**PROJECT SUMMARY**

**Overview:**

This Faculty Early Career Development Project combines teaching and research activities around the theme of climate change demography and sea level rise driven migration. Using demographic models, this project explores the sociodemographic trajectory of climate migration driven by sea-level rise in the United States. The warnings of sea-level rise driven migration first appeared in the scientific literature in the late 1970s when increased recognition that disintegrating ice sheets could drive people to migrate from coastal cities. Since those warnings, scientists have chosen to model these migrants as age-less, sex-less, race-less individuals, ignoring important relationships between migration, sociodemographic characteristics, and the built environment. The exclusion of demographic and built environment factors in sea-level rise migration has created a generation of knowledge largely divorced from a half-century of migration scholarship. This five-year project seeks to remedy this gap by modeling the sociodemographic characteristics of sea-level rise migrants to understand the social and demographic implications of this population shift. Drawing on matrix population models, migration systems theory, sophisticated flood hazard models, and Census data, this work will produce a dynamic projected distribution of the US population, inclusive of sea-level rise, sociodemographic characteristics, and the built environment and will provide a new foundation for modeling population exposure to climate stressors in an era of global environmental change.

The PI aims to combine his intellectual project of understanding the demography of climate change with a pedagogical project providing students and career professionals with an in-depth understanding of the likely demographic shifts driven by climate change this century. By partnering with professional organizations, the PI’s integration of on-campus teaching with career professional training will span climate change, demography, sociology, forecasting, and public planning.

**Intellectual Merit:**

The proposed research project couples social and physical science in dynamically coupled demographic change and sea-level rise models to better understand climate migration and answers the Intergovernmental Panel on Climate Change’s call to develop coupled natural human system impact assessments.

**Broader Impacts:**

This project will provide one of first completely integrated demographic projection models which accounts for both demographic change and climate change. It will also develop novel integration of socioenvironmental data that will inform other studies of climate impacts, climate migration, and ultimately “climate change demography.” This research will also have broad impact on public and policy conversations about climate change and, by partnering with professional organizations for training, will allow local governments to incorporate the findings into their sustainability planning and their deployment of critical infrastructure. The outcomes of this research will likely lead to development of public policy in both coastal and landward communities facing sea-level rise and climate migration. Moreover, the educational activities advanced by this project will offer both undergraduate and graduate students crucial training in demographic methods, climate change, and the integration of climate and society.

**CAREER: Toward the Demography of Climate Change: Demographic change and migration due to sea-level rise in the United States**

**PROJECT DESCRIPTION**

**I. Introduction**

Scientists first sounded the alarm of potential “major dislocations in coastal cities” (Mercer, 1978) due to a disintegrating West Antarctic Ice Sheet and sea-level rise more than forty years ago. Since those early warnings, sea-level rise continues to be widely regarded as one of the most costly and visible future impacts of global climate change (McGranahan et al., 2007a; Nicholls et al., 2011; Strauss et al., 2015). With the global coastal population projected to eclipse one billion people this century (Neumann et al., 2015), sea-level rise is expected to affect and, in many cases, displace hundreds of millions of people (Hauer et al., 2016; Nicholls et al., 2011).

While the scientific community understands that climate change and sea-level rise will affect millions of people in the United States and across the world, we face a critical knowledge gap about the impacts of rising sea levels on human migration. Previous attempts to model sea-level rise and migration eschew two important considerations. First, sea-level rise migration models lack the crucial feedback loop whereby sea-level rise migrants alter the demographic trajectory in both their origin and destination. If sea-level rise forces millions of people further inland, a potential domino effect could result, further enhancing migration to more distant locations and further suppressing migration to coastal areas (Curtis and Schneider, 2011; Döös, 1997; M. E. Hauer et al., 2020a). Second, modelers have chosen to model migrants as age-less, sex-less, and race-less individuals (Hauer et al., 2016; McGranahan et al., 2007a; Neumann et al., 2015; Nicholls et al., 2011; Strauss et al., 2015), ignoring the well-established relationship between migration, the built environment, and sociodemographic characteristics (Black et al., 2011b; Clark and Maas, 2015; De Longueville et al., 2019; Dieleman, 2001; Zahran et al., 2008). This sociodemographic ignorance is particularly important given the demographic shifts anticipated this century (Colby and Ortman, 2017). Those with the least resources are least likely to migrate when facing environmental pressures (Black et al., 2011b) and by ignoring this well-established relationship, past sea-level rise migration models likely overestimate those most likely to migrate and grossly underestimate those who might be “trapped” in coastal communities. These gaps combine to create divergent estimates of *who* will be most affected and *how* sea-level rise will ultimately alter population distributions. The challenge is to develop better coupled natural-human systems for assessing sea-level rise impacts that properly couple climate projections with projections of sociodemographic change.

My research to date has provided the building blocks to overcome the shortcomings outlined above. I published the first complete projections of populations at-risk to sea-level rise in the US (Hauer et al., 2016) and the first projections of potential destinations of sea-level rise migrants (Hauer, 2017). In that research, I answered *how* *many* people are at-risk to sea-level rise in the United States and if sea-level rise displaces these people, *where* they are likely to migrate, but my research still treated migrants as sociodemographic blank slates. The proposed project goes further and will answer *who* sea-level rise will impact and likely displace and *how much* sea-level rise will dynamically alter the demographic trajectory of both coastal and inland areas.

This five-year project connects my past research by examining the sociodemographic and built environment changes due to sea-level rise in the United States and remedies the challenges outlined above by modeling the sociodemographic characteristics of sea-level rise migrants within a dynamic population model. I ask the following central questions: What are the socio-demographic characteristics of people who will be impacted by sea-level rise? How might changes in future age structures alter migration dynamics for those impacted by sea-level rise? How might differences in exposure to sea-level rise hazards influence migration decisions in coastal communities? To what extent will sea-level rise migration alter the distribution of the demographic trajectory of US population? How might changes in the built environment enhance or suppress this migration? In addressing these questions, this project answers the Intergovernmental Panel on Climate Change’s (IPCC) call to “construct impact assessments in which biophysical futures are coupled with socioeconomic futures”[[1]](#footnote-1). Drawing on demographic models and migration theory, the research component of this proposed project will produce a dynamic projected distribution of the US population, inclusive of sea-level rise, sociodemographics, and the built environment and will provide a new foundation for modeling population exposure to climate stressors in an era of global environmental change.

Pursuing this project will also facilitate the PI’s educational goal of bringing the insights from “climate change demography” to bear on the training that undergraduate and graduate students receive at Florida State University and to the broader public in a three-pronged pedagogical education project. First, most undergraduate students at Florida State University are from Florida and I will provide in-depth understanding of the demographic context of climate change for students of the state most impacted by sea-level rise. Second, FSU is home to one of the oldest degree-granting Demography programs in the US, housed in the Center for Demography and Population Health. The Demography of this project will directly enhance the education of both masters and doctoral graduate students in the Population Center. Third, many cities are starting to plan for climate migration, and I have partnered with several professional organizations whose members are hungry for these insights to inform their long-range planning processes. Finally, this proposal also funds a graduate student for five years, enhancing my career development in terms of academic mentoring.

**II. Background and Overview**

The implications of sea-level rise on human migration first appear in the scientific literature more than forty years ago (Mercer, 1978; Schneider and Chen, 1980), when scientists started to sound the alarm of a disintegrating West Antarctic Ice Sheet and the potential “major dislocations in coastal cities”(Mercer, 1978). Since those early warnings, sea-level rise and associated impacts continue to be widely regarded as one of the most costly and irreversible future consequences of global climate change (Change, 2014; McGranahan et al., 2007b; Nicholls et al., 2011; Strauss et al., 2015). Scientific projections of global mean sea-level rise for the year 2100 range from a low of 0.4 meters to a high of 2.5 meters (Jevrejeva et al., 2012; Stocker, 2014; Sweet et al., 2017), depending on assumptions of future anthropogenic greenhouse gas emission levels, thermal expansion of ocean masses, sea surface temperatures, rates of melting and decomposition of Antarctic and Greenland ice sheets, and isostatic adjustment as large ice sheets disappear. These sea-level rise projections are likely conservative and high-end sea-level rise is increasingly realistic (Bamber et al., 2019). With the global coastal population projected to eclipse one billion people this century (Neumann et al., 2015), sea-level rise is expected to affect and, in many cases, displace hundreds of millions of people (Hauer et al., 2016; Nicholls et al., 2011).

Since the first studies to quantify population displacement due to sea-level rise (Schneider and Chen, 1980) and document changes in human migration related to sea-level rise (Mimura, 1999), fundamental understanding of sea-level rise and human migration has rapidly advanced with the development of basic theory on climate change migration (Black et al., 2011b; Döös, 1997; Hauer, 2017; McLeman, 2014), empirical case studies of historical analogues for future sea-level rise (Arenstam Gibbons and Nicholls, 2006; Bailey et al., 2014; Fussell et al., 2014a; Hauer et al., 2019; Trincardi et al., 2016), integrated economic analysis and modelling of sea-level rise retreat (Fankhauser, 1995; Yohe et al., 1996; Yohe and Schlesinger, 1998), explicit models of sea-level rise migration (Adams and Kay, 2019; Chen and Mueller, 2018; Davis et al., 2018; Hauer, 2017), as well as contentious policy discussions on the need for coastal retreat and adaptive infrastructure (Hino et al., 2017; Koslov, 2016; Maldonado et al., 2014; Pilkey et al., 2016). In some cases, studies even question *if* sea-level rise will spur widespread migration at all (Kniveton, 2017; Laurice Jamero et al., 2017).

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Description automatically generatedMultiple sea-level rise hazards, not just complete inundation, jeopardize US coastal cities (Strauss et al., 2015). Some coastal residents presently experience multiple sea-level rise impacts such as recurrent flooding from tides or storms (Jacobs et al., 2018; Moftakhari et al., 2015). Numerous historical analyses in the US context (Arenstam Gibbons and Nicholls, 2006; Bailey et al., 2014; Fussell et al., 2014a; Hauer et al., 2019; Hori et al., 2009; Thiede and Brown, 2013) find sea-level rise can overwhelm resilient coastal residents with strong emotional ties to place and adaptive infrastructure (Bailey et al., 2014), leading to abandonment (Arenstam Gibbons and Nicholls, 2006). When people do migrate in response to sea-level rise hazards in the US, they more often migrate to urban job growth centers (Hori et al., 2009), rather than making small, incremental migrations (Hauer et al., 2019), and, if migrating in response to a tropical cyclone such as Hurricane Katrina in New Orleans or Hurricane Maria in Puerto Rico, tend to migrate back to their home community (Alexander et al., 2019; Curtis et al., 2015).

**Figure 1. Migration from sea-level rise is multifaceted and is influenced by environmental hazards as well as political, demographic, economic, and social factors. This project will focus on the intersection of the environmental and demographic factors. Adapted from Hauer et al. 2020.**

Sea-level rise influences human migration in multiple ways. The most straightforward, apparent, and existential migration pressure involves permanent, irreversible inundation of low-elevation areas, under which a certain rise in sea level renders the built environment uninhabitable (Hauer et al., 2016; Poulter and Halpin, 2008; Strauss et al., 2015). Migration is widely understood as a choice in which individuals weigh the economic, social, and emotional costs and benefits of moving (Black et al., 2011a; Clark and Maas, 2015; De Longueville et al., 2019; Dieleman, 2001). Thus, the decision to migrate is multidimensional (**Figure 1**) (Clark and Maas, 2015; Coulter et al., 2016; Dieleman, 2001).

Most sea-level rise migration studies only model migration along environmental factors (Davis et al., 2018; Neumann et al., 2015; Nicholls et al., 2011), or couple environmental factors with economic (Chen and Mueller, 2018) or social factors (Robinson et al., 2020). Conspicuously missing from these models is the integration of *demographic* and *housing* factors. This omission is particularly egregious given the availability of high-quality demographic data in the United States and the relative simplicity of integrating demographic change into migration models.

Despite these rapid advancements, clear significance of this dimension of global environmental change in the US, the lively debate surrounding the topic, and the variety of perspectives and methodologies offered in the literature, several scientific challenges remain. Notably, a fully integrated, dynamic demographic/sea-level rise model. This project will fill this dynamic demographic/sea-level rise modelling gap by incorporating migration modeling within a demographic change model called the Demographic Metabolism (Lutz and Muttarak, 2017; Ryder, 1985).

1. **Migration Modeling**

Migration decisions, undertaken by individuals and households, are more than a function of sea-level rise risk, risk perception, and policies to mitigate or adapt to risk. Migration is widely understood as a choice in which individuals weigh the economic, social, and emotional costs and benefits of moving (**Figure 1**) (Black et al., 2011a; Clark and Maas, 2015; De Longueville et al., 2019; Dieleman, 2001). Even in circumstances where there is environmental pressure to migrate away from an area, people make choices about when they move, their destination, who to move with, and whether to return (Findlay, 2011; Fussell et al., 2014b; Seto, 2011). These decisions depend on whether the environmental pressure experienced is rapid or slow onset, short or long duration, and risks to the built and natural environment, human health, or all of these (Black et al., 2011a).

The decision to migrate is multidimensional, involving perceptions, demographic, economic, social, and housing market factors (**Figure 1**) (Clark and Maas, 2015; Coulter et al., 2016; Dieleman, 2001). Past experience with severe flooding causes people to perceive future flooding events as riskier (Grothmann and Reusswig, 2006; Knocke and Kolivras, 2007; Solberg et al., 2010), amplifying possible forward-looking migration responses (Black et al., 2013; Kayastha and Yadava, 1985). Perceptions of the risks of sea-level rise combine with many other factors to influence the decision to move into or away from coastal areas. Therefore, sea-level rise may marginally increase existing migration out-flows and decrease migration in-flows to coastal areas (Curtis and Schneider, 2011). Consequently, those who are most likely to move away from sea-level rise hazards are those who can best absorb costs and extract benefits associated with migrating: healthy, skilled, working-age adults, who can increase lifetime potential earnings by moving to higher wage labor (Greenwood, 1997; Harris and Todaro, 1970; Lee, 1966; Morrison and Clark, 2011; Plane et al., 2005; Stark and Bloom, 1985). In areas heavily threatened by sea-level rise, evidence already suggests the hazards of sea-level rise translate into reduced housing values (McAlpine and Porter, 2018) and in Atoll Island Nations, migration consists of mainly young, working-age people leaving the islands for economic opportunities (Campbell and Warrick, 2014; Donner and Webber, 2014; Farbotko and Lazrus, 2012; Shen and Gemenne, 2011). However, in different contexts and increasingly over time, sea-level rise hazards, livelihood changes, protective infrastructure, housing availability, and demographic change will variably factor into migration decisions.

While sea-level rise may displace coastal populations in the future, urbanization and coastal amenities support large costal populations, and continue to drive pro-coastal migration. For millenia, people have settled in river deltas and coasts for their natural resources and amenities, including fresh water, ecosystem services, transportation, and recreational opportunities. These environmental resources and amenities, as well as the disamenities associated with sea-level rise and cyclones, are capitalized in housing prices and wages (Cragg and Kahn, 1997; Rappaport, 2009; Roback, 1982) – capitalization that sea-level rise directly threatens (McAlpine and Porter, 2018). Sea-level rise, however, is unique among environmental stressors as it ultimately implies the conversion of habitable land to uninhabitable water. Thus, environmental factors could swamp or even amplify the other migration decision factors resulting in migration. When sea-level rise is integrated over long periods of time, important demographic and housing factors will play an increasingly important role in sea-level rise migration decisions as underlying demographic forces shape the likelihood of migration (Massey, 1999).

Additionally, many coastal communities will deploy adaptation strategies to reduce exposure to climate hazards (Adger et al., 2018; Black et al., 2011b; McLeman and Smit, 2006). Broad adaptation responses include protection, accommodation, and retreat that operate as either obstacles to keep residents in coastal communities (protection/accommodation) or facilitate migration (retreat). Protective infrastructure in coastal communities will act to reduce the push factors of sea-level rise and, by virtue of being “safer” than unprotected coastal areas, will act to enhance the pull factors of coastal communities. Coastal communities with better housing markets, local infrastructure, and economies could continue to be destination communities, even in the face of sea-level rise so long as the coastal hazard does not overwhelm local adaptative measures.

When people do migrate, they tend to either move short distances or follow preexisting ties to human capital hotspots (Findlay, 2011). These migrations can be captured using Migration Systems Theory, a branch of migration research that uses all origin-destination combinations as the object of study as opposed to any single origin-destination pair (Fawcett, 1989; Massey et al., 1993). Migration decision factors like those found in **Figure 1** are embedded within the preexisting migration system and tend to drive locational decision making after an environmental event as people leverage established networks of social capital and kin networks (Curtis et al., 2015; Hugo, 2011; McLeman, 2014). Migration systems are remarkably stable after an environmental event allowing high confidence in migration prediction (Hauer, 2017; M. E. Hauer et al., 2020b; Lu et al., 2016). Thus, by combining preexisting migration information and demographic information, it is possible to forecast both who is most likely to migrate due to sea-level rise and where they are most likely to go.

1. **Demographic Metabolism**

While sea-level rise is a research priority in multiple physical science disciplines, relatively few social scientists have begun to quantify its impacts. Studies typically focus on how future climate change could impact society within the context of present conditions and circumstances (e,g., Emrich and Cutter 2011; Frazier et al. 2010; Hsiang et al. 2017; Martinich et al. 2013). Yet with climate impacts expected to worsen as we approach the end of the century due to intensified warming, the direst climate impacts may not depend on present conditions. Rather, they will depend on future conditions.

The literature on sea-level rise displacement is split between using current and projected populations. This schism leads to massively divergent estimates of sea-level rise induced migration, ranging from a low of 88 million (Desmet et al., 2018) to as high as 1.4 billion (Neumann et al., 2015). When studies do employ projected populations, they tend to rely on time series forecasts of populations rather than a demographic projection method (e.g. (Desmet et al., 2018; Hauer et al., 2016; Hinkel et al., 2014; Neumann et al., 2015)) or employ spatial resolutions far larger than those implied by sea-level rise (Curtis and Schneider, 2011). A demographic projection best captures the important underlying trends in population change while a time series projection, focusing on total populations, largely misses these trends in sociodemographic change. For example, the well-documented population growth of both communities of color and the elderly in the U.S. (Colby and Ortman, 2017), suggests that future generations of these groups are likely to be disproportionately impacted by future climate change impacts. By focusing on current populations, the potential for *emerging* climate impacts could go undetected and renders the future climate risk as both static (population) and dynamic (environmental); demographers refer to population change as ‘population dynamics’ not ‘population statics’ after all. Or important components of demographic change are missing in time series forecasts. The interaction between coastal demography and sea-level rise will pattern future demographic change and climate impacts.

Extreme heat, sea-level rise, increasing droughts and wildfires, and significant economic damage are but a few impacts expected of climate change this century (Field, 2014). Moreover, these impacts will be unequally distributed across regions and populations by class, age, sex, and race, disproportionately impacting marginalized peoples and groups (Field, 2014; Skoufias, 2012). Climate research increasingly tries to capture this disproportionality in both climate impacts and migration models. The US population will experience widespread aging by the century’s end (Gerland et al., 2014) and the well-documented relationship between age and migration propensity (Rogers, 1988) suggests that youthful populations are more likely to migrate than older populations. What are the implications for “migration as adaptation” if older people migrate less than younger people? Migrants continue to migrate to the economic engines in coastal cities (Nicholls et al., 2020) but will changing demographics alter this migration dynamic? Time series models cannot answer these questions, but the explicit demographic model of the proposed research equips this proposal to address these important questions.

Furthermore, relatively few subnational population projections in the US exist. County-level population projections are typically only available through the gray-literature (such as through the Federal and State Cooperative for Population Projections) or through for-proﬁt companies and oftentimes only comprise several states rather than the whole US. These projections, while incredibly useful, tend to employ a variety of methods, input data, time horizons, and demographic groupings making inter-state and inter-projection comparisons difﬁcult. The lack of rigorous small-area population projections by detailed demographic subgroups has likely hampered our understanding of general subnational demographic change in the US and our understanding of climate impacts.

Norman Ryder’s cohort approach to demographic change (nicknamed the “*demographic metabolism*”) is an ideal methodological vehicle (1985) for exploring sea-level rise and human migration within a demographic framework. With specific calls for use in climate change research (Lutz and Muttarak, 2017), demographic metabolism is a theoretical framework that argues that “the process of social change can be analytically captured through the process of younger cohorts replacing older ones” (Lutz, 2012: 284) along multi-dimensional sociodemographic characteristics (e.g., age, gender, race, educational attainment, income, poverty, etc.). The cohort aged 15-19 in 2020 becomes the 20-24 cohort in 2025 after adjusting for the components of population change: births, deaths, and migration. This approach creates remarkably reliable sociodemographic forecasts over decadal time scales for two key reasons: 1) many sociodemographic characteristics are either established at a young age (e.g., the proportion of people with a high school education aged 25-29 in 2015 is a good predictor of those aged 60-64 with a high school education in 2050), and 2) sociodemographic change is embedded within the age-structure (e.g., life course analysis shows that earnings steadily increase after age 18, peaking around age 65, before declining through retirement). A Demographic metabolism framework allows underlying societal change to occur in concert with environmental change in an analytically and computationally tractable manner.

**III. Research Plan**

1. **Methods Overview**

This project examines the demography of climate migration in the United States associated with sea-level rise. Following migration scholars and demographers who have studied climate migration (Call et al., 2017; Chen and Mueller, 2018; Fussell et al., 2014b; M. E. Hauer et al., 2020a), this five-year project combines a migration systems approach (Curtis et al., 2015; Fawcett, 1989) with matrix population models (Caswell, 2001) and sophisticated flood hazard models to project the changes in the future US population distribution due to sea-level rise. I propose to utilize a multi-dimensional predictive model of sociodemographic change called demographic metabolism(Lutz and Muttarak, 2017)*.*  **Figure 2** is a general schema of the input data, demographic model, and sample outputs. The following research questions drive the analysis described below:

1. What are the socio-demographic and housing characteristics of people who will be impacted by sea-level rise?
2. How might changes in future age structures alter migration dynamics for those impacted by sea-level rise?
3. How might differences in exposure to sea-level rise hazards influence migration decisions in coastal communities?
4. How might changes in the built environment enhance or suppress this migration?

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**Figure 2. Overall modelling schema. Using data from the First Street Foundation's Flood lab, IRS migration data, and Census Data as inputs to a Matrix Population Model based on the Demographic Metabolism. The output of the model includes origins/destinations of projected sea-level rise migrants and their associated sociodemographic characteristics.**

To accomplish the goals of this project, I will build a matrix population model based on three primary sources of data. (1) the First Street Foundation’s Flood Lab flood hazard model which provides the necessary modeling for displacement. (2) IRS migration data which provides the probabilities of migrating from county to county. (3) Census and American Community Survey data provide the necessary sociodemographic and housing data. While I separately describe the three primary data sources of this project below, I will ultimately incorporate all three sources into a single multi-regional matrix demographic (Rogers, 1973).

1. **Population Projection Model**

The core model that powers the analysis is the population projection model. In my previous work, I developed advanced spatially-explicit flood models and small-area population projection models (Hauer et al., 2016, 2015). In 2019, I published a complete set of county-level population projections for the United States using matrix population models (Hauer, 2019) and open-sourced the R code.

Following my previous work (Hardy and Hauer, 2018; M. Hauer et al., 2020; Hauer et al., 2019, 2016, 2015), I will deploy the population projection model at the Census Block Group geography in all 437 affected coastal counties in the U.S. and then aggregate results to the county-level. One of the most well accepted approaches for projecting populations is the cohort-component method, which uses migration, birth, and death rates to forecast population changes within an area (Smith et al., 2006). Unfortunately, birth, death, and migration information are not published at Census Block Group geography, precluding the use of the cohort-component method for this project. However, cohort-change ratios (Hamilton and Perry, 1962; Swanson et al., 2010) are a long-established, mathematically equivalent, short-hand method of mimicking the cohort-component method at sub-county geographies. To prevent run-away growth in the block groups, I will control the overall population totals to previously projected populations at the county-level in a ‘top-down’ projection framework (Hauer, 2019).

The proposed projection model will include demographic detail for eighteen five-year age groups (0-85+), two sex groups (Male and Female), and four race groups (White NH, Black NH, Other NH, and Hispanic). I do note that the population projections do not account for potential racial identity changes over the life course – changes that are likely to occur (Alba, 2018) – and are a limitation in my analysis. By incorporating age, sex, race, income, and educational attainment into my demographic metabolism model, I can accurately forecast the sociodemographic characteristics of people at risk to sea-level rise. The focus on these five characteristics will allow the identification of more socially vulnerable groups, since attributes of these characteristics—women, racial minorities, poverty-level income, low educational attainment—have been associated with increased levels of social vulnerability to environmental hazards and climate change ([Denton 2002](#_ENREF_9); [Leichenko and Silva 2014](#_ENREF_24); [Shepherd and KC 2015](#_ENREF_37); [Lutz and Muttarak 2017](#_ENREF_26)).

In keeping with my past work, I will use an ex-post-facto error analysis to report the accuracy, bias, and uncertainties, ensuring the resultant projections are accurate and credible. Cohort-change ratios have a long history with error rates on par with or better than most demographic projection models and appropriate prediction interval coverage.

Projections inherently rely on historic trend data, and therefore performance tends to suffer when growth greatly deviates from historical patterns. However, I have shown that my small-area demographic projections outperform accuracy expectations over multiple decadal intervals (Hardy and Hauer, 2018; Hauer, 2019; Hauer et al., 2016, 2015) and numerous scholars have demonstrated the reliability of (and need for) long-range population projections for climate change and other applications at small scales (Gerland et al., 2014; Jones and O’Neill, 2016; Lutz and Muttarak, 2017; Neumann et al., 2015). However, these projections, like all projections, involve the use of assumptions about future events that may or may not occur. Any small error in the projections early in the projection horizon could cascade into considerable errors decades later in the projection. Documenting their creation, open sourcing the computer code, and extensively evaluating their accuracy and uncertainty will ensure confidence in their accuracy and usefulness.

This matrix model requires three primary sources of data: (1) census data provides the important population vector and change ratios while the American Community Survey data allows breakdowns by sociodemographic characteristic and migration propensity curves; (2) flood hazard data allows me to calculate the proportion of each block group permanently and semi-permanently inundated and thus potential sea-level rise migrants; (3) IRS migration data provides the probability of migrating between locations.

1. **Census and American Community Survey Data**

The US decennial census provides detailed demographic data in complete geographic coverage of the US. These data are the goto demographic data source and considered a “gold standard” in demographic analysis. For this project, the decennial data provide the population count upon which I apply the rest of the modeling.

Decennial data, while of the highest quality, contain virtually no sociodemographic data. The Census Bureau collects detailed sociodemographic data via the American Community Survey, the largest detailed demographic survey in the US. Each year more than 2.5 million US households respond to the American Community Survey in geographic coverage as small as the Census Block Group – only the Census Block is smaller. I will use income and educational attainment data from the American Community Survey to further stratify my model by income and by education. The American Community Survey also contains detailed housing data that will be paramount for modeling the influence of the built environment on migration patterns with variables that include housing tenure and housing age, amongst others.

In previous research I used publicly-available Census Data to show counties in Louisiana sinking into the Gulf of Mexico exhibit little if any sub-county migration toward more landward parts of the county (Hauer et al., 2019). I did not have access to confidential microdata precluding a more robust analysis with other, important determinants of migration. With a 5-year project, I will explore the use of a Federal Research Data Center to access the American Community Survey microdata to conduct more robust analyses on sub-county migration patterns. At Research Data Centers, qualified researchers can apply for access to restricted-use microdata from a variety of statistical agencies to address important research questions, but it must mutually benefit the researcher and the Census Bureau. If access is granted, I will examine sub-county migration in coastal communities experiencing the greatest threat to sea-level rise and recurrent tidal flooding and how sociodemographic variables and the built environment might influence the relationship between sea-level rise and sub-county migration. Access to a Research Data Center is not integral to the proposed research but would provide robust modeling.

1. **Flood Hazard Data**

In my past work, I’ve worked with advanced spatially-explicit flood models to model exposure to sea-level rise (M. Hauer et al., 2020; Hauer et al., 2016, 2015) and for this project I will partner with the First Street Foundation to use their Flood Lab flood hazard model. In April 2020, First Street Foundation invited me to use Flood Lab for a project of my choice because of my previous work on sea-level rise. The First Street Foundation gathered more than 65 academic flood modelers to calculate flood probabilities in the past, present, and future for a holistic U.S. based flood hazard probability model. The flood model accounts for every major flood type, including tidal flooding, riverine

flooding, precipitation, and storm surge in a hydrodynamic flood model to calculate flood probabilities. This data will allow me estimate how many people and when they are at risk of permanent and semi-permanent submergence and thus migration.

1. **IRS Migration Data**

The general matrix population projection approach does not allow for migration between geographies. However, a multi-regional matrix implementation (Rogers, 1973) allows for a computationally tractable solution that requires the probability of migrating between all locations.

I will use the IRS migration data to calculate and project the probability of migrating between locations. The IRS began publishing annual county-to-county migration data in 1990, using every Form 1040, 1040A, and 1040EZ in the IRS Individual Master File (Gross, 2005). These data cover 95% to 98% of the tax-filing universe and their dependents (approximately 87% of US households (Molloy et al., 2011)). The IRS data contain over 4.4 million county-year observations and 300 million migrants, making it the largest migration data source for count flows between counties available in the United States. Because the IRS derives migration information from tax filings, these data are likely to underrepresent those who do not file taxes (DeWaard et al., 2016; Gross, 2005), namely undocumented populations, the poor, the elderly, and college students (Gross, 2005). However, the overwhelming majority of households file US tax returns and the extraordinarily large administrative database make them an attractive data source for conducting migration research in the United States despite this limitation.

Time series modeling of the IRS migration data will allow me to project the evolution of the migration origins and destinations, allowing migration links to wax or wane over time. Past accuracy evaluations of similar migration forecasting approaches yield feasible migration projections (Davis et al., 2018; Hauer, 2017; Robinson et al., 2020).

I am already intimately familiar with the IRS migration data, using them in past research (Hauer, 2017) and publishing open-source R code to process and compile the more than 2,000 individual IRS migration files into a single, flat data file (Hauer and Byars, 2019). This familiarity will allow me to seamlessly transition the IRS data into a multi-regional Leslie matrix.

1. **Data Preservation**

Please see the Data Management Plan in this proposal.

1. **Anticipated Outcomes and Significance of Research Activities**

This project will yield significant insights in scholarship on climate migration and demography. It will provide one of, if not the, first completely integrated demographic projection model accounting for both demographic change and climate change. It will also develop novel integration of socioenvironmental data that will inform other studies of climate impacts, climate migration, and ultimately “climate change demography.”

I anticipate multiple high-impact journal articles from this project. I expect to disseminate the data and results at major scientific conferences, with career professional partner organizations (see Educational Plan below), and through preprint servers making research results available quickly and easily accessible to other scientists, journalists, and policy makers. I am an open science advocate and will open-source the underlying data and code through R and GitHub for any scientific publication. I am also social media savvy and will use various platforms to improve access to publications, computer code, and data.

I anticipate publishing my results in high-impact peer review journals. My previous research on sea-level rise modeling has been published in both high-impact general science journals and high-impact discipline specific journals and I anticipate publishing the results of this project in similar outlets. I also anticipate my results will shift the conversation around climate modeling to be more inclusive of demographic outcomes. Additionally, I anticipate that the modelling approach and open-source code will shape future climate-demography endeavors.

The dissemination of the results with career professional partner organizations (see Educational Plan below) will allow local governments to incorporate my findings into their sustainability planning and their deployment of critical infrastructure. The outcomes of this research will likely lead to development of public policy in both coastal and landward communities facing sea-level rise and climate migration.

Additional detail on merit and impact is found in the subsequent sections below.

**IV. Educational Plan**

The educational objective of this proposal is three-fold focusing on undergraduate students, graduate students, and career professionals. Specifically, I will develop a new undergraduate course in “Climate Change Demography” with specific modules on climate migration and demographic consequences. Second, I will develop a graduate seminar on “Forecasting” for the Master of Demography curriculum with specific modules on matrix population models. Third, I have partnered with two professional organizations for training and dissemination of results to career professionals. Additionally, I will continue my work in the Center for Demography and Population Health and will seek speaking opportunities at both Population Centers and Environmental Studies departments across the country during the period of this award. I will also update the courses I already teach in Population Data and Demography with added material on climate change. Notably, this proposal also fully funds a doctoral student for five years, enhancing my academic mentoring throughout the period of the award.

Combining research activities with teaching and outreach is a key component of both this project and my long-term career goals. I am poised to implement the education plan successfully.

1. **Undergraduate Climate and Society**

I plan to develop a new undergraduate course in “Climate Change Demography” with results from this project. This project integrates projected climate impacts along race, gender, and class (the various sociodemographic characteristics in the Demographic Metabolism) as well as infrastructure and housing. A new course will provide enough time to focus more on demographic change within in the context of climate change and further enhance my career as the go-to “climate demographer” in the US. I will incorporate the research component of this project into multiple course modules on sea-level rise, sociodemographic change, climate migration, and adaptive infrastructure and will spend the final three weeks of the course to teach the undergraduates how the varying concepts of “climate change” and “demography” come together under a single climate impact – sea-level rise – bringing some of the more esoteric theories and concepts to the tangible. Most undergraduate students at Florida State University come from somewhere in Florida. Since Florida is the state most impacted by sea-level rise, the enhanced curriculum should be of both scholarly and personal interest to most students.

Additionally, I currently teach an undergraduate level “Climate and Society” course in the Department of Sociology and will enhance this course with results from the research component. The course focuses on multiple aspects of climate change including responsibility, impacts, adaptation/mitigation, driving forces, etc. The curriculum plan currently includes a one-week module on climate migration but lacks both comprehensive integration of climate change with other sociodemographic factors such as race/gender/class and integration between climate migration and sociodemographic factors. Climate and Society classes and materials tend to focus on historic impacts along sociodemographic characteristics (ie, Hurricane Katrina on the race/ethnic composition of New Orleans) and rarely discuss projected impacts among different groups. But understanding the projected impacts along different sociodemographic axes is a key component of climate impacts.

1. **Forecasting and Graduate-level Demography Students**

Second, I plan to introduce a graduate seminar on “Forecasting” in the Center for Demography and Population Health where I am a research associate. This course will be housed in my home department of Sociology but open to any graduate student at FSU. The course goals include facilitating graduate research interests while introducing key forecasting methodologies, specifically those related to demographic analysis. Forecasting is routinely near the top of the most important skills for our Master of Demography graduates when surveyed, making demographic forecasting integral to their graduate education and many of our master’s students incorporate forecasting in their theses. This course will provide crucial methods training for aspiring demographers pursuing academic or private sector employment.

Forecasting is a key component of this research proposal between the climatic forecasting, demographic metabolism, matrix population models, and migration modeling. I spent nearly ten years directing the Applied Demography Program at the University of Georgia where I routinely produced demographic projections for government clients. My professional experience, academic research incorporating forecasting, and this proposal make me well-positioned to develop and teach a graduate course on forecasting to meet the core requirement of the Master of Science – Demography degree.

1. **Career Professionals**

In Years 2-5 of this project, I will conduct training and dissemination with two partner professional organizations: The American Society of Adaptation Professionals (ASAP) and the National League of Cities (NLC) (see letters of commitment). I began a long-term engagement with ASAP and NLC in the summer of 2019. The city of Ann Arbor MI was working with ASAP and NLC to incorporate climate migration into their strategic planning and all three organizations brought me in to help advise Ann Arbor’s efforts. In our conversations, ASAP and NLC described a strong hunger among their members, largely local governments, for more information and training in how to better prepare their infrastructure for climate migration. Rust belt cities such as Duluth Minnesota, Buffalo New York, Ann Arbor Michigan are beginning to incorporate potential climate migration in their long-range strategic planning or in their sustainability planning. ASAP and NLC described a strong demand for better information and training.

ASAP’s mission is to connect people working on climate change adaptation with each other so communities, regions, cities, and states would no longer start from scratch when building their climate resilience. Feedback from ASAP’s members lead them to create a Climate Migration & Managed Retreat, member-led working group to better understand the implications and impacts of climate migration including the socioeconomic. NLC is both a resource and an advocate for more than 2,000 member cities in the US. NLC’s Sustainability program area provides elected leaders and their staff with convening and peer-learning opportunities to deploy more equitable, sustainable, and resilient solutions.

I will conduct a 1-day training session on the results of this project at the annual conferences of ASAP and NLC, serving the dual purpose of educating public planners on climate migration and disseminating the results of this project to those who can directly implement it into their long-range planning efforts. In Year 2, the training and outreach activities with ASAP and NLC will focus on previously conducted research – research that the pilot activity with the City of Ann Arbor found particularly useful in their city planning. Years 3, 4, and 5 will focus more on the direct research outputs from this proposal when the project is much more advanced.

1. **Anticipated Outcomes and Significance of Educational Activities**

All the educational activities described here will assist students in developing skills to critically analyze their interests from multiple disciplinary perspectives to gain greater awareness of climate change and demography. These educational activities span climate change, demography, sociology, and forecasting. Outreach activities with career professionals will multiply the scientific impact of the proposed research and ensure a broad impact on society by informing long-range strategic planning efforts of adaptation professionals across the country.

I strongly believe in relating course concepts to real world applications and routinely utilize “case studies” (McDade, 1995) from my own scholarship and experiences in my courses to help students internalize the lessons. Connecting course concepts to the real world is particularly important for teaching climate change and teaching the implications and potential solutions to climate change requires holistic integration of the physical and social (Lehtonen et al., 2018). This proposal provides ample “case studies” through the proposed research, proposed outreach, and integration of physical and social science. The partnership with professional organizations will provide numerous case studies for on-campus undergraduate and graduate education and I will seek out career professionals who attend the ASAP and NLC annual trainings to serve as potential guest speakers in my undergraduate and graduate classes, further integrating the research and educational activities.

Additionally, the graduate research assistant funded by this project will be encouraged to present findings and pursue professional development with my guidance and mentorship. I plan to assist the graduate student in writing grants, in developing the graduate student’s intellectual program, and in their searches for postdoctoral or other academic positions. The anticipated outcome is for the graduate student to present at least once per year at a major academic conference, publish at least one lead-author peer reviewed article, write a grant proposal, and secure a postdoctoral job during the time of this award.

**V. Research and Educational Activities Timeline**

The requested start date for this project is May 11, 2021 and will be completed in five years. Throughout the entire period of the award, I will 1) follow and analyze professional literature published on the topic of this proposal; 2) draft academic articles to submit to peer-reviewed journals; 3) mentor the doctoral student; 4) seek public speaking opportunities; 5) attend professional organization conferences for observational research and for disseminating findings; 6) attend academic conferences to disseminate findings; and 7) redesign instructional materials my existing courses/modules. Additional major research and educational activities are listed below.

Year 1: In the first year of the project, I will focus on building the county-level, multi-regional Leslie matrix population projection model and will begin development of a professional training module for the career professional partner organizations.

Year 2: I will complete the county-level model and build the sub-county sea-level rise model, develop a demography forecasting course, and conduct professional training.

Year 3: I will link the county and sub-county projection models, develop a graduate seminar, and conduct professional training.

Year 4: I will work on publishing the complete, integrated migration and population projection results and conduct professional training.

Year 5: The final year of the grant will be dedicated entirely to manuscript writing and dissemination and professional training.

**VI. Integration of Research and Educational Activities**

As also described above, the research and educational activities will more fully integrate my research and teaching pursuits by allowing me to actively teach material I am studying in myresearch, with the benefit of enhancing demography education for a multitude of students at FSU. Student feedback on this material will help to sharpen my thinking on demographic research. All of the activities I plan to undertake in this project will allow me to engage much deeper in both the demography and climate change literatures than I have previously done. I will utilize FSU’s Center for the Advancement of Teaching to perform annual external evaluations of my curriculum and courses to ensure continual integration of the research and improvement of my teaching.

**VII. Prior Research and Outreach**

My previous scholarship focused primarily on sea-level rise and human migration, including a review of sea-level rise and human migration in *Nature Reviews Earth & Environment* (M. E. Hauer et al., 2020a). Leveraging a small area demographic projection technique of my creation (Hauer et al., 2015), I published the first projection of those at-risk to sea-level rise in the United States (Hauer et al., 2016) and the potential destinations of those migrants (Hauer, 2017). I also published a complete set of detailed county-level population projections for the United States (Hauer, 2019). My research in these areas relies on detailed information on the built environment including transportation, adaptative infrastructure, and housing data. These research activities provide the theoretical and methodological foundation upon which the proposed project builds and directly informs the direction and analysis of this project.

I also have extensive outreach experience, spending nearly 10 years at the Carl Vinson Institute of Government at the University of Georgia, a public land-grant university, where I directed the Applied Demography Program before coming to Florida State University. The Vinson Institute is essentially cooperative extension for Georgia but for non-agriculture related research. I worked with state, local, and federal officials to translate academic scholarship into policy-relevant, real-world applications, and have given well over 300 public presentations, interviews, and training sessions on my scholarship. I am well positioned to ensure the proposed outreach activities with ASAP and NLC will have the broadest possible impact.

**VIII. Intellectual Merit of Proposed Work**

The scholarly contributions and broader impacts of this proposed research are multiple. In many ways, climate change impacts are unique in science: It involves consideration of both physical and social science, in concert. But the impacts are not marginal. Coupling social and physical science to better understand climate change impacts is a key challenge in the 21st century. Climate change will impact nearly all aspects of society and interrogating the potential trajectory of climate migration, in particular, will influence current and future debates about climate change broadly, inclusive adaptation planning, mitigating climate change, and the trajectory of American society. Climate migration is an important component of climate change many scientists and practitioners are eager to tackle. But many attempts to model this migration rely on overly simplistic migration assumptions and models, ignoring important demographic factors that shape migration. As a corrective, this project works under the assumption that to understand climate migration, we must first account for demographic influences. The exclusion of demographic factors in climate migration has created a generation of knowledge largely divorced from a half-century of migration scholarship. The intellectual merit of this proposal lies in its potential to produce crucial interdisciplinary insight into who, when, and where climate migration is likely to occur this century in response to sea-level rise.

**IX. Broader Impacts of the Proposed Work**

This research will produce a series of articles on sea-level rise, human migration, climate change demography, and demographic change. This research will also have broad impact on public and policy conversations about climate change by partnering with the National League of Cities and the American Society of Adaptation Professionals to directly influence adaptation planning across the United States, in both coastal and inland communities. I am an open science advocate and I will publish all research materials on preprint servers and github, making them accessible to anyone interested in the research. The course instruction and training that will stem from this project will impact both undergraduate and graduate students entering the professional workforce. Finally, with the partnerships with NLC and ASAP, this project will also directly bridge the scientific endeavor with outreach as it enhances public and academic dialogue surrounding the societal implications of climate change.

**X. Results from Prior NSF Support**

**A.** Award # 1939841

**B.** NSF EAGER CoPe: Impassable During High Water: Sea Level Change, Commuting, and Climate Gentrification (Award Period 10/01/2019–09/30/2021; PI: Mathew E. Hauer; Co-PI: Valerie Mueller and Glenn Sheriff)

**C.** This project is ongoing. **Intellectual Merit:** The most significant outcome of this project to date is an in-prep paper concerning reductions in commuting times in Miami FL due to extreme water levels associated with high-tide events. To our knowledge, this is one of the first studies to examine sea-level rise impacts on commuting patterns and the racialized burden of sea-level rise hazards. **Broader Impacts:** Identifying road segments, locales, and demographic groups vulnerable to sea level change will be of great value to coastal cities faced with developing long-range adaptation strategies. These tools will not only allow cities to understand how neighborhood demographic composition is being affected by flood risk, but also determine which business areas are likely to be impacted by impediments to commuters.

**D.** Data continue to be collected and analyzed by the PIs; research materials are available upon request.

**E.** The current proposal is unrelated to NSF support of this project. This is not a proposal for renewal.

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