Objectives of the proposed work and expected significance

Over the next several decades the bulk of the world's projected population growth will occur in cities and towns located largely in the developing world, predominantly in Asia and Africa. Rapid urbanization will stretch the ability of government and planners to adequately service growing populations, particularly in poorer areas or those lacking abundant access to resources. Further confounding these problems over the next several decades are the likely impacts of climate change such as rising sea levels, an increase in large/powerful storms, and a rising number of extreme heat events. Human vulnerability to climate-related hazards is in no small part a question of geography, a function of the spatial confluence of human development and the changing physical environment. Climate modelers pay close attention to the relationship between scale and the physical processes that dictate the geographic characteristics of climate outcomes. Currently, however, a key impediment to our understanding of vulnerability is a lack of understanding of the multi-scale processes that drive changing patterns in the spatial distribution of the population.

Understanding vulnerability and projecting its possible future evolution is an important component of effective risk management/adaptation policy and consequently of sustainable development. Vulnerability[1] to weather and climate hazards is a function of human exposure to extreme weather/climate events as well as characteristics of society that make it more difficult to cope with or adapt to those events (Figure 1). Over the past several decades there has been a massive investment of both public and private resources aimed at understanding and modeling the physical science of climate change. Significantly less attention has been paid to understanding the factors that govern potential human exposure to climate-related hazards, including the spatial distribution of human settlement. While demographers continue to provide the framework for producing alternative scenarios of global, national, and regional population change, as well as urbanization trajectories, many current attempts to assess future climate vulnerability consider only the existing spatial distribution of the population (Strauss et al., 2012), a decision that reflects the lack of understanding of human spatial processes and the forces that drive them, and subsequently an inability to model spatial change.

Theoretical approaches to the problem of spatial development vary across the social sciences. Economists traditionally consider residential land-use as one of many competing interests in the urban hierarchy, with patterns of development occurring as a function of wealth, transportation, access to employment, and utility. Geographers often perceive spatial change as the outcome of quasi-natural processes embedded in urban hierarchies, whereas demographers explain population outcomes through the demographic rates that govern change over time. In this work we will attempt to bring together the sometimes disparate theoretical lenses and tools of these disciplines to assess the factors that operate at multiple scales to drive spatial population change. By approaching this work from a inter-disciplinary perspective we hope to advance the body of knowledge concerning the relationship between spatial population dynamics and characteristics of the population, and in doing so create a theoretically consistent set of models.

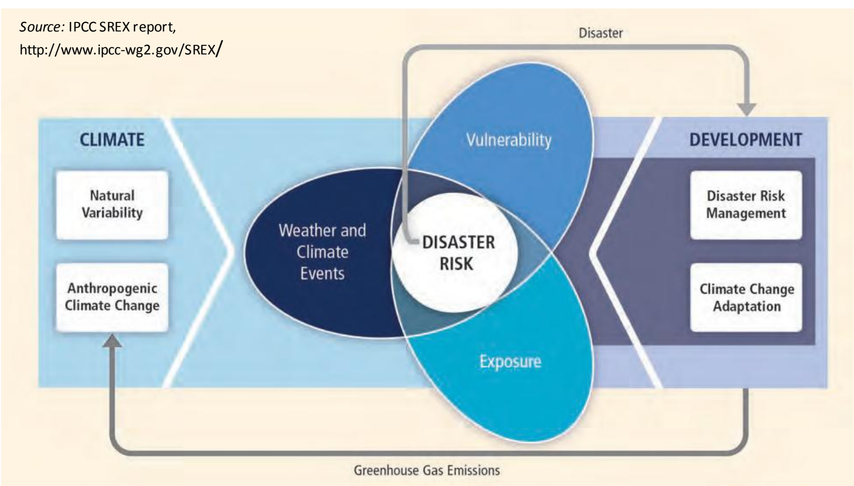

Figure 1. The importance of exposure and vulnerability to climate-related hazards to risk management and sustainability.

Our primary hypothesis is that a distinct hierarchy exists in the processes driving spatial

[1] Definitions of vulnerability vary widely in the literature (Fuessel and Klein, 2006). In some cases, as shown in Figure 1, vulnerability and exposure are defined separately, while in many cases exposure is considered a component of vulnerability. We employ the latter definition in this proposal

patterns of population change. We believe that, embedded within these processes, are indicators that will advance our understanding of how humans orient themselves across the landscape. Given that relatively little attention has been given to multi-level modeling of spatial change, there is currently little theory addressing the simultaneous multi-level processes that lead to distinct patterns of spatial development. We will attempt to fill this void, drawing on the strengths of a number of different perspectives from the social sciences, and in doing so will contribute to the study of human vulnerability to climate-related hazards. Our proposed work is organized into three phases designed to address the following goals:

1) Identify the drivers of spatial population change and isolate how they operate/vary at different scales.
2) Construct a theoretically consistent modeling framework for explaining and projecting alternative spatial population patterns that account for multi-level processes.
3) Investigate the sensitivity of projected exposure/vulnerability to climate-related hazards under alternative spatial population scenarios for selected regions of the world.

We propose to begin this work with a multi-scale analysis of spatial population change using an econometric growth model that incorporates a geographic measure of population agglomeration (population potential), spatially explicit demographic rates, and geographic characteristics to assess and isolate the drivers of spatial change at varying scales and considering alternative spatial resolutions. Building on results from this analysis we then propose constructing a model for explaining and projecting spatial population patterns based on a family of gravity-type models often used in urban/transportation geography as well as economics. We adopt the gravity framework because we believe it is well suited to capture and model the multi-scale processes responsible for changes in the spatial distribution of the population. The gravity model is generally interpreted in geography/economics as aimed at capturing the intensity of interaction between places (i.e. person trips, trade, diffusion of innovation), as well as the determinants of migration (people choose to live in a particular place, i.e. settle there, remain, or leave, due to attractiveness of the place, and friction of distance for commuting, etc). As such, it is one of the most widely used tools of spatial analysis. We propose a novel approach to parameterizing the gravity model, one which considers the spatial relationship between population change and demographic characteristics of the population in addition to geographic characteristics of the landscape. Finally, we propose to carry out an assessment of vulnerability to certain climate-related hazards (i.e. sea-level rise and storm surge, drought, and urban heat events) under alternative spatial scenarios for selected regions of the world, including the United States and China. In this final phase of our proposed work we aim to illustrate the importance and applicability of our theoretical based work as it pertains to human vulnerability and sustainable development.

At the core, this proposal merges geography and demography in ways that heretofore have not been explored: To date, geographic modeling even of population distribution has ignored demographic theory, and population forecast models championed by demographers are aspatial, although on occasion demographers have employed gravity-type models (e.g., Cohen, 2008). While these disciplines may seem like close allies, their pedagogical traditions and approaches to analysis and models are rather distinct. Differences are even more pronounced when such modeling efforts are applied to climate models, leading to much different approaches for relating population factors to climate change mitigation and adaptation.

The proposed project is supported by a group of experts with backgrounds in the disciplines, and climate applications, noted throughout this proposal. Bryan Jones, a recent PhD, is a geographer that has been working with and developing spatial population models for application to global climate change analyses over the past several years. His recent doctoral work used geographic theory and methods to create a population projection for the US. Deborah Balk, Professor at Baruch College at the City University of New York (CUNY) and Associate Director of the CUNY Institute of Demographic Research, is an expert in spatial demography and applications to climate change adaptation with long-time engagement in interdisciplinary research combining the social and Earth sciences. Brian O'Neill, an Earth Systems Scientist, leads the Integrated Assessment Modeling (IAM) group within the Climate Change Research section at the National Center for Atmospheric Research (NCAR), and his work brings together the natural and social sciences to examine issues related to climate change mitigation and impacts. Mark Montgomery, Professor at Stony Brook and Senior Associate at the Population Council, is an econometrician whose research has focused on the demographic forecasting and urbanization in the developing world. Professors Balk and Montgomery are long-time colleagues on city-growth modeling and urban poverty estimation and both are based in New York. Dr. O'Neill leads the group in which Dr. Jones currently work. In the proposed activities, Dr. Jones would relocate to New York. The research activities of Drs. Balk, Montgomery and O'Neill –which bring demography and climate change together for adaptation and mitigation— were the focus of an article in Nature Climate Change (Smith, 2011). The work proposed by Dr. Jones would be an important concrete step in bridging the adaptation and mitigation foci, as well as merging geographic and demographic theory and modeling in a population forecasting application.

Review of literature and recent work by research team

The proposed work will advance two nascent fields – large-scale spatial population projections and models of future city growth – and place both of those efforts in the context of climate-change. Assessment of climate-change impacts, particularly with respect to vulnerability requires an effort that integrates both approaches and scales. Below we summarize the key literature as well as contributions from the fellow and his proposed mentors.

Large-scale spatial population projections

Spatially explicit projections of global population are of growing importance in scenario-based assessment of, for example, the spatial distribution of land use, demand for food and water, energy usage, and emissions (e.g., Raupach et al., 2010; Rockström et al., 2009; Small, 2004). Similarly, spatial population data are frequently used to assess human vulnerability to the potential consequences of global climate change (e.g., Arnell, 2004; Balk et al., 2009a). The biophysical data used in high-resolution global change models are most often organized on a regular lattice grid while demographic data are typically aggregated according to existing administrative boundaries (Balk et al., 2006). The gridding of demographic data is thus a necessary step for inclusion in most high-resolution global change models. Over the past two decades there have been significant improvements in the quality and availability of gridded distributions of the existing global population (e.g., CIESIN, 2011; Dobson, 2000). However, to date there are very few spatially explicit projections of the future distribution of the global population, and methods for producing such projections are in the early stages of development. Most of the existing spatially explicit projections are constructed using simple scaling techniques or trend extrapolation (e.g., Gaffin et al., 2004; Bengtsson et al., 2006; Van Vuuren et al., 2007; Hachadoorian et al., 2007). By definition these data reflect a future world in which the spatial population structure does not change, or changes only through continuation of the most recent sub-regional trend. Neither approach is theoretically grounded or substantiated through observed historical trends.

A recently developed hybrid approach (Nam and Reilly, 2012) draws on the historic correlation between certain national-level socio-economic data and the rank-size distribution of population in grid-cells. The model combines the geographic tradition of looking for mathematical regularities in spatial processes embedded in urban systems with socio-economic indicators that can be linked with certain patterns of development (most notably urban primacy and tendency towards horizontal or vertical development). While more theoretically grounded than other projections, the model suffers from two notable shortcomings; it enforces the base-year rank-size distribution of grid cells on all future spatial projections and it lacks a mechanism for dealing with lightly populated grid cells (the rank-size correlation appears to break down below a certain density threshold). The former ensures that every grid cell will occupy the same place in the rank-size distribution, which confounds the ability of the model to project both new urban development and broad population redistributions (such as the general movement to the South and West in the American population). The latter leads to large portions of the world's land-area being left out of the modeling framework.

One of the more sophisticated methods currently available, developed as part of the Greenhouse Gas Initiative at IIASA2 (Gruebler et al., 2007), utilizes a gravity-based spatial allocation model to produce scenario dependent projections. More specifically, the method draws on the geographic concept of population potential (Stewart, 1942) to downscale future projections of national-level population change to a raster grid. These data have been used in scenario-oriented climate research based on the widely cited IPCC SRES3 scenarios (e.g., Riahi et al., 2007) and more recent scenarios currently in development for the next IPCC assessment report (e.g., Lamarque et al., 2010). The IIASA approach represents a unique

[2] International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
[3] Special Report on Emissions Scenarios (Nakićenović et al., 2000)

application of the population potential model in which potential is used as a dynamic tool for downscaling projected future population change. While gravity-type models have a long a successful history in urban/transportation geography, they are sometimes criticized for lacking the sophistication necessary to apply causation (Pearl, 2000). Furthermore, in this application the model was not tested against observed data, so it is difficult to comment on the validity of the results.

Recently Jones and O'Neill (NCAR - paper forthcoming) developed an enhanced version of the potential-based allocation model which, in addition to accounting for several of the widely cited problems with the population potential model (e.g., see Craig, 1987; Frost and Spence, 1995; Pooler, 1987), includes a mechanism for calibrating the model to historical data in order to capture and replicate observed patterns of spatial change. Additionally, the methodology is the first large-scale procedure to incorporate geospatial data in the algorithm. The NCAR model is rooted in theory regarding spatial patterns of urban settlement, in particular Clark's (1951) negative exponential monocentric city. The calibration procedure essentially estimates a population change gradient that describes the direction (e.g., sprawl versus concentration) and speed of spatial population change. However, like many gravity-type applications, it is difficult to infer causation from this methodology. Examples of spatial outcomes produced by the IIASA and NCAR models are presented in Figure 2.

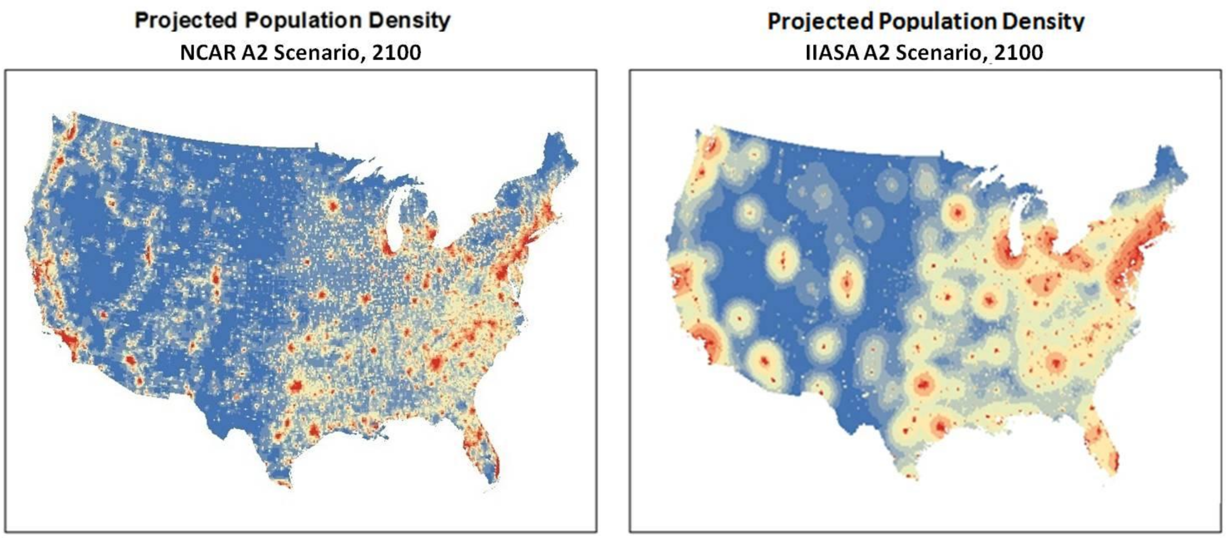

Figure 2. Spatial population scenarios for the continental United States, NCAR and IIASA models.

City Growth

With the overwhelming share of future population growth to take place in the cities and towns of the developing world, it is shocking to realize that the method long used by the United Nations' Population Division to project city population size is little more than a simple extrapolation (National Research Council, 2003).[4] The basic demographic components of growth—urban fertility, urban mortality, migration—are not factored into the UN's city projections despite the fact that these factors are prominently featured in their national-level and long-term global projections (UN, 2011). No spatial considerations are taken into account. Coastal cities are not distinguished from those inland even though coastal cities have considerably higher population densities; isolated cities are treated no differently than cities in such close proximity that they seem poised to fuse in larger agglomerations; and no recognition is taken of the natural barriers (e.g., slope) that can hinder or redirect city growth (McGranahan et al., 2005). The UN methods thus ignore a vast body of theory and empirical findings in the fields of geography, demography, economics, and the earth sciences on the central role of spatial and demographic factors in

[4] It has been tweaked but not substantially changed since the late 1970s.

urban growth. Most importantly, the UN city size forecasts are now known to perform poorly, exhibiting a pronounced tendency to over-state urban totals (NRC, 2003; Cohen, 2004; Bocquier, 2005).[5]

Recent work by Montgomery and Balk (Balk et al., 2009b) builds on the UN's underlying data, but places those data in a spatial context, using new forecasting methods, and applies demographic rates for urban areas (since city-specific rates are themselves not available) to construct demographic defensible city-growth estimates. Figure 3 below illustrates the output of this modeling effort.

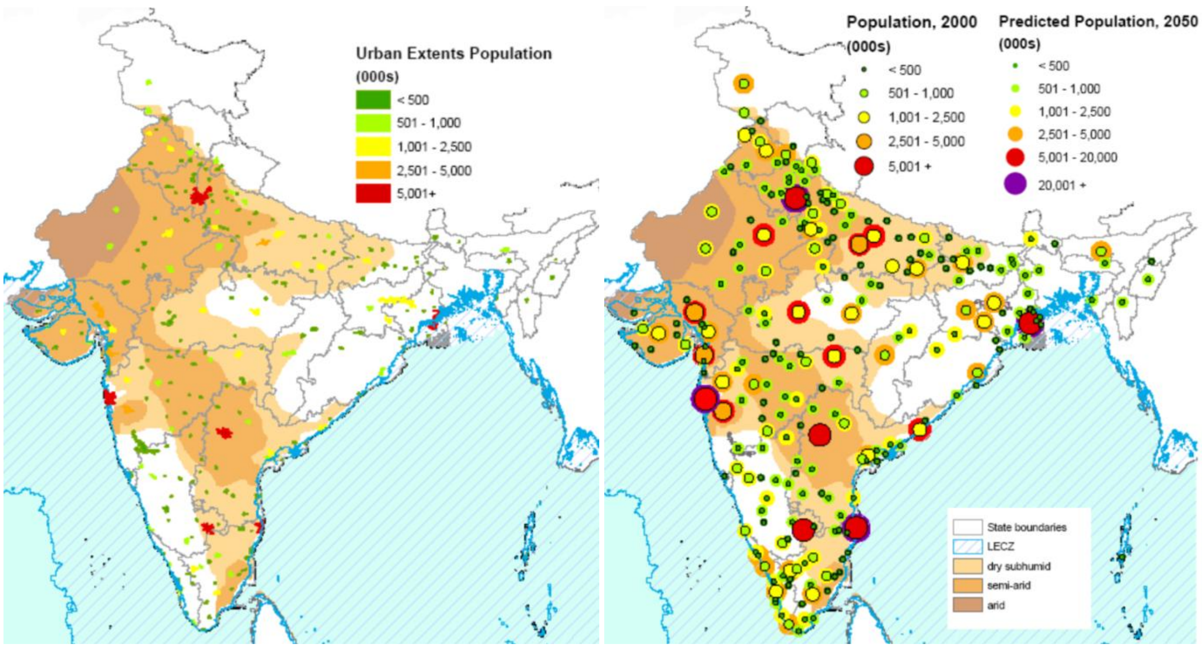

Figure 3. Spatial outputs of City-Growth Forecasting Model (Balk 2009).

The left-panel depicts city population based on satellite-derived urban extents from GRUMP data base where as the right-panel depicts city-population estimates (2000) and forecasts (2050) as points. Both maps indicate areas of climate-related vulnerabilities: arid zones and low elevation coastal zones (LECZ). The underlying spatial input units (i.e., states) for the demographic rates, is shown as well.

In the above example, however, rates of urban in-migration have yet to be included. Those data are now ready for inclusion in future modeling efforts. This approach, unlike any before it, allows us to place city population forecasts in a spatial context. For example, with these data we now know that some 45 percent of the residents of drylands ecosystems – nearly 1 billion people globally – live in the cities and towns of poor countries (Safriel el al., 2005; McGranahan et al., 2005).

Yet to date, research on climate change in drylands has focused mainly on the implications for farmers and pastoralists, leaving the urban consequences largely unexamined. In a recent study, Balk, Montgomery, and colleagues (McDonald et al., 2011) find that 150 million people currently live in cities with perennial water shortage, defined as having less than 100 liter per person per day of sustainable surface and groundwater flow within their urban extent. By 2050, demographic growth will increase this figure to almost 1 billion people. Climate change, within the same time frame, will cause water shortage for an additional 100 million urbanites. Beyond that horizon, when city growth has plateaued, the full force of the effects of climate change will be born.

<u>Climate Science & Vulnerability</u>

As illustrated in Figure 1, risks from weather and climate-related events arise from the interaction of these events with vulnerable populations. Temperature and precipitation extremes could have a number of deleterious effects. Heat waves have been associated with increased prevalence of

[5] The UN Population Division is well aware of the faults of its forecasting method, and Balk and Montgomery have been working with the Division since 2005 to devise alternative methods that are better-justified in scientific terms yet feasible for the Division to implement.

cardiovascular diseases, asthma and other lung diseases (McMichael et al., 2003), and contribute to excess deaths particularly among the urban elderly (Kosatsky, 2005; Schar and Jendrizky, 2004; US-EPA 2008). Droughts exacerbate water-stress, which could affect more than half of world's population by the middle of the century (World Resources Institute, 2000). Rising temperature and changes in precipitation patterns may extend the zones that are favorable for vectors conveying infectious diseases such as malaria and dengue fever (McMichael et al., 2003, 2004; Campbell-Lendrum et al., 2005).

These impacts and the estimated number of people being affected depend not only on the spatial pattern of climate change, but also on the spatial distribution of future population, their socioeconomic status, and demographic characteristics such as rural/urban residence, age, household structure, and education attainment (Jiang and O'Neill, 2007). Spatial analysis of current hotspots of climate-related hazards (cyclones, droughts, floods, and the landslides) shows that those hazards are largely concentrated in areas that on average have lower income, higher population density and higher fertility rates (Jiang and Hardee, 2011). Anticipating future impacts therefore requires accounting for demographic and socio-economic trends. Yet many impact studies either ignore such trends, or account for them in highly simplified ways, for example by identifying continental-scale regions where urban populations and urban heat waves are both expected to increase (McCarthy et al., 2010). Approaches that combine such large-scale modeling and analysis with an ability to account for smaller scale differences in exposure and vulnerability are badly needed (Wilhelmi and Haydn, 2010).

Research Plan

This proposed work is aimed at advancing the knowledge base concerning the drivers of changing patterns in the spatial distribution of human populations, and how the processes affecting change operate at multiple scales. We adopt an inter-disciplinary perspective, considering theory and tools of analysis often employed in econometric analysis, urban and transportation geography, as well as traditional demography. As such, the work seeks to improve the theoretical knowledge base by considering a new approach to questions traditionally bounded by the constraints of disciplinary paradigms. As an additionally result of this work we hope to contribute to the body of work concerned with assessment of exposure and vulnerability to climate-related hazards. The project consists of three broad phases:

1) Identify the drivers of spatial population change that are operating across scales and as a function of geography. We employ an econometric regression based approach that draws on demographic and geographic characteristics of the population in addition to geophysical characteristics.
2) Incorporate the knowledge and linkages generated in the econometric analysis into a gravity-based model of spatial allocation and test the ability of the methodology to reproduce past changes in the spatial distribution of the population. We augment the gravity-model with empirical data regarding multi-scale relationships between spatial patterns of change and demographic characteristics of the population and test the hypothesis that the gravity-framework is better suited (than an econometric model) for modeling processes occurring at multiple-scales.
3) Construct projections of alternative spatial population outcomes and match them with spatially explicit climate outcomes. In particular we will consider the potential vulnerability to sea-level and storm surge, as well as extreme precipitation, urban heat events, and drought. To facilitate this process we will use high-resolution elevation data for coastal regions, and recently produced climate model projections (including those produced at NCAR) archived in the CMIP5 database (Taylor, 2012)

The ultimate goal of this work will be to apply a theoretically consistent model to produce global-scale spatial population scenarios. However, we intend to build incrementally towards a global model by first investigating several individual countries. We will begin by considering the United States and China, where we will separately carry out all three phases of the proposed methodology. From these results we will construct hypotheses concerning the affect of scale and resolution on the drivers of spatial change, as well differences that may result from socio-economic/cultural influence on the demographic components of spatial change. We will then apply our proposed study to a larger sample of nations/regions in order to test these hypothesis and further evaluate our methodology. In this stage of the research we will be careful to select a representative sample of countries such that we can investigate most, if not all, of the predominant observed patterns of spatial change[6]. In doing so we will generate the information necessary to construct global-scale projections of future spatial scenarios.

Data

To achieve the goals presented in this three-phase research project we will draw on a wide-variety of data sources, including national censuses, surveys, and geophysical data sets. The modeling efforts described above use much different data inputs, and modeling strategies. These are summarized below.

Table 1. Data and source; NCAR spatial population model, city-growth forecasting model, and proposed gravity-hybrid model.

Model Type Reference	NCAR Spatial Population Jones (2012)	City-Growth Forecasting Balk et al. (2009)	Proposed Model	Source
Overview				
Geographical extent	US	Developing World	Global	
Time period (inputs)	1950-2000	1950-2008 (variable)	1950-2010	
Time period (outputs)	1950-2100	1950-2050	1950-2100	
Model Type	Gravity	Classical, Bayesian regression	Gravity hybrid	
Data inputs				
Spatial units	US Census Populated Places, County boundaries	GRUMP urban extents, Subnational administrative regions, Point locations (UN Cities Database)	Best available subnational boundaries, populated places, nighttime lights time series	Balk and Montgomery internal database (based on national statistical offices sources and www.gadm.com), UN Cities database
Demographic Variables	Population Counts	Population counts Fertility rates Child mortality rates In-migration rates	Population counts Fertility rates Child mortality rates In-migration rates	IPUMS, DHS, MICS, WFS, various national censuses (e.g. USCB)
Urban Classification	Urban/Rural	Statistical concept for city classification City-size	Urban/Rural	GRUMP (CIESIN et al, 2008)
Geophysical	Elevation Slope Surface Water Protected Land	Ecozones	Ecozones Elevation Slope Surface Water Protected Land	MA (2005) NASA, 2009 NASA, 2009 USGS, 2000 WDPA, 2011
Data outputs				
Spatial format	Grid	Point (vector)	Grid	
Spatial projection	Yes	No	Yes	
Spatial resolution	7.5'	n/a	Varying (7.5' or higher)	

Spatial Population Data

Carrying out phases one and two of the proposed work requires two spatially explicit historical population distributions, one of which can be a current distribution, for each country we intend to investigate and/or test our model. At a minimum, as is noted above, this includes a sample of nations representative of the various observed patterns of spatial population change beginning with the United States and China. Data from at least two periods are necessary to provide a snapshot of changes in the spatial distribution of the population such that we may calibrate and test our modle. We currently have gridded population data for the United States for each of the decennial census periods from 1950-2010 at

[6] At this point we are currently investigating the availability of data for several candidate countries, including India, Brazil, and Kenya. We will aim for a sample that is representative of the various stages of development, growth rates, and urbanization rates exhibited by countries worldwide.

2.5’ and 7.5’.   We constructed these data in ArcGIS using four spatial layers: (1) census block groups, (2) census tracts, (3) populated places points, and (4) county population. For each time period we overlayed a raster grid on the populated places point layer and assigning the population from each point to the appropriate grid cell. We then overlayed the finest resolution polygon layer available[7] over the populated places data and remove the point-based population from the appropriate polygon. The remaining population, that not accounted for by the point data, was assumed to be uniformly spread across the polygon and was allocated to grid cells by overlaying the raster grid on the polygon layer. Using this procedure, we will produce a third set of spatial data for the period 1950-2000 at 30” to enhance our ability to assess the impact of resolution on the drivers of spatial change at different scales.

We will follow a similar procedure to grid historical population data for other countries included in this research, using both point data and polygon data at the highest available resolution to construct gridded distributions[8]. Population data for China will be provided by Leiwen Jiang, a demographer currently working with O’Neill as part of the IAM group at NCAR. Upon completing all three phases of the proposed work with the United States and China, we will select additional countries for inclusion in this work as we continue to build towards a global model. As part of his current work at NCAR Jones has a graduate research assistant that will be searching for, compiling, and gridding historical population data for various countries over the next several months. We intend to include these data in our proposed research.

To carry out the third phase of the proposed research at the global-scale will require a globally consistent base-year spatial data set, both to carry out spatial projections and in the proposed investigation of human vulnerability to climate hazards. In this capacity we will employ the Center for International Earth Science Information Network (CIESIN) GRUMP (Global Rural Urban Mapping Project) database. GRUMP includes population count grids, population density grids, roughly 75,000 urban settlement points, urban-extents grids, land/geographic unit area grids, national boundaries, national identifier grids, and coastlines. The gridded data are available at 30” resolution, from which we will aggregate to 2.5’ and 7.5’ to facilitate our analysis of resolution and scale in assessing vulnerability.

Vital Rates and Demographic Characteristics

Data on demographic rates come from much different sources in the developing and developed world. For the developed world, as in the prior work by Jones, data come from census data sources. Similar data are available for developed countries. Vital registration data, at the county-equivalent level can also supply information on demographic rates, when such data are not available in the national census data collection. For the developing world, (where data are harder to get and of more variable quality), Balk and Montgomery over the past 5 years, have brought a spatial organization to a collection of non-spatial data that supply information on population, demographic rates and other socioeconomic characteristics. Data derived from censuses provide full coverage for finely-disaggregated spatial units; surveys offer greater substantive breadth on population characteristics but are statistically representative only for higher levels of aggregation than represented by the census data. The methods used in their city-growth model was developed so that it would not require the availability of full record-level census micro-data, as that would unduly restrict application of the methods. Instead, they draw upon the publicly available samples of census micro-data in the University of Minnesota's Integrated Public Use Microdata Series (IPUMS), International collection. All data used in this analysis are either publicly available or held in the collections of the Investigators. The boundaries of the census units can change over time, especially for the smallest such units.

The IPUMS collection includes data from which fertility, mortality and can be estimated, and also include place of birth and place of residence between one and five years prior to the census; these are the key ingredients for estimating migration. The subnational level of aggregation in the IPUMS collection varies by country. (Administrative units vary in geographic size as well as population.) The

[7] The 1950 census data were aggregated into tracts and block groups only within larger urban agglomerations. Elsewhere in the country the smallest level of aggregation was the county. We selected polygons from the 1960-2000 census data that matched those from 1950 for purposes of consistency across all time periods.

[8] We will use night time lights data to supplement this algorithm in areas where the units of aggregation are large (Baugh et al., 2010; Zhang et al., 2011).

IPUMS collection includes data for developed and developing countries. To date, in the work of Balk and Montgomery, only data for developing countries has been used.

Another important data source is the recently released spatial data from the Demographic and Health Surveys (DHS) that correspond to first-administrative regions over time. Since the late 1990s, the DHS program has collected coordinates for its sampling clusters in many countries, making it possible to locate these clusters in relation to the census units. The survey sampling frames for demographic data are typically robust at first-order administrative units, and sometimes for very large cities thus allowing for combining the smallest and most recent census unit with various geographic identifiers for other census and survey units. While the DHS is the most complete data source for poor-data countries, prior to the DHS, the World Fertility Survey (WFS) supplies estimates for regions that would use a time series. (We have georeferenced these regions.) Similarly, UNICEF's Multiple Indicator Cluster survey (MICS) are contemporaneous to the DHS but cover somewhat different countries and subject areas.

To look closely at vulnerability we can then attach to these units the best publicly-available data on age and sex composition; births, deaths, and migration; and education, housing and poverty-related characteristics. (Typically, censuses release fewer variables at the most disaggregated level than at more aggregated levels but the modeling proposed here allows for variable resolution inputs, as needed.)

The vast majority of census and survey micro-data also include an urban stratifier so that for survey regions or finer census units, without knowing what particular city an individual lives in, we can create rates of urban fertility, mortality, or in-migration, for example. Balk and Montgomery have processed all these data and linked them to specific cities (the UN Cities Database). Jones used urban classifications of the US Census in prior modeling. Thus the two approaches – and data inputs – are highly compatible, though the particulars of the temporal and spatial resolution of data for each country may differ in the proposed work.

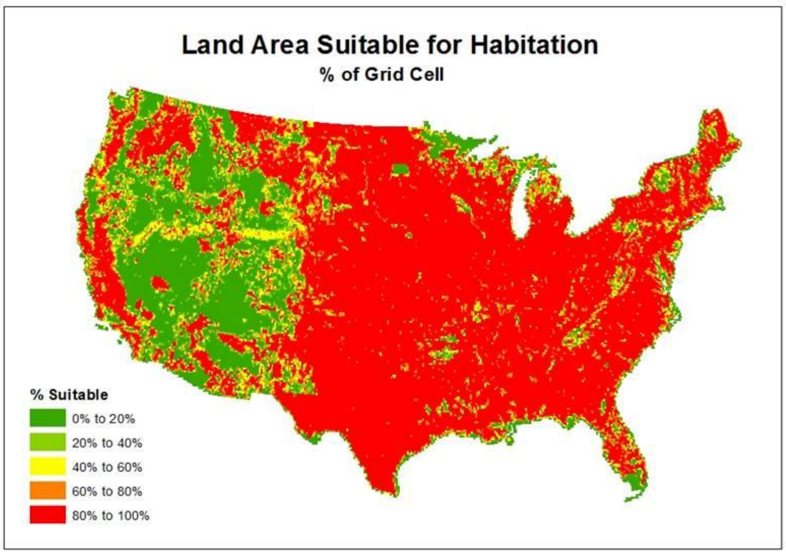

Figure 4. Geospatial mask for the continental United States.

Geophysical Data

To further improve the quality of our spatial projections we propose using additional geospatial data to restrict the allocation of projected future population to areas suitable for development and habitation. To accomplish this we will employ four geospatial data layers (see Table 1); surface water, elevation, slope, and protected land. From these data we will create a single spatial mask which includes surface water, any land exhibiting a slope or elevation deemed unsuitable for habitation, and land designated as protected from development by the federal or state governments[9]. We will overlay the spatial mask and the grid cell polygon layer and remove from each grid cell the area of the spatial mask contained by that cell, leaving for each cell a measure of the land suitable for development and habitation. Figure 4 contains an example of the application of the geospatial mask to the continental United States.

Climate-Model Output

Climate model output will be obtained from the publicly available CMIP5 database. CMIP5 is a climate model intercomparison project in which global climate models from around the world ran a standardized set of emissions and concentration scenarios (Taylor, 2012), including those describing the

[9] Gap Analysis Program (GAP) status 1,2, or 3 (USGS, 2011).

Representative Concentration Pathways (RCPs). There are four RCPs spanning a range of climate forcing, from a rapid increase over the next century and beyond to a peak and decline scenario achievable only through mitigation (Moss et al., 2010). We will focus on model runs from the NCAR Community Climate System Model (CCSM; Gent et al., 2012; Meehl et al., 2012) for two main reasons: we have access to the modelers involved in producing and in analyzing these scenarios, and CCSM includes a representation of urban areas in its land surface model, making it possible to simulate urban heat island effects which can lead to increased surface air temperatures in cities and therefore a better representation of urban heat events (Oleson et al., 2012).

Phase One: Identify the drivers of spatial population change that are operating across scales and as a function of geography.

We will begin this research by examining the factors driving changes in the spatial patterns of human settlement across multiple spatial scales. We will employ an econometric growth model similar to that used by Kim and Montgomery (2011) to construct city-growth forecasts in the developing world. We will then link the cell-specific results from this analysis to phase two of our proposed work through the parameterization of a gravity-type spatial allocation model. The grid cell will constitute the unit of analysis, for which we will consider varying levels of spatial resolution ranging from 7.5' to 30" (roughly 10.5 and 0.75 kilometers in the mid-latitudes). The model will include as right-hand variables the total fertility, child mortality, and net migration rates. Balk et al. (2009) found a strong relationship between the fertility rate and city growth in Asia, and not surprsingly, a negative relationship between growth and child mortality. It has been further suggested that, as fertility and mortality rates decline throughout the developing world, that migration will replace vital characteristics of the population as the strongest driver of local/regional population change (e.g., Rees and Kupiszewski, 1999), thus we expand on the city-growth model and include a measure of net migration in our analysis. In addition to demographic characteristics, we include as right hand variables geographic characteristics of the grid cell such as ecozone (e.g., dryland, forest, cultivated, etc) and population potential (a relative measure of population agglomeration), as both were also found to influence city-growth in Asia (Balk et al., 2009). We will apply the model at varying scales to assess variation in the factors driving change related to both scale and location (i.e., processes working at regional versus local scale, and/or differences in the factors driving spatial change at different geographic locations) . Using the United States as an example, we will apply the model at the national, census division, state, county level, and/or city-level.

Table 2. Explantory variables and hypothesized scale of maximum influence

Variable	Scale of Strongest Influence
Total Fertility Rate (TFR)	Local
Child Mortality Rate (Q)	Local
Net Migration Rate (NM)	Regional, Local
Population Agglomeration (V)	Regional, National
Ecozone (X)	Regional, National

Based on the past work of Jones, as well as Montogomery and Balk, we hypothesize that the importance and influence of certain factors affecting the spatial distribution of the population will vary based on scale and the resolution of the input data. Table 2 reviews the explanatory variables discussed in the previous paragraph, and the scale at which we expect each to exhibit its strongest influence over spatial change. For example, we expect that population agglomeration will exhibit a stronger influence over broad scale changes in the distribution while fertility rates will help differentiate smaller scale patterns of change. To test these hypotheses we construct an econometric growth model (assuming spatial correlation in the disturbances)to spatially explicit historical population data. As a left-hand variable we consider a cell-specific continuous growth rate, extracted from historical population counts from at least two time periods:

$$g_{i,t_0} = \frac{(lnP_{i,t_1} - lnP_{i,t_0})}{(t_1 - t_0)} \quad (1)$$

We then model the rate of change as:

$$g_{i,t} = \beta_0 + \beta_1 TFR_{i,t} + \beta_2 Q_{i,t} + \beta_3 NM_{i,t} + \beta_4 V_{i,t} + X_i + u_{i,t} \quad (2)$$

Where TFR is the total fertility rate of cell i (taken from the administrative unit in which cell i resides), Q is the child mortality rate (also taken from the administrative unit in which cell *i* resides), NM is the net migration rate, V is population potential, X is a set of dummy variables indicating the ecozone in which cell i resides, and u is the random effect component where:

$$u_{i,t} = \rho \sum_{j \neq i} w_{ij} u_{j,t} + \varepsilon_i \qquad (3)$$

where ρ is the spatial autocorrelation coefficient and w_{ij} is a spatial weight. We derive cell-specific estimates of net migration by extracting the population change that cannot be explained by applying state-level fertility and mortality rates:

$$NM_{i,t} = \left[\left(P_{i,t_1} - P_{i,t_0}\right) - \left(b_{i,t} - d_{i,t}\right)\right]/1000 \qquad (4)$$

Where $P_{i,t1} - P_{i,t0}$ is the change in population between time t and $t+1$, and $b_{i,t}$ and $d_{i,t}$ are the total number of births and deaths over the period (extrapolated from state-level fertility and mortality rates). It has been shown that city-growth rates vary as a function of total population (Balk et al., 2009). We use population agglomeration as a surrogate for city-size in our model, measured as the population potential of each grid cell:

$$V_i = \sum_{j=1}^{n} \frac{P_{j,t}}{D_{ij}} \qquad (5)$$

where P_j is the population at each point j, and D_{ij} is the distance between each point *j* and point *i* for which potential is calculated. The concept of population potential, first introduced by Stewart (1942), is borrowed from the physical sciences as the demographic corollary to Newton's law of gravitational potential. Considered across all points in an area, potential represents a relative measure of the proximity to the existing population at each point within the area (Warntz and Wolff, 1971). In practical terms potential is a distance weighted measure of neighborhood population density, measured in people per unit of distance. O'Kelly and Horner (2003) show that this metric is similar, but not identical to population density.

Outputs from this first proposed phase of our research include the identification of the factors driving and/or associated with patterns of spatial population change. These results will aid in constructing a theoretical framework for the proposed objective of phase two, constructing a theoretically consistent modeling framework for producing alternative spatial population scenarios that account for multi-level processes. Additionally, we anticipate that results from phase one will be used to contribute to the existing literature regarding spatial patterns of population change, particularly in urban geography.

Phase Two: Construct and evaluate spatial population projection model

The second phase of this proposed research involves two primary objectives: (1) construct a theoretically consistent gravity-based model for producing spatial population projections and (2) test that model against the econometric growth model using historical data. The former represents our attempt to apply the theoretical knowledge generated in the first phase of this work to the development of a unified design to improve our understanding of human vulnerability to climate-related hazards while the latter establishes the validity of the model in a test against historical data and an alternative methodology.

As a starting point we will consider the gravity framework of the NCAR spatial population model, which uses historical population data to estimate population change gradients, and the demographic data that drives the city-growth model to produce a hybrid gravity approach to modeling spatial population. Population change gradients indicate how urban distance-density gradients are changing over time, which in turn indicates a certain type of broad socio-economic development pathway. For example, a shallowing gradient is indicative of a sprawling development pattern which often includes the diffusion of job opportunities and socio-economic amenities across a larger quasi-urban region (typical in wealthier societies). Conversely, vertical type development, or concentration, leads to steeper density gradients that often are indicative of higher fertility rates, large urban-to-rural migration rates, concentrated economic opportunities, and poorer societies. Demographic characteristics of the population can be correlated to specific types of growth/change patterns at multiple-levels of analysis. In the first phase of the proposed work we isolate these relationships. In this phase we incorporate them into our gravity framework.

Before applying the model, we determine which explanatory variables merit consideration for inclusion in our model (based on results from phase one) and how to structure our multi-scaled approach (again based on results from phase one). In regards to the latter we anticipate three possibilities: (1) a multi-scale model with varying components based on the scale of application, (2) a multi-level model with varying components based on the resolution of application, and (3) a scale/resolution consistent model in which the components of the model remain the same but parameter estimates vary as a function of both the scale and resolution of application. We will select option 1 if we find that the scale of application impacts which explanatory variables found to be significant in driving spatial change. In option 2 we consider a multi-level model in which population projections are downscaled from the national/regional level first to a coarse resolution grid according to a model of broad-scale spatial change, and then to a higher resolution grid according to a second model calibrated to reflect changes over a smaller spatial area. We will select this option if the influence of the drivers of spatial change vary as a function of spatial resolution. If the scale of application and/or resolution don't impact which explanatory variables are significant then we will select option 3, a scale/resolution consistent model.

Our spatial population algorithm downscales national/regional population projections to sub-national raster grids. Beginning with a gridded distribution of the base-year population the model consists of two steps: (1) construct a population potential surface by calculating potential for each grid cell and (2) distribute projected change in the national/regional population to grid cells proportionally according to their respective population potentials. This process is repeated for each time step to complete the spatial projection.

Potential for each cell is calculated as

$$v_{i,t} = a_i l_i \left[\left(\sum_{j \neq i}^{m} P_{j,t} e^{-\beta_t d_{ij}} \right) + P_{i,t}^{\alpha_{i,t}} \right] \qquad (6)$$

where $v_{i,t}$ is potential of cell i at time t, a_i is a cell-specific adjustment factor that removes border effects from the procedure, l_i is a geospatial mask indicating the portion of each cell that is suitable for human habitation, $P_{j,t}$ is the population of grid cell j, d is geographic distance between two grid cells, α and β are parameters, and j is an index of the m cells within a 100 km window[10] around cell i. The β parameter is a universal parameter which is calibrated and applied according to the scale of analysis (i.e., state, county, etc). It is indicative of the shape of the distance-density gradient controlling the broad pattern of horizontal/vertical development. The α parameter is a cell-specific measure, indicative of the likelihood that demographic characteristics of the local population will lead to proportionally larger or smaller gains/losses in population. Thus wrapped up in the α parameter are all those factors that influence local population change at a fundamental level (fertility, mortality, and migration propensity).

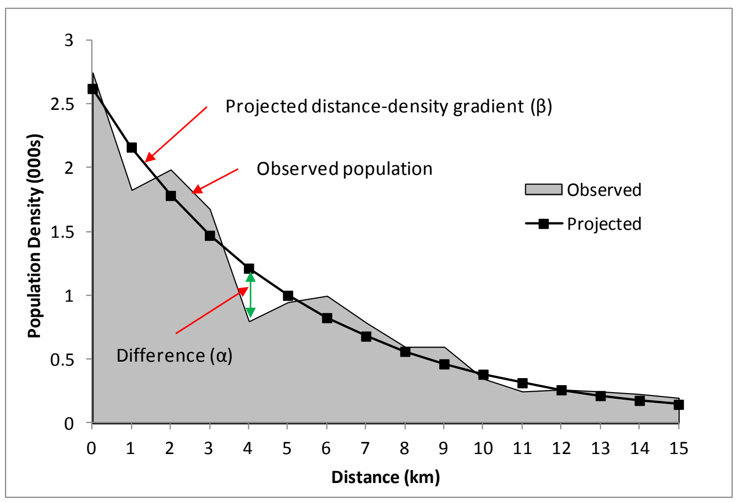

Figure 5. Envisioning the α and β parameters.

In order to carry out step 1 we must produce estimates of the α and β parameters. We propose employing two separate procedures. The β parameter is designed to capture broad-scale patterns of change found in the distance-density gradient (see Figure 5). The negative exponential function in Equation 6 is very similar to Clark's (1951) negative exponential function which has been shown to

[10] A measure of the average sphere of interaction. For example, a distance of 100 km encapsulates 98.5% of all person trips in the United States according to the 2009 National Household Transportation Survey (NHTS, 2009).

accurately capture observed density gradients throughout the world (Bertaud and Malpezzi, 2003). The Clark formulation includes a single distance-decay parameter which can be extracted by fitting the function to observed spatial data. To estimate β we will employ a similar technique, and fit the model in Equation 6 to the historical data. For purposes of estimating β we will hold α constant at 1 (the value it would assume in the Clark formulation) and adjust the value of β such that we minimize error:

$$\frac{P_{i,t}^{obs}}{P_{A,t}^{obs}} = \frac{P_{i,t}^{mod}}{P_{A,t}^{mod}} + \varepsilon_i(\beta) \qquad (7)$$

where $P_{i,t}^{obs}$ is the observed population in cell i and $P_{A,t}^{obs}$ is the observed total population, while $P_{i,t}^{mod}$ is the modeled population in cell i and $P_{A,t}^{mod}$is the modeled total population (which will match $P_{A,t}^{obs}$ as it is a function of the exogenous population projection(s) that are being downscaled through this algorithm).

In this proposed model the α parameter is a cell-specific measure that is indicative of the impact of local demographic and/or geographic characteristics on spatial population change. To estimate the parameter for each grid cell we first use the value of β from Equation 7 to generate a projected population field (still holding α constant at 1). The gradient of spatial change in this projection will be relatively smooth (see “Projected” in Figure 5). For each cell there will be an error in the projected population (the difference between the observed and projected populations in Figure 5). We hypothesize that these errors can be explained by including a measure of the local demographic/geographic characteristics, which is contained in the α parameter. Moving forward, we calculate the value of α necessary to eliminate ε_i (from Equation 7) for each individual cell. We call this value the observed α. We will then estimate the relationship between observed α and cell-specific demographic/geographic characteristics by fitting a spatially autoregressive model:

$$\alpha_{i,t} = X_{i,t}\beta + u_{i,t} \qquad (8)$$

and

$$u_{i,t} = \rho W u_{i,t} + \varepsilon_{i,t} \qquad (9)$$

where X is the set of explanatory variables, u the random effect component, ρ is the spatial autocorrelation coefficient and W is a spatial weight matrix. From this procedure we estimate a set of cell specific α values. Finally, to produce a spatially explicit population projection we use our estimates of α and β and exogenous projections of national/regional population change and apply our model as specified in Equation 6.

We have hypothesized that the drivers of spatial population change operate in a distinct hierarchy across multiple scales. The hybrid gravity approach proposed here is designed to capture and account for the drivers of spatial population and the manner in which they affect change at varying scale and resolution. We propose to test the performance and validity of our model using historical data, beginning with the United States and China. For example, in the case of the United States, we will estimate parameters and apply our model to gridded 1950 US census data in an attempt to replicate the structure of the 2010 population, and we will compare our results to spatial projections produced using the NCAR spatial population model and the econometric growth model (Equation 2) from phase one. We will then move on to the third and final phase of our proposed research; an assessment of human vulnerability to climate-related hazards.

Phase Three: Assessment of vulnerability in selected regions of the world

In the final phase of this proposed work we will use our model in a study of human vulnerability to specific types of climate-related hazards, namely, sea-level rise and storm surge as well as urban heat events and drought. We will investigate the future exposure/vulnerability, and sensitivity in these measures, that results from alternative spatial population scenarios (driven by alternative demographic futures).

For each region of the world we investigate (beginning with the US and China and working towards the global-scale) we will produce a series of spatial scenarios that incorporate different assumptions regarding future vital and demographic characteristics of the population. For example, we might in one scenario consider an high-population, slow economic-growth storyline (similar to the SRES A2 scenario) in which fertility remains highly influential in affecting local growth, while in another consider a medium-population, rapidly economic-growth storyline (similar to the SRES A1 scenario) in which migration becomes the primary driver of population change. We will then overlay these data with physical data and/or climate model output to measure exposure/vulnerability.

Balk and colleagues produced the first estimates of population (urban, rural and total) living in a low-elevation coastal zone (McGranahan et al., 2007). Other studies have further examined coastal exposures (e.g., Licher et al., 2011), yet no study has forecasted changes in both population and the coastal zone. Our proposed evaluation of vulnerability to sea-level rise and storm surge will be supported by digital elevation data and constructed using ArcGIS software. For sea level rise, global climate models such as those participating in CMIP5 do not have the capacity to simulate all the main influences on global sea level, and also do not model local changes in coastal land elevation (e.g., subsidence or glacial rebound). Therefore we will employ benchmark scenarios for increased levels of storm surges. For example, we will calculate the number of people living in areas that would be inundated by a 2-meter storm surge, representative of events that could become commonplace in the US by the end of the century (Tebaldi et al., 2012). Results will indicate both the predicted portion of the population (for each region of analysis) that is vulnerable to alternative projections of rising sea-levels and potential storm surge as well as the variation in these predictions that results from alternative demographic futures (indicating the degree to which demographic characteristics of the population could potentially impact future vulnerability).

We propose a similar procedure to assess potential exposure to drought and urban heat events. We will extract projected temperature and precipitation variables from CCSM for our study regions (see Peacock, 2012, for the example of the US) and use them to calculate indexes for extreme heat and precipitation events at the grid cell level, allowing for calculation in turn of numbers of people exposed to these events. For heat stress we will focus on urban areas where the urban heat island will be an exacerbating effect. Heat events will be measured by simple variables such as temperature and humidity (e.g., a heat wave index based on three consecutive night-time temperatures, Meehl et al., 2004), but also derived quantities such as apparent temperature (Steadman, 1984) and simplified wet bulb globe (Willett and Sherwood, 2010).

As a final step we will begin to anticipate the impact of feedback to climate-related hazards on spatial projections of the population. While it is not possible to model feedback through the use of observed historical data (the appropriate physical/spatial population data do not exist on a large enough scale), we can think responses within the hybrid-gravity framework through the inclusion of an additional spatial layer which indicates geographic exposure to varying degrees of risk. Then, by systematically varying the anticipated response to risk (by decreasing the attractiveness of at-risk grid cells) we can investigate the sensitivity of the projections to different levels of feedback and/or comment on the degree to which feedback can change future vulnerability.

From these results we expect to shed light on the importance of the spatial distribution of the population in the assessment of human vulnerability to climate-related hazards. Furthermore, we believe we will generate new knowledge concerning the impact of demographic characteristics of the population on spatial population outcomes, and improve upon existing methods for projecting spatial distributions into the future. Planning for a sustainable future, particular in urban areas and across the developing world, requires a working knowledge of the factors that drive vulnerability. This final phase of our proposed research is designed to provide a small taste of the potential broader impact of this work.

Professional Development Plan

The fields of climate mitigation and climate adaptation are remarkably distinct, including among those who study the human aspects of climate-change. Dr. Jones comes from the climate-mitigation tradition. His work as a fellow will not only place him squarely among those who study climate adaptation, but his proposed modeling will force connections in theory, modeling and data sharing between the two approaches. This is an important development for a young scholar, as well as for the scientific community.

At CUNY, Dr. Jones will enroll in two doctoral-level demographic methods courses (basic and advanced mathematical demography) to acquire formal tools for undertaking some of the proposed activities. CUNY's Institute for Demographic Research (CIDR) was created in 2007 and is a burgeoning center of demographic thought and analysis in New York City. It will afford Dr. Jones an opportunity to work in a demography center rather than a geography one. Dr. Jones would become an Institute Affiliate and be expected to participate in the intellectual life of the Institute – attend and give seminars, participate as a guest lecture in various demographic classes, and participate actively in national and international professional meetings. Professor Balk would act as Dr. Jones' mentor. Balk, who is Associate Director of CIDR, and who has managed very large research projects, has considerable experience training students and mentoring junior colleagues of many levels. Jones would himself be assisted by a student research assistant, who he would supervise under the direction of Balk, as needed.

CIDR has a full suite of administrative and computing resources that would support Jones' work. CUNY also hosts a Center for Sustainable Cities (CISC), headed by Professor William Solecki, who is lead author on the Urban Areas Chapter of the Fifth Assessment of the IPCC. (Balk is an active member of the CISC advisor panel.) Jones would be encouraged to take advantage of such local expertise.

Also in New York, Jones work would include frequent interactions with Professor Montgomery. (Montgomery's office is very near to CIDR, and he and Balk hold project meetings frequently.) Therefore frequent interaction between Jones and Montgomery (and Balk) will be possible. In-depth collaboration, particularly on the model specifications, is expected. Balk and Montgomery will help Jones foster develop new networks among demographers interested in climate-related applications at academic and applied institutions, many of whom are located in New York.

Jones will also interact with Brian O'Neill of NCAR, who will be the partner mentor for this project. This interaction will consist of monthly phone conferences as well as visiting NCAR 1-2 times per year. During these visits Jones will be able to interact with others in the Integrated Assessment Modeling group that O'Neill leads, as well as climate modelers producing and analyzing output from NCAR climate model simulations, particularly important to phase 3 of the project. One of Jones' visits each year will be timed to attend the meeting of the Societal Dimensions Working Group of the NCAR climate model, a recently formed group of researchers within and outside of NCAR aimed at facilitating interaction between climate modelers and scientists in other fields employing model results in interdisciplinary research. These meetings will provide Jones the opportunity to interact with a broad array of researchers working at the interface between the natural and social sciences as related to climate change. He will have the opportunity to present his work at these meetings as well as in NCAR seminar series.

Finally, annual team meetings will be held at CUNY, attended by all participants. To present research findings, Jones will participate in at least one of the annual meetings of the Population Association of America, the American Association of Geographers, and the American Geophysical Union, each year, with the explicit goal of deepening interest in interdisciplinary approaches to understanding the connection between population and climate change. (He will participate in more conferences, as the budget allows.)