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Flood risk discounts in the Danish housing market

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Abstract

We investigate the effects of the risk of flooding and rising sea levels on the prices of single-family homes in Denmark. To that end, we combine data on the universe of housing transactions in Denmark since 1992 with rich data on the flood risk exposure of all Danish houses.

Flood risks are substantial: between 0.9 and 1.2 per cent of Danish houses are at risk of flooding today, and nearly twice as many houses will be exposed to flood risk by 2071.

Houses that are exposed to flood risk today are sold at a price discount of around 6 per cent. For your average house, that corresponds to a discount of around 100,000 DKK.

Flood risk discounts vary over time: they increased temporarily after a severe flood in 1999, even in areas that were not affected by this particular flood.

There is evidence of sea level rise pricing: houses that are not exposed to flood risk today, but will be exposed to flood risk in the future due to rising sea levels, are priced at a discount of 3-4 per cent.

Introduction

One of the most salient consequences of climate change is a rise in sea levels. Countries with long coastlines and low altitudes, like Denmark, the Netherlands, Canada and the United States, will therefore need to prepare for more frequent and more extreme floods.[1] The increased exposure to floods leads to many questions: for example, how costly are such floods? And who is affected by them?

When answering these questions, a particularly important market to focus on is the market for single-family houses. As houses are immobile assets, they are affected by geographic risks like flood risk. This is especially true in Denmark, where no house is more than 50 kilometres away from the shore. Houses are also economically important, as they are often the most important household assets.[2] Thus, many households would lose a large share of their wealth if a flood were to destroy their house. And even if their house was spared, households with houses that are exposed to flood risk might lose a large fraction of their wealth if potential buyers were to become more cautious about flood risks.

Rising sea levels could therefore have important implications for the Danish housing market, as it threatens housing wealth directly through the destruction of properties and indirectly through reductions in house valuations.

Houses are also an important source of collateral for loans and mortgages. Thus, understanding whether and how flood risk

[1] For a recent overview of the scientific literature on sea level rise and its implications for extreme sea level events (i.e. floods), see Oppenheimer et al. (2019).

[2] For an overview of the importance of housing wealth for Danish households, see Browning, Gørtz & Leth-Petersen (2012).

affects house prices is important for financial regulators.

How important flood risks are, where and when they do arise and how sea level rise will affect them are still unanswered questions.

Here, we provide an overview of the exposure to flood risk of single-family houses in Denmark. We document the exposure of houses to flood risk, both today and under a number of different sea level rise scenarios. Moving beyond aggregate numbers, we investigate the geographic distribution of flood risks: flood risks are not only highly concentrated in a few municipalities, they are also highly concentrated within these municipalities.

The results are based on granular data on flood risk at the level of individual houses, provided by the Technical University of Denmark (DTU).[3] Specifically, for each house in Denmark, flood risk is measured as the expected level of flooding given a 20, 50 or 100-year flood. A 100-year flood has a 1 per cent probability of occurring in any given year, based on historically observed water levels.

As sea levels rise, more houses will be exposed to flood risk. The data also shows how the exposure of each house to flood risk will change under various scenarios provided by the International Panel on Climate Change (IPCC) for Denmark.[4]

We combine this data on flood risk with data on the universe of housing transactions in Denmark, going back to 1992, and rich data on housing characteristics. Therefore, we can study the effect of flood risk on house prices, controlling for many important housing characteristics.

Geography plays an important role for flood risk. Denmark, a flat country with a long coastline and many islands, is uniquely suited to investigate the relevance of flood risk. We find that a substantial share of Danish houses, about 1.2 per cent, is exposed to the risk of a flood that is expected to occur once every 100 years.

Sea level rise will increase the fraction of houses which is exposed to flood risk substantially: under the most likely scenario (the IPCC RCP 4.5 scenario), about 1.8 per cent of houses will be exposed to a 100-year event by 2071. In a very pessimistic scenario (the IPCC RCP 8.5 scenario), almost 3 per cent of Danish houses will be exposed to a 100-year event by 2071.

After describing the flood risk exposure of Danish single-family houses, we next investigate whether home buyers factor flood risk into house prices. As we will describe below, it is still a hotly debated question in the academic literature whether that is the case or not. We contribute to the academic debate by answering two questions: first, is the fact that a property is exposed to flood risk today factored into house prices? Second, is the future increase in flood risk due to sea level rises factored into house prices?

Identifying a causal link between flood risk and house prices is challenged by the fact that exposure to flood risk correlates with other housing characteristics that are priced, such as the location of a house. For instance, if people value living near the sea, or if more affluent post codes are more exposed to flood risk, this might lead us to underestimate the true flood risk discount.

Our data set allows us to address this challenge, since we look at many additional house characteristics, among them the elevation above sea level and the distance to the coast. In our identification of the effect of flood risk, we follow Bernstein et al. (2019) and compare houses that differ in terms of their

[3] The flood risk data combines regional data on the historical probability distribution of water levels with flooding simulations based on a detailed elevation map of the surface of Denmark and various sea level rise scenarios.
[4] The RCP 4.5 scenario is described in Thomson et al. (2011), the RCP 8.5 scenario in Riahi et al. (2011).

Sea level rise will roughly double the fraction of houses exposed to flood risk by 2071

Table 1

scenario	time	20-year horizon	50-year horizon	100-year horizon
baseline scenario (RCP 4.5)	2021	0.93	1.13	1.26
	2041	1.35	1.60	1.79
	2071	1.72	2.05	2.21
pessimistic scenario (RCP 8.5)	2021	0.93	1.13	1.26
	2041	1.53	1.78	2.03
	2071	2.39	2.72	2.95

Note: This table displays the fraction of houses that are exposed to 100-year flood events at different time horizons and different . The realistic scenario assumes a sea level rise for Denmark under the RCP 4.5 scenario by the intergovernmental panel on climate change (IPCC), the pessimistic scenario the RCP 8.5 scenario.
Source: Authors' calculations, based on data from the Sales and Valuation Register (SVUR), the Central Register of Buildings and Dwellings (BBR), and DTU.

exposure to flood risk, but have otherwise similar characteristics.

We find that houses that are exposed to flood risk at a 100-year horizon are on average priced at a 6 per cent discount relative to houses that are not exposed to flood risk. This corresponds to a discount of around 100,000 DKK for your average house.[5] Importantly, this is true conditional on comparing houses located at similar distances to the sea.

This discount is similar when we only consider houses that are exposed to flood risk at a 50-year horizon or even a 20-year horizon. This suggests that what matters to house buyers is whether a house is exposed to flood risk or not, while the exact probability of a flood is less important. In line with this, we also find similar discounts across groups of houses with different expected water levels conditional on a flooding.

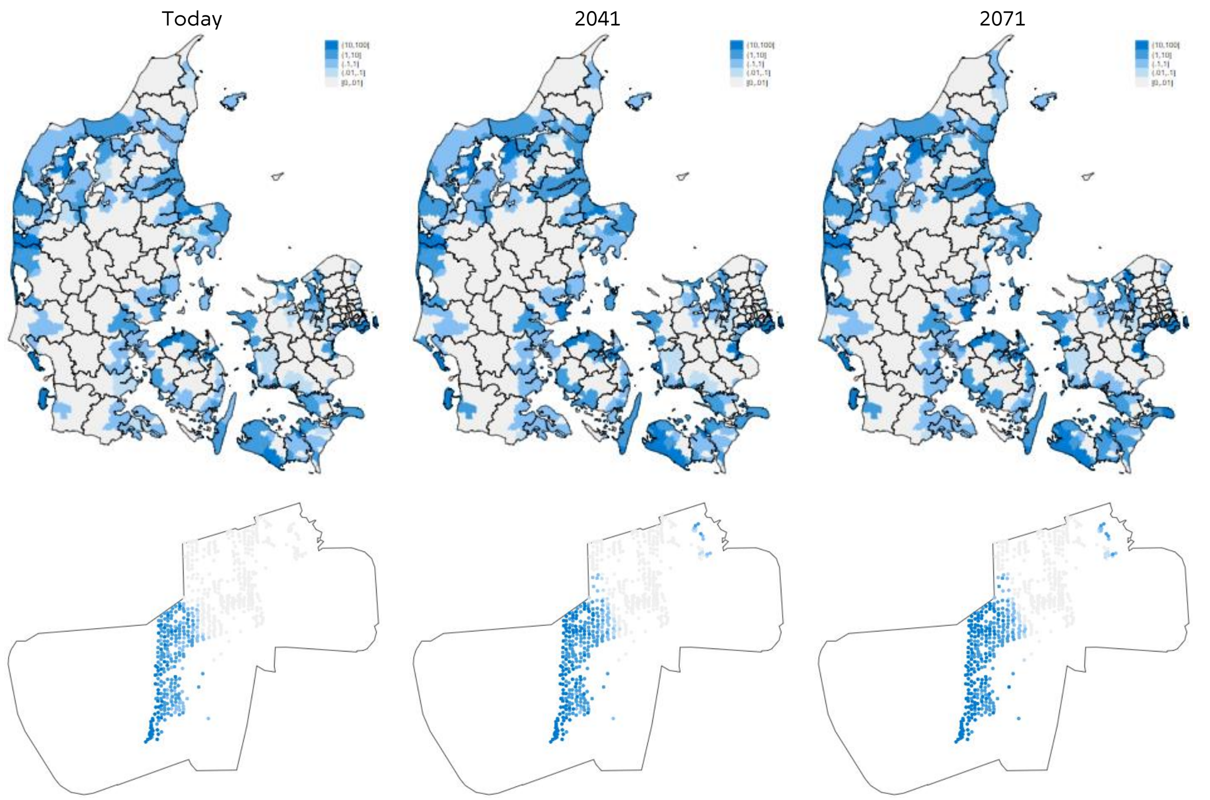
We find that the flood risk discount is higher after a flood occurs: following a great flood in Denmark in 1999, we saw higher discounts, which returned to the average level after around three years. A possible interpretation is that the occurrence of a flood temporarily increases the salience of flood risk in the minds of house buyers. They then demand higher discounts until the flood fades from new home buyers' memory.

We also find evidence regarding the pricing of future flood risks due to sea level rise: houses that are not exposed to flood risk today, but will be exposed to flood risk in the future, are priced at a lower discount of around half the discount on houses that are exposed to flood risk today. There could be multiple interpretations of this result: first, it could be that home buyers rationally discount future flood risk. A second possibility is that home buyers are short-sighted, meaning that they price today's flood risk, but not future flood risk due to a sea level rise. A third possibility is that households are still very uncertain about the change in flood risk due to sea level rises.

[5] 0.063 (see Table 1) x 1,603,820.00 DKK (see Table 5) = 101,040.66 DKK, to be exact.

The geographic distribution of flood risk; exposure to 100-year flood events per 100 houses

Chart 1



Note: The top row of this chart shows the fraction of houses exposed to flood risk today (left), in 2041 (middle) and in 2071 (right) at the post code level. The black outlines are municipalities. The bottom row of this chart displays the flood risk of clusters of at least five houses within municipalities for Tårnby, which is the municipality with the most exposed houses. About 20 per cent of houses exposed to flood risk are in this municipality. We display only single-family houses. Clusters of houses that are not exposed to flood risk are displayed in grey. The four shades of blue correspond to quartiles of flood risk exposure, with darker shades of blue implying that the water level will be higher for a specific house if a 100-year flood occurs. The data is from 1992 to 2020. Bornholm is excluded due to visualization purposes.

Source: Authors' calculations, based on data from the Sales and Valuation Register (SVUR), the Central Register of Buildings and Dwellings (BBR), and DTU.

What does the existing academic literature have to say about the effects of flood risk and sea level rises on house prices?

Whether sea level rise is incorporated into house prices or not is still an open question in the academic literature: there is evidence for the United States (US) that investors are already pricing the negative consequences of rising sea levels. For example, Bernstein et al. (2019) find for the US that houses exposed to sea level rise trade at a 7 per cent discount, and that these discounts are driven by institutional investors. Ortega and Tapinar (2018) and Giglio et al. (2015) also find evidence that sea level rise is priced. In contrast, Murfin and Spiegel (2020) do not find evidence for the pricing of sea level rise. There is also evidence that beliefs matter substantially for sea level rise discounts to arise: in the US, flood risk discounts are lower in areas where households are more skeptical about climate change (Baldauf et al. (2020), Bakkensen and Barrage (2017)).

Flood risk is priced in the housing market

Table 2

	(1)	(2)	(3)	(4)	(5)	(6)
flood risk exposure (100 years)	-0.0245	-0.00485	-0.0702***	-0.0675***	-0.0632***	-0.0237
	(-0.21)	(-0.18)	(-3.18)	(-3.62)	(-3.32)	(-0.83)
size dummies	Yes	Yes	Yes	Yes	Yes	Yes
age dummies	Yes	Yes	Yes	Yes	Yes	Yes
K	No	Yes	No	No	No	No
K x D	No	No	Yes	No	No	No
K x D x T	No	No	No	Yes	No	No
K x D x T x R	No	No	No	No	Yes	No
K x D x T x R x E	No	No	No	No	No	Yes
Observations	910095	910085	909997	792531	507959	450656

Note: This table shows the effect of flood risk exposure at the 100-year horizon on house prices from estimating the following equation:

$$\ln \mathrm{p_{it}} = \alpha + \beta_{\mathrm{flood}}\mathrm{flood\_exposure_i} + \beta_{size} size\_dummies_i + \beta_{age} age\_dummies_i + \gamma_K \times \gamma_D \times \gamma_E \times \gamma_t \times \gamma_R + \varepsilon_{it}$$

All specifications include 100 size quantile dummies and 100 age quantile dummies. *K* stands for 4-digit post code dummies. *D* stands for distance-to-sea dummies. *T* denotes year-times-month dummies. *R* denotes dummies for the number of bedrooms of a house. *E* denotes 1-metre elevation bins. Standard errors are clustered at the post code level. The data is from 1992 to 2020. t statistics in parentheses, * p<0.1, ** p<0.05, *** p<0.01

Source: Authors' calculations, based on data from the Sales and Valuation Register (SVUR), the Central Register of Buildings and Dwellings (BBR), and DTU.

Many of these studies measure exposure to sea level rise by whether a house will be permanently under water if the sea level rises by a certain amount. In contrast, our unique data on historical flood episodes enables us to estimate the pricing of the higher exposure to flood risk caused by the sea level rise. This is an important distinction, as severe floods leading to extreme, but temporary spikes in the water level can destroy many more houses than a modest increase in the sea level per se. Our estimates should be seen as the response of house prices to an increase in the risk of a rare disaster, in this case a catastrophic flood, not the response to sea level rises more generally.

Another literature looks at flood risk today without considering changes in flood risk due to sea level rises: Bin and Landry (2013), Atreya et al. (2013) and Atreya and Ferreira (2015) find evidence for the US that house prices factor in flood risk discounts after a flood occurs, but that these discounts diminish over time. They argue that this transitory effect reflects the salience of flood risk. Our finding that flood risk discounts increased after the flood of 1999, even for unaffected, exposed houses, is in line with this literature. Relative to these papers, our data allows us to study the interaction of flood risk and sea level rises due to climate change.

Flood risk in Denmark: today and in the future

In this section, we explore how flood risks are geographically distributed in Denmark, and how sea level rise will affect the distribution of flood risk. Due to rising sea levels, more areas will be affected by flood risk, and the areas that are affected today will also be affected more intensely.

Around 1 per cent of houses are exposed to flood risk today

Table 1 shows the fraction of single-family houses in Denmark that are exposed to flood risk. We consider a house to be exposed at the 20, 50 or 100-year horizon if it is expected to experience any flooding in case of a 20, 50 or 100-year flood. In 2021, 0.93 per cent of houses traded over the sample period (1992-2020) are exposed to some flood risk at a 20-year horizon. This means that in every year, there is a 5 per cent risk that any of these houses are flooded. An additional 0.2 per cent of houses are exposed to flood risk at a 50-year horizon, implying that there is a risk of 2-5 per cent that they are flooded in a given year. Finally, another 0.13 per cent of houses are exposed to flood risk at a 100-year horizon. This means that 1.26 per cent of houses have at least a 1 per cent risk of being flooded in a given year.

Sea level rise will roughly double the fraction of houses exposed to flood risk by 2071

There is still substantial uncertainty about the degree to which sea levels can be expected to rise over the next century, as the actual sea level rise will depend on the carbon emission reductions that can be achieved. Therefore, our sea level rise projections are based on different scenarios.

In a sea level rise scenario that implies a substantial reduction in carbon emissions by the middle of the century (the IPCC RCP 4.5 scenario), the fraction of houses exposed to flood risk at the 100-year horizon is expected to increase to 1.79 per cent of houses traded over the sample period by 2041 and 2.21 per cent of houses by 2071. Thus, over the next 50 years, the fraction of single-family houses in Denmark that are exposed to flood risk will nearly double. This scenario is widely considered to be the most likely. We will refer to it as the baseline scenario.

In a scenario that implies no reductions in carbon emissions (the IPCC RCP 8.5 scenario), the fraction of houses exposed to flood risk will increase to up to 2.95 per cent. This scenario is widely considered to be unlikely, and we will refer to it as the pessimistic scenario.

Flood risk is highly concentrated in a few municipalities in Denmark

The top row in Chart 1 shows the share of houses in a given post code in Denmark that are exposed to flood risk, with darker shades of blue representing a higher share of flood risk exposure. Here, we define a house as exposed to flood risk if it will be under water if a 100-year flooding event occurs. From left to right, we show the fraction of houses that are exposed to flood risk today, in 2041 and in 2071 in the baseline (RCP 4.5) scenario. Overall, while there are properties that are exposed to flood risk along the entire coast of Denmark, flood risk is highly concentrated in a few areas, marked by the darkest shade of red. For example, more than 30 per cent of the houses that are exposed to flood risk are in Tårnby and Dragør close to Copenhagen.

Even within municipalities, flood risk is concentrated

In the bottom three panels of Chart 1, we show the distribution of flood risk in the municipality with the highest fraction of exposed houses, Tårnby, and how this distribution is expected to change over time in the baseline (RCP 4.5) scenario. Each dot in the chart is a cluster of at least five houses. We sort houses into four groups, based on the water levels if flooded, with darker shades of blue corresponding to higher water levels. Clusters of houses that are not exposed to flood risk are displayed in grey. Flood risk is concentrated in the west of the municipality. As the sea level is expected to rise, more and more houses will be exposed to flood risk, with some houses in the east of the municipality also becoming exposed. In addition, the houses that are exposed will experience a higher water level if flooded.

Flood risk discounts in the housing market

In this section, we investigate how flood risk affects house prices. First, we explain our identification strategy and present the baseline results. Next, we separately vary the probability of flooding and the level of flooding. Finally, we use the flood of 1999 to study how the flood risk discount responds to an increase in the salience of flood risk.

Baseline model and identification

In our baseline specification, we compare houses that are sold in the same month in the same municipality, located at the same distance to the coast and with the same number of bedrooms. Moreover, we control flexibly for the size and the age of houses. The identifying assumption for a causal effect of flood risk on house prices is that conditional on this rich set of characteristics, there are no unobserved characteristics that are correlated with flood risk and affect house prices. In particular, it is very important that we control for distance to the coast, which is a characteristic that is valued and highly correlated with flood risk. We describe our methodology in more detail in Box 5.

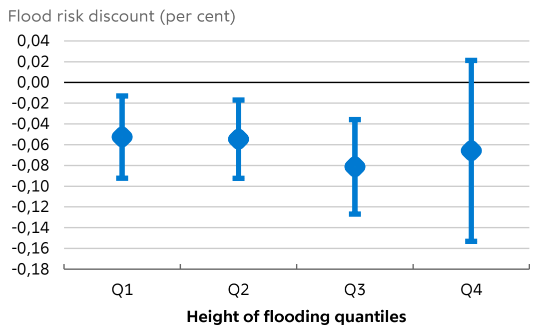
Results

Table 2 presents the baseline results. Model (1) is a regression that controls flexibly for size and age by introducing 100 fixed effects for each of these variables, but which contains no additional fixed effects. In this regression, we find that higher flood risk exposure is associated with a lower house price, though the coefficient is not significantly different from zero at the 10 per cent confidence level. Model (2) additionally controls for post code fixed effects. This increases the coefficient slightly, implying that houses with high flood risk exposure tend to be in municipalities with low house prices. Model (3) additionally controls for the distance to the sea, using fine-grained distance-to-the-sea bins. This results in a negative effect of flood risk on house prices that is both strongly statistically significant and economically large. The coefficient implies that houses that have a risk of being flooded of at least 1 per cent per year are traded at a discount of 7 per cent relative to houses in the same municipality located at a similar distance to the sea, and of similar size and age.

Next, model (4) introduces time fixed effects, which does not change the size of the coefficient much relative to model (3). When introducing fixed effects for the number of rooms in model (5), we again find a similar discount of around 6 per cent. Finally, when also introducing one-metre elevation bin fixed effects in model (6), the effect of flood risk exposure falls and is no longer significant.

In unreported results, we explored the role of elevation further. In short, in contrast to the US, where Bernstein et al. (2019) still find sufficient variation in flood risk conditional on elevation, the geography of Denmark is such that conditional on controlling for interacted post code, distance-to-the-sea bin and elevation bin fixed effects, there is not much variation in flood risk exposure. Nevertheless, model (6), which compares houses with different exposures to flood risk, but the same number of bedrooms, located in the same municipality, with the same date of sale, located at the same distance to the sea and at the same elevation above sea level, still finds a weakly negative effect of flood risk on house prices.

A higher water level during a flood does not imply a higher flood risk discount Chart 2



Note: This chart shows how flood risk discounts vary with the height of the water level during a flood. We estimate the following equation:

$$\ln p_{it} = \alpha + \beta_{flood,j} \sum_{j=1}^{4} flood\_exposure_i 1(i \in Q_j) + \beta_{size} size\_dummies_i + \beta_{age} age\_dummies_i + \gamma_K \times \gamma_D \times \gamma_E \times \gamma_t \times \gamma_R + \varepsilon_{it}$$

That is, we replace the flood risk indicator with separate dummies for each water level quartile. All specifications include size and age dummies, as well as interacted post code, year-month, number-of-bedrooms and distance-to-sea dummies. Standard errors are clustered at the post code level. The confidence intervals displayed are at the 95 per cent level. The data is from 1992 to 2020.

Source: Authors' calculations, based on data from the Sales and Valuation Register (SVUR), the Central Register of Buildings and Dwellings (BBR), and DTU.

Height of the water level during a flood
In the previous subsection, our measure of flood risk only reflected whether houses are exposed to flood risk or not. One concern with this measure is that households do not care about flooding if the water level during a flood is low. As we have information on the height of the flooding conditional on a given flood risk event, we can also investigate how flood risk discounts vary with the height of the flooding. For that purpose, we sort the exposed houses into four groups by the quartile of their flood risk intensity.

Chart 2 displays the flood risk coefficients. Consistent with the idea that the coefficients capture flood risk, we find that for the first three flood risk intensity quartiles, a higher intensity of flooding is associated with a larger discount. However, these coefficients are not statistically distinguishable from each other.

For the highest flood risk quantile, we find a smaller and very imprecisely estimated coefficient. In unreported results, we show that houses in the highest flood risk intensity quartile are much cheaper, smaller, older and more rural than other houses. One possible explanation for why we do not find a discount for these houses is that they are bought by people with different attitudes and perceptions about flood risk compared to the rest of the market.

The probability of flood risk exposure
Table 3 varies the probability of the flood risk exposure. Model (1) repeats our baseline specification, showing a flood risk discount of around 6 per cent for houses that have a probability of being flooded of at least 1 per cent per year.

Model (2) restricts the set of houses exposed to flood risk to include only those that will be exposed at a 50-year event, finding a similar effect of flood risk on house prices for those houses that have a risk of being flooded of at least 2 per cent per year.

Model (3) restricts the set of exposed houses further to those that are exposed at the 20-year horizon. Thus, it only defines houses as exposed that have a probability of being flooded of at least 5 per cent. The result is again a similar flood risk discount of around 6 per cent. This shows that houses that are exposed to some flood risk are priced at a discount, independently of how likely the flood event is.

Model (4) includes dummies for all three sets of houses, finding that the negative effect of flood risk on house prices is similar for all sets of houses. A possible interpretation of this result is that home buyers can only distinguish whether

Flood risk exposure at different time horizons is not priced

Table 3

	(1)	(2)	(3)	(4)
flood risk exposure (100 years)	-0.0632***			
	(-3.32)			
flood risk exposure (50 years)		-0.0626***		
		(-3.08)		
flood risk exposure (20 years)			-0.0586***	-0.0640***
			(-2.64)	(-2.80)
Only 50yr exposure				-0.0645**
				(-2.32)
Only 100yr exposure				-0.0554*
				(-1.74)
size dummies	Yes	Yes	Yes	Yes
age dummies	Yes	Yes	Yes	Yes
K x D x T x R	Yes	Yes	Yes	Yes
Observations	507959	507959	507959	507959

Note: This table varies the time horizon of flood risk exposure. It is based on estimating the following equation:

$$\ln p_{it} = \alpha + \beta_{flood} \text{flood\_exposure}_i + \beta_{size} size\_dummies_i + \beta_{age} age\_dummies_i + \gamma_K \times \gamma_D \times \gamma_E \times \gamma_t \times \gamma_R + \varepsilon_{it}$$

Model (1) is the baseline specification, which measures flood risk exposure to a 20-year event. Model (2) additionally includes houses that are exposed to flood risk from a 50-year event, model (3) additionally also houses that are exposed to flood risk from a 100-year event. Model (4) includes separate dummies for houses that are exposed only at the 50-year horizon and only at the 100-year horizon. All specifications include 100 size quantile dummies and 100 age quantile dummies. *K* stands for 4-digit post code dummies. *D* stands for distance-to-sea dummies. *T* denotes year-times-month dummies. *R* denotes dummies for the number of bedrooms of a house. Standard errors are clustered at the post code level. The data is from 1992 to 2020. t statistics in parentheses, * p<0.1, ** p<0.05, *** p<0.01

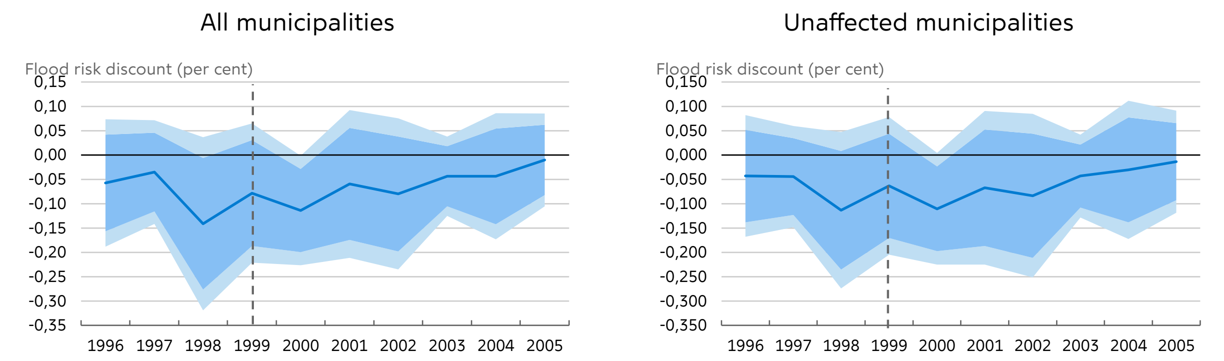
Source: Authors' calculations, based on data from the Sales and Valuation Register (SVUR), the Central Register of Buildings and Dwellings (BBR), and DTU.

a house is exposed to flood risk or not, but do not know the exact probability of a flood.

Difference-in-difference specification

To provide further evidence on how flood risk affects house prices, we now investigate the effect of a flood in Denmark: on 3 December 1999, a severe storm, the so-called December Hurricane, struck the coast of Denmark. This is considered to be the second most severe flood

The flood risk discount increased around the December Hurricane of 1999 Chart 3



Note: This chart shows the pricing of flood risk around the 1999 December Hurricane. It is based on an estimation of the following equation:

$$\ln p_{it} = \alpha + \sum_s \beta_{flood,s} flood\_exposure_i \times year_s + \beta_{size} size\_dummies_i + \beta_{age} age\_dummies_i + \gamma_K \times \gamma_D \times \gamma_E \times \gamma_t \times \gamma_R + \varepsilon_{it}$$

The top panel reports the coefficient for the full sample, the bottom panel the coefficient for the sample that excludes directly affected areas. All specifications include age and size dummies, as well as interacted post code (K), year-times-month (t), number-of-bedrooms (R) and distance-to-sea (D) dummies. Standard errors are clustered at the post code level. The confidence intervals displayed are at the 95 per cent level. The data is from 1992 to 2020.

Source: Authors' calculations, based on data from the Sales and Valuation Register (SVUR), the Central Register of Buildings and Dwellings (BBR), and DTU.

in Denmark in centuries, with the most severe storm (called "the great drowning") having been recorded in 1362. As a result of the December Hurricane, seven people died, around 800 were hospitalised and insurance companies recorded claims of around 13 billion DKK.[6]

Importantly, the flood only affected the west coast of Denmark in Jutland, with Zealand and Funen not being affected. This allows us to rule out that discounts on houses on Funen and Zealand were driven by actual flooding damage and not flood risk. Our hypothesis is that houses on Zealand that are exposed to flood risk were nevertheless sold at a larger discount after the storm, as flood risk suddenly became very salient.

We compare houses before and after the storm that are located in the same municipality, at the same distance to the sea, with the same number of bedrooms and that were sold in the same month, but with different exposures to flood risk. This is thus a difference-in-difference design.

The left panel of Chart 3 shows the flood risk coefficient for the full sample over time. Before 1999, the coefficient on flood risk is negative. In magnitude, it is similar to the unconditional flood risk coefficient that we estimated in Table 2, model (5), but it is not significantly different to zero at the 5 per cent confidence level.[7][8] In December 1999, the flood happened. In 2000, the coefficient falls, becoming significantly different to zero at the 1 per cent confidence level. From then onwards, the flood risk coefficient increases strongly and becomes statistically indistinguishable from zero again.

The coefficient in the full sample could not only reflect flood risk, but also whether houses were actually damaged by the flood. To isolate the indirect effect of flood risk, we therefore investigate how the flood risk discount evolved

[6] See e.g. https://www.dmi.dk/vejr-og-atmosfare/temaforside-decemberorkanen-1999/.

[7] The lower significance is due to a loss in statistical power, as we now estimate one flood risk coefficient for each single year instead of one flood risk coefficient for the entire sample.

[8] There is a fall in the coefficient in 1998, where there was no flood. However, the coefficient is very imprecisely estimated compared to all other years.

for houses that were not located in municipalities which recorded flooding damage in December 1999 or January 2000, according to the damage statistics of the Danish storm council. The right panel of Chart 3 shows the flood risk coefficient for this group of houses. Similar to before, the flood risk coefficient falls in 2000 and returns to zero from then onwards. It is significantly different to zero at the 5 per cent level in 2000.

Why do we find an even stronger flood risk discount for houses that were not exposed to the flood than for houses that were exposed to the flood? One important reason might be that houses that were damaged by the flood became very difficult to sell: in this case, we would observe fewer transactions of houses that were damaged by the flood, and thus also fewer sales prices. the estimate would therefore underestimate the flood risk discount in affected areas.

The pricing of sea level rise

In this section, we investigate whether expected future flood risks due to sea level rises are factored into house prices. For that purpose, we test whether houses that are not even exposed to a 100-year flood today, but might be exposed to a 100-year flood from 2041 onwards or 2071 onwards, are traded at a discount.

Table 4 shows the results. Again, Model (1) in the first column repeats our baseline specification from Table 2. Models (2) and (4) increase the set of houses to additionally include those that will be exposed to 100-year flooding events in 2041, finding a lower coefficient than in the baseline regression. Models (3) and (5) extend the sample further to include houses that are exposed to 100-year flooding events at the earliest in 2071, finding even lower coefficients.

Models (6) and (7) include dummies for all three sets of houses, finding a discount for houses that are exposed to flood risk today similar to before. Relative to similar houses that are not exposed to flood risk, these houses trade at a discount of around 7 per cent. Houses that will be exposed to flood risk from 2041 onwards trade at a discount of 3-4 per cent. The coefficient for houses exposed from 2041 onwards is about half the coefficient today. We also find a significant effect for houses that will be exposed to flood risk in 2071. That coefficient is similar to the discount on houses that are exposed from 2041 onwards, but it is less precisely estimated.

These coefficients imply a discount of 3-4 per cent of the house value or between 60,000 DKK and 70,000 DKK for your average house, which is economically large. When comparing the different scenarios, we find no big difference between the discount on houses that would be exposed in the realistic RCP 4.5 scenario and those that would be exposed in the pessimistic RCP 8.5 scenario in terms of the size of the coefficients.

Conclusion

We investigate the effect of flood risk and sea level rise on house prices. Using data that combines historical sea level information with sea level rise projections enables us to measure the exposure of single-family houses in Denmark to flood risk at different points in time. We merge this data with the universe of housing transactions in Denmark and rich data on housing characteristics.

To identify the effect of flood risk, we rely on a specification that compares houses with similar observable characteristics. We find that flood risk is priced, even after controlling for the distance to the sea of a house. In our preferred specification, in which we compare houses of the same size in the same post code, sold in the same month of the same year, and located at a similar distance to the sea, exposure to flood risk reduces house prices by around 6 per cent.

We provide additional evidence on the flood risk discount over time by employing a difference-in-difference scheme around a severe flood in Denmark in 1999. We find that in the years after the flood, flood risk discounts increased even in regions that were not hit by the flood. This suggests that the salience of flood risk varies over time, and increases after actual floods. It is important because it implies that floods are not only associated with direct economic losses through the damage they cause, but also with indirect economic losses through losses in house valuations.

We find that the expected future increase in flood risk due to sea level rise is priced, but at a lower discount. In particular, we find that houses that are not exposed to flood risk today, but will be exposed after 2041, are sold at a discount of around 3-4 per cent. This might be a sign that future flood risk due to climate change is not particularly salient, that it is discounted, or that households are uncertain about the extent of the sea level rises.

Exposure to future flood risk due to sea level rises is priced, but at a lower discount Table 4

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
flood risk exposure (100 years)	-0.0632***					-0.0682***	-0.0709***
	(-3.32)					(-3.54)	(-3.69)
RCP4.5 2041 flood risk exposure (100 years)		-0.0545***					
		(-3.53)					
RCP4.5 2071 flood risk exposure (100 years)			-0.0530***				
			(-3.67)				
RCP8.5 2041 flood risk exposure (100 years)				-0.0532***			
				(-3.53)			
RCP8.5 2071 flood risk exposure (100 years)					-0.0506***		
					(-3.88)		
Only exposed from 2041, RCP4.5						-0.0336**	
						(-2.16)	
Only exposed from 2071, RCP4.5						-0.0403*	
						(-1.91)	
Only exposed from 2041, RCP8.5							-0.0391**
							(-2.41)
Only exposed from 2071, RCP8.5							-0.0363**
							(-2.31)
size dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes
age dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes
K x D x T x R	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	507959	507959	507959	507959	507959	507959	507959

t statistics in parentheses
* p<0.1, ** p<0.05, *** p<0.01

Note: This table varies the time horizon of flood risk exposure. It is based on estimating the following equation:

$$\ln p_{it} = \alpha + \beta_{flood} flood\_exposure_i + \beta_{size} size\_dummies_i + \beta_{age} age\_dummies_i + \gamma_K \times \gamma_D \times \gamma_E \times \gamma_t \times \gamma_R + \varepsilon_{it}$$

Model (1) is the baseline specification, which measures flood risk exposure to a 100-year event. Model (2) additionally includes houses that are exposed to flood risk from a 100-year event in 2041 in the RCP 4.5 scenario, model (3) additionally also houses that are exposed to flood risk from a 100-year event in 2071 in the RCP 4.5 scenario. Models (4) and (5) redo the same results for the RCP 8.5 scenario. Models (6) and (7) include separate dummies for houses that are exposed at the 100-year horizon only from 2041 and only from 2071 in the RCP 4.5 and RCP 8.5 scenarios, respectively. All specifications include 100 size quantile dummies and 100 age quantile dummies. *K* stands for 4-digit post code dummies. *D* stands for distance-to-sea dummies. *T* denotes year-times-month dummies. *R* denotes dummies for the number of bedrooms of a house. Standard errors are clustered at the post code level. The data is from 1992 to 2020.

Source: Authors' calculations, based on data from the Sales and Valuation Register (SVUR), the Central Register of Buildings and Dwellings (BBR), and DTU.

Data description – data construction and sample selection

Box 3

Our data ranges from 1992 until 2020. The unit of observation of the data is a single housing transaction. We combine data from three different sources: first, we use data from the Danish Central Register of Buildings and Dwellings, which contains information about house characteristics, like total square metres. Second, we use data from the Danish Customs and Tax Administration about houses, which contains house prices. Third, we obtain flood risk indicators for each location in Denmark from the Danish Coastal Authority. The following section describes these data sources. To allow a mapping between these different data sources, we focus on single-family houses.

Flood risk indicators

We obtain detailed information on flood risk from the Technical University of Denmark (DTU). For each house, we obtain the expected water level in different flood scenarios, e.g. the water level that is expected to occur at least once every 100 years. The local expected flood intensity in each scenario is obtained from probability distributions of the maximum water level over different time horizons, measured at 67 water level gauge stations all over Denmark. For our baseline results, we use the average maximum water level that is expected to occur over a 100-year horizon. This data on water levels is then combined with a detailed elevation map based on a 4-metre raster of Denmark to simulate the expected maximum increase in water level for each location over different time horizons and in different climate change scenarios. The simulation incorporates currently existing protective measures such as floodgates and dykes. Finally, for the projected flood risk increases due to sea level rises, the output from this simulation is combined with mean sea level rise projections for Denmark.[9]

Housing data

We combine the data on flood risk for each house with information about housing transactions and housing characteristics. Our house price data consists of prices from actual sales, which we obtain from administrative records from the Danish public Sales and Valuation Register (SVUR) of the Danish Customs and Tax administration. In our main analysis, we focus on single-family houses. We use the following data: the sales price and the time of sale. The unit of observation in the data is a sale. The data on house prices can be linked to data on housing characteristics: The Central Register of Buildings and Dwellings of the IT and Development Agency contains detailed information on every building in Denmark. We obtain the following data: total square metres, the number of bedrooms, the type of property (house, apartment, summer house), the location of the property, its age, the number of bathrooms, the post code and municipality the house is in, the coordinates of the house and so on. In addition, since we know the exact location of each house, we use the geographic software QGIS to calculate the distance of each house from the sea.

[1] In total, we obtain 18 scenarios: the mean water level rise in connection with 20, 50 and 100-year events today, in the RCP 4.5 scenario in 2041-2070 and 2071-2100 and in the RCP 8.5 scenario in 2041-2070 and 2071-2100, and the 95 per cent quantile water level rise in the RCP 8.5 scenario in 2071-2100.

[9] In total, we obtain 18 scenarios: the mean water level rise in connection with 20, 50 and 100-year events today, in the RCP 4.5 scenario in 2041-2070 and 2071-2100 and in the RCP 8.5 scenario in 2041-2070 and 2071-2100, and the 95 per cent quantile water level rise in the RCP 8.5 scenario in 2071-2100.

Data description – houses exposed to flood risk are broadly similar to other houses

Box 4

Summary statistics

Table 5

	all houses	never exposed	exposed today	exposed after 2041	exposed after 2071
house price (2015 DKK, '000)	1545.92	1542.47	1603.82	1833.09	1809.43
	(1292.56)	(1283.85)	(1438.72)	(1960.69)	(1658.27)
price per m2 (2015 DKK)	9551.18	9526.88	10111.83	11090.08	11561.62
	(7958.71)	(7919.61)	(9026.39)	(10123.64)	(9780.66)
no. of sales	2.39	2.39	2.41	2.38	2.35
	(1.28)	(1.27)	(1.30)	(1.27)	(1.22)
age (years)	47.20	47.14	48.31	51.13	51.37
	(32.71)	(32.66)	(34.15)	(36.32)	(35.16)
total m2	144.55	144.67	139.02	140.97	137.26
	(46.13)	(46.15)	(45.39)	(45.40)	(42.89)
no. of rooms	4.83	4.84	4.66	4.68	4.61
	(1.42)	(1.42)	(1.41)	(1.42)	(1.36)
distance to sea (km)	7.84	7.99	1.39	1.00	0.94
	(8.90)	(8.94)	(1.68)	(1.35)	(1.07)
elevation (m)	29.06	29.68	1.53	1.72	1.82
	(21.82)	(21.67)	(2.74)	(1.11)	(1.45)
Observations	1255520	1227742	15776	6665	5337

Mean coefficients; SD in parentheses

Note: This table displays summary statistics for the subsample of housing sales that are exposed to 100-year flood events and the subsample of housing sales that are not exposed to flood events. The projections are based on the RCP 4.5 scenario.
Source: Authors' calculations, based on data from the Sales and Valuation Register (SVUR), the Central Register of Buildings and Dwellings (BBR), and DTU.

Table 6 shows summary statistics for our final sample. The data set runs from 1992 to 2020. It comprises around 1.25 million observed transactions. The average sales price is 1.46 million DKK, in 2015 prices. The average price per square metre is around 10,000 DKK. Houses are sold an average of 2.4 times between 1992 and 2020. The typical house is 47 years old and has a floor area of 145 square metres and five rooms. It is 8 kilometres from the sea and 30 metres above sea level.

Table 6 also splits the sample according to whether houses are exposed to a 100-year flooding event or not. Houses that are exposed to flood risk are slightly more expensive and have higher square metre prices. They are sold as often as houses that are not exposed to flood risk, suggesting that they are similarly liquid. They are also similar in terms of size and age. However, houses that are exposed to flood risk are much closer to the sea than houses that are not exposed to flood risk, and their elevation is much lower.

Econometric method

Box 5

Baseline model and identification

To identify the causal effect of flood risk on house prices, we follow Bernstein et al. (2019) and estimate the following hedonic regression:

$$\ln p_{it} = \alpha + \beta_{flood} \text{flood\_exposure}_i + \beta_{size} size\_dummies_i + \beta_{age} age\_dummies_i + \gamma_K \times \gamma_D \times \gamma_E \times \gamma_t \times \gamma_R + \varepsilon_{it}$$

Here, $flood\_exposure_i$ is a dummy variable for flood risk exposure. In our baseline specification, we measure flood risk exposure at the 100-year horizon. This is the most restrictive specification, which focuses only on houses with salient flood risk at a relatively short time horizon. $size\_dummies_i$ and $age\_dummies_i$ are dummies for each size and age centile, which non-parametrically control for house size and age. γ_t is year-times-month fixed effect. γ_D a distance-to-coast fixed effect. There are eight bins for distance to coast, with cutoffs 32.25, 62.5, 125, 250, 500 metres, and 1 and 2 kilometres. We drop all observations that are farther away from the sea than 10 kilometres, as no observations that far away from the sea are exposed to flood risk. γ_E is an elevation level fixed effect. We choose 10-metre elevation bins for this fixed effect. γ_K is a post code fixed effect and γ_B a number-of-bedrooms fixed effect. ε_{it} is an error term, which we cluster at the municipal level.

Flood risk intensity

In the previous subsection, our measure of flood risk only reflected whether houses are exposed to flood risk or not. As we have information on the height of the flooding conditional on a given flood risk event, we can also investigate how flood risk discounts vary with the intensity of flood risk exposure. For that purpose, we sort the exposed houses into four groups by the quartile of their flood risk intensity. We then estimate the following regression:

$$\ln p_{it} = \alpha + \beta_{flood,j} \sum_{j=1}^{4} \text{flood\_exposure}_i 1(i \in Q_j) + \beta_{size} size\_dummies_i + \beta_{age} age\_dummies_i + \gamma_K \times \gamma_D \times \gamma_E \times \gamma_t \times \gamma_R + \varepsilon_{it}$$

This implies that we allow the flood risk coefficient to vary across the intensity quartiles for flood risk. We include interacted post code, distance-to-the-sea, time and number-of-bedrooms fixed effects to compare similar houses.

Difference-in-difference specification

We estimate the following specification:

$$\ln p_{it} = \alpha + \sum_{s} \beta_{flood,s} \text{flood\_exposure}_i \times year_s + \beta_{size} size\_dummies_i + \beta_{age} age\_dummies_i + \gamma_K \times \gamma_D \times \gamma_E \times \gamma_t \times \gamma_R + \varepsilon_{it}$$

$\beta_{flood,s}$ is the time-varying coefficient of flood risk. This is a difference-in-difference design: we compare houses before and after the storm that are in the same municipality, are located at the same distance to the sea, have the same number of bedrooms and are sold in the same month, but with different exposures to flood risk.

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Climate change

Climate change is impacting society already today and will have further consequences in the future. A successful green transition will require unprecedented efforts, both in Denmark and abroad.

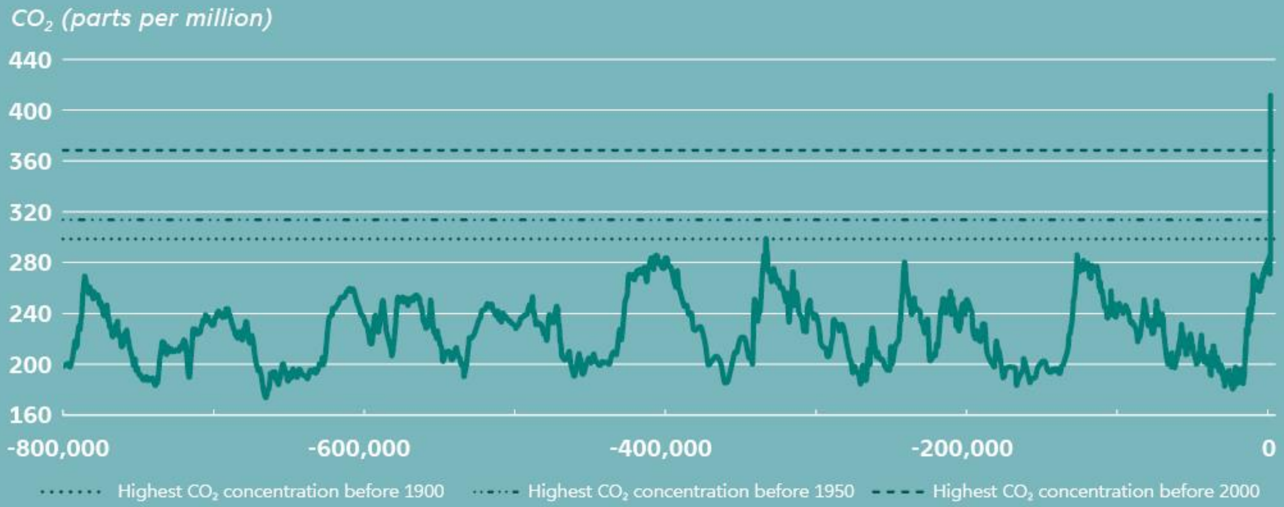
As a case in point, climate change and the transition to a greener economy will impact corporate earnings and economic activity. This may compromise price and financial stability in Denmark, which it is Danmarks Nationalbank's objective to ensure. It is therefore essential that Danmarks Nationalbank increases its knowledge of how, and by how much, the climate challenges will impact various parts of the economy.

Against this backdrop, Danmarks Nationalbank will focus on climate challenges in a series of publications.

CO_2 concentration in the atmosphere

800,000 BCE to 2019 ACE

The chart shows the number of carbon dioxide molecules per million molecules of dry air.



Source: National Oceanic and Atmospheric Administration (until 1957) and National Aeronautics and Space Administration (from 1958).

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