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Modes of climate mobility under sea-level rise

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Abstract

Exposure to sea-level rise (SLR) and flooding will make some areas uninhabitable, and the increased demand for housing in safer areas may cause displacement through economic pressures. Anticipating such direct and indirect impacts of SLR is important for equitable adaptation policies. Here we build upon recent advances in flood exposure modeling and social vulnerability assessment to demonstrate a framework for estimating the direct and indirect impacts of SLR on mobility. Using two spatially distributed indicators of vulnerability and exposure, four specific modes of climate mobility are characterized: (1) minimally exposed to SLR (**Stable**), (2) directly exposed to SLR with capacity to relocate (**Migrating**), (3) indirectly exposed to SLR through economic pressures (**Displaced**), and (4) directly exposed to SLR without capacity to relocate (**Trapped**). We explore these dynamics within Miami-Dade County, USA, a metropolitan region with substantial social inequality and SLR exposure. Social vulnerability is estimated by cluster analysis using 13 social indicators at the census tract scale. Exposure is estimated under increasing SLR using a 1.5 m resolution compound flood hazard model accounting for inundation from high tides and rising groundwater and flooding from extreme precipitation and storm surge. Social vulnerability and exposure are intersected at the scale of residential buildings where exposed population is estimated by dasymetric methods. Under 1 m SLR, 56% of residents in areas of low flood hazard may experience displacement, whereas 26% of the population risks being trapped (19%) in or migrating (7%) from areas of high flood hazard, and concerns of depopulation and fiscal stress increase within at least 9 municipalities where 50% or more of their total population is exposed to flooding. As SLR increases from 1 to 2 m, the dominant flood driver shifts from precipitation to inundation, with population exposed to inundation rising from 2.8% to 54.7%. Understanding shifting geographies of flood risks and the potential for different modes of climate mobility can enable adaptation planning across household-to-regional scales.

1. Introduction

Estimates of displacement induced by sea-level rise (SLR) range from 88 M to 1.4 B people globally by 2100, depending on whether the estimates assess permanent inundation or consequences for low-elevation coastal zones as a whole (Nicholls *et al* 2011, Neumann *et al* 2015, Hauer *et al* 2016, 2020, Kulp and Strauss 2019, Oppenheimer *et al* 2019). The definitions of who is 'at-risk' focus on exposure to SLR and related hazards (Hauer *et al* 2020, McMichael *et al* 2020), which in addition to permanent inundation of land can include flooding from tidal, precipitation, groundwater, coastal storm surges, and compound events (Oppenheimer *et al* 2019, Jane *et al* 2020, Kirezci *et al* 2020, Tellman *et al* 2021). However, social and economic risks may extend to communities substantially beyond flooded areas as the spatiotemporal dynamics of flood risks are realized through housing markets, insurance and risk-transfer mechanisms, and adaptation investments. Notably 'climate gentrification' (Keenan *et al* 2018, Robinson *et al* 2020) and affordable housing shortages (Buchanan *et al* 2020) can result from increasing demand for housing in safer areas. Furthermore, disaster-related displacement (Myers *et al* 2008, Gray and Mueller 2012) and declining property values and household wealth from SLR and extreme flooding have the potential to exacerbate existing social inequity. Our understanding of how SLR affects communities should therefore include *direct impacts* of coastal flooding and *indirect impacts* (e.g. the increased demand for housing in safer areas), both of which may contribute to climate-related movement, or *climate mobilities*, and are important in determining the scale and nature of SLR impacts (Boas *et al* 2019, Wiegel *et al* 2019, Wrathall *et al* 2019). Climate mobilities will occur where risks are intolerable and other adaptation options are inadequate across varying community needs.

Policies to facilitate movement away from high-risk coastal areas are emerging (McLeman and Smit 2006, Bardsley and Hugo 2010, Black *et al* 2011a), but have yet to be designed with a capacity to anticipate the indirect impacts from market forces that are particularly important from an equity perspective. Studies have mainly focused on the direct impacts of SLR, assessed by modeling future spatial patterns of permanent inundation and/or extreme event flood zones and then intersecting them with spatially distributed social data (e.g. population density, racial and ethnic population fractions) (Hauer *et al* 2016, Hauer 2017), whereas capturing indirect impacts is more complex. Wealthier, higher-capacity neighborhoods are generally understood to have greater ability to handle the shocks and stressors of climate change than socioeconomically vulnerable or marginalized communities (Fussell *et al* 2010, 2014). Assessing social implications of both direct and indirect impacts is dependent on a measure of a community or individual ability to cope and adapt to flooding, i.e. social vulnerability (e.g. Flanagan *et al* 2011, Cutter 2003, Wisner *et al* 2014). In other words, there are two key considerations for anticipating both the direct and indirect impacts of SLR and responses to it in a policy and equity relevant way: exposure and vulnerability.

1.1. The climate mobility framework

A climate mobility framework that captures how varying levels of social vulnerability and flood exposure under SLR shape outcomes is shown in figure 1 (McLeman and Smit 2006, Barth and Rollins 2019): (1) low vulnerability and low SLR exposure corresponds to minimally impacted populations (**Stable**), (2) low vulnerability and high exposure corresponds to those with higher capacity to relocate (**Migrating**), (3) high vulnerability and low exposure corresponds to those indirectly displaced by economic pressures (**Displaced**), and (4) high vulnerability and high exposure corresponds to those directly impacted by flooding with lower capacity to relocate (**Trapped**). The framework is a simple but effective typology that explains the scope and distribution of SLR risks as potential drivers of climate mobilities at present and in the future.

The **Stable** quadrant (figure 1) corresponds to neighborhoods with low socioeconomic vulnerability and low direct exposure to SLR, culminating in low mobility pressure (Mortreux and Barnett 2017, Adams and Kay 2019). Stable areas are not areas of zero risk, but generally higher levels of wealth, among other factors, indicate higher capacity to adapt. As SLR increases, spillover effects from high-risk areas (e.g. rising insurance rates and densification needs) could influence the relative stability of these areas. The **Migrating** quadrant characterizes neighborhoods with high direct and low indirect SLR risk and high socioeconomic and financial security. Households in these areas may have more flexibility in deciding how and when to relocate as a risk mitigation strategy. Further, these wealthier areas may also have political advantages and more government-supported capacity to facilitate movement out of high-risk areas, which could contribute to growing disparities across neighborhoods (Brady 2015, Binder and Greer 2016, Koslov 2016, Portes *et al* 2018, Mach *et al* 2019, Siders 2019). The **Displaced** quadrant represents neighborhoods with high socioeconomic vulnerability and low direct exposure to SLR and flooding resulting in higher indirect SLR risk. Households in these neighborhoods face risks of being priced out of their communities as wealthier households and climate resilience investments move towards these areas resulting in the 'climate gentrification' phenomenon (Anguelovski *et al* 2019, Keenan *et al* 2018). These cascading impacts include not only housing prices but also the availability of jobs, transportation, and other social services (Robinson *et al* 2020). Finally, the **Trapped** quadrant refers to neighborhoods with high socioeconomic vulnerability and high direct and indirect SLR risk, which may lead to immobility pressures. Households may have fewer liquid assets at their disposal in order to mitigate direct SLR flooding risks or relocate (Foresight 2011, Black *et al* 2011b, Adams 2016, Wrathall *et al* 2019). Historic trends in disaster relief across multiple agencies suggest that lower income households and people of color are less likely to receive disaster relief benefits, further reducing their capacity to recover from storms

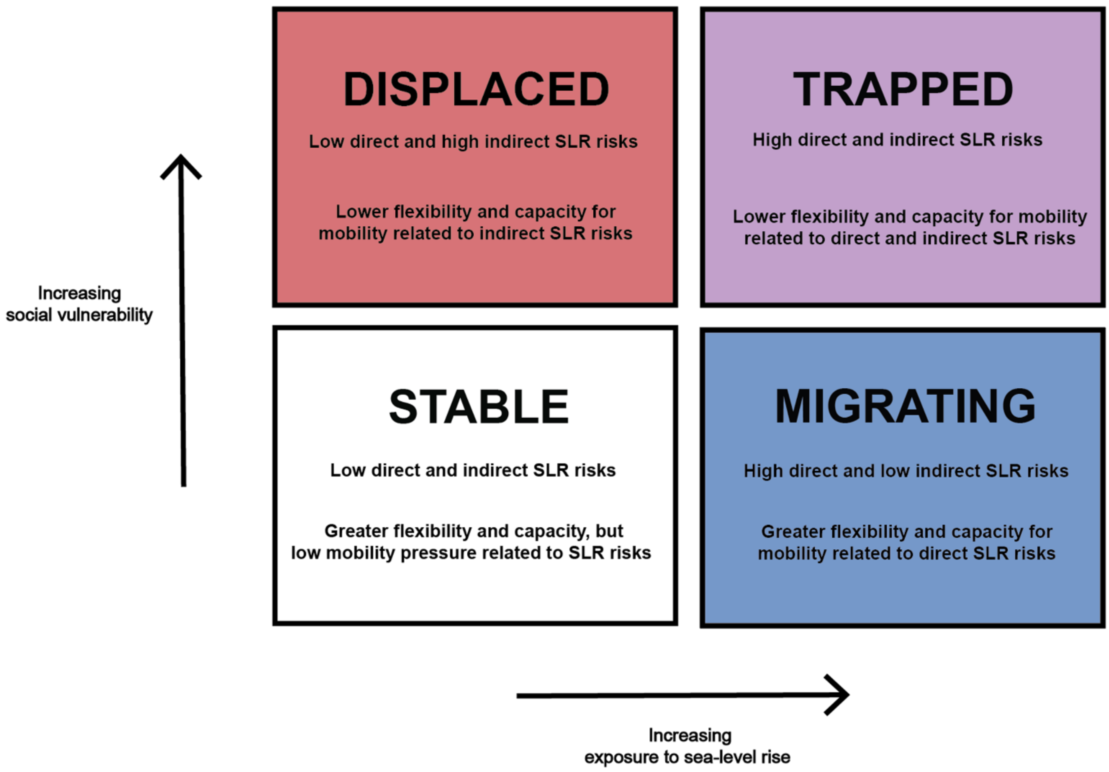

Figure 1. Conceptual model of exposure and vulnerability related to climate mobility. Exposure to sea-level rise and related flooding (horizontal) and socioeconomic vulnerability (vertical) shape sea-level rise risks, adaptive capacity, and potential drivers of climate-related mobility. Four categories of climate-related mobility drivers and outcomes are illustrated. 'Direct SLR risk' refers to risk from physical exposure to sea-level rise and related flooding, whereas 'indirect SLR risk' refers to risk from secondary sea-level rise impacts (e.g. on housing availability and cost burden).

(Bullard and Wright 2012, Howell and Elliott 2018, NAC 2020). Studies (Martinich *et al* 2013, Lincke and Hinkel 2018, Siders and Keenan 2020) also suggest that economically robust SLR protection will favor protecting wealthier, denser areas over poorer, less populated areas.

1.2. Present study

In this study, we apply the climate mobility framework and discuss its potential to inform adaptation policy and practice in the context of Miami-Dade County (MDC), Florida, USA, an area where climate mobility pressures are expected to increase over time. Sea-level is projected to rise to 0.7 m by 2060 and to 2.1 m by 2100 (NOAA High Scenario; Sweet *et al* 2022), and updated projections consistently estimate regional SLR acceleration across scenarios (Compact 2020). Climate Central estimates a 2 m rise would affect almost 1 M MDC residents and place $129 B in property at risk (estimates reflect the 2010 Census; Climate Central 2014a, 2014b). Further, recent migration trends within MDC suggest that the population is increasing, accelerated by the COVID-19 pandemic, an emerging technology industry, tax incentives, and favorable climate (Stein 2022). MDC is also the second most unequal metropolitan area in the United States (Gini index for income inequality: 0.508) with 47.8% of its population employed in low-wage service work (Florida and Pedigo 2019). Approximately 53.3% of MDC residents are foreign born, and 69.1% of all residents are Hispanic/Latino (U.S. Census 2015–2019), reflecting the county's history as a place of refuge for Central and South American and Caribbean communities. Conversely, the county's legacy of Jim Crow laws, discriminatory redlining policies, and forced relocation of Miami's Black and African American communities resulted in the settlement of these communities on inland, higher elevation areas, where concerns are emerging about their ability to remain in these increasingly desirable locations (Mohl 2000, Dluhy *et al* 2002, Connolly 2014). Regional adaptation plans (Resilient 305 2019, MDC 2021) have emerged to guide response options yet do not fully consider the potential for compound flooding in assessing direct impacts of SLR and are not sensitive to indirect impacts. Flood and vulnerability analyses produced in the South Florida region do not consider these forces in relation to climate mobility (Bolter *et al* 2014, Montgomery *et al* 2015). However, evaluations of the multiple ways in which households within coastal communities are vulnerable to accelerating SLR are needed to inform and support equitable and effective adaptation investments in MDC and beyond.

The climate mobility framework is applied by creating a building-scale database for MDC containing estimates of social vulnerability and flood exposure, and then aggregating the data to municipal and county scales for estimates of climate mobility. Social vulnerability is based on present-day social data. We acknowledge that this approach does not fully capture the interdependence between exposure and vulnerability stemming from social adjustments to changing hazards, but it is effective for assessing the present-day mobility stresses (both direct and indirect) and the sensitivity of mobility to varying degrees of SLR, and is a widely used approach (Emrich and Cutter 2011, Martinich *et al* 2013). Assessments of future social trends that encompass social vulnerability (e.g. the shared socioeconomic pathways (O'Neill *et al* 2017) are not readily available at hyper-local scales such as U.S. census tracts (Birkmann *et al* 2015). However, flood exposure is estimated for four different amounts of SLR (+0, +1, +2 and +3 m) representative of present and potential future climates.

2. Methods

2.1. Social vulnerability

Social vulnerability represents the capacity of a person or community to anticipate, withstand, and recover from exposure to environmental hazards (Cutter 2003, Flanagan *et al* 2011, Wisner *et al* 2014), and it is estimated across census tracts to infer such capacity with respect to both direct and indirect impacts of SLR. Following Rufat (2013), social vulnerability is estimated in a relative sense through cluster analysis. We used model-based clustering through the Mclust R package (Scrucca *et al* 2016), which incorporates a Gaussian finite mixture model fitted with an expectation-maximization algorithm to identify clusters of areas that share similar characteristics across MDC. This approach enables understandings of how specific characteristics and processes converge geospatially and contribute to vulnerability as opposed to using aggregated or weighted indicators to measure 'absolute' vulnerability (Rufat 2013). Relative vulnerability supports policy interventions across similar areas over absolute methods suited to identifying highly vulnerable areas (Chang *et al* 2015, 2018, Hummel *et al* 2018). Our specific focus on factors relevant to SLR and flooding in the region builds from social vulnerability assessments at national and state levels (Flanagan *et al* 2018, U.S EPA 2019, CalEPA and OEHHA 2017) and at the local and regional scale for South Florida (Bolter 2014, Montgomery *et al* 2015).

Thirteen different indicators were drawn from U.S. American Community Survey data (2015–2019; US Census Bureau 2020) and U.S. Housing and Urban Development Comprehensive Housing Affordability Strategy data (2013–2017; CHAS 2019) to support cluster analysis. We selected indicators based on relevance to the MDC context incorporating correlation analyses (figure SM 1), determinations of estimate reliability, and sensitivity testing (table 1). Indicators are ranked in descending order by relative vulnerability and further grouped into three sets based on similarities: low, moderate, and high social vulnerability. Neighborhoods with higher proportions of people or households under any given indicator are generally understood to have higher social vulnerability with two exceptions. First, in MDC, higher proportions of foreign-born persons do not necessarily indicate higher vulnerability (unless this proportion is coupled with higher proportions of limited English speakers), and second, higher median household incomes have an inverse relationship with social vulnerability. See supplemental methods 1.1 and 1.2 for details.

2.2. Inundation and flooding

Previous work on displacement from SLR has mainly relied upon estimates of (permanent) inundation, yet (episodic) flooding caused by precipitation and storm surge also drives displacement and is sensitive to sea level (via backwater effects). We therefore take a more comprehensive approach to SLR exposure by considering inundation and flooding as multi-hazard phenomena (Moftakhari *et al* 2019). We characterize the spatial distribution of flood depth for three different hazard drivers: (1) inundation from high tides and groundwater surfacing, (2) flooding from extreme precipitation, and (3) flooding from storm surge. We differentiate between 'inundation' and 'flooding' in alignment with Flick *et al* (2012) and Hauer *et al* (2021) and use these terms throughout the rest of the paper. Furthermore, as an overall measure of SLR exposure, we consider the composite hazard taken as the maximum flood depth across all hazard modalities on a point-by-point basis (FEMA 2015, Moftakhari *et al* 2019).

Both inundation and flooding analyses rely on a 1.5 m resolution Digital Elevation Model (DEM) of MDC from 2018, with 6.2 cm vertical accuracy, available from NOAA's Digital Coast online data portal (National Oceanic and Atmospheric Administration NOAA 2018). The DEM was further processed, or hydro-conditioned, to resolve drainage pathways along open channels and culverts connecting open channels (Kahl *et al* 2022). The hydro-conditioning process was assisted by publicly available canal hydrography data (canal centerlines and widths) accessed through the online Miami-Dade County Open Data Hub. To support modeling of flooding from precipitation and storm surge, spatially distributed resistance parameters (Manning n) were also resolved at the same resolution as the DEM based on land use/land cover data available from Open

Table 1. Indicators and associated metrics in the analysis of social vulnerability. For Miami-Dade County (MDC), Florida, United States, profiles of social vulnerability, especially as relevant to sea-level rise risks, are assessed and constructed across census tracts based on these indicators and associated metrics.

INDICATOR	METRIC	RELATION TO SOCIAL VULNERABILITY	CITATIONS
SENIORS *(AGE 65+)*	Percent of individuals aged 65 and older living alone	Elderly populations are generally considered more socially vulnerable, although higher proportions of affluent elderly populations, who may have lower social vulnerability, live along coastal areas in Florida	Morrow 1997; Wang and Yarnal 2012
BLACK POPULATION *(BLACK POP)*	Percent Black population	In MDC, high proportions of Black residents in an area are indicative of the legacy of Jim Crow policies, discriminatory redlining policies, and ongoing racial segregation of neighborhoods	Connolly 2014; UM Office of Civic and Community Engagement 2016
FOREIGN BORN *(FOREIGN B)*	Percent of individuals born outside United States	In MDC, 53.7% of persons are foreign born, and social vulnerability may be unevenly distributed across different nationalities	Montgomery and Chakraborty 2015; U.S. Census Bureau (2020b)
LIMITED ENGLISH *(LIMITED ENG)*	Percent of limited English-speaking households (all languages)	In MDC, high proportions of limited English speakers can signal linguistic isolation challenging access to public services, information, and economic opportunities	Boyd 2009; Xiang *et al* 2021
NO HIGH SCHOOL DIPLOMA[a] *(HS DIPLOMA)*	Percent population age 18+ without a HS diploma	Education levels are tied to income and poverty, which can shape social vulnerability	Morrow 1997; Flanagan *et al* 2011; Rufat *et al* 2015
LIMITED MOBILITY *(VEHICLE)*	Percent households with workers aged 16 and over and with no vehicles available	High levels of this indicator could indicate vulnerability to extreme events or events where immediate mobility is needed to avoid hazards	Morrow 1997; Flanagan *et al* 2011; Bullard and Wright 2012
POVERTY LEVEL *(POV LEVEL)*	Percent population living below the poverty level	In MDC, 15.7% of residents live in poverty; census tracts with median incomes below the poverty level are considered more vulnerable	Rufat *et al* 2015; U.S. Census Bureau 2020c
RENTER *(RENTER)*	Percent renter occupied households	Renters generally face lower economic loss from flooding but higher rates of displacement and job loss; disaster relief programs tend to favor property owners	Kamel 2012; Rufat *et al* 2015
HOUSING BURDEN[a, b] *(RENTER CB)*	Percent of renter occupied households that contribute more than 30% of income to housing costs	Cost burdened renters pay more than 30% of their income towards housing costs, thereby reducing disposable income and increasing social/financial vulnerability	Greiner *et al* 2017
PUBLIC BENEFITS *(SNAP)*	Percent households receiving SNAP benefits	Higher proportions of households receiving Supplemental Nutrition Assistance Program (SNAP) benefits indicate food insecurity and social/financial vulnerability	Dilly *et al* (2001); Fitzpatrick *et al* (2021)
UNEMPLOYMENT *(UNEMPLOYED)*	Percent unemployed workers aged 16 and older	In Florida, the average monthly, seasonally adjusted unemployment rate from 2015–2019 was 4.2%. Census tracts with unemployment rates higher than 4.2% may be considered more socially/financially vulnerable	U.S. Bureau of Labor Statistics (2021)
NO HEALTH[a] INSURANCE *(UNINSURED)*	Percent population without health insurance (in and not in labor force)	Ponding conditions from flooding may impact health due to waterborne diseases or effects of dampness (e.g., mold). Greater social vulnerability in areas with lower insured rates	Bloetscher *et al* 2016
MEDIAN INCOME *(INCOME)*	Household median income	MDC median household income is $51 347. Census tracts with lower median income may be considered more socially/financially vulnerable	U.S. Census Bureau 2020a

[a] Reflects a pooled estimate or more than one metric within indicator.

[b] Housing Burden is the only indicator derived from U.S. Housing and Urban Development Comprehensive Housing Affordability Strategy data (2013–2017; CHAS 2019). All other indicators were derived from U.S. American Community Survey 2019 5 year data (2015–2019; U.S. Census Bureau 2020a).

Street Map and tabulated values of Manning *n* for different land uses (Schubert *et al* 2022).

Inundation depths from high tides and groundwater surfacing were computed separately for present day sea level and SLR scenarios involving +1, +2, or +3 m vertical offsets, and then combined into a single 'inundation' data layer. Inundation from high tides was computed by planar extrapolation (i.e. bathtub modeling) to hydraulically connected areas (Poulter and Halpin 2008), with Biscayne Bay as the source of inundation. The baseline for coastal inundation is current epoch mean higher high water (MHHW), defined at NOAA tide gage 8723 214 (National Oceanic and Atmospheric Administration NOAA 1983–2001). Inundation from surfacing groundwater is estimated for the present-day by taking a decadal average (1 January 2010–31 December 2020) of phreatic heights resolved by a regional groundwater model at 25 points aligned with USGS groundwater gages (Sukop *et al* 2018). Water heights were subsequently interpolated to the location of all DEM grid cells using ordinary Kriging. To estimate inundation from surfacing ground water for the SLR scenarios (+1, +2 and +3 m), the present-day water surface was shifted vertically upwards. Previous research has documented that long-term changes in the groundwater table are consistent with rates of SLR in the region (Sukop *et al* 2018), but we acknowledge that this linear adjustment of water tables to SLR only approximates a more complex system response that may become less robust with distance inland from the coast and with more varied geologic formations. All inundation modeling (planar extrapolation, kriging, and depth estimation) was carried out using ArcMap GIS Software (Esri, Redlands, CA).

Flooding depths for the 1% annual chance storm surge and 1% annual chance rainfall were estimated using the Parallel Raster Inundation Model (PRIMo), which simulates flooding dynamics over storm event time scales by solving the two-dimensional shallow-water equations (Sanders and Schubert 2019, Kahl *et al* 2022, Schubert *et al* 2022, Sanders *et al* 2023). PRIMo is the first hydrodynamic model to realize fine-resolution capabilities (1.5 m resolution for this study) in a regional scale model spanning large metropolitan areas while accounting for urban drainage infrastructure such as culverts, storm pipes, and levees (Bates 2023). This is accomplished with a unique dual-grid model structure that reduces computation costs more than 100× compared to a conventional fine-grid model, and with a highly efficient parallel computing algorithm that realizes the full potential of modern computing architectures (Sanders and Schubert 2019). The MDC implementation of PRIMo (PRIMo-MDC) is configured to span the developed portions of MDC and portions of Biscayne Bay (504 km^2), and to be forced by spatially distributed and time-varied precipitation and time-varied total water levels within Biscayne Bay (figure 2). For parallel computing, the PRIMo-MDC grid is decomposed into 224 tiles each containing a grid of 1000 × 1000 DEM pixels, each assigned to a separate processor for parallel execution. Post-processing of model outputs involves reassembling the tiled data (i.e. event-maximum flood depth) into a single raster grid for subsequent exposure analysis.

The 1% annual chance precipitation scenario is configured using spatially distributed rainfall depths for the 1% annual chance 24 h duration event available from NOAA Atlas 14 (National Oceanic and Atmospheric Administration NOAA n.d.) (Perica 2014). Additionally, the downstream boundary condition for the precipitation scenario is set to MHHW, as defined at NOAA tide gage 8723 214 (National Oceanic and Atmospheric Administration NOAA 1983–2001). The storm surge scenario was configured to approximate the 1% annual chance still water level estimated by a combined ADCIRC/SWAN model developed for the most recent FEMA Flood Inundation Study for MDC (FEMA 2021), which varied in height from ∼1.8 m (NAVD 88) along the northern part of the MDC coast to ∼2.7 m (NAVD) along the central and southern parts of the MDC coast. In particular, a storm surge height of 2.5 m (NAVD88) was used for the whole MDC coast, and a 14-hour sinusoidal shape was used for the rise and fall of the coastal water level starting at a water level matching MHHW (0.069 NAVD88). The duration of the coastal storm surge was chosen to match Hurricane Irma, which hit MDC in 2017 cresting at 1.176 m NAVD88 band lasting 14 h based on measurements at NOAA tide gage 8723 214 (National Oceanic and Atmospheric Administration NOAA 1983–2001). Future storm surge scenarios were created by shifting this sinusoid upwards by +1, +2 and +3 m, and re-running PRIMo-MDC. We note that future precipitation scenarios were not considered separately from the baseline scenario, despite potential changes from backwater effects. Preliminary results showed that the coastal storm surge scenarios resulted in much greater flooding along the coast than the precipitation scenarios, so the backwater analysis was not needed. A composite hazard layer indicative of the compound flood hazard was created by considering both the inundation and flooding scenarios (at each sea level). The composite hazard depth is taken as the maximum across all scenarios (FEMA 2015, Moftakhari *et al* 2019). We note that the composite hazard is strictly reflective of the effects of increasing SLR and does not account for future changes to precipitation intensities, storm surge intensities, and groundwater dynamics. This approach allows for a comprehensive assessment of flood exposure by SLR hazard modality which, when paired with social vulnerability estimates, enables characterization of climate mobilities. This approach realizes first-order estimates of changes in climate mobilities with SLR.

2.3. Estimating exposure and vulnerability across residential buildings

We used a dasymetric approach to estimate population across all residential buildings within MDC. Building stock data were obtained from the Miami-Dade County Open Data Hub (2022), and data describing the volume of each residential building was used to inform the top-down redistribution of census-tract-scale population estimates to the building scale (Schug *et al* 2021). This approach builds upon several other recent efforts to downscale population data (Maroko *et al* 2019, Huang *et al* 2021, Schug *et al* 2021). See supplemental methods 1.3. including table SM 1 for additional detail.

Flood exposed populations were estimated by the number of people in buildings experiencing at least 3 cm of inundation or at least 30 cm of flooding. We estimated inundation and flooding depths at the building scale by averaging all pixels intersecting the building footprint, based on data available from the Miami-Dade County Open Data Hub (2022). A larger tolerance (30 cm) was used for flooding to be consistent with standards for exposure used by FEMA for shallow flood hazard mapping (FEMA 2020), whereas a lower tolerance (3 cm) was used for inundation because any amount of permanent standing water has been recognized to have significant social, health, and financial impacts to communities (Moftakhari *et al* 2018). Social vulnerability levels (1–8, from methods above) were assigned to all buildings within the corresponding census tract. We obtained data on climate mobility by aggregating data over scales larger than census tracts including municipal and county scales.

2.4. Quantifying modes of climate mobility

Populations were classified into the four modes of climate mobility (figure 1) following social vulnerability and exposure assessment. Buildings (and then populations) were classified as either low social vulnerability (levels 1–3) or high social vulnerability (levels 4–8) and classified as being either over or under the threshold for exposure (either flooding or inundation). Hence, populations within the four modes of climate mobility were tabulated at both the individual and municipal scale as follows: Stable (low social vulnerability, not SLR exposed,), Migrating (low social vulnerability, exposed,), Displaced (high social vulnerability, not exposed) and Trapped (high social vulnerability, exposed). We repeated this procedure across all scenarios. See supplemental methods 1.4 for more details.

3. Results

3.1. Social vulnerability

The spatial distribution of social vulnerability across MDC is shown in figure 2 with profile-specific indicator levels featured in SM 2. The first set of profiles (1, 2, and 3; figure 2) is determined to have the lowest vulnerability with some of the highest median household incomes reflecting wealthy and upper-middle- and middle-income households. Profile 1 has the highest proportions of Non-Hispanic White residents (figure SM 3). The second set of profiles (4 and 5; figure 2) reflects tracts with lower-middle-income to working-class populations with low unemployment rates and median incomes around the county median household income ($51 347; 2019). Profile 4 covers the most census tracts ($n = 125$) of all profiles and has the largest proportions of the Hispanic/Latino population (median value = 63.9% of individuals across all census tracts within the profile; figure SM 3). Profiles 6, 7, and 8 represent communities with the highest social vulnerability relevant to SLR risks and have the lowest median incomes reflecting low-income communities. Profiles 7 and 8 display the highest levels of social vulnerability with tracts reflecting residents with high uninsured rates, high proportions of households living below the poverty line and receiving SNAP benefits, and the lowest rates of home ownership and the highest proportions of renters that are cost burdened. Profile 8 also features the highest proportions of residents that are foreign born and have limited English speaking skills, while the spatially contiguous profiles 6 and 7 have the highest concentration of Black residents attesting to the geographic racial segregation still present in MDC (figure SM 3).

3.2. Present and future flood hazards

Our fine-resolution compound flood hazard modeling (figures 3(a) and (b)) makes clear that present-day flood risks in MDC are derived from extreme rainfall and, to a lesser extent, storm surge, but future flood risks will be increasingly derived from permanent inundation stemming from higher tides and a groundwater table that surfaces within inland areas (figures 3(c)–(f)). At present day, extreme rainfall is the dominant flood hazard driver across MDC, storm surge is the dominant flood hazard driver along the southern coast of MDC, and inundation has limited impact in the northwest and southeast portions of MDC (figure 3(c)). With 1 m SLR, inundation emerges as the dominant hazard driver along the southeast coast and western portions of MDC, and scenarios involving 2 m and 3 m of SLR show progressively more areas across MDC where inundation becomes the dominant flood hazard driver (figures 3(d)–(f)).

3.3. Changes in flood exposure

Our building-level flood exposure analysis revealed that up to 92.2% of the MDC population considered in this analysis will be impacted by either flooding or

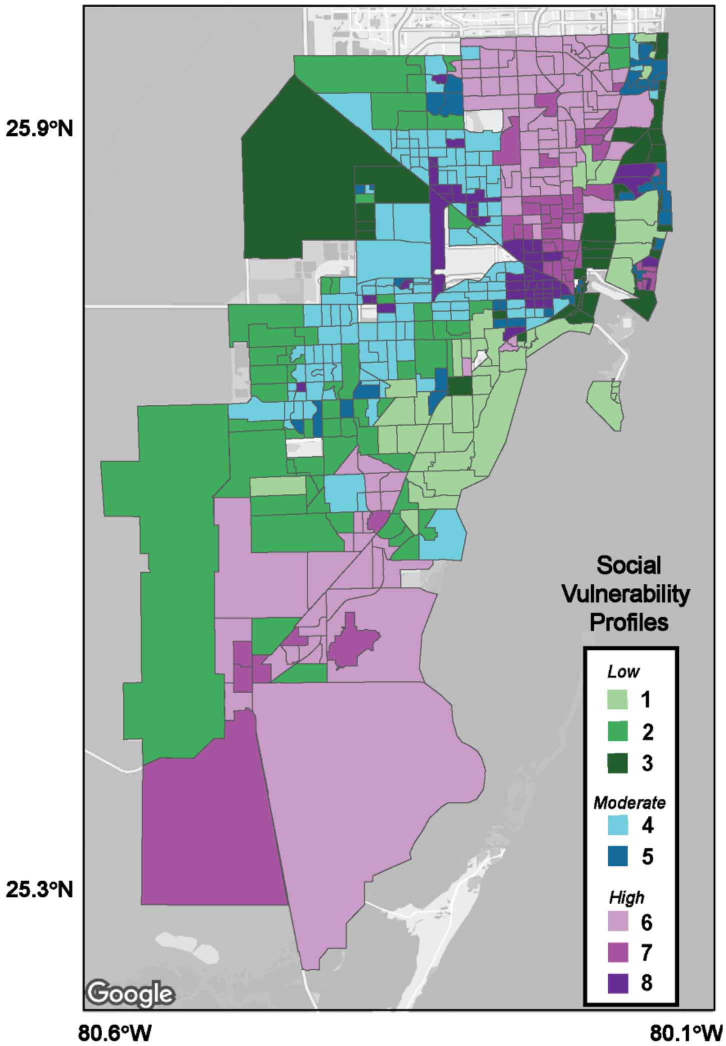

Figure 2. Social vulnerability profiles in Miami-Dade County. The map depicts the spatial extent of each social vulnerability profile across Miami-Dade County census tracts, from low social vulnerability (profiles 1–3) to high social vulnerability (profiles 6–8). See SM 2 for an indicator-level assessment (table 1) for each profile.

inundation by 3 m of SLR (figure 4). Under present-day conditions, unaffected populations (residencies with flood hazards below thresholds of impact) make up the largest segment of the population (84.2%; figure 4(a)), while precipitation hazards represent the most significant driver of flood exposure (14.6%), greater than storm surge (1.1%) or inundation (0.1%; figure 4(a)). With 1 m of SLR, a shift occurs with a fraction of the population impacted by storm surge (9.2%), a small fraction (2.8%) affected by inundation, and a commensurate reduction in those unaffected (74.4%; figure 4(b)). Following a 2 m increase in SLR, a substantial increase in the fraction of the population affected by inundation (54.7%) occurs, representing the dominant driver of exposure and a greater than 19-fold increase compared to current conditions and (figure 4(c)). We note that the amount of precipitation and storm surge exposure does not actually decline but that inundation becomes a more significant hazard marked by permanence, and we therefore chose to mark the occurrence of inundation as the greater impact. Finally, with 3 m of SLR, we estimate 86.8% of the current population (~2.2 M) will be affected by inundation, leaving only 7.8% of the population unaffected (figure 4(d)). The vulnerability levels of the populations falling within each driver of flood exposure are also shown in figure 4, revealing that flooding impacts populations across levels of social vulnerability. This result reinforces the goal of this study to assess climate mobilities robustly considering both direct and indirect pressures on populations. Exposure to each of these threats will lead to a sorting of local populations into those with capacity to move and relocate by choice (Migrating), those who relocate by necessity (Displaced), and those who cannot relocate (Trapped).

3.4. Climate mobility at the county scale

County-level assessments of climate mobility depict Displacement (62%) as the dominant mode of present-day climate mobility (i.e. populations of

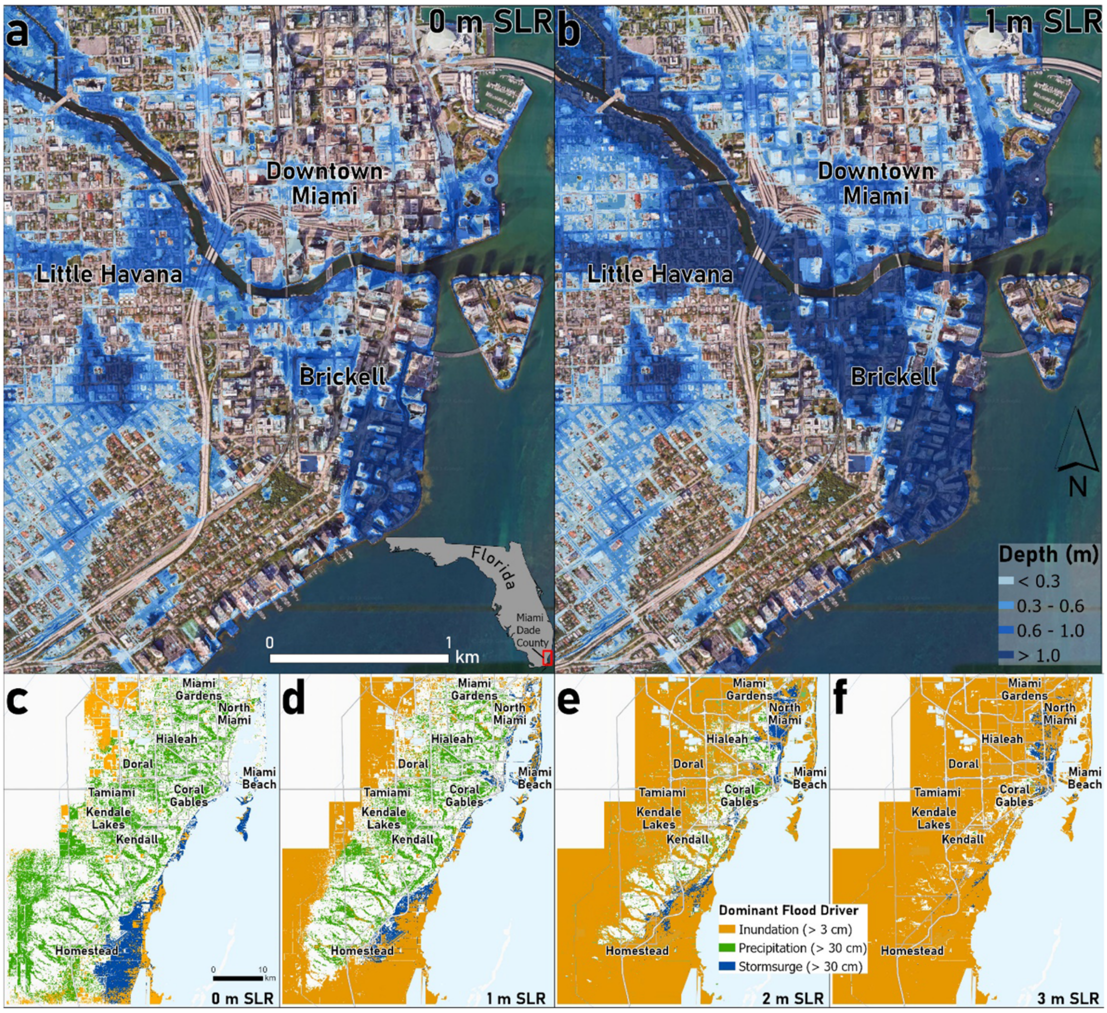

Figure 3. Flooding exposure in Miami-Dade County. (a)–(b) Panels depict flood exposure modeling overlayed on street-level imaging of a section of Downtown Miami in Miami-Dade County under 0 m (a) and 1 m (b) SLR scenarios. In each, the greatest modeled flood depth is specified (i.e. as the greatest depth of precipitation, storm surge, or groundwater flooding). (c)–(f) Panels depict county-wide spatial distribution of flood hazards under SLR. In each, the dominant flood driver is specified as inundation for depths of 3 cm or higher or, alternatively, precipitation-driven or storm surge-driven flooding at depths of 30 cm or higher.

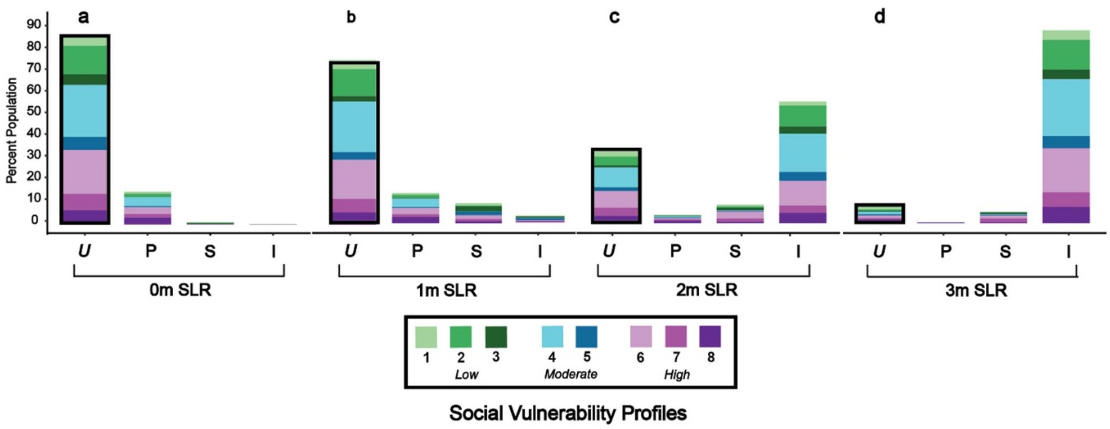

Figure 4. Population exposure by flood hazard. (a)–(d) Each plot shows the percentage of residents exposed to different types of flood hazards under increasing SLR (*0–3 m SLR*) across social vulnerability profiles. For each SLR scenario (a)–(d), each resident is characterized as unaffected by flooding (*U*, outlined in black), inundated at a depth of 3 cm or higher (*I*), or, if neither of those categories, flooded by precipitation (*P*) or storm surge (*S*) at 30 cm or greater depth (*P* or *S* based on whichever is greater depth). Residents, then sorted into social vulnerability profiles, are shown from low (profiles 1–3) to high (profiles 6–8) social vulnerability within each bar.

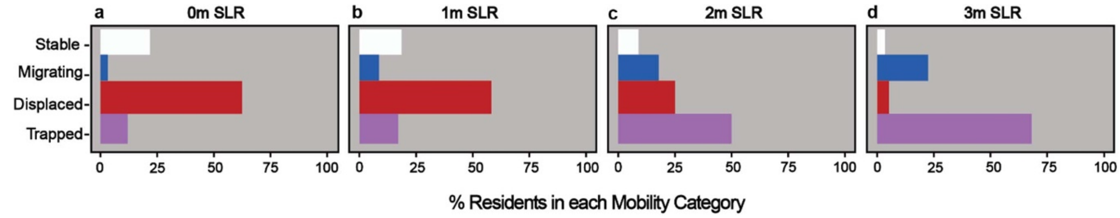

Figure 5. County-wide climate mobility designations for 0–3 m SLR. The percent of residents is specified for each climate mobility mode: Stable (white)—low social vulnerability, not SLR exposed (as in figure 1); *migrating* (blue)—low social vulnerability, SLR exposed; *displaced* (red)—moderate/high social vulnerability, not SLR exposed; and *trapped* (purple)—moderate/high social vulnerability, SLR exposed. SLR exposure, considering both flooding and inundation, corresponds to figure 4.

higher social vulnerability feeling pressures arising from indirect impacts of policies and people seeking more resilient areas; figure 5(a)). The second largest mode is Trapped (12%; i.e. high social vulnerability populations in areas of high inundation or flooding exposure). With 1 m of SLR and an increase in storm surge flood hazard (figure 4), there is an increase in both Migrating (7%) and Trapped (19%) populations (figure 5(b)), and with 2 m or more SLR, there is a substantial increase in the fraction of the population that is Migrating (18%) and Trapped (49%), with reductions in the Stable (8%) and Displaced populations (25%; figure 5(c)). At 3 m of SLR, Trapped (69%) and Migrating (23%) populations represent the dominant modes of climate mobility, and very few populations remain in areas of low flood or inundation exposure, Stable (3%) or Displaced (5%); figure 5(d)).

3.5. Climate mobility at the municipal scale

Our municipal-level assessment highlights the degree to which municipalities may face risks of depopulation and insolvency in the future, as climate mobility pressures vary across MDC municipalities for present-day (figure 6(a)) and future SLR (figures 6(b)–(d)). Consistent with the county-wide results (figure 5), figure 6(a) shows most municipalities clustered in the Displaced quadrant (upper left) with only one municipality (Key Biscayne) with 50% or more of its total population exposed to flooding or inundation. By 1 m of SLR, 9 municipalities have 50% or more of their total populations exposed to flooding or inundation, including vulnerable populations in Aventura and Miami Beach (Trapped), and significant populations in lower vulnerability municipalities such as Bay Harbor Islands and Golden Beach (Migrating; figure 6(b)). However, by 2 m of SLR, 27 out of the 34 municipalities in MDC, along with Unincorporated Miami-Dade, have 50% or more of their total populations exposed to flooding, with 17 municipalities categorized with primarily Trapped populations. With 3 m of SLR, all MDC municipalities, except for Coral Gables, are estimated to have 50% or higher of their total populations exposed to flooding. Seventeen of these municipalities have 90% or higher of their total populations exposed to flooding or inundation, including Surfside and Bal Harbor (Migrating) or Hialeah, Sweetwater, and Opa-Locka (Trapped). In this scenario, Displaced populations are highest in the City of Miami (19.5%) and Stable populations are highest in Coral Gables (41.9%), attesting to the high levels of county-wide exposure.

4. Discussion

SLR is accelerating through time, necessitating a long-term commitment to adaptation across coastal societies (Haasnoot *et al* 2021, Sweet *et al* 2022). Our assessment of drivers of SLR-related mobility in MDC reveals the potential consequences of flooding and inundation as well as indirect impacts under increasing SLR, especially if global-to-local risk management remains inadequate. As SLR increases to 3 m, only 7.8% of current residents in MDC would remain unaffected, with vast implications for municipal tax revenues and individual wealth and well-being. Our framework facilitates identification of differing climate mobility modes across communities at fine-scale granularity to inform effective and equitable adaptation decision making.

Most assessments of SLR risk evaluate exposure to chronic inundation from a higher sea state. We go beyond this, first, through assessment of multiple flood-hazard drivers across increasing SLR to improve understanding of differential exposure and associated impacts (Hauer *et al* 2021). We observe populations exposed to flooding or inundation increasing from 15.8% at 0 m to 92.2% under 3 m SLR (figure 4). Mobility assessments indicate up to 22.6% of residents under Migrating pressures for high SLR scenarios, revealing a proportion of residents who may be better positioned to leave through time (Binder and Greer 2016, Brady and Alexander 2015, Koslov 2016, Siders 2019), while immobility pressures for Trapped residents increase almost six-fold as SLR increases from 0 m (12%) to 3 m (69%), given fewer capacities to adapt within communities of moderate and high social vulnerability (Howell and Elliot 2018, Lincke and Hinkel 2018, de Koning and Filatova 2020, Siders and Keenan 2020, Bell *et al* 2021). Residents

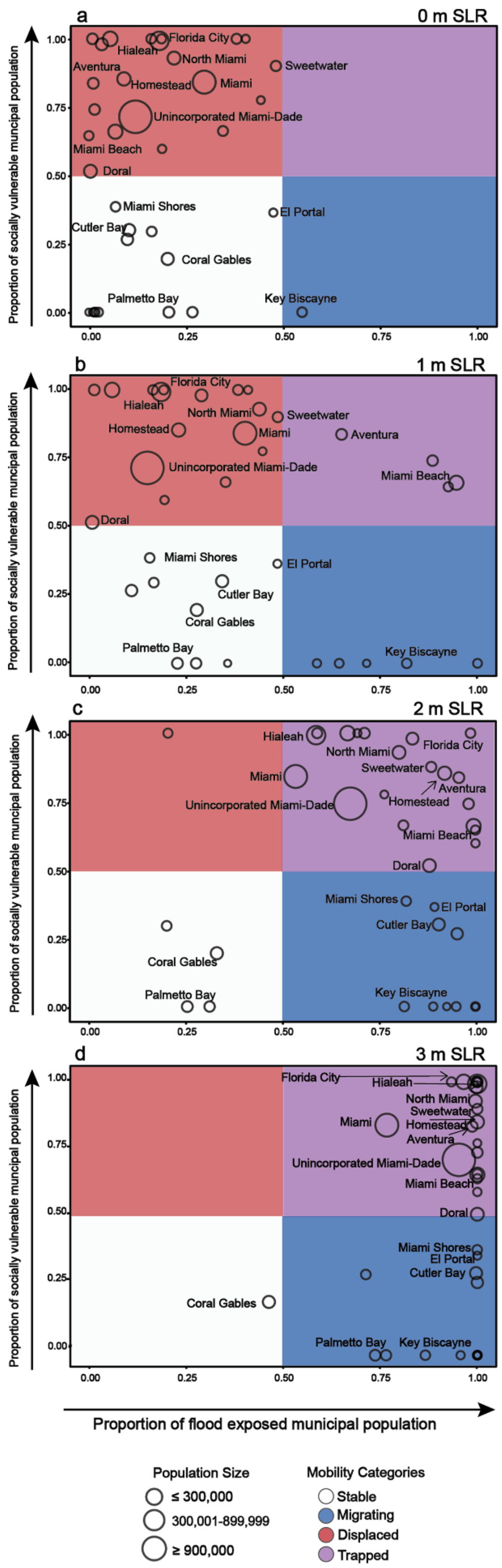

Figure 6. Climate mobility designations by Miami-Dade County municipality. Each MDC municipality is depicted by its proportion of flood exposed or inundated municipal population under scenarios of increasing SLR (*x-axis* of (a)–(d), scenarios for 0–3 m SLR as in figures 3(a)–(d)), and by the proportion of its municipal population that is socially vulnerable (*y-axis* of (a)–(d)). Circle size reflects the total population of each municipality, and quadrant color reflects climate mobility categorizations according to figure 1: Displaced (red; upper left), Trapped (purple; upper right), Stable (white; bottom left) and Migrating (blue; bottom right). A subset of municipalities is labeled for illustration.

categorized within the Migrating or Trapped categories in the 0 m or 1 m SLR scenarios occupy the highest risk areas in MDC and may need to confront issues of climate mobility and immobility in the near term. Recent reporting has recognized that present-day flood risks in MDC fall across highly vulnerable communities and have identified specific municipalities such as Hialeah and Opa-Locka as vulnerability hot spots—a conclusion also supported through our municipal assessment (Colman 2020, UCS 2016; figure 6).

Second, we highlight the scope of indirect SLR risks. A small percentage of current residents (8%) remains in areas unflooded as SLR increases. Residents categorized as Displaced under high SLR scenarios (5%), primarily in the City of Miami, have the highest risk for potential residential displacement as the demand for relatively safer housing increases (Aune *et al* 2020, de Koning and Filatova 2020). These results are supported by climate gentrification concerns that have been recognized by recent reporting featuring neighborhoods in the City of Miami such as Little Haiti (Johnson 2019, Chery and Morales 2023) and by empirical studies (Keenan *et al* 2018, Butler *et al* 2021). Stable residents represent the smallest proportion of residents (3%; 3 m SLR), illuminating how few residents can remain in MDC without severe flood or inundation exposure under high levels of SLR, though desirability for flood resilient areas is increasing (Rivero 2023). Where possible, densification efforts within Stable areas may present a solution for accommodating population shifts overtime.

Finally, the spatiotemporal shift in flooding has long-term implications for adaptation and mobility within MDC (Desmet *et al* 2018, Haasnoot *et al* 2021). The shift in residents from Displaced to Trapped between 1 m and 2 m SLR represents an under-prioritized threat to the long-term viability of MDC, whereby both coastal and inland residents are exposed to inundation. Inundation is the prevalent flood hazard driver at 2 m and beyond, contributing to county-wide Migrating or Trapped pressures (figure 5). Without drastic interventions and transformation of the landscape, 54.7% of MDC residents will experience permanent inundation as SLR approaches 2 m. Repetitive floods may trigger mobility decisions for residents in the near term, driven primarily by precipitation (figure 4(a)). However, given the immense long-term exposure to SLR risks and limitations on climate adaptation financing, decision makers and communities face consequential tradeoffs between who will be forced to leave MDC and which communities may be safeguarded.

Our assessment has implications for social equity and long-term risk management within adaptation policy at the municipal level. Addressing flood risk in the U.S. requires coordination among federal, state, county, and local governments, and an understanding of climate mobility pressures at the municipal scale is important to guide equitable prioritization of limited resources across municipalities. Heavy mobility pressure within at least 9 municipalities where 50% or more of all residents are categorized as Migrating or Trapped may occur at 1 m of SLR. As SLR increases, the municipalities with the largest percentages of Trapped residents are home to high proportions of Black and Hispanic residents who may depend on their homes as assets and foundations for intergenerational wealth, as well as those residents who have fewer assets. These municipalities may find themselves at the highest risk for asset devaluation and future insolvency (Treuer *et al* 2018, Shi and Varuzzo 2020) and require innovative solutions in the near term.

Our work has limitations. The framework assesses climate mobility pressures for people and communities given dynamic SLR risk, trends in disaster relief, current understandings in literature, and present-day socioeconomic and demographic patterns. Understanding the pressures associated with spatiotemporal differences in SLR impacts, across multiple measures of social vulnerability and exposure, may provide decision-makers with critical information needed to weigh future priorities and plan strategically for the long term. The present analysis, however, does not account for future demographic or economic changes or adaptation interventions and therefore does not forecast or predict outcomes but rather categorizes SLR risks and associated mobility pressures if levels of social vulnerability and population are constant and no structural policy changes are made.

5. Conclusion

Exposure to climate risks will contribute to mobility through direct and indirect pathways over time. The climate mobility framework presented here—intersecting spatially distributed and contextually rich measures of social vulnerability and flood exposure—offers a method for classifying the proportion of populations who are likely to fall within one of four modes of climate mobility: Stable, Migrating, Displaced or Trapped. While previous regional studies have discussed conditions that could spur future climate mobility, our approach captures the spatiotemporal shifts in mobility stemming from multiple hazard drivers (rainfall, storm surge, or inundation) that change over time and lays the foundation for socially informed adaptation decision-making.

Our results suggest the most frequent mode of mobility across the region is now Displacement, but with SLR, Trapped and Migrating modes of mobility will increase, reducing the number of people who are Stable. Furthermore, the shift from flooding hazards to inundation hazards marks a state change in the mobility hazard driver, whereby residents and municipalities across the entire county face significant individual and fiscal risks from a chronic and persistent hazard, raising concerns about future regional stability if a cycle of depopulation and devaluation arises. Differentiation between the flood hazard drivers impacting communities is not a feature of many coastal adaptation plans now, and our approach reveals a core transformation that will be consequential for regional climate mobility and associated adaptation planning.

The framework presented here is grounded in foundational determinants of risk—flood exposure and social vulnerability—which could be estimated for any region of the U.S. and beyond, and is broadly applicable to coastal communities with strong land-tenure rights. Furthermore, its simplicity makes it a powerful assessment tool to aid scenario planning as well as community-based adaptation project prioritization. Understanding the potential responses of highly diverse populations to chronic inundation, on top of episodic flooding, is important not only for equitable and effective adaptation measures in Miami-Dade County, but for many other communities across the U.S. Given existing political economies, equitable adaptation and decision-making is far from guaranteed. Failure to account for differential and dynamic SLR risks over time may exacerbate existing inequalities or contribute to unmanaged retreat, whereas by contrast, their incorporation may enable proactive and more equitable adaptive responses.

Data availability statement

The data that support the findings of this study are available upon request from the authors.

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