Title: The ability of societies to adapt to 21st century sea-level rise

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Authors:

Name	Affiliation Number	Affiliation
Jochen Hinkel	1	Global Climate Forum (GCF), Neue Promenade 6, 10178 Berlin, Germany
	2	Division of Resource Economics, Albrecht Daniel Thaer-Institute and Berlin Workshop in Institutional Analysis of Social-Ecological Systems (WINS), Humboldt-University, Berlin
Jeroen C.J.H. Aerts	3	Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands.
Sally Brown	4	Faculty of Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton, Highfield, Southampton SO17 IBJ, United Kingdom.
Jose A. Jiménez	5	Laboratori d'Enginyeria Marítima, Universitat Politècnica de Catalunya·BarcelonaTech, Barcelona, Spain
Daniel Lincke	1	Global Climate Forum (GCF), Neue Promenade 6, 10178 Berlin, Germany
Robert J. Nicholls	4	Faculty of Engineering and the Environment and Tyndall Centre for Climate Change Research, University of Southampton, Highfield, Southampton SO17 IBJ, United Kingdom.
Paolo Scussolini	3	Institute for Environmental Studies, Vrije Universiteit Amsterdam, Amsterdam, the Netherlands.
Agustín Sanchez-Arcilla	5	Laboratori d'Enginyeria Marítima, Universitat Politècnica de Catalunya·BarcelonaTech, Barcelona, Spain
	7	International Centre for Coastal Resources Research, Barcelona, Spain
Athanasios Vafeidis	8	Institute of Geography, Christian-Albrechts University Kiel, Kiel, Germany.
Kwasi Appeaning Addo	9	Department of Marine and Fisheries Sciences, University of Ghana, Legon-Accra, Ghana

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Against the background of possible substantial sea-level rise, an important question is, to what extent are coastal societies able to adapt? This question is often answered in the negative by referring to sinking islands and submerged mega-cities. While these risks are real, the picture is incomplete because it lacks consideration of adaptation. This Perspective explores societies' abilities to adapt to 21st century sea-level rise by integrating perspectives from coastal engineering, economics, finance and social sciences, and provides a comparative analysis of a set of cases that vary in technological limits, and economic, financing, and social conflict barriers to coastal adaptation.

Recent literature has reinforced concerns about possible substantial sea-level rise (SLR) due to rapid melting of ice sheets[1] which may lead to 21st century global mean SLR of 2 m or more.[2–4] Discomfortingly, the potential for high-end SLR may remain even if the ambition of the Paris Agreement to limit the temperature increase well below 2°C above pre-industrial levels is met. This is due to the large uncertainties associated with ice-sheet responses and sea levels continuing to rise for thousands of years even if greenhousegas concentration will be stabilized during the 21st century.[5,6]

Against this background, an important question is to what extent societies are able to adapt and maintain human settlements safe from SLR and associated extremes during the 21st century. Following the current sea-level rise literature and the media, this question is often seemingly answered in the negative by referring to, for example, the "complete flooding and submergence of entire mega-cities."[5] or showing emblematic cities around the world submerged by the sea.[7] While these headlines illustrate that SLR may constitute a major challenge to coastal societies, they are incomplete and possibly misleading in that they neglect coastal adaptation. This is specifically true because adaptation could reduce some coastal impacts by several orders of magnitude.[8,9] Furthermore, coastal societies have a long history of adapting to environmental change and local SLR because coasts are amongst the most dynamic environments on Earth.[10] For example, a number of coastal mega-cities in river deltas have experienced, and adapted to, relative SLR of several meters caused by land subsidence during the 20th century.[11]

Efforts that integrate across biophysical and social dimensions of SLR impacts and adaptation are limited in the otherwise vast literature on SLR. This perspective provides such an effort and addresses the question of societies' abilities to adapt to 21st century SLR by analysing a set of diverse cases from around the world in terms of four main factors that have been empirically found to constrain societies' abilities to adapt (Fig. 1). These factors are defined in Box 1. We assess technical limits and economic barriers under 21st century SLR and socio-economic development, assuming current technology. Following the empirical social science literature on adaptation barriers,[12–14] we assess financing barriers and social conflict barriers mainly for the present situation with limited speculation on how these barriers may evolve during the century.

Figure 1: Coastal adaptation constraints. *Coastal adaptation is situated within interacting natural and social sub-systems and my be constrained by technological limits, and economic, financing, and social conflict barriers. Adapted from Nicholls et al.*[15]

The purpose of this effort is not to analyse which criteria are actually used in decision making nor to prescribe how decisions should be made. For example, the presence of an economic barrier does not mean that coastal societies actually decide using social benefit-cost analysis, nor that societies should not adapt, because there are many other reasons for adaptation beyond monetary ones, such as human safety or nature conservation. Rather, the purpose of this analysis is to study how different factors combine in a given case, so that further research and policy attention can be aimed at those factors that are critical in the given case. The combination of constraints found has thereby indications on possible pathways for overcoming these. For example, the presence of both finance and economic barriers suggest that future efforts should focus on grant finance, while if only financing barriers are present, concessional and private finance may also be sought.[16]

The cases have been chosen to cover different coastal landforms, income groups, types of coastal impacts, as well as urban and rural settings (Table 1). While the cases we consider here are coastal, the framework is generic and can be applied for integrated analysis in other fields of adaptation.

Box 1: Adaptation limits and barriers

A growing literature has categorized factors that have been observed to constrain adaptation. This literature distinguishes between limits beyond which human activities cannot be maintained and barriers which can be overcome through adequate efforts, technology, deployment of economic and human resources, management and institutional change.[14,17–19] For social constraints it is preferable to use the term barrier rather than limit, because what may be considered a social limit is mutable and depends on cultural context and human values.[12] Here, we consider the following four adaptation constraints, because they i) have been found to be most relevant in previous empirical analysis;[13,20,21] and ii) represent the perspectives of the main groups of actors involved in coastal adaptation.

Technological limits arise when there are no adaptation options available to effectively reduce the impacts of SLR, including the consideration of the time needed for implementing options. Asserting technical limits requires the subjective choice of an adaptation goal.[12] Here we consider the goal of maintaining human settlements safe from SLR and associated extremes through protection and accommodation measures as this perspective has been prominently represented in societies for centuries by coastal engineering.[10] We deliberatively exclude the coastal adaptation measure of retreat, because it is, in principle, always possible and hence never technologically limited. Asserting technical limits also entails the choice of a level of acceptable risks (or probability or consequence) as any coastal protection or accommodation measure may fail and there is no absolute or objective measure of effectiveness or safety.[17]

Economic barriers arise if the implementation and maintenance of adaptation are more costly in monetary terms than the impacts they avoid, as assessed through social benefit-cost analysis (BCA). BCA comes along with several well-known limitations that have been widely discussed in the climate change literature. First, not all costs and benefits can be adequately monetized.[22] Second, results are very sensitive to the choice of the discount rate applied.[22–24] Third, costs and benefits are aggregated across actors, which means that socially preferred options may differ from those preferred by individual actor.[25,26] To capture this issue specifically relevant to adaptation, we include the barrier of social conflicts as described below. Nevertheless, BCA constitutes a prominent public decision making perspective on coastal adaptation and is legally prescribed in countries such as the US, the UK and The Netherlands.

Financing barriers arise if it is difficult to access financial resources for adaptation, including from public budgets, development and climate finance and private sources.[18] This perspective has been included, because it is central to the adaption finance activities under the United Nations Framework Convention on Climate Change (UNFCCC), as well as to donor and development finance organisations and public authorities involved in funding adaptation.

Social conflict barriers arise whenever stakeholders' conflicting interests impede or exacerbate adaptation. In the social sciences, the concept of social conflict is a fundamental one for understanding why or why not societies manage to act collectively in that they develop informal and formal institutions such as culture, laws, policies, social norms and conventions that guide human behaviour to resolve social conflicts.[27–31] Social conflicts may arise due to diverging private interests (e.g., a Catalan tourist operator favouring beach nourishment and an environmental activist opposing), diverging public interests at different levels of administration (e.g., conflicting building codes at Federal, State and City levels in New York; also called institutional crowdedness barrier[13]) or between actors' interests and existing institutions (e.g., populations of remote islands opposing a population centralisation policy in the Maldives; also called cultural constraints,[12,18] or political (economy) barriers[20,25]). Here, we apply the broad concept of social conflict, because this represents the perspectives of diverse stakeholders involved and constitutes the first step in any analysis of governance issues. From there, analysis can proceed to exploring more specific questions regarding the nature of the social conflict and how this may be overcome.[14,30]

Case	Dominant coastal characteristics				Adaptation constraints			
	Coastal landform	**World Bank country income group 2017**	**Human settlements**	**Mean population density (people/km²)***	**Technological limits**	**Economic barriers**	**Financing barriers**	**Social conflict barriers**
Bangladesh	Delta	Lower middle income	Rural	*1,100			X	X
Catalonia	Beaches, deltas, cliffs	High income	Rural/urban	*900				X
Ho Chi Minh City	Delta	Lower middle income	Urban	*3,900		Some	X	X
Maldives	Atoll islands	Higher middle income	Urban	**63,000				X
			Rural	*1,500		X	X	
New York City	Estuary	High income	Urban	*11,000			X	X
Netherlands	Delta, beaches	High income	Rural/urban	*500				X

Table 1: Coastal adaptation cases considered in this paper, their coastal and social characteristics, and adaptation constraints found in maintaining human settlements safe from 21st century sea-level rise. * Mean population density values are based on the UN-adjusted GPWv4 year 2010 population density dataset.[32] For the administrative boundaries of the case studies we used the Global Administrative Areas (GADM) dataset version 2.0 (http://www.gadm.org/). For New York City, Ho Chi Minh City and the Maldives mean population density was calculated for the entire administrative area of the city. For Catalonia, Bangladesh and the Netherlands mean population density was calculated for the LECZ (low elevation coastal zone; areas ≤ 10m and hydrologically connected to the ocean). For Bangladesh, the districts of Cox's Basar, Bandarban, Chittagong, Ramgamati and Khagrachhari were excluded as they are outside the delta. For the definition of the LECZ we used CGIAR-CSI SRTM v4.1 elevation data.[33] ** Population density for the capital island of Malé taken from http://worldpopulationreview.com/countries/maldives-population/.

Bangladesh

Bangladesh, largely situated on the delta of the Ganges-Brahmaputra-Meghna rivers, is widely recognised as one of the most hazardous large countries on Earth, having rural population densities exceeding 1,000 people/km^2, and being impacted by river and sea floods, salinization and drought, exacerbated by climate change, SLR and land subsidence.[34,35] There are extensive diked polder systems which protect agriculture, against most flooding (Fig. 2), but failures during more extreme tropical storms are common, causing agricultural damage. Upgrade of these dikes is ongoing and higher reliability can be expected in the future. Experiments are also in progress with controlled sedimentation to raise land levels, termed tidal river management.[36,37] All of these measures are part of Bangladesh Delta Plan 2100,[38] a holistic, integrated and long-term plan that the government is currently developing, learning from the Dutch Delta Programme experience.

Technological limits. From a technological point of view, high-end SLR would be extremely challenging, but the technological measures that are needed either exist or are being developed. For example, in rural areas, tidal river management combined with of order 10^9 tonnes of sediment delivered by the rivers per year offers great potential to build land elevation with sea level.[39] Changes in land use such as from agriculture to aquaculture are also feasible and already occurring. Urban areas would need to be protected with more conventional methods. Rising salinity is a challenge which might be countered by a range of measures such as salt tolerant crops and freshwater reservoirs. While these options are available much more assessment and trials of their application are required, recognising that this may be made more challenging due to other barriers mentioned below.[40]

Economic barriers. With a dense rural and urban population, adaptation provides large direct and indirect monetary benefits, such as avoided damages and reduced health effects of flood events. All the options mentioned above are expected to have benefits exceeding their costs, although it is hard to find detailed analyses demonstrating this.

Financing barriers. Bangladesh is the biggest recipient of climate adaptation funds, and is also a major recipeint of donor aid, receiving $2.6 billion in 2013.[41] Many NGOs such as the Red Cross Red Crescent are active, such as in the provision of cyclone shelters. Significant efforts have been funded, but future funding needs are large[38] and the maintenance of existing polder systems is often constrained by a lack of funds.[42]

Social conflicts**.** Bangladesh's dense population and intense land use means it is easy for conflict to emerge. For example, conversion of agriculture to aquaculture has given rise to conflicts associated to land grabbing, salinization impacts and reduced labour demand.[43] Tidal river management removes large areas of land from use while the land is being flooded and raised, which affects households income. At the same time, there is profound change with major rural to urban migration and agriculture progressively diminishing relative to the national economy, so adaptation is occurring on an evolving stage.[44]

Figure 2: Polder system in coastal Bangladesh south of Khulia. *Polders are low-lying tracts of land enclosed by dikes, which are widespread in densely populated deltas with the main goal of promoting agriculture. The polder dikes and drains will require substantial upgrade to remain effective under rising sea levels. Courtesy Robert Nicholls.*

Catalonia

The 600 km long Catalan coastal zone in the Spanish Mediterranean concentrates about 62% of the population and about 65 % of the GDP of Catalonia, with tourism being the main economic activity (>10% of GDP).[45] The major SLR-induced impacts are related to enhanced shoreline erosion due to the combination of narrow beaches and lack of accommodation space.[46] The SLR impacts of coastal flooding and inundation are low due to the steep coastal topography, with the exception of some lowlands.[47,48] Currently, adaptation measures are oriented towards maintaining beaches for recreation and enhancing protection of the hinterland through artificial nourishment (i.e., counteracting shoreline erosion by replacing the eroded sand).

Technological limits. There are no technological limits for these adaptation measures. Some challenges relate to the availability of adequate sand volumes for nourishment,[49] because the sand used for nourishment needs to have a grain size compatible (i.e., similar or coarser) with the eroded sand or nourishment needs to be combined with additional measures to reduce sediment mobility. In the past, nourishment has not always been effective because it was carried out mainly reactively when major erosion impacts were already observed.

Economic barriers. Generally, beach nourishment is highly beneficial in areas of tourism development due to the large contribution of coastal tourism to Catalan GDP.[50] Empirical studies have found that beaches in front of hotels raise prices of hotel rooms by up to 17% along the Catalan coast.[51] Unit costs for sand are, however, expected to rise in the future, because the shallow near-shore sites from which most of the sand is gained today are expected to be exhausted, which will increase the distance between sand source sites and nourishment sites.

Financing barriers. Currently*,* there are no financing barriers as beach nourishment is publicly financed by the Spanish Government. The required annual nourishment costs will, however, increase with SLR and it is not clear how long public finance can be maintained in the future.

Social conflicts. Increasing social activism is questioning the long-term sustainability of a beach nourishment strategy due to its potential negative ecological impacts on high-value coastal ecosystems such as endemic *Posidonia* sea-grass meadows.[52] In addition, the multi-level governance structure for coastal zone management generates conflicts between national, regional and local administrations, limiting the implementation of effective adaptation policy.[53] The Spanish Central Government takes beach nourishment decisions within the so-called Maritime-Terrestrial Public Domain, the Regional Government is responsible for land use planning outside this domain, and the local municipalities are responsible for urban planning adjacent to this domain.[54,55] For example, in 2016 a group of coastal municipalities northwards of Barcelona opposed obtaining sediment for beach nourishment by nearshore dredging claiming that this would promote unsustainable coastal management.

Ho Chi Minh City

As a fast-growing delta metropolis, Ho Chi Minh City, Vietnam, is heavily affected by frequent flooding today, a phenomenon that will exacerbate with SLR, changes in precipitation extremes and present rates of land subsidence of about 1 cm/year.[56] A combination of adaptation measures could be implemented to substantially reduce flood risk, including i) building a system of ring dikes around the urban area,[57] ii) elevating districts where people and assets most concentrate, and iii) retrofitting buildings to reduce damage in households and small businesses. So far, only limited private adaptation has been carried out in the form of retrofitting existing houses and elevating land for new houses (Fig. 3).

Technological limits. Considering all measures together, there are no apparent technological limits to coastal adaptation. Elevating districts should effectively reduce flood risks even under high-end SLR. As SLR progresses, all of these measures will need to be combined and substantially upgraded over time.[58]

Economic barriers. Investing into most of the aforementioned measures promises high benefit-cost ratios.[59] Using a discount rate of 5%, for example, elevating areas at high risk and retrofitting buildings would have 21st century benefit-cost ratios of 8-11 and 15, respectively, and net present values of US$ 33-48 billion and US$ 69-73 billion, respectively, assuming a SLR between 50 and 180 cm. Under the same assumptions, a ring dike would have benefit-cost-ratios of 1.2 for 50 cm SLR, but negative for 180 cm SLR.

Financing barriers. Adaptation faces deep financing challenges. So far, the city has not managed to secure finance for the highly beneficial flood protection options, even in the face of vast damage and nuisance during every monsoon season. A ring dike, for example, would require investments in the order of US$ 1.4 to 2.6 billion.[60]

Social conflicts. One conflict that has been found to inhibit large scale investment is disagreement on adaption measures between authorities at various administrative levels.[57] For example, the Ministry of Agriculture and Rural Development favours the ring dike, whereas the city government opposes it for both environmental reasons and fear of protests.[61] A ring dike would likely trigger conflict between urban and rural populations, since rural citizens outside the ring dike will suffer even greater floods. Building-scale measures would not lead to this particular conflict, but they would also not keep water out of Ho Chi Minh's streets, hampering the transformation of the city into the modern business hub that it aspires to be.

Figure 3: Stilt houses on a river bank in Ho Chi Minh City, Vietnam*. This flood-mitigation measure is widely applied by the poorest, most exposed and vulnerable share of the population and stands in*

stark contrast to the new high-rise residential apartments on the background. Courtesy Stijn Koole (Bosch Slabbers Landscape + Urban Design).

The Maldives

The Maldives consist of 1,192 atoll islands with a mean elevation of approximately 1.5 m above mean sea level. One third of the country's population of 400,000 lives in the urban capital island of Malé (Fig. 4), which is one of the world's most densely populated cities.[62] To relieve this population pressure the Maldives have constructed a new island, Hulhumalé, on a reef-flat directly adjacent to Malé and included adaptation by raising the island to just over 2 m above mean sea-level.[63]

Technological limits. Island expansion and construction by land claim is a mature and wide spread technology, common in the Maldives and many other parts of the world. The elevated island Hulhumalé will be safe from flooding until SLR reaches approximately 0.6 m and thereafter it could suffer from periodic flooding due to energetic swell waves.[64] Island raising, however, can further continue even under high-end SLR, and further adaptation such as dikes, early-warning systems and shelters can supplement this. The highly permeable substrate of all Maldives islands should be noted as a possible challenge.

Economic barriers. Island construction is, for densely populated atoll nations, at relatively low cost, because the reef-flats that need to be filled with sand are shallow (1-2 m in the case of Hulhumalé), which minimises sand requirements. The cost of reclaiming Hulhumalé were about US$ 30 per m². While no detailed benefit-cost analysis is available, adaptation through land reclamation and fill around Malé is deemed to have a high benefit-cost ratio even when raising islands by 2 m due the high real-estate prices (about US$ 2,000 per m²). Contrary to this, land raising is not economically beneficial in areas of low population density, which includes most of the remote islands.

Financing barriers. Island construction was financed by the Government of the Maldives and a concessional loan form the Saudi Fund for Development.[65] Generally, land reclamation is attractive for investors, because investments can be paid back in the short term through real-estate revenues generated on the newly created land. In addition, the Maldivian economy has been attractive for investors, because it has been growing at an average rate of 7.4% over the last 30 years.[66]

Social conflicts. The main social conflict regarding adaptation is a distributional one between the urban elites on one hand and the peripheral islands on the other hand.[67] The former favour a centralisation of population and services on a few well-protected islands with the dual goal of reducing costs of services (National Population Consolidation Policy) and of reducing coastal risk (Safer Island Strategy). These policies, however, meet the opposition of inhabitants of smaller and more remote islands as they are perceived to "destroy the country's 3,000-year-old cultural identity and its social fabric."[68]

Figure 4: Malé, the capital island of The Maldives. *High and increasing population densities in Malé have led to the reclamation of the nearby island of Hulhumalé, which can bee seen in the background of the photo. (c) Shahee Ilyas https://commons.wikimedia.org/w/index.php?curid=621195*

The Netherlands

While a large part of The Netherlands already lies below sea levels, and complex defences against sea floods are in place, SLR entails a number of challenges including i) salt intrusion stressing agricultural production and freshwater provision in the west;[69] ii) the Maeslant barrier, protecting Rotterdam city and harbour, ceasing to be effective under 50 cm SLR; and iii) the IJssel lake system not providing necessary flood and drought relief with > 30 cm SLR;[70,71]. Furthermore, coastal flood impacts will be compounded by increases in Rhine and Meuse river peak discharges.[72] These challenges are currently being addressed in the context of the Delta Programme through a combination of measures including sand nourishments, dunes, dyke improvements, river widening and urban planning and adaptation.

Technological limits. The dominant impression is that the Netherlands can technically cope with future SLR of 0.9 m by 2100,[71] or 1.5 m/century, although with “major improvements.”[70] Research also showed that with an investment of ~€80bn, it is possible to preserve territorial integrity of the Netherlands even under 5m SLR, using current engineering technology.[73,74]

Economic barriers. For the Netherlands as a whole, coastal adaptation to 0.8m SLR was deemed economically highly beneficial, with an overall benefit-cost ratio of 5 using a discount rate of 4%.[75] Adaptation cost are estimated to €1.6 to 3.1 billion per year up to 2050 (about 0.5% of the current Dutch GDP), while the cost of doing nothing are much higher.[76] BCA are not available for higher SLR, but ballpark estimates suggest that under 5m of SLR, protection cost may exceed the cost of evacuation.[73]

Financing barriers. The Delta Programme 2015 has already allocated €1.2 billion per year for adaptation through the Delta Fund until 2028. State funding is assumed to be continued afterwards, and it is foreseen that regional (the Water Boards) and local entities (municipalities) will supplement these resources. Water Boards are autonomous governmental bodies that have their own independent tax revenue system to maintain water infrastructure.

Social conflicts. The Netherlands has a long history of developing institutional arrangements (i.e., the Water Boards) for dealing with saline-, fresh water and flooding conflicts and these are likely to be effective in the future, at least under moderate levels of SLR.[77] Current conflicts relate to areas where dikes have been relocated in order to allow for larger peak flows. For some river widening projects, a dozen of farms have either been rebuilt on elevated hills or have been relocated, which has triggered huge debates.[78] Under high-end SLR, large investments to protect the west of the country may spark a debate over the distribution of resources with the population in the safe eastern parts, which already feels neglected by the population in low lying cities in the west.[79]

New York City

Historical flood events have shown that hurricanes and winter storms can have considerable impacts on New York City (NYC), as illustrated by Superstorm Sandy in 2012 causing more than US$ 20 billion of damage.[80] SLR and population growth will further increase the potential consequences of flooding. In the aftermath of Hurricane Sandy, NYC has been formulating flood adaptation strategies, which include a wealth of potential measures such as enhancing building codes, building dikes (“the big U”), installing large scale storm surge barriers, and “green” engineering measures to enhance resilience of wetlands against storm surges.[81]

Technological limits. Theoretically, there are no technological limits for this case. The main technological challenge involved in implementing adaptation measures is that they have to fit into the existing high-density building stock, which increases costs.[82] Furthermore, a change of buildings codes will effectively only pertain to new buildings.

Economic barriers. The investment costs for different combinations of adaptation measures vary from US$ 14.7-23.8 billion for strategies containing large scale levees, to US$ 11.6 billion for a “hybrid” strategy targeted at protecting critical infrastructure and enhancing building codes.[83] When only considering the current climate conditions, benefit-cost ratios for all combinations of measures are below 1 (discount rate 4%). However, when also considering 21st century SLR of up to 1m, all benefit-cost ratios are above 1, with the highest one being 2.5 for the hybrid strategy.

Financing barriers. After Sandy, the Federal Government made available US$16 billion for disaster recovery and adaptation through the Disaster Relief Appropriations Act (2013), but the allocation of this money is proceeding slowly. To date, US$ 4 billion have been allocated by NYC, mostly to recovery.[84] About US$ 1 billion has been spent on adaptation projects in NYC and New Jersey under the Rebuild by Design program.[85] The novel aspect of this program is the bottom-up process to develop projects as joint efforts between the public, research, private sector and government.

Social conflicts. One main distributional conflict in the context of coastal flood risk management in the US relates to the National Flood Insurance Program subsidising flood insurance for home-owners in order to stimulate them to enrol into the program. In addition, this creates disincentives for households to implement disaster risk reduction measures such as flood proofing their homes.[86,87] Another issue has been conflicting and fragmented policies issued by Federal, State and City level authorities regarding building codes. The federal National Flood Insurance Program assigns building codes to be implemented in 1-in-100 year flood zone, while State and City authorities have added additional and conflicting requirements as to how much to elevate new buildings (called freeboard).[87] State and city-level policies are under revision right now to address this issue.

Lessons learned across cases

Technological limits. In the cases considered a number of technological challenges such as the lack of space for building protection infrastructure in densely populated cities are observed, but these do not constitute technological limits but rather raise costs. While the cases chosen represent a wide variety of contexts and SLR-related coastal challenges, this does not mean that generally no technological limits exist. For example, coastal protection is technologically extremely challenging for Miami, because protected areas can be flooded from below due to the underlying porous limestone. Pumps can be implemented to deal with the flooding issue, but this reduces groundwater storage and limits the effects of infiltration pumps to reduce salinity intrusion into the aquifers.[88]

In principle, technological limits could also arise in the case of adaptation options not offering a low enough level of residual risk for societies to accept (See Box 1). In our cases and beyond we currently do not find evidence supporting this point and also expect that this will not be the case under 21st century SLR. Currently, at least 20 million people accept the risk of living up to several meters below normal high tides in countries such as Belgium, Canada, China, Germany, Italy, Japan, the Netherlands, Poland, Thailand, the UK, and the USA.[89] In principle there is no technical obstacle to engineer coastal protection to very high standards, as for example the discussion on so-called “unbreakable dikes” illustrates.[90] Hence residual risks can be managed, but should never be forgotten or taken for granted.

In any case, it seems that economic, financing and social conflict barriers are reached before technological limits arise. The core questions concerning adaptation technology are how much this will cost, whether societies will be able to access sufficient finance and resolve the distributional conflicts associated with spending large amounts of public money on coastal protection rather than on other policy domains. It should also be noted that coastal protection may lead to many unfavourable side effects such as the loss of tourism due to a decline in beach attractiveness and the loss of coastal ecosystem through coastal squeeze, which in turn may trigger social conflicts as elaborated further below.

Economic barriers. Few economic barriers are found in the six cases considered here. On the one hand this is due to coastal adaptation research generally focusing on the hotspots of coastal social impacts. In those low-lying areas with high population and asset densities it is generally economically highly beneficial to protect against even high-end SLR. Hence, it is very unlikely that we will see mega-cities submerged by SLR during the 21st century. On the other hand, the high benefit-cost ratios found here, as well as in earlier global analyses,[9] illustrate why massive coastal protection is widespread today and is likely to continue to be so during the 21st century, even if prices for sand and other materials rise.

Conversely, protecting rural coastal areas and agricultural land will generally have benefit-cost ratios below one, at least when only considering market values of benefits. When also considering non-market values, hard protection may actually lead to negative benefits, because it constrains coastal wetlands such as mangroves and marshes to migrate inland with rising sea level.[91] A solution may be offered by so-called nature-based adaptation measures, which provide coastal protection together with additional ecosystem service benefits, however there are still large uncertainties about the effectiveness of these solutions.[92,93]

Financing barriers. Coastal adaptation seems to be frequently constrained by inaccessible finance, even if benefit-cost ratios are high. One reason for this is that it is difficult to convert the benefits of coastal adaptation into revenue streams for financing the up-front investment, because benefits, such as the avoided damage of extreme sea-level events, occur stochastically over a long time horizon, and are distributed across stakeholders. An interesting exception occurs when adaptation is combined with the creation of short-term revenue streams via real-estate development on land either newly created or made more valuable through coastal protection, as illustrated in the case of the Hulhumalé, Maldives; as well as through urban land-reclamation projects in other parts of the world.[94]

Social conflicts. Social conflicts are present in all the cases investigated here and very likely also beyond these. Two types of conflicts were observed. The first one relates to actors that are negatively affected by adaptation measures. In Catalonia, for example, the tourism sector welcomes beach nourishment since it directly benefits, while those living from natural resources (e.g. fishermen) show a growing opposition. This type of conflict can generally be expected in coastal adaptation, because SLR and coastal adaptation redistribute risks and benefits amongst stakeholders, creating winners favouring adaptation and losers objecting to it. The second type of conflict relates to the distribution of public money between coastal actors receiving public support for adaptation and non-coastal actors paying for this through taxes, as found in the cases of The Netherlands, NYC and Catalonia.

In many parts of the world, coastal adaptation is further complicated by existing conflicts over resources. For example, illegal coastal sand mining is currently a major driver of coastal erosion in many parts of the developing world.[95] In Ghana, for example, lack of law enforcement, lack of employment opportunities for the youth, and high demand for sand from the construction industry continue to make this practice attractive.[96]

Other social barriers. While the four types of limits and barriers considered here cover main societal perspectives on coastal adaptation, they are not exhaustive. Even when no conflict of interest is present, a lack of capacity of governance structures to plan, implement, enforce, monitor and maintain coastal adaptation measures may constrain adaptation.[18,97] In the Ho Chi Minh City case, for example, the limited experience in dealing with large projects has been reported as a barrier to adaptation.[57] A lack of capacity is particularly problematic when it comes to the maintenance of coastal protection infrastructure as this has caused many coastal disasters in the past such as in New Orleans,[98] just to mention one prominent example. In other countries in which coastal defence systems have existed over a long time, effective governance arrangements for maintenance, such as the Water Boards in the Netherlands, have emerged. Mixed experiences with both bottom-up and top-down governance structures have been gained in Bangladesh since the introduction of the Dutch-like polders in the 1960s.[42] We have left this dimension aside, because it is difficult to make the concept of governance capacity operational for a high-level comparison of diverse cases as done in this paper.[99]

Evolution of limits and barriers. Adaptation constraints will evolve over time. Technological change may help to overcome technological limits and economic barriers (i.e., by reducing adaptation unit cost). The effect of this is likely to be small for classical "hard" coastal engineering measures as these are mature technologies, but potentially larger for emerging nature-based solutions. For financing and social conflict barriers it is more difficult to speculate how these will evolve during the 21st century. On the one hand, economic growth and better institutions may help to overcome these barriers. On the other hand, these barriers may aggravate as the overall expenditure for adaptation rises with sea-levels and this will have to compete for public expenditure with other needs, such as pensions and unemployment. In any case, financing barriers are likely to persist in the near future, because in the developed world austerity policy generally reduces public investment levels,[100] and in the developing world, where many countries rely on donor funding, the adaptation finance gap is large.[101]

Outlook and future research

Taken together, our results suggest bifurcating coastal futures during the 21st century. On the one hand, urban and richer areas will continue to have engineered coasts with higher and higher defences, with radically altered landscapes, and possible catastrophic consequences in the case of defence failure. On the other hand, rural and poorer areas will struggle to maintain safe human settlements and will eventually retreat from the coast. Such retreat is likely to involve massive social conflict, forcing societies to address difficult questions concerning transfer payments, compensation and liability for loss and damage.[102] Looking beyond 2100, this picture may or may not change. As sea-levels will continue to rise for millennia, the world is already committed to a long-term SLR in the range of 1.2 to 2.2 m under present levels of global warming, and this commitment could increase to 25-52m within the next 10,000 years under cumulate emissions of 1280 and 5120 PgC.[5] This means that our heirs could either see a world similar to the one described in this paper or a radically different world with sea levels tens of meters higher. Irrespective of the deep uncertainties in future sea-levels, strong mitigation efforts can, and are needed to, reduce the risks of high-end sea-level rise.

In addition to mitigation efforts, research is needed to advance coastal adaptation by finding ways to overcome prevailing barriers. Towards this end, we advance two avenues of research. One avenue concerns research and experimentation for overcoming technological challenges and economic barriers. So-called green or nature-based options[92] seem to promise multiple co-benefits, amongst them the capacity to self-adjust to SLR.[103] But research is needed to better understand effectiveness, optimal timing and benefit-cost ratios together with other socially relevant criteria such as risk tolerance and social desirability associated with both traditional and novel adaptation options across the full ranges of SLR and socio-economic uncertainties.

A second, much less developed research avenue concerns understanding and designing governance arrangements for overcoming financing barriers and social conflicts. This needs to be a priority, as these are today clearly the most critical barriers to adaptation. Research should thereby target both international arrangements for enhancing the scale and effectiveness of adaptation finance mechanisms under the UNFCCC and beyond, as well as project-based financial arrangements for leveraging public funds, also through the involvement of private investors and project developers.[16] Due to the potential severe distributional consequences of SLR and adaptation, specific attention needs to be placed on distributional justice, compensation and transfer payments to poorer and rural areas for which the economics of adaptation is less favourable.

Corresponding author

Correspondence should be addressed to Jochen Hinkel <hinkel@globalclimateforum.org>.

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Author contributions

JH conceptualised this study, drafted the general parts of the paper and contributed to drafting each case study. JCJHA carried out and drafted the New York case study. SB, DL, RJN and JH carried out and drafted the Maldives case study. RJN and SB carried out and drafted the Bangladesh case study. JAJ and ASA carried out and drafted the Catalonia case study. PS carried out and drafted the Ho Chi Minh City case study. PS and JCJHA carried out and drafted the Netherlands case study. KAA and NV contributed to the drafting the discussion.

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