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THE MEDITERRANEAN SYSTEM: A HOTSPOT FOR CLIMATE CHANGE AND ADAPTATION

Adaptation to sea level rise in France

Gonéri Le Cozannet[1] · **Anny Cazenave**[2]

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Abstract

Sea level rise due to climate change is an ongoing process that will continue for centuries and millennia. In response to this, France is increasingly considering sea level rise in its coastal risks and land use policies. Here, we show that despite real progress in coastal adaptation policies made so far, major challenges remain. We report progress regarding the consideration of ongoing erosion and flooding during storms, in particular owing to an evolving national regulation increasingly supporting the implementation of a nationally defined integrated coastal zones management strategy. Yet, chronic flooding at high-tides in ports and cities expected to emerge in the 2030s, as well as permanent flooding and shoreline retreat projected to take place within centuries without major protection works remain largely unaddressed to date. Major questions remain in terms of adaptation finance and other measures supporting coastal adaptation such as climate services. Finally, the topic of coastal adaptation lacks connections with the broader context of transformations needed to address climate change, biodiversity losses, and meet the sustainable development goals. The case of France exemplifies how an evolving adaptation planning, which takes decades to implement, can ultimately fall short of effectively addressing major transformational challenges and achieving climate resilient development. We argue that a clear and transparent public debate on climate change and the nature of solutions could help bridge the gap between ongoing adaptation and transformative measures in line with the challenges.

Keywords Sea-level rise · Coastal adaptation · France

1 Introduction

Sea level is one of the best indicators of current climate change (IPCC 2019; Cazenave and Moreira 2022). This is so because sea level variations result from changes in the different compartments of the Earth's climate system in response to internal climate variability, as well as natural and anthropogenic forcing factors. These responses include ocean warming, melting of land ice, and changes in water storage in continental river basins. Sea level rise is also a major threat posed by current global warming. Being a slow but long-term process, sea level will continue to rise over the coming centuries at rates that will depend on future greenhouse gas emissions and will negatively impact populations living in the world coastal zones as well as infrastructures and coastal ecosystems (Oppenheimer et al. 2019).

During the twentieth century, tide gauges were the only tools allowing direct observations of sea level variations. Tide gauges measure the relative variations of sea level with respect to the crust; thus, vertical movements of the crust are also recorded by tide gauges. Although, coverage of in situ measurements is limited to continental coasts and islands, tide gauge records are highly valuable for estimating the evolution of the mean sea level over the past decades. The most recent studies indicate that between 1900 and 1990, sea level rose by about 15 cm on average (Dangendorf et al. 2017; Palmer et al. 2021). Since the early 1990s, climate-related sea level variations are routinely measured at global and regional scales by a constellation of high-precision

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✉ Gonéri Le Cozannet
G.LeCozannet@brgm.fr

Anny Cazenave
anny.cazenave@univ-tlse3.fr; anny.cazenave@gmail.com

1 Bureau de Recherches Géologiques et Minières, Orléans, France

2 Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Toulouse, France

altimeter satellites, such as Topex/Poseidon and its successors, the Jason series (Escudier et al. 2018). Unlike tide gauges that also record crustal motions (Woppelmann and Marcos 2016), satellite altimetry only measures absolute sea level variations.

Over the period January 1993–December 2023, the altimetry-based global mean sea level has risen on average at a rate of 3.4 ± 0.3 mm per year (Fig. 1). This corresponds to an average elevation of about 15 cm over the last 30 years. What is most striking is the marked acceleration of the phenomenon. Between 1993 and 2002, sea level rise was around 2 mm per year. Since 2013, the rate of rise now approaches 5 mm per year.

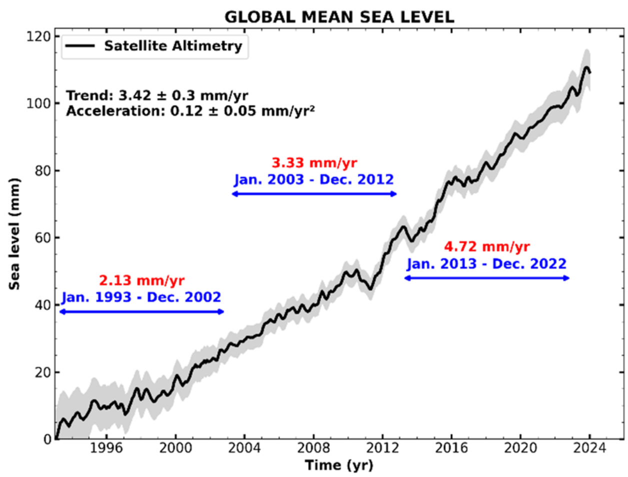


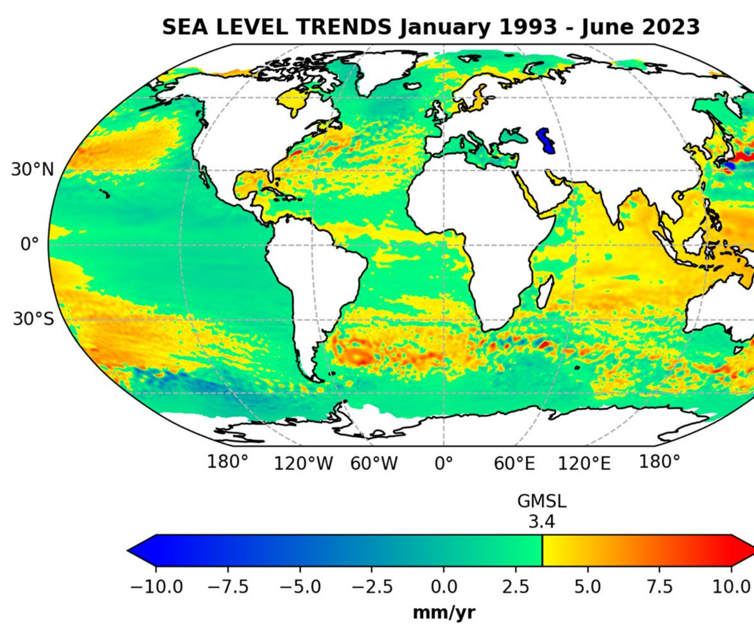
Fig. 1 Satellite altimetry-based global mean sea level evolution between January 1993 and December 2023 Source: LEGOS; updated from Cazenave and Moreira 2022

Owing to their global coverage of the oceanic domain, satellite observations also show that sea level rise is not uniform. In some regions, sea level rates can be 2–3 times faster than the global mean (Fig. 2).

The two main causes of present-day global mean sea level rise are ocean warming via thermal expansion of seawater, and melting of continental ice (glaciers, Greenland and Antarctica), in response to anthropogenic greenhouse gas emissions. We now have at our disposal different observing systems allowing us to quantify these different contributions (e.g., Dieng et al. 2017, Nerem et al. 2018, WCRP 2018, Horwath et al. 2022). The international Argo network of about 4000 automatic floats provides ocean temperature and salinity measurements down to 2000 m depth, with near global coverage (Riser et al. 2016). In addition, the GRACE space gravimetry mission launched in 2002 measures mass changes in the Earth system, including the loss of ice mass of Greenland and Antarctica (Landerer et al. 2020). Other space techniques such as radar interferometry and radar and laser altimetry are also used to estimate ice mass losses from the polar ice sheets. Comparing the observed global mean sea level with the sum of ocean thermal expansion and land ice loss shows good agreement (e.g., Horwath et al. 2022; Barnoud et al. 2023). Thus, the global mean sea level budget is almost closed over the altimetry era within the data uncertainties.

At regional basin scale, the observed spatial trend patterns in sea level mostly result from a result of non-uniform ocean heat storage (Stammer et al. 2013; Hamlington et al. 2020; Cazenave and Moreira 2022). However, in smaller seas, other factors contribute, e.g., changes in salinity. This is the case in the Arctic Ocean and in the Mediterranean Sea (see Fig. 3 showing the satellite altimetry-based spatial

Fig. 2 Regional sea level trends from satellite altimetry over January 1993 to June 2023. The global mean sea level (GMSL) trend of 3.4 mm/year over the period is indicated on the *color bar* (transition from *green to yellow*). Source: Copernicus Climate Service (https://climate.copernicus.eu) and LEGOS



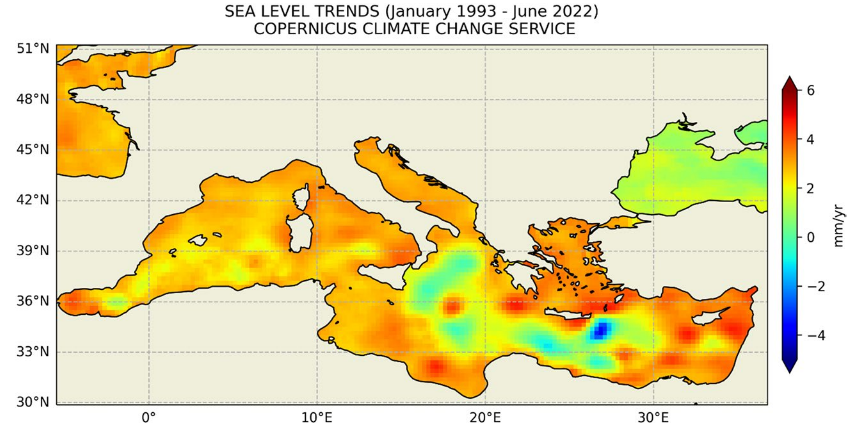


Fig. 3 Regional sea level trends between 1993 and June 2022 in the Mediterranean Sea from satellite altimetry Source: LEGOS

trend patterns in sea level in the Mediterranean Sea) and the Glacial Isostatic Adjustment, e.g., in Norther Europe and North America (Spada 2017).

Most recent climate simulations project a global mean sea level elevation up to +1 m by 2100 (compared to the early 2000s) in a scenario of high greenhouse gas emissions (IPCC 2019, 2021), and possibly much higher (between 1.5 and 2 m) in case of runaway melting of Greenland and west Antarctica ice sheets (IPCC 2021).

While still modest, present-day sea level rise has already significant effects on some low-lying coastal regions (in particular during extreme events, since the higher the sea level, the more likely it is that waves and water levels exceed coastal defenses). Yet, an increasing number of early impacts of sea level rise such as high-tide flooding in ports is reported worldwide (IPCC 2021). Clearly a ten times higher sea level elevation projected by the end of this century will impact many coastlines worldwide. Moreover, at the coast, sea level results from the superposition of the global mean rise, large-scale regional changes, and small-scale coastal processes (e.g., shelf currents, small-scale eddies, sea water density changes in river deltas and estuaries), with the regional and local factors possibly amplifying the global mean rise. How to adapt to such a still poorly quantified but inescapable threat is a complex problem faced by many countries which have important maritime facades.

2 Adaptation to sea level rise

2.1 Options to adapt to sea level rise

Different options have been proposed to adapt to sea level rise (IPCC 2019). We briefly summarize them below (on the basis of the synthesis made by Oppenheimer et al. (2019) and Bongarts et al. (2021)).

In coastal areas developing rapidly, avoiding to build new infrastructure in areas exposed to flooding and erosion reduces future lock-ins. This approach is sometimes called "***avoidance***" (Cooley et al. 2022).

For existing infrastructure, responses to sea level rise can be classified as follows (IPCC 2022): (1) engineering protection, (2) soft protection, (3) accommodation (4) ecosystem-based adaptation, and (5) retreat.

Engineering protection consists of building coastal defenses such as dikes, seawalls, and estuarine barriers to prevent from flooding, salinization, and shoreline erosion. This strategy has been developed in Europe (e.g., in the Netherlands, United Kingdom, Venice) and in many Asian countries such as South Korea or Japan (Oppenheimer et al. 2019). Engineering protection can also result in land reclamation such as in Singapore or the Maldives, resulting in advances seaward (Van der Pol et al. 2023). However, engineering protection has several drawbacks. It is costly and it is not always well accepted by coastal societies where coastal defenses prevent from accessing to the seashores. Besides, seawalls and dikes may degrade coastal ecosystems through habitat loss, and may favor intrusion of non-native invasive species (Cooper et al. 2016; Nourisson et al. 2018; Orton et al. 2023). For this reason, the summary for policymakers of the last IPCC report presents hard defenses against flooding as a case of severe maladaptation from the perspective of ecosystems (IPCC 2022). From the perspective of ensuring people's safety, this option is obviously efficient and widely implemented (Pranzini et al. 2015). The challenge here is to find a balance between the need to protect infrastructure and people while leaving space for sediments and coastal ecosystems, upon which many coastal communities depend on (Cooley et al. 2022).

Soft protection is subject to growing interest worldwide because it produces less negative impacts than hard protection (Oppenheimer et al. 2019). It often consists of sand-based nourishment of beaches and dunes. This practice is receiving increased interest in several coastal areas, e.g., in the Netherlands with the Sand Engine, a mega-nourishment project (Luijendijk et al. 2017). It points out, however, the problem of sand availability in some regions and potential decrease of coastal ecosystem services depending on how sand nourishment is performed. Furthermore impacts on ecosystems can be sizeable depending on how nourishment is performed (Cooley et al. 2022).

Accommodation is another strategy whose objective is to adapt existing infrastructures to climate change and natural hazards (Oppenheimer et al. 2019). These include interventions at the level of buildings to reduce damages in case of flooding (e.g., elevated electrical devices or waterproof doors) or to improve urban drainage or innovations such as floating housing in sheltered waters. An important benefit of accommodation is the low cost of measures compared to protection and relocation, yet the approach is less effective and reaches its limits in areas exposed to waves or high water levels (Creach et al. 2020; Bednar-Friedl et al. 2022).

Ecosystem-based adaptation includes the restauration of salt marshes, mangroves and coral reefs where available, leaving Posidonia dead-leaves on beaches to reduce erosion (Telesca et al. 2015), or to reduce peak water levels during a storm as seawaters spill into wetlands (Oppenheimer et al. 2019). While limited in efficiency for high rates of sea level rise, this approach is generally considered as very positive as it provides multiple benefits to coastal species while reducing coastal erosion and flooding (Bednar-Friedl et al. 2022). This option is often used in combination with protection, retreat or accommodation.

Finally, ***retreat*** consists of relocation of populations and infrastructures (Oppenheimer et al. 2019). For island populations, this may involve moving to new countries, although the potential for internal relocation is real even in atoll islands (Duvat et al. 2022). Relocation clearly poses a broad range of social, cultural psychological, and economic issues. It is deployed differently around the world, the largest project so far being the relocation of the capital of Indonesia from Java to Borneo due to a range of environmental and political issues, including sea level rise and subsidence and was also implemented in Southern France in the 2010s along a 10 km sandspit (Rocle et al. 2021). While difficult to implement today due to a range of operational and social constraints, this option should receive more attention in the future as sea levels will continue to rise (Cooley et al. 2022).

A first step to develop a coastal adaptation strategy can consist in assessing how these different options are implemented already (Fig. 4). For example, Europe is characterized by a longer history of engineering coastal protection than other regions. This has consequences for the adaptation strategies that can be deployed.

2.2 Defining objectives of coastal adaptation and identifying co-benefits and trade-offs

At the scale of decades to centuries, the lower efficiency of accommodation means that coastal adaptation practitioners will need to choose between protection and relocation. This dilemma is often not explicitly stated, because few stakeholders consider time horizons beyond 2100 or the possibility of rapid collapse of the Antarctic ice-sheet (Cooley et al. 2022). This may result in lock-ins such as the development of low-lying areas that are complex or too costly to protect. Furthermore, adaptation measure take time, sometimes decades, to be implemented (Cooley et al. 2022). Hence, there is a risk that the implementation comes too late to prevent damages from high-tide flooding or storm surges. Finally, coastal zones, as any other place in the world, need to do much more than just adapting to sea level rise: they need to achieve sustainable development goals, including those related to biodiversity and mitigation of climate change. Thus, rather than just adapting, the challenge that coastal stakeholders will have to face is to implement climate resilient development in coastal areas (Philippenko and Le Cozannet 2023).

On the long term (decades to century), the benefits of implementing climate resilient development in coastal zones is obvious: it contributes to managing sea level rise, reduces the loss of coastal sedimentary and ecological system services such as those offered by wetlands and beaches (Toimil et al. 2023), and it avoids reaching limits to adaptation.

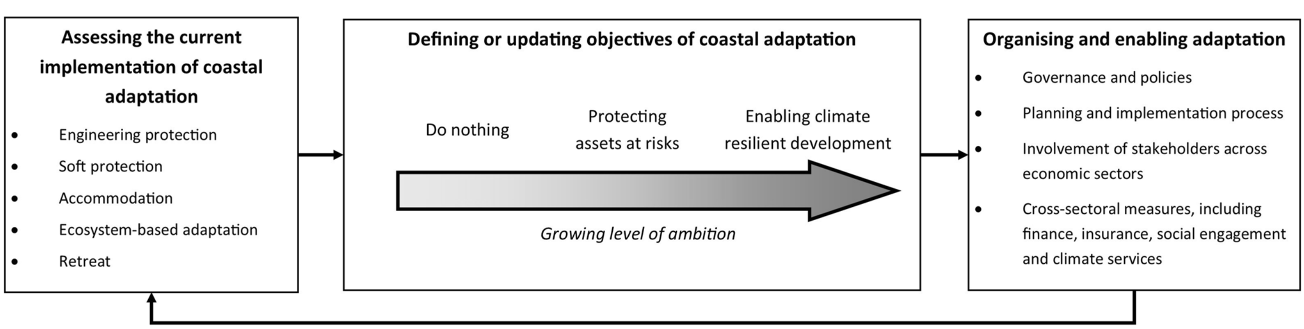


Fig. 4 Building coastal adaptation requires being clear about the current status, the objectives of adaptation and considering all dimensions of adaptation, including its implementation and governance (Based on Oppenheimer et al. 2019; IPCC 2022; Cabana et al. 2023)

Yet, implementing climate resilience now also comes with immediate benefits: while implementing coastal adaptation options, there is an opportunity to restore coastal ecosystems. Nature-based solutions can be typically created while implementing relocation, because this option creates space that is available for coastal ecosystems such as wetlands. However, even while implementing coastal protection, there are also opportunities to create habitats, for example by creating and integrating habitats in and around coastal infrastructures (Temmerman et al. 2013; Schoonees et al. 2019).

Breaking current development trends and implementing coastal resilient development is obviously a challenge that requires careful attention to the transitions. The latest IPCC report (IPCC 2022) identifies three actions that can make responses to climate change more efficient in coastal areas: anticipation and planning, alinement with sociocultural values and economic development, and engagement with coastal communities. On top of that, the IPCC reminds also the need to define clear goals and priorities to enable climate resilient development. Applied to coastal areas, this means deciding where coasts will be protected whatever future sea level rise and adaptation costs, and where softer approaches to coastal management, including relocation and nature-based solutions, can be implemented.

2.3 Organizing and enabling adaptation

Once goals are clear, it must be recognized that adaptation and resilient development are not only an engineering and ecological problem (Cabana et al. 2023). On the contrary involves social and economic dimensions that need to be characterized to assess the credibility of adaptation and climate resilient development. Several perspectives can be taken to characterize and monitor ongoing adaptation, including:

- The policy process setting the governance of adaptation to sea level rise: this involves participatory development of responses (e.g., Loizidou et al. 2023), regulations and decisions across scales, from multi-national to local scales.
- The iterative planning process consisting in assessing risks, assessing options, implementing responses, and evaluating the outcomes (Bednar-Friedl et al. 2022).
- The sectoral aspects of coastal adaptation in sectors such as urban and land management, agriculture, fisheries and aquaculture, tourism, health and maritime transport.
- The cross-sectoral measures supporting coastal adaptation, including adaptation finance, insurance, social engagement and climate services (IPCC 2022).

Assessing the status of the different dimensions of coastal adaptation shown in Fig. 4 is one way to assess the status of current coastal adaptation. In the coming section, we proceed to such an assessment in France.

3 The case of France

In this section, we assess how France is responding to sea level rise (see a map of mainland France in Fig. 5). Such an assessment is not straightforward, because coastal adaptation is an evolving process that involves multiple actors. Here, we proceeded by reviewing policy documents, most often written in French, and therefore hardly accessible to an international audience.

3.1 Adaptation options: the slow emergence of relocation and ecosystem-based coastal management

The French ministry of Environment reports that the French shoreline is about 20 000 km long (including oversees regions and territories), of which 22% is eroding (https://www.ecologie.gouv.fr/adaptation-des-territoires-aux-evolutions-du-littoral). As the population density at the coast is 2.5 times larger than the national average, this can affect a large number of people directly or indirectly. For example, up to 50,000 houses representing 8 billion Euros are exposed to shoreline retreat according to a national assessment (Cerema 2019).

Coastal management in France has been largely dominated by engineering-based adaptation over the last 70 years (Planton et al. 2015). The last major marine flooding event in mainland France (the Xynthia storm in 2010) also resulted in new investments in coastal defenses. However, environmental considerations and costs are motivating new approaches such as relocation and ecosystem-based management.

While France is still largely implementing engineering coastal protection, some concrete actions show that other approaches are at least being experimented. In 2012, the Ministry in charge of Environment launched an experiment to consider relocation in several coastal locations covering a wide range of coastal contexts: cliffs in Guadeloupe and Northern France, high- and low-energy beaches along the Mediterranean and South-West Atlantic coasts, including in areas that are already protected with coastal engineering infrastructures (MEDDE 2014). While relocation is still considered cautiously, it ultimately became the only viable option in some cases, such as the emblematic Signal Building in Southwestern France, an area where waves and currents cause a rapid retreat of sandy shorelines (Vandenhove et al. 2024). Yet this example raised social, legal, and economic issues, in particular regarding compensations to households who are losing their apartments. Another example of relocation is the road located on the sandspit between

Fig. 5 Map of mainland France showing areas located below the highest astronomical tides today. These areas are not flooded due to natural and man-made protections. Data: IGN (Lidar topography), SHOM (sea level at highest astronomical tides), Openstreet map, BRGM interactive viewer available at https://sealevelrise.brgm.fr/slr/

Sète and Marseillan in the Southern Mediterranean France (Rocle et al. 2021). Relocation is also considered for the village of Miquelon (St Pierre and Miquelon territory), which is highly exposed to flooding and where some inhabitants prefer to invest in higher locations that will remain unaffected by sea level rise over decades, rather than in a low-lying flood plain that might be too costly to protect within decades (Philippenko et al. 2021).

Regarding ecosystem-based adaptation, an important experiment is developing under the impulsion and leadership of the French Coastal Conservation Agency. This agency has the strategic objective to own coastal land to prevent its urbanization and preserve natural coasts. In ten coastal sites, the Conservation Agency is experimenting ecosystem-based approaches, consisting, for example, in removing the 1st rank of coastal defenses, building new defenses inland, thus saving land and restoring natural processes in wetlands (https://www.lifeadapto.eu/) (see e.g., Louisor et al. 2022). These experiments could promote a larger implementation of nature-based solutions and, to some extent, relocation, in coastal areas of France because the Conservation Agency is interacting with many stakeholders (e.g., elected representatives, communities at risks, farmers).

To summarize, there are some signs that France is trying to move away from a strategy mostly based on coastal protection. This objective to promote softer approaches is relatively clearly stated in the national strategy for integrated coastal zones management (MEEM 2017) and the recent law on climate and resilience adopted in 2021 provides legal instruments to support relocation and dynamic land use planning in areas exposed to shoreline changes (MTE 2021a). However, this national objective has generally taken the form of experiments at local scales, suggesting that stakeholders are still in the process of legitimizing relocation as a coastal adaptation strategy (Rocle et al. 2021) and that there is a disconnection between the national objectives and coastal development on the ground (Mineo-Kleiner et al. 2021). Assessing the potential for going beyond experiments requires examining the other aspects of coastal adaptation, beyond measures affecting the coastal environment. The next section examines how the governance of coastal adaptation has evolved in France over the last 25 years.

3.2 Consideration of sea level rise in coastal adaptation governance in France

The area in which France has made the most progress in terms of coastal adaptation to sea level rise is land use planning. This is supported by two distinct processes: the ongoing adaptation planning stimulated by climate change, and the regulations and strategies focused on coastal areas (Fig. 5).

For more than a decade, France has established a national adaptation plan to climate change to implement concrete actions for adapting by 2050 the French territories (including overseas territories) to regional impacts caused by the changing climate. Two versions of the plan have been published so far (CGEDD 2015; MTES 2015). A 3rd version is currently in preparation. The plan addresses various impacts of climate change, including fires, water availability, and resources, decrease of land and marine biodiversity and shoreline erosion and retreat. It proposes strategies to increase economic resilience in response to the changing environment.

The plan includes the consideration of sea level rise scenario of 60 cm by 2100 for coastal risk prevention plans, which turned into a legal decree in 2011 (MEDDTL 2011) (Fig. 6). In addition, the decree requires to consider 20 cm of

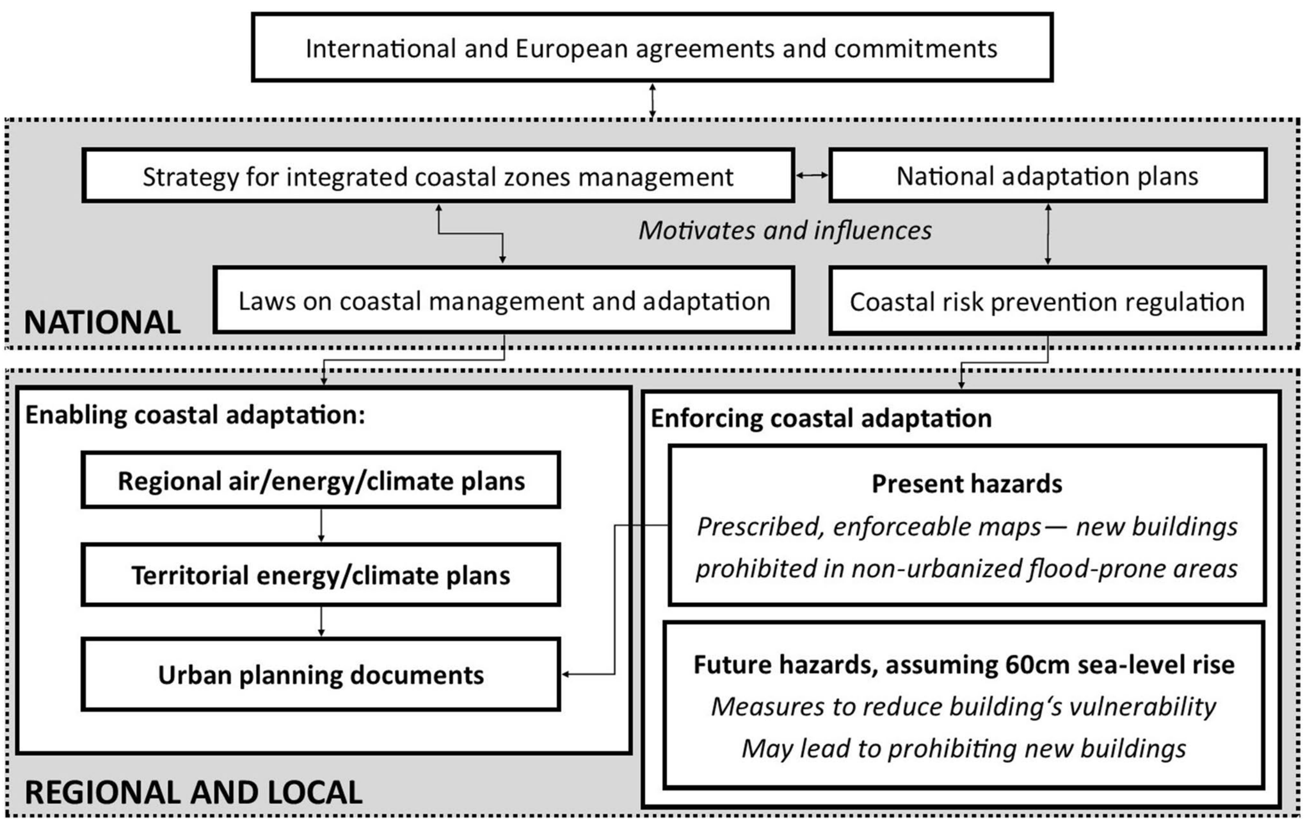


Fig. 6 Simplified coastal adaptation framework in France (based on Deboudt 2010; DGPR 2014; MTES 2015)

sea level rise in all hazard maps as a first step toward taking climate change into account. The reference sea levels are not precisely defined in the decree establishing these scenarios, but they refer to the 4th assessment report of the IPCC which provide projections relative to the period 1980–1999. This approach is resulting in hazard maps limiting further urbanizations in low-lying coastal areas, and therefore supports the avoidance strategy (Deboudt 2010; see Sect. 2.1).

Within this framework, coastal risks include coastal flooding during storms, shoreline erosion, and aeolian dune migration now and in 2100, assuming 60 cm sea level rise. The progressive rise of sea levels and the times of emergence of processes like chronic flooding at high tides are not specifically considered within this regulation. Similarly, sea level rise impacts beyond 2100 and above 60 cm are not considered within this policy. New national climate scenarios have been announced by the national government in 2023. This should result in updated national sea level scenarios.

In parallel to these enforceable plans, France is giving tools and support to its local to regional authorities to promote adaptation, in particular through regional and local land use planning tools and the strategy for integrated coastal management that considers coastal impacts of sea level and extreme events, shoreline evolution, and many other coastal management issues (MEEM 2017). The French national strategy for shoreline management is promoting a softer approach to coastal management. It puts forward: (1) anticipation of long-term changes, (2) integration of coastal ecosystems in the adopted solutions, (3) improved knowledge of ecosystem services and of the perspectives of their evolution, (4) dedicated adaptation plans depending on the territories, (5) simultaneous consideration of socio-economic challenges and environmental impacts of shoreline retreat. This strategy is supported by an evolving regulation. For example, regional and local plans addressing climate and environmental challenges can include an adaptation section. Yet, these plans generally do not operationalize adaptation well, and they often lack credible connections with other policies relevant to adaptation (MTE 2021b). For example, the regional plan of the Pays de La Loire region includes objectives on coastal research, on communication and on incentives to encourage softer coastal zones management, but no precise objective that embraces the challenge of the centuries of sea level rise to come (SRADDET Pays-de-la-Loire, 2022). The 2021 law on resilience and climate has delivered legal tools to support softer approaches toward coastal management (MTE 2021a).

The binding coastal risks prevention plans can be a cause of social conflicts (Perherin et al. 2017; Perherin 2017). Making certain areas unbuildable clashes with the development objectives of local authorities, whose stakeholders sometimes seek to limit the application of these plans or challenge certain assumptions. On the other hand, the non-binding adaptation plans have not resulted in remarkable conflicts so far, but, as shown above, their objectives are generally vague on the topic of coastal adaptation. In some cases, relocation experiments have been interrupted (case of the city of Hyères located along the Mediterranean coast) or some stakeholders such as farmers have expressed strong reservations about relocation experiments (case of the Brouage wetland on the Atlantic coast; as reported in the newspaper Le Monde in April 2023 https://www.lemonde.fr/planete/article/2023/04/09/combattre-la-mer-ou-la-laisser-envahir-le-territoire-face-a-la-montee-des-eaux-le-dilemme-de-la-charente-maritime_6168838_3244.html). However, the severity of these social conflicts is much lower than those caused by the implementation of coastal risk prevention plans (Perherin et al. 2017), which in some cases led to national government ministers to intervene (case of the Dol wetland, on the English Channel coast in 2014).

3.3 Other dimensions of adaptation

Figure 7 presents our assessment of the current status of adaptation to sea level rise in France. It is based on a literature review (mostly the grey literature) and our experience as scientists in coastal adaptation science and practice. Importantly, this assessment is limited to sea level rise and does not consider the other dimensions of coastal adaptation to other biophysical changes such as eutrophication, acidification, heatwaves, droughts or heavy rains. Figure 6 shows that the main dimension of coastal adaptation to sea level rise in France concerns land use, as shown in the previous sections. However, there is margin to progress in this area by considering multiple possibilities depending on the actual stakeholder's decision context (Hinkel et al. 2019).

Figure 7 recognizes that the policy process has been improved in the last 20 years, but it also highlights that the present-day practice entails the risk that once present-day regulation is applied, stakeholders consider that the problem of sea level rise has been resolved. For example, using the 60 cm sea level scenario in the design of infrastructures or hazards maps enables to comply with the regulation, without addressing the issue of infrastructures and land use planning management when sea levels have risen above this threshold. While efficient in ensuring that sea level rise is considered (Lioubimtseva and Da Cunha 2020), the French enforceable regulation seems also to contribute shifting the debate from strategic visions and decisions to technical debates on the application of the regulation (Perherin and Meur-Ferec 2022). This may contribute making the narrative on coastal adaptation to sea level rise in France unclear.

Planning, implementation, and monitoring display progress too, as shown for example by projects such as the relocation on the sandy Lido from Sètes to Marseillan. However, methods most widely used in countries such as the

Dimensions of coastal adaptation	Consideration of sea-level rise	At national level	At regional to local level
Policy process		Nationally-defined scenarios apply, but these scenarios do not reflect the entire range of potential needs presented e.g. in Hinkel et al. (2019) and are mostly focused on the mid-century and 2100. New scenarios will be published in 2024.	Regions and localities can adjust nationally defined sea-level scenarios, to take into account e.g. local subsidence or their own needs. Some localities and sectors refer to sea-level scenarios of 1m in 2100. Longer term issues are considered in a few cases only (e.g., Coastal Conservation agency).
Planning, implementation and monitoring.		Limited promotion of state-of-the-art methods to plan adaptation (e.g., adaptation pathways, framework, feasibility/effectiveness approach as in IPCC, 2022). Implementation is limited by financial and social constraints. Lack of authoritative criteria to identify mal-adaptative outcomes. The national adaptation plan has been evaluated, the high climate council plans to evaluate adaptation more precisely in its 2024 report	Technical considerations dominate over discussions on the objectives of coastal risk prevention plans; options are assessed locally; limited evidence that state of the art methods to plan adaptation are used; the alignment with the national strategy for integrated coastal management, which promotes nature based solutions, is often unclear. Some successful relocations and renaturation projects have been implemented (e.g. sandy Lido in Sète; Coastal Conservation Agency projects), but many remain experimental and small in scale.
Sectoral aspects		The main sectoral focus at national level is on housing and land use. Other sectors are starting to be considered at national level such as coastal waste management, tourism and the potential relocation of coastal campsites and the adaptation of coastal transport infrastructures. There is limited evidence that sectors such as agriculture, fisheries, health are considering adaptation to sea-level rise. New nuclear plants are announced in several coastal locations without consideration of high-end and committed sea-level changes.	The sectoral aspects can vary a lot depending on each location, but in general the main sectoral focus at local and regional level is housing as well. Concerns are starting to emerge on chronic flooding in ports and low-lying areas, especially in oversees territories.
Cross-sectoral aspects		Sea-level rise is receiving increasing attention in the area of emergency management and insurance; Estimates of adaptation needs suggest that national adaptation funding is not yet up to the challenge; the national climate service DRIAS includes a demonstrator on sea-level rise; the elaboration of national climate plans and laws include consultation with stakeholders.	The lack of funding and the unequal treatment of various shoreline retreat mechanisms is identified as a major cross-sectoral issue at local to regional level; lack of engagement with coastal communities at risk to explain the rationale for adaptation to sea-level rise; coastal observatories deliver information, but they are unequally funded and their ambition vary a lot depending on the regional and local context.

Fig. 7 Consideration of sea level rise across various dimensions of coastal adaptation in France (Building upon Magnan et al. (2022) (Method), and Suanez et al. (2012), DGPR (2014), CGEDD (2015), MEEM (2017), Perherin et al. (2017), Perherin and Meur-Ferec (2022), Louisor et al. (2022), I4CE (2022), HCC (2023), Cour des Comptes (2023) and other references in section 3 (Content)

Netherlands or Great Britain such as adaptation pathways are very little used. Similarly, few assessments of adaptation measures are available. Yet, state agencies such as the Ademe, the French agency for ecological transition, have provided methods to support adaptation. This suggests that the expertise is available but that the efforts and time dedicated to adaptation design and planning are not sufficient today (I4CE 2022).

Regarding sectoral aspects, a particularly important point is the limited consideration of chronic flooding, especially in ports. This contrasts with the IPCC reports (IPCC 2022), which identifies chronic flooding as a most urgent adaptation challenge in coastal area. Yet, major infrastructure is exposed to chronic flooding at high tide, for example in Guadeloupe (Le Cozannet et al. 2021). The 2023 report of the "Haut Conseil pour le Climat" (HCC, a body set up by the French government) mentions chronic flooding, which is encouraging (HCC 2023). In the energy sector, the recent decision to announce new nuclear plants in coastal areas was not preceded by any consideration of high-end or committed sea level rise, which is surprising given that nuclear plants are a critical long-living energy infrastructure that is often cited in the scientific literature on high ends (Stammer et al. 2019).

Cross-sectoral dimensions of adaptation are clearly lagging behind. A major problem that is identified is on financing coastal adaptation. In this area, local and regional authorities request clarifications to the national government both in terms of amounts invested in adaptation and fair treatment of the different hazards. Specifically, unlike sandy shoreline erosion, cliffs erosion is eligible to public investments for relocation and for the national reinsurance mechanism. In practice, this creates conflict situations that lead to a national measure to compensate a particular building and circumventing this classification. Announcements have been made to resolve this issue in a 2025 law. Another request related to finance is the creation of a national fund to finance relocation. Depending on estimates, this fund may require between 50 and 150 Million Euros per year to anticipate the costs of private houses relocation. Other cross-sectoral issues are also obvious, such as the role and ambition of a national climate service for coastal adaptation to sea level rise, which would require funding as well (I4CE 2022).

The evaluation shown in Fig. 7 suggests that the 1st condition of success of coastal adaptation identified in the summary for policymakers of the 6th Assessment Report of IPCC to align coastal adaptation with development priorities and sociocultural values is not met. In fact, current development priorities at local scales are often not consistent with the objectives of mitigation, adaptation, and the preservation of biodiversity, which are promoted at national level to some extent (MEEM 2017). For example, urban sprawl in the Mediterranean coastal zone is slowing down, but still continuing despite scientific evidences that land artificialization needs to be reduce to prevent flood risks and limit biodiversity losses (Robert et al 2019). This suggest that there is not yet a clear vision of climate resilient development in coastal areas in French coastal zones.

To sum up, considering adaptation in its various dimensions as in Fig. 7 leads us to conclude that, although progress is being made, coastal adaptation in France still has a long way to go and has some difficult cases to discuss and resolve. Even more worryingly, adaptation to rising sea levels is only part of the challenge ahead: at the same time, a set of consistent measures to adapt to all the impacts of climate change, to decarbonize activities, and to limit the loss of biodiversity should be put in place to progress toward sustainable development goals. This includes transformative measures in the area of urbanism (e.g., greening cities), transport (favor public transport, cycling and walking), agriculture (support to agroecological principles), and water (fair demand-oriented measures) as set out in IPCC (2022), which are not clearly set out today in development priorities.

4 Discussion and conclusion

The above review shows that despite real progress, coastal adaptation in France is still facing important issues, as summarized below:

– Adaptation problems are posed by chronic flooding, which are starting to emerge now, and those related to sea level rise beyond 2100 or above 1m.
– Difficulties arise in adopting adaptation planning tools that have demonstrated useful in other countries such as adaptation pathways.
– The coastal adaptation policy has a strong focus on housing, with less attention to other factors
– Significant delays exist to set up enablers of adaptation such as finance mechanisms, climate services, and social engagement.
– There is significant disconnection between the national ambition to leave space for ecosystems and sediments set out in the national integrated coastal management strategy and its application on the ground, where protection is often demanded.
– As already raised by Perherin and Meur-Ferec (2022), the regulation in place on sea level rise has the advantage of guaranteeing a minimum consideration to sea level rise, but this also shifts the political debate on the future of coastal zones to technical discussions on the implementation of the regulation.

We have identified cases that correspond to the definition of maladaptation, as set out in IPCC (2022), such as the lack of consideration of committed and high-end sea level rise for coastal infrastructure planning, especially new nuclear plants. This is part of a larger problem identified by the think-tank I4CE (2022), which reports that at least 50 billion Euros of investment in France every year are potentially vulnerable to climate change, but do not consider adaptation convincingly. Coastal adaptation to sea level rise entails high risks of maladaptation. These risks stem from the impacts of coastal protection to ecosystems, to the long-term commitments to sea level rise, as well as due to the high costs of coastal adaptation, which may divert financial resources away from other critical adaptation needs such as health, urbanism, water or agriculture. Given this substantial risk, it could be interesting to consider conditioning national coastal adaptation funding to the credibility of other adaptation, mitigation, and biodiversity protection measures implemented by regional and local authorities. Such a holistic approach could help better integrate coastal adaptation within a more resilient and sustainable response to the multifaceted challenges posed by climate change and biodiversity losses.

As many other countries in the world, France is just beginning to be affected by an unprecedented event in the human history: the onset of climate-induced sea level rise and associated coastal changes. This will drastically reshape coastal areas that are densely used already, but it is yet unclear how. Will dikes, seawalls, and barriers dominate the response or will we leave space for sediments and ecosystems and preserve some coastal landscapes? As noted in the latest IPCC report (IPCC 2022), the governance supporting coastal adaptation requires decades to be put in place. This is illustrated above for France, which is developing this governance and implementing some experiments to explore the possibilities to escape from a response dominated by engineering solutions. Yet, the time available to discuss and plan adaptation is shrinking as adaptation requires time to be implemented, while at the same time, sea level rise is accelerating. In this context, we argue that there is a need for a transparent public debate explaining options to deal with sea level rise over the coming decades, with associated economic, social, and environmental impacts and co-benefits.

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Declarations

Conflict of interest Gonéri Le Cozannet has been interacting with a number of elected representatives from all parties except far-right populists over the last 5 years, to contribute, within his modest means, to improving adaptation policies in France. Some of these parties are supporting the adaptation policies above, others are criticizing them or request changes.

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