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Financial constraints and short-term planning are linked to flood risk adaptation gaps in US cities

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Adaptation is critical in reducing the inevitable impact of climate change. Here we study cities' adaptation to elevated flood risk by introducing a linguistic measure of adaptation extracted from financial disclosures of 431 US cities over 2013–2020. While cities with a higher flood risk have higher adaptation, more than half of high-risk cities have below-average adaptation levels. We explore three factors associated with this adaptation gap, defined as a city's adaptation being lower than predicted based on flood risk. We do not find that Republican cities are more likely to have an adaptation gap. Instead, our results point to the importance of financial constraints: cities with one standard deviation smaller unrestricted-fund-to-expense ratio are 6.6% more likely to have an adaptation gap. We also provide evidence on the importance of long-term planning: cities with a planning horizon shorter by one year are 4% more likely to have an adaptation gap.

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Climate change poses an imminent threat to humanity's vulnerability to rising sea levels, higher temperatures, and other negative consequences of changing weather patterns¹. It is unlikely that these challenges could be avoided even under the optimistic scenario of limiting global warming to 1.5 °C. The places with a high concentration of risk and population have to adapt—i.e., invest in reducing the harmful impact of climate change. This underscores the urgency of concerns about the existence of an adaptation gap, the difference between current levels of adaptation and the levels needed to reduce the impacts of climate risks¹.

Understanding the factors behind the adaptation gap is crucial to inform policymaking in the wake of escalating climate risks. However, systematic evidence on the adaptation gap has been hindered by data scarcity. The details of cities' existing infrastructure and future adaptation plans are not readily available and must be collected at the individual city level. Because of data limitations, the existing literature resorts to examining case studies, conducting surveys, or using socio-economic variables to approximate cities' adaptation^{2–5}.

Here, we provide large sample evidence on adaptation gaps by extracting and analyzing adaptation data from 8726 hand-collected financial disclosures of 431 US cities over 2013–2020. US cities regularly report audited financial disclosures containing material information about adaptation, which guarantees that important existing and future adaptation programs will be picked up by textual analysis. For our textual analysis, we create and validate a dictionary that is specifically designed to capture city-specific hard and soft adaptation strategies for flood risk. To study adaptation gaps in cities, we combine this textual data with independent flood risk assessments, hand-collected partisanship data, as well as financial and socio-economic city characteristics (see Methods).

We empirically examine whether the factors cited in the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) Cross-Chapter Paper 2 are associated with adaptation gaps. Specifically, IPCC AR6 identifies three factors, or “enabling conditions,” that can enable and incentivize adaptation by cities: behavioral change, financial resources, and good governance¹.

First, IPCC discusses the importance of local beliefs about and perceptions of climate risks in enabling adaptation. To assess the importance of local beliefs in flood-risk adaptation gaps, we examine political affiliation. In the US, partisanship is a major factor correlated with attitudes toward climate change, with Republicans expressing more skepticism about the issue^{6–10}. If the Republican constituents place a lower probability on climate hazards due to their political views^{11,12}, we would see lower levels of adaptation in cities with Republican leaders. On the other hand, responsible managers are expected to plan ahead and assess future hazards, make preparations, and invest in adaptation measures, especially in areas with high flood risk. If political affiliation does not change climate-change risk assessment but merely affects the partisan rhetoric, we would observe no difference in real adaptation actions between Republican and non-Republican cities.

Second, IPCC AR6 identifies the financial constraint as another factor contributing to cities' under-investment in adaptation^{1,13}. Cities with scarce resources don't have enough funds to invest in the necessary infrastructure, technology, or programs to adapt to the impacts of climate change. Tackling flood-related climate risks is costly: according to the 2020 data from the CDP (previously called the Climate Disclosure Project), an average adaptation project for flood risk in the US costs \$307 million¹⁴. Moreover, a CDP survey finds that among cities that did not have an adaptation plan, 25% cite financial constraint as a barrier¹⁵. Consequently, we expect cities with limited funding and credit to be more likely to exhibit a gap in adaptation.

Finally, IPCC AR6 highlights good governance as its third enabling condition^{1,16,17}. Good governance manifests in a long

planning horizon. Long-term planning is particularly important in addressing flood risk, which is projected to increase due to rising sea levels and changing precipitation patterns. In contrast, short planning horizon may prevent a city from incorporating long-term risks into its decision-making process¹. This idea is similar to corporate myopia, where more short-term financial disclosure causes managers to make myopic decisions, such as under-investing in long-term capital expenditures^{18–20}. We predict that cities with a shorter-term capital budget outlook are more likely to have an adaptation gap. Such myopia can be a result of financial constraints, where cities with higher interest rates put more emphasis on short-term results. However, shorter planning horizons can also stem from governance frictions. These can include poor organizational structure, electoral term limits, agency problems within the local government, and local officials lacking the necessary knowledge, resources, or expertise to plan effectively^{21–25}.

Our analysis reveals significant variation in the level of adaptation across US cities (Figs. 1a, 2). While there is a positive correlation between a city's flood risk and its adaptation, we observe a concerning gap: over half of high-risk cities adapt less than predicted by their flood risk exposure. Upon further examination, we find that cities with financial constraints and shorter planning horizons are more likely to experience this adaptation gap (Figs. 3, 4). In contrast, we do not find that political affiliation is associated with having an adaptation gap. Cross-sectional tests show that state grants and high local household income do not fully mitigate these constraints and that the financial constraints appear to be more important in the areas that face high flood risks and in the counties where the citizens expect their local officials to do more to combat the consequences of global warming (Fig. 5).

Results

We follow the literature and consider two adaptation categories: hard and soft adaptation^{26–31}. Hard adaptation includes building physical infrastructure and upgrading existing infrastructure, such as seawalls and drainage systems. Soft adaptation involves using natural solutions, such as beach nourishment and mangrove restoration, to decrease flood risk.

To quantify adaptation at the city level, we create a city-specific adaptation dictionary and leverage it to conduct a textual analysis of a comprehensive collection of financial disclosures, including budgets, annual comprehensive financial report (ACFR), and bond prospectuses, that we gather manually. Our dictionary contains 177 keywords in three categories: hard adaptation, soft adaptation, and general adaptation (see Supplementary Table 1 for the keywords and Supplementary Note 1 for more details). General adaptation includes phrases that represent climate adaptation but cannot be classified into soft or hard adaptations, such as “flood relief” and “flood reduction”.

Our main adaptation measure is the number of adaptation sentences in budgets and ACFRs per city-year. We choose the number of sentences as our main measure because based on our reading of cities' financial disclosures, we believe that the number of sentences correlates closely with the number of adaptation activities. Similarly, in other natural processing language papers that examine climate risks, a sentence is often used as the smallest unit for analysis³². This is because a sentence typically constitutes a single, complete logical statement within the text, often embodying one distinct idea (see Supplementary Note 4 for excerpts from financial disclosures to illustrate this point). We discuss robustness (and provide corresponding results) to alternative definitions of our measure in Supplementary Note 6.

While we collected a total of 8726 financial reports, we require a city-year to have both budgets and ACFRs to ensure consistency of

our measure across city-years. We identify 3161 city-year observations from 431 cities with both budgets and ACFRs (Supplementary Table 2). For each city-year, we combine information from budgets and ACFRs to create three metrics: (1) main adaptation, which is the total count of general, hard, and soft adaptation sentences, (2) hard adaptation, which is the number of hard adaptation sentences, and (3) soft adaptation, which is the number of soft adaptation sentences. Among this sample, 2011 city-years also have at least one bond prospectus. For this subsample, we separately create a measure labeled as main+bond adaptation, which is the total count of general, hard, and soft adaptation sentences from budgets, ACFRs, and bond prospectuses.

The 3161 city-years have an average of 19.94 main adaptation sentences in their budgets and ACFRs, with a mean of 14.99 hard adaptation and 1.63 soft adaptation sentences (Supplementary Table 3). Consistent with cities discussing adaptation actions in their budget's capital improvement plans, budgets have the highest average adaptation of 16.32 sentences, while ACFRs contain an average adaptation of 3.64 sentences. Our second measure, which incorporates bond prospectuses, has a mean of 28.69 sentences over 2011 city-years, confirming our intuition that bond prospectuses provide additional information about cities' adaptation. Supplementary Figs. 1 and 2 illustrate the variation in adaptation over time and across different states.

To ensure that adaptation captures meaningful variation in cities' actions, we conduct several validation and robustness tests (see Methods and Supplementary Note 3 for more details). First, we find evidence that adaptation is positively correlated with a city's expenses from capital improvement and emergency-related funds. Second, we show that cities with higher adaptation receive larger insurance discounts in a program that rewards communities that are more prepared against flood risks. Third, we replicate prior research that shows climate risk is priced in municipal bond spreads^{33,34} and find that adaptation mitigates the positive association between climate risk and bond spreads. To further confirm the validity of our measures, we conduct robustness analyses where we adjust the definition of adaptation to exclude the most common keywords (drainage and stormwater) and a falsification analysis with a placebo measure unrelated to climate risks that captures police and public safety. We also conduct sensitivity tests using alternative measures such as groups of keywords and the number of keywords (Supplementary Note 6).

Topics of adaptation. The most commonly used adaptation-related terms are those associated with stormwater management and drainage, followed by references to flood-related measures. Other frequently utilized groups of keywords pertain to adaptation infrastructure, such as seawalls, inlets, and levees (Fig. 1a).

Topics of adaptation sentences vary across document types, with budgets (Fig. 1b) mostly describing the roles of departments and programs related to adaptation and the details of capital improvement projects, ACFRs (Fig. 1c) focusing on funding allocation, and bond prospectuses (Fig. 1d) discussing the intended use of funds. The relative importance of these topics is relatively stable over time within each document type (see Supplementary Note 5 for more details on the topic analysis).

Adaptation and flood risk. We first examine whether cities with higher flood risks are engaging in more adaptation to gauge the prevalence of an adaptation gap. We find a strong correlation between flood risk and adaptation in the regression analyses that account for population, document size, and state- and year-fixed effects (Supplementary Table 4 Panel a). The relationship is most evident in coastal regions, particularly the Gulf Coast (Fig. 2a). A ten percent rise in flood risk is linked to a 5.2% increase in main

adaptation in 2013, with this connection becoming progressively stronger over time, reaching 8.7% in 2020 (Fig. 2b). When we examine hard and soft adaptation separately, we observe that flood risk has a higher correlation with soft adaptation than with hard adaptation in 2013. Subsequently, the correlation gradually increases over time for both hard and soft adaptation (Fig. 2c).

Moreover, cities in the top quartile of flood risk increase their main adaptation by 19% following the exposure of major hurricanes, further confirming that flood risk is one of the defining factors in adaptation decisions (Supplementary Table 4b). This result is consistent with previous research demonstrating that extreme events can draw attention to a particular issue and prompt proactive action in response^{35–37}.

Factors related to having an adaptation gap. While adaptation is positively correlated with flood risk, our data show notable adaptation gaps. In more than half of the cities where over 10% of properties are at risk of flooding, main adaptation is smaller than that of an average city with less than a 10% flood risk.

We examine the factors associated with adaptation gap. It is challenging to determine which cities have a “true” adaptation gap, as estimating the optimal adaptation level for a particular city is difficult. However, it is possible to measure the relative adaptation gap, which represents how far a city is from adaptation levels predicted based on flood risk. We first estimate the predicted level of adaptation based on a linear regression model with flood risk, population, and length of disclosures for a given state and year. We then define adaptation gap as an indicator variable that is equal to one when the actual adaptation is lower than the predicted adaptation.

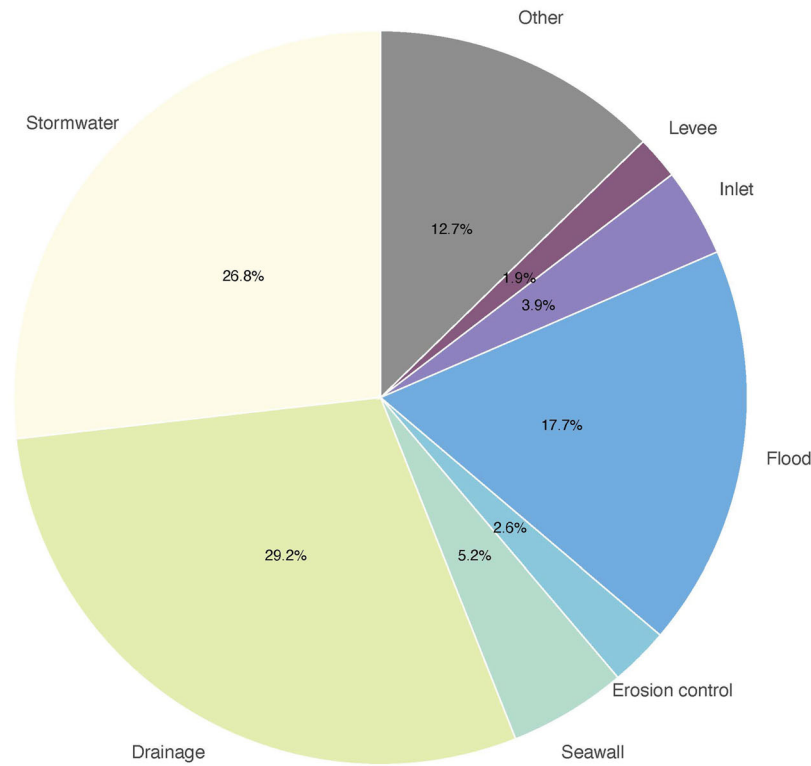
Contrary to concerns about the partisan divide in climate change beliefs^{6–10}, we do not find that Republican cities are more likely to have an adaptation gap across all dimensions except for soft adaptation gap that is 9% more likely to be observed in cities with a Republican city leader (Figs. 3a and 4). These findings suggest that having a Republican city leader does not necessarily lead to decreased investment in hard adaptation. However, it may affect the city's decisions regarding using nature-based solutions, such as beach nourishment or restoration of coral or oyster reefs.

We find evidence that financial constraint and shorter planning horizons are correlated with having an adaptation gap (Fig. 4 and Supplementary Table 5a). Cities with one standard deviation lower unrestricted-fund-to-expense ratio (UFB/Total Expense) are associated with a 6.6% (0.08×0.82 , where 0.82 is the standard deviation of UFB/Total Expense) higher chance of having an adaptation gap. This result holds for hard adaptation gap but is not statistically significant for soft adaptation gap. For soft adaptation gap, we find that cities with one standard deviation lower logged total debt per capita are associated with a 7.3% (0.08×0.91 , where 0.91 is the standard deviation of logged total debt per capita) higher chance of having an adaptation gap. Additionally, the explanatory power of financial constraints on the adaptation gap reduces over time (Fig. 3b).

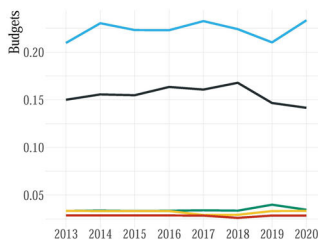
We find strong evidence that cities with shorter planning horizons are more likely to have an adaptation gap, and this effect persists over time (Fig. 3c). Cities with a one-year shorter budget planning horizon are 4% more likely to have an adaptation gap (Fig. 4). This result holds for hard adaptation gap but not for soft adaptation gap.

Heterogeneity in adaptation gap distribution. We conduct four cross-sectional tests to better understand the nature of cities with an adaptation gap.

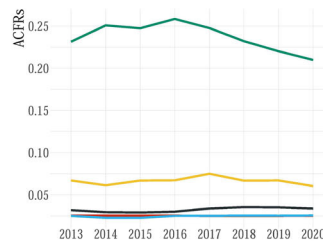
Panel a: Most common adaptation keyword groups.



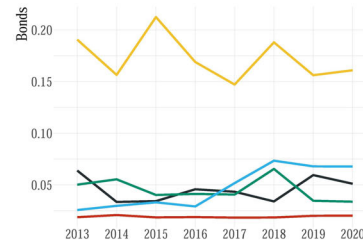
Panel b: Budgets



Panel c: ACFRs



Panel d: Bonds



Topic
 - Capital improvement projects
 - Funding allocation
 - Intended use of funds
 - Personnel
 - Program/department details

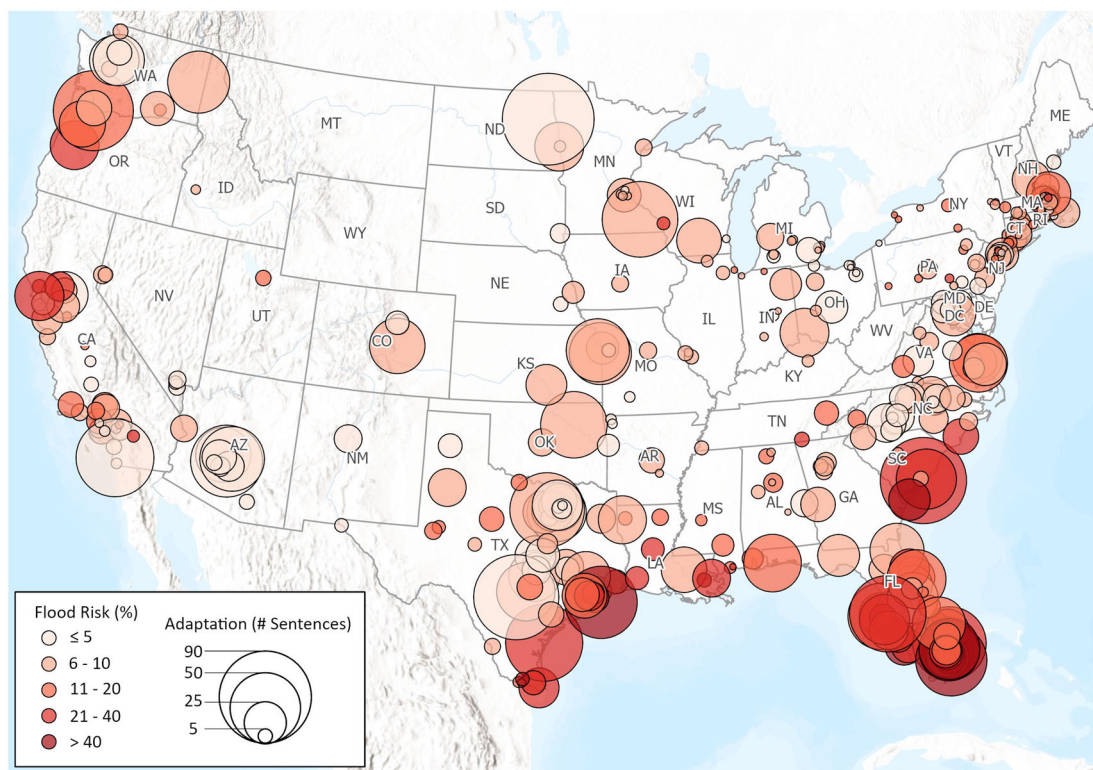
Fig. 1 Adaptation themes. **a** shows the most common keyword groups, along with their relative appearance frequency. To form the groups, we allocate all our dictionary words based on keyword commonality. For example, any expressions that contain the word “flood” is part of the flood group. We display the top seven groups and present the rest as “Other”. **b-d** present five main topics extracted using LDA from the sample of adaptation sentences in budgets (**b**), ACFRs (**c**), and bond prospectuses (**d**) over the sample period, 2013–2020. To better identify topics, we exclude sentences that are likely tables from the text data. *Capital improvement projects* (black line) captures sentences that describe the proposed capital improvement projects. *Funding allocation* (green line) covers descriptions of the funds spent or funding allocation for the capital projects. *Intended use of funds* (yellow line) captures the remaining tables that were not removed using our table identification approach. These sentences pertain to adaptation-related projects or districts and specify the intended use of funds. *Personnel* (red line) captures generic sentences that list the names of personnel. *Program/department details* (blue line) provides details on the role of departments or programs related to adaptation, such as inspecting and managing stormwater capital improvement projects. In each of the **b-d**, we plot medians of topic loading values across documents over time.

First, since adaptation gap is more concerning in high-flood-risk cities¹, we separately examine the potential constraints for cities with below- and above-median flood risk within a state. Financial constraints are more important for cities in high-flood-risk areas (Fig. 5a). Both high- and low-flood-risk cities have smaller adaptation gaps when they have longer planning horizons. Political beliefs do not have a significant relationship with adaptation gap in either subsample.

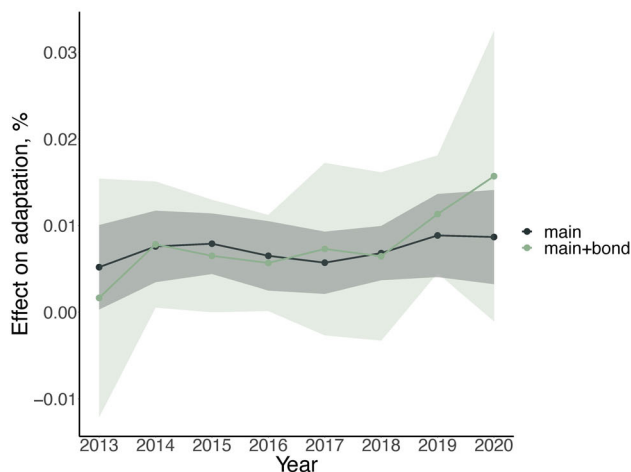
Second, we consider the variation in constituents’ beliefs. Local constituents’ beliefs shape local policies³⁸ and local

beliefs about climate change affect the adaptation behavior of individuals³⁹. We find that financial constraint is binding in counties where more constituents believe that local officials should do more to address climate change (according to the data from 2021 Yale Climate Opinion Survey, Fig. 5b). One interpretation is that in cities where the capital constraint is more binding, the citizenry is more concerned and expects their city leaders to do more adaptation. Partisanship and planning horizon do not differentially vary in areas with different beliefs.

Panel a: Map of adaptation and flood risk



Panel b: Flood risk and *main* adaptation



Panel c: Flood risk and *hard* and *soft* adaptation

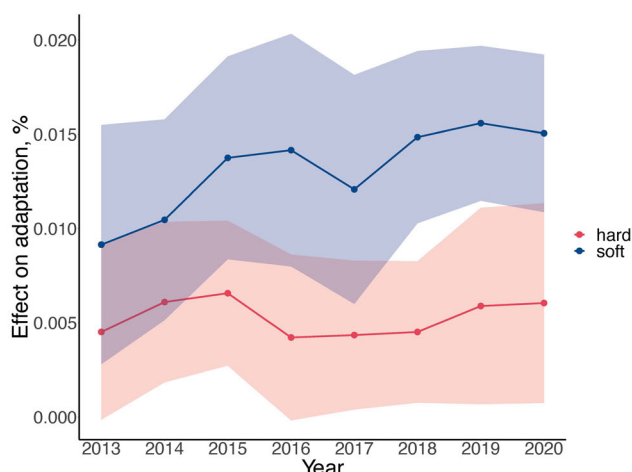


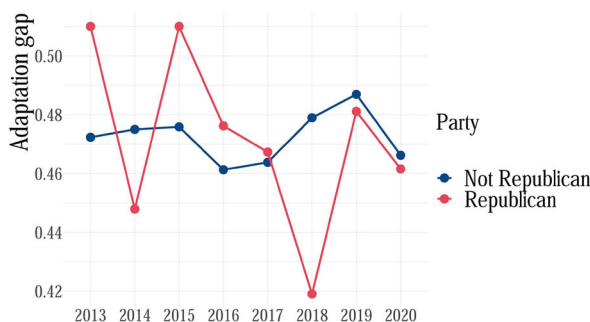
Fig. 2 Cities with higher flood risk do more adaptation. **a** maps *main* adaptation measure for our sample cities. The size of the bubble increases as adaptation measure increases, and the color intensifies with higher flood risk. **b**, **c** plot point estimates of the effect of flood risk on adaptation, following eq. (1). **b** displays the results for *main* (black) and *main+bond* (green) measures. **c** shows results for *hard* (pink) and *soft* (blue) adaptation. 95% confidence intervals are shaded with corresponding colors.

Third, we consider the role of state grants. If financial constraints explain low adaptation in certain cities, public funding, such as the availability of state grants, might mitigate this constraint¹³. To examine the role of state grants, we hand collect information about the size of state grants available for cities to fund their climate adaptation projects. State grants cannot fully mitigate the financial constraints (Fig. 5c). While the coefficient magnitude on UFB/Total Expense is smaller in states with large grants, it remains negative and statistically

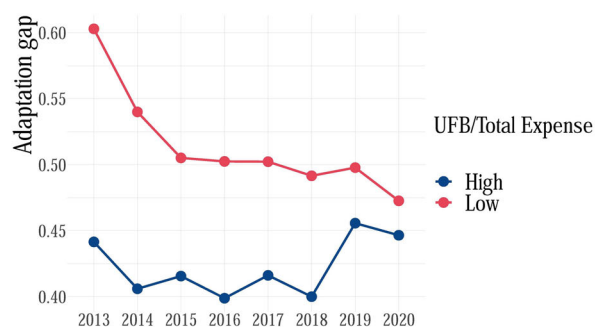
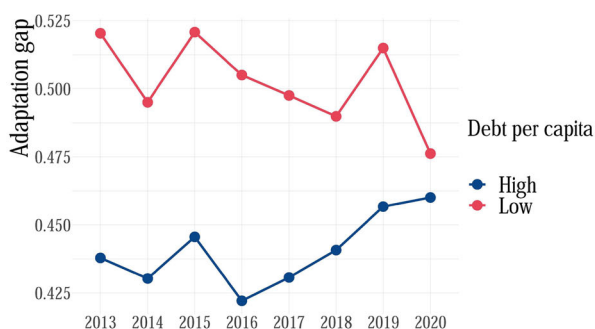
significant. Notably, a short planning horizon remains binding in both subsamples.

Finally, we consider the variation in local household incomes. Prior literature finds that financial constraint is more binding in regions with lower economic development since these regions are more likely to have other competing needs for budget allocation⁴⁰ and that private funding from local households can also contribute to adaptation funding¹. However, we find that variation in average household income does not change the relationship between

Panel a: Political affiliation



Panel b: Credit constraint



Panel c: Capital budget outlook

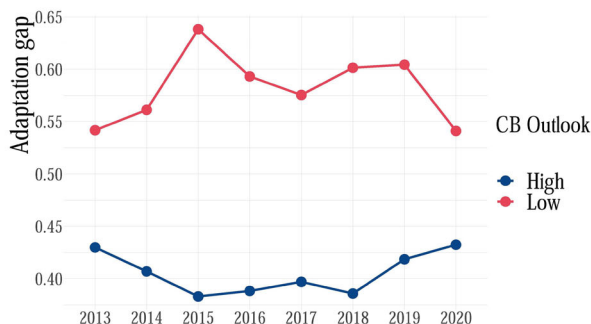


Fig. 3 Adaptation gap over time. This figure presents mean *main adaptation gap* over the sample period, 2013–2020. **a** plots adaptation gap by political affiliation (Republican in pink, and not Republican in blue). **b** plots adaptation gap by whether cities’ financial ratios is above median debt per capita (left; low debt per capita in pink, and high debt per capita in blue) and is above median ratio of unrestricted fund balance to total expenses (right; high unrestricted fund ratio in blue, and low unrestricted fund ratio in pink). **c** plots adaptation gap by whether cities’ capital budget outlook is above median (low capital budget outlook in pink, and high capital budget outlook in blue).

adaptation gap and political affiliation, capital budget outlook, and financial constraints (Fig. 5d).

Discussion

Closing the adaptation gap is a key issue, especially for cities, which are our front-line defense against geomorphological climate risks¹. It is important to understand constraining factors associated with the adaptation gap as it may help policymakers tailor policy solutions. Here, we provide a large-sample evidence that underscores the prevalence of an adaptation gap among US cities. We find an

adaptation gap to be primarily related to financial constraints and short planning horizons.

In contrast to the existing studies that find partisanship to be a significant social barrier to climate mitigation in the US, and perhaps surprisingly, we don’t find that political affiliation is significantly associated with having an adaptation gap^{6–10}. This finding implies that while political affiliation affects climate change beliefs, such beliefs do not compromise political agents from taking adaptation actions to alleviate the damage from flood risks. Even if Republican cities are less inclined to link rising flood risks to climate change, they still tackle these risks to protect the local

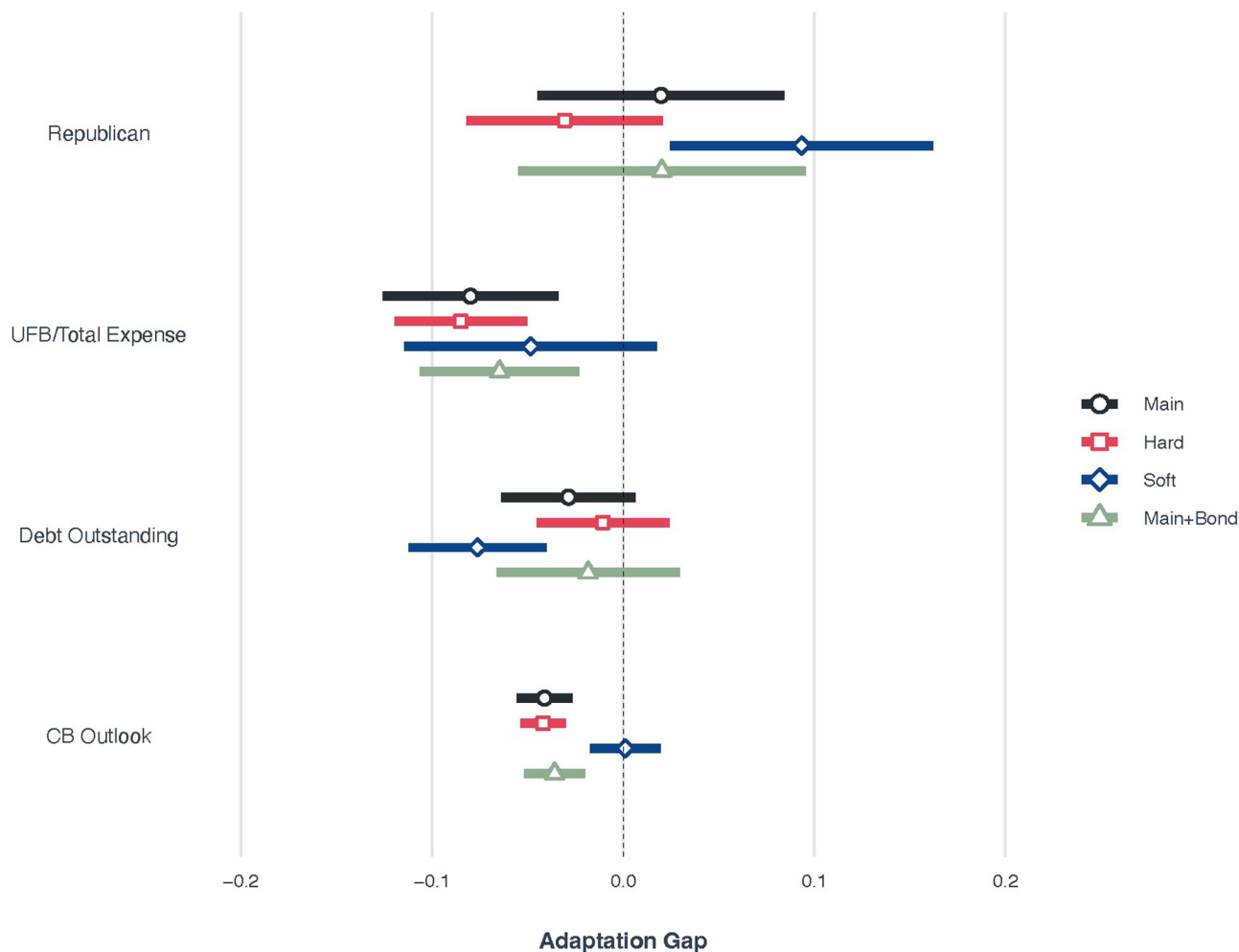


Fig. 4 Determinants of adaptation gap. This figure plots the estimates of the eq. (2). We plot coefficients for *main* (black), *hard* (pink), *soft* (blue), and *main+bond* (green) adaptation gap. *Republican* is an indicator variable equal to one if the city has a Republican mayor. *UFB/Total Expense* is unrestricted fund balance scaled by total expenses. *Total Debt per Capita* is total debt outstanding scaled by the population of the city. *Capital Budget Outlook* is the reported number of years in the capital budget. Bands indicate 90% confidence intervals. Full regression results are presented in Supplementary Table 5a.

economy and residents. It's also worth noting that as compared to adaptation, the political divide might be more prominent in climate mitigation discussions where certain words like “greenhouse gas” and “climate change” are politically charged^{6,7}.

We find strong evidence that capital constraint is related to having an adaptation gap and that the existing state grants do not mitigate this constraint. This finding highlights the importance of studying funding channels that can alleviate capital constraints, including private financing and public-private partnership^{41–43}. Additionally, we find that adaptation can mitigate the funding constraint by reducing the cost of capital. In our validating analyses, we find that adaptation reduces the flood risk premia in municipal bonds documented in the prior literature (Supplementary Note 3 Table SN 3.1c)^{33,34}. Future studies can also examine the role of traditional and green bonds in facilitating the funding of adaptation projects.

A short planning horizon is also significantly related to having an adaptation gap. Notably, the higher discount rate implied by financial constraint is only partly related to the planning horizon: the correlation between the planning horizon and the unrestricted-fund-to-expense ratio is just 12% (Supplementary Table 3c). Therefore, while improving funding access can partially ease the constraint related to myopic planning, it will probably not provide a complete solution. In fact, a shorter capital budget

outlook is associated with an adaptation gap in all four of our cross-sectional analyses. Myopic planning is likely associated with governance issues, electoral terms and term limits, and the political agent's career profile^{21–24}. Consequently, a policy intervention can involve fostering governance practices and implementing better planning mechanisms that account for the long-term, such as mandating 5 or 10-year budget forecasts.

In sum, our paper calls attention to closing the adaptation gap, and suggests a need to address capital constraints and short planning horizons. While our findings do not establish causation, we offer a preliminary investigation of the adaptation gap by introducing textual measures of adaptation. In our analyses, we consider three factors suggested in IPCC AR6 to explain the adaptation gap. We acknowledge that these three factors are not exhaustive. Future research can investigate other explanatory variables. Our findings extend the existing literature that studies cities' climate adaptation in larger samples beyond case studies. Prior papers acknowledge the lack of comparable data on cities' climate adaptation, which our systematic textual-analysis method addresses, providing us with a larger sample size with time variation to better examine constraints in adaptation⁴.

Future studies can establish causal links between adaptation gap and city characteristics. Our methodology can be extended to global samples as cities' financial disclosures should be publicly available, albeit with variations in national requirements. Researchers can use

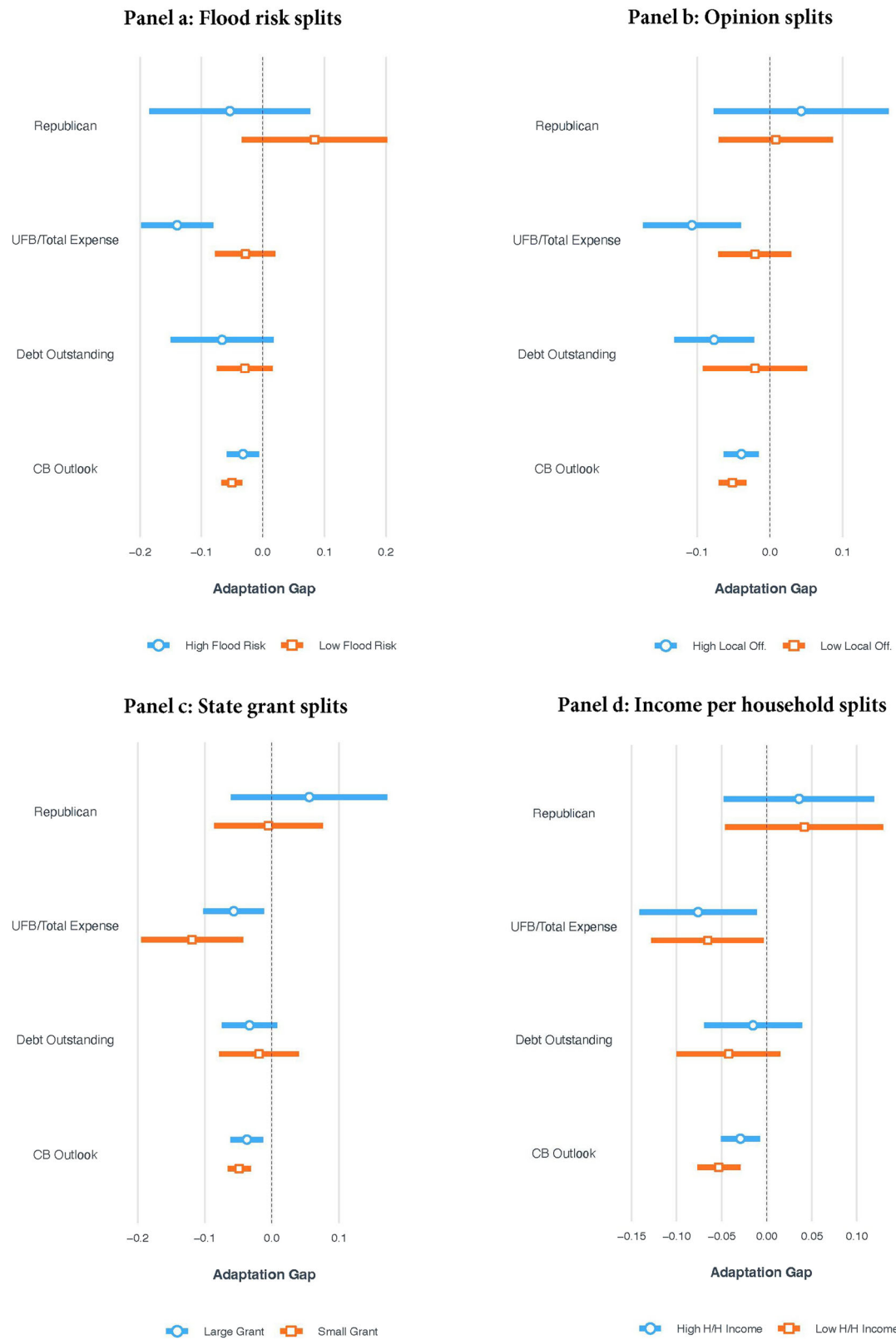


Fig. 5 Determinants of adaptation gap. This figure plots the estimates of the cross-sectional splits of eq. (2). **a** shows the split by above-median within-state flood risk (high flood risk in blue, and low flood risk in orange). **b** presents the split by the results of the Yale Climate Opinion poll, where *High Local Off.* (blue) corresponds to the counties where a high percentage of respondents believe that local officials should do something about climate change, and *Low Local Off.* (orange) corresponds to the counties where this number is low. **c** shows the results by whether relatively large (blue) or small (orange) amounts of state grants available. **d** shows the results of the split by above-median household income (high household income in blue, and low household income in orange). Bands indicate 90% confidence intervals. Full regression results are presented in Supplementary Table 5b.

our measures to better understand cities' adaptation efforts (or lack thereof), a topic emphasized in IPCC AR6. Households and firms can use our data to locate cities with adaptation gaps to help monitor and demand local governments to adapt or facilitate local governments with their respective constraints.

Methods

Textual measure of adaptation. We define adaptation as a city's actions to lower the damage from immediate and future flood hazards, which reduces the geomorphological flood risk faced by the city. We obtain this definition by narrowing down a more general definition by IPCC AR6 in the context of cities and flood risk¹.

We make two choices when developing our textual analysis methodology: we use a dictionary-based approach for textual analysis⁴⁴, and we focus on one dimension of climate risk—flood risk. Dictionary-based approach provides a simple and transparent interpretation of our textual measures and is used in recent literature examining climate risks in the corporate setting^{45,46}.

We explore adaptation to flood risk for three reasons. First, flood risk is a direct result of climate change, with warmer global temperatures leading to heavier precipitation, more hurricanes, and rising sea levels⁴⁷. Second, flood risk is the most salient risk faced by the cities in the US and dominates other risks in terms of both the numbers and damage costs⁴⁸. And finally, flood risks can be addressed by investing in a specific set of infrastructure solutions^{28,49}, which allows us to develop a precise dictionary of keywords that capture adaptive actions related specifically to flood risk.

Following the existing climate science literature, we consider two categories of adaptation: hard adaptation and soft adaptation^{26–31}. Hard adaptation involves the construction of physical infrastructure and improvements to the existing infrastructure. Such infrastructure is intended to either limit the extent of the city's flooding (e.g., seawall) or to enhance the city's ability to channel the water so that stormwater doesn't flood the city (e.g., drainage systems). Hard adaptation involves high capital investment, but can be effective immediately once construction completes²⁸.

Soft adaptation involves the use of nature and sediment-based solutions to reduce flood risks, such as beach nourishment, bioswales, and mangrove restoration. Relative to hard adaptation, soft adaptation has potential benefits on the wider ecosystem conservation and may also be more aesthetically beneficial for tourism²⁸. However, the dependency on nature involves a longer duration and relies on the availability of natural resources (e.g., sand)³¹.

Adaptation dictionary. Our dictionary contains three types of keywords: general adaptation, hard adaptation, and soft adaptation. General adaptation includes general phrases that represent climate adaptation but cannot be classified into soft or hard adaptations, such as “flood relief” and “flood reduction”.

To create our adaptation dictionary, we first thoroughly read and extract a list of initial keywords and phrases from diverse sources that detail adaptation strategies that can be applied to cities. Specifically, we gather initial keywords and phrases from the following documents: (i) the cities 2020 reporting guidance in CDP⁵⁰, (ii) the city climate hazard taxonomy issued by the C40 Cities Climate Leadership Group⁵¹, (iii) the climate change summary for policymakers issued by the Intergovernmental Panel on Climate Change¹, (iv) nature-based solutions guide for communities by FEMA⁵², (v) nature-based solutions resource guide by the White House⁵³, and (vi) relevant academic papers that focus on climate change adaptation^{26–30,54–56}.

Next, we expand our initial keyword list by incorporating adaptation-related keywords used by cities that are not present in

the sources previously mentioned. To do this, we read through the financial disclosures of a selected subset of cities over time in order to find additional relevant words for our keyword list. The subsample includes cities in Florida, Louisiana, Massachusetts, South Carolina, and Washington, DC. We choose cities in these states because they are exposed to relatively high flood risk. We add Washington, D.C. to the sample because it is not directly on the shore but has high flood risk exposure and outlines its planning approach in detail. This process allows us to capture words and phrases that local governments use to describe their climate adaptation actions, but which may not be commonly used in guidance and reports issued by other organizations. Examples of adaptation keywords obtained through this process include “detention storage systems” and “stormwater improvement.”

Following Li et al. (2023), we use single-word unigrams and two-word bigrams to form a hybrid dictionary that we then apply in our textual analysis⁴⁵. To validate that none of our unigrams are irrelevant, we extract all of the bigrams that contain a given unigram, and then manually examine the most frequent bigrams and unigrams. During this process (described in Supplementary Note 1), we update our list of keywords if we find any that are frequently used in irrelevant phrases and sentences. Supplementary Note 1 Table SN 1.1 presents the relative frequency of the keywords from our constructed dictionary. Our resulting dictionary contains 177 adaptation-specific words and can be found in Supplementary Table 1a. Supplementary Table 1b provides examples of sentences that contain words from the general, hard, and soft adaptation dictionaries.

Sample. Our sample contains both coastal and non-coastal cities. Coastal cities are especially vulnerable to the impacts of climate change, including sea-level rise and increased frequency and intensity of coastal storms. These impacts can lead to increased flood risk, shoreline erosion, and damage to infrastructure, homes, and businesses. However, including non-coastal cities is also important because climate risks exacerbate the chances of heavy rainfall, rising water levels in rivers or lakes, or rapid snowmelt^{57–59}. Inland cities are also vulnerable to flash floods, which can result from intense rainfall over a short period of time.

We collect municipal financial documents spanning 2013–2020 for 431 cities in 45 states and the District of Columbia. Our data collection focuses on cities located in states along the East and Gulf coasts, where the risk of flooding is higher. In particular, we have obtained financial information from cities that meet three criteria: they have financial data available in Muni Atlas, flood risk data from First Street Foundation, and a population of over 40,000 people, as recorded in the 2010 census. For the remaining states, to ensure the feasibility of our data collection, we have selected cities with populations of 80,000 people or higher. We further augment our sample to include the cities used in ref. ⁶⁰. We have restricted our sample to larger cities because smaller cities often only provide budget information in the form of tables rather than detailed documents, limiting comparability with cities that provide the full budgets. Because we were not able to locate both the annual report and budget documents for certain cities, our final sample contains 431 cities. On average, cities in our sample have a population of 234,100, where 8.64% (or 8126) of properties are at risk of flooding (see Supplementary Table 2). Flood risk is salient for cities in both coastal and non-coastal states: 37% of coastal and 32% of non-coastal cities have more than 10% properties exposed to flood risk.

Financial disclosures data. Financial disclosures are uniquely positioned to provide comprehensive and verifiable information about cities' adaptation over time. Financial disclosures are

required to be regularly posted and contain material information about adaptation. This guarantees that every important project or plan will be picked up by our textual analysis without the discretion of selective disclosure. These characteristics of financial reporting make it a more valuable source of information for analysis compared to other types of text, such as standalone adaptation plans that are voluntarily published by a subset of cities and are not typically updated annually. Another advantage of using financial disclosures is the ability to capture both forward-looking and backward-looking information. Specifically, in annual reports, cities discuss conditions of the current adaptation infrastructure. In budgets and bond prospectuses, cities provide forward-looking information about planned adaptation projects for addressing climate risks. These reports also include historical adaptation as cities maintain the adaptation projects, such as by setting up “seawall funds.”

The primary source of ACFRs and bond prospectuses is the Electronic Municipal Market Access (EMMA) website. We download the annual budgets and ACFRs that are not available on EMMA from the current city government’s website or from its Wayback Machine version. If the disclosures are not available online, we obtain the documents by contacting city officials directly. We convert these disclosures into a format that is amenable to text analysis by cleaning and preprocessing the data. Further details about our data-cleaning methodology can be found in Supplementary Note 2.

Validation. To ensure that our measure of climate adaptation accurately captures meaningful variation in cities’ actions, we conduct several validation and sensitivity tests. We summarize the findings here and include a detailed discussion of each validation test in Supplementary Note 3. Each validation test involves a subset of cities with data availability, which contrasts with our textual measure with availability for all cities. First, we test if a higher level of adaptation translates into increased spending on infrastructure projects. We find evidence that adaptation is positively correlated with a city’s expenses from capital improvement and emergency-related funds (Supplementary Note 3 Table SN 3.1a). Second, we test if adaptation is correlated with lower flood insurance premiums. We find that cities with higher adaptation receive a larger insurance discount in a program that rewards communities that are more prepared against flood risks (Supplementary Note 3 Table SN 3.1b). Third, we replicate prior research that shows climate risk is priced in municipal bond spreads^{33,34} and find that adaptation mitigates the negative association between climate risk and bond spreads (Supplementary Note 3 Table SN 3.1c). These three validation tests remain robust when we adjust the definition of adaptation to exclude the most common keywords (drainage and stormwater) (Supplementary Note 3 Table SN 3.2). We replicate these three validation tests using a placebo textual measure based on the number of sentences about safety and do not find the results above (Supplementary Note 3 Table SN 3.3). Additionally, in Supplementary Note 4, we provide excerpts of sample disclosure, and in Supplementary Note 5, we describe topic analysis, both of which also provide support that our adaptation measures capture cities’ adaptation actions.

Robustness. In addition to validating our adaptation measures, we conduct various tests to show that our main inferences are robust to using alternative ways to measure adaptation using our textual data. Specifically, our results are robust to limiting the appearance of a single keyword to one, five, and ten appearances in each document. The results are also robust to using the number of keywords, groups of sentences, or scaling

the number of sentences with the total number of sentences. We include a detailed discussion of each robustness test in Supplementary Note 6.

Other data. We use flood risk data from the First Street Foundation, a non-profit organization that measures America’s flood risks using scientific research and technology. They predict long-term weather patterns and map detailed geomorphological data in order to estimate the likelihood of flooding. More specifically, we use their 2020 National Flood Risk Assessment data, which captures the percent of properties that face a substantial risk from any type of flooding event, including storm surges, high tides, and the rise in sea level⁶¹. Substantial risk is defined as a more than 1% annual probability of flooding that reaching 1 cm or higher, which is the same measure used by the Federal Emergency Management Agency (FEMA). Since these data are available at a zipcode level, we aggregate the data to a city level by adding up the total number of properties and the properties at risk, and then by calculating the percent of properties at risk at the city-level. To illustrate what this measure captures, we use cities in Florida as an example: Miami (coastal) has an incredibly high flood risk of 40%, while Orlando (inland) has a somewhat lower, but still substantial flood risk of 6%.

Financial and demographic data come from Muni Atlas, which has information on local governments that has \$50 million in debt outstanding. For financial variables, we use data on city’s outstanding debt and fund expenses. For demographic variables, we include annual population, which Muni Atlas collects from the American Community Survey that is published once a year. As a partitioning variable, we use the average income per household from Muni Atlas. From Muni Atlas, we also retrieve the six-digit CUSIP numbers associated with each city, which helps us identify bond prospectuses on EMMA.

We use the number of years a city plans ahead for in its capital budget outlook to proxy for the planning horizon. We manually extract the number of years presented in a city’s capital budget plan by reading through each budget document. As an illustration, Supplementary Note 4 Fig. SN 4.1 provides a sample capital improvement budget table for the city of Tampa, which had a capital budget outlook of 5 years in the budget prepared for the fiscal year 2018.

Our data on political affiliation combines the data from OurCampaigns.com with the hand collected data for city-years where the city leader (mayor or city manager) or her political affiliation was not found on OurCampaigns.com⁶². To gather this data, we first identified the names of the city leaders in power during a specific year. Next, we searched for their political affiliation on the city’s website, in news articles, and by contacting the cities directly. The final data has three categories: Republican, Democratic, and Other. The first two categories identify the representatives of corresponding parties, and Other refers to the city leaders who identify as independents or belong to another party.

We use the 2021 Yale Climate Opinion Survey data, which provides county-level beliefs about climate change in the US⁶³. We use the county-level responses to the following prompt to capture people’s concern about the impact of climate change: “Your local officials should do more to address global warming.” We take the percentage of the respondents who agree with this statement and label it Local Officials. In the cross-sectional regression, we use the median value of Local Officials as the partitioning variable.

We manually search for the availability of state grants that cities can apply for to invest in adaptation. Since the way grants are presented involves much heterogeneity, to compare across states, we

identify the largest monetary value of a grant a city can receive in each state (State Grant). In the cross-sectional regression, we use the median State Grant of \$65,000 as the partitioning variable.

Estimating adaptation gap. To examine the prevalence of the adaptation gap, we first regress adaptation on flood risk. We estimate the following equation:

$$\begin{aligned} \text{Adaptation}_{i,t} = & \beta_1 \text{Flood Risk}_{i,t} + \beta_2 \text{Log}(\text{Population})_{i,t} + \beta_3 \text{Log}(\text{N Sentences}) \\ & + \text{Fixed Effects}_{i,t} + \varepsilon_{i,t}, \end{aligned} \quad (1)$$

where $\text{Adaptation}_{i,t}$ is the number of adaptation sentences for city i at year t . To reduce the influence of a few keywords with high frequency, we winsorize all our adaptation measures at the 99th percentile. $\text{Flood Risk}_{i,t}$ is the percent of properties subject to flood risk. We control for a city's population and the total number of sentences in the financial reports. We take the logarithm for these two control variables to resemble a normal distribution. We include state-fixed effects and year-fixed effects to control for time-invariant changes in each state and for time trends. We cluster standard errors by state. This grouping accommodates within-city intertemporal correlation in unobservables as well as correlations in unobservables across cities within the same state both within the same time period and across time periods. Our results remain robust when we cluster standard errors by state and year (Supplementary Note 7).

Conceptually, the regression model aims to estimate the "expected" adaptation based on a city's flood risk. Hence the main variable we control for is flood risk. We also control for the number of sentences and include state-fixed effects to account for heterogeneities in disclosures (such as level of detail and state-level format differences). We control for population because flood risk damage is positively correlated with population (e.g., if a few people live in a city, we do not expect to see high adaptation). We include year fixed effects to account for the general increase in disclosure related to climate change. We rely on the outcome of this regression to estimate the adaptation gap (Supplementary Table 4a). We define Adaptation Gap indicator variables as equal to one if the residuals from Supplementary Table 4 Panel a regression are negative.

To examine the factors related to having an adaptation gap, we run the following regression:

$$\begin{aligned} \text{Adaptation Gap}_{i,t} = & \beta_1 \text{Republican}_{i,t} + \beta_2 \text{UFB/Total Expense}_{i,t} \\ & + \beta_3 \text{Log}(\text{Total Debt per Capita}) + \beta_4 \text{Capital Budget Outlook}_{i,t} \\ & + \text{Fixed Effects}_{i,t} + \varepsilon_{i,t}, \end{aligned} \quad (2)$$

where $\text{Adaptation Gap}_{i,t}$ is an indicator that equals to one if the residual from Supplementary Table 4a regression is negative. We also conduct a sensitivity test using alternative definitions of Adaptation Gap, where we require the residual to be smaller than -0.5 and -1 (Supplementary Note 8). $\text{Republican}_{i,t}$ is an indicator variable equal to one if the city has a Republican city leader. $\text{UFB/Total Expense}_{i,t}$ is unrestricted fund balance scaled by total expenses, a measure that describes the amount of funds relative to the total expenses that are not restricted and can be spent however the city chooses to. It is important that cities that are prone to natural disasters have sufficient fund balance⁶⁴. $\text{Total Debt per Capita}_{i,t}$ is the total debt outstanding scaled by the population of the city. $\text{Capital Budget Outlook}_{i,t}$ is the reported number of years in the capital budget. We include state-fixed effects and year-fixed effects to control for time-invariant changes in each state and for time trends. Our sample in this analysis is slightly smaller because some cities do not have UFB/Total Expense and Total Debt per Capita in Muni Atlas.

Salient climate events and adaptation. Previous research demonstrates that extreme events can draw attention to a particular issue and prompt individuals to take proactive action in response^{35,36}. For example, we observe an increase in adaptation for cities in Florida starting in 2016, which is the year Hurricane Matthew struck and caused six deaths and large damages⁶⁵. We identify the first time \$1 billion hurricane events hit the U.S. states using the U.S. Billion-Dollar Weather and Climate Disasters data from the NOAA National Centers for Environmental Information (NCEI)⁴⁸. We use these data to compare our textual measure for cities with low (control) and with high (treatment) flood risks within a state. We expect that after a hurricane, cities with a higher flood risk will have a higher adaptation than cities in the control group. Specifically, we test:

$$\begin{aligned} \text{Adaptation}_{i,t} = & \beta_1 \text{High Flood Risk}_{i,t} + \beta_2 \text{High Flood Risk}_{i,t} \times \text{Post}_{i,t} \\ & + \beta_3 \text{Log}(\text{Population})_{i,t} + \beta_4 \text{Log}(\text{N Sentences}) \\ & + \text{Fixed Effects}_{i,t} + \varepsilon_{i,t}, \end{aligned} \quad (3)$$

where $\text{Adaptation}_{i,t}$ is the number of adaptation sentences for city i at year t . $\text{High Flood Risk}_{i,t}$ is an indicator that equals one if the city's flood risk belongs to the upper quartile within a state. $\text{Post}_{i,t}$ is an indicator that equals one for observations after which the state experienced the first hurricane identified in the NCEI dataset. We control for the size and resources of the cities by including the logarithm of the annual population from Muni Atlas and the logarithm of the total number of sentences. We include state-year fixed effects to account for time-varying local conditions. We cluster standard errors by the state to address the potential correlation within states. To exclude the possibility that we are capturing the restoration efforts after the hurricane, in Supplementary Note 9, we identify and remove hurricane-affected cities from our analysis and the results remain robust.

Limitations. In this work, we do not account for certain forms of adaptation that are difficult to quantify through textual analysis of financial disclosures, such as zoning, building codes, or migration-related measures. This is because those measures are not always outlined in financial disclosures, but are outlined in other policy documents. However, sometimes the best response to increased flood risk is these other forms of adaptation, including to retreat. We encourage future research to examine these important dimensions of adaptation.

Our focus in this study is on adaptations to flood risk. However, it's important to note that climate risks to cities can manifest in various forms beyond just flood risk, including exposure to extreme temperatures, droughts, and wildfires. Further research can explore adaptation to these forms of climate risk.

Data availability

Data associated with this analysis are available here: https://github.com/AnnaNakhmurina/cities_adaptation.

Code availability

The codes developed for the textual analysis of the financial documents and the codes associated with generating figures and tables in this analysis are available here: https://github.com/AnnaNakhmurina/cities_adaptation.

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Author contributions

S.L. and A.N. both contributed to the data construction, analysis, and writing.

Competing interests

The authors declare no competing interests.

Additional information

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