Despite the higher susceptibility to floods and a growing climate crisis, more than 10% of the world's population lives in low-elevation coastal zones – and that share is increasing. **Guy Michaels** and colleagues present a detailed picture of housing in these areas – and how rising sea levels may reshape cities.

Rising sea levels and the future of coastal cities

Low-elevation coastal zones are home to more than 10% of the world's population – and that share is growing. But the attraction of these areas poses problems due to their susceptibility to floods, including from tropical storms, which affect many millions of people around the world every year.

The problem of flooding is acutely felt in the United States where expected annual losses from tropical storms alone are currently estimated at $57 billion, of which a third is borne by taxpayers. To make matters worse, global sea levels are rising, with varying consequences for different coastal areas. The US Atlantic and Gulf coasts experienced some of the fastest local rates of sea level rise in the world during the 20th century. This trend is expected to continue, increasing the frequency of flooding.

Against this backdrop, it is important to understand where housing construction in coastal areas is taking place. To investigate this, we have assembled a new dataset on the location of housing and flood risk across thousands of kilometres of coast, spanning major urban centres, small towns and rural areas on the US Atlantic and Gulf coasts.

The data, which cover two decades, are at a highly disaggregated spatial scale. They include information on housing from the census and land cover from satellite imagery, as well as measures of proneness to rising sea levels, flood damages and regulatory restrictions. These data allow us to explore construction in areas

Despite rising sea levels, US coasting housing was increasingly built in flood-prone locations during the 1990s and 2000s

where flood risks for residents and taxpayers are both high and rising, due to climate change.

We use these data to document how the existing housing stock and new construction vary by distance to the coast. The result is a novel and detailed picture of housing in coastal zones, and its relationship to the vulnerability of different locations to flooding and rising sea levels.

Our analysis also allows us to answer questions such as: Why does housing concentrate near, but not right at, the coast? Why are coastal cities asymmetric? Why is new housing increasingly built on flood-prone areas, which were previously avoided? And why does this happen especially on the urban fringes?

Finally, we study how rising sea levels may reshape cities, and consider implications for increasing costs of flooding and taxpayer subsidies, the economic decline of some neighbourhoods, and lengthening commutes.

We begin by documenting nine stylised facts, which we group into three broad take-away findings:

The shape of coastal locations in 1990

■ First, housing unit density peaks near, but not right at the coast, and it declines more steeply on the coastal side.
■ Second, coastal places are asymmetric: their central business district (CBD) is closer to the coast side edge.
■ Third, this asymmetry increases with city size.

What explains the shape of coastal locations?

■ Fourth, census blocks that are prone to rising sea levels are much more sparsely built; but conditional on proneness, blocks closer to the coast are more densely built.
■ Fifth, proneness to rising sea levels rises steeply near the coast.
■ Sixth, damage from flooding also rises steeply as we approach the coast.
Together, these stylised facts suggest a tension between the benefits of coastal proximity and the costs of proneness to flooding, which increases steeply near the coast.

Patterns of growth from 1990 to 2010

■ Seventh, net new construction from 1990 to 2010 was more than twice as prevalent in locations prone to rising sea levels as in the 1990 stock of housing.
■ Eighth, areas prone to rising sea levels were more likely to be developed in dense census tracts.
■ Finally, in the densest census tracts, new construction focused on medium-risk areas prone to rising sea levels, while avoiding the riskiest ones.

New construction in flood-prone coastal areas has been concentrated around cities and not in rural areas

We show that our nine stylised facts are robust to excluding census blocks that were mostly shielded from private residential construction because they are protected areas, military bases or parks. We also find evidence consistent with our stylised facts when we use data on built area, based on satellite imagery, that cover all construction rather than just housing data.

To account for the nine stylised facts, we develop a model of a monocentric coastal city. In the model, coastal areas are characterised by both an amenity, which declines linearly with the distance to the coast, and a 'disamenity' (flood-proneness), which declines convexly with the distance to the coast.

The city founder chooses a location that trades off these two factors – close to the coast, but not right at it. This location becomes the city's focal point – the CBD. Residents then choose where to live, and they prefer locations close to the CBD, both because of their high net amenity value and because of the shorter commute.

Housing density peaks around the CBD, but declines more steeply on the coast side, because of the convex flood-proneness. The city expands over time into previously empty areas on both sides. On the coast side, this expansion involves building on increasingly flood-prone land.

Taken together, our nine stylised facts and our model of a coastal city, which helps us to account for what we observe in the data, suggest that coastal cities face 'soft barriers' related to flood risk. Soft barriers are locations that are not used for housing development in most circumstances, but are nevertheless built on as cities expand. Construction on soft barriers – another example is construction in areas prone to wildfires – may involve risks not only to residents but also externalities (for example, for taxpayers or the environment), which may require policy intervention.

We extend our model in several ways, including to allow for sea level rise and government subsidies to flood-prone areas. We then simulate our model to explore challenges that low-elevation coastal cities may face in the coming decades. These simulations point to four potential concerns for low-elevation coastal cities.

Climate change will make it expensive and difficult to sustain low-lying coastal communities

■ First, the problem of housing in flood-prone locations looks set to worsen. This could be because cities expand towards the coast, because of rising sea levels, or because both happen simultaneously. This development threatens to increase flooding costs for both residents and taxpayers.
■ Second, even if coastal cities grow on aggregate, some neighbourhoods within them may experience economic decline, as increased flood risk causes demand for housing to decline. This problem is exacerbated in the case of economically stagnant cities.
■ Third, rising sea levels further distort the shape of coastal cities, leading to them becoming increasingly 'misshapen' and significantly lengthening the time costs of commuting to work.
■ Finally, these cities face a potential crisis if their CBD comes under threat of being permanently submerged.

Various government policies could mitigate the problems we highlight, especially the rising exposure of taxpayers. First, governments could consider taxing new developments in flood-prone areas, if there are viable alternative uses to the land that are not taxed. The limiting case is an outright ban on extensive margin developments, although enacting and enforcing such a ban might be difficult.

Second, governments could offer subsidies only to existing housing. One such policy is the UK government's Flood Re, which provides subsidised flood insurance only to 'grandfathered' housing, built before 2009.

Governments could also attach further conditions to their subsidies. These conditions could include stricter building standards, such as construction on stilts imposed by the US federal government when compensating the victims of Hurricane Sandy.

Alternatively, governments could restrict the number of times a given property is bailed out, or offer other incentives to move instead of rebuilding, as Canada has recently done.

With rising sea levels proceeding at pace, the costs to taxpayers of fixing neighbourhoods or even cities may at some point become prohibitive. An example of how far things have deteriorated in another part of the world can be seen in Indonesia, where the government is investing heavily in moving its capital from flood-prone Jakarta.

Ultimately, of course, slowing down climate change and rising sea levels could also reduce the costs, especially those associated with large-scale urban moves. This remains a central policy challenge.

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