise the sustainability of the whole region.

This overview of research has to include also social sciences dealing with the relationship between all stakeholders (scientists, public authorities, social networks, education and training bodies...) and also experts, public and activists involved in global change debates.

Numerous actors are necessary for research of this magnitude. There is still a central role for 'professional' research structures (universities, institutes, foundations etc.) but all stakeholders must be involved in participatory research because they are all affected by the transformation of their environment (Georghiu and Cassingena Harper, 2011; OECD, 2019). Cities become major actors in reflection and analysis on the transformations to be introduced in adaptation and mitigation dynamics (LealFilho, 2020). Civil society, and especially younger generations, must also be involved in all aspects of research, development and innovation in order to renew a relationship of trust with the world of scientific research, via participatory sciences, for example (Rocle and Salles, 2018). They should also increase the awareness that lasting and equitable solutions can only be based on solidarity at all levels of human societies (Dangendorf, 2016).

Conclusion

The uncertainty associated with sea level rise remains high, and the heterogeneity of the evolution in shoreline development by site is large (Wong *et al.*, 2014; Duvat, 2019), which does not make decision-making easy (Havas *et al.*, 2010). In addition, resistance to change remains widespread and strong (Könölä *et al.*, 2011), raising the need for scenarios that help people's representations of the future and the impacts of current decisions, such as those developed in this paper. Additionally, the behavioural, societal, technological, economic and political changes required to reverse the trend in climate change have very high costs, when they are calculable. Indeed, as an example, the world scale shift from the carbon energy system (coal, oil and gas) to low carbon and renewable technologies will require huge investments. The increasing magnitude of mega-fires, heat waves, inundation and other extreme events in numerous regions is now known. These events now directly impact the agriculture sector, cities, ports, industrial infrastructures, ecosystemic services, etc... (Hanson *et al.*, 2011. Hallegate *et al.*, 2013; Leadley *et al.*, 2010, Neumann *et al.*, 2015). All these sectors will have to adapt to rapid changes, much more rapid than in the previous centuries.

The eight scenarios presented here show that if vigorous and sustainable climate change mitigation policies are not implemented consistently at all decision-making levels by 2040 at the latest, coastal adaptation efforts will have to consider 'severe' or 'extreme' situations by the end of the century. The IPCC and other independent research bodies show that the Earth system is not on a good trajectory in terms of risks of global warming, and there is little time to act if we want to avoid the most severe scenarios (IPCC, 2018; Oppenheimer *et al.*, 2019).

Early and major mitigation, which requires concerted global action, would limit the sea level rise and by extension reduce the coastal adaptation efforts required, which in turn are regional and local policies and actions. Measures to adapt to the risk of sea level rise, such as the construction of seawalls, upgrading of barrier beaches, the reinforcement of coastal and shoreline ecosystems (mangroves, coral reefs etc.), or strategic retreat, are to be designed according to the particular local coastal conditions (morphology, population, urbanisation, infrastructure and ecosystems) and local

risk culture (Hanson *et al.*, 2011; Hallegatte *et al.*, 2013; Magnan *et al.*, 2016). In all cases, acting jointly by anticipating sea level rise, the use of nature-based solutions and limiting climate change will reduce the costs of coastal adaptation and limit crises. These observations provide many avenues to structure research.

Of course, we have to acknowledge the limits of this foresight method: schematic trends and values for sea level rise in 2100, numerous assumptions which cannot be scientifically established (as they remain hypotheses), world-scale analysis when a more regional approach should be more relevant. But, beyond the warning of decision makers about the reasonable priority to be given to mitigation, these scenarios show that a change of conceptual framework is necessary in adaptation strategies, because of both the irreversibility of the current changes and the limits of the technological solutions available to combat them in the context of the acceleration of climate change.

The scenarios have an additional practical use as they offer to decision makers, and notably the politicians and experts in charge of research policies, a broad set of possible evolutions of the sea level rise and its consequences on the medium and long term. In all scenarios, interdisciplinary research needs to be improved involving all actors, from local networks of pro-active citizens to the United Nations, as there is only a minority of scenarios leading to “moderate” or “serious” manageable situations and all of them require steady, long-standing, world scale efforts. Therefore, there is a strong need for research to better understand, quantify and project the processes over time, assess their impacts, and convince decision-makers to anticipate necessary coastal transitions, and prepare in most cases to manage crisis situations.

This foresight study has shown a suite of scenarios combining outlooks on future development, mitigation, sea level response to climate change and coastal adaptation. Its utility lies in allowing decision makers to better understand the causal links leading to more or less vulnerable coastlines. Regular revision of these scenarios through synthesis of observation and models would allow them to remain prescient in the future.

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Acknowledgments and composition of the working group

AllEnvi, French National Alliance for Environmental Research, brings together the strength of 28 public research partners in order to programme and coordinate the country's environmental scientific strategy. To inform its choice of research priorities, AllEnvi has a multidisciplinary foresight group (known by its French name, GT Prospective) made up of representatives from member organizations. In February 2017, AllEnvi asked GT Prospective to conduct the study ‘Rising sea levels: consequences and expectations through to 2100, shedding light with foresight’.

The authors thank AllEnvi for funding the resources necessary for nine workshops and the mission to the Netherlands. In the Netherlands, they thank the French Embassy and experts from Rijkswaterstaat and Deltares for their availability. They also thank INRA for providing a project manager, Audrey Bethinger, for the duration of the study.

The authors' recognition also goes to all the experts who contributed to this study, notably the two documentalists who carried out the bibliographical research (M.H. Pépin at Météo France and M. Le Gall at Ifremer) and those who participated in workshops, interviews and study tour: M. Bernardot (Univ. Le Havre), X. Bertin (Univ. La Rochelle), J.P. Billaud (Univ. Paris-Nanterre), F. Carnus (BRL Ingénierie), A. Cattaneo (Ifremer), A. Cazenave (CNES), J. Chardon (Min. Défense), M. Devès (IPGP/AFPCN), C. Didier (Ineris), N. Dörfliger (BRGM), A.M. Duval (Cerema), F. Gemenne (Sciences Po), S. Guedon (Ifsttar), C. Hérivaux (BRGM), C. Jolly (OCDE), M. Lafaye (CNES), M. Largemain (Min. Défense), J. Lobry (Irstea), A. Magnan (IDDRI), M. Meerpoel (ICL), B. Meyssignac (LEGOS), R. Nichols (Univ. Southampton), J.L. Oliver (Acad. Outre-mer, de l'eau), S. Penet (FFA), S. Petitet (Cerema), J. Rougerie (Institut de France), A. de Rouw (IRD) and J.L. Valantin (consultant).

Supplementary material 1; further information on the method

The work was based on nine one-day workshops bringing together a multidisciplinary group of about 30 experts from the organisations cited for the authors and in the acknowledgements above. These workshops ran from June 2107 through to the final workshop on research questions in November 2018.

This foresight study follows one of the scenario methods, based on a morphological analysis of the system. This method, well adapted to the complexity of the question posed, is broken down into eight steps:

1. Precise formulation of the question and definition of the temporal and spatial horizon
2. Bibliographical research and analysis ('state of the art' on the issue)
3. Identification of the 'coastal system' and its driving variables and grouping of components
4. Retrospective analysis of the variables and development of projection assumptions at the horizon set
5. Construction of the morphological table, bringing together the assumptions for each of the variables
6. Development of scenarios
7. Writing of stories for each scenario
8. Analysis of the issues and consequences of the scenarios, especially for research

Numerous bibliographic sources were consulted: Web of Science, Scopus, EDS - Ebsco, Europresse, Scholar, Revues.org, OpenEdition, UN, FAO, World Bank and European Union websites. Key words searched concerned aspects directly related to sea level rise (climate, storms, coastal erosion, salinisation etc.) and also its geopolitical, economic and social aspects (demography, urbanism, agriculture, migrations).

Firstly, 414 scientific articles were identified that discussed the phenomenon of the rise in sea level and its consequences. These were summarised and pooled for collective work. Over the course of the study, 30 more articles were exploited. These documents helped to feed the choice of assumptions for variables within the six components of the 'coastal system': Population, Urban planning and Infrastructure, Environment and natural resources, Agriculture and food, Coastal economics and Coastal governance. We must also add a seventh component which gives the global geopolitical and economic context (see Table 3).

Table 3: Assumptions for evolutions in the variables within components (morphological table)

Component	Variable	Assumption 1
Population	P1- Share of population exposed	Gradual withdrawal (from coastal areas)
	P2 - Internal and international migration	Staggered departures as water gradually rises
	P3 - Degree of health vulnerability of populations	Access to infrastructure limits health vulnerability of populations
Urbanism and infrastructure	U1 - Urban dynamics	Coastal megacities and strong coastal urbanisation
	U2 - Infrastructure resilience level	High vulnerability
	U3 - Adaptation of exposed coastal areas	Resisting rising sea levels
Environment and natural resources	EN1 - State of freshwater resources (quantity and quality)	Controlled resource exploitation and use
	EN2 - Soil state (salinisation, erosion etc.)	Reduced salinisation and pollution
	EN3 - Dynamics of coastal and shore ecosystems (habitats, biodiversity)	Translation and/or modification without alteration of ecosystem functions
	EN4 - Modification of coastline	Moderate erosion and marginal retreat
Agriculture and food	AA1 - Availability of agricultural land	Agricultural land reduced by more than half in coastal area
	AA2 - Agricultural production systems	Adaptation of species cultivated and agricultural practices
	AA3 - Importance of aquaculture and fishing	Supplies maintained through sustainable fishing and aquaculture
	AA4 - Food security	Reduction in economic access to agricultural products
Coastal economy	EC1 - Coastal economy	Multiplication in ways of adding value
	EC2 - Solidarity and sharing (for adaptation and crisis management)	Brutalisation of social relations without negotiable solutions
Coastal governance	G1 - Awareness of coastal risks (rulers and society)	Gradual appropriation of SLR issues
	G2 - Reactivity and degree of commitment (proactivity, acceptability, education)	Passivity without involvement
	G3 - Level of coordination and sharing - local and global scales	High and global
Global context	C1 - Overall economic growth	Planned shrinking economy
	C2 - Energy mix (fossil fuel dependence and internal trade)	Synergies between all actors for the decarbonation of economy
	C3 - Awareness of climate issues at the global scale (leaders and society)	Appropriation of climate change issues
	C4 - Global geopolitical governance	Generalised chaos
	Physical context of the rise in sea levels in 2100	MODERATE +0.5m; slow rise; EXE +

Assumption 2	Assumption 3	Assumption 4	Assumption 5
Share in coastal zone remains stable (despite growing world population)	Gradual increase in population (in coastal zone)	Strong demographic growth combined with migrations within/towards coastal megacities	
Evacuations accelerating, some major cities affected	Repeated crises causing mass exoduses		
Coastal areas are sectors of high health vulnerability	Unfettered development of coastal megacities further increases health vulnerability		
Fragmentation of cities and urban dispersion - strong coastal urbanisation	Weak coastal urbanisation and coastal towns in network with hinterland		
Average vulnerability	Controlled vulnerability (resilience)		
Live with elevation, gradual adaptation (incremental change)	Organised withdrawal, transformational change	Absence of strategy	
Progressive degradation, alteration of ecological functions	Transfer of external water resources to coastal area		
Moderate salinisation and pollution	High levels of salinisation, pollution and soil sealing		
In situ adaptation/modification, alteration of ecosystem functions	Disappearance of ecosystems		
Predictable significant local withdrawal	Unpredictable localised withdrawal	Significant generalised withdrawal	
Effective protection of agricultural land	Disappearance of agricultural land in coastal area		
Crops replaced by livestock	Synergies between agricultural and aquaculture systems		
Reduction in fishing volumes; little or no aquaculture	Increase in volumes, above all from strong and diversified aquaculture		
Disturbance or occasional ruptures in access	Reduction in food diversity	Food access secured by diversifying sources of supply	
Forced and anarchic strategic withdrawal	Planned strategic withdrawal and recovery via hinterland	Floating economy, 'offshorisation'	Displaced economy, location of distant land
Solidarity at all levels	Gradation into 2 extremes: cartel of the rich, solidarity among the poor	'Everyone for themselves' reduced by redistribution and humanitarian approach	Insurance financing and judicialisation
Persistent denial	Outward awareness	Growing rifts between rulers and societies and between themselves	
Minimal involvement	Strong reactivity and gradual mobilisation of stakeholders	Early proactivity and involvement of all actors	
Non-existent, everyone for themselves!	Targeted, networked coastal towns	Multinational companies, GAFAM takes the lead	Regional, communities with common destinies and hardships at the regional scale
Dual growth (rich vs poor)	Stop & go growth (crises)	Inflicted shrinking economy, chaos	
Fragmentation of energy production and consumption	Energy chaos, priority given to national energy security	Priority given to energy autonomy (priority given to local sources)	
Denial	Outward awareness	Rifts	
Fragmentation, stability in mosaics in a turbulent multipolar world	Generalisation of cybernetic order based on AI	Domination by 2 superpowers	Multi-centre interdependence and solidarity
SERIOUS +0.5m; fast rise EXE+	SEVERE +1m; fast rise EXE++	EXTREME +2m; fast rise EXE++	

Table 4: Selection of assumptions for each variable and for each scenario

See separate table N°4