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PERSPECTIVE

Adaptation to multi-meter sea-level rise should start now

Gonéri Le Cozannet[1,*], Robert J Nicholls[2], Gael Durand[3], Aimée B A Slangen[4], Daniel Lincke[5] and Anne Chapuis[6]

1 BRGM, Risk and Prevention Division, Coastal Risks and Climate Change Unit, 3 Avenue Claude Guillemin, Orléans 45000, France
2 Tyndall Centre for Climate Change Research, University of East Anglia, Norwich NR4 7TJ, United Kingdom
3 University Grenoble Alpes, CNRS, IRD, Grenoble INP, IGE, 38000 Grenoble, France
4 NIOZ Royal Netherlands Institute for Sea Research, Department of Estuarine and Delta Systems, Yerseke, The Netherlands
5 Global Climate Forum, Neue Promenade 6, 10178 Berlin, Germany
6 University Grenoble Alpes, CNRS, INRAE, IRD, Grenoble INP, IGE, 38000 Grenoble, France
* Author to whom any correspondence should be addressed.

E-mail: g.lecozannet@brgm.fr

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1. Introduction

Sea-level rise will fundamentally change coastal zones worldwide (Cooley *et al* 2022). A global two meters rise of sea level will be exceeded sooner or later within a time window ranging from one century to as long as two millennia, depending on future greenhouse gas emissions and polar ice-sheet melting (Fox-Kemper *et al* 2021). Here, we show that in addition to climate mitigation to slow this rise, adaptation to two meters of sea-level rise should start now. This involves changing our mindset to define a strategic vision for these threatened coastal areas and identify realistic pathways to achieve this vision. This can reduce damages, losses, and lock-ins in the future, identify problems before they become critical and exploit opportunities if they emerge. To meet this challenge, it is essential that coastal adaptation becomes core to coastal development, especially for long-lived critical infrastructure. Coastal adaptation will be an ongoing process for many decades and centuries, requiring the support of climate services, which make the links between science, policy and adaptation practice.

2. When will sea-level rise exceed two meters?

Observations show that global sea levels have already risen by 0.20 $\pm$ 0.05 m between 1901 and 2018. Global mean sea-level rise has accelerated from 1.3 $\pm$ 0.7 mm yr^{-1} between 1901 and 1971 to 3.7 $\pm$ 0.5 mm yr^{-1} between 2006 and 2018 (Fox-Kemper *et al* 2021). Global mean sea-level rise is a consequence of human-induced climate change: greenhouse gases emitted into the atmosphere since the 19th century are causing an accumulation of heat in the Earth system, which in turn causes ocean warming and thermal expansion, as well as the melting of land-based ice-sheets and glaciers.

Unlike other adverse impacts of climate change such as mean and extreme temperature increase and precipitation changes, sea levels will not stop rising when mean global climate temperature is stabilized (IPCC 2021). On the contrary, sea levels will continue to rise for centuries to millennia (Clark *et al* 2016, Mengel *et al* 2018). The latest IPCC report assessed estimates are that if climate change stabilizes at 1.5 °C globally, global mean sea level rise will exceed 2 m over the next two millennia, and even 6 m over the next ten millennia (Fox-Kemper *et al* 2021). Furthermore, paleo-evidence shows that during the last interglacial, 116 000–129 000 years ago, sea levels were 5–10 m (likely range) higher than today while global mean temperatures where 0.5 °C–1.5 °C higher than in the preindustrial period. Finally, stabilizing global climate change below 1.5 °C is becoming increasingly unrealistic due to the slow implementation of climate policies and solutions (Matthews and Wynes 2022). All this evidence shows that even under very optimistic assumptions, 2 m of sea-level rise is almost inevitable and only the timing is uncertain.

Two meters of sea-level rise can be exceeded much earlier with higher emissions: the probability of this event reaches 17% soon after 2200 for an intermediate greenhouse gas emissions scenario (SSP2-4.5) (figure 1). For higher greenhouse gas emissions, this could occur during the second half of the 22nd century, and even by 2120 if the Antarctic ice-sheet starts to collapse, a low-likelihood event that cannot be excluded over those timescales according to the latest

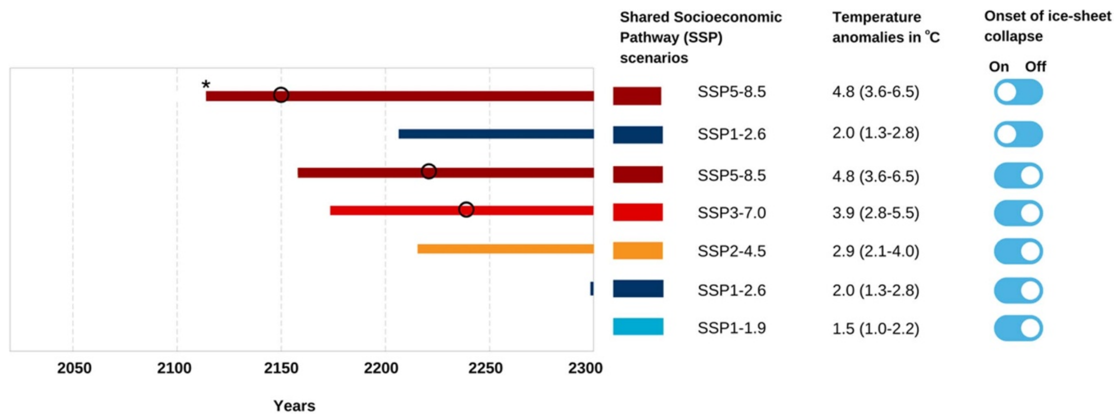

Figure 1. Year by which a rise of 2 m of sea-level rise above the 1995–2014 average is projected to be exceeded depending on the different shared socioeconomic pathways (SSP) and on physical processes included in ice-sheet melting models (data from Fox-Kemper *et al* 2021; based on Le Cozannet *et al* 2022). Bars represent the 17th-83rd percentiles, circles represent median values and the asterisk * marks an early date by which the probability of exceeding a 2 m sea-level rise exceeds 17%, assuming SSP5-8.5 and processes in which there is a low confidence (see figure 2 for regional implications, IPCC 2021 for the terminology on uncertainties and Kopp *et al* 2023 for details about sea-level rise uncertainties and ambiguity in the 6th Assessment Report of the IPCC). The mean surface air temperature anomalies are given for 2081–2100 relative to 1850–1900: average and very likely range (data from IPCC 2021). Adapted with permission from Le Cozannet *et al* (2022).

IPCC (Intergovernmental Panel on Climate Change) report (Fox-Kemper *et al* 2021). High greenhouse gas emissions such as SSP5-8.5 are considered less likely today due to current climate policies and the ongoing deployment of options such as renewable energy production (Hausfather and Peters 2020). Yet, global mean temperatures of 4 °C above the preindustrial mean in 2100 cannot be excluded, for example in case of reversal of current mitigation trends, or for high values of the climate sensitivity (Kemp *et al* 2022).

Sea levels are not rising uniformly, but coastal managers should not expect this regional variability to postpone the occurrence of a 2 m rise in sea levels significantly. Figure 2 shows that for very high greenhouse gas emissions and an early onset of ice-sheets collapse, 2 m of sea-level rise would be exceeded between 2100 and 2130 for the vast majority of inhabited coastal zones. In areas affected by land subsidence such as susceptible cities overexploiting groundwater in Asia, two meters of relative sea-level rise can be exceeded during the 21st century with large human impacts and adaptation needs (Nicholls *et al* 2021b). In fact, relative sea-level rise already exceeded 2 m in parts of cities such as Tokyo and Jakarta during the 20th century due to ground subsidence (Cao *et al* 2021).

Two meters of sea-level rise will reshape coastal areas worldwide. According to the literature published so far, the most visible and urgent impacts of sea-level rise today are higher and more frequent water levels at high tides and during storms, resulting in enhanced chronic flooding and risks of coastal defenses being overtopped and salinization of wetlands (Oppenheimer *et al* 2019, Cooley *et al* 2022). Two meters of sea-level rise will enhance erosion and cause permanent flooding of unprotected low-lying areas that are critical for human development and unique ecosystems. For example, 1.2 billion people and 114 trillion US dollars of assets are currently located in the 100 year global coastal flood plain, that is, areas with a 1% annual chance of flooding (Values based on Lincke *et al* 2022). These values increase by 250% for 2 m of sea-level rise. Furthermore, risks grow faster than exposure: in Europe, current projections suggest that coastal flood losses will increase by orders of magnitude by the end of the 21st century assuming no adaptation (Vousdoukas *et al* 2020). Finally, indirect costs of coastal disasters can propagate across sectors and regions and result in even more economic losses (Mandel *et al* 2021). Such quantified assessments, while uncertain, give an indication of the scale of the problem if adaptation needs are ignored.

3. How might we respond?

The previous section shows that the commitment for 2 m of sea-level rise is now well established. This section examines the implications for coastal management and provides recommendations on mitigation and adaptation responses. To address this challenge, we urge all actors to greatly reinforce climate change mitigation efforts to avoid exceeding global warming levels agreed in Paris in 2015. This will postpone the exceedance of a two-meter sea-level rise farther into the future and bring multiple co-benefits such as reducing other climate risks and enabling the achievement of the Sustainable Development Goals (IPCC 2022). Because the potential for ice-sheet collapse remains poorly understood and debated, we also recommend to sustain and strengthen monitoring for early warning signs of such collapse and to prepare a response that can be implemented quickly if this collapse is initiated (Haasnoot *et al* 2020).

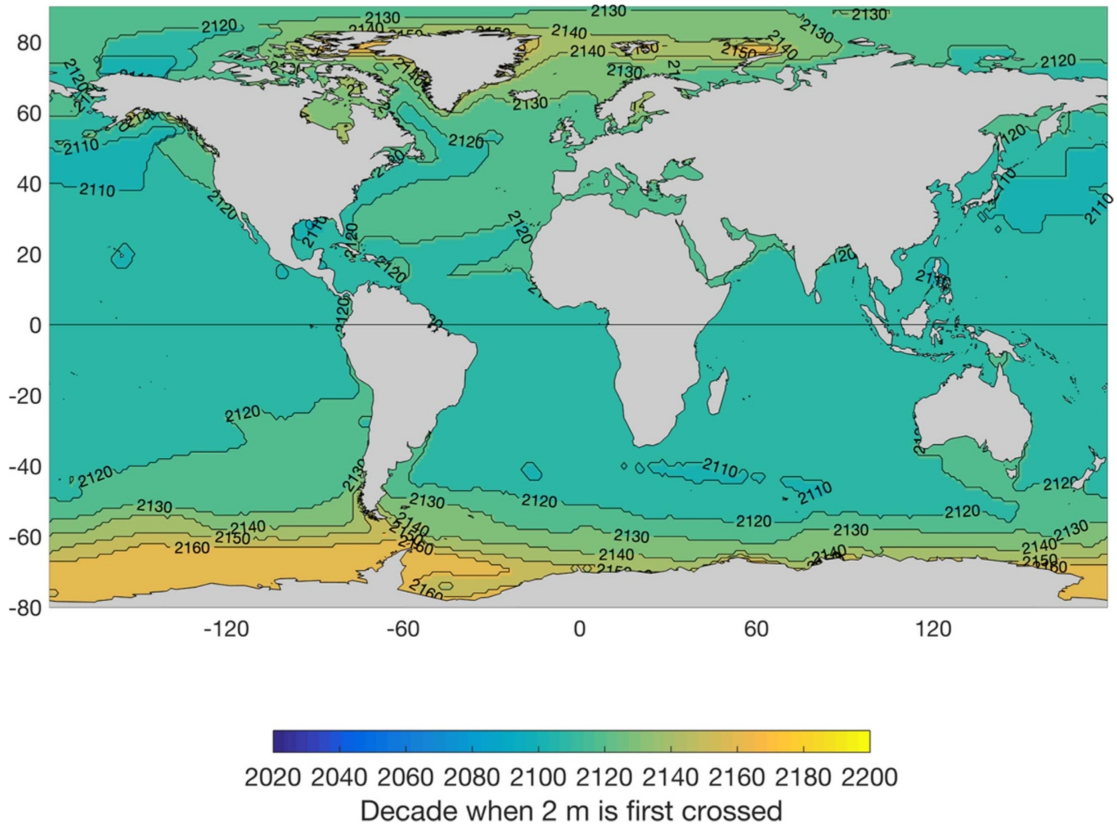

Figure 2. Early potential occurrence of a 2 m rise of regional sea-level rise assuming very high greenhouse gas emissions (SSP5-8.5) and the onset of ice-sheet collapse (data from Fox-Kemper *et al* 2021). The color scale represents the first year of the decade in which a 2 m relative sea-level rise is exceeded in different regions around the globe, based on the 17th percentile of SSP5-8.5 projections (see asterisk * in figure 1). Local subsidence may cause an earlier exceedance in some cities and deltas. Adapted with permission from Le Cozannet *et al* (2022).

Lastly, we recommend that all coastal zones stakeholders acknowledge the commitment for adaptation, the need to consider all options, including the potential for relocation, and think and act strategically to avoid large damages, losses and lock-ins in the future and exploit opportunities if they emerge (Haasnoot *et al* 2021a).

Two meters of sea-level rise may seem a too distant future for many stakeholders. Yet, some critical infrastructure already built or is being considered now in low-lying coastal and estuarine zones will still exist in one or two centuries, and the expanding footprint of coastal development must also be considered. This includes ports, coastal cities and their defenses such as surge barriers, industrial infrastructure and nuclear power plants and spent fuel facilities. Unique cultural heritage assets are at risk from sea-level rise (Marzeion and Levermann 2014, Reimann *et al* 2018), including Venice, which started developing as a marine empire and cultural center one millennium ago! Coastal landfills and contaminated soils are numerous in coastal areas and threaten pollution of estuarine or coastal waters if flooded or released (Nicholls *et al* 2021a). Finally, the conservation of coastal habitats such as wetlands and intertidal biotas will require space for migration inland, which conservation authorities need to consider (Cooley *et al* 2022). Decisions taken now are creating a legacy for future generations when they will be confronted by two meters of sea-level rise and more.

Some coastal stakeholders are already considering two meters of sea-level rise in their coastal land use planning decisions. For example, the United Kingdom has explicitly provided low-likelihood/high impact sea-level rise scenarios, which are considered by relevant stakeholders such as those managing London's coastal defenses, including the Thames Barrier (Ranger *et al* 2013). This is supporting an adaptive management approach where stakeholders engaged in adaptation will be able to adjust the timing of their plans if observations show that changes are happening faster (or slower) than expected, including constructing a new downstream surge barrier. Coastal stakeholders in other countries can learn from emerging applications and adjust them to their local context.

There are benefits for coastal adaptation practitioners who identify risks from multiple meters of sea-level rise and initiate adaptation responses today. First, some coastal adaptation actions require decades to plan and implement (Cooley *et al* 2022). Thinking well in advance limits the risk of reactive

Figure 3. Typical actions to initiate adaptation responses to 2 m of sea-level rise. Actions displayed with a warning sign require specific attention for a potential early occurrence of this event, e.g. due to rapid coastal subsidence (locally) or ice-sheet collapse (globally). Adapted with permission from Le Cozannet *et al* (2022).

or unmanaged responses. Second, coastal zones are projected to continue to undergo rapid development in the next few decades, especially in Asia and Africa (Neumann *et al* 2015, Haasnoot *et al* 2021b). This offers an opportunity to develop resilient coastal areas directly. In other words, considering that two meters of sea-level rise will be exceeded sooner or later while developing land and cities can increase the options open to future generations. Third, many coastal ecosystems are degraded today: habitats such as corals reefs, beaches, dunes, wetlands, estuaries habitats are being lost due to coastal development, unsustainable ecosystems exploitation, warming coastal waters, pollution and eutrophication, as well as invasive species (IPBES 2019). Defining a long-term vision for coastal areas offers an opportunity to better manage these ecosystems. Fourth, the remaining carbon budget is limited and the demand for many raw materials is growing rapidly (OCDE 2019). Building resilient infrastructure and creating resilient coastal zones now avoids a legacy of coastal transformations that may be more difficult to implement with increasing challenges to exploit mineral resources such as sand suitable for construction and nourishment (Torres *et al* 2021).

Many adaptation actions can be started today (figure 3). The ground can be prepared by raising awareness, strengthening governance and engaging with communities, scientists and science communicators to increase climate literacy. Risks from two meters of sea-level rise can be assessed now, especially for long-living, high-value or critical infrastructure and ecosystems. Adaptation options can be identified and their financial and socio-cultural feasibility, effectiveness, co-benefits and limits assessed. Adaptation implementation can focus on measures with high social, economic and environmental co-benefits, taking advantage of opportunities, whether this involves new development or the maintenance or improvement of existing solutions (Oppenheimer *et al* 2019). Such opportunities emerge when coastal communities are considering land-use or development projects compliant with adaptation challenges (IPCC 2022). Strategic assessment will allow identifying where the status quo approach will no longer work (Sayers *et al* 2022) and where intergenerational justice issues may be raised. For other measures representing significant investments and trade-offs such as protection, attention should be given to neither implementing actions too late, nor too early. Monitoring adaptation progresses can be performed using adaptation pathways identifying to what extent current decisions contribute to the long-term objectives, leave many adaptation options open or create future lock-ins (Haasnoot *et al* 2020). All these actions can be supported by climate services for adaptation to sea-level rise. Rather than considering the problem as a fixed term project, this requires an ongoing and iterative process that evolves over time (figure 3).

While adapting to two meters of sea-level rise, stakeholders will have to manage the consequences of having exceeded other planetary boundaries. This includes not only other impacts of climate change such as heatwaves, drought, intensifying precipitation and their consequences for people, ecosystems, water management, agriculture, industry, but also pollution (Persson *et al* 2022), unsustainable land use, the decline of ecosystem services (IPBES 2019), and other factors such as rapid human-induced subsidence and sediment starvation. Responding to the combination of these threats and their consequences on coastal socio-ecosystems while addressing the societal demand for improved quality of life and economic development creates a challenge for decision makers. To meet this challenge, it is essential that coastal adaptation becomes a core element of coastal development.

To respond to the almost inevitable exceedance of 2 m of sea level rise, three actions are urgently needed: (1) massive and immediate reduction of greenhouse gas emissions, to slow down sea-level rise, limit the amplitude of sea-level rise in the long term and give more time to adapt; (2) stronger engagement with adaptation to multi-meters of sea-level rise, focusing on long-living and high-value assets and on measures with immediate co-benefits; and (3) develop science and climate services to anticipate early signs of acceleration of sea-level rise, assess risks and adaptation options and provide actionable information to coastal adaptation practitioners. Here, the potential actions identified in figure 3 can be used and further expanded by researchers and practitioners to improve the response to 2 m of sea-level rise.

The climate is warming quickly. Sea-level rise is accelerating and coastal adaptation takes time. We need to think strategically; what is our vision for the different coastal and estuarine areas around the world over the decades and centuries to come?

Data availability statement

Data shown in figure 1 can be accessed through the NASA portal: https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool.

All data that support the findings of this study are included within the article.

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Authors contributions

Concept and early drafts: GLC, RN and GD; AS and AC: contributed to sea-level sections and figures; DL: coastal impacts; All contributed to the final version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

Ethics statement

The authors testify that they follow the European Code of Conduct for Research Integrity.

ORCID iDs

Gonéri Le Cozannet https://orcid.org/0000-0003-2421-3003
Robert J Nicholls https://orcid.org/0000-0002-9715-1109
Gael Durand https://orcid.org/0000-0001-8979-2355
Aimée B A Slangen https://orcid.org/0000-0001-6268-6683

Daniel Lincke https://orcid.org/0000-0003-4250-5077
Anne Chapuis https://orcid.org/0000-0003-2439-1563

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